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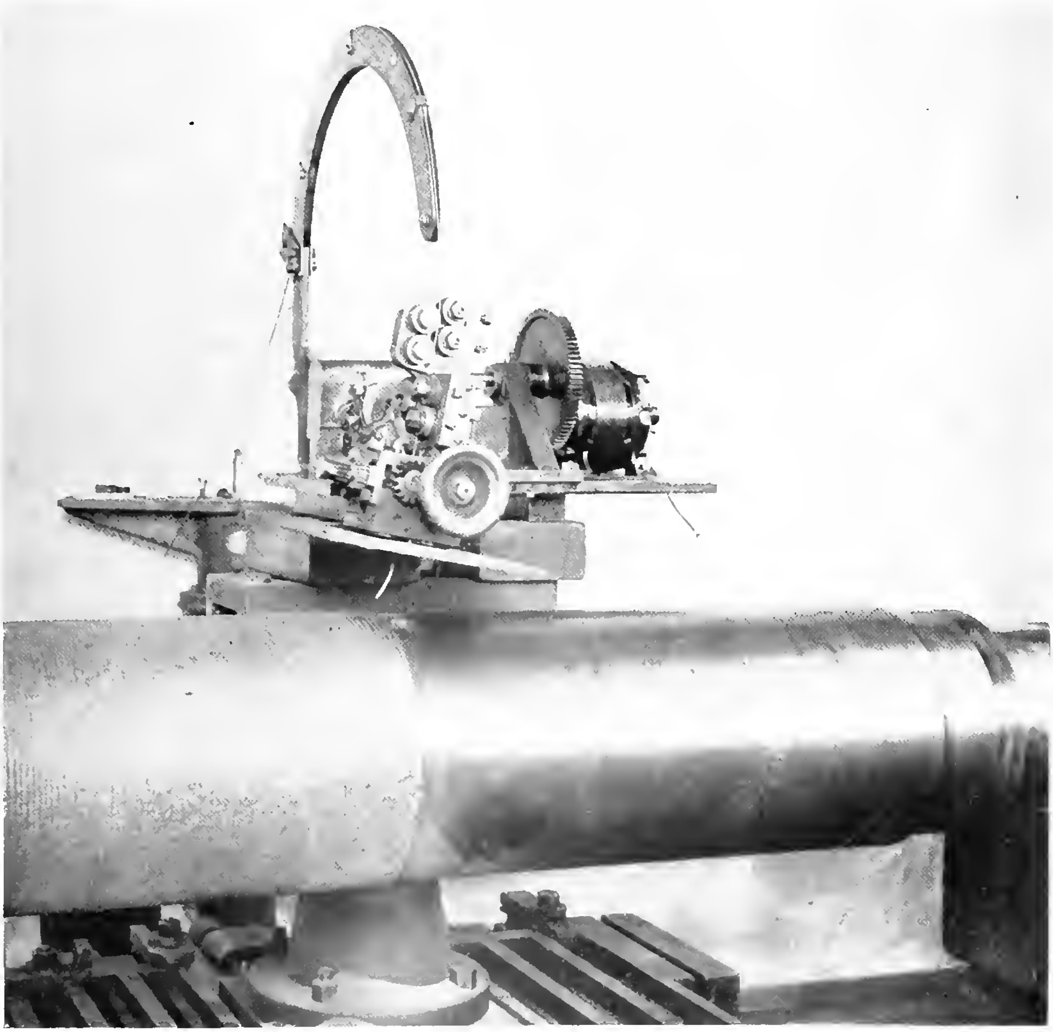

AUTOMATIC ARC WELDING MACHINE
In Operation on a 14-in. Shaft, Increasing the Diameter $\frac{3}{8}$ in.
by Means of Self-feeding Wire Electrode

GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

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WILLIAM LEROY EMMET

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GENERAL ELECTRIC REVIEW

EDISON MEDAL FOR 1919 IS AWARDED TO WILLIAM LeROY EMMET

The Edison Medal Committee of the American Institute of Electrical Engineers recently announced that the Edison Medal for the year 1919 had been awarded to William LeRoy Emmet "for inventions and developments of electrical apparatus and prime movers."

This is a signal honor for Mr. Emmet—an honor right well deserved as reward for his valuable work in the electrical industry, and for the courage and masterly ability which he displayed in evolving the steam turbine from an obscure embryonic stage of development to the most highly improved and satisfactory prime mover known; and in later years for his advocacy and development of a system of electric propulsion for ships of the navy and other large vessels which has been phenomenally successful in application and which has every indication of being epoch making.

Mr. Emmet was born at Pelham, N. Y., July 10, 1859, son of William Jenkins and Julia Colt (Pierson) Emmet, grandson of Robert and Rosina (Hubley) Emmet, and great-grandson of Thomas Addis Emmet (q.v.), the first one of the family in America. The latter was the distinguished Irish patriot and leader in the Society of United Irishmen in 1798, and an elder brother of the ideal patriot of the Irish race, Robert Emmet, who was executed in Dublin in 1803.

He was educated at schools in Canada, New York, and subsequently entered the United States Naval Academy, where he was graduated in 1881. He served as a cadet midshipman until 1883 at Annapolis and on board U. S. S. *Essex*, and re-entered the Navy as junior lieutenant in 1898, serving as navigator on the U. S. S. *Justin* during the period of the Spanish War.

Mr. Emmet first became associated with electrical work in 1887 when he entered the employ of the Sprague Electric Railway & Motor Company. He later went with the Buffalo Railway Company as electrical engineer, and soon afterwards accepted a position with the Edison General Electric Co., in the Chicago district. His association with the General Electric Company began with its organization in 1892.

Prior to his achievements in the steam turbine field, he attained prominence through his work in developing the general use of alternating current, and a number of inventions, which since have come into universal use, stand to his credit. Among his more important electrical inventions are the oil switch and varnished cambric cable; he also invented several types of transformers, several different forms of insulation for alternators, and many devices that are employed in connection with the Curtis steam turbine. His most brilliant accomplishments, however, have been more in the nature of an institutor of new methods and ideas than an inventor and a great deal of his most useful work could not be patented nor perhaps even classified as invention. His qualifications have specially fitted him for finding new scope for the talent and facilities of the Company's organization.

Mr. Emmet is the author of "Alternating Current Wiring and Distribution" (1894), and of numerous important papers presented before the American Institute of Electrical Engineers and other engineering societies. He is a member of the American Philosophical Society, American Institute of Electrical Engineers, American Society of Mechanical Engineers, Society of Naval Architects and Marine Engineers and of the Naval Consulting Board of the United States. He is also a member of the University and Engineers' Clubs of New York, the Mohawk Golf, Tobique Salmon, Mohawk, Edison, and Schenectady Boat Clubs. He received the honorary degree of D. Sc. from Union College.

Some Developments in the Electrical Industry During 1919

By John Liston

Publication Bureau, General Electric Company

Mr. Liston's annual review has been a feature of our January issue for a number of years. It is always an instructive and interesting summary of the recent developments in the industry, and this year the author has more to tell than ever before. The year 1919, in spite of a bad start, was one of the best business years that we have known and was chock-full of new enterprise.—Editor.

With the termination of hostilities, the Electrical Industry, as the result of its previous intensified efforts in research work and constructive production for war purposes, found itself possessed of a rich heritage of scientific achievement, much of which could be practically applied to meet commercial needs.

Even at the beginning of the first year of peace, the readjustment to a peace basis, which had begun promptly after receipt of the news of the signing of the armistice, was well advanced in many lines. Thus, projects which had perforce to be abandoned during the war, were again carried forward, and, combined with the urgent requirements of reawakened industries for electrical apparatus, resulted in an unprecedented volume of output by the end of the year, despite the unfavorable conditions at its beginning.

Among the many prominent developments, one of the most important is not electrical, although it is a direct product of the electrical industry. This is the very marked increase in the equipment of merchant ships with geared-turbine drive, as the result of the favorable operating records made by ships so propelled, some of which have been in service for a period of more than three years (Fig. 1) without replacement of, or repairs to, their turbine installations.

Another important item is the adoption, for the first time, of electrical propulsion for large cargo boats and the standardization of this method for the larger ships of our navy.

In aviation work, the supercharger has given every indication of present and potential value in this special field, while the radio developments referred to constitute a complete new system which is susceptible of widespread application on a commercial basis.

As in previous articles on this subject, the electrical apparatus, turbines, etc., referred to are all products of the General Electric Company, but references to their development will serve as an indication of the tendencies in design and construction as well as the general trend of progress in the electrical manufacturing industry as a whole.

Fig. 1 S.S *Hanna Nielsen* Propelled by a 2500 h.p. Two-plane Type Marine Geared Turbine. This ship has an active service record of over four years without any repairs or replacements being required for its turbine equipment

Turbines

The removal of the pressure on turbine production which characterized the period of the war, the release from government control and the consequent rescheduling and cancellation of turbines on order, together with conditions which had arisen due to shortage in skilled labor and other wartime handicaps, had the effect of temporarily arresting turbine development at the beginning of the year.

In a short time, however, the situation changed radically: new parts were manufactured to replace those which, due to wartime conditions, were below the high standard which in recent years has been demanded in turbine construction, and in addition an average of two turbines per month of from 15,000-kw. to 35,000-kw. capacity were produced, as well as full output in smaller units.

Due to the high price of fuel, economy in steam turbine operation is an increasingly important consideration. New development has, therefore, been along the line of improved economy, even in comparatively small ratings.

A number of the large single cylinder turbines (Fig. 2) which were designed primarily for stations where economy is essential were specially successful in actual service. They are very carefully proportioned so that at the point of maximum economy the velocity ratios and steam areas will be conducive to higher efficiency than has hitherto been possible.

Some interesting facts in regard to modern turbine economies are found in figures published during the year showing the overall station economy obtained in two moderate sized stations. The New Cornelia Copper Company, with 7500-kw. turbines, operating in conjunction with a spray pond, produced under average operating conditions a net kilowatt hour from 18,837 B.t.u. This corresponds to a thermal efficiency of 18.15 per cent.

In comparing the economy of this cooling pond station with that obtainable in tide water plants, allowance should be made for the obtainable vacuum under operating conditions, and the increased pumping head due to the spray nozzles. This point is illustrated by the results obtained at the plant of the Arizona Power Company, where with a 6000-kw. turbine and cool water, a net kilowatt hour was produced from 18,628 B.t.u. or a thermal efficiency of 18.3 per cent.

While these economies are rendered possible by the turbine design, they are also due in considerable degree to intelligent operation and careful selection of all auxiliary station apparatus.

In smaller capacities improved economies have been secured by refinements in design. In addition to driving generators (Fig. 3) these turbines are used for driving, through gearing, large pumps for municipal pumping plants. In this class of work economy is of the utmost importance, as the units operate at full load for practically 24 hours a day and 365 days a year.

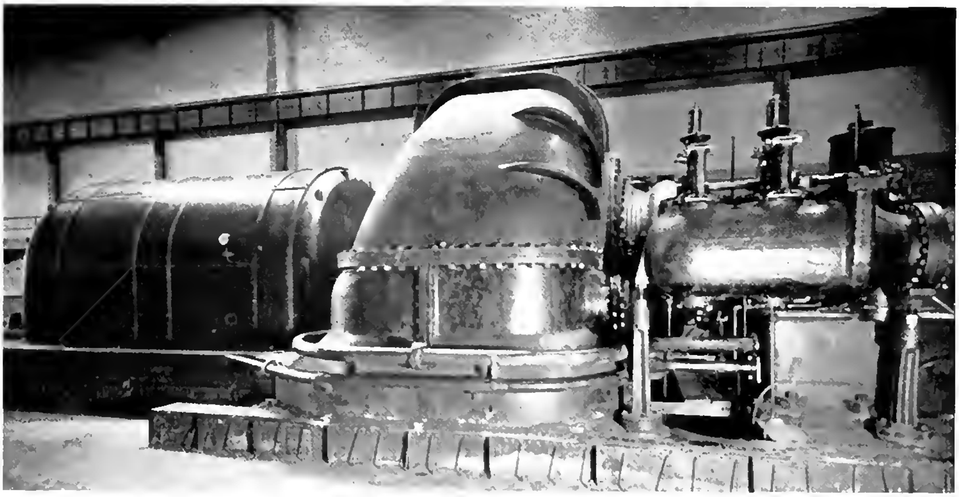

Fig. 2. 25,000-kw., 1800-r.p.m., 17-stage Turbine Direct Connected to 25,000-kw., 60-cycle Alternating Current Generator. This set is typical of the large turbo-generators produced during 1919

Marine Geared Turbines

On November 1, 1919, there were 245 cargo boats in service which were equipped with G-E marine geared turbines having an aggregate rating of 612,500 h.p. Of these, 130, with a total horse power of 320,000, were installed after January 1, 1919.

The turbine sets, comprising five-stage ahead and two-stage astern units and one-plane double reduction gears, were built in horse power ratings of 1800, 2400, 2500, 2600, 2800, 3000 and 4000, and are specifically designed for propelling modern cargo boats, oil tankers and refrigerating ships. The curve, Fig. 4, shows the very rapid increase in the number of units installed since 1915.

Practically all ships equipped since 1916 have the so-called one-plane type; i.e., the turbine and gear shafts all lie in one horizontal plane; this inherently simple design being adopted owing to the necessity for the speedy production of propulsion apparatus for ships to carry on the world war trade.

The pre-war 2500-h.p. geared turbine of the two-plane type is shown in Fig. 5. This design was adapted to the units required for emergency shipbuilding during the war, and gave practically 100 per cent of continuous service without replacement; this while in the hands of the ever changing crews which manned the ships both during and succeeding the war.

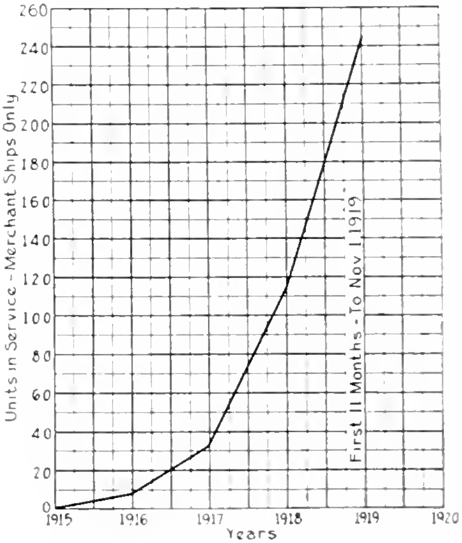

Fig. 4. Marine Geared Turbines in Service in Merchant Ships up to Nov. 1, 1919

A very large percentage of the gears of the pre-war two-plane type have been in service for nearly four years with negligible replacements. With the liberal increase in

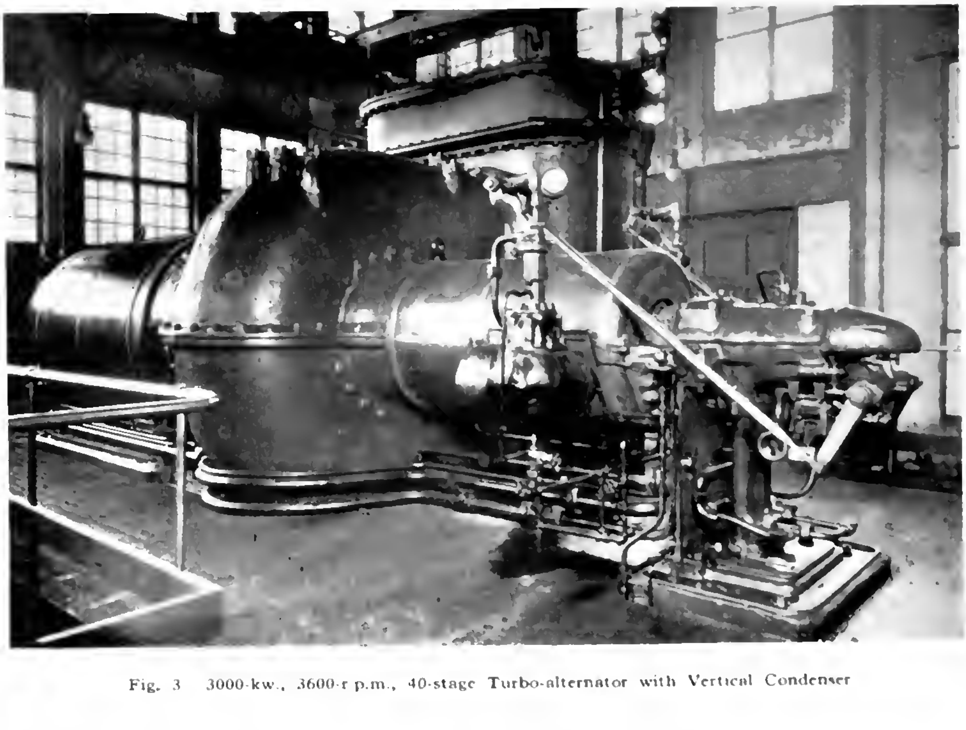

Fig. 3 3000-kw., 3600-r.p.m., 40-stage Turbo-alternator with Vertical Condenser size and consequent lower tooth pressure, and with the immense amount of experience gained in design, installation, lubrication, care and maintenance, a practically indefinite life can reasonably be predicted for this type of apparatus.

Four of the twelve 6000-h.p. units for the propulsion of the "B" type of ship being built at Hog Island were shipped, and the balance are now being finished at the rate of one complete turbine equipment every two weeks.

These units (Fig. 6) consist of a six-stage ahead and two-stage astern cross-compound turbine divided into a high-pressure and a low-pressure section, and double reduction twin drive one-plane type gears; each turbine section developing one half of the full power.

The design of the steam connections is such that in case of necessity one section can propel the ship independently of the other section. The maneuvering is easily accomplished through the operation of one double levered throttle valve.

Torpedo Boat Destroyers

The last three of six turbine driven destroyers, viz., the *McKean*, No. 90, the *Harding*, No. 91, and the *Gridley*, No. 92, had their trial trips and went into service early in the year.

Each propulsion unit, of which there are two for each destroyer, consists of one 800-h.p., 1856-r.p.m., seven-stage cruising turbine, immediately forward of and connected by a flanged coupling to a 13,500-h.p., 3497-r.p.m., 16-stage ahead and one stage astern main turbine (Fig.7) driving through twin single reduction gearing. The propeller shaft revolves at 452 r.p.m. when running full speed ahead.

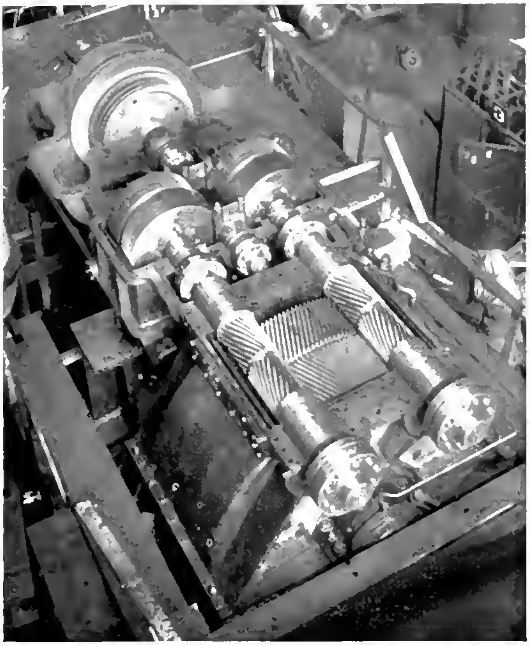

Fig. 5. Pre-war Type 2500-h.p., Two-plane Marine Geared Turbine

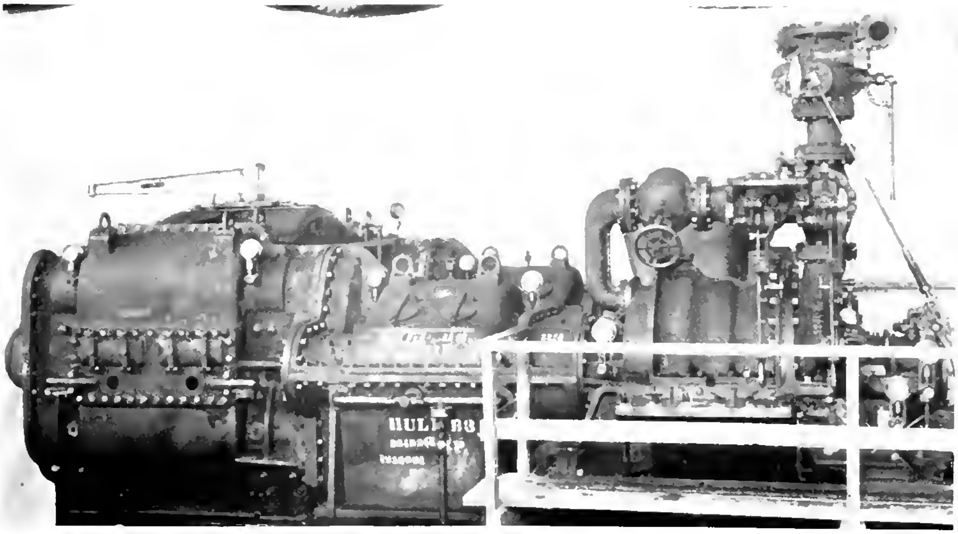

Fig. 6. Testing a 6000-h.p. Cross Compound Turbine Set for Driving *B* Type Cargo Boat

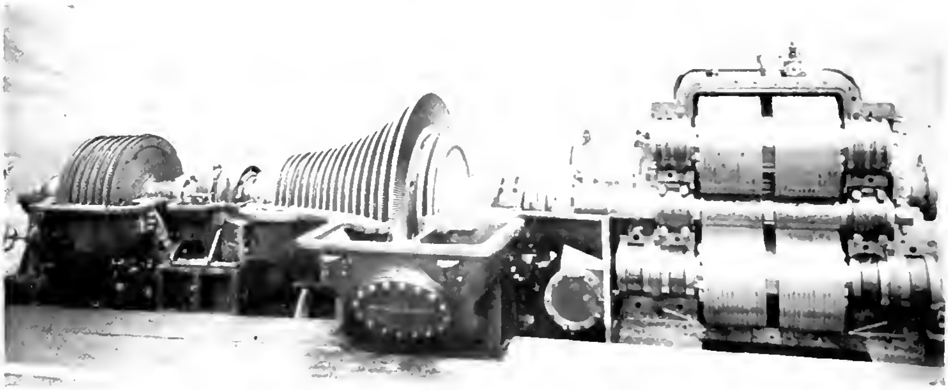

Fig. 7. Destroyer Type Cruising and Main Turbines and Reduction Gear
Cruising Turbine, 800 h.p.; Main Turbine, 13,500 h.p.

The total speed reduction from the main turbine speed to the low-speed gear, or propeller speed, gives a ratio of 7.74 to 1.

These turbines operate at 250-lb. gauge steam pressure and 28-in. vacuum exhaust; the cruising turbines delivering power up to 1856 r.p.m. (or about 20 knots), with the main turbines only delivering power above this speed. The design of the main turbine permits steam to be admitted to either the first or fourth-stage nozzles, depending upon the speed required.

The last of eighty propulsion units similar to those referred to above were completed in May, 1919, for forty destroyers (Nos. 296-335), thirty-six of them having been completed before the armistice (Fig. 8).

Lighting and Power Sets for Ships of the U.S. Navy

Many sets, consisting of a multi-stage high-speed steam turbine connected through flexible speed-reducing gears to a multi-polar direct-current generator in capacities of 300 and 400 kw., were supplied to the government for use on battleships and battery charging submarine tenders.

The turbines are built in both condensing and non-condensing types, are mechanically strong and simple in design, and embody the necessary emergency, back pressure and circuit breaker devices thoroughly to protect them in service against the possibilities of damage even when in charge of inexperienced operators.

A larger unit for this specific service, of 500-kw. capacity, was developed in 1919 to meet the rigid specifications of the navy department. The turbines are of either the four-stage condensing or non-condensing type, with a speed of 5000 r.p.m. when operating at 250-lb. gauge steam pressure and vacuum exhaust for the condensing unit, or when exhausting against 10-lb. gauge back pressure for the non-condensing machine.

Fig. 8 U. S. Destroyer *Robinson* in Santa Barbara Channel

This design will, in a great many cases, replace the 300-kw. sets where additional demands have been created for light and power, and the smaller units are no longer of sufficient capacity to meet the requirements. The 500-kw. size will also be installed on new battleships and battle cruisers.

Electric Propulsion

A great many turbine-generator propulsion sets for installation aboard merchant ships are under construction at the present time and one equipment is now being installed on the *Powhatan* of the West Coast Steamship Company.

The turbines are rated 3150 h.p., have 8 stages, operate normally at 3000 r.p.m. and are direct connected to 2350-kw., 50-cycle, 1150-volt alternating-current generators. Energy for excitation purposes is furnished by two high-speed turbine generator sets.

The propulsion is accomplished by one 60-pole, 3000-h.p. motor which is connected to the propeller shaft and revolves at 100 r.p.m. at full speed ahead.

The turbines are designed for admitting exhaust steam from the ship's auxiliaries to a lower stage, and every advantage is taken to obtain a high over-all operating efficiency.

Maneuvering is normally accomplished by two levers mounted on the main operating panel which is located close to the turbine-generator set; the speed lever being mechanically connected to the turbine governor, and the motor control lever being electrically connected to the main exciter contactors. In this manner the handling of the ship for ahead or astern operation is easily and simply accomplished.

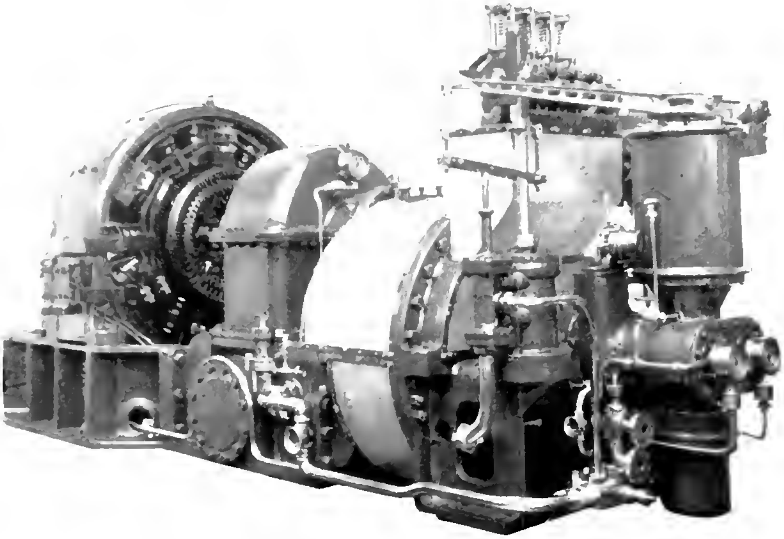

Fig. 9. 300-kw. Lighting and Power Geared Turbo-generator Set

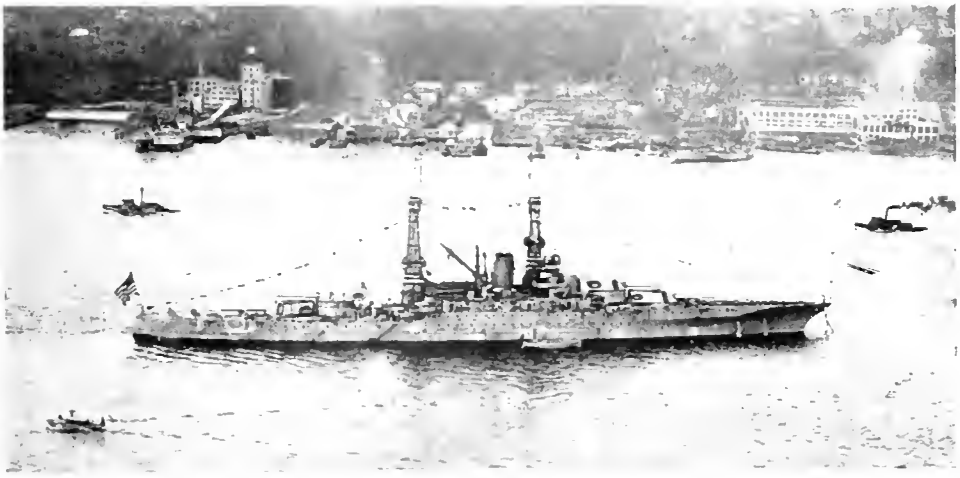

Fig. 10. Airplane View of U S.S. *New Mexico*. The first electrically-propelled battleship

U.S. Battleships

During the year many service investigations were made aboard the U.S.S. *New Mexico,** the first capital ship of the American Navy to be electrically propelled by turbine-generator sets (Fig. 10); and much valuable data have been thus obtained which will be applied in the design and operation of future electrically driven ships.

Fig. 11. Scout Cruiser *Salem*, the first ship to use spring thrust propellor shaft bearings

The apparatus for the new battleships *California* and *Maryland* is practically completed, and that for the *West Virginia* is well under way. Many improvements and innovations are embodied in these units based on the experience gained in connection with the *New Mexico's* sets.

For the battleship two units with a total of 60,000 h.p. will be required, and for the battle cruisers four sets will be installed, giving a total capacity slightly in excess of 180,000 h.p. to give a maximum speed of 33 knots.

The battleships will each be propelled by four 15,000-h.p., 2-phase, 5000-volt, 221-r.p.m. motors, while the battle cruisers will each have eight propelling motors with a unit rating of 22,500 h.p., 3 phase, 5000 volts at 330 r.p.m.

Spring Thrust Bearings

An interesting detail of the equipment of some of the electrically propelled ships is the use on the propeller shafts of spring thrust bearings having characteristics similar to those which were originally developed for use as suspension thrust bearings on vertical shaft waterwheel-driven generators.

These bearings have been in use in hydro-electric plants for several years and, as they have successfully carried the thrust of rotating loads up to 550,000 lb. in this service, they were adopted as a standard equipment for G-E vertical shaft generators, and their recent adaptation to meet the requirements of marine service was a logical development.

The pioneer installation was made in March, 1918, on the 26-knot twin screw scout cruiser *Salem* (Fig 11) which is driven by two 10,000-h.p. turbines through reduction gears. The thrust exerted by each propeller shaft when rotating at 380 r.p.m. is 80,000 lb., and the thrust bearings, which are similar in design to that shown in Fig. 12, are each located in a housing bolted to the reduction gear cases, thus forming an integral part of the turbine equipment.

Fig 12. Spring Thrust Bearing for Marine Propellor Shafts

After six months of active service, these spring thrust bearings, upon examination, proved to be in as good condition as when

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*See General Electric Review, April, 1919, and G E Booklet Y-1307.

they were installed, and, in fact, indicated no appreciable wear.

During 1919 bearings of this type were in production for different classes of electrically propelled ships, among them being four cargo boats, two coast guard cutters, and a fishing trawler.

The cargo boats are eleven knot single screw craft, each of which will utilize a 3000-h.p. motor to drive the propellor shaft at 100 r.p.m., giving a thrust of 57,000 lb. A spring thrust bearing is located at the forward end of the motor shaft and its housing constitutes a part of the bearing bracket or end shield of the motor; this being the first marine application of a combination motor end-shield and thrust bearing.

Lubrication of the thrust bearing and motor journal bearings will be supplied by a pump, driven from the motor shaft.

On the 16-knot, single-screw coast guard cutter the thrust bearing will be located aft of the 2600-h.p. 130-r.p.m. driving motor and will be subjected to a thrust of 33,000 lb. It will be lubricated by the turbo-generator oiling system.

The 10½-knot single screw trawler with a 400-h.p., direct-current driving motor has a self-oiling thrust bearing (Fig. 13) located aft of the motor and sustains a thrust of 7500 lb. with the propeller revolving at 200 r.p.m.

It should be understood that these spring thrust bearings are all of the single-collar type, are self-aligning, and show greatly reduced friction losses as compared with the rigid multi-collar type heretofore used for propellor shafts.*

Radiator Cooling

Among the latest features considered in the development of the turbine-driven alternator is that of a closed system of ventilation.

Under certain conditions long air ducts of large cross-section for the inlet and outlet of cooling air required by the alternator are highly objectionable, not alone from a consideration of the loss of the valuable space which they might occupy, but sometimes on account of the openings being in a region of poisonous or injurious gases.

In such cases a closed system of ventilation is desirable. With this arrangement, however, it is necessary to remove the heat of the generator losses from the cooling air, which is used over and over again. Generally an air washer may be utilized for this purpose to the best advantage, but there are important cases where the use of an air washer is impossible because of the character of the available cooling water.

In order to meet such special conditions, it is now considered quite advisable, as a result of numerous tests, to utilize a water cooled radiator of the fin and tube type whose function would be the reverse of that of an automobile radiator.

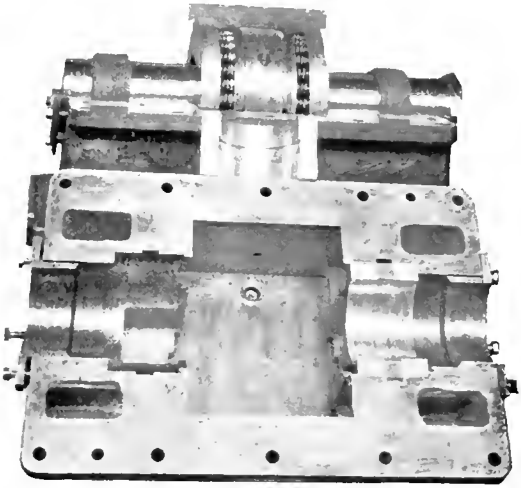

Fig. 13. Spring Thrust Bearing Installed on Steam Trawler

It may be surprising to know that a radiator having a core of 100 cubic feet would have a good margin in capacity for cooling the air from a 25,000-kv-a. turbine alternator.

That the use of a radiator is quite feasible from a consideration of space, resistance to air flow, rate of heat transfer, etc., will be explained by an article in the February issue of the GENERAL ELECTRIC REVIEW. The advantages of this system are specially valuable on shipboard.

The Supercharger

In connection with turbine research work, there was developed a turbine-driven supercharger for airplane engines, utilizing the energy of the exhaust gases of the engine to drive a small centrifugal compressor which can supply air, at sea-level density, to the engine intake at high altitudes.

The importance of this airplane auxiliary, which makes it possible to maintain high engine efficiency at high altitudes, can be appreciated when it is understood that engines not provided with a supercharger de-

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*Article GENERAL ELECTRIC REVIEW, February, 1919, by H. G. Reist.

liver only 50 per cent of their sea-level energy at 18,000 ft. elevation, while at 25,000 ft. the reduction is about 75 per cent.

The supercharger was first developed in the laboratory, and after factory tests was taken to the summit of Pikes Peak, Colorado, where for several weeks it was subjected to long continued operation tests in connection with an airplane engine. Its satisfactory performance under these conditions gave every assurance of its safety and practical value, and on August 2, 1919, the pioneer flight of an airplane equipped with a G-E supercharger took place at McCook Field, Dayton, Ohio.


Fig. 14. LePere Biplane Equipped with G-E Supercharger in Test Flight Above McCook Field, Dayton, Ohio

A LePere biplane (Fig. 14) driven by a 12-cylinder Liberty Motor was used, and at an elevation of 18,400 ft. it attained a speed of 137 miles per hour as compared with its best previous performance, under similar conditions but without the supercharger, of 96 miles per hour.

The turbine rotor and the light weight impeller of the compressor are mounted on a common shaft (Fig. 15) and normally rotate at about 22,000 r.p.m., a simple valve in the exhaust piping of the airplane engine permitting the pilot full control of its operation. The weight of the entire equipment, including all necessary piping, is about 100 lb.

Electric Traction

Activities in the electric traction field were largely confined to the installation of automatic substations and the purchase of the one-man, light-weight safety cars. Electrification projects in the course of construction progressed satisfactorily, but few new developments were initiated. Because of the lack of financial resources, there was very little addition to power equipment by electric railways, with exception of the automatic substation.

Electrification

The principal electrification in the United States, and without doubt the most important project of its kind, is the Chicago, Milwaukee & St. Paul Railway, which has completed a 217 mile extension across the state of Washington from Othello to the cities of Seattle

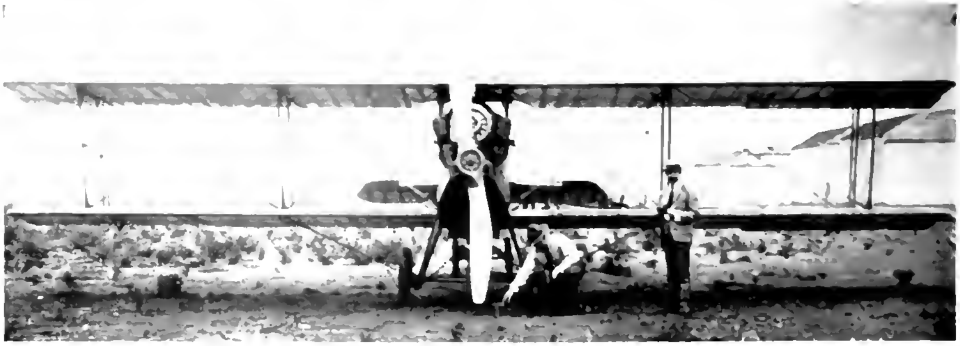
Fig. 15. Biplane Equipped with a G-E Supercharger which can be seen back of the upper blade of the propellor

and Tacoma. The substations and the transmission lines are now ready for operation, and the overhead construction is completely installed. Locomotive deliveries were completed by the end of the year and electrical operation over the entire distance should be an accomplished fact early in 1920. Two freight locomotives were placed in operation in October, 1919, on the 2.2 per cent grade west of the Columbia River, releasing for other service five steam engines ordinarily used for pusher service on this grade.

The five bi-polar gearless passenger locomotives (Fig. 16) are now completed, the first unit having been shipped on November 1, 1919.

The electrification of the government owned steam suburban lines radiating from the city of Melbourne, Australia (Fig. 17), progressed materially during the year. About 200 miles of line are now operating electrically, the major part of the work having been completed since the war, which held up all construction work.

The contracts for this work were awarded some time ago, and included orders for 400 complete motor car equipments. Each equipment consisted of four GE-239, 750 1500-volt motors, multiple unit control, air compressors, and other accessories. Orders were later placed for four 1500-kw., 1500-volt synchronous converters which are now in operation, and control equipment was also furnished for 400 trail cars. This 1500-volt direct current electrification is apparently operating with all the success which was predicted for it, and work is being pushed rapidly on the completion of the remaining suburban lines

Fig. 17. 1500-volt Direct Current Multiple Unit Train on Victorian Railway, Melbourne, Australia

The Salt Lake, Garfield & Western Railway completed its change-over to electrical operation during the summer and is now operating about 21 miles of line with multiple unit equipment and G-E automatic substations.

Another electrification which will begin operation during the present year is the Hershey Cuban Railway, which will operate a line about 60 miles in length between

Fig. 16. 265-ton Gearless Passenger Locomotive in Test for Chicago, Milwaukee & St. Paul Railway

Havana and Matanzas, Cuba. About one half of this road is now operating with steam engines and the remainder will be new construction.

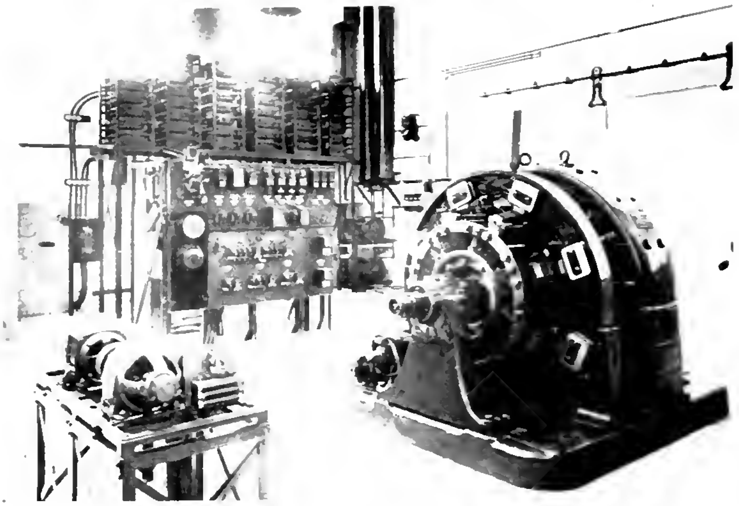

Fig. 18. 1000-kw. Automatic Railway Substation Installed for Pacific Electric Railway

The electrical equipment furnished includes G-E power and substation machinery, overhead line material, motor-car equipment and locomotives. The trolley potential will be 1200 volts direct current and the substations are of the standard automatic type, each containing two 500-kw. 600-volt synchronous converters operating in series. A third unit will be installed in each station as a spare.

There are seven electric locomotives on order, each weighing 60 tons. These will be used for hauling raw sugar and other freight to ports for shipment. The passenger traffic over this line will be handled by multiple unit motor cars, fifteen of which will be used, each equipped with four GE-263 motors and Type PC control.

Automatic Substations

The continued popularity of the automatic substation (Fig. 18) is shown in the increased orders for various types and sizes up to 2000-kw. and 1500-volts direct current. The largest unit so far constructed is a 2000-kw. synchronous motor-generator set now being installed for supplementing the power supply to the Michigan Central R.R. operating electric locomotives through the Detroit river tunnel.

Automatic substation equipment was sold in Cuba, Australia and New Zealand, and inquiries were received from other foreign countries. At the end of 1919, there were approximately 50 G-E equipments in operation and about twenty more either under construction or being installed.

Safety Cars

One of the most popular outfits in the electric railway field during the past year was the light weight safety car, large numbers of which were utilized to replace heavier equipment. Results obtained from the operation of these cars indicate that their use will, to a certain extent, assist operating companies in keeping down the cost of operation without the necessity of resorting to increased fares. Practically all safety cars employ the type K-63 controller, which was specially designed for this service. For motive power, the GE-258 motor has continued to be most popular (Fig. 19).

Fig. 19. Light Weight Safety Cars for Eastern Wisconsin Electric Co., equipped with GE-258 motors and K-63 control

In order to meet the preference of some railways for a motor of this size with standard sleeve bearings instead of ball bearings, the GE-264 railway motor was designed and a considerable number of these are now in service. Approximately 1400 of these two motors have been sold during the present year. Other equipment for the light weight safety car includes the CP-25 air compressor and straight air brakes with safety devices (Fig. 20).

Fig. 20. Safety Car Handling Rush Hour Traffic at the Indiana Steel Co. Terminal, Gary, Ind.

Equipment for Metropolitan Railways

On account of the lack of financial means for adding to their electrical equipment, there was little activity in the purchase of equipment for heavy city, subway and elevated lines. Orders were placed, however, for 600 more GE-248 railway motors for the Brooklyn Rapid Transit Company, making a total of approximately 1600 of these motors now in service. The Boston Elevated Railway Company is also putting in service 200 electro-pneumatic air brake equipments and has placed orders for 232 GE-259 motors with tapped fields for replacing motors of an obsolete type now in use.

Electric Locomotives

Aside from the five 265-ton passenger locomotives which were completed for the new Chicago, Milwaukee and St. Paul electrification,* there were also two 70-ton switchers for the same line, which are now in operation on the Rocky Mountain Division.

Work is nearing completion on the 50-ton, 1200-volt locomotives ordered some time ago for the South Manchurian Railway in China, and on four 60-ton, 1200-volt locomotives for the Cienfuegos, Palmira and Cruces Railway in Cuba.

Other locomotives under construction include seven 60-ton units for the Hershey Cuban Railway previously mentioned, and a 30-ton switching locomotive for Harlowton Mills at Lawrence Mass., and other industrial types.

Miscellaneous Railway Equipment

The power limiting and indicating system installed along the lines of the Chicago, Milwaukee and St. Paul electrification has shown interesting possibilities. By the use of this scheme, the Company has been able to maintain an unusually high load factor, thus securing very nearly the minimum power rate provided for in the contract with the Montana Power Company.

High-speed Circuit Breakers

The intensive study of methods to protect direct current machines, particularly the 60-cycle 600-volt synchronous converter, from flashing, was continued during 1919 with important results and there were developed three graduated forms of protection which will now give immunity under all operating conditions.

First, commutating poles of a high reluctance type with much stronger field windings than those previously used were designed, tested in service and adopted as standard. This insures ample protection where operating conditions are favorable.

Second, where greater protection is required the machines can be provided with a type of flash barrier which has fully demonstrated its value in railway service on lines where severe short circuits are of frequent occurrence.

Third, the highest degree of protection includes the use, with the foregoing, of a newly developed high speed circuit breaker (Fig. 21) which has fully demonstrated its value under tests of much greater severity than those imposed by the most unfavorable conditions encountered in actual service.

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* See article by W. D. Bearce in December, 1919, GENERAL ELECTRIC REVIEW.

Standard circuit breakers have always been much too slow in operation to prevent flashovers on heavy short circuits. Repeated tests have indicated that a circuit breaker, to prevent flashover, should operate, stop the current rise and reduce it below the flashing value in something less than the time required for a commutator bar to pass from one brushholder to the next. On a 60-cycle machine this means a speed of approximately eight one-thousandths of a second, whereas the ordinary circuit breaker operates in about eight to ten one-hundredths of a second.

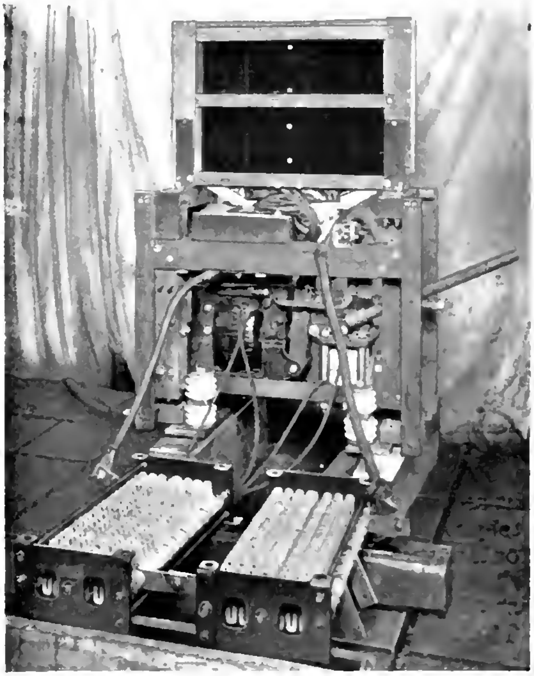

Fig. 21. High Speed Circuit Breaker, showing Limiting Resistance and Connections Used During Test

A simplified diagram, illustrating the principal features of this breaker and the connections for the negative side of a generator, is shown in Fig. 22.

F_1 and F_2 represent a laminated field structure something like that of an ordinary alternating current magnet. The poles of F_1 and F_2 are bridged by a very light armature A pivoted at P, which is held in contact with the field by a shunt coil S_1 energized from any convenient constant voltage source, such as the exciter circuit or the main bus.

The series bucking bar S_2, which electromagnetically trips the breaker, is located between the poles of the field magnet in a plane perpendicular to the plane of the laminations and in very close proximity to the armature, so that a given current flowing in it produces a maximum change in the armature flux with a minimum change in the flux interlinking the shunt winding S_1.

The tension spring attached to the armature provides a means of adjusting the breaker and also gives the high speed opening of the contacts. The main contact tips C_1 and C_2 are of the solid copper type used so successfully on railway contactors. The blowout coil S is of the series type and designed to give a very intense magnetic field at the contacts.

Several hundred short circuit tests were made of this circuit breaker on the Chicago, Milwaukee & St. Paul 3000-volt motor-generator sets and also by short circuiting the trolley conductors at various distances from the substations, and there were no cases of failure in the protection afforded. Five of these circuit breaker equipments have already been provided for locomotives and eight for the substations on this system.

At the Railway Convention at Atlantic City, Oct. 4-10, 1919, a 300-kw., 600-volt, 60-cycle synchronous converter protected by a high speed circuit breaker was subjected to short circuit from two to three times per hour. This public test was continued with entire success throughout the five days of the convention.

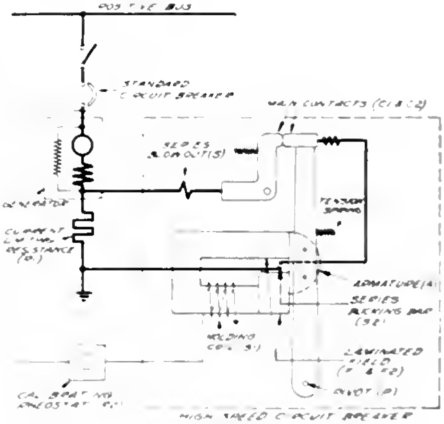

Fig. 22. Connections of JR High Speed Circuit Breaker, Schematic Diagram for Negative Side of Generator

Automatic Generating Stations

The success of the automatic generating station at Cedar Rapids, Iowa (Fig. 23), and the many railway automatic substations in service has encouraged the development of other generating and substations along automatic lines.

An automatic hydro-electric generating station was developed for the Blue River Power Company at Seward, Neb. This plant consists of a 240-kv-a., 120-r.p.m., 60-cycle, 2400-volt waterwheel-driven generator, and three 80-kv-a., 24,000/2400-volt transformers, and is the first of several stations to be installed on this system.

A second installation is for the Ontario Power Company at Ontario, Cal. This consists of one 500-kv-a., 60-cycle generator direct-connected to a Pelton waterwheel. Instead of being entirely automatic this station is controlled by pilot wires from a manually operated station a few miles below on the same stream.

When the operator desires to start the remote controlled plant, he closes the control circuit, which opens the nozzle to the Pelton wheel. When the machine is up to speed, he synchronizes it and then increases the load to any desired amount by a further opening of the nozzle.

The machine can be shut down at the will of the operator by closing a second control circuit, but in case of necessity, due to overload or hot bearings, this generator will shut down automatically.

Fig. 23. Automatic Hydro-electric Generating Station, Iowa Railway & Light Company. General view showing three 60-cycle, 500-kv-a., 60-r.p m., 2200-volt automatically-controlled generators

Automatic Distributing Stations

An automatic distributing station was developed for the Malden Electric Company, Malden, Mass. This substation equipment comprises one 3000-kv-a. transformer plant fed over one 22,000-volt line, with a second as a spare. It feeds three 3-phase feeder circuits and three single-phase feeder circuits which are controlled by automatic oil circuit breakers with a so-called notching relay.

This relay (Fig. 25) will close a circuit breaker if it has tripped out, and reclose it if it trips out the second time within a brief period. If the short circuit has not cleared itself by this time and the circuit breaker trips out a third time, the circuit will remain open until the circuit has been cleared and the switch closed by an operator. Thus the notching relay automatically performs the usual duties of an operator when a switch is tripped out in a substation.

Fig. 24. Temperature Relay, with Cover Removed, used for Protection against Hot Bearings in Automatic Generating Stations

One of the 3-phase feeder circuits leads to several constant current series lighting transformers. The switch in this circuit is opened and closed by means of a Warren time clock, and in addition is under the control of the notching relay.

Radio Communication

It was demonstrated during the war that practically continuous day and night transoceanic radio service could be effectively maintained. It is now a matter of history that radio was largely used for communication between the United States and the armies in Europe and that the great war was brought to a close by negotiations conducted by radio.

The work of the year 1919 was directed to adapt the system of radio communication which had been developed, to the increasing demands of commercial communication in peace times. An analysis of conditions of the radio art as left by the war shows that while radio has proven efficient and reliable, the systems which were used were inadequate to meet the great volume of international commercial traffic which is reasonably to be expected.

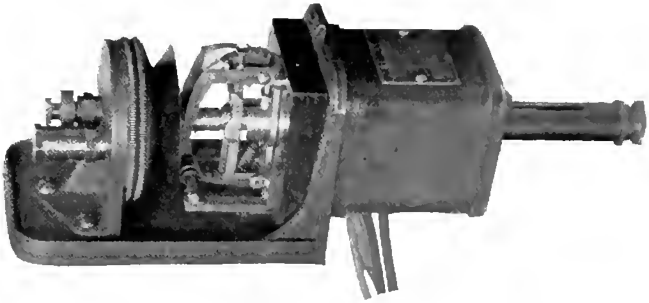

Fig. 25. Notching Relay, Single-pole, Single-throw, 600 Volts. Contacts are opened and remain open until reset by hand, if three separate impulses are given on the coil circuit within a definite time of each other

The practical and commercial aspects of these new demands are being met by the construction of a large number of 200 kw. radio frequency alternators with auxiliaries for equipping radio stations in all parts of the world.

These high power radio equipments (Fig. 26) are of the type which were used during the war in the Naval Radio station at New Brunswick, N. J., which was depended upon by the Navy for communication with Europe during the war and for the peace negotiations.* It was also through this station that transatlantic radio telephonic messages were sent, and the telephone communication established between officials in Washington and President Wilson's ship at sea.†

The new equipments which are being constructed embody a number of features which will make possible increased traffic capacity. The methods that have been proposed for this purpose are:

1. Closer spacing of wave lengths, making possible seven commercial wave lengths within the range now occupied by one station.

2. Increasing the speed of transmission from 20 words a minute to 100 words a minute or more.

3. Improvements in the receiving device whereby several communications can be carried on with the same wave lengths, by adjusting the receiver so that the messages are intercepted only from one direction without interference with other messages which

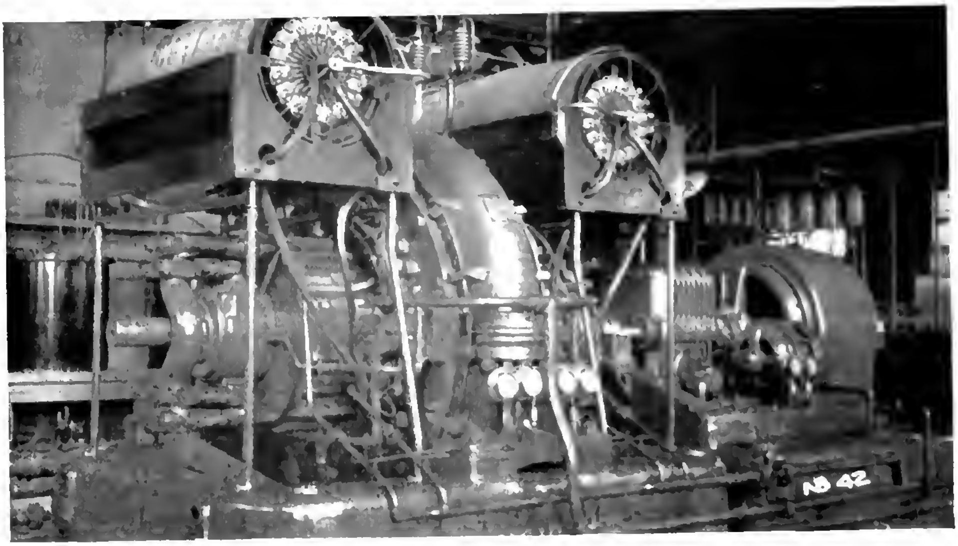

Fig. 26. 200-kw. High Frequency Induction Motor-driven Alternator of the Type Adopted for Commercial Radio Service

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* See article by J. R. Hewett in GENERAL ELECTRIC REVIEW, August, 1919.

† See paper by E. F. W. Alexanderson in A.I.E.E. Proceedings October, 1919.

are carried by the same wave lengths in other directions.

The increase of the number of radio stations in the world by the closer spacing of wave lengths is made possible by the use of the high frequency alternator, and particularly by the accurate method of speed regulation which has been developed. Thus different alternators may be operated to transmit different messages at speeds and frequencies differing only by 1 per cent, whereas the speed of each alternator is regulated to within one tenth of 1 per cent.

Although the alternators are driven by ordinary induction motors from commercial power supply, this accurate regulation of speed has become possible by the new type of saturation regulator (Fig. 27) which has been developed for this purpose. This regulator is a choke coil containing iron, and is connected in series with the power leads of the induction motor. The inductance or choke effect of this coil is controlled by a vibrator regulator of the ordinary power station type, which again is controlled by a sensitively tuned high frequency circuit. In this way an induction motor driven from an ordinary power supply can be made to operate at a speed varying not more than one tenth of one per cent, although the load on the motor is varying continuously in accordance with the dots and dashes of the telegraph code.

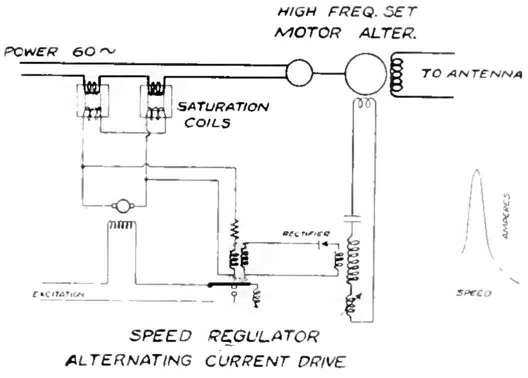

Fig. 27. Arrangement for Speed Regulation of Induction Motor Driven by High Frequency Alternator

The increase of the transmitting speed to one hundred words per minute or more for telegraphy, and in fact the complete control of the radiation by the human voice, has been accomplished by the magnetic amplifier (Fig. 28) which is a device based upon saturation of an iron core and operated analogously by the saturation regulator controlling the power flow to the induction motor. In order to commercialize high speed sending new types of relays have been developed which control the saturating current of the magnetic amplifier for telegraphy at speeds considerably more than one hundred words per minute.

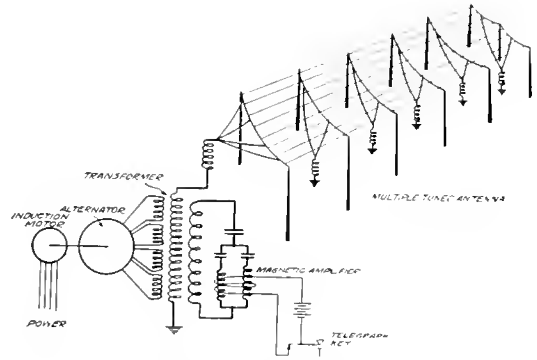

Fig. 28. Relation of Magnetic Amplifier to Other Parts of Radio Transmission Equipment

For the reception of high speed signals a new type of photographic recorder has been developed. The recorder is a highly sensitive type of oscillograph which prints on a sensitized strip of paper the dots and dashes of the high speed telegraph messages. This machine, which has been developed in commercial form, not only exposes the photographic tape but develops and dries the tape so that it comes out of the machine ready for translation on the typewriter.

The method of high speed transmission and reception of messages not only makes possible a larger volume of radio traffic but makes the messages for practical purposes as secret as the messages over telegraphic wires.

The increase of radio traffic by several communications on the same wave length is made possible by the development of the "barrage receiver" (Fig. 29), and other methods of simultaneous sending and receiving.* The barrage receiver is constructed on the principle that the messages are received on two or more antennae which have different sensitiveness to signals from different directions. The instrument can be adjusted so that a signal from any one or from several directions can be neutralized by bucking the wave received on one antenna against the wave received on another antenna,

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* Paper on Simultaneous Sending and Receiving, Proceedings of I.R.E., August, 1919.

whereas the signal from the desired direction is not neutralized but in fact intensified by the simultaneous action of the two or more antennae.

Thus a receiving station may be located close to a transmitting station which transmits on the same wave length and yet be insensitive to the signal transmitted by that station, whereas it receives signals from the other side of the ocean.

Fig. 29. Radio Receiving Set with Barrage Section

A receiving device operating on a similar principle was installed on President Wilson's ship, the *George Washington*, thereby making it possible to speak through the radio transmitter of the ship and at the same time listen to the signals from shore. By the use of this apparatus two-way conversation was held successfully between the ship at sea and officials in Washington, who were speaking over the telephones in the War and Navy department, connected with the high power radio station at New Brunswick.

The Research Laboratory

In the realm of pure science there was brought out a new theory of atomic structure, which, it is believed, constitutes one of the most important advances in theoretical chemistry that has been made for many decades.

The applicability of X-ray spectrum analysis to the study of atomic structure was greatly extended by the discovery that single large crystals are not required, but that the material may be studied in powdered form. This work has indicated the possibility of a new method of not only qualitative but of quantitative analysis by means of X-rays.

Early in the year a new X-ray tube designed specially for dental work was produced and is now available commercially.

A new portable X-ray outfit, including a new tube, can be operated from an ordinary lamp socket, and thus makes it practicable, for the first time, to take X-ray plates of a patient in his own home.

The war-stimulated development of radio sets using vacuum tubes was continued. The highest power vacuum tube set ever installed on shipboard was placed on the *George Washington* last spring for the President's use.

The range of pressures over which the ionization gauge can be used was considerably extended. This gauge still constitutes the best known means of measuring an exceedingly high vacuum.

A water-japan was developed in the laboratory during the war, but was not placed in production until 1919. Its characteristics are such that it bids fair to replace ordinary japan to a large extent, since it gives an equally good coat, and at the same time completely eliminates the element of fire risk.

Alternating Current Machines

The maximum unit capacity for synchronous condensers will be doubled, as compared with existing units, by the installation of a 30,000-kv-a., 600-r.p.m., 6600-volt, 3-phase, 50-cycle condenser which was under construction and nearing completion at the close of the year.

This machine (Fig. 30) will be located at Los Angeles, Cal., in the Eagle Rock substation of the Southern California Edison System where, in combination with two 15,000-kv-a. condensers already installed, it will be utilized to maintain constant voltage on a 150,000-volt transmission line about 240 miles in length. It is provided with a 150-kw. 250-volt direct connected exciter.

On account of its unusual size and the exceptional stresses which will be imposed on the revolving parts, the rotor is built up of laminated steel discs in place of the usual cast spider. The total weight of the machine is about 322,000 lb., the stator weighing 120,000 lb., the rotor 170,000 lb. and the base, bearings, etc., about 32,000 lb.

Ventilation will be provided by means of air conducted from the basement, through

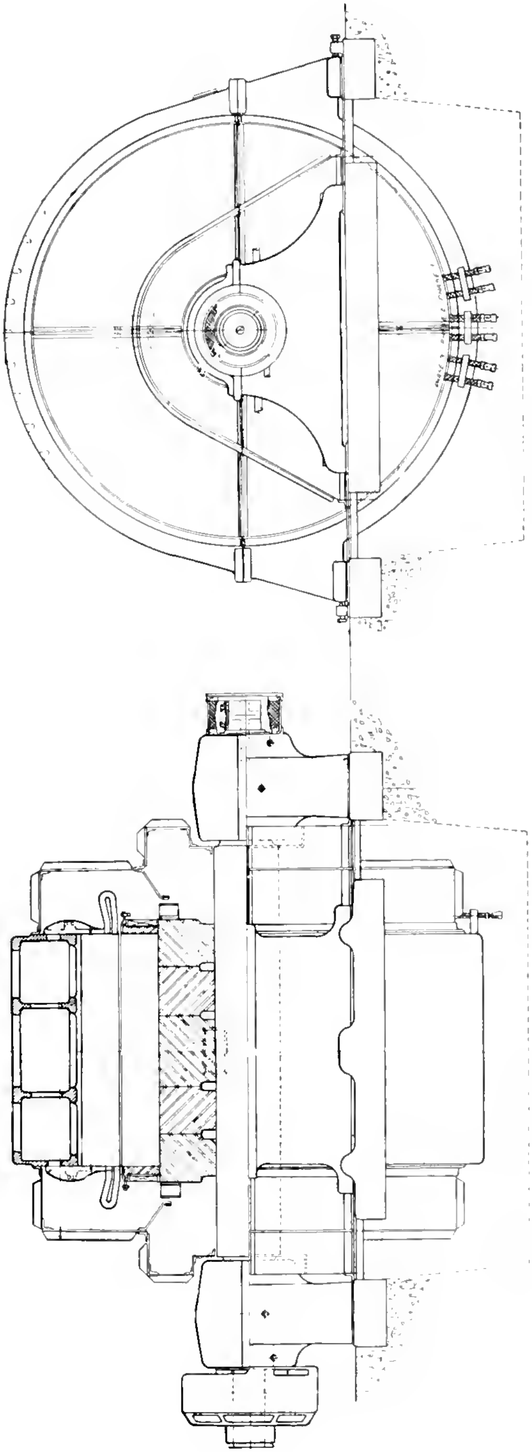

Fig. 30. 30,000-kv-a., 600-r.p.m., 6600-volt, 3-phase, 50-cycle Synchronous Condenser which when completed will have a greater capacity than any existing machine of this type

the machine, and discharging vertically. The guaranteed losses for this record capacity machine are less than 3 per cent.

The previous maximum voltage for synchronous condensers was also exceeded by the construction of two 12,500-kv-a., 500-r.p.m., 22,000-volt, 3-phase, 50-cycle units (Fig. 31) for the Andhra Valley Power Supply Co., of Bombay, India*

In view of its exceptional rated voltage, special insulation was required, and under test the coils successfully withstood a potential of 50,000 volts.

The 32,500-kv-a. 12,000-volt waterwheel-driven generator which was referred to in last year's article was completed and shipped during the year (Fig. 32). It is now being installed for the Niagara Power Co. and represents the maximum capacity for machines of this class.

Among the large alternators under construction is a 26,700-kv-a., 300-r.p.m., 6600/13,200-volt generator which will be direct driven by a 1500-h.p. induction motor. As this machine is intended solely for testing oil switches, it is designed with very low reactance so as to secure the largest possible current values under short circuit.

There is also an exceptionally large motor-generator set designed for use as a frequency converter. The motor is rated 12,000 kv-a., 7500 volts, 3 phase, 30 cycles, and the generator 15,000 kv-a., 5000 volts, 60 cycles. The set will be reversible in operation and will be installed at the Battle Creek, Mich., station of the Consumers Power Co., where it will tie in the 30 and 60-cycle systems.

A complete new line of small vertical shaft waterwheel generators was placed in production. These represent 170 different ratings ranging in capacity from 30 to 1000 kv-a. with speeds of from 360 to 100 r.p.m. for potentials of 240, 480, 600 and 2300 volts.

These machines (Fig. 33) were designed specially to meet the demand for an efficient, moderate priced generator, particularly for low head operation on relatively small streams, and to permit the economical extension of the small automatic generating station.

An important feature of the standard equipment is the plate type combined suspension spring thrust and guide bearing with which all sizes are equipped. These bearings as well as the lower guide bearings are all self oiling.

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*Article by M. C. Olson in GENERAL ELECTRIC REVIEW, November, 1919.

A noticeable tendency during the year was the increased use of synchronous motors for driving air compressors, ice machines, flour mills, rubber mills, pulp grinders, jordan engines, etc., which is indicative of a growing appreciation of this type of motor for mechanical work combined with power-factor correction and a better understanding among industrial engineers of the true economy of reasonable expenditures to maintain high power-factors on their lines.

During 1918 the increased use of synchronous motors in this way was more than 100 per cent over preceding years, and a further increase of about 65 per cent was shown by installations made in 1919. The capacities in greatest demand ranged from 125 to 600 h.p.

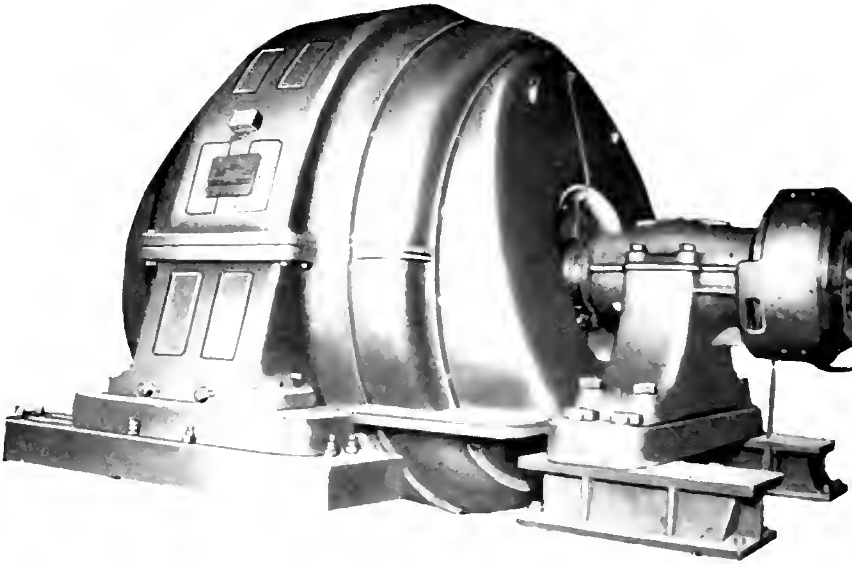

Fig. 31. One of Two 12,500-kv-a., 22,000-volt Synchronous Condensers, which has a higher voltage rating than any previously built machine of this type

Mine Hoists

An important installation placed in service in the latter part of 1919 is that of the C., B. & Q. R. R. at its mine operated by the Valier Coal Company in southern Illinois. The drive consists of a 1350-h.p. direct current motor (Fig. 34) direct connected to a single cylindrical drum on which two ropes wind for balanced operation of two self-dumping skips. The motor is served by a 1000-kw. flywheel motor-generator set, operated by public service power.

The most noteworthy feature of this installation is its semi-automatic operation. The trip may be started either by an operator on the hoist platform, in the usual manner, or by the skip tender at the bottom of the shaft, and is automatically retarded and brought to rest, stopping accurately in the dump and at the loading chute.

A similar installation has been in operation several years for the Inspiration Consolidated Copper Company, but at a rope speed of only 750 feet per minute, whereas the present equipment with a rope speed of 1500 feet per minute represents a considerable advance in the practice of automatic control of mine hoists.

These installations indicate the possibilities of a more general adoption of automatic features of operation in mine hoist service.

The Oliver Iron Mining Company placed in operation ten induction motor-driven mine hoists at the Norrie-Aurora Mines, Ironwood, Michigan. This installation consists of five 875-h.p. 360-r.p.m. motors (Fig. 35) for ore hoists, and five 400-h.p. 360-r.p.m. motors for man hoists, all operating on 2200-volt, 60-cycle circuits with liquid rheostat control. These hoisting equipments are noteworthy by reason of the carefully worked out system of safety devices and also as representing what is probably the largest aggregation of induction motor-driven hoists in a single mining system.

Among the larger hoisting equipments under construction is one for the Homestake Mining Company, Lead, South Dakota, comprising a 1400-h.p., 63-r.p.m. direct-connected hoist motor with a 1100-kw. flywheel set and 66,000-lb. flywheel

Fig. 32. Rotor of 32,500 kv a. Waterwheel Generator Being Erected in Power Station

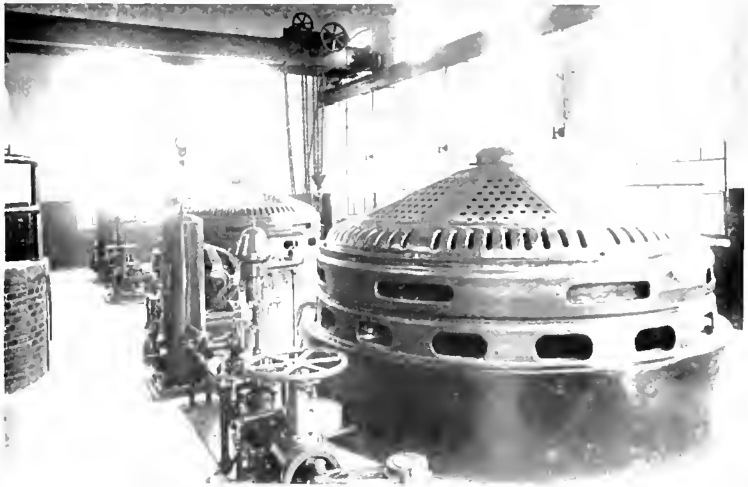

Fig. 33. Typical Installation of 300-kv-a., 120-r.p.m., 2300 volt Waterwheel driven Vertical Shaft Generators

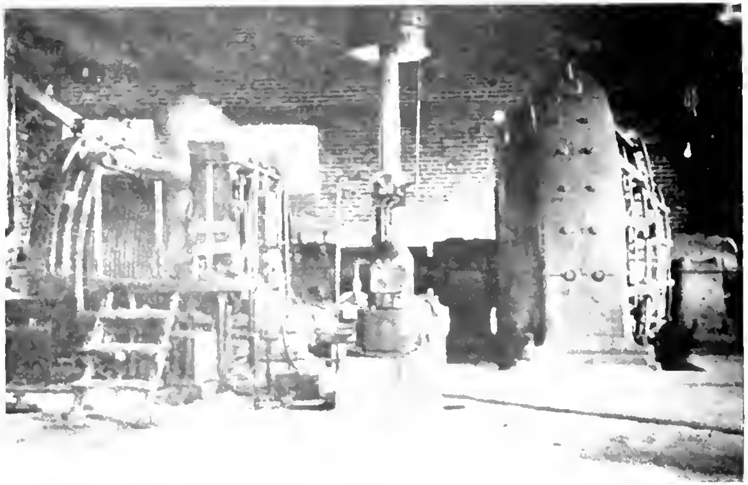

Fig. 34. 1350 h.p. Direct Current Motor Driving Single Drum Hoist at the Mine of the Valier Coal Company, Ill.

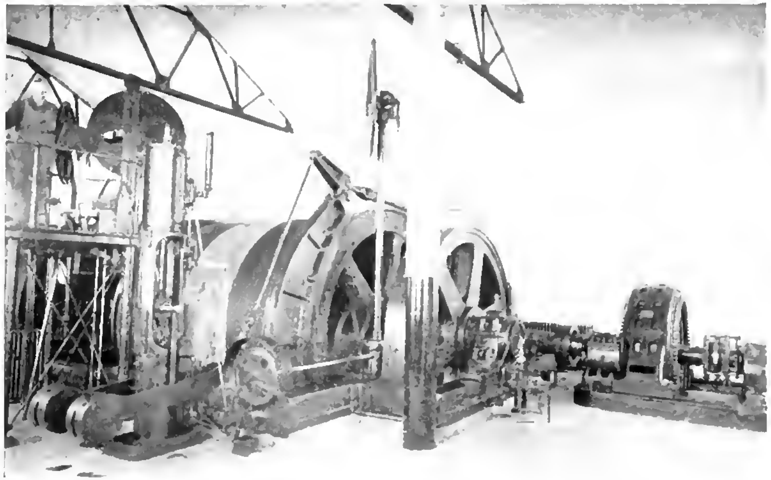

Fig 35. 875 h p , 360 r p m , 2200-volt Induction Motor Geared to Mine Hoist, Oliver Iron and Mining Company, Ironwood, Mich.

Toward the close of the year an order was received for two 5000-h.p. mine hoists for the Randfontein Central Gold Mining Company, Ltd., of South Africa. When these are completed they will be of considerably greater capacity than any existing electrical mine hoists.

The apparatus comprising each of these hoisting equipments includes the following: two 2500-h.p., 106-r.p.m., 600-volt direct-connected motors supplied by a 375-r.p.m. motor-generator set consisting of a 5000-h.p., 2000-volt slip-ring induction motor driving two 2000-kw., 600-volt generators with a 60-kw. exciter. Ward Leonard control will be used

These hoists will serve a 5000-ft. shaft and will carry five tons of ore per trip at a rope speed of approximately 4000 ft. per minute.

Roller Bearing Hoist

The one-ton Sprague hoist which has been on the market for a number of years was redesigned to include roller bearings throughout. This detail change is of considerable practical importance as it solves the lubrication problem which has always been a difficult one with hoists of this capacity on account of the lack of attention which frequently characterizes their use.

The roller bearings are packed in grease, which does not need to be renewed more than two or three times a year.

Electric Winch

An improved totally enclosed vertical winch (Fig. 36) was brought out, equipped with a vertical motor which can be either of the series wound direct-current type, or the slip-ring alternating-current type.

This winch is now produced in a number of ratings, up to 12,000 lb. pull, at 25 ft. per minute. A large number of them with direct-current motors and with a rating of 8000 lb. 50 ft. a minute, are being installed along the route of the New York State Barge Canal, where they will be used for warping canal-boats up to the docks.

Electric Shovels

A radical departure from previous practice is found in a recently developed electrical shovel equipment in that it eliminates all rheostat losses and the possibility of heavy peak loads and requires no overload relays or other form of protection for the electrical machinery.

The equipment comprises a four-unit synchronous motor-generator set (Fig. 37) with a direct connected exciter. There are three generators, one for supplying current direct to the two 170-h.p. hoist motors and one each for the 60-h.p. swinging and crowding motors, so that each of these three motor circuits is supplied by an individual generator. The hoist generator is rated at 250 kw. and the other two at 50 kw. each. A master controller is provided for each circuit and the control is effected entirely by voltage variation.

Due to the length of the motor-generator set and the possibility of mechanical strains to which it might be subjected when installed on a platform which must frequently be moved over rough ground in service, the set is divided into two pairs of machines, each pair being mounted on a separate base. The two shafts are united by means of a flexible coupling.

There is also a motor for operating the dipper trip, which is rated at 50-lb. torque and is thrown in or out of circuit by means of a push button switch located in the handle of the crowder motor controller. This small motor is energized from the 110-volt alternating-current lighting circuit. The other motors are all 230-volt direct current.

This unique set was constructed for use on a coal stripper shovel similar to that shown in Fig. 38, but its extreme simplicity renders it readily adaptable for the operation of any size or type of electric shovel.

Steel Mills

During the year there was added approximately 40,000 h.p. (normal continuous rating) to the existing capacity of main roll drives installed by the General Electric Company.

The electrical equipment driving the 40-in. reversing blooming mill at the Sparrows Point plant of the Bethlehem Steel Co. was put in service in April and has been in successful operation since that time. This equipment has a double unit reversing motor having a normal continuous capacity of 5000 h.p. (Fig. 39) at 50 r.p.m. and a momentary torque capacity of approximately 2,000,000 lb. at one foot radius at any speed from zero to 50 r.p.m. Power for this blooming mill motor is derived from a flywheel motor-generator set (Fig. 40), consisting of two 2000-kw. generators, one 3000-h.p., 6600-volt induction motor, and one 50-ton flywheel, operated at a speed of 375 r.p.m.

The layout of the Sparrows Point mill is such that the blooms, which are rolled from ingots in the 40-in. blooming mill can be delivered without reheating to a 24-in. six-stand continuous billet mill which is driven by a 4000-h.p., 83-r.p.m., 6600-volt induction motor (Fig. 41).

The product of this billet mill can be delivered direct to an 18-in. six-stand, continuous billet and sheet bar mill which is driven by a 3250-h.p., 94-r.p.m., 6600-volt induction motor.

Fig. 36. Sprague Vertical Dock Winch with Self-contained Electrical Equipment

Fig. 38. Electric Stripping Shovel, Piney Fork Coal Company, Smithfield, Ohio

During the early part of the year the new mills at the Fairfield Works of the Tennessee Coal, Iron & Railroad Co. were put in operation. The first mill to be started was the United Engineering & Foundry Co.'s 36-in. by 110-in. plate mill, which is driven by a 4000-h.p., 82-r.p.m., 6600-volt induction motor with direct connected flywheel (Fig. 42).

The 45-in. reversing blooming mill has an electrical equipment which is the largest reversing blooming mill equipment in this country. It is driven by a double-unit reversing motor having a normal continuous capacity of 5600 h.p. at 55 r.p.m. and a momentary torque capacity of 2,300,000 lb., at one foot radius, at any speed from zero to 50 r.p.m. Power for this reversing motor is derived from a motor-generator set consisting of three 2000-kw. generators, one 4000-h.p., 6600-volt induction motor, and one 50-ton flywheel operating at a speed of 360 r.p.m.

The structural and bar mill consists of one stand of three-high 28-in. rolls driven by a 2500-h.p., 82-r.p.m., 6600-volt motor, and three stands of 26-in. rolls driven by a 3000-h.p., 6600-volt motor with double range modified Scherbius speed regulating set, by means of which the motor speed may be varied from 130 to 155 r.p.m., the synchronous speed being 144 r.p.m.

The most revolutionary installation in the Fairfield Works is the electric drive for the hydraulic intensifier for the 1250-ton bloom and slab shear in the blooming mill. For reasons of mill layout it was necessary for a single shear to be used, powerful enough to cut 12-in. by 44-in. slabs and fast enough to keep ahead of the mill on 8-in. by 8 in. or 6-in. by 6-in. billets to be cut in comparatively short lengths.

To obtain this combination of power and speed a hydraulic intensifier was decided upon which would ordinarily be steam

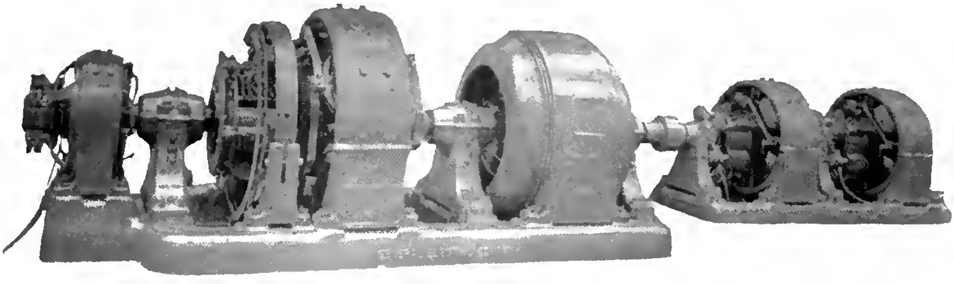

Fig. 37. Four-unit Synchronous Motor-generator Set for Current Supply to Electric Shovel

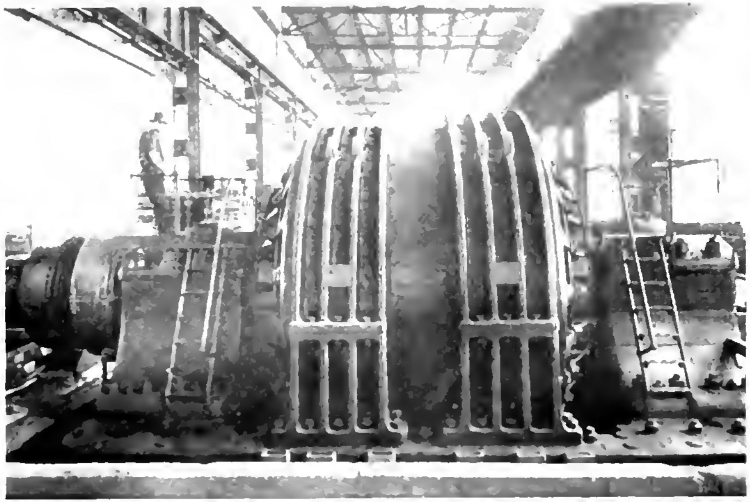

Fig. 39. 5000 h.p., 40/120 r.p.m., 1200 volt Motor Driving 40 in. Reversing Blooming Mill

Fig. 40. Flywheel Motor-generator Set for Reversing Blooming Mill, one 3000 h.p., 375 r.p.m., 6600 volt Induction Motor; two 2000 kw., 600 volt Generators; one 50 ton Flywheel

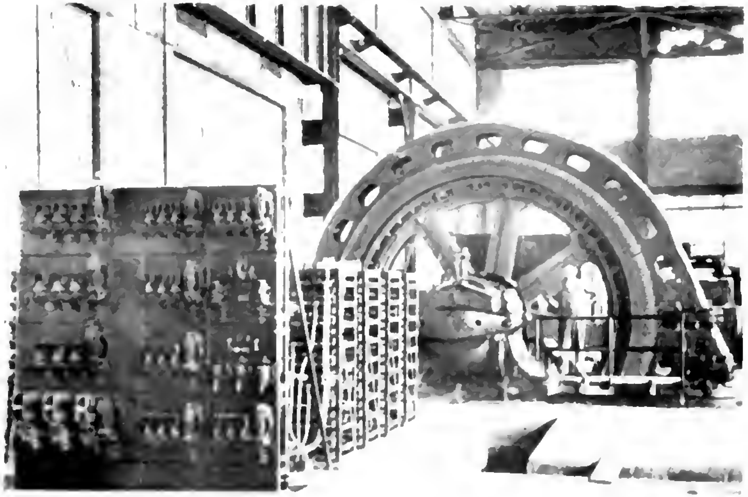

Fig. 41. 4000 h.p., 83.3 r.p.m., 6600 volt, 25 cycle Induction Motor with Starting Resistance and Control Panel Used in Connection with a 24 in. Continuous Billet Mill

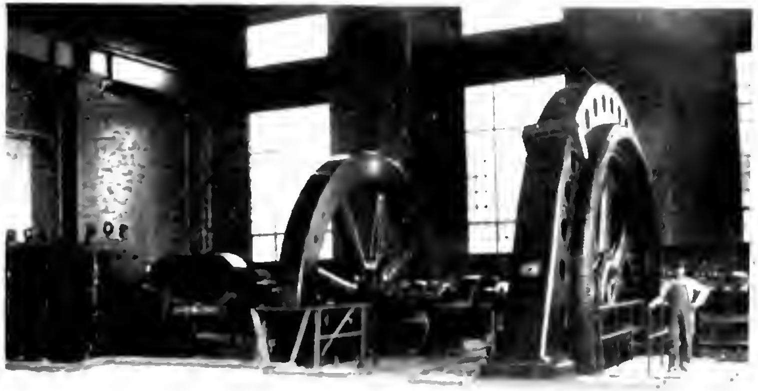

Fig. 42. 4000 h.p., 82 r.p.m., 6600 volt Motor Driving 110 in. Plate Mill

driven. But as this would have required a boiler plant for this drive alone, the builder of the shear proposed an Ilgner-Ward Leonard reversing drive with rack and pinion to replace the steam cylinder of a steam intensifier.

This drive comprises a direct current motor, 700 h.p. continuous capacity, 86 r.p.m., with a momentary capacity of 2450 h.p., a flywheel motor-generator set and a special control system. The electric drive has shown itself ample for all demands upon it and has thoroughly justified its selection.

There in now under construction an electrical equipment for a 40-in. reversing blooming mill, for the Tata Iron & Steel Co., at Sakchi, India. This equipment is similar to that installed on the 45-in. blooming mill at the Fairfield Works of the Tennessee Coal, Iron & Railroad Co., already described, except that the induction motor driving the flywheel set is a 50-cycle instead of a 60-cycle machine.

For the Superior Sheet Steel Co., of Canton, Ohio, construction work was started on two 1000-h.p., 300-r.p.m. induction motors each to drive a 30-in. sheet mill. This represents a departure from standard sheet mill practice in the use of a 300-r.p.m. motor which necessitates a gear ratio of approximately 10 to 1. The majority of installations in the past have used gear ratios of approximately 8 to 1.

One of the most interesting applications of induction motors with modified Scherbius speed regulating sets is that at the Riverdale Plant of the Acme Steel Goods Co. The mill is a 10-in. continuous hoop mill, and consists of a roughing train of six horizontal rolls and a vertical edging roll driven by a 900/530-h.p., 325/197-r.p.m. induction motor with modified Scherbius speed control; an intermediate stand driven by a 50/100-h.p., 300/600-r.p.m. direct current motor, and a finishing train consisting of five stands of horizontal rolls driven by a 1800/1200-h.p., 240/160-r.p.m. induction motor with modified Scherbius speed control.

Extensive developments at the plant of the Buffalo Bolt Company, Buffalo, N. Y., included the replacement of a direct current motor driving a merchant mill by an induction motor with modified Scherbius speed regulating set.

Printing Presses

A new type of combined predetermined speed and full-automatic control for printing machines was developed. The equipment (Fig. 43) consists essentially of a combined CEMF and current limit type self-starter, with dynamic brake and vibrating field relay. A separate field rheostat, operated by pilot motor, is under the control of the push-button stations.

The speed can be changed from the push-button stations through a range of 3:1, or the field rheostat setting can be left at any point and the motor will automatically accelerate to the speed corresponding to this setting.

An exceptional printing press equipment produced in 1919 is shown in Fig. 44. This is a direct-current, full-automatic printing-press control for handling a large newspaper press driven by two 100-h.p. motors, each motor being equipped also with a 10-h.p starting-motor for obtaining the slow motion and threading-in speeds. The two panels are arranged for parallel operation, the pilot motors being coupled together so that the load between the two 100-h.p. motors will be equally divided by a proper division of the armature or field resistances.

The printing press which these motors drive is one of the largest in existence.

Dynamometers

In order adequately to meet conditions brought about by the increasing size of aviation and marine gasolene engines, a new electric dynamometer (Fig. 45) of exceptional size was constructed for testing them.

During the war a considerable number of dynamometers were built for testing Liberty motors. These were rated at 400 h.p. at 1700 r.p.m., whereas the new machine has a rating of 600 h.p. at 1200 r.p.m., and has a maximum speed of 2000 r.p.m.

Fractional Horse-power Motors

The outstanding feature in regard to fractional horse-power motors, that is, motors rated at from ¾ h.p. down to 1/200 h.p., was the enormous increase in production achieved during 1919. As compared with 1918, this increase represents an advance of about 150 per cent, and as compared with 1916 of over 300 per cent.

During the ten years in which these small motors have been in standardized quantity production, the field of their utility has steadily broadened, and, whereas they were originally used on a very limited number of household devices and other light weight machines, they are now applied to more than 100 different classes of standard devices.

Originally the motors were applied as an auxiliary to the device which they operated, but with the steady growth of their popularity, the driven machine has in many cases been modified so that now the motor drive often constitutes an integral part of the complete outfit. The motor designer, on the other hand, has modified the mechanical details of the motor from time to time so as to render possible the most compact arrangement of the completed device, combined with the most efficient application of the electrical energy.

Fig 43. Sprague Automatic Predetermined Speed Control Panel

Every type of these small motors is designed with as much care and manufactured with as great accuracy and attention to detail as the huge turbines or waterwheel generators which supply the large central stations and transmission lines of the country, and the same care is also exercised in their test. Each unit, no matter how low its rating, is given an individual shop test before shipment. This policy has resulted in a reliability in operation which has recommended itself, not only to the engineer, but also to the users of the motor driven machines.

By means of electrical exhibits, demonstrations by central stations and sales agents, and by advertising, education in regard to the adaptability of electric motors has been carried on, with the result that in all household devices such as washing machines, vacuum cleaners, small pumps and air compressors, etc., where power application is required, the fractional horse-power motor is now generally recognized both by the manufacturer and the general public as giving entirely dependable service.

Transformers

A number of small transformers designed to be used between one line and neutral of a 66,000-volt, 3-phase grounded neutral system have been operating successfully for several months. They are especially suitable for use as small town lighting transformers or control transformers in automatic sub-stations, but some of them have been used with entire success for the much more severe service of "pulling" oil wells.

These transformers have one end of the winding permanently grounded to the core and tank and are provided with a terminal (Fig. 46) for connecting to the grounded neutral of the system. The insulation is graded from the grounded end to the line end which passes through the single cover bushing.

The cost of high voltage bushings is a large percentage of the total cost of these small transformers, and the saving thus effected by the use of only one bushing makes it possible for small communities near high tension transmission lines, but remote from the usual central station or sub-station facilities, to secure economical electric service.

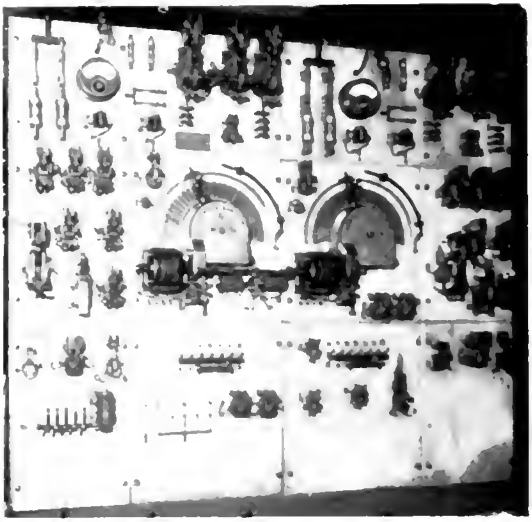

Fig. 44. 2100-h.p. Sprague Control Panel Arranged for Four motor Control, Chicago Tribune

The demonstrated advantages of the four-part "distributed core" (Form K) used for many years for small lighting transformers have led to the extension of this construction (Fig. 47) to larger units, and during the past year it was standardized for single phase transformers up to 1000 kv-a. at 33,000 volts. This represents a very considerable increase in both voltage and capacity as compared with maximum rating of previous years.

The use of alternating current for arc welding has led to the development of a special transformer for supplying this current. Alternating current arc welding requires an operating potential of from 25 to 30 volts across the arc, while to strike and hold the arc with the ordinary bare metallic electrode an open-circuit potential of about 100 volts is required. Added to this, varying operating conditions require that the welding current be adjustable through a considerable range, generally from 100 to 200 amperes.

The transformer designed for this special service consists of a primary and a secondary coil assembled on the center leg of a five-legged core. The secondary coil is generally placed at the bottom of the core and firmly secured. The primary coil is placed above the secondary and attached to a suitable mechanism by which it may be raised or lowered, varying the gap between the primary and secondary coils, thus giving a means of adjusting the welding current. The transformer is enclosed by a metal screen and is mounted on casters so that it may be readily moved from place to place.

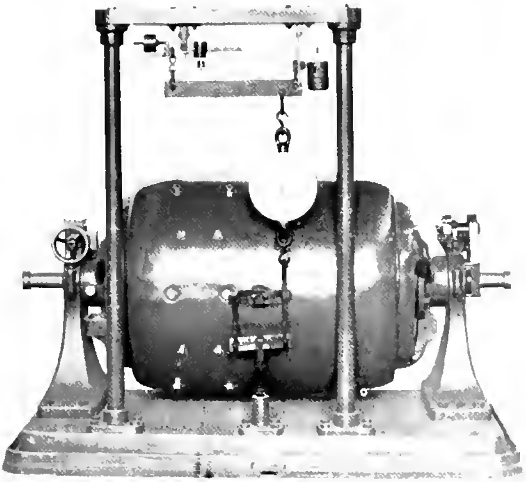

Fig. 45. 600-h.p. Sprague Electric Dynamometer

The low voltage winding of furnace transformers, those supplying synchronous converters, or any in which high current is required, is usually divided into a number of multiple circuits, each consisting of a helical coil of several turns interleaved with the high voltage winding (Fig. 48).

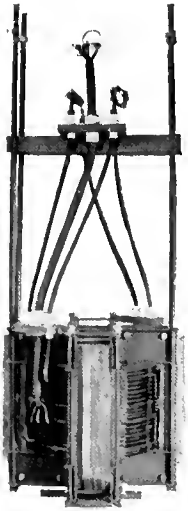

Fig. 46. 15-kv-a., 34,500/60,000 Y-115/230 Form KD Transformer with One Side Grounded

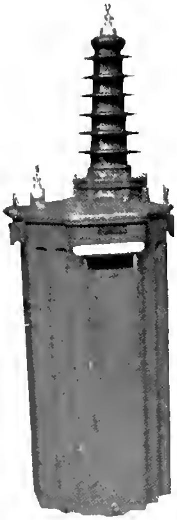

Fig. 47. 1000-kv-a. Form K Transformer, High Voltage Side

This type of coil consists of a number of strands of rectangular wire one above the other, wound about a form, each turn or disc separated from the adjacent one by an oil duct (Fig. 49). The discs are braced by spacers located radially across the face of the coil.

The great mechanical strength of this winding as well as the excellent thermal and electrical characteristics have led to the extension of its use to higher voltages (Fig. 50), and its application to the concentric type of winding. It has been found adapted to voltages ranging from 2300 to about 15,000, depending upon the capacity of the transformer.

The oil conservator* which has recently been described in detail has so completely met the need which brought about its development that during 1919 its use was greatly extended and it is now recognized as standard equipment for transformers of 500 kv-a. and over for use on high potential circuits of 80,000 volts and above.

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* "A New Form of Tank for Static Transformers," by W. S. Moody, GENERAL ELECTRIC REVIEW, October, 1919, page 756.

One of the developments that might be classed as a refinement, yet one which will appeal to all those who have anything to do with the installation of transformers, is the new trunnion-shaped lifting lug (Fig. 51). These lugs replace the hooks previously riveted or welded to the tank band for lifting the complete transformer.

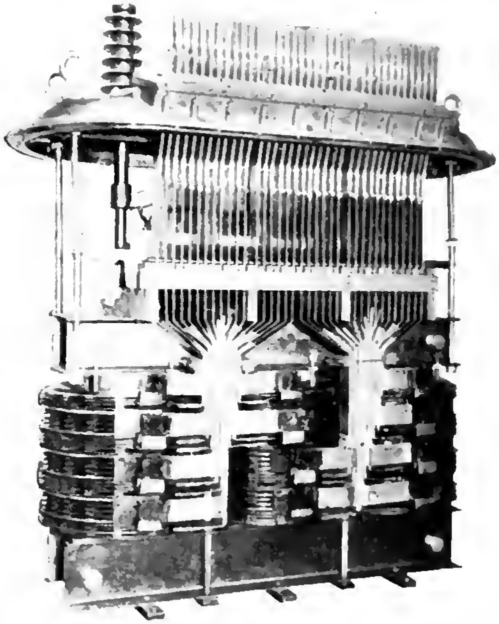

Fig. 48. Internal Arrangement of Arc Welding Transformer

Being circular in section this type of lug is as well adapted for lateral as for vertical stresses and the continuous shoulder prevents the rope or sling hook from slipping, no matter at what angle it may be necessary to exert the lifting force.

Another detailed improvement consists of a combination dial thermometer and diagrammatic name plate (Fig. 52). In addition to its attractive appearance, it is an advantage to the operating engineer to have the connection diagram and the thermometer both located at the most convenient point on the tank surface, and at the correct height to be most easily read by the average man.

High Voltage Bushings

Development work was completed on two companion lines of high voltage bushings for current transformers and metering outfits. These bushings are now in production and are designed for voltages of 25,000 to 73,000 inclusive. One line is for use with transformers of 200/400 ampere capacity (Fig. 53), and the other for transformers of 400/800 ampere capacity (Fig. 54).

The general construction of these bushings follows the design of previous standard bushings of the solid type, consisting of a paper insulated tube, the upper end of which is enclosed within a petticoated porcelain shell. Four cables through the center metal tube connect with the two sections of the double ratio winding of the transformer, and terminate at the top of the bushing in a series-multiple connection board, by means of which the ratio of the transformer may be changed simply by changing the connections at the top of the bushing. This connection box is weatherproof and the bushings are designed for outdoor installation.

In the case of the 200/400 ampere bushings, the line conductors are brought out of outlets on opposite sides of the connection box. In the 400/800 ampere bushings, both line conductors are brought out through one opening in the connection box in order to eliminate the heating in the iron box by neutralizing the magnetic effects of the opposing currents.

For power transformers, a complete line of double conductor bushings (Fig. 55) for a maximum operating potential of 7500 volts in current carrying capacity up to 3000 amperes is now available. Two leads from the transformer winding are brought through a single opening in the cover by means of a double outlet porcelain. The principal advantage of this construction consists in the elimination of the heating in the cover and bushing support, which is present when a single conductor carrying high currents is passed through an iron cover or bushing holder.

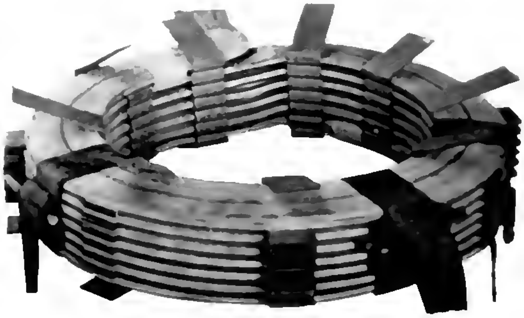

Fig. 49. Helical Coil with Offset Turns for High Current Interleaved Disc Coil Transformer

In the double conductor bushing, the incoming and outgoing leads pass through a single opening and the magnetic effects of the currents which are flowing in opposite directions are neutralized, so that heating of the cover and bushing support is entirely eliminated. This permits the use of iron supports and bushing holder at a much reduced cost as compared with non-magnetic alloys.

A second advantage is a reduction in the number of cover openings to accommodate the incoming and outgoing leads. A single round opening is all that is required for this double conductor bushing. This reduces the number of joints which must be made weather-tight, and sometimes oil-tight, and provides a more compact arrangement of parts on the transformer cover.

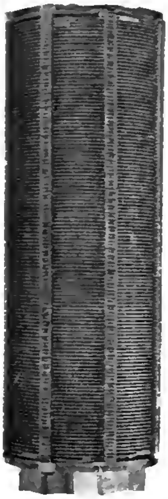
Fig. 50. Helical Coil Concentric Winding

A line of solid type interchangeable bushings from 15,000 to 73,000 volts inclusive, and for current capacities up to 800 amperes was fully standardized, and higher current ratings are being added to the present line. These bushings are designed for use on power transformers, potential transformers, oil circuit breakers and lightning arresters.

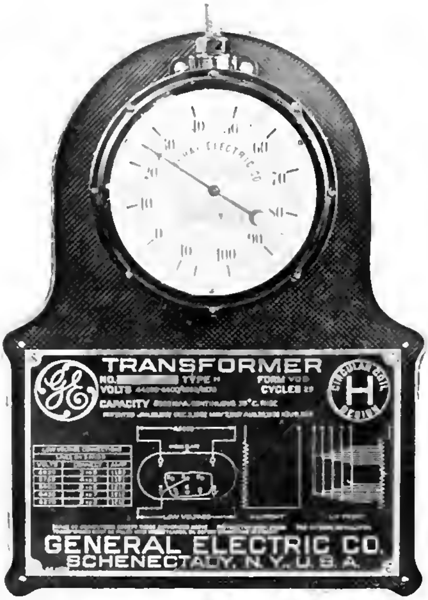

Fig. 52. Supporting Plate for Dial Thermometer and Name Plate

The bushing proper is identical for the different classes of service, and is accommodated for the different uses (Figs. 56 and 57) by exchanging the terminal parts and other accessories, all of which are detachable.

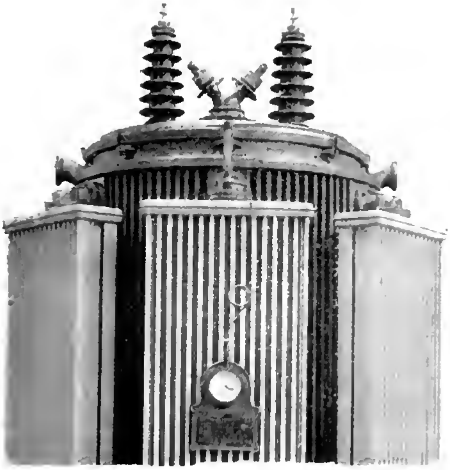
Fig. 51. Transformer with Trunnion shaped Lifting Lugs and Combination Dial Thermometer and Diagrammatic Name Plate


Fig. 53. 73,000-volt Current Transformer Bushing of 200/400 Ampere Capacity with Cover Raised to Show Series-multiple Connection Board


Fig. 54. 25,000-volt Current Transformer Bushing of 400/800 Ampere Capacity with Cover Raised to Show Series-multiple Connection Board


Fig. 55. Double Conductor Bushing for Transformers. Working Voltage 7500 Current Capacity, 2500 Ampere

This interchange of detachable parts can be made readily by the user, who is thus afforded the advantage of standardization of bushings on the several classes of apparatus, and a reduction in the number of spare bushings which must be carried for replacement purposes. All of these bushings are for outdoor as well as indoor service.

The standardization of bushings for operating voltages above 73,000 and up to 250,000 has been completed, and these bushings are now in regular production for power transformers, potential transformers, oil circuit breakers and lightning arresters.

These bushings (Figs. 58 and 59) are of the oil filled type and are designed for both out-

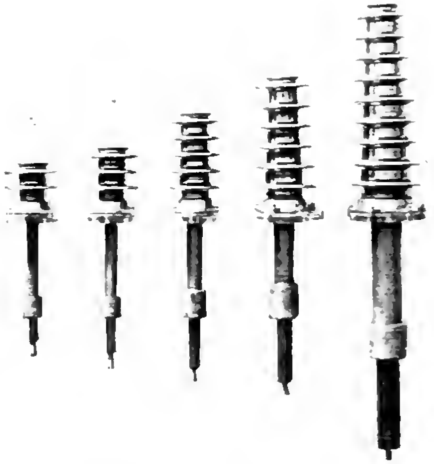

Fig. 56. Interchangeable High Voltage Bushings, as Used on Constant Potential Transformers

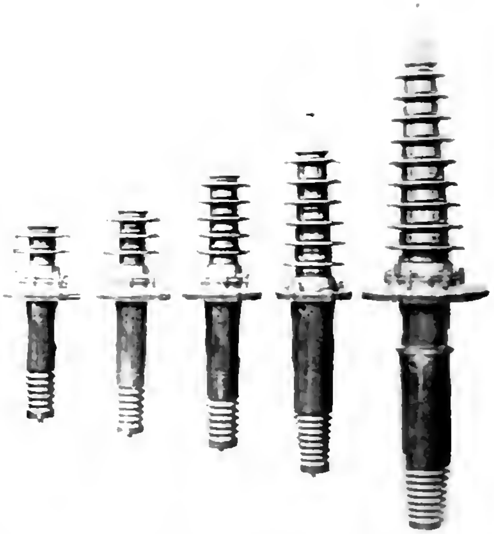

Fig. 57. Interchangeable High Voltage Bushings, as Used on Oil Circuit Breakers

Fig. 58. Interchangeable High Voltage Bushings, 400 Amp., Equipped with Various Terminal Accessories

Fig. 59. Filled Type, Flange Clamped Porcelain High Voltage Bushings for Transformers, Oil Circuit Breakers, and Lightning Arresters

door and indoor service on the various classes of high voltage apparatus. Their interchangeability* is accomplished by exchange of the detachable terminal parts and accessories, which adapt the bushing proper to the class of apparatus on which it is to be used.

Feeder Voltage Regulators

The development of feeder voltage regulating apparatus progressed normally during 1919. No radical changes were made in any of the designs but they were improved and extended to meet ever increasing requirements.

A 600-kv-a. 3-phase, self-cooled, automatically-operated regulator of the outdoor design (Fig. 60) was completed during the first part of the year and a duplicate unit is now nearing completion. This is one of the largest capacity self-cooled regulators of the outdoor type ever built.

For certain classes of work, specially electrolytic and furnace control, which require a very appreciable voltage range, the standard design of regulator is comparatively large and costly. A combination of a regulating switch, connected to taps of the transformer supplying the load, and an induction regulator for gradually varying the voltage between the steps of the switch and also eliminating the breaking of any appreciable current by the regulating switch, was suggested many years ago and various designs and combinations have been built.

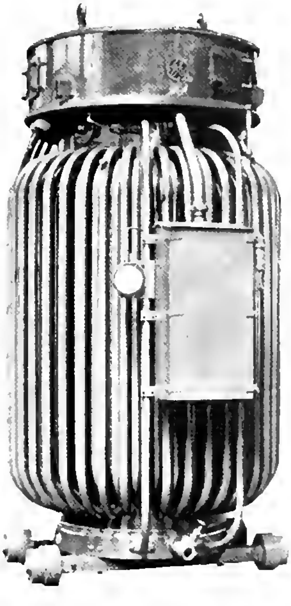

Fig. 60. Automatic, Oil Immersed, Self Cooled, Outdoor Polyphase Regulator

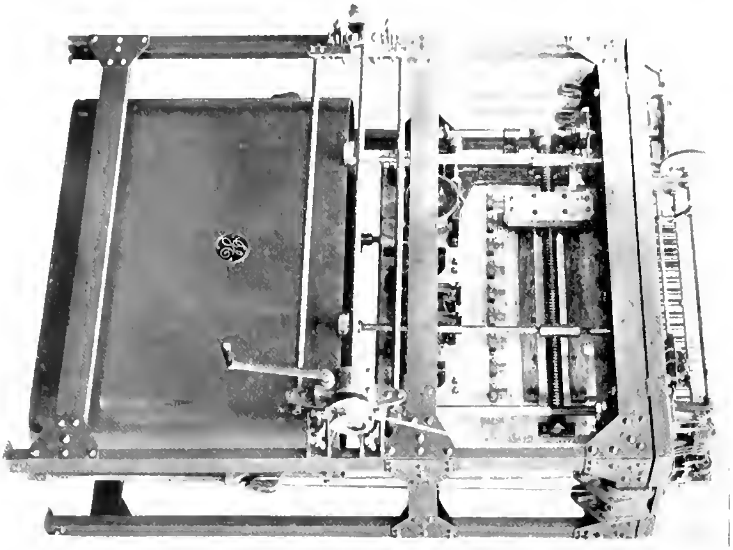

Fig. 61. Regulating Switch, (Front View with Oil Tank and Casings Removed for Inspection)

Only recently, however, has an apparently satisfactory combination been developed, one design of which is shown in Fig. 61. This illustration shows only the switch, as the regulator is of standard design but arranged with slip rings so as to allow of continuous rotation.

With this combination of switch and regulator, the latter may be any percentage of the kilovolt-ampere capacity of a single regulator which would otherwise be required to give the same voltage range, depending only on the number of taps it is feasible to bring out of the transformer supplying the load.

The advantage of the combination is its high efficiency and power factor compared with a single regulator, its only disadvantage being that it is more complicated. The switch shown was designed and built to produce a range of from 40 to 80 volts on the secondary side of a 1000-kw., 11,000-volt transformer, the voltage regulation being obtained by a gradual voltage change between the successive transformer taps.

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* "Interchangeable High Voltage Bushings," by E. D. Eby, GENERAL ELECTRIC REVIEW, November, 1919.

Voltage Regulators

A new counter electromotive force voltage regulator (Fig. 62) was developed for the control of direct current generators. The principle upon which it operates is as follows:

A small motor (Fig. 63) is used with its armature in series with the field of the direct current generator to be regulated. The field of this small motor is energized from the armature of the generator, but is controlled by means of a set of contacts carried on a very sensitive control magnet which, in turn, is connected to the generator busbars.

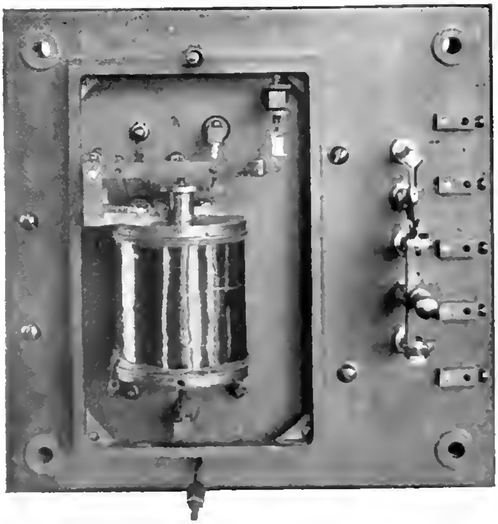

Fig. 62. Voltage Regulator for One Direct Current Generator (Front View)

Assuming that the voltage of the regulator tends to drop, due either to load conditions or to changes in the speed of the prime mover, the control magnet will allow a spring to close the contacts, short circuiting the field of the small motor. This will immediately cause its voltage to drop, allowing more field to be applied to the generator which will tend to raise the voltage.

The voltage is in this way immediately restored to the point where the contacts start to open, and at this point they will continue to vibrate, thereby holding an average field on the small machine. The period of time during which these contacts are in or out of engagement is determined by the tendency of the voltage to rise or fall.

Assuming that the voltage of the generator tends to rise, the contacts of the control magnet will open, allowing full field to be applied to the small motor, which will force it to generate a higher counter electromotive force, which will in turn immediately cause the voltage of the main generator to decrease until it reaches normal. At this point the contacts will again start to vibrate, holding an average field on the small machine necessary to obtain the proper voltage to meet the new condition of speed and load.

Referring to the diagram (Fig. 64), it will be seen that there is a resistance in series with the field of the small motor, its purpose being to limit the current when the contacts on the control magnet close and short circuit the field of this motor. In addition, the motor is supplied with an eddy current brake which is excited from a coil connected in series with the generator field. This brake is necessary to prevent excessive speed of the small motor.

In addition this brake is supplied with an adjustable air gap so that the speed may be kept to a safe value. A double-pole, double-throw switch is supplied so as to permit cutting this motor out of the circuit when it is desired to operate with hand regulation.

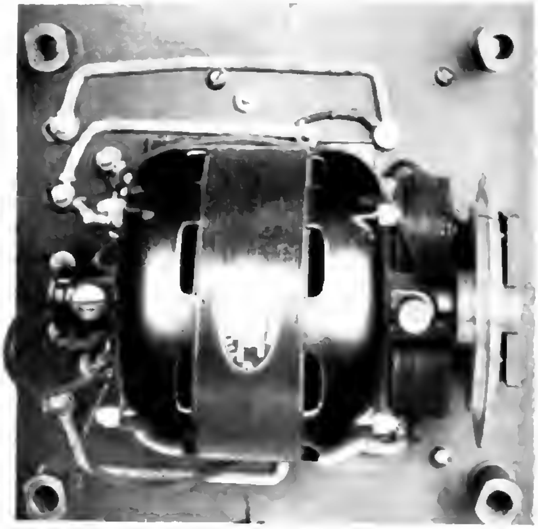

Fig 63 Voltage Regulator or One Direct Current Generator Back View

Static Condensers

During the past year, a number of important changes were made in the design of static condensers. The capacity of the individual condenser unit itself (Fig. 65) was increased from 2 kv-a. to 5 kv-a., thereby reducing the number of units required to make up equipments and the amount of floor space required by the assembled condenser.

In order to obtain the increased capacity per section, the number of couples has been increased, and also the number of paper laminations forming part of each couple.

For 2300-volt service, the condenser units are designed for direct installation in the line, but for 220, 440 or 550-volt circuits they are designed for 1200-volt operation, and an auto transformer is therefore furnished for stepping up the supply voltage.

With the earlier equipments, an auto transformer was furnished to step up the supply voltage to 800 volts, but, inasmuch as the capacity of the condenser varies as the square of the applied voltage, it will be readily appreciated that the active material is now being used more economically, and that a considerable saving has been effected which has practically counterbalanced the increases in cost which would otherwise have been incurred if these changes had not been made.

The auto transformer furnished with three-phase equipments is provided with a lead from the neutral connection, so that the neutral may be grounded, and any possibility of an abnormal voltage being impressed on the supply system is entirely eliminated.

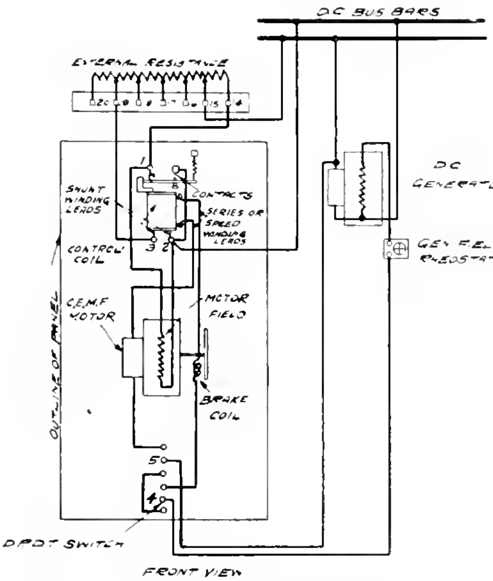

Fig 64. Connections for Voltage Regulator with One Arrangement of One Direct Current Generator

In order to provide as great a factor of safety in the design of the units as formerly, the laminations between the condenser plates have been increased and the clearances in each unit have also been increased. An additional terminal has been provided on each unit to permit ready grounding to the rack structure, thereby preventing any danger of a difference of potential existing between the condenser unit and the rack.

Fig. 65. Detail Assembly of Static Condenser Units Showing Bus and Fuse Arrangement

The construction of the racks upon which the condensers are assembled (Fig. 66) has been changed from pipe framework to an angle iron supporting structure. The numerous pipe fittings have been replaced by angle iron supporting braces which have not only reduced the weight but have materially simplified and strengthened the entire structure. Provision has been made for mounting the various auxiliaries, such as discharge resistances and disconnecting oil circuit breaker, directly upon the rack, thereby making the complete outfit self-contained.

Lightning Arresters

When the oxide film lightning arrester discharges, experience has shown that the conversion of the lead peroxide into an insulating plug is so rapid that the arc rises only very slightly on the gap and, in consequence, sphere gaps alone are used. These permit a compact construction and made it possible for the first time to provide protection of the spark gap from the weather as an integral part of a high tension outdoor lightning arrester equipment.

A number of arresters similar to that shown in Fig. 67 were prepared for service during the year. With this housing, the sphere gaps on the outdoor oxide film lightning arresters can be more closely adjusted than if exposed gaps are used and their pro-

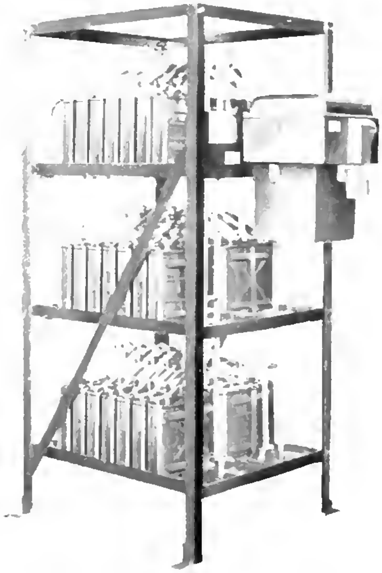

Fig. 66. Typical Static Condenser Showing Arrangement of Rack, Condenser Units and Switch

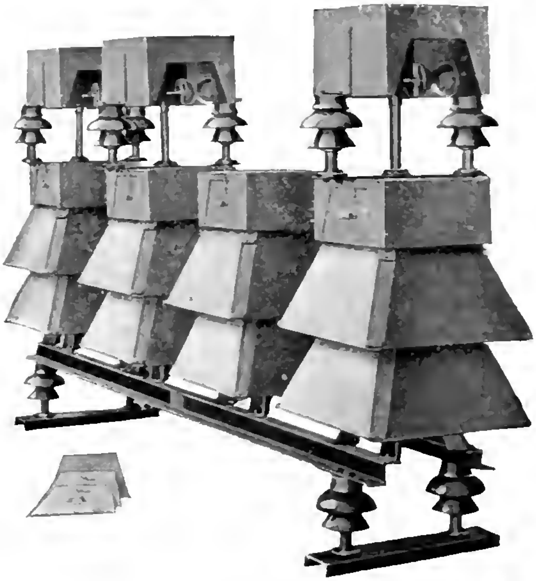

Fig. 67. Oxide Film Lightning Arrester for Three Phase Outdoor Service, 15,000-25,000 Volts, showing Shielded Hemisphere Gap

tective value is thereby rendered equivalent to that of an indoor type.

For more than three years the oxide film type of arrester has been in operation under service conditions on circuits up to 66,000 volts, and as it does not require daily charging, as does the aluminum cell type, it has proved to be not only effective but also economical in the cost of attendance and has been installed in many places where the need of daily charging the aluminum cell type would preclude its use.

The mechanical details of the arrester have been simplified and improved during the past year and subjected to a standardization of parts as the result of commercial experience and continued experiment. The structure of the improved form is indicated in Fig. 68.

Electric Welding

A new direct current welding outfit was produced (Figs. 69 and 70) which delivers current directly to the arc at the required voltage without the use of any form of ballast resistance or external regulating device.

This result is obtained by means of a dual magnetic circuit, one section of which generates constant potential in part of the armature by means of a shunt field receiving excitation from this part of the armature winding while the armature reaction and a differential series field cause a varying voltage in the other part of the armature winding. The constant potential is 30 volts, while the other component varies from positive 30 volts on open circuit to negative 30 volts on short circuit.

The generator rating is 200 amperes, no exciter is required, and either a-c. or d-c. motors or belt drive can be used. The outfit is self contained, including a control panel.

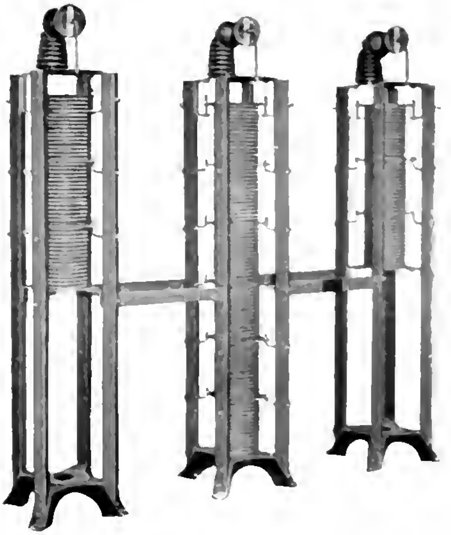

Fig. 68. Oxide Film Lightning Arrester for Indoor Service on Three Phase Circuit 15,000-25,000 Volts

and is compactly mounted on a structural iron sub-base so that it can be readily moved about. It weighs about 1300 lb.

A new automatic welding machine, for work varying from 25 mils to one quarter inch, was also produced. It consists essentially of a pair of feed rolls (Fig. 71) which are driven at varying speeds by a small direct current shunt wound motor. The rolls deliver the electrode wire to the working face, and, when the welding arc is drawn, the field and armature of the motor are instantaneously influenced by the voltage across the arc and respond by increasing or decreasing the rate of feed of the wire, thereby regulating the length of the arc to the value for which the machine is adjusted. Above the feed rolls, wire straightening rolls are provided to insure accurate feeding of the wire and the proper location of the arc.

This machine may be operated from any direct current welding circuit and will use any size of electrode, up to its mechanical limits, with equal precision in operation, as neither of these factors enters into the question of the rate of feed control, which is governed solely by the voltage across the arc.

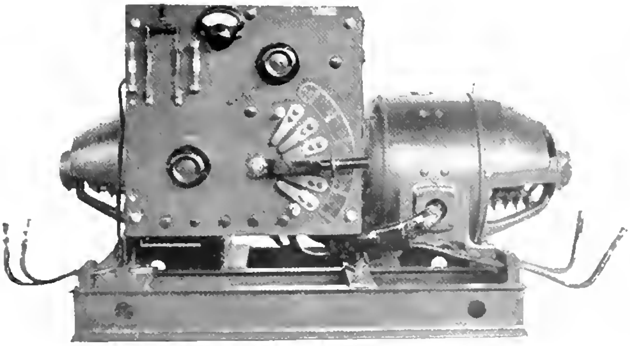

Fig. 69. 200-ampere Arc Welding Generating Set with Control Panel (Front View)

The equipment includes a panelboard on which relays, regulating switch, etc., are mounted for the control of the motor. The complete outfit is very compact, having a length of 4 ft., a width of 18 in., and is about 6 in. in height.

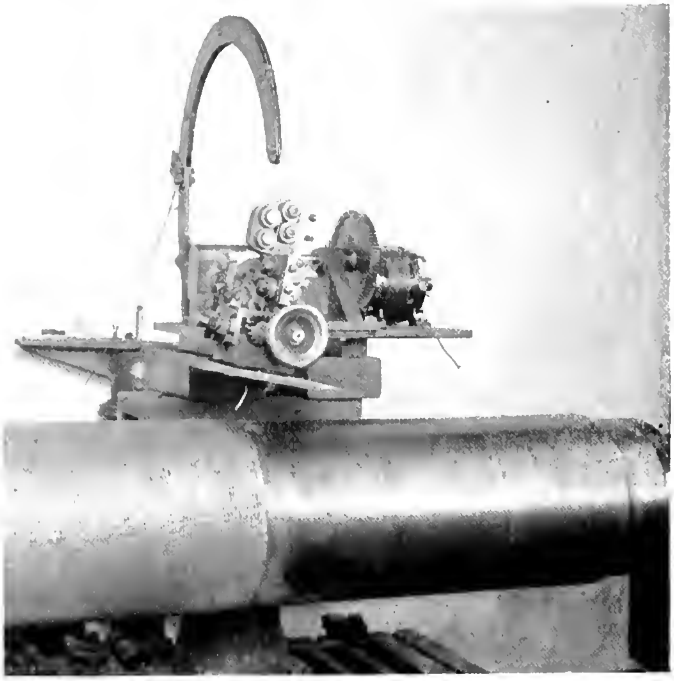

Fig. 71. 14-in. Shaft with Fit Increased $\frac{3}{8}$-in. in Diameter by Automatic Arc Welding Process

The rate of increase in the use of electric welding, which was greatly stimulated by the rapid production and repair requirements of our various industries during the war, has been well maintained. This is indicated by the fact that in 1918 the number of electric welding outfits sold was more than double that of any preceding year, while 1919 in turn gave a further increase of 100 per cent over 1918.

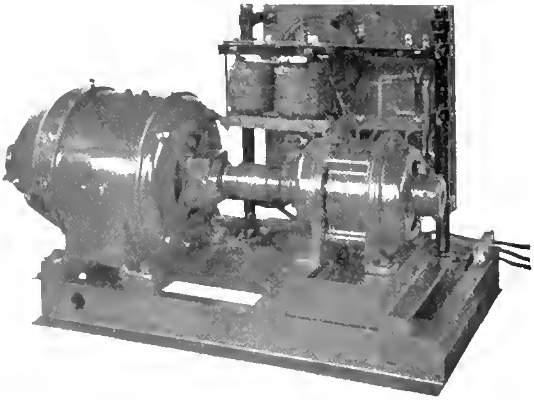

Fig. 70. 200-ampere Arc Welding Set (Back View)

Industrial Heating

A new form of electric solder melting pot was developed in which the heating is self-regulated. The pot (Fig. 72), which can be operated at any voltage from 100 to 125, consists of a substantial iron casting, on the sides and bottom of which the heating units are clamped. The sides and bottom of the pot are jacketed with corrugated asbestos board protected by welded sheet steel. The leads are brought out through insulating bushings in the bottom plate.

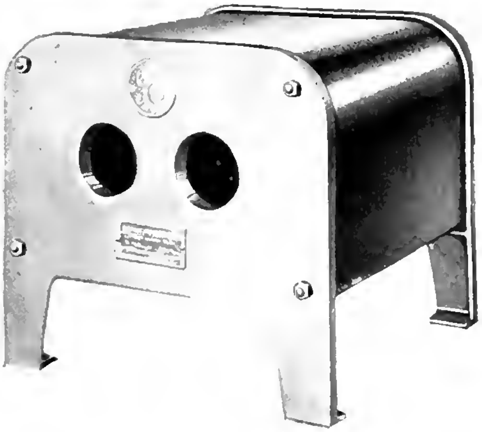

Fig. 72. Self Regulating Electric Melting Pot

The material of which the units are made is of such a nature that the temperature of the solder cannot rise above a predetermined point.

When the pot is cold and the current is first turned on, the electrical resistance of the units is low. This allows the maximum current to flow (Fig. 73) and gives quick initial heating. As the temperature rises the resistance of the units increases, thereby reducing the amount of current used. When the maximum temperature is reached, it remains constant and the flow of current is maintained at a minimum value. This means that the solder will never reach a temperature at which it will appreciably oxidize and form the usual heavy coating of slag.

For light and intermittent service the self contained electric soldering iron is very satisfactory, but for moderate and heavy duty work it is frequently desirable to use the ordinary soldering copper which must be heated in a furnace. When fuel fired furnaces are used for this service, they have many disadvantages, such as noxious fumes, excessive heat, a high fire risk, etc., and to obviate these there was developed an electrically heated two compartment muffle furnace (Fig. 74).

It consists of two special steel alloy muffles, wound with nichrome wire on insulators made of a compound which retains its electrical resistance at high temperatures. Two specially moulded nonpareil bricks jacket the muffles and are protected by a two-piece sheet metal casing. Four tie rods from front to back hold the furnace together and the terminals are brought out through a bushing in the bottom of the furnace.

The 110-volt furnaces provide three heats by means of a three way switch. On high heat the muffles are in parallel giving the maximum wattage (1500 or 2000), equally divided between the muffles. On intermediate heat one muffle across the lining is heated, the other by its proximity being kept at a low temperature for holding an iron warm. On low heat, both muffles are in series, providing sufficient heat to keep the furnace at a working temperature when not in use. The 220-volt furnaces can only be operated on one heat, and the muffles are in parallel.

An electric muffle furnace was also developed for tool room work, where it is essential to obtain temperatures as high as 850 deg. C.

The furnace proper (Fig. 75) consists of an arched muffle, approximately 8½ in. wide, 1⅝ in. high and 15 in. long (inside dimensions) around which is wound a spiral coil heating unit, covered with a compound to protect the wire from injury. Around the entire muffle there is 2½ in. of nonpareil heat insulating block. The outside casing is constructed of sheet steel, firmly riveted and mounted on legs approximately 6 in. high.

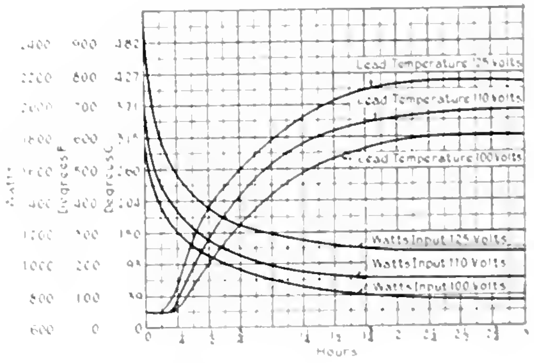

Fig 73. Characteristics of Self Regulating Melting Pot

The door is hung on a rod supported by hinges and may be operated by a handle on either side; a ball weight is also provided to hold the door securely closed or open as desired. To eliminate heat losses around the door there has been mounted approximately 2 in. of insulating block on the door itself.

On the top of the furnace there is a control panel, provided with pilot lamp, line switch, and a triple-pole double-throw switch for obtaining high and low heat in the furnace. The overall dimensions of this furnace are 23⅞ in. wide, 2 ft. 10⅜ in. high, 2 ft. 5¾ in. long.

When starting the furnace it is only necessary to close the main line switch, and the control switch should then be thrown to the blades marked high heat. When the furnace is on high heat the pilot lamp will be lighted.

It requires approximately two hours to bring the furnace to maximum temperature and when this temperature has been reached the switch should be immediately thrown to blades marked low heat and should be left on low heat as long as the furnace is continuously operated.

The furnace consumes 4 kw. on high heat and 1.8 kw. on low heat, and on the basis of power being supplied at 2 cts. per kilowatt hour, it may be operated one day at a cost for power of approximately 45 cts.

Fig. 74. Electrically Heated Soldering Iron Furnace

There is practically nothing about this equipment to get out of order and the furnace itself is so built that the heating element is protected from harm. One other feature is the fact that it may be operated without discomfort in a small room, as it does not radiate heat.

The cartridge type of heating unit was first developed about thirteen years ago. The units which have been used until about a year ago contained a lava core on which heating coils (nichrome wire) were wound. This was inserted in a brass tube lined with mica which acted as an electrical insulator and a very close fit insured high thermal efficiency. One end was plugged with a brass disc, over which the end of the tube was swaged. The terminals were brought out through the other end through a brass washer with two holes, the leads being insulated by smaller mica washers.

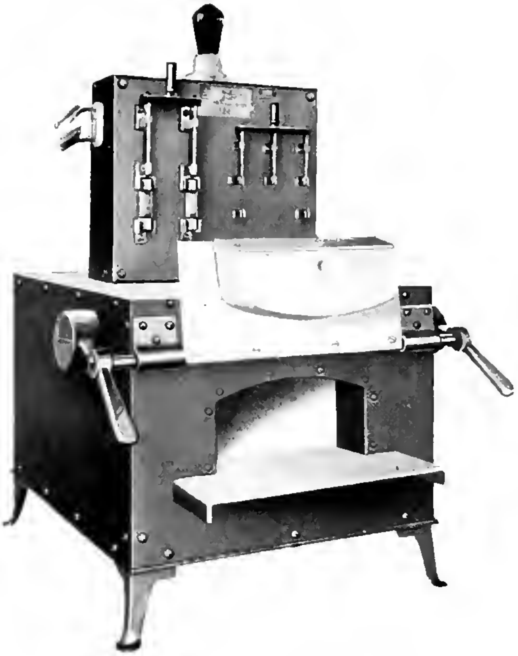

Fig. 75. Electric Muffle Furnace for Tool Room Work

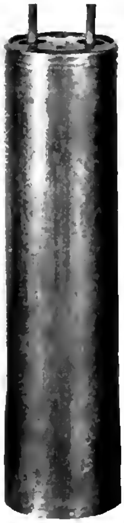

Fig. 76. Magnesium-Oxide Insulated Cartridge Unit

Recently this unit has been modified, in that pure magnesium oxide is applied in place of the mica heretofore used as an insulator. This oxide, in powdered form, is vibrated through the unit (Fig. 76) in such a manner as to completely surround it with a uniform insulating layer which will not break down under extreme temperatures or excessive vibration.

The units are used in shoe and cigarette machines, glue pots, soldering irons, water boilers, paper box machines and in heating moulds; in fact, wherever localized heating is needed the cartridge unit will usually solve the difficulty, but they are not designed for operation in the open air or directly immersed in liquids.

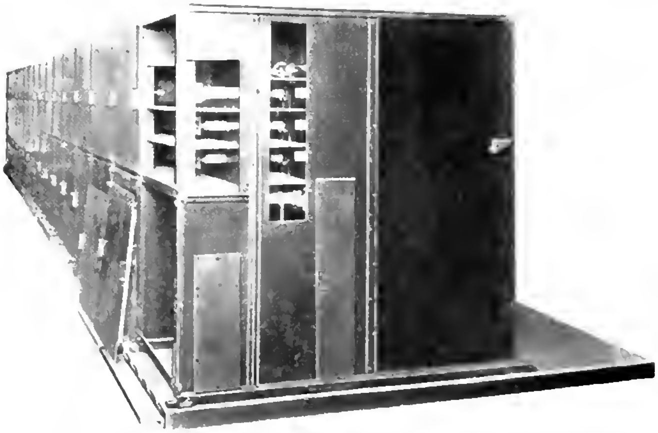

Fig. 78. Safety Enclosed Unit Removable Truck Type Switchboard, showing Bus and Cable Compartments

Switching Apparatus

As in preceding years, progress was continued during 1919 in the development of safety enclosed switching apparatus and the line of truck type safety panels which previously covered feeder circuit control only, was extended to include generator, synchronous motor and lightning arrester panels. In addition to their essential safety features these panels (Figs. 77 to 79) have several other notable advantages:

The removable truck type is delivered "knocked down" as far as the compartments are concerned, but the removable trucks are completely assembled. The work required then consists only of placing them in position and leveling the housings and tracks for the trucks. The high grade fitting work and the adjustment of parts to insure interchangeability have all been attended to at the factory before shipment. The installation therefore is reduced largely to the assembly of fitted parts and does not require a staff of skilled mechanics to insure a finished job.

After the switchboard is in operation, if repairs are required, the particular truck affected is pulled out and a spare truck substituted. Any necessary repairs to the truck can be made conveniently, quickly, thoroughly and safely in a suitably equipped work shop to which the truck can be wheeled.

Existing units can be increased in capacity very advantageously, as the disconnecting devices are identical for all capacities up to 600 amperes. The compartments have the same dimensions for the same type of breaker, as do also the removable trucks. This means that a larger capacity breaker of the same type may be substituted in the same truck

Fig. 77. 76 in Safety Enclosed Unit Removable Truck Type Switchboard

and compartment, and connection copper increased to give a circuit of the desired increased rating.

The vital factor of safety in handling is assured, for with the truck element in place for operation all the live parts are completely enclosed, while with the truck rolled out for inspection, changing oil or repairs, all truck parts are accessible, and at the same time, dead electrically.

The new stationary type of safety enclosed switchboard follows closely the design of the ordinary open type board, except that it is built of metal throughout. Steel front panels (Fig. 80) are used, upon which can be mounted any equipment required.

All switching equipment, including oil circuit breakers, field switches, lever switches, or air circuit breakers are of the back-of-board type so that a dead front, and therefore a safe switchboard, is assured. The back and ends are enclosed by grille (Fig. 80) so that no live parts are accessible except to an authorized operator.

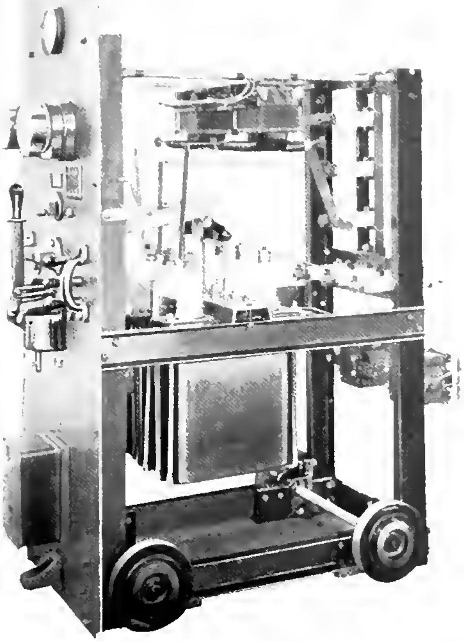

Fig. 79. Safety Enclosed Unit Panel Removable Truck Type, showing Circuit Breaker Equipment

*Motor operated oil circuit breakers are now made in removable truck form so that either the entire breaker or any individual pole may be easily and quickly removed for inspection, adjustment or replacement.

The motor mechanism is mounted on top of the cell (Fig. 81) in the usual manner and an interlocking arrangement possessing several safety features is part of the standard equipment.

Fig. 80. Safety Enclosed Unit Panel Stationary Type, 250 Volts with D-C. Motor Starter and Rheostat

The swingout type of safety enclosed panel (Fig. 82) is an ingenious self-contained unit which obviates the need of providing separate locations and supports for the instruments, instrument transformers, disconnecting switch, oil circuit breaker and conduit end bells, or other devices for bringing the leads to and from the breaker.

It is especially suitable for use in exposed positions in mills and factories, as there are no live exposed parts with which workmen can come in contact.

The panels occupy small space, can be set up singly or in groups, and can also be moved readily from place to place if desired.

They can be swung in and out, as shown in Fig. 83, and when a panel is out all the apparatus mounted on it is dead and fully accessible.

An interlock between the housing and the oil circuit breaker prevents the panel from

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* "Recent Developments in Circuit Breakers," by J. W. Upp, General Electric Review, November, 1919.

being swung out, except when the oil circuit breaker is in the "off" position, as shown by an indicator on the panel, and the disconnecting device is therefore carrying no current.

Similarly, the interlock prevents the panel from being swung back into operating position when the oil circuit breaker is held in the "on" position. It can be locked in either the open or the closed position.

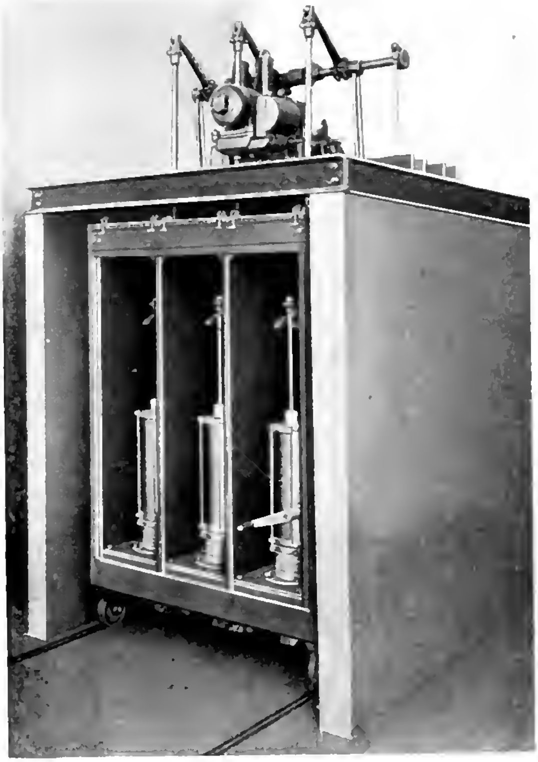

Fig. 81. Removable Truck Oil Circuit Breaker Bottom and Back Connected, Oil Tanks Mounted in Parallel

Safety requirements in switching apparatus are not limited to those controlling high potential circuits or to the use of oil circuit breakers. It is essential also that air break devices be so enclosed that accidental contact with live parts be prevented. In view of this, the development of enclosed apparatus was continued also for the air circuit breaker and switch. Complete lines of both were produced either as individual devices or to form component parts of a safety enclosed switchboard for the control of direct current generators or feeders.

Safety enclosed and dead front air break circuit breakers (Fig. 84) are equipped with magnetic blowout instead of carbon break. The breaker and its slate base are supported from a front panel or plate upon which the operating lever is mounted in an inverted position.

When used in a switchboard this front plate is a part of the switchboard panel. When the breaker is mounted in a box as an individual device it forms the front of the box. Links extend through the panel to a roller, which butts against a special casting on the breaker proper when the lever is pulled out to close the breaker. The lever and mechanism are mechanically free from the breaker proper (Fig. 85), which makes it possible to remove the front plate with the lever and inspect the breaker parts.

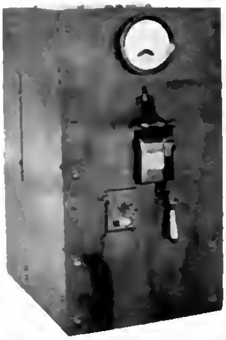

Fig. 82. Safety Enclosed Unit Swingout Type Panel in Operating Position

Fig. 83 Swingout Type Panel Swung Out for Inspection of Circuit Breaker

A trip rod which engages the trip button on the breaker extends through the front plate, thus allowing the breaker to be tripped manually without removing the front plate and a window is provided in the front plate through which the breaker contacts are visible. An indicating device showing the open or closed position of the breaker is also mounted on the front plate.

The safety enclosed lever switches (Fig. 86) may be mounted in a box (Fig. 87) or used in conjunction with other apparatus to make up safety enclosed panels. The capacities of these switches as used either on a panel or in a box are limited by the sizes of the 250 and 600-volt enclosed fuses approved by the National Board of Fire Underwriters. This at present is 600 amperes.

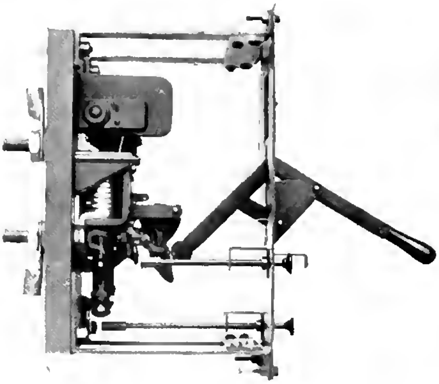
Fig. 84. Dead Front Circuit Breaker (Closed)

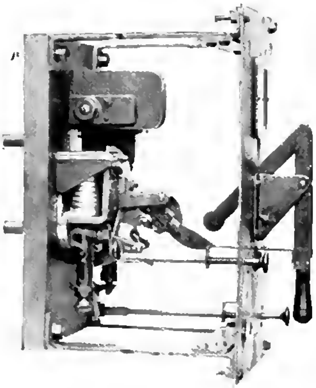
Fig. 85. Dead Front Circuit Breaker (Open)

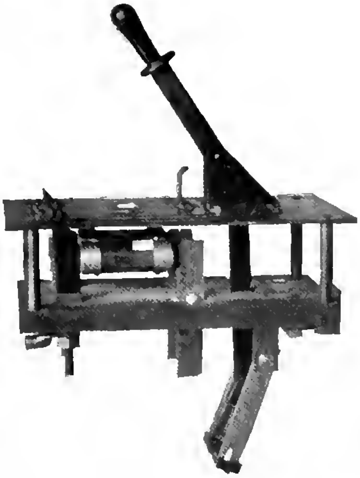
Fig. 86. Dead Front Lever Switch, Double-pole, Single-throw

Enclosed lever switches are divided by the underwriters into two classes; viz, Class *B*, which includes simply a lever switch enclosed in a box and Class *A*, which specifies that the cover and switch shall be so interlocked that the fuses are accessible only when dead electrically.


Fig. 88. Enclosed Lever Switch

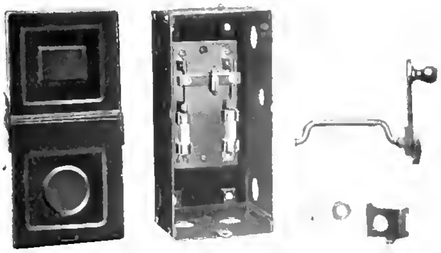
Fig. 89. Disassembled View of Enclosed Lever Switch

Under this latter class comes the new Type LM-4 enclosed switch (Fig. 88) mounted in a rectangular box and cover, both made from punched parts, and therefore light, and at the same time strong and durable. A front-connected lever switch mounted on an insulating base is located inside and operated by an external handle at the side of the box. This handle is attached to a "U" shaped shaft which engages a hook shaped punching (Fig. 89) mounted on the cross bar of the switch. The handle is so interlocked with the cover that the fuse compartment cannot be opened unless the switch is open (Fig. 90), and conversely, the switch cannot be closed unless the compartment cover is closed. "On" and

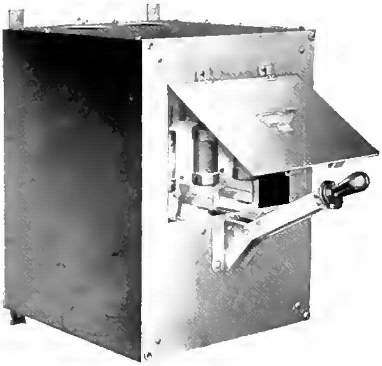
Fig. 87. Dead Front Lever Switch, Triple-pole, Single-throw, Mounted in Steel Box

"Off" positions of the switch are indicated on the box.

This switch is built double and triple pole in 30, 60 and 100-ampere capacities, and is rated at 250 volts a-c. or d-c. It can be mounted with safety directly on a machine tool for the control of the individual motor, or can be used on any feeder circuit within its rating.

Fig. 90. Enclosed Lever Switch with Fuse Compartment Open

Grouped together or with instruments and rheostat, on a suitable frame, with connections between switches and other apparatus installed in conduit, a complete panel can be built which is compact, totally enclosed, and safe. Such panels can control generator or feeder circuits within the switch rating.

Very nearly identical with this switch (type LM-4) is the type LM-5 switch developed for use in connection with a compensator for motor starting. This switch is rated at 500 volts a-c. in 30, 60 and 100-ampere capacities. It varies in construction from the LM-4 only in that greater spacings are required on account of the increased voltage rating, and the addition of terminals on the hinge clips which are connected to the starting throw of the compensator, thus shunting the excessive current at starting around the fuses. Both types are arranged for conduit or open wiring.

Several new types of relays were placed in production during the year. The mechanically balanced differential relays (Fig. 91) are intended for the protection of parallel transmission lines against unbalanced current in the phases, such as would be occasioned by a fault in one of the lines. As the current increases in the lines, the difference in current must also increase before the relay will operate. This compensates for a normal inherent difference in impedence in the two lines. Fig. 92 shows the results obtained on outgoing lines.

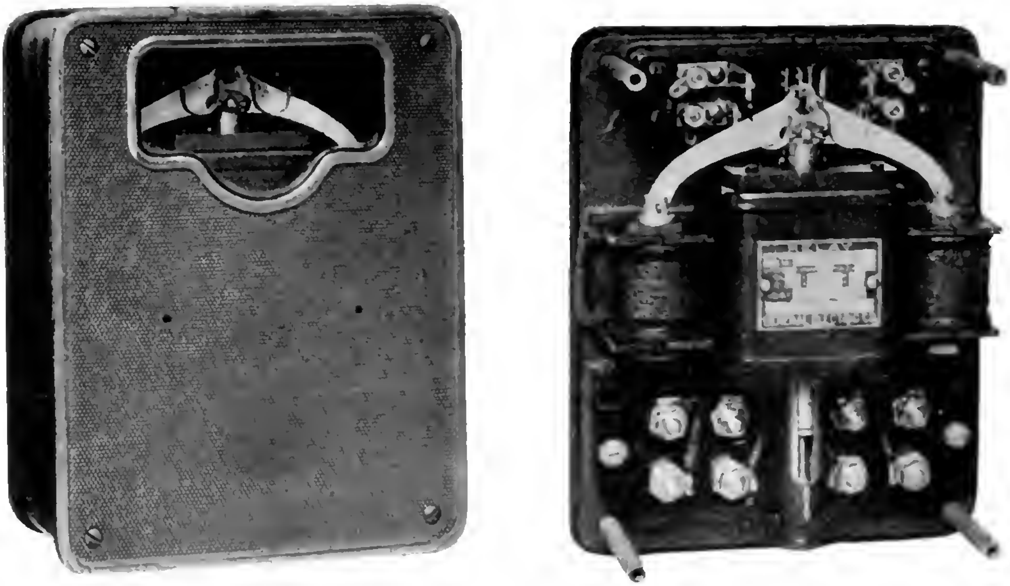

Fig. 91 Mechanically Balanced Differential Relay with Circuit Closing Double throw Contacts, 5 Amps.

In operation the relay trips the line carrying the greater current. It may be used, therefore, for outgoing lines, or, providing there is some other source of power to insure that the injured lines will carry the greater current, for incoming lines. The simplicity of this relay is a valuable characteristic for the use referred to. This relay operates on current supplied by current transformers only. It has a noteworthy advantage, in the case of short circuits, over relays operated by potential coils, as the latter lose their effectiveness when the potential of the circuit falls off.

The relay consists of three solenoids (Fig. 93), the two smaller outside solenoids tending to hold down the moving mechanism, while a differential current passing through the larger center solenoid will tend to raise it. When the difference becomes sufficiently great to overcome the weaker of the two small solenoids, the contact mechanism will operate on the side to trip the breaker carrying the heavier current. So long as a balanced condition exists within the operating values, the relay will not trip either breaker no matter how high the current may be in the two.

Where differential protection is used for alternators, each circuit should be equipped with a device for opening automatically the field circuit of the alternator after the oil circuit breaker connecting this alternator to the busses has been opened. This requirement demands either solenoid operation for the field switch, or a manually operated field switch equipped with a shunt trip coil.

A circuit closing auxiliary switch should be provided on the oil circuit breaker, to insure the breaker opening before the field switch.

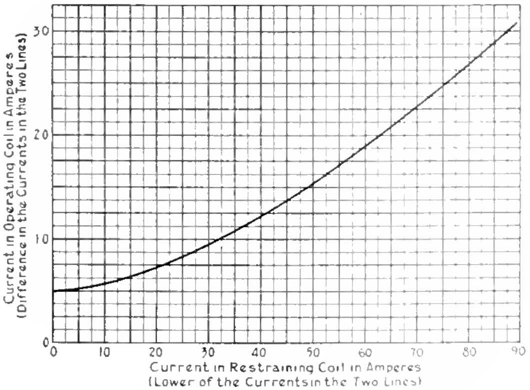

Fig. 92. Operation Characteristics of Mechanically Balanced Differential Relay

With the breaker open there will be less liability of damage to the field circuit, due to the high voltage which would be induced if it were opened when heavy currents were passing through the armature. Opening the field last also reduces the possibility of the alternator falling out of step with the remainder of the system, and thereby increasing the disturbance on the system. It is, of course, evident that under none of these conditions is the difficulty entirely overcome by the opening of the oil circuit breaker first.

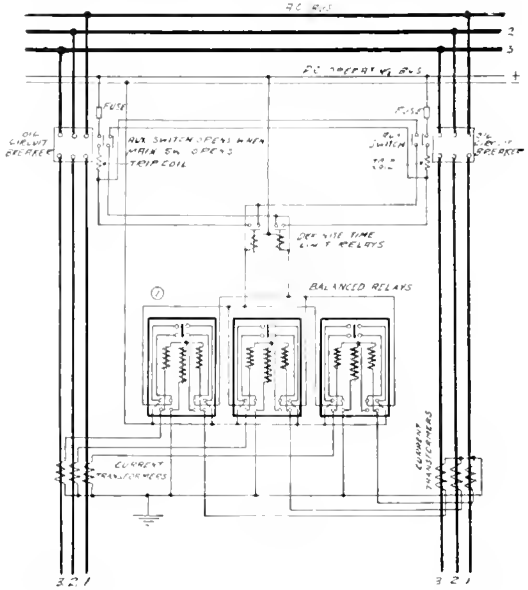

Fig. 93. Diagram of Connections of Differential Relays in Combination with Definite Time Limit Relays on Two Parallel Lines

The trouble is, however, sufficiently reduced to consider it the preferable method.

For this service Type PQ-6 relays (Figs. 94 and 95) with hand reset contacts are used to insure tripping the circuit for the field switch, after the main circuit breaker is opened. By resetting the relay contacts the field switch may be reclosed with the main circuit breaker still open.

Hesitating control relays have been in use for a long time where the electrically operated circuit breakers controlled are equipped with an auxiliary switch automatically to break the coil circuit of the control relay. The relay closes instantaneously but "hesitates" about one second after being deenergized before the contacts open again. By this time the breaker will have been positively latched closed.

An earlier type of hesitating control relay made use of an oil dash pot, but in the new design (Fig. 96), the time delay is obtained by means of a heavy copper tube surrounding the relay plunger and inside the operating coil. When the coil is energized, the plunger is raised and the contacts closed. When the circuit of the operating coil is broken, the usual inductive "kick" starts up a heavy current in the copper tube, which in turn tends to maintain the flux. As a result the flux dies always slowly, and in approximately one second the plunger falls again and opens the contacts.

Fig. 94. Instantaneous Hand Reset Relay

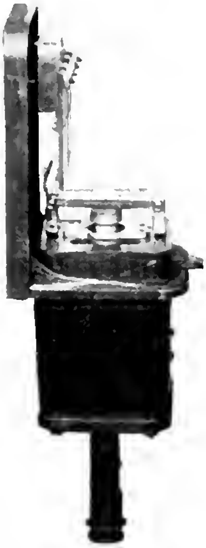

Fig. 95. Type PQ-6 Instantaneous Hand Reset Relay with Cover Removed

A development that promises to assume large proportions is the application of electrically energized position indicators in connection with systems of remote electrical control.

The operation of this type of indicator is based on the fact that two machines of the induction type (Fig. 97) which are excited from the same source and suitably interconnected, will rotate in synchronism.

Position indicators operating on this principle were originally used on the lock control boards of the Panama Canal, for showing at the board by means of miniature replicas the positive and progressive movements of miter gates, chain fenders, water valves and water levels. A subsequent application was made in the form of signal pedestals for the transmission of orders between the switchboard and the generator rooms at the Keokuk hydro-electric plant of the Mississippi River Power Company.

At the present time there is being built a lock control board for the New Orleans industrial canal, which connects the Mississippi River with Lake Pontchatrain. The lock system, control board and position indicators are similar to those used at Panama.

A further application of position indicators under consideration is in connection with a number of floating dry docks, designed for the emergency fleet corporation. These dry docks are of the multiple pontoon type (Fig. 98) and the proposition is to control all the operations of listing, submerging and raising from a central station, as opposed to past practice of local control under the direction of the dock master.

The scheme provides for a control board, located at the head of the dock in such a position that the operator has a complete view of the dock itself and performs all the manipulations that are required by merely pushing a button or throwing a switch lever.

For the purpose of orientation, the top of the board is laterally divided in the same number of sections as there are pontoons in the dock, and each section contains the necessary devices for the control of its pontoon.

Fig. 96. Hesitating Control Relay

The board is equipped with individual indicators (Fig. 99) for reading the water levels in the six compartments into which each pontoon is divided. Flood valve indicators are used to show at all times the actual position of the main flood valves which are used to fill the pontoon for submerging. A list indicator will always show the divergence from horizontal alignment. This can be controlled to a nicety by the manipulation of flood valves and pumps and with the aid of the water level indicators.

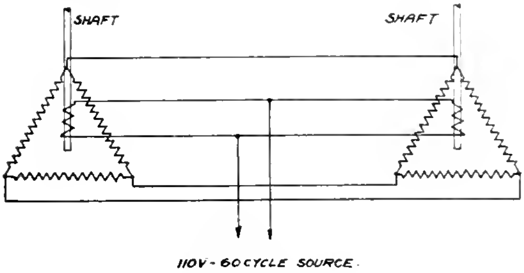

Fig. 97. Wiring Diagram, showing Interconnection of the Two Electrical Units of the Position Indicator

The indicators are actuated by suitable transmitter machines which can be briefly described as follows:

The water level transmitter (Fig. 100) consists of a float attached to a chain which passes over a sprocket wheel and has a counter weight at its other end. Thus the variations of the water level rotate the wheel the shaft of which is geared to a position indicator machine (See Fig. 97), which in turn transmits its position to the water level indicator. The transmitter is mounted on the deck of the pontoon and is protected by a weatherproof housing. It is further provided with a dial for local reading of the water level.

The list transmitter (Fig. 102) consists of a weatherproof casing, also mounted on the deck of the pontoon and containing a position transmitter to which a pendulum is geared. The pendulum will naturally maintain a vertical position and the listing of the pontoon will therefore cause the transmitter to rotate. This rotation is in turn transmitted to the indicator on the board where it is readily interpreted into degrees of list.

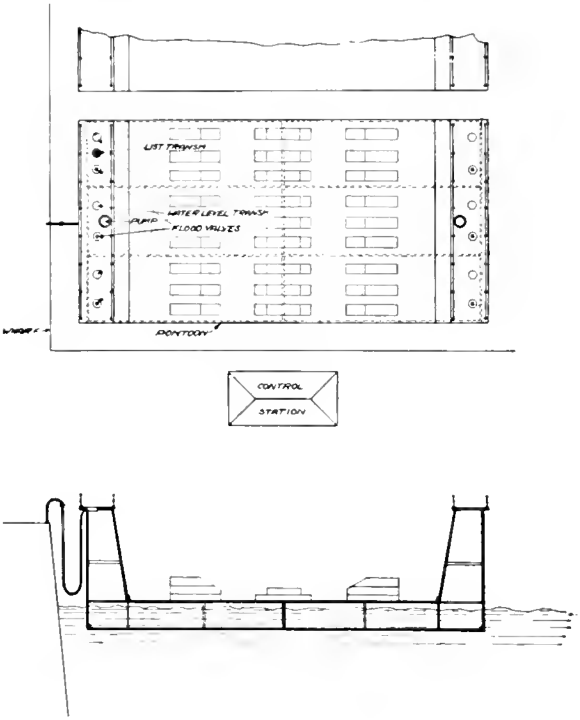

Fig. 98. Plan and Section of Multiple Pontoon Dry Dock, showing Location of Transmitters

The flood valve transmitter is connected to the rising stem of the flood valve machinery, the position of which is transmitted to the

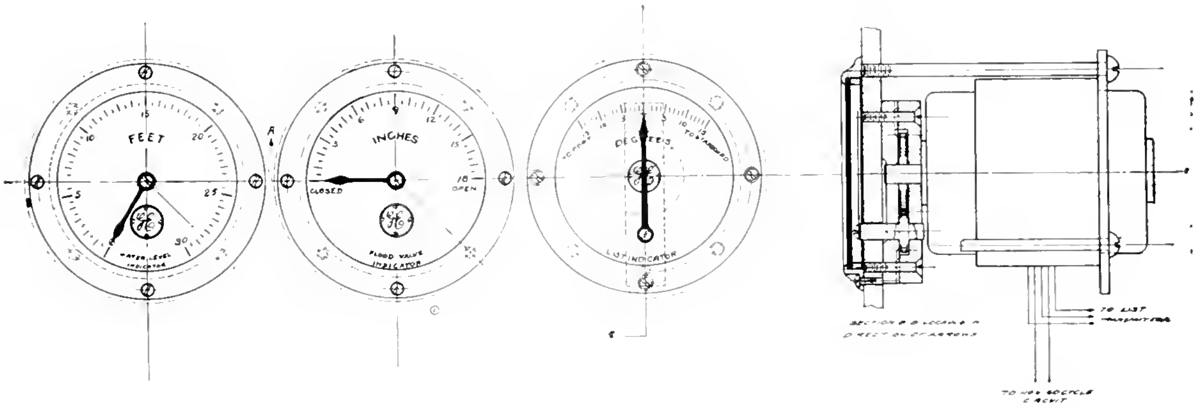

Fig. 99 Arrangement of Water Level, Flood Valve and List Indicators

flood valve indicator on the board. Six control switches and flood valves and two push button switches for the pumps complete the equipment for each section.

A further development in which position indicators will figure is in the form of rudder position indicators and revolution and direction indicators for ships. In fact there are numerous new fields for the application of the principle.

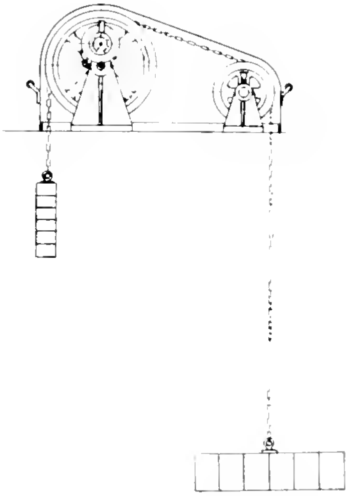

Fig. 100 Water Level Transmitter

Lighting

The total sales of incandescent lamps (excluding miniature) in the United States during the year 1919 is estimated to be 175 millions of lamps, a decrease of 11 millions (about 6 per cent) from the previous year. The number of lamps sold each year from 1890 to date is shown by the curves in Fig. 101.* The sales of Gem lamps, which have a carbon filament, are included in the sales of carbon lamps. The Gem lamp is no longer on the market, its manufacture having been discontinued in the early part of 1919. The tantalum lamp was on the market from 1907 to 1912, but on account of the relatively small numbers sold, it is not shown on the curves.

Of the total sales in 1919 it is estimated that 162 millions ($92\frac{1}{2}$ per cent) are tungsten filament lamps, a decrease of 4 millions from the previous year's sales, and 13 millions are carbon lamps ($7\frac{1}{2}$ per cent), a decrease of 7 millions. It will be noted that the relative

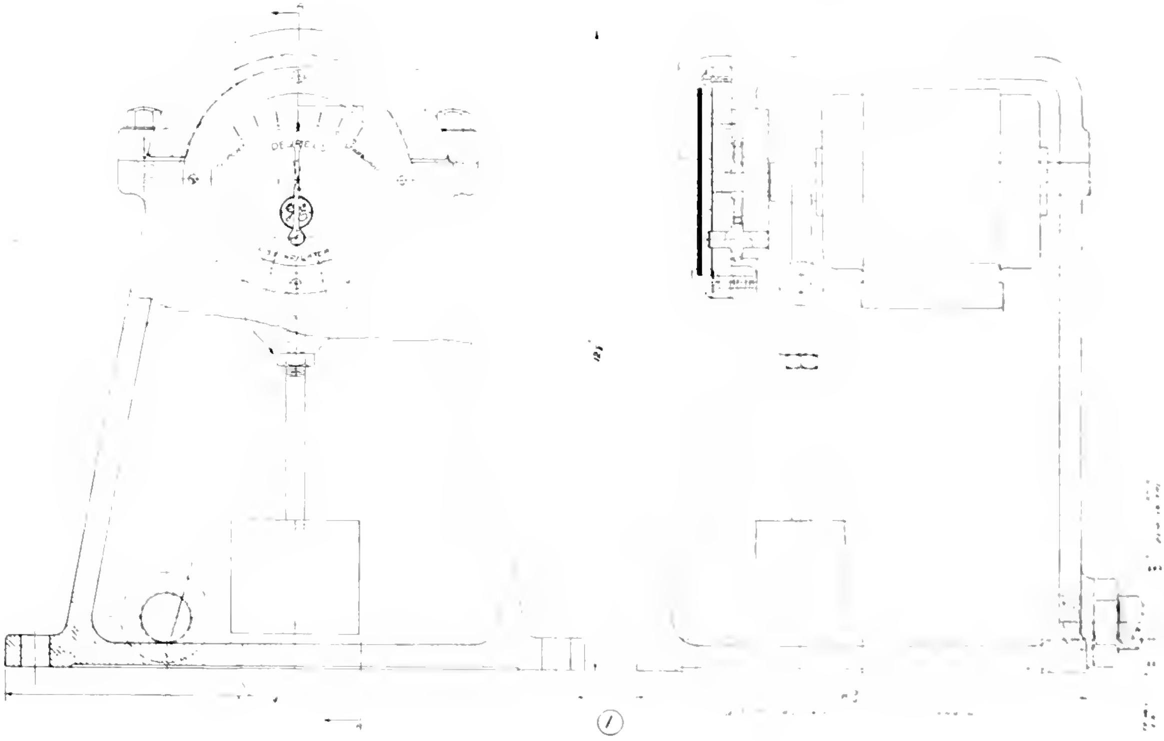

Fig. 102 List Transmitter and Local Indicator

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* Since this estimate was made the actual increase in the number of lamps sold has been so great that the corrected figures for 1919 will probably exceed those for 1918.

number of tungsten filament lamps has increased over the previous year, as is shown by the curve (Fig. 103), which gives the number of tungsten filament lamps in per cent of all lamps sold in the United States from the commercial introduction of this lamp in 1907 to date.

The white Mazda lamp (Fig. 104) was put on the market during the past year. This is a 50-watt Mazda C lamp for 110 to 125-volt service, the bulb being made of milky white glass to diffuse the light. It should be seen lighted to fully appreciate the beautiful soft light it gives.

The milk-white diffusing glass of the bulb is translucent rather than transparent, being of sufficient density to protect the eyes from the brilliancy of the filament when lighted, yet radiating practically all the useful light rays, softened and evenly diffused. The white Mazda lamp actually gives approximately the same quantity as, and better diffused light than, the 50-watt clear Mazda lamp.

Mazda B lamps (Fig. 105) specially designed to withstand rough usage, were also recently put on the market. They are known as Mill Type Mazda lamps, and are made in 25 and 50-watt sizes for 110 to 125 and 220 to 250-volt service. The mount supporting the filament is flexible, connected by a steel wire "shock absorber" and every other filament loop is anchored in the middle to prevent one leg of the filament overlapping another and becoming short circuited.

There has been quite a change in the past few years in the channels through which lamps are sold, central stations largely giving up the handling of lamps, as indicated by the fact that the direct sales of a large Lamp Works to central stations is now relatively, in proportion to sales, about one half that of five years ago.

In regard to lighting practice, the year 1919 may be characterized as one of unusual activity. With the removal of war restrictions, conditions rapidly returned to normal, and in many classes of lighting higher standards were reached. While the progress was perhaps most rapid in store lighting, the general advance in industrial lighting was probably the most remarkable. One of the lessons taught by the war was the importance of good lighting as a means of increasing manufacturing production.

Authoritative tests had shown production increases as high as 20 per cent, due to improved illumination. State industrial commissions and compensation insurance companies have been advocating better lighting for safety. Improved reflector equipment had become available, and a foot-candle meter permitted quick and easy surveys of lighting intensities. These and other conditions working together stimulated interest in industrial lighting, and give promise of even wider use of better lighting in the future. The industrial lighting codes (Fig. 106) have begun to influence factory lighting in the several states, where adopted, to which were recently added California and Oregon. Several other states appear to be on the verge of similar action.

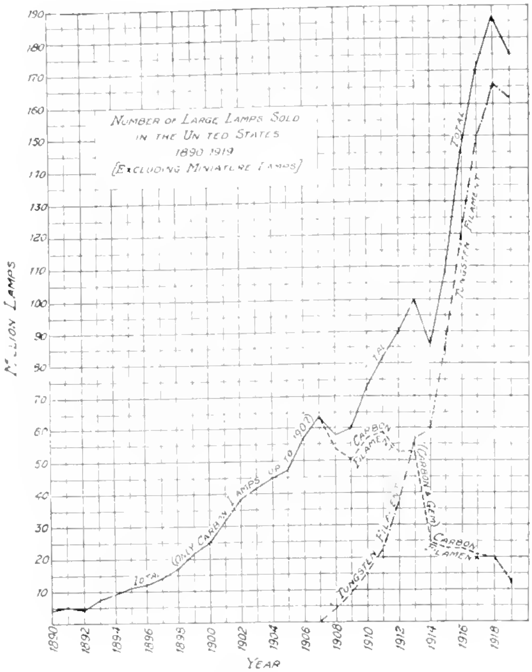


Fig. 101. Number of Incandescent Lamps Sold in the United States (excluding miniature lamps)

The automobile headlighting problem received considerable attention, and improved regulations for safer driving lights were adopted in several states, including California, Connecticut and Pennsylvania. Additional tests by committees of the Illuminating Engineering Society and Society of Automotive Engineers have confirmed the specifications already prepared.

Among the new types of lamp accessories, it may be mentioned that the RLM Standard dome reflectors (Fig. 108) are now being made and strongly recommended by practically all of the leading manufacturers of steel reflectors, thus helping to assure good industrial lighting.

Quite a number of new fixtures and accessories have become available during the year. Among these may be mentioned the "Ace," which consists of a combination reflector, diffuser and enclosing globe (Fig. 109) made of one piece of glass.

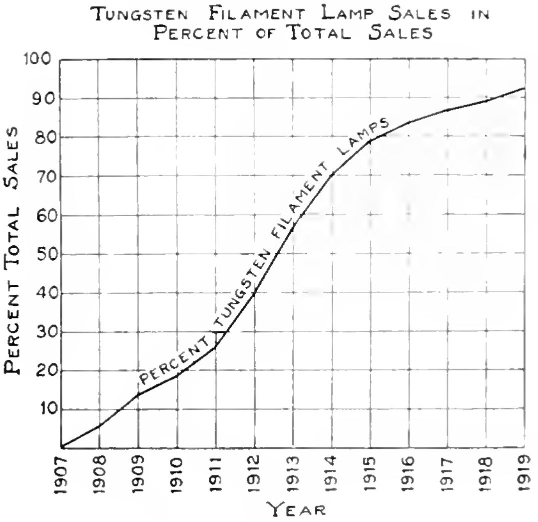


Fig. 103. Tungsten Filament Lamp Sales in Per Cent of Total Sales

A dense opal coating on the upper portion reflects a large percentage of light downward, but still provides suitable illumination on the ceiling. A lighter opal on the lower part conceals the lamp filament and diffuses the direct light. A clear section between avoids loss in transmitting the reflected light

The whole forms a large diffusing light source which gives a decided downward direction to the predominating light. It is large enough so that the lamp can be tightly enclosed without overheating, and dust can thus be excluded from the interior. It finds application in stores, offices, drafting rooms, and the better class of workrooms.

The Duplexalite fixture (Fig. 110) has been widely applied during the year in residence, hotel and commercial lighting. This is a fixture of the semi-indirect type, so arranged as to minimize the light projected horizontally While the light controlling part of the fixture is standardized, it lends itself to decoration by means of silk shades, thus permitting the expression of individual taste. Many very attractive installations have been made, including room lighting in leading hotels.

The incandescent lamp for moving picture projection is receiving more extended application. Quite a number of improvements are still being made in the lamps and optical systems, and it is probable that incandescent lamps will soon prove applicable for larger screens and longer throws than were originally contemplated.

The new developments in street lighting were not either radical or revolutionary in scope but tended toward simplification of apparatus and maximum utilization of light.

In the pendent unit for series Mazda lamps, the most important addition was the combination of Holophane dome refractors and stippled or rippled outer globes (Fig. 112). The refractor when used alone has not been universally satisfactory, although its use has been very general. The collection of dust and dirt is still serious in some communities and this deposit can collect on three surfaces, viz., the lamp bulb, and the inner and outer faces of the refractor. Where dust and smoke are prevalent and where the glassware is not cleaned frequently, this condition may account for a fifty per cent absorption of light By enclosing the dome refractor in a stippled globe, only one surface is exposed. In these globes the diffusion is obtained by protuberances and depressions in the surface of clear glass which breaks up the light but does not interfere with the directional effect

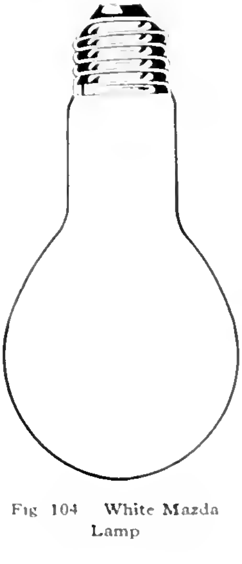


Fig 104 White Mazda Lamp

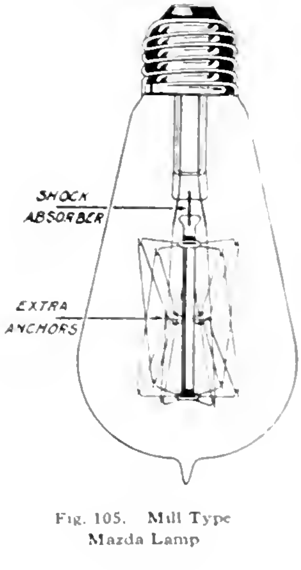
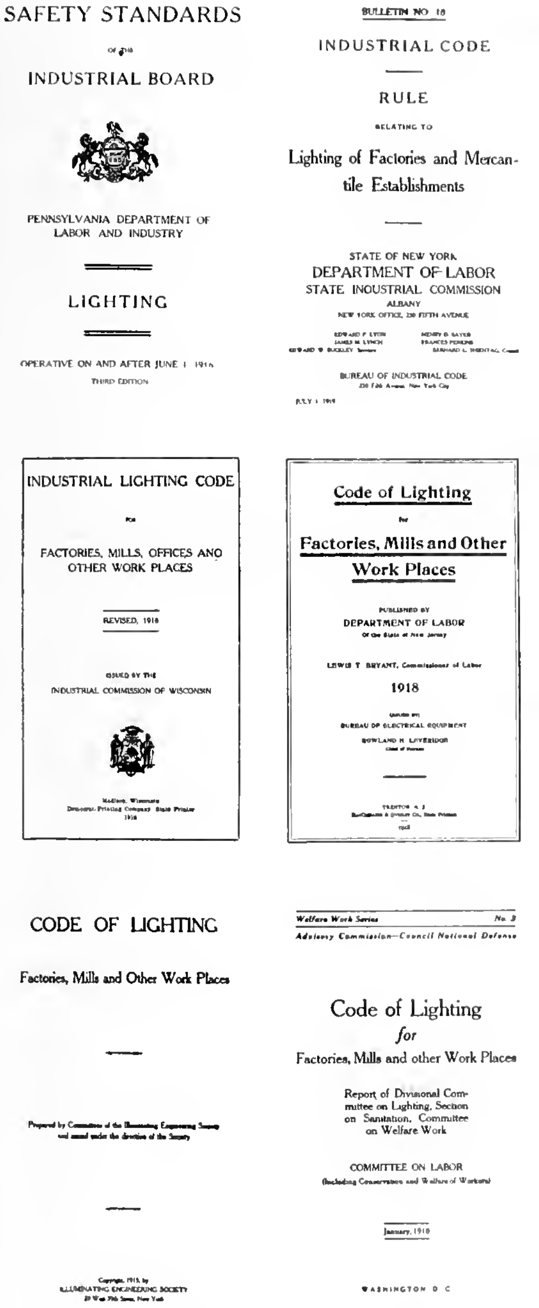


Fig. 105. Mill Type Mazda Lamp

of the refractor; the absorption being practically that of clear glass.

There is an attractive installation of these units at Niagara Falls, N. Y.



SAFETY STANDARDS
OF THE
INDUSTRIAL BOARD

PENNSYLVANIA DEPARTMENT OF
LABOR AND INDUSTRY

LIGHTING

OPERATIVE ON AND AFTER JUNE 1 1916
THIRD EDITION

BULLETIN NO. 18
INDUSTRIAL CODE

RULE
RELATING TO
Lighting of Factories and Mercantile Establishments

STATE OF NEW YORK
DEPARTMENT OF LABOR
STATE INDUSTRIAL COMMISSION
ALBANY
NEW YORK OFFICE, 230 FIFTH AVENUE

BUREAU OF INDUSTRIAL CODE

JULY 1 1919

INDUSTRIAL LIGHTING CODE
FOR
FACTORIES, MILLS, OFFICES AND
OTHER WORK PLACES

REVISED, 1918

ISSUED BY THE
INDUSTRIAL COMMISSION OF WISCONSIN

Code of Lighting
for
Factories, Mills and Other
Work Places

PUBLISHED BY
DEPARTMENT OF LABOR
Of the State of New Jersey

LEWIS T. BRYANT, Commissioner of Labor

1918

BUREAU OF ELECTRICAL EQUIPMENT
ROWLAND H. LEVERIDGE

CODE OF LIGHTING

Factories, Mills and Other Work Places

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Welfare Work Series No. 3
Advisory Commission—Council National Defense

Code of Lighting
for
Factories, Mills and other Work Places

Report of Divisional Committee on Lighting, Section
on Sanitation, Committee
on Welfare Work

COMMITTEE ON LABOR
(Including Conservation and Welfare of Workers)

January, 1918

WASHINGTON D C

Fig. 106. Some Typical Lighting Codes, Indicative of the Growing Appreciation of the Importance of Adequate Industrial Illumination

The single light of high candle-power has proved more popular than the clusters of lower candle-power lamps from a standpoint of economy, efficiency and appearance. The standards themselves are becoming slender and unobstrusive, while the new globes are of more graceful shapes with smaller top and bottom openings and with as low absorption as is consistent with perfect diffusion. Recent forms (Fig. 113) show a serious effort to harmonize the architectural features of the pole, casing and top.

Fig. 107. Lighting Fixture Using One-piece Porcelain Combined Radial Wave Reflector and Refractor Holder

In an effort to reduce manufacturing operations and to increase the safety factor, there was produced a unit (Fig. 107) moulded of one piece of porcelain, combining a radial wave reflector and a refractor holder. This should simplify the question of maintenance and replacement as it increases enormously the insulation of the unit.

To increase the actual illumination secured with luminous arc lamps (Fig. 111), the ingredients of the electrodes were compounded under great pressure. This permits a high efficiency mixture, giving 30 to 40 per cent more light than the standard electrodes with at least equal life. If the standard intensities are satisfactory, the compressed electrodes will yield an increased life of 30 to 40 per cent.

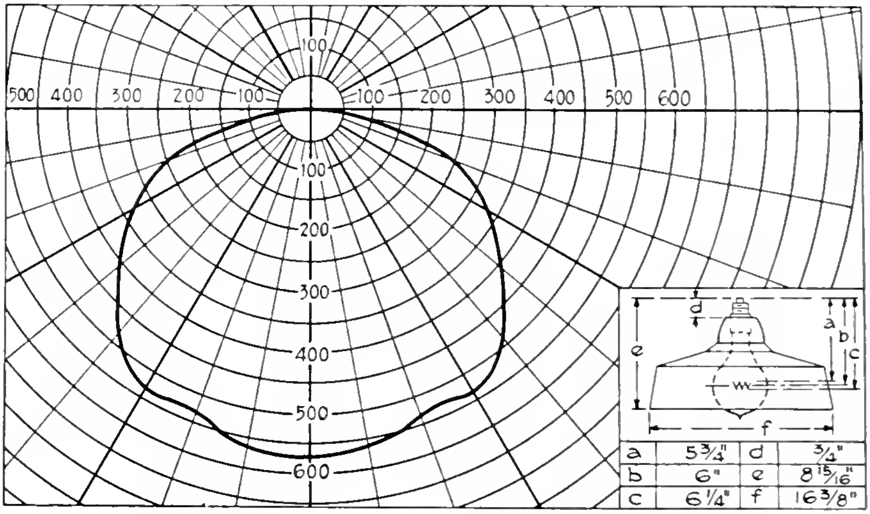

Fig. 108. Photometric Test of RLM Standard Dome Reflector, showing Distribution of Candle-power in a Vertical Plane

With this electrode, it should be possible to use a glass mirror internal reflector which adds a further improvement to the effective illumination. In the luminous arc 60 per cent of the light is above the horizontal. The present porcelain reflector cannot be made particularly efficient and becomes of less value as it is discolored by fumes. The glass reflector will be initially of higher efficiency and will be more easily cleaned.

Pendent luminous lamps have been regularly furnished with clear globes. With the increased light from the new electrodes it is now desirable to use a blown rippled globe which gives an appreciable degree of diffusion with no greater absorption than the clear glass.

The increased efficiency electrodes also permit the use of a lower wattage adjustment on each lamp without reducing the effective lighting. This saves 40 watts per lamp and increases proportionately the capacity of the rectifier. In Detroit for instance, they are operating 90 to 94 low wattage lamps on each 75-light rectifier.

Unusual interior lighting effects were secured at the Chicago and Buffalo Electrical Shows in 1919; in each case the required illumination being combined with a unique artistic scheme of decoration consistently adhered to throughout.

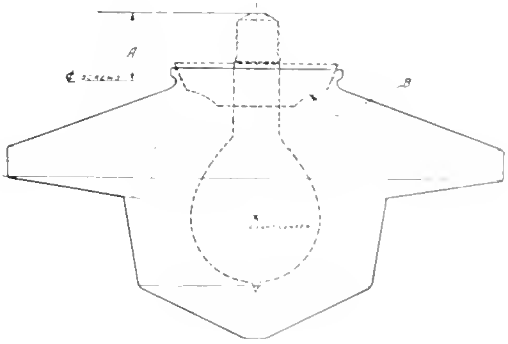

Fig 109. The "Ace" Combination Reflector, Diffuser and Enclosing Globe

Fig 110 The Duplexalite Fixture

At the Coliseum in Chicago (Fig. 111) the display was called the "City of Aladdin" and represented a Chinese market place, illuminated by Chinese lanterns.

In the center there stood the "Palace of Aladdin," a structure 50 feet in height studded with glass jewels and utilizing panels and plates of a new form of painted mirrored glass, flood lighted by concealed searchlights.

At the Buffalo show an entirely different, but equally striking effect was obtained by using an ultra-modern decorative scheme (Fig. 115) in which 4500 illuminated discs were distributed among the roof girders for the purpose of neutralizing or camouflaging these girders. The discs were covered with geometric designs in metallic paints and the color tones from the sides of the building to the center line of the roof were graded so as to give an effect of height. Thirty stage spotlights were used to illuminate these discs.

All other lighting at the show was produced by 5000 white Mazda lamps which were, in this way, displayed in quantity for the first time.

As the electrical industry devoted all its energies from the beginning of hostilities to the intensified production of apparatus and supplies which were utilized either directly or indirectly in National service, it also, with the coming of peace, developed forms of artistic illumination especially designed to serve as a visible welcome to our returning soldiers and sailors. This special application of illuminating engineering has been generally referred to as "Victory Lighting."

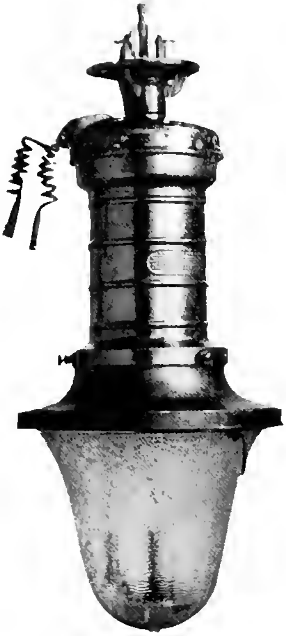

Fig. 111. Series Luminous Arc Lamp Equipped with Clear Rippled Outer Globe

Fig. 112. Pendent Novalux Unit with Stippled Globe and Dome Refractor

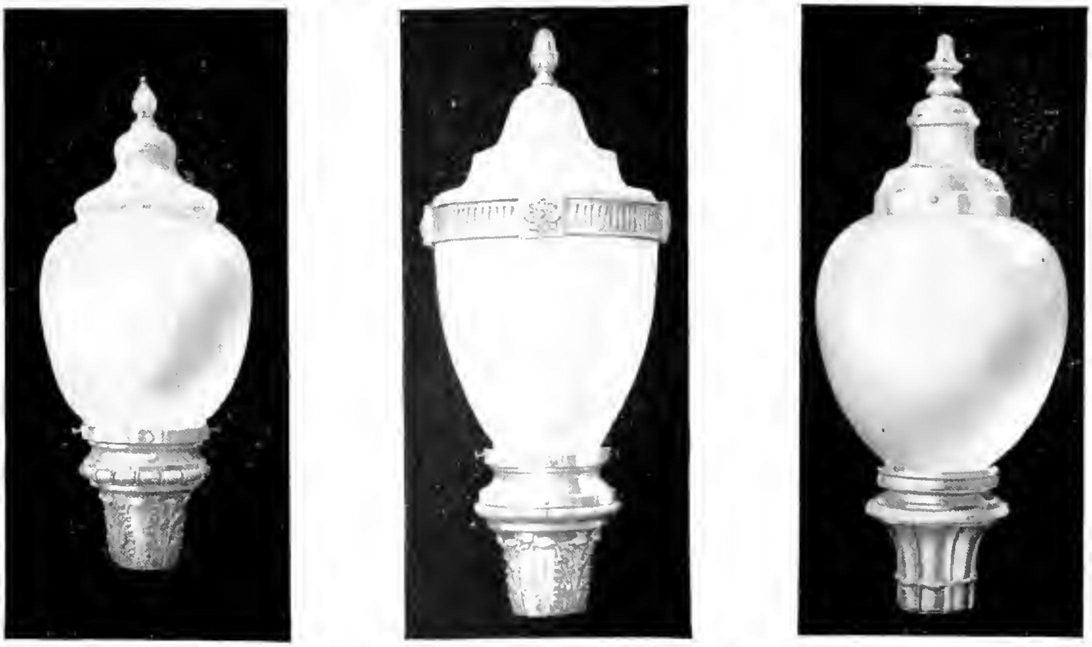

Fig. 113. Typical Ornamental Single Light Street Lighting Units

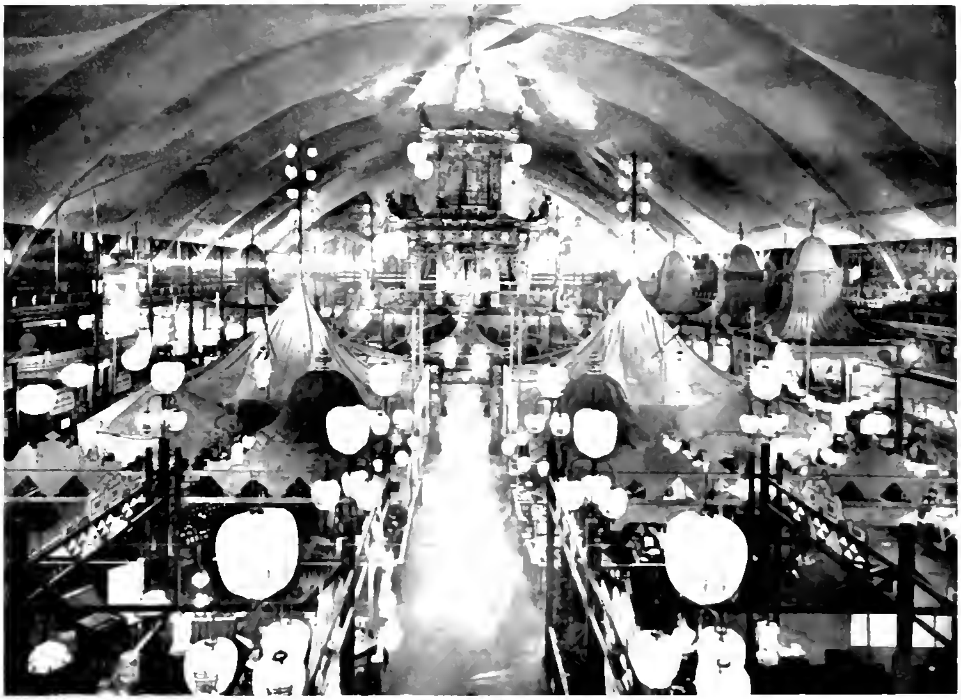

Fig. 114. "City of Aladdin"—Chicago Electric Show

Fig. 115 White Mazda Lamps Buffalo Electric Show

Fig. 116 "The Jeweled Portal for the Victorious Army," New York City

Fig. 117 The Jeweled "Altar of Victory," Chicago, Ill.

An excellent example of Victory Lighting is the "Jeweled Portal for the Victorious Army" (Fig. 116) in New York City. The two vertical shafts of the portal, 80 feet in height, are each surmounted by a sunburst of glass jewels and between them is suspended an ornamental jewelled curtain in geometric design; the complete portal containing about 30,000 of these jewels. The lighting of the portal was accomplished by means of 24 18-in. arc searchlights which were provided with color screens to give variety to the lighting effects produced.

In Chicago the corresponding display took the form of a huge "Altar of Victory," the central feature being a curtain of jewels (Fig. 117) suspended from two candelabra each 90 feet in height, which were also studded with glass jewels. The 30,000 jewels which were utilized in this manner were illuminated by 60-in. army searchlight projectors located at a distance from the altar supplemented by a number of small flood lights located on the platform at the base of the altar and at other nearby points.

A less elaborate but very attractive example of "Victory Lighting" is shown in Fig. 118. It consists of a sunburst shield containing more than 1600 5-watt Mazda lamps with which the required yellow and red effects were produced by the use of color caps on the lamps. The background was painted as a sunburst so that even by daylight the shield presented an attractive appearance.

The central figure is the flag, which is seen flashing in waving motion against the steady brilliancy of the shield of victory.

Fig. 118 The Incandescent "Shield of Victory," Schenectady, N. Y

Thermostatic Metal

By Henry Herrman

Metals Division, Fort Wayne Department, General Electric Company

For use in the temperature controlled devices it manufactures, the General Electric Company sought in vain to find on the market a thermostatic metal of the same high standard of quality as the remaining parts of the devices. It naturally set about to strengthen this weak point and in consequence developed the metal described below—a duplex metal superior in characteristics to any domestic or foreign product The attention of manufacturers of devices influenced by temperature is directed to the usefulness of this material, as its field of application has already proved to be far greater than originally contemplated. —Editor.

Thermally responsive devices have been taxing the inventive minds of the world for many years. Various combinations of materials having widely different coefficients of expansion have been used in various manners to get a thermally responsive device. The thermostatic element of these early devices consisted of separate strips of zinc and steel riveted together; hard rubber rods operating in connection with glass tubes; separate strips of brass and steel attached at the outer ends in such a way as to form a bellows-like combination; and many similar adaptations along the same lines, all designed to produce motion as the temperature varied. All of the combinations tried were found lacking in one very important respect; that is, the permanency of position or what may be called permanent zero. Upon material changes of temperature the deflection which took place strained the connection between the two materials with the result that they shifted slightly with regard to each other, and therefore any pointer or mechanism which they controlled assumed a new position when the basic temperature was again reached. This common defect in the earlier thermostatic elements lead the Germans to develop a duplex metal with an absolutely homogeneous joint, the two dissimilar metals being manipulated so that at the surfaces of connection they were completely alloyed. In this way a thermostatic metal having permanency of position was obtained.

A secondary part of the problem lay in the choice of metals having coefficients of expansion sufficiently different to give a large deflection. For use in the thermostatically operated devices of its own manufacture, the General Electric Company developed a bimetallic thermostatic material which is similar to the German material in that the two metals are permanently united, but which is superior in many characteristics; for instance, its deflection per degree is 18 to 20 per cent greater than that of the foreign product. The combination of metals used is actually the one which gives the greatest deflection per degree of temperature change that can be obtained with reliability.

In its manufacture a bar of metal having the lower coefficient of expansion is placed in a mould and heated by an oxy-acetylene flame to a bright red. A fluxing agent is then sprinkled on the surface and the bar is brought to its fusing temperature. On this fluxed surface a layer of the metal having the higher coefficient of expansion is melted by the oxy-acetylene flame. The surface of this layer is then brought to a molten state by the oxy-acetylene flame and molten metal of the same composition is poured on to build up the de-

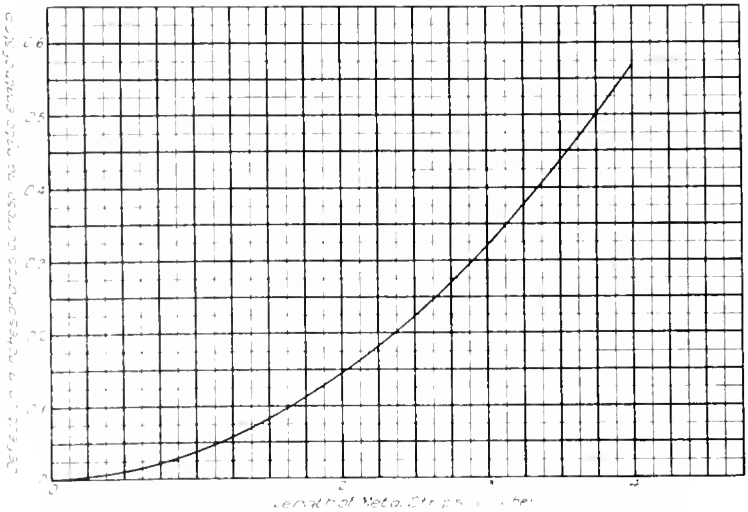

Fig 1. Deflection Obtained from Thermostatic Metal Strip Subjected to Different Temperatures. Size of strips 4 in. long, $\frac{3}{16}$ in. wide, 0.030 in. thick

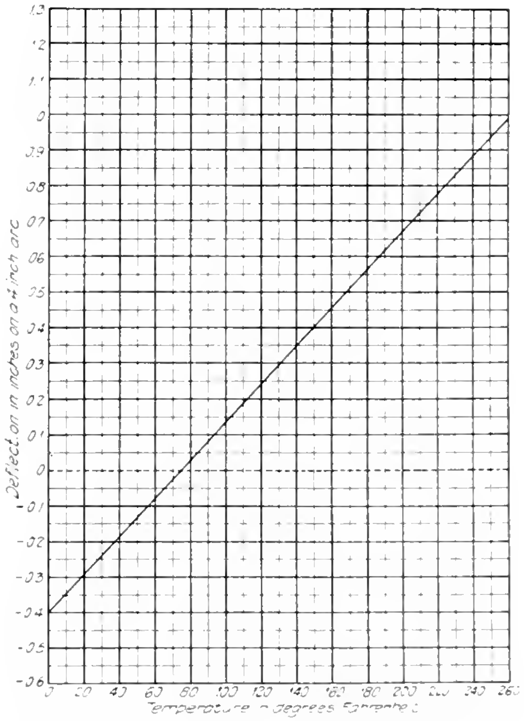

Fig. 2. Deflection Obtained from Thermostatic Metal Strips of Different Lengths When Subjected to a Temperature Change of 100 Deg. F. Size of strips $\frac{3}{16}$ in. wide, 0.030 in. thick

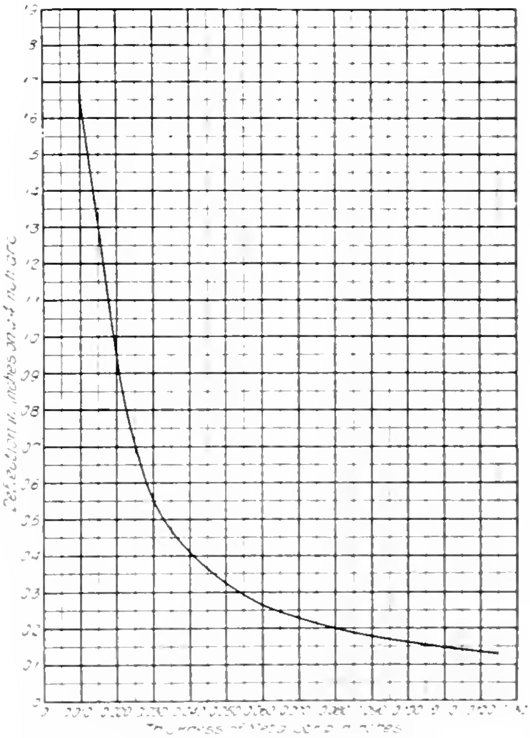

Fig. 3 Deflection Obtained from Different Thicknesses of Thermostatic Metal Strip Subjected to a Temperature Change of 100 Deg F. Size of strips 4 in. long $\frac{3}{4}$ in. wide

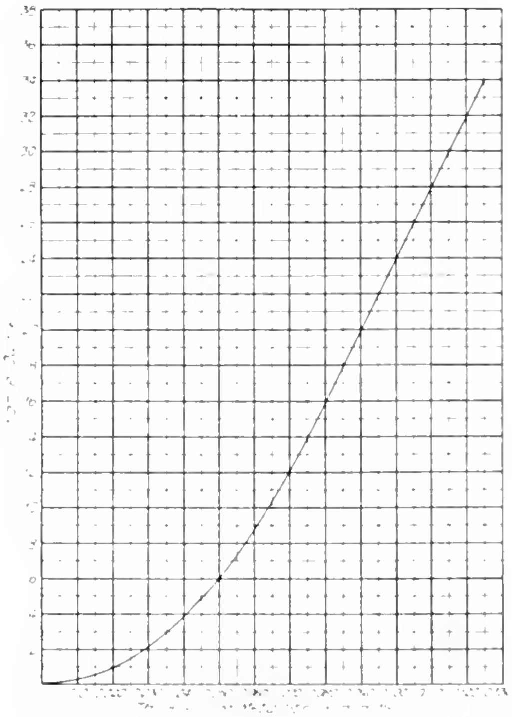

Fig. 4 Force Exerted by Thermostatic Metal Strips of Various Thicknesses for 100 Deg F Temperature Change Size of strips 4 in long, $\frac{3}{4}$ in wide

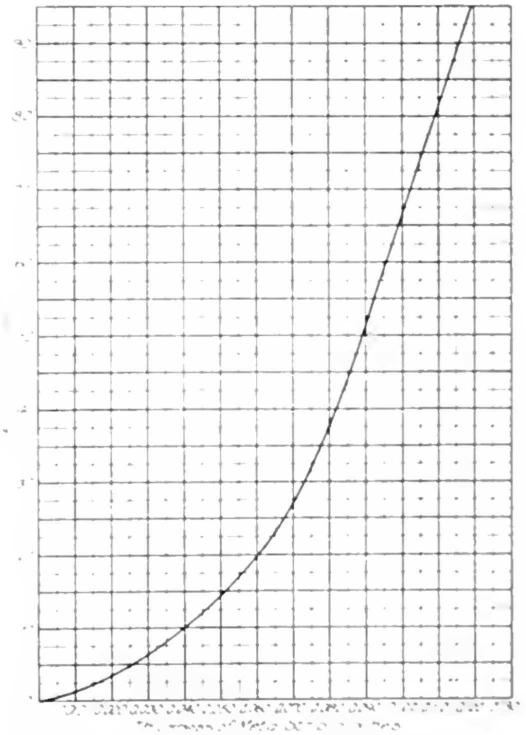

Fig. 5 Force Required to Obtain Permanent Set of Thermostatic Metal Strips of Various Thicknesses Size of strips 4 in long $\frac{3}{4}$ in wide

sired thickness. The resulting composition ingot is shaped, cleaned, rolled, and annealed.

After the thorough superiority of this domestic made duplex metal had been demonstrated, the Company placed its manufacture on a larger scale in order that the metal would be available to other manufacturers of devices who can use it to good advantage in their products. In some of the applications of this thermostatic metal, it is used for the purpose of temperature indication, in other applications it is used for temperature control, while in still other applications it is used to compensate for or neutralize errors in apparatus due to changes of temperature. These available applications have already resulted in the use of the metal in:

Fig. 6. Photomicrograph of Thermostatic Metal, showing Union Between Components

Oven thermometers
Electric heaters
Ice machines
Refrigerators
Thermostats
Scientific instruments
Automobile ignition control
Battery charging control
Electric signal control
Carburetors
Computing scales
Speedometers
Steam radiators
Sterilizers
Gas range valves
Automobile shutters
Heating pads
Flatirons, etc.

It is of interest to note the laws which express the characteristic action of this metal. Careful laboratory tests show that

1. ***Deflection upon Temperature Change Varies***
   Inversely as the *thickness*
   As the square of the *length*
   Not affected by changes of *width*
   Directly with *degrees temperature change.*
2. ***Force Exerted upon Temperature Change Varies***
   As the square of the *thickness*
   Not affected by changes in *length*
   Directly as the *width*
   As the square of the *degree temperature change.*
3. ***Weight Required for Permanent Set Varies***
   As the square of the *thickness* (between narrow limits)
   Inversely as the *length*
   Directly as the *width.*

The curves in Figs. 1, 2, 3, 4 and 5 illustrate the action of the metal under certain varying conditions.

Under the sclerescope the yellow of the metal shows a hardness of 23, and the white side a hardness of 35, based upon a one per cent carbon steel (hard) as 100.

Fig. 6 shows a photomicrograph of the union of the two metals and indicates how impossible it is for one metal to slip upon the other as temperature changes cause the metal to bend. So permanent in fact is the union found to be that no amount of bending or twisting will separate the two metals; therefore it is possible to form the combined metal element into various shapes and to anneal it after the forming operations. Even on heating the bond will not be broken below the melting point of the metal which has the lower melting temperature, and it is found that the metal can be used safely at any temperature below 500 deg. F.

The force that the thermostatic metal is capable of exerting without taking permanent set is dependent upon the thickness of the strip. Fig. 4 shows that the metal on bending with temperature change will exert considerable force for the mechanical operation of various devices without taking permanent set.

Another feature of interest is the fact that both materials used in forming the thermostatic metal are very resistant to corrosin, so that it can be used in any location reasonable for the use of metal without deterioration or change in its operating characteristics.

Electric Propulsion of Merchant Ships

By W. L. R. Emmet

Lighting Department, General Electric Company

In view of the successful applications of electric drive to large naval vessels, and the unforeseen limitations met in the turbine gear drive of cargo vessels, the author of this article shows how suitable is electric drive for ships of the merchant type. The article was read as a paper before the Society of Naval Architects and Marine Engineers, New York City, November 13 and 14, 1919.—Editor.

The use of electricity for propelling ships was first advocated in the case of large warships in which it affords particular advantages in the matter of cruising economy through change of speed ratio, interchangeability, space distribution, etc. The first application, however, was made in the case of the U. S. collier *Jupiter*, which is in most features a ship of the merchant type. The demonstration of geared-turbine propulsion came after the first serious proposals of electric drive, and the advantages which have been attributed to the geared method have suspended such activities as were considered in this country in the direction of electric drive for merchant ships, while, in the case of warships, electric drive activities have been uninterrupted. In the meantime certain electrically driven ships built in Europe, and operated with very high degrees of superheat, have shown wonderful fuel economy, and many more such ships are being equipped.

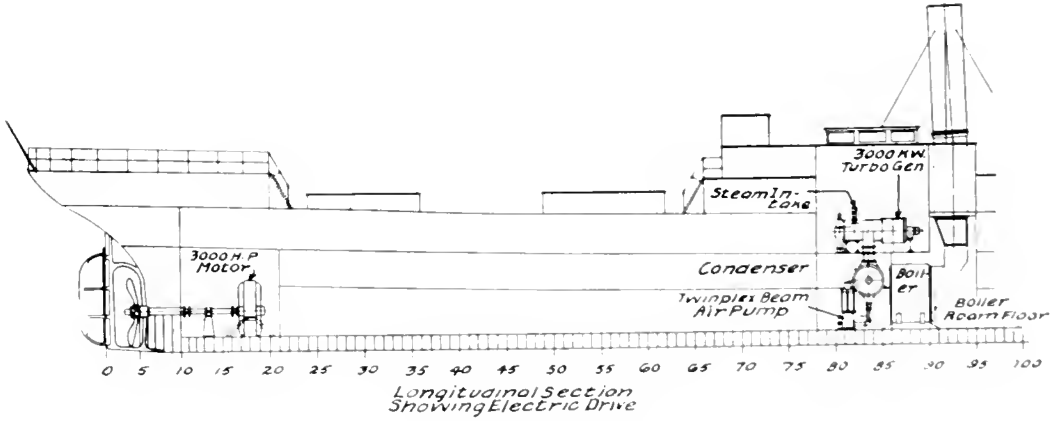

Fig. 1 Diagram showing Arrangement of Apparatus in an Electrically Propelled Merchant Ship

The larger American shipbuilders, having their own facilities for machinery construction, have, not unnaturally, been opponents of electric drive; and the Emergency Fleet Corporation, which for some time has represented ownership, has for various reasons discontinued such activities in this direction as had been planned.

Two or three years ago the writer was of the belief that the geared equipments then being made afforded a solution of the problem which in cost and results would probably prevent the commercial success of electric drive in merchant ships, although it was realized that the margin of possible advantage was small. Since that time improvements in electrical designs have been developed, and limitations of gear possibilities have appeared which put the question in a different light; and it is now the writer's belief that electric drive is justified in all large ships and that it will very soon develop a wide application notwithstanding the great efforts of skill, organization, and capital which have been given to the introduction of the gear drive for vessels of all classes.

The discussion of this subject is largely a matter of comparison with other methods, and the purpose of this article is to make clear what is proposed in a specific case and to suggest comparisons which may affect relative value.

The case selected is that of a vessel of 8800 deadweight tons, length 424 feet,

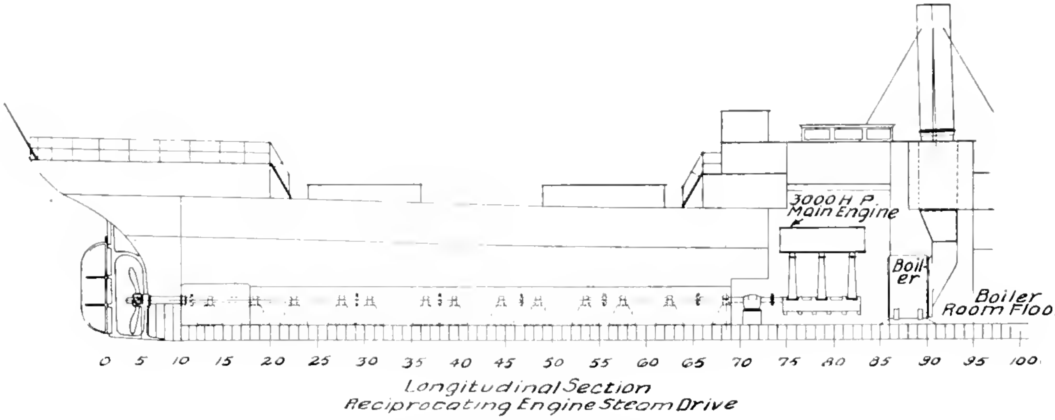

Fig. 2. Diagram showing Arrangement of Equipment in Merchant Ship Propelled by Triple Expansion Steam Engine

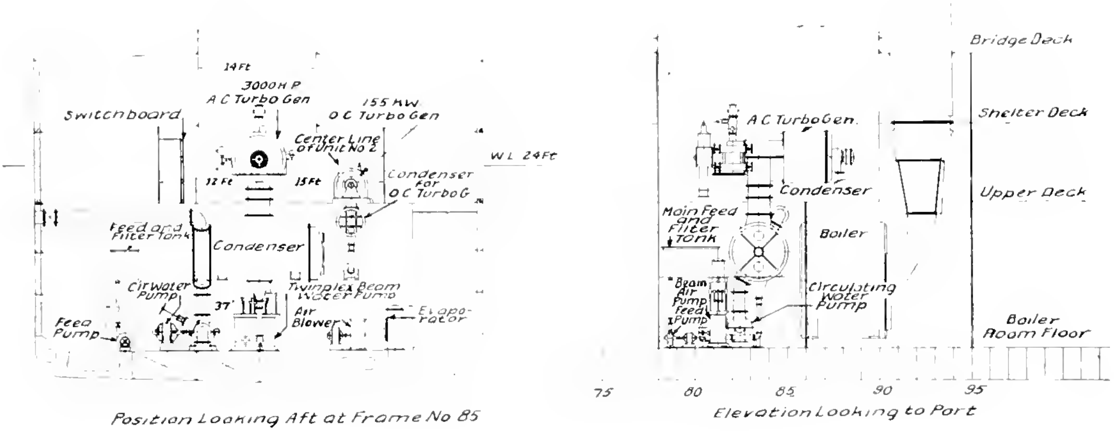

Fig. 3. Details of Turbo-electric Propelling Equipment

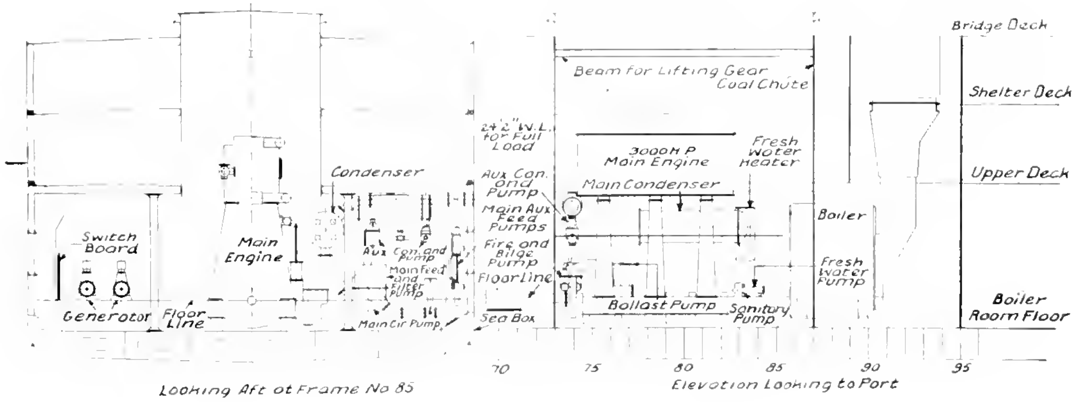

Fig. 4. Details of Triple Expansion Engine Equipment

beam 54 feet, having a cubic capacity of 460,000 cubic feet and capable of making 11.5 knots with 2500 shaft horse power delivered to a propeller operating at 100 revolutions per minute. Figs. 1 and 3 show an electric propelling equipment applied to such a ship; and, for comparison, Figs. 2 and 4 show an equipment with triple-expansion engines. It will be observed that the motor s placed as far aft as convenient, affording space for disassembling and for removal of the tail shaft. The generating unit and controlling equipment are placed near the boilers in such a manner as to afford a maximum convenient saving of cargo space, the condenser being suspended below the turbine in the same compartment with boilers. The auxiliaries are distributed in convenient locations in the turbine room and in the space below near the condenser.

The weight of this equipment, including generating unit, motor, controlling mechanism and direct-current exciter, will be about 67 tons.

Auxiliaries

In connection with such equipments it is proposed to use, as much as possible, electrically driven auxiliaries. It is necessary to maintain an electrical supply independent of the main generator for purposes of excitation and lighting. The losses involved in the operation of larger auxiliary generating equipment are relatively much less, and there is no increase of complications. With such an equipment it is proposed to install two 150-kw., turbine-driven, direct-current auxiliary generating units, one being required for service and the other installed as a spare Excitation and lighting will only amount to 40 kw., leaving 110 kw. available for any possible auxiliary uses. A little more than half of this should be sufficient for normal conditions. While the ship is at sea, for reasons of simplification and economy, it is proposed to exhaust the auxiliary generating unit into one of the lower stages of the main turbine at a pressure somewhat above the atmosphere, so that some of this exhaust steam will be available for feed water heating if that obtained from steam-driven auxiliaries is insufficient. In port, these auxiliary units would be exhausted into an auxiliary condensing plant which would be idle while the ship is at sea.

Motor Compartment

The motor carries the thrust bearing and is also equipped with a simple, slow-moving oil pump which maintains automatic lubrication in the motor compartment. This lubrication can be arranged with a storage tank and with an emergency drip supply to the low-speed bearings contained in the after compartment, so that, even if the oil pump should fail, many hours might elapse before injury could result to any of the bearings. With such an arrangement the self-lubrication of this compartment becomes entirely simple and safe, and with occasional inspection it should be operated without an attendant and without any passage connecting it with the engine-room; in fact, there is nothing that an attendant need do in this compartment, and there would be quite as much reason for keeping an attendant on the truck of an electric locomotive where the electrical and lubricating conditions are far more complicated.

Space Saving

It will be observed that the omission of the shaft alley and the diminution of space required for the engine-room materially increases the cargo space and simplifies its shape. This increase amounts to something over 12,000 cubic feet, nearly three per cent of the total capacity of the ship. The omission of the shaft alley, shafting, and supporting bearings effects a weight saving of about 60 tons, and there will be an additional weight saving in the machinery itself since the electrical equipment will weigh about nine tons less than the engine equipment for such a ship.

Economy

If this equipment is operated with 200 pounds steam pressure, 200 deg. F. superheat, and a vacuum of 28.5 inches, the steam consumption per shaft horse-power hour, not including auxiliaries, will amount to 9.5 pounds. Under normal conditions at sea, with most of the auxiliaries driven electrically, this should give a steam consumption for all purposes not greater than 11 pounds per shaft horse-power hour. Such a steam consumption will require at least 30 per cent less fuel for all purposes than would be required by a good reciprocating engine equipment operating without superheat, and even if an equal superheat were used with a reciprocating engine equipment, the gain would still be over 20 per cent.

In this connection it must be considered that large numbers of American ships are now being equipped with reciprocating engines and without superheat, although it has been amply demonstrated abroad that the use of high superheat is practical and economical.

If such a ship were in operation 250 days in a year between California and Australia, burning fuel oil at $1.00 per barrel, the saving in fuel over a similar engine-driven ship operating without superheat would amount to about $17,000, and the increased freight capacity leaving California would amount to 585 tons, which is 7½ per cent of the dead-weight tonnage.

Reliability

A study of the records and uses of such electrical apparatus as is applied in this case will show that the equipment is less liable to interruption of service than any other form of single-screw equipment which is applied to vessels. With such an equipment, however, arrangements could easily be made by which the ship could be navigated about half speed with the main generating unit out of service. This could be done by providing a motor-generator set or rotary converter so arranged that the power of the auxiliary generating units could be delivered to the main motor. In an electrically propelled ship, electricity is produced simply for one definite purpose, and the arrangement is simpler and more reliable than shore applications where power is taken from large distributing systems. It is also possible to provide automatic means which, by interrupting excitation, guard against the possibility of serious damage through possible accidents or insulation failures. Such electrical apparatus of the type used in ships is very easily repaired, and even when damaged, can generally be temporarily connected so as to be operative. The knowledge necessary for such repairs is very easily imparted and is constantly being practiced in our industries by persons who have had little or no electrical training.

Reliability of Gearing in Ships

To make comparison of such an equipment with a gear-driven ship is much more difficult, since a great variety of arrangements of turbines and gears have been applied to ships of this type. In the matter of reliability, as has been said, the electrical equipment is entirely beyond question, while many evidences of serious trouble and deterioration have developed in geared ships of most types which have been produced. Gears have been very successful in many warships, but these are subject to only occasional short periods of high-power service. In some merchant ships, gears have been very successful; and in others, most serious trouble has been encountered. Variations of results in similar equipments in different ships illustrate some of the possible uncertainties. Parsons' original gear applications operated with a single reduction, very small diameter pinions, and a large diameter gear on the propeller shaft. Some of these have been reported to be very successful, but the gains in economy shown in Parsons' publications are nothing like so great as those accomplished by high-speed turbines with double reduction gears. There have, however, been many cases of failure with gears of this type. In fact, there seems to be no type of gearing with which trouble has not been experienced after long service in cargo vessels.

Recent production of so-called "Standard English ships" shows that they are being equipped with double-reduction gearing; and at the same time that this change of method is being adopted in England, the use of single reduction is being extensively advocated and applied here. Although all the original American equipments in merchant ships were double reduction, the writer has seen a solid-gear, double-reduction equipment of American make in which the gears were badly worn and pitted after 17,000 miles of service, and in this case the proportions of gears are closely equivalent to those which have been adopted in the new standard English ships, and the conditions of design and manufacture were quite as good.

These indisputable facts and many others certainly indicate that gearing for ships has not yet reached a state of finished development.

One of the uncertainties of gear operation in ships is illustrated by the very great difference in durability of gears in ship propulsion and in shore uses. In trials on shore, gears have borne without blemish, for equal periods, loads equivalent to approximately four times the average loads which have caused bad destruction of similar gears at sea. This is illustrated by the photograph in Figs. 5 and 6, and the data given in the titles are characteristic of many other similar experiences which have developed.

The reasons for these astonishing differences have never been adequately explained. Fig. 7 shows a record taken from a torsion coupling on a cargo vessel operating in ballast in a moderate seaway. This record shows that the torque on the propeller shaft varied from zero to approximately 75 per cent overload under certain wave conditions. The effect of bad weather on the endurance of gears has often been observed, and it is quite possible that variations much greater than that here shown may at times be experienced. In this case the ship was pitching only four degrees. Part of the small, quick variations shown in this record were caused by a transmitting ring which ran slightly out of true in the instrument, but otherwise the conditions were such that the record must be substantially correct.

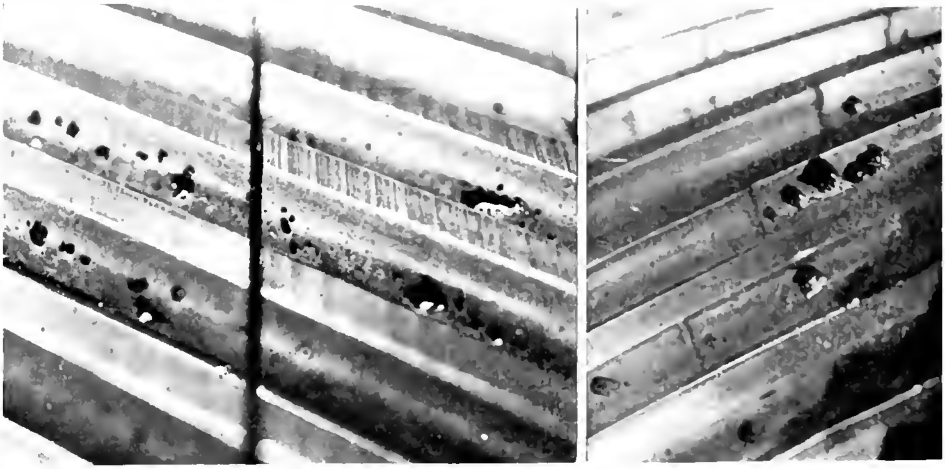

Fig. 5. Low Speed Ship Gear and Pinion Pinion diameter 11 44 in Pitch $3\frac{1}{2}$ in Normal load 1150 pounds per inch face. Tooth speed 1272 feet per minute. Time run, about 400 hours at sea

Another matter of uncertainty in geared-turbine equipments is that of the temperature in the turbines. The operation of turbines in the reverse direction occasions large temperature variations, and temperature variations constitute a fruitful source of danger to turbine structures. Fig. 8 shows a record for temperature taken by a pyrometer situated between the nozzle and bucket of the last stage of a marine turbine while the turbine was being operated at normal speed in the reverse direction. It will be observed that the high temperature shown by that record was produced in an extremely high vacuum by the introduction of small amounts of steam.

A turbine when operated in the reverse direction has a friction loss something like ten times as great as when it operates in a normal direction. In the General Electric shops it has been discovered that reversing wheels of marine turbines turn blue with heat when operated at normal speed in a vacuum of 20 inches. While no definite information can be given concerning the possible effects of high superheat in reversals of a marine turbine, the facts here given indicate that such effects may be serious and should, if possible, be avoided. A turbine which is kept running in its normal direction is not subject to any large temperature variations

The economies incident to the use of superheat on shipboard are very great and cannot long be neglected, although there have been few applications of superheat to American ships. The following extract from a letter from Van Nievelt, Goudriaan & Co., Rotterdam, Holland, illustrates the superheat possibilities in engine-driven ships:

"We are using during the last five years, in our multitubular boilers $3\frac{1}{2}$-inch tubes, very high funnels and Diamond blowers, and have no trouble at all in getting sufficient steam. We have practically no leakage at the connections of the pipes and boxes. The original pipes are still in use, the capacity of a 20-ton evaporator is sufficient for supplying feed water."

"Three of our steamers have been running half a year without superheaters with a coal consumption of 24 to 25 tons. After fitting superheaters the consumption was about 22 tons, making a saving of at least 10 per cent."

In electrically driven ships the gain is quite as great as is here shown, and no practical difficulties can result even from degrees of superheat which would be impracticable with reciprocating engines

Efficiency of Transmission

The selection for comparison of a ship of low power is unfavorable to electric drive in the matter of transmission efficiency, the conditions being better for this method in ships of higher power. The generator designed for this case has an efficiency of 95.6 per cent and the motor 95.9 per cent, making the transmission efficiency, including cable loss, etc., 91.6 per cent. In machinery designed for certain high-power ships, the efficiency is as high as 94 per cent.

Fig. 6. Experimental Gear Disc and Pinion. Pinion Diameter 7.28 in. Pitch 4 in. Load carried 3000 pounds per inch face. Tooth speed 7000 feet per minute. Time run 263 hours in Schenectady. Has made 8 times as many tooth engagements as above with a pressure which, considering smaller pinion diameter, is relatively four times as heavy

To determine the efficiency of gear transmission as compared with the figures just given, very careful tests have been made at Schenectady. A 2400-horse-power ship turbine was connected through two sets of double-reduction gearing to a generator, and the steam consumption was tested at various degrees of load and speed; then the same turbine was connected to the same generator without gearing, and tests were run with the same conditions and the same degree of steam flow. All this was done on a testing stand where conditions are uniform and accurate, the gears ran with perfect smoothness, and all conditions were favorable. Since the comparison gives the loss of two gears, the differences are considerable and the determination should be very close to the correct value. This test showed that the performance of a single gear is as follows:

Shaft Horse-power	R.P.M.	Loss of Gearing	Efficiency of Gears
2400	87	125 h-p.	95.0 %
1420	77	80 h-p.	94.7 %

In addition to these gear losses, we must also consider the loss in friction of the reversing turbine, which is estimated from reliable data to be 28 horse power, and we must also consider the bearing losses on about 100 feet of shaft, which in perfect alignment will be 8.5 horse power. These additional losses reduce the transmission efficiency to 93.5 per cent, leaving only 1.9 per cent advantage to the gearing. With the shaft more or less out of line and the gears operating under sea conditions, it is probable that the losses given would be greatly increased. Noise is an indication of loss, and most marine gears are at times noisy, while the gears in this test were almost silent. The gears tested in this case were of the General Electric Alquist type, and it might be claimed that other kinds of gears would be more efficient but it is obvious that, under fixed load and with similar gear speeds and diameters, there could be no advantage in any other type even if it ran with equal smoothness.

Cost

In the present condition of prices, it is very difficult to compare costs, but the cost estimates of the General Electric Company on electric equipments for cargo boats and geared equipments of recent design indicate that the electric is slightly cheaper. If we consider savings in shafting support, shaft alley, oiling system, etc., the saving with electric drive should be as much as 20 per cent of the cost of the driving machinery.

Propeller Speeds

In ships requiring less than 3000 horse power, there is some practical disadvantage in using propeller speeds below 100 revolutions per minute because of the large number of motor poles required if a high-speed turbine is adopted. Studies recently made by the Navy Department and elsewhere have indicated that there is practically no disadvantage in using a propeller speed of 100 revolutions per minute on an 11-knot, 2400-horse-power ship, but in all cases of electric drive the matter of propeller speed should be carefully studied. In ships of higher power it is not desirable to use extremely high turbine speeds, and therefore there can be no difficulty about propeller speeds. Even in low-power ships,

Fig. 7. Record from Torsion Spring Coupling on S.S. *Jebsen* in Ballast in a Moderately Rough Sea. Average r.p.m. 78 Average shaft horse power about 2000. Part of the smaller fluctuations shown came from an untrue collar in the instrument; otherwise record is correct

lower turbine speeds could be used if expedient but this is disadvantageous to a small turbine, and the relative advantages and disadvantages should be duly considered.

Operating Force

The history of the electrical industry has repeatedly shown that persons who have not used electrical apparatus assume that its operation requires a high order of skill and expert knowledge, and of this assumption we have already heard much in connection with electric drive for ships. A vast amount of experience has repeatedly shown that this assumption is the direct reverse of the truth, and a little thought as to the conditions in electrical apparatus should make the reason obvious. Conductor circuits are much simpler mechanically than pipes and mechanical motions, and electrical machinery is simply a combination of electric circuits with motion of rotation. The connections are easily shown by diagrams, and little mechanical skill is required to make them. The work of insulation can be so done that, under such conditions as exist in ship installations troubles which might involve difficulty of repair by unskilled persons are very improbable. In all the extensive uses of electricity in mills, mines, railways, and other industries, it has seldom failed to become popular immediately with the operating forces. In no case has this been more marked than in the ships which have been driven electrically. Large electrical apparatus is generally simpler than small, and the machinery used to propel a ship is in many respects simpler than that which is used to light it. Instead of introducing difficulties to the operating force, the adoption of electric drive will eliminate them and make ships much less dependent upon the skill and resourcefulness in their crews.

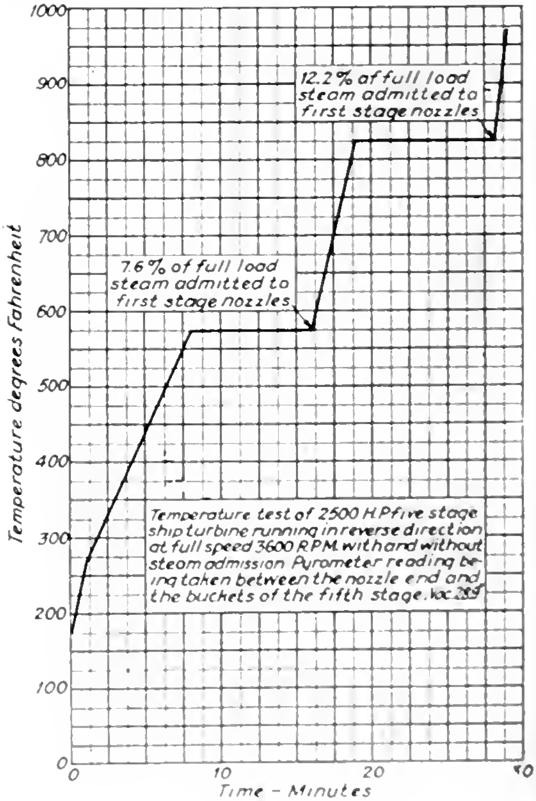

Fig. 8

Improving the Mazda Automobile Headlight Lamp

By L. C. Porter

Commercial Engineer, Miniature Department, Edison Lamp Works of the General Electric Company

Lamps that are intended for use with lens systems or parabolic reflectors must have the light source located along the axis, usually at the focal point, and it is readily seen that manufacturing methods must be adopted which will insure uniform dimensions in lamps of a given type, as only with such lamps can replacements be made quickly and satisfactorily. This article describes the manufacture of Mazda automobile headlight lamps stage by stage, and indicates that every effort has been made to secure a product as nearly uniform in dimensions and performance as is possible.—Editor.

During the war the greatest need in the manufacture of headlights was quantity production with minimum labor and time. Now, however, the pressing need for minimum labor is past and more attention can be given to perfecting the quality, and uniformity of product is one of the things that is being given special attention. Since the armistice was signed an engineer has been appointed to study the manufacturing methods and suggest changes which will result in more perfect automobile headlight lamps. He has instituted a system of gauges and inspections which is proving remarkably effective. It may be interesting to describe in detail the present method of manufacturing a typical lamp, say the 6-8-volt, G-12 bulb, 21-c-p. Mazda headlight lamp and to point out recent improvements and call attention to the inherent variations required for practical manufacturing in large quantities.

The stem of the lamp is made from straight glass tubing received in long pieces. This tubing is gauged for thickness and diameter. It is then cut up into short pieces of the proper length for the stem, by pushing the end of the tube against a stop and then moving it to a rapidly revolving emery wheel, see Fig. 1.

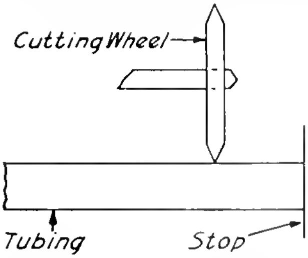

Fig. 1. Tubing for Lamp Stems Being Cut to Proper Length by Emery Wheel

The next operation is to put these short tubes into an automatic flare machine, which heats one end of the tube by means of a Bunsen flame and then spreads it out with a rotating metal plunger (see Fig. 2). Until recently this flaring was done by hand, resulting in a considerable variation in the spread of the flare and consequently in the length of the stem. With the automatic machine, however, the plunger enters a certain fixed distance and, being of constant diameter, there is less chance for variation in length. In order, however, to see that everything is working properly a certain percentage of all stems

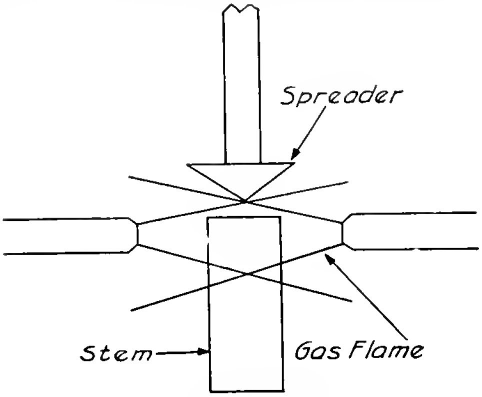

Fig. 2. Flaring End of Tubing for Junction with Bulb after Assembly of Filament

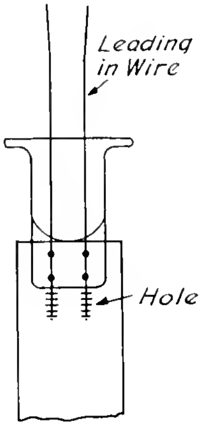

Fig. 3. Method of Inserting Leading-in Wires

are gauged for length and the results of these tests are recorded.

The next operation is the insertion of the leading-in wires (see Fig. 3) in the stem. The glass tube is placed in a machine, flare end up, and the two wires stuck down into holes in the rod holding the glass. Occasionally one of these wires will be slightly bent, or a particle of dirt will get into one of the holes, thus preventing the wire from going in its full depth. After the wires are in place the glass is rotated and heated by Bunsen flames until soft and then the glass is pinched together to make the seal. Formerly the leading-in wires were cut to just the required length and when it happened that a wire did not go to the very bottom of the hole, the result was leads of uneven length on the mount (see Fig. 4). Now, however, all leads are made two milli-meters longer than necessary, and after being sealed in the stem are trimmed off by a semi-automatic machine which fixes the distance from the top of the flare to the ends of the leading-in wires (see Fig. 5) and assures leads of uniform length. This means a considerable waste of nickel, but the high cost thus entailed is warranted by the more uniform product obtained.

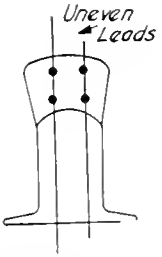

Fig. 4. Uneven Lengths of Leading-in Wires—Often a Result of Cutting Leading-in Wires to Exactly the Required Length

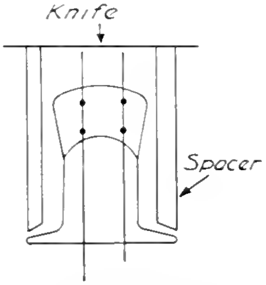

Fig. 5. Leads of Uniform Length Insured by Trimming After Sealing In

The next process is to bend the leading-in wires preparatory to welding on the filament. This used to be done by hand, but is now accomplished semi-automatically by a metal plunger, the stem being held against the top of the flare to keep the overall length constant (see Fig. 6). The stem is now ready for the filament, which is made as follows:

The lamp under consideration being a 6-8-volt, $2\frac{1}{2}$-ampere lamp, it will be gas-filled and will require a coiled filament. To make this the tungsten wire is automatically wound around a fine steel wire. The winding machine makes a constant number of turns, then allows the coil to pass along, leaving a short piece of straight wire before making another coil. The result is a series of connected coils wound on a steel wire, as shown in Fig. 7.

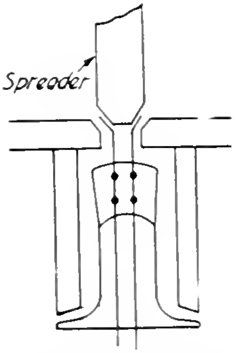

Fig 6. Leading-in Wires Being Shaped Ready for Attachment to Filament

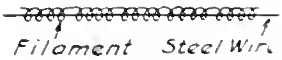

Fig. 7. Forming Filaments by Winding on Fine Steel Wire

These coils are then cut apart with a pair of pliers, this work being done by hand and there must necessarily be some slight variation in the length of straight wire beyond the coil, though a standard of two milli-meters has been set. These little coils are next bent by hand into a V shape, the operator picking out, as nearly as practical, the center of the coil as the bending point.

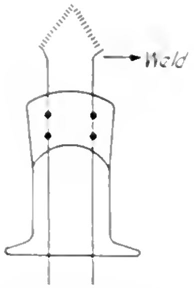

Fig 8 Showing Shape and Position of Filament After Being Electrically Welded to Leading in Wires

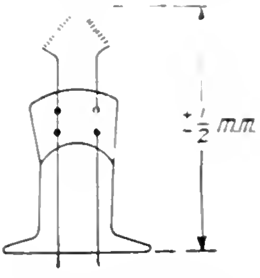

Fig 9 Permissible Limits of Variation in Assembly of Lamps

The filament coils are then put into a hot acid bath which dissolves out the steel core on which they are wound. The filaments are then heat treated at 1000 deg. C. in hydrogen gas, which removes all impurities and leaves them ready for mounting.

The filament is now laid on the leading-in wires and is semi-automatically electrically welded to them (see Fig. 8). In this process it can be seen that there must necessarily be some slight variation in the length depending on the angle at which the filament is bent and the exact position in which it is laid on the leading-in wires. The variation in overall length of the mount which has been set to take care of these conditions is plus or minus one half millimeter measured from the bottom of the flare to the point of the filament (see Fig. 9). This is gauged by a sliding rule (see Fig. 10), the mount being placed on the slide and brought up until the point of the filament touches the upper stop. The mount is now ready for sealing in the bulb.

The bulb is blown in a mould, but, strange as it may seem, the diameter of the bulbs will vary somewhat. In the mounting machine the bulb is held in a ring and the height of the bulb will vary slightly with its diameter (see Fig. 11).

In order to set the bulb properly a steel ball, of the exact size of a correct bulb, is made with a hole in it which allows the rod that holds the mount to rise exactly the right distance to bring the filament center in the center of the bulb (see Fig. 12). This device is used in setting the machine. The mount is then put on the rod and the bulb placed down over it (see Fig. 13). The bottom of the bulb and the flare of the stem are then melted together by rotating them in a Bunsen flame. After this is done it is necessary to "work" the glass at the joint a little to prevent cracking. This used to be done by removing the bulb and mount while still hot and drawing the latter down a little by hand, thus stretching the glass. Now, however, it is done by blowing compressed air in through the exhaust tube and stretching the joint by expanding it. There must necessarily be some variation in length

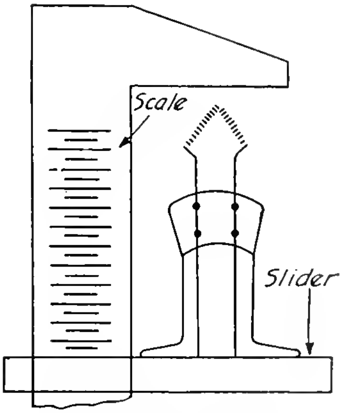

Fig. 10. Method of Gauging Overall Assembly Length

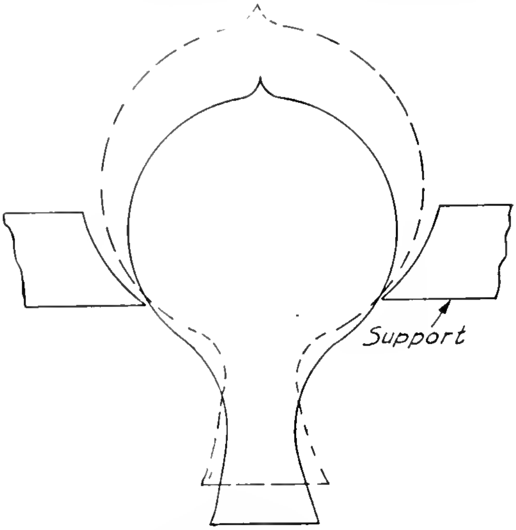

Fig. 11. Showing How Height of Bulb in Mounting Machine Varies with Bulb Diameter

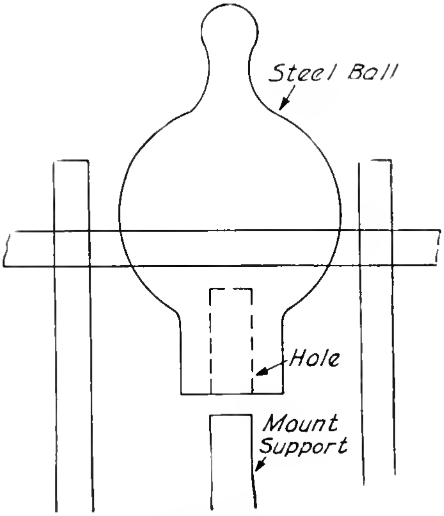

Fig. 12. Means Employed for Mounting Filaments in Center of Bulb

in that process and also the shape of the neck of the bulb will vary somewhat. The bulb and the mount are now ready for the base.

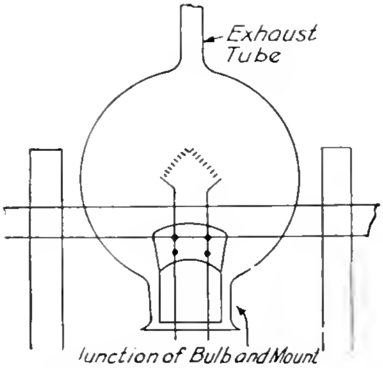

Fig. 13. Bulb in Position Over Filament and Mount, Ready for Melting Together

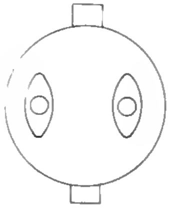

Fig. 14 End View of Lamp Base showing Position of Leading-in Wires with Respect to Pin

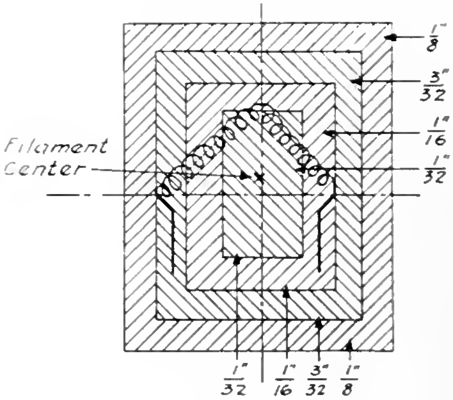

Fig 15. Chart for Determining Position of Light Center

The two leading-in wires from the stem are stuck through the holes in the bottom. These holes are at 90 deg. from the pins on the base and thus determine the plane of the filament (see Fig. 14). The base is filled with glue and set into a heater to harden the glue. In this process if the wires happen to be slightly bent or twisted, the plane of the filament will vary somewhat from 90 deg. from the pins, and even if the operator twists it around to 90 deg. the wires are liable to cause it to spring back before the glue hardens. There must, therefore, be some leeway allowed in this respect. The slight change in shape of the neck determines to some extent the distance that the base will go up on the bulb before striking the glass.

Fig. 16. Optical Device for Testing Light Center Length of Lamps

It is easy, therefore, to see that with conditions as pointed out it is practically impossible to keep the light center length of the filament (distance between the nearer edge of the pins on the base and the center of the filament) to an absolute figure. The allowable tolerance in the light center length is 3/32 in.; i.e., if the center of the filament is not more than 3/32 of an inch above nor more than 3/32 of an inch below the $1\frac{1}{4}$-in. distance from the top of the pins, it is acceptable. The filament must also lie entirely within 5/64 in. of the axis of the lamp passing through the center of the base and the tip. A certain percentage of every run of lamps is tested for these variations.

The device for testing the light center length consists of an optical projector which throws an image of the filament on a calibrated screen, see Figs. 16, 17 and 18. From this it can be easily determined just where the center of the filament comes. The center of the filament is taken as the central point of the triangle formed by the two filament legs and a line joining the points where they are welded to the leading-in wires. The testing device enables the lamp to be rotated 90 deg. so that the filament image can be inspected as to its axial positon.

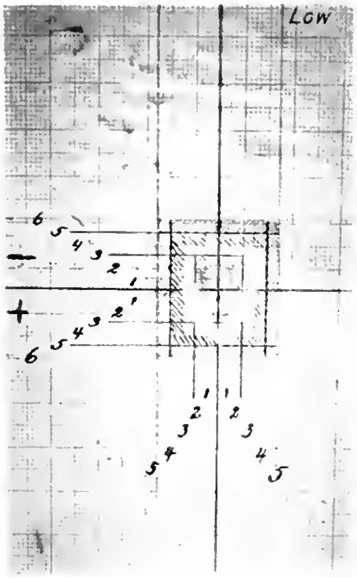

Fig. 17. Test for Variation in Light Center Length

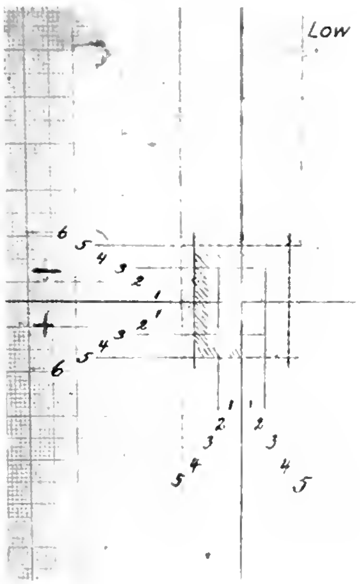

Fig 18. Test for Variation of Filament from Axis

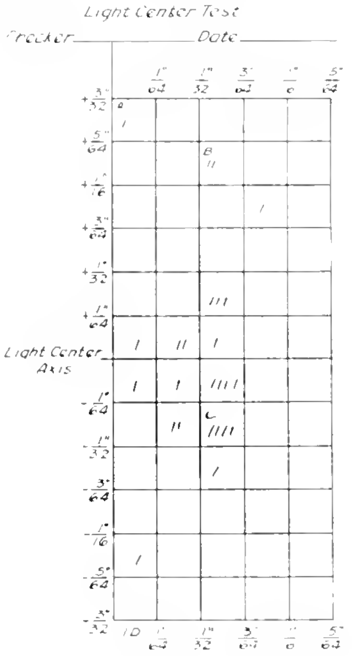

Fig. 19

In recording the test of a batch of lamps the form shown in Fig. 19 is used, which shows that of 26 lamps tested, one had a light center length of 1 11/32 in. (1¼ in. 3/32 in.) with some part of its filament 1/64 in. off from the axis (Square A); two had light center lengths of 1 5/16 in. with some part of the filament 3/63 in. off the axis (Square B); four had light center lengths of 1 7/32 in. (1¼ in. 1/32 in.) with some part of the filament 3/64 in. off the axis (Square C) and one lamp had its filament outside of the light center length limit of 3/32 (Square D), etc.

Records are kept of all the tests and inspections during the entire process of manufacture and these are plotted as curves so that the engineer in charge can see at a glance just how the production is running and whether the various parts of the lamps are becoming more or less uniform.

The lamps which do not come within the specifications are opened and the defect corrected where possible. In cases where this is not practical the lamp is destroyed.

New methods of construction and tests are continually being taken advantage of and every possible means is used to make the Mazda automobile lamps, as well as other types, the most unifom and best miniature lamps on the market.

An Absolute Method for Determining Coefficients of Diffuse Reflection

By F. A. Benford

Illuminating Engineering Laboratory, General Electric Company

In this article the author describes an exceptionally accurate method which he originated and developed to measure the coefficient of reflection of a diffusing surface. In addition to the method being more accurate than its predecessors, it is simple, is independent of the color of the standard lamp, and furnishes absolute, not relative, values.—Editor.

Character of Method

The test method herein described has several features that are perhaps unique; and, because of the extreme simplicity of the photometric work, this method is believed to offer possibilities for precision determinations of the coefficient of reflection of diffusing surfaces. It is an absolute method because no photometric standards are involved; the brightness measurements may be made with uncalibrated lamps and unknown instrument constants, the only condition being that the lamps and other accessories maintain their constancy during the test.

Outline of Method

The brightness of the interior surface of a spherical integrator depends upon three factors: (1) the quantity of light received from the light source, (2) the coefficient of reflection, and (3) the solid angle of the spherical surface, if an incomplete sphere. It is by taking advantage of the last factor that there are obtained two separate equations relating brightness, with flux, coefficient, and solid angle; and in the solution of these equations all factors except the two readings of comparative brightness, the solid angles corresponding to the two brightness readings, and the unknown coefficient of reflection are eliminated.

The test equipment consists of a sphere that has one or more removable sections, leaving sections of known solid angle, and whose interior surface is coated with the substance under test. A lamp, preferably with a concentrated filament, and a lens to project a sharp beam of light through an opening into the sphere, furnishes the light for the test surface. The surface that is to serve as a working standard of comparison may be either the milk glass of a brightness photometer, or a diffusing surface with constant illumination if a spectrophotometer is used. The section of the test surface under observation must not receive any direct light from the entering beam.

Derivation of Equation

Let the unknown, but constant, quantity of light entering the sphere be indicated by F_0, and let the brightness determination be B_1 when the part-sphere has an area A_1, the total area of the complete sphere being S. If the coefficient of reflection is K, then there is reflected from the section under direct illumination the quantity

$$F = KF_0 \text{ lumens}$$

on the first reflection.

It is the basic property of the integrating sphere that light reflected from any point on the diffusing surface is uniformly distributed over the entire surface. If, now, any section of the sphere is missing, the amount of light that escapes is directly proportional to the area of the opening, or, inversely, the light received on each reflection is proportional to the surface present. We may then write for the light received from the first reflection

$$F_1 = \frac{A_1}{S} KF_0 \text{ lumens} \qquad (1)$$

Upon the second reflection there is the useful flux

$$F_2 = \frac{A_1}{S} KF \left(\frac{A_1}{S} K \right) = \left(\frac{A_1}{S} K \right)^2 F_0 \text{ lumens} \qquad (2)$$

and each succeeding reflection is less by the factor $\frac{A_1}{S} K$ which is thus the common ratio in the convergent infinite series

$$\frac{A_1}{S} KF_0 + \left(\frac{A_1}{S} K \right)^2 F_0 + \left(\frac{A_1}{S} K \right)^3 F_0 + - - - \text{lumens} \qquad (3)$$

the sum of which represents the total useful light due to the infinite series of reflections. Calling this total F, we have

$$F = \frac{A_1 K F_0}{S \left(1 - \frac{A_1}{S} K \right)} \text{ lumens} \qquad (4)$$

If A_1 and S are expressed in square centimeters, we may find the illumination in phots by dividing the useful flux by the area illuminated

$$E=\frac{A_1KF_o}{A_1S\left(1-\frac{A_1}{S}K\right)}=\frac{KF_o}{S\left(1-\frac{A_1}{S}K\right)}\text{ photos}\qquad(5)$$

and the brightness of the point under observation is

$$B=\frac{K^2F_o}{S\left(1-\frac{A_1}{S}K\right)}\text{ lamberts}\qquad(6)$$

The photometer reading will be proportional to B, and by using a proportionality constant N we may write

$$NR_1=\frac{K^2F_o}{S\left(1-\frac{A_1}{S}K\right)}\text{ lamberts}\qquad(7)$$

Rearranging, we get

$$NR_1S-NR_1A_1K=K^2F_o\text{ lumens}\qquad(8)$$

Selecting another solid area A_2, we get another brightness reading R_2 and

$$NR_2S-NR_2A_2=K^2F_o\text{ lumens}\qquad(9)$$

Solving for K, we get from (8) and (9)

$$NS(R_1-R_2)-NK(R_1A_1-R_2A_2)=0$$

$$K=\frac{S(R_1-R_2)}{R_1A_1-R_2A_2}\text{ numeric}\qquad(10)$$

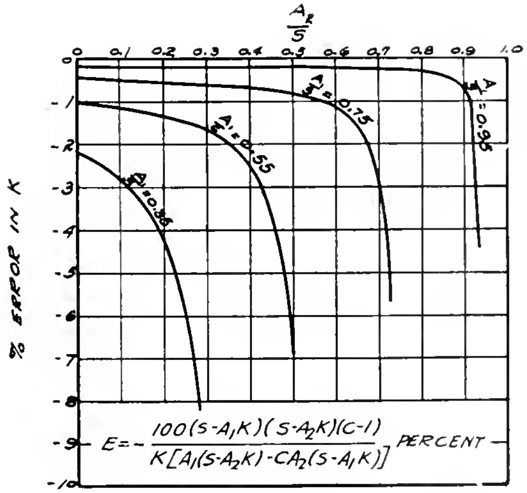

Fig. 1. Curves of Errors in the Result Due to +1′, Error in Determining the Ratio $R=\frac{R_2}{R_1}$ for a Coefficient of 0 90

Dividing both numerator and denominator by S, we get the spherical areas expressed as parts of a complete sphere

$$K=\frac{R_1-R_2}{R_1\frac{A_1}{S}-R_2\frac{A_2}{S}}\text{ numeric}\qquad(11)$$

Equation (11) is the desired expression for the coefficient of reflection. If R_1 and R_2 are taken with a brightness photometer, then K must be defined as the average coefficient for light from a lamp at $T°$ as modified by the projection lens. If a spectrophotometer is used, then K is independent of the light source but it is defined as the coefficient for wave lengths λ_1, λ_2, etc.

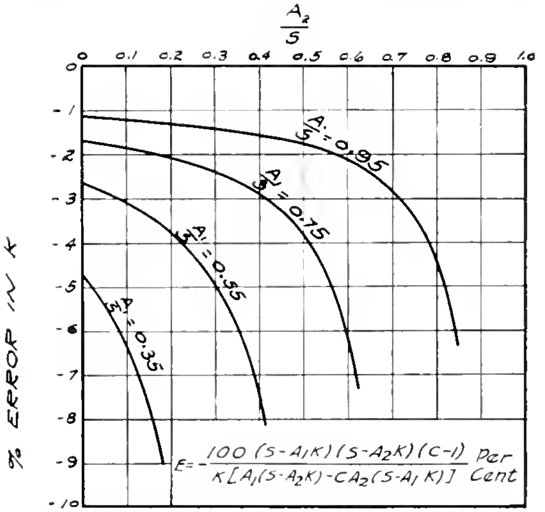

Fig. 2. Curves of Errors in the Result Due to +1% Error in Determining the Ratio $R=\frac{R_2}{R_1}$ for a Coefficient of 0.50

Selection of Best Working Conditions

From equation (11) it appears that any two sections A_1 and A_2 may be used without regard to their relative size. This would be true if the photometric quantities R_1 and R_2 could be determined without error; but, as such is not the case, it is proposed to determine if for a given error in the ratio $\frac{R_2}{R_1}$ there is any particular selection of A_1 and A_2 that will give the most favorable working conditions.

Effect of Errors in Photometry

As R_1 and R_2 are merely proportional to the brightness, it will be sufficient if we determine the result of an error in their ratio $\frac{R_2}{R_1}$.

Denoting the incorrect ratio by

$$R'=C\frac{R_2}{R_1}\qquad(13)$$

and the error by

$$E=\frac{K'-K}{K}\qquad(14)$$

we get the expression

$$E=-\frac{(S-A_1K)(S-A_2K)(C-1)}{K[A_1(S-A_2K)-CA_2(S-A_1K)]} \quad (15)$$

after using equations (14), (11), (13), and (7) in the order named.

As this last equation is too complicated to analyze by inspection, it has been plotted in Figs. 1 and 2 for various combinations of A_1 and A_2 and for $K=0.9$ and $K=0.5$.

In spectrophotometric analysis in particular it is important to have very bright test surfaces, and in order to obtain this condition the test sphere must be small. After making allowance for an opening to admit the light and another for observing, the remaining surface cannot greatly exceed 95 per cent of the complete sphere. With this value for A_1 (in the remainder of this article A_1 and A_2 are used in place of $\frac{A_1}{S}$ and $\frac{A_2}{S}$) and $K=0.9$, the choice of A_2 is seen from the curves to lie between zero and 0.8 S. In this entire region a photometric error of 1 per cent in the ratio of R_2 to R_1 will give an error in the result of less than three-tenths of one per cent. It is under these conditions that the method may properly be called a precision method.

Taking $A_1=0.75S$, the best value for A_2 lies between zero and $0.50S$ and the error rises to 0.5 and 0.8 per cent. If A_1 is $0.55S$, the best value of A_2 will give an error of more than one per cent in the final result. From these data it is evident that the largest possible value of A_1 gives the most favorable working conditions.

The selection of A_2 will in practice probably always be near the upper limits mentioned. If too small a section A_2 is used, the results are more liable to be affected by stray light or by light from the sphere being reflected back from the surroundings.

In Fig. 2 the error equation is plotted for the same values of A_1 and A_2 as before, but a coefficient of 0.5 is assumed for the test surface. A comparison of the two sets of curves for $K=0.9$ and $K=0.5$ shows that the latter gives very inferior accuracy, which means that the method is best suited for surfaces having high coefficients, and if the coefficient is much below 0.5 the method may fail through multiplication of the usual photometric inaccuracies.

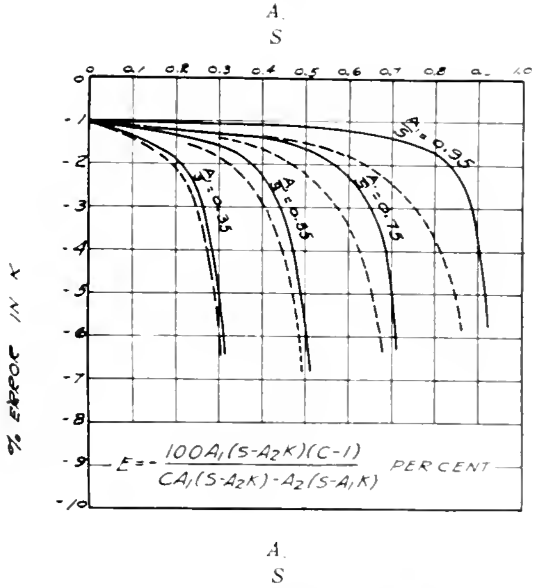

Fig. 3 Curves of Errors in Result Due to 1 , Error in Measuring A_1; Full Lines of Coefficient of 0.90. Dotted Lines for Coefficient of 0.50

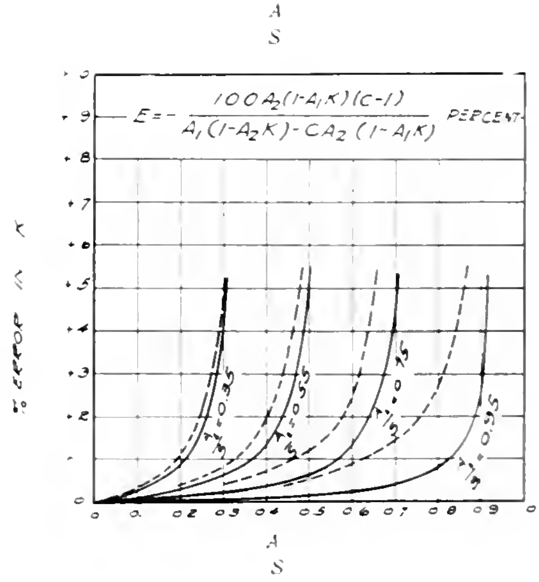

Fig. 4. Curves of Errors in Result Due to 1 Error in Measuring A. Full Lines for Coefficient of 0.90 Dotted Lines for Coefficient of 0.50

Effect of Errors in A and A

In general, the sphere can be built up of sections whose areas are known with a high degree of accuracy. The high accuracy obtainable when only the photometric work is in error is due to the fact that R_1 and R_2 have symmetrical positions in the numerator and denominator of equation (11), both of which are increased or both decreased, thus minimizing the effect upon the result. With A_1 and A_2 *the case is different*, and in Fig. 3 is shown the result of using a value for A_1

one per cent high. The equation for determining the error is given. From the solid curves (for $K = 0.9$) it is evident that the angular (or surface) measurements should be made with great care, because the resulting error in the final result is always larger. The results when testing a surface having a coefficient of 0.50 are less accurate, but for low values of A_2 the difference is not great.

An error of one per cent in A_2 has much less effect upon the results than the same error in A_1. The error in K actually approaches zero as A_2 decreases, and here is found the best reason for selecting A_2 as small as possible. There is a practical limit fixed by the necessity of having one section of the surface for receiving all the direct light from the lamp and another surface for observing, i.e., illuminated only by reflected light. These two surfaces are not necessarily continuous or joined. A practical consideration that bears on the selection of A_2 is the return of light escaping from the part-sphere. This return light increases at a greater rate than the openings $S-A_1$ and $S-A_2$; and unless the conditions are highly favorable for quenching all the reflected light, the error due to this cause may overbalance any supposed advantages of a small value for A_2. Another lower limit is fixed by the difficulty of measuring a small section as accurately as a large section.

In general, it would seem that the rules for practice are:

(1) Make A_1 as large (in proportion to S) as possible.

(2) Make A_2 one half to three fourths as large as A_2.

(3) Quench all stray light from the part-sphere.

(4) Use the method with caution when K is less than 0.50.

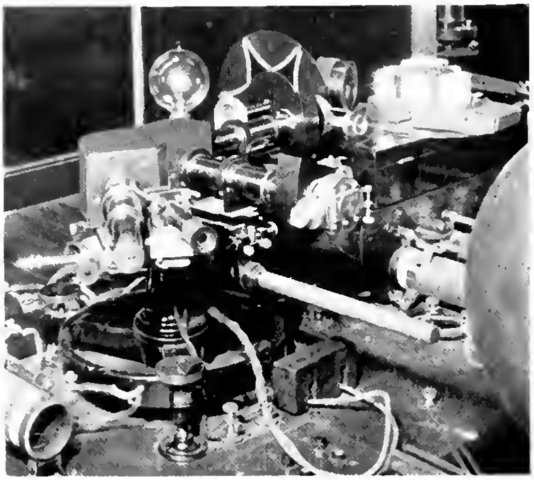

Fig. 6. Photograph of the Testing Set-up Used in Determining the Coefficient of Reflection of Magnesium Carbonate, Fig 5, by the Part-sphere Method

Coefficients of Magnesium Carbonate

By the method just described, a test was made of the reflection coefficient of magnesium carbonate. The material was obtained at a drug store and the package bore the inscription "Silk-finished Magnesia Carbonate for technical use." The blocks were

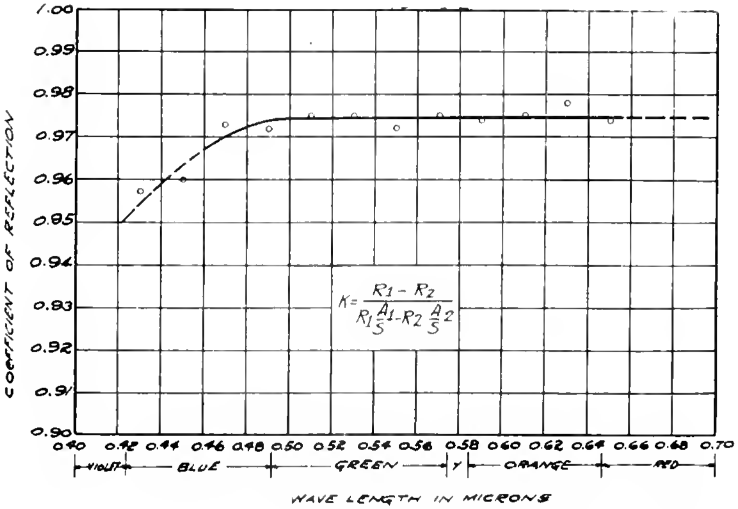

Fig 5. Spectrophotometric Test of Coefficient of Reflection of Magnesium Carbonate by Part-sphere Method

2 by 2 by 2½ inches and nothing was known about their chemical purity. A 45-deg. bevel was cut around one end of each block, and the end was then turned out to a concave spherical surface with a radius of 1.125 inches. When five of these blocks were assembled as shown in the photograph of the test equipment, Fig. 6, they formed five sixths of a sphere, and the removal of one block left two thirds of a sphere. In order to have definite edges, the bevels and sides of the block were blackened with draughting ink, which was found to stay on the surface and not penetrate. Owing to the extreme fragility of the carbonate, it was found impossible to get perfectly sharp edges all around, and there was a little blackened area visible at all points. From measurements on the cracks, it seems that the assumed areas A_1 and A_2 are about one per cent too high. The true values for K thus would seem to be slightly greater than given in Fig. 5, if no account is taken of the effect of stray light. A few readings with three and two blocks showed a progressive decrease of several per cent for the lower values of A_2; and as it is believed that the stray light just about compensates for the errors in A_1 and A_2 mentioned above, the results are given as found, and they are probably within one per cent of correct at all points except possibly at 0.43μ, where the intensity was near the lower reading limit.

The lamp and focusing lens for the part-sphere are shown near the top of the photograph, and the comparison lamp is in the metal sphere at the extreme right-hand side. During the test the part-sphere was surrounded by screens and the white sides of the blocks were covered. The color compositions of the two beams entering the collimators were quite different, the readings at different parts of the spectrum ranging from 50.3 to 73.9; and there was considerable unevenness due to the lens and the paint and diffusing glass of the metal sphere. These variations of course canceled out as they affected R_1 and R_2 alike. Ten readings were taken at each point, and the apparent high photometric accuracy shown by the agreement of the points with a smooth curve is in line with the data of Fig. 1.

Regarding the high coefficients, it can only be said that the figure $K = 0.88$ published a number of years ago is obviously too low, as it has been found possible to get this value with a reflectometer, which is known to read low. Correcting the reading of this instrument for the equivalent spherical area of the nickel band, and using for the nickel its test coefficient of 0.53, the coefficient of magnesium carbonate is 0.970 which is evidence in favor of the accuracy of the data here given.

A large number of experimenters have at various times used magnesium carbonate as a standard of reflection, and exact knowledge of its coefficient is of considerable importance in several types of photometry.

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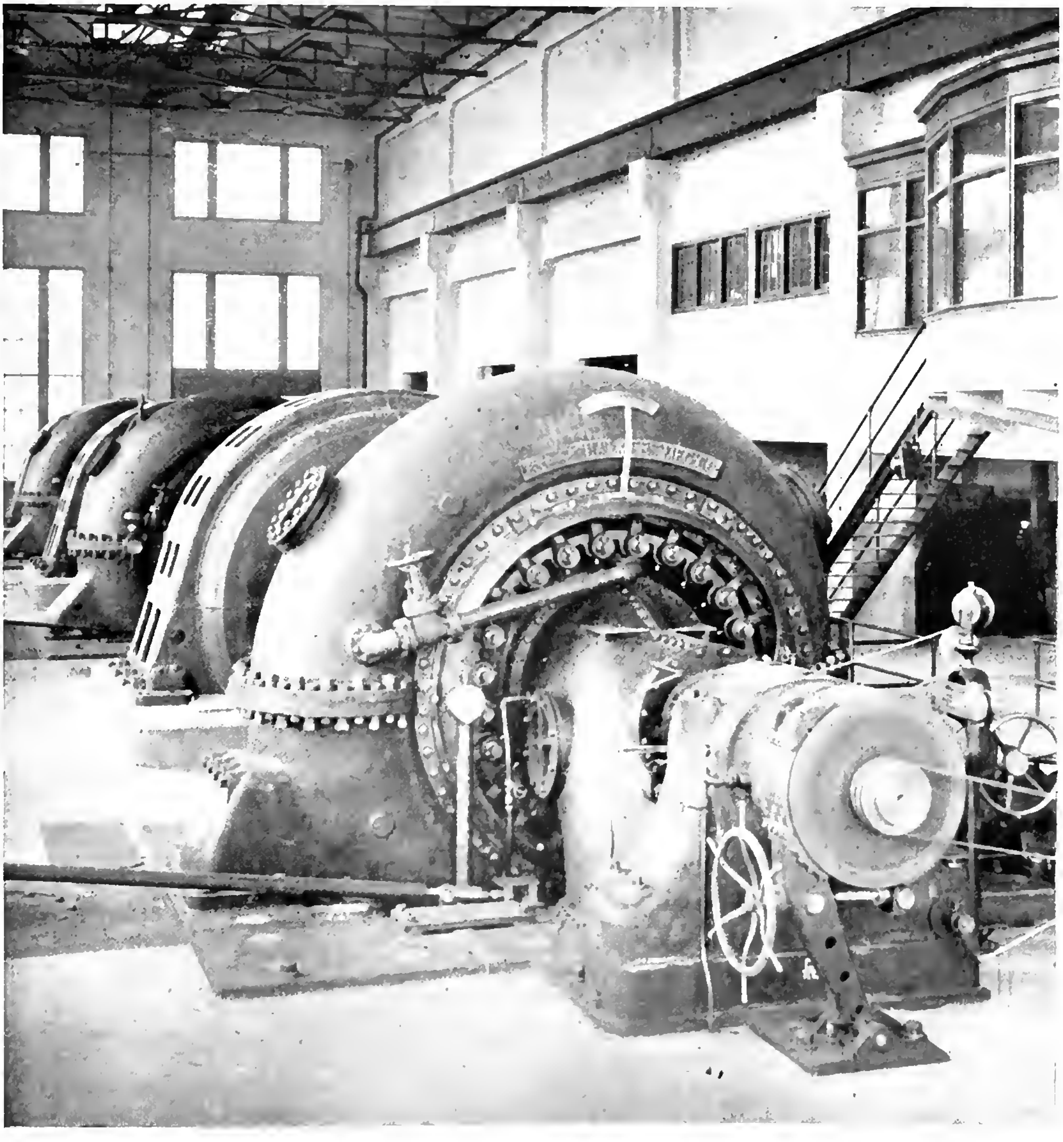

Large modern alternators must be driven by waterwheels or steam turbines because only these types of prime mover are of sufficient caliber for the purpose. This illustration shows one 20,000-kv-a. and two 16,300-kv-a. waterwheel-driven alternating-current generators, and our frontispiece shows a 45,000-kw. steam turbine-driven generator

A Group of Articles on

SYNCHRONOUS GENERATORS AND MOTORS


NORMA

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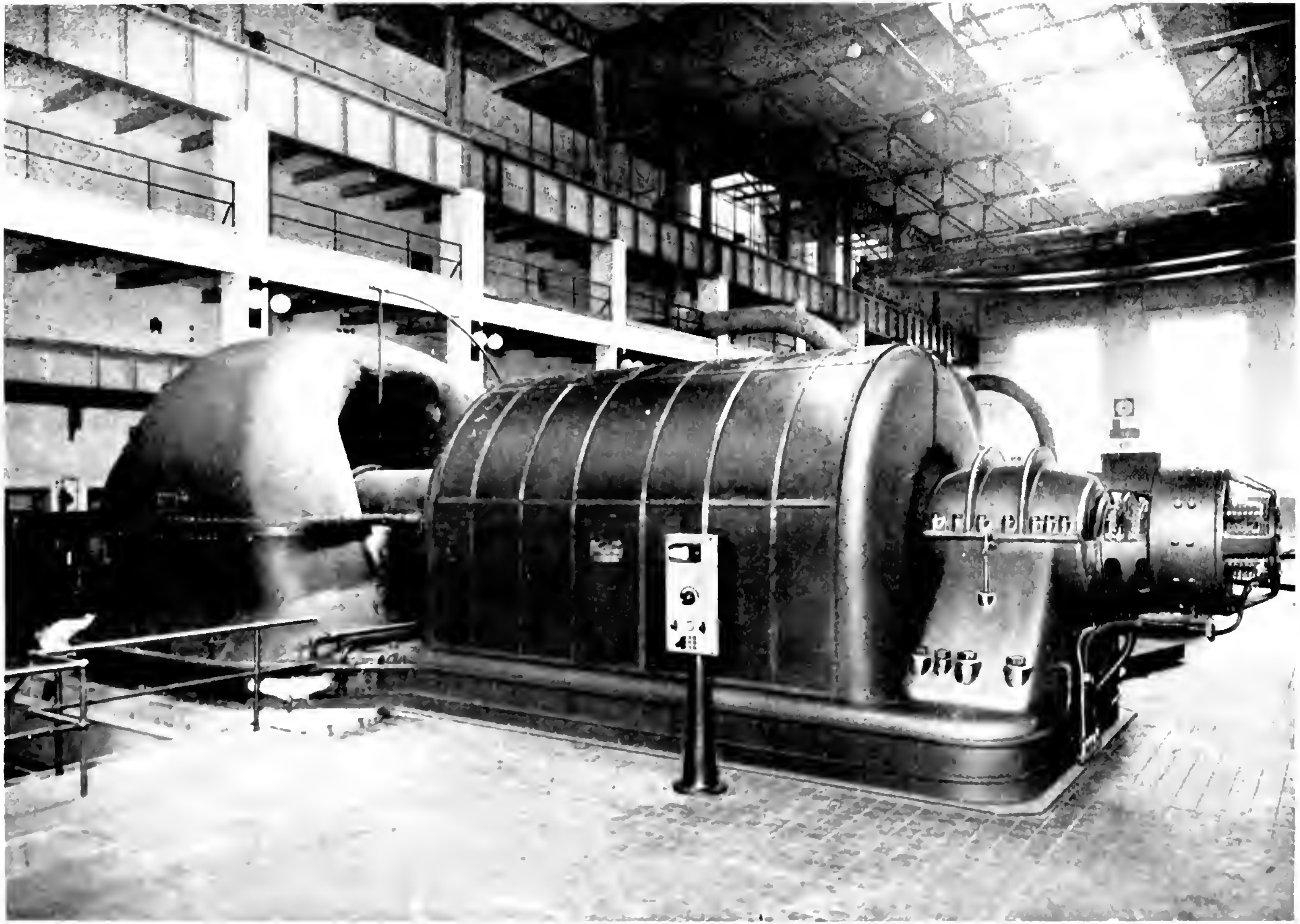


5,000 K.W. CURTIS TURBINE GENERATOR INSTALLED IN THE POWER PLANT OF THE DETROIT EDISON COMPANY

The first commercial alternator built and sold by the Thomson-Houston Company in the '80s was rated according to the number of 16-c.p. carbon lamps it could light. Its capacity was 200 lamps. On the same basis of comparison the alternator shown here would light close to a million lamps, but with the modern tungsten lamp the number would be increased to about three millions. The power of this giant is roughly equivalent to that of 3000 automobiles, taking a high figure for the average power actually utilized by the latter.

GENERAL ELECTRIC REVIEW

THE STATUS OF THE SYNCHRONOUS GENERATOR

Alternating-current generation and transmission are the cornerstone of the electrical industry. Only in a few instances where the energy is used directly on the spot, as in the manufacture of aluminum, is direct current generated on a large scale. That this would ever be the case, however, was directly contrary to the belief of most electrical men in the early '80s.

Following on the heels of the invention of the incandescent lamp by Mr. Edison, inventors and manufacturers busied themselves with the development and sale of direct-current dynamos for operating the lamp. Although Professor Elihu Thomson had succeeded in building some of the most satisfactory direct-current generators then on the market, he foresaw the wonderful opportunities offered by alternating current for long distance transmission and set to work to improve the alternating current system and overcome the strong prejudice which existed against it. His inventions made possible the safe distribution of low voltage alternating current, and once this fact had been demonstrated, the development of alternating-current apparatus progressed with astonishing rapidity—the inherent superiority of alternating current as a medium for moderate and long distance transmission had been established. Mr. W. J. Foster, in his article in this issue, traces the progress in alternator design from the early machines of Elihu Thomson to the inception of the polyphase revolving field machines of today.

Often in the development of alternating current generators, as with most engineering development, there has appeared, sometimes only a step ahead of current achievement, a formidable barrier to further progress—some limiting factor that seemed to block the way.

In the early days it was a question of voltage and insulation, then of prime movers of adequate capacity. As the size of machines increased limits were obviously being approached in the definite pole revolving field construction because of centrifugal stresses; and almost simultaneously the problem of adequate cooling and ventilation thrust itself into consideration. Each of these limits has been pushed farther and farther along the road of progress as it threatened to become a serious factor; new insulations were devised, the steam turbine replaced the reciprocating engine, salient pole construction surrendered to the smooth core rotor, and force draft succeeded to natural ventilation.

In the steam turbine generator we have arrived at the 45,000 kilowatt unit and have under consideration still larger machines. On the electric end at least we do not appear to be confronted with any new limitations—we are merely overtaking some of our old problems in new guise. Centrifugal stresses in the rotor were for a time brought within safe limits by the elimination of salient poles; but with the great axial length and massive field coils that are required in the largest machines, these stresses are again approaching the limit of safety. Also, it is becoming exceedingly difficult to dissipate the heat that is generated in these solid rotors—air velocities through the air gap are now in the neighborhood of 12,000 feet per minute. In the stator, likewise, ventilation is becoming a serious factor; also, it is becoming increasingly difficult to support the end windings so that they will resist the tremendous forces that act to wreck them under short circuit.

In waterwheel-driven alternators the requirement of being able to withstand double speed introduces difficulties in the design of the revolving element, as the larger diameters have made it impracticable to adopt the smooth core rotor for these machines.

The largest waterwheel generators have been of the vertical type, and one of the greatest problems has been to provide a satisfactory thrust bearing to support the entire revolving element, including the water thrust. Considerable trouble from scored and burned bearing surfaces was experienced with the older types of thrust bearing, and it was obvious that the maximum allowable weight for this design had been reached. The spring thrust bearing and an efficient oiling system, however, have shifted the limiting factors in the size of waterwheel generators to other elements in the construction.

Closely related to the synchronous generator are the synchronous motor, synchronous condenser and frequency converter, and the significant position of this class of apparatus with respect to the future expansion of electric power generation and utilization emphasizes the value of the special series of articles appearing in this issue. B. M. E.

Early Days in Alternator Design

By W. J. Foster

Alternating-current Engineering Department, General Electric Company

The author takes us back to the days when some of the first experimental work on alternating-current generators was being performed by the predecessors of the General Electric Company. Professor Elihu Thomson's inventions and his appreciation of the advantages of alternating current were largely instrumental in overcoming the early prejudices against the commercial use of alternating current, and some of his work is illustrated and described in this article. The evolution of the alternator is traced from Professor Thomson's early experimental machines, through the first commercial machines of the Thomson-Houston Company and the monocyclic generators of Steinmetz, to the early polyphase generators built between the years 1894 and 1900. During this period the first turbo alternator was built and tested. Some remarks in explanation of the great range of frequencies that were to be found in the early days are of interest.—Editor.

W J Foster

The Alternating Current Engineering Department of the General Electric Company, as now constituted, may be said to date from January, 1894. Hence, the quarter-century mark has been passed. For the origin of the Department we must go back to the constituent companies that merged into the General Electric Company in 1892; in fact, it is necessary to go even further back, to the time when there were no organized companies manufacturing electrical machinery. The real origin is to be found in the work of Prof. Elihu Thomson; first, in the Philadelphia High School; second, in the American Electric Co., New Britain, Conn.; and third, in the Thomson-Houston Electric Co., Lynn. The fundamental patents were taken out about forty years ago by Prof. Thomson. These have been added to from time to time by him and by others connected with the Department.

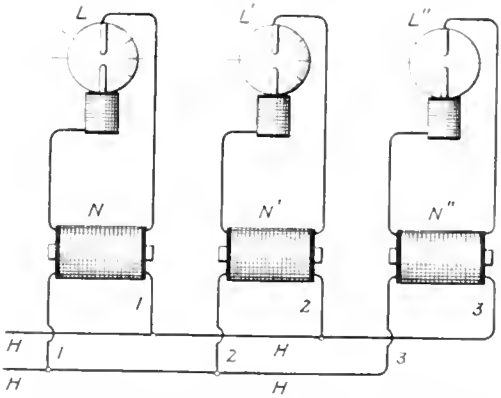


Fig. 1 Sketch from Drawings of a Patent Application Prepared January 13, 1879, showing Induction Coils in Parallel as Arranged and Tested Out by Elihu Thomson at Franklin Institute

The alternator had no commercial value until means for delivering the current, and apparatus for applying it to some useful purpose, had been devised. Naturally, lighting was the first use made of the alternating or "reversed" current. Some idea of the part taken by Prof. Thomson and his associates in this work may be obtained from Figs. 1, 2 and 3.

Fig. 1 is reproduced from Fig. 5 in the drawings of a patent application by Elihu Thomson, prepared January 13, 1879, containing the following description of the illustration:

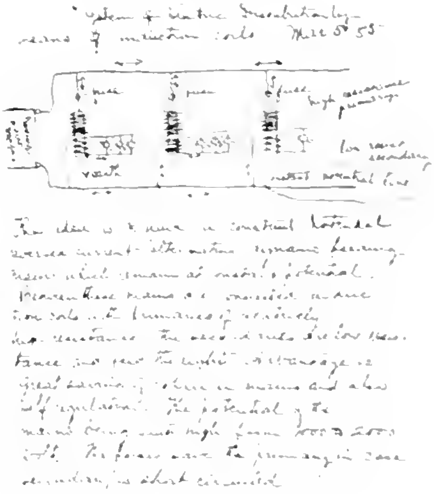


Fig. 2 Taken from Personal Notes of Elihu Thomson

"Fig. 5 shows the method of employing a vibrating lamp where a single undulatory or reversed current is employed to operate a number of lamps, the main circuit remaining unbroken. *H H H* is the main circuit from the machine furnishing reversed currents, it being branched at *1, 1, 2, 2, 3, 3,* through the primary wire of induction coils *N*, *N'*, *N''*. The secondary wire of each induction coil has its terminals connected to the terminals of the lamps *L*, *L'*, *L''*. The variations or reversals in the primary circuit *H H H* cause variations or reversals in the secondary circuits, of which the lamps *L*, *L'*, *L''* form a part. Since the secondary currents traverse the coils *C* of the lamps, vibrations are thereby imparted to the electrode *E* as before."

Fig. 3 shows sketches and explanations of the sketches taken from the note-book of Prof. Thomson's assistant, Mr. E. W. Rice, Jr., now President of the General Electric Company.

Fig. 2 is reproduced from Prof. Thomson's own notes of a later date.

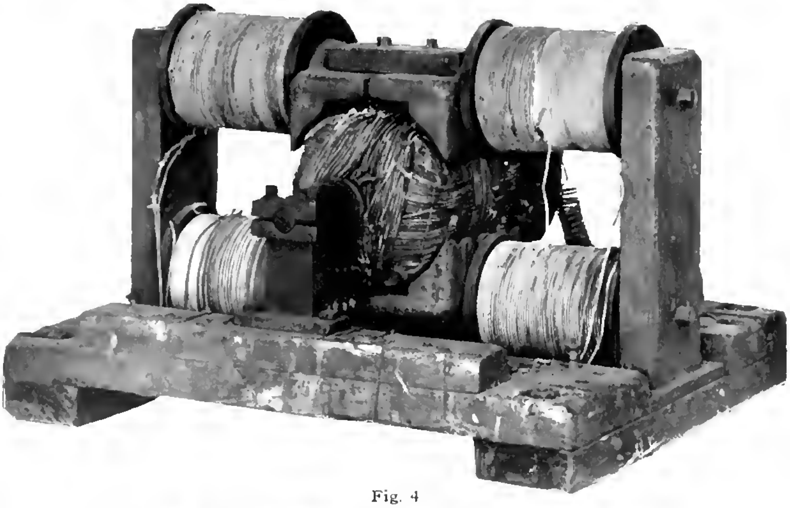
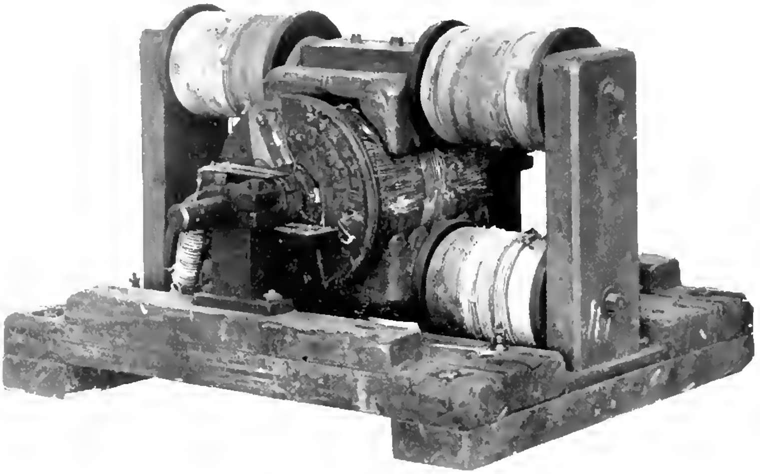
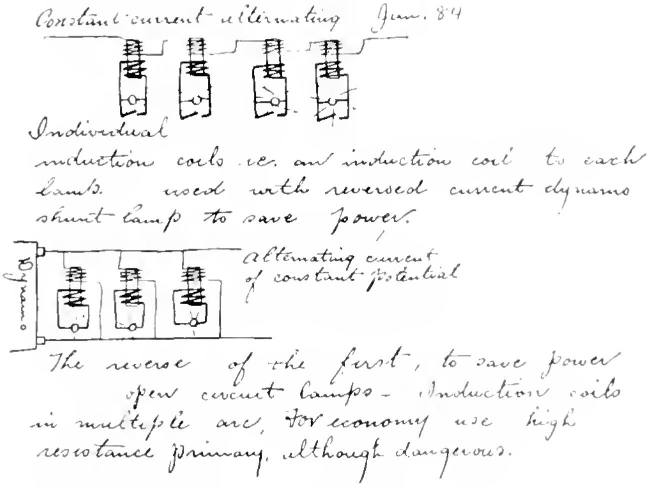


Fig. 4



Figs. 4 and 5. Alternating-current Dynamo Built by Elihu Thomson in 1878. Front and Back Views



Constant current alternating Jan. 84

Individual induction coils i.e. an induction coil to each lamp. used with reversed current dynamo shunt lamp to save power.

Alternating current of constant potential

The reverse of the first, to save power open circuit lamps - Induction coils in multiple arc, for economy use high resistance primary, although dangerous.

Fig. 3 Taken from Notes Made in January, 1884, by Elihu Thomson's Assistant, E. W. Rice, Jr.

Fortunately, some of the first machines built by Elihu Thomson are still in existence and have been photographed for this article. Figs. 4 and 5 show the dynamo built in 1878 and operated in the Franklin Institute, Philadelphia, before the days of the incandescent lamp, or of any of the many applications of electricity to the useful arts as we know them today. This particular machine, as shown in the illustrations, had a revolving armature and windings connected to a commutator for furnishing direct current, as well as windings connected to slip rings for alternating current. The immediate use that was made of this alternator was the operation of an arc light. Fig. 6 shows two of the transformers invented by Prof. Thomson in order to make use of the alternating current, and Fig. 7 one of the lamps for furnishing light at the Franklin Institute.

During the next few years Prof. Thomson's energies were occupied largely in the development of direct-current dynamos, arc machines, arc lamps, etc. During this time Mr. Edison developed the carbon-filament incandescent lamp. Other inventors and manufacturers developed and put on the market direct-current dynamos of suitable potential to operate the lamps. The operation of incandescent lamps from the direct-current dynamos proved to be a success. When it was proposed to make use of alternating current with stepdown transformers, in order to distribute over a wider range, objection was made on the ground of danger to life. This was the situation when Prof. Thomson again attacked the problem of distribution at higher potentials. His efforts resulted in inventions, patented about 1885, that made the distribution perfectly safe. He then took up actively the design of commercial alternators. Fig. 8 shows his first alternator, built in Lynn, in 1885. It was a revolving-field separately-excited machine, and was used for commercial purposes in the shops of the Company. Fig. 9 shows an early type of transformer having a ring core, the invention of which made possible the adaptation of the alternator for lighting one of the Company's factories.

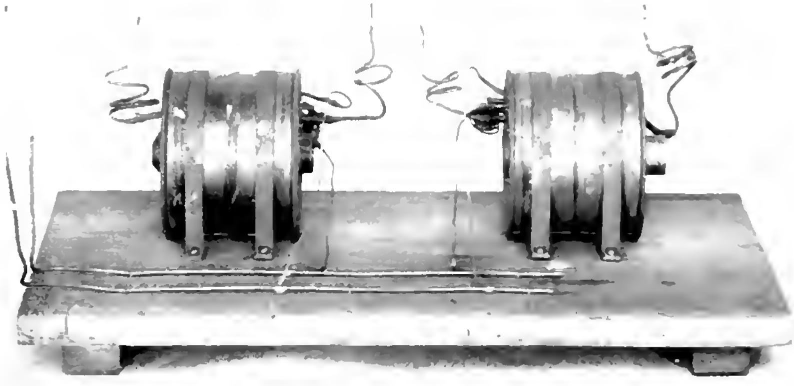


Fig 6 Transformers Made in 1878

It is interesting to note that of the two constituent Companies that merged into the General Electric, the Thomson-Houston developed alternating-current machines and apparatus, as well as direct-current, while the Edison General Electric Company confined its operation to direct current alone. Diametrically opposite policies prevailed in these two Companies in their attitude toward alternating current. The Edison, with its three-wire system of distribution for lighting, took the position that such a system was the best possible. Moreover, this Company opposed the use of the alternating current on the ground of the danger to life and limb. In the early days it was a sort of superstition that alternating current was far more dangerous at any given voltage than direct current. The adoption of alternating current by some of the states for inflicting capital punishment added greatly to the popular prejudice against it. It is hard for us to realize at the present time how deep seated was that prejudice. This commercial warfare continued for some time after the inventions of Prof. Thomson had made the alternating-current low tension perfectly safe from the possibility of contact with the high tension of the primary distribution.

The first alternators sold by the Thomson-Houston Company and installed for furnishing lights to customers were built early in 1887. Two of them were tested and shipped in May of that year; one to the Lynn Electric Light Company, and the other to New Rochelle, N. Y. The latter was first in operation, having been started up by one of the engineers from the factory, Mr. A. L. Rohrer. The only photograph we have of it (Fig. 10) was taken by Mr. Rohrer; there was no Photographic Department in those days.

Fig 7 Vibrating Lamp Used in 1879

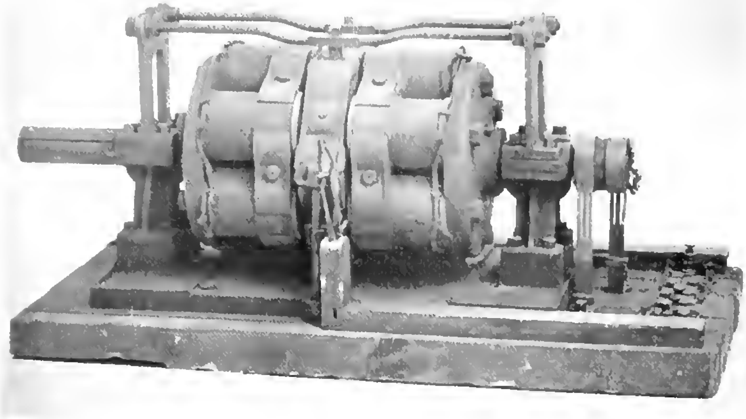


Fig. 8. First Alternator Built by Elihu Thomson in 1885

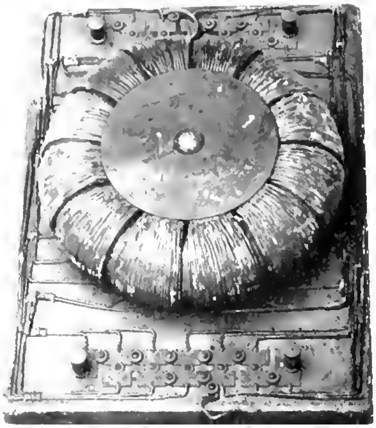


Fig. 9 Transformer Used to Light Factory at Lynn in 1886

The picture was taken in the basement of Factory B of the old Thomson-Houston Works, West Lynn. The alternator stands on a hand-truck at the left. It was of the "revolving armature" type, was single-phase of about 900 volts, had 6 poles occupying a horizontal position, and ran at a speed of 1250 r.p m. It was self-excited, the excitation being furnished by a separate winding connected to a six-part commutator on the same

Fig 10. View in Basement, Factory B, Thomson-Houston Works, Lynn, in May, 1887, showing the First Alternator Built for a Customer

shaft. Its capacity was 200 16-c-p. lamps and it was named the "A2." Several of them were built and sold.

A larger alternator, the "A4," with capacity for 400 16-c-p. lamps, was the next production of the Thomson-Houston Company.

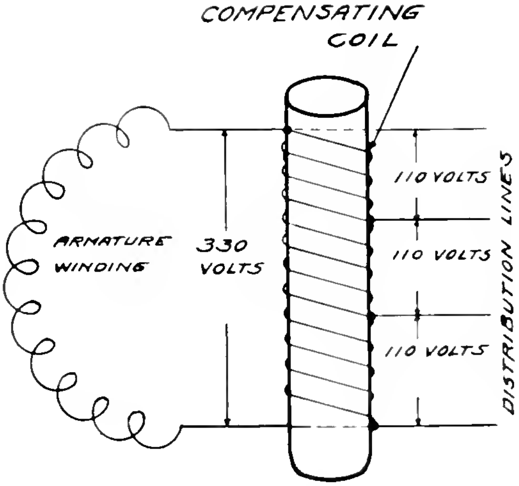


Fig 11 Compensating Coil of the A6B Alternator of Thomson-Houston Co Four-wire Distribution at 330 Volts Without Stepdown Transformers

This alternator had radial poles, eight in number, and ran at 1500 r.p.m. The next in order was a 10-pole, 1500-r.p.m. machine, known as the "A6" and capable of lighting 600 lamps. There was a modification of this alternator known as the "A6B," or the "Compensated." The term "compensated" in this case did not have the significance of maintaining constant potential for changes in load, but obtained its significance from the feature of distribution. The system of distribution was a four-wire circuit with lamps connected three in series between the several distributing wires, thus minimizing the drop of potential on the intermediate wires. Inasmuch as 110-volt lamps were used, the alternator was wound for 330 volts as shown in Fig. 11.

A larger alternator of the same periodicity as the "A6," viz., 125 cycles, was soon developed and was known as the "A12," or "1200 lighter."

The next development consisted of a line of machines with rectifying commutators, but of the same general type and construction, in the naming of which a different significance was given to the numeral. These were the "A18," "A35," "A70" and "A165," in which the numeral signified the kilowatts. About 1891 this line was changed from smooth-core armatures to toothed armatures. Modifications were made in the shaft and bearings, thereby increasing the ratings to "A25," "A50," "A100" and "A240," respectively. These machines were still bought with reference to the number of lamps that could be carried; the "A25" for 500 lamps; the "A50," 1000 lamps, etc. When it was definitely settled that a 16-c-p. carbon-filament incandescent lamp required over 50 watts and that there were transformer and line losses to be allocated to the lamps, the ratings of the alternators were raised 20 per cent; hence the line became "A30," "A60," "A120" and "A300."

The first three sizes were in great demand and gave good satisfaction. They had two windings on the fields; one excited from an outside source and the other, or the composite field winding, excited from the rectifying commutator, a two-part affair standing at the middle point of the armature winding. Fig. 12 is a photograph of one of these alternators.

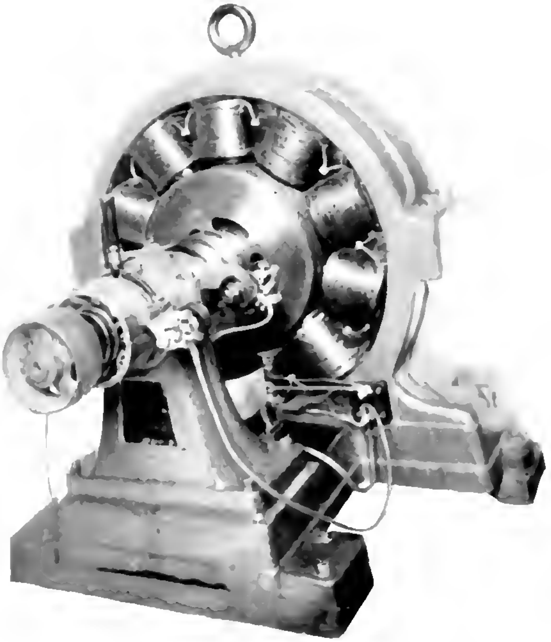


Fig 12 A 35 Alternator of Thomson-Houston Co

During the years 1887 and 1888 Prof. Thomson built the first experimental induction motors, including a single-phase motor having a commutator. The first induction motors built by the Company, with reference to commercial use, were brought to test early in 1892. As a result of the tests it was decided to proceed with the development of motors of two or three sizes. The necessity then sprang up for polyphase generators, or some system of operating polyphase motors from single-phase circuits. The monocyclic generator was conceived by Mr. Charles P. Steinmetz, as something that would supply the want.

Monocyclic Generator

The monocyclic generator in its conception was a dynamo from which could be obtained single-flow energy and polyphase potentials. Fig. 14 is a cut of one of the commercial machines as built during the '90s, with diagrams of the armature and field windings shown in Figs. 15 and 16. All of the earlier types and sizes, either belted or direct connected, had revolving armatures with rectifying commutators and compounding windings on the fields. It is interesting to note that the first field coils of copper strip wound on edge were made for one of these monocyclic revolving armature generators that had 80 poles and was driven by a Corliss engine at 90 r.p.m.

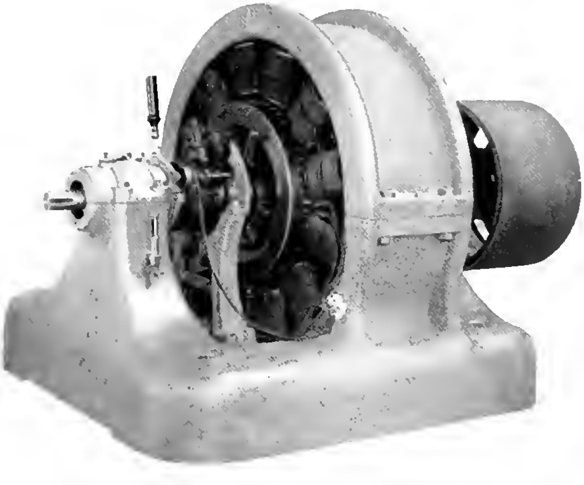


Fig 14. A Standard Revolving Armature Monocyclic Generator

Many revolving field monocyclic generators were designed and built in the years 1897 to 1900, in both belt-driven and direct-connected units. At least ten or twelve sizes, ranging from 50-kw. at 300 r.p.m. to 1500-kw. at 90 r.p.m., were developed for direct connection to steam engines. These generators were entirely separately excited.

Polyphase Generators

The demand for generators for power purposes increased so rapidly during the period 1894 to 1900 that numerous three-phase and two-phase generators and motors were developed. As a result, lighting circuits were run more and more from polyphase circuits. At the same time, the rating that could be

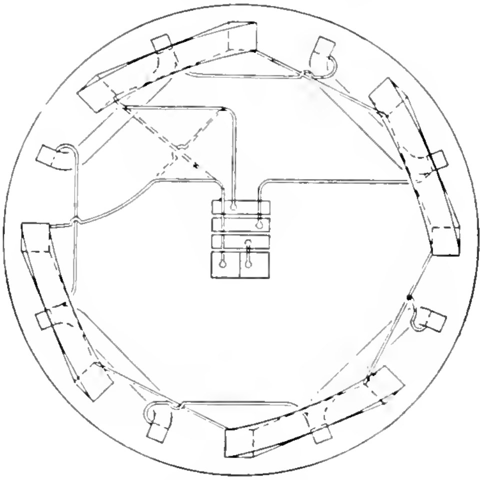


Fig. 15. Diagram of Armature Connections of Revolving Armature Monocyclic Generator

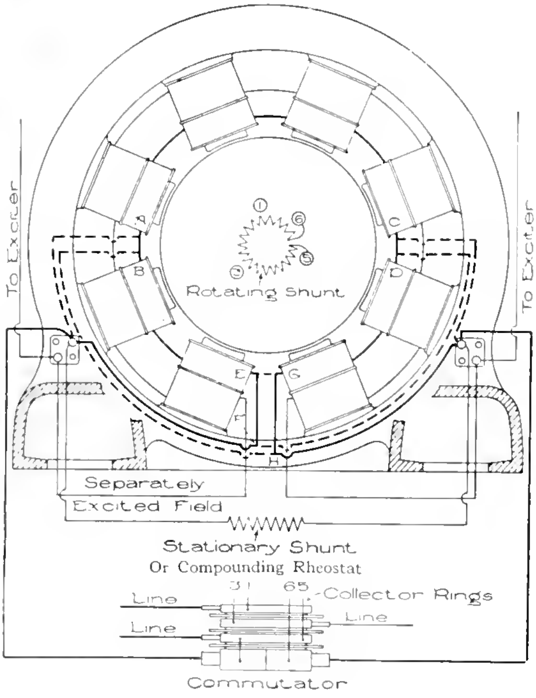


Fig. 16 Field Windings of Monocyclic Generator

given to a machine was much higher if it were polyphase than monocyclic. As a consequence, the manufacture of monocyclic machines was eventually abandoned.

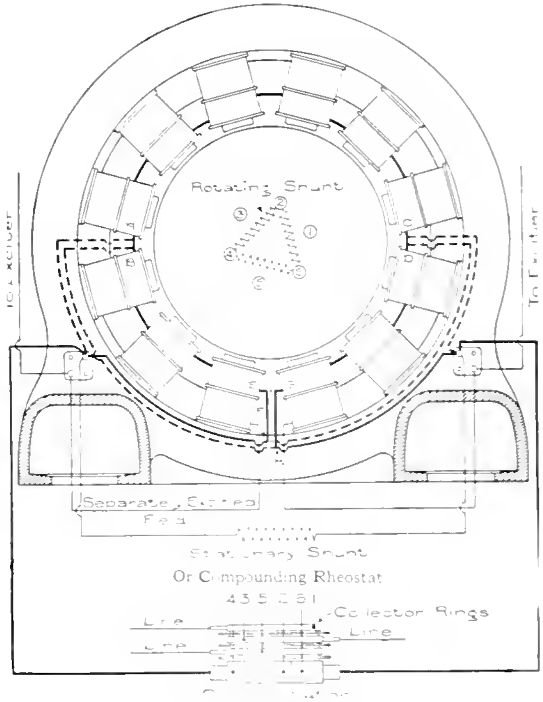


Fig. 17. Connections of Three phase, Revolving Armature Compound Generator

During this same period it became apparent that revolving-field alternating-current machines had decided advantages over those of the revolving armature type, as higher voltages were possible and also greater capacity. The characteristics of these machines in the matter of inherent voltage regulation were of great importance. Generators were being used for both power and lighting purposes. Power applications were chiefly through induction motors; consequently, the power-factor of the generator was too low to permit of maintaining a steady potential on lighting circuits, no matter how alert was the operator at the switchboard. The customer's specifications regularly called for 6 or 8 per cent inherent regulation. By this was meant that if full non-inductive load were thrown off the generator, the potential on open-circuit would not be more than 6 or 8 per cent greater than under load. The situation was relieved by the development of field regulators that controlled the excitation, maintaining constant voltage by regulating the field of the exciter.

Compensated Polyphase Generators

Nearly all the first revolving-armature three-phase generators had two field windings, one excited from an external source, usually a small direct-current generator driven by belt from a pulley on the shaft of the alternator. The other field winding received its excitation from a rectifying commutator, the excitation varying directly as the current output. The connections are shown in Fig. 17. The commutator was a three-part affair, consisting of three castings each having one segment for every pair of poles. The commutator was located mechanically immedi-

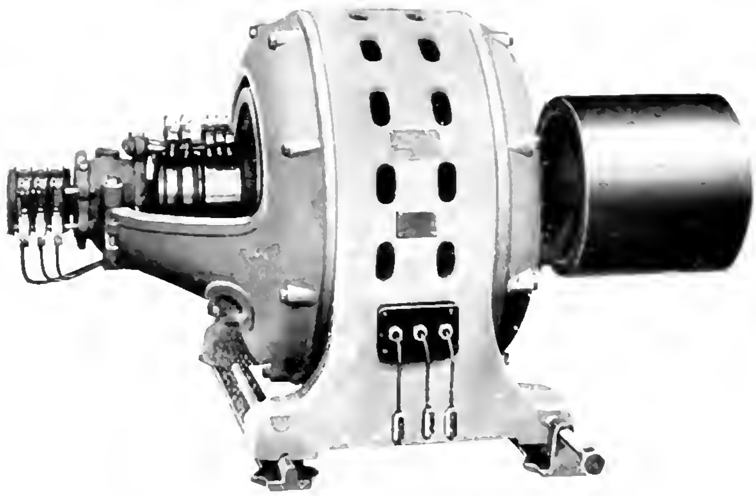


Fig. 18. Three-phase, Revolving Field Compensated Generator with Exciter Mounted in End Shield of Stator

ately adjacent to the three collector rings on the shaft inside the bearing. It was located electrically in the "Y" of the winding, the continuity of the winding being established outside, or through the field coils and the stationary shunt. There was also a closed connection between the inner ends of the three windings through the rotating shunt, which was located mechanically inside the armature spider. This shunt had non-inductive windings as it carried alternating current, a small percentage of the total current.

Compensated Generators

For the purpose of compensating for voltage drop, due to load, in revolving field generators, exciters were developed with taps brought out from equidistant points in the armature winding to collector rings, similar to those in synchronous converters. The voltage generated by the exciter was varied in accordance with the load by use of series transformers feeding into the windings of the exciter through its collector rings. The compensation for different power-factors was regulated by adjusting the mechanical position of the exciter, and the amount of compounding for any given power-factor by means of taps on the series transformer. Fig. 18 shows one of the belt-driven three-phase generators of which a complete line was developed and built for a period of several years.

There was also developed a line of low-speed engine-driven three-phase generators with geared exciters, as shown in Fig. 19. The connections shown in Fig. 20 are very complicated. This fact, together with the skill required in properly adjusting the position of the magnet frame of the exciter, frequently resulted in dissatisfaction. These generators operated well, provided the attendants were well informed and careful in handling the machines. The application of this method of compensating for potential drop was applied to single-phase and two-phase as well as three-phase generators.

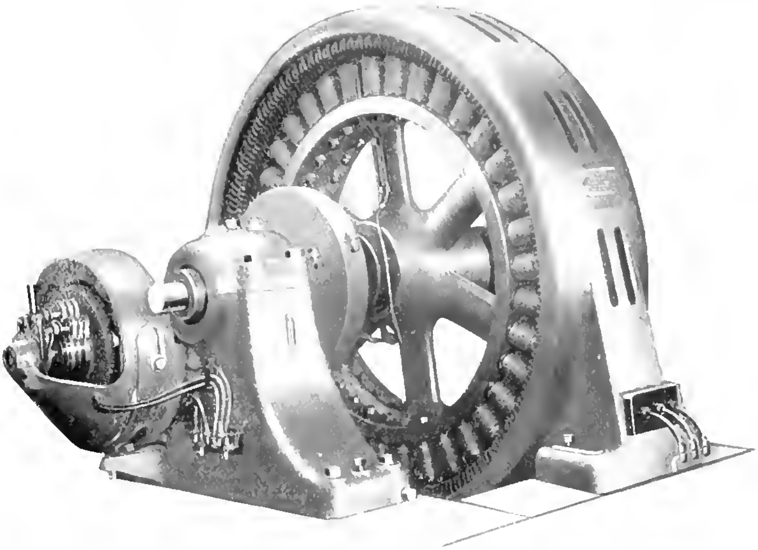


Fig. 19. Three-phase Compensated Generator with Geared Exciter

Turbo-generators

The first work in steam turbine driven generators was done in 1896, several years before the original 500-kw. Curtis turbine unit was developed.

The turbo-generator built in 1896 was a single-phase 50-cycle 500-kw. 2500-volt 3000-r.p.m. horizontal inductor-type alternator. It had a single armature with totally enclosed slots and armature coils of the pancake type grouped and connected up to make four poles, as shown in Fig. 21. Excitation coils were mounted on both ends of the armature or stator. The magnetic circuits closed through shells at the two ends into the shaft and thence back into the rotor proper, which had two polar projections diametrically opposite, as shown in Fig. 22. This generator was brought to test in October, 1896, and proclaimed its periodicity by emitting acoustic waves of great intensity that illustrated in a startling manner the nodes and antinodes of the text books. With injunctions staring us in the face, we made haste to change the body of the rotor into cylindrical shape by the addition of brass filling pieces so shaped as to produce a true cylinder. It was gratifying to have the electrical tests prove satisfactory.

The first commercial Curtis turbine unit was designed, built, and tested in 1901. It was installed and operated for several years in the Power House of the Schenectady Works. The generator was a three-phase 40-cycle 500-kw. 1200-r.p.m. horizontal-shaft machine with a salient-pole rotor. A 1500-kw. 60-cycle horizontal-shaft generator of the same type was next developed. Then followed vertical units, the first of them with salient pole rotors, which were eventually built in sizes up to 7500 kw.

Cylindrical rotors with distributed field windings were first designed in 1903 and 1904.

The two-pole machines had radial slots; the first of the four and six-pole rotors were made with two field coils per pole assembled in parallel slots. This construction resulted in the inner of the two coils having a greater depth and, consequently, a greater number of turns than the outer coil, since the two coils bottomed on a chordal line. This type of rotor was designed in order to have form-wound field coils that could be easily assembled or replaced, and with the expectation that the cost would be less than for the radial-slot type where the coils had to be assembled turn by turn with much of the insulation applied in place. It was soon found that machines with such rotors could not be rated as high as those of the same diameter with radial slots of the increased number possible and, furthermore, the potential wave was inferior. Hence, the cylindrical rotor with radial slots, as built today, soon superseded in all designs the parallel-slot type of rotor.

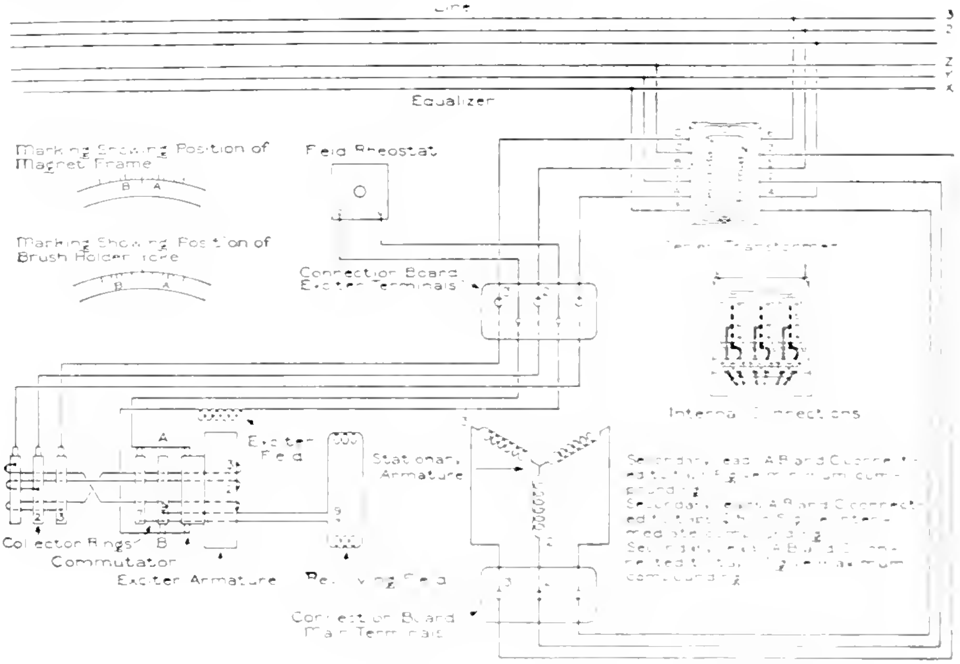


Fig. 20 Connections of Three-phase, Revolving Field Compensated Generator

Periodicity

Neither voltage nor periodicity was seriously considered in the earliest days; in fact, there were no instruments for measuring voltage when the first experimental alternators were built. Even at the time the first commercial machines were brought to test, the potential was measured by the incandescent lamp and not by a meter.

It probably was a matter of chance that a periodicity of 125 cycles was established for the first line of alternators built by the Thomson-Houston Electric Company. The first alternators shipped from the Works were 6-pole 1250-r.p.m. machines, hence, 62½ cycles. From design considerations, the number of poles was increased to eight and the speed to 1500 on next larger size—hence, 100 cycles—then to ten poles at same speed for still larger sizes—hence, 125 cycles. This periodicity gave way to lower periodicities when other use than lighting became general for alternators, and when it became desirable to direct connect alternators to prime movers. It is interesting to note that the first commercial induction motors were 50-cycle machines, this periodicity having been decided upon as a good one after the first tests. The polyphase machines, both generators and motors, that were first installed, viz., those in Southern California and in the state of New Hampshire, were 50-cycle machines. However, other manufacturers were developing 60-cycle machines and that soon became the prevailing frequency except for railway work, involving rotary converters, where 25 or 30 cycles had been decided upon as proper periodicity.

The advantage to be gained by using a smaller number of poles than that required for 60 cycles in connection with certain engine-driven units, in sizes from 500 to 1000 kw. at speeds of 100 and 120 r.p.m., led to the decision to use 40 poles for 120 r.p.m. and 48 for 100-r.p.m. This started the use of 40 cycles. One of these installations was in a cotton mill in New England. Induction motors for this periodicity were developed at the same time. Other mill owners became interested and some of them ordered duplicate equipments, etc. In a short time 40 cycles had become quite strongly entrenched in certain localities. It was at one time thought by many interested parties that 40 cycles would prove the prevailing periodicity, as it would prove satisfactory for both arc and incandescent lamps and at the same time would be suitable for synchronous converters, for which 60 cycles then appeared to be almost impossible.

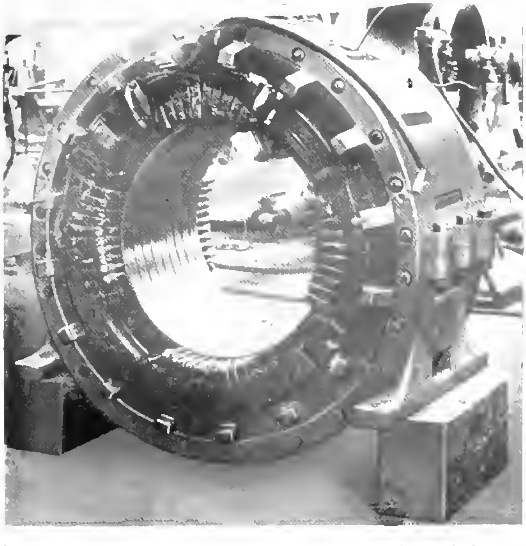


Fig. 21. Armature of 50-cycle, Single-phase, 500-kw., 3000-r.p.m Turbo-generator Built in 1896

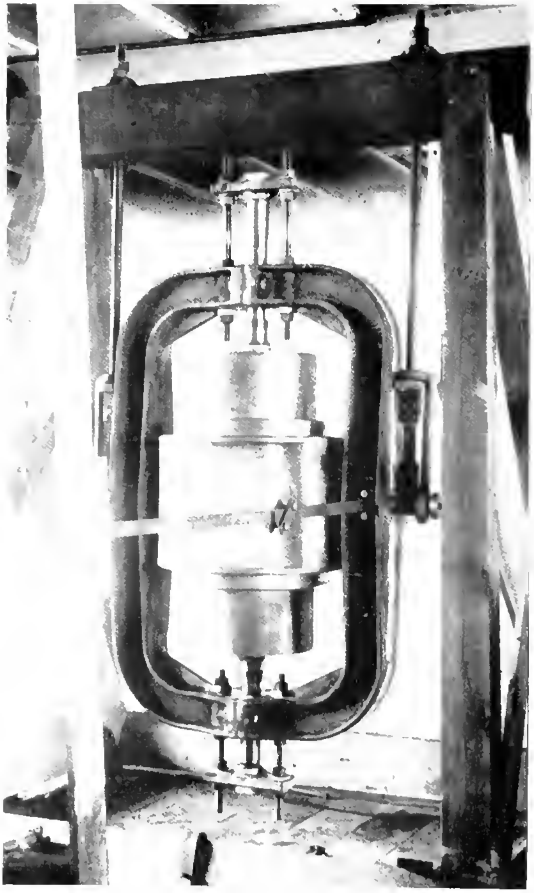


Fig. 22. Rotor of 500-kw., 3000-r.p.m. Turbo-generator in Balancing Device

Near Periodicities

Many installations in different parts of the country were made of periodicities that were not exactly those for which machines in general were being built. Some conspicuous cases of this kind were the following:

Hydraulic development near Portland, Ore., about 1892, was undertaken for 200-r.p.m. vertical-shaft waterwheels. Twenty-pole generators were decided upon as giving a good design for the capacity of the waterwheel that was contemplated. This gave a periodicity of $33\frac{1}{3}$ cycles. As a consequence, one of the two large systems of the Portland Railway, Light & Power Company grew up at 33 cycles.

Two or three years later, due also to the speed of the waterwheel, a frequency of $34\frac{2}{3}$ cycles was started at St. Anthony Falls, Minneapolis. As a result, the Twin City Rapid Transit Company has a large amount of 35-cycle apparatus.

The speed of the waterwheel installed at Chambly Falls, Quebec, gave to the Stanley inductor two-phase generator a periodicity of $66\frac{2}{3}$ cycles. A little later, the speed of 175 r.p.m. of the waterwheels installed at Lachine Rapids gave a periodicity of $58\frac{1}{3}$ cycles.

Frequency changers have been responsible in certain places for periodicities not exactly those considered standard. To change from exact 25 to 60 cycles in a frequency changer restricts the speed to 300 r.p.m., consequently, the costs in small sets are very high. Numerous frequency changers have been built with 4 and 10 poles, respectively, instead of 10 and 24, resulting in a periodicity of $62\frac{1}{2}$ cycles when connected to 25-cycle systems, or of 24 cycles when connected to 60-cycle systems. There have also been developed frequency changers with 6 and 14 poles, giving $58\frac{1}{3}$ cycles when driven from 25-cycle systems.

In this connection it is interesting to note how admirably adapted to frequency changing is 300 r.p.m. This speed gives exactly correct changes from 25 to 60, 25 to 50, 25 to 40, 25 to 35, 25 to 30, 40 to 60, 40 to 50, or 50 to 60 cycles.

Engine-driven Units

During the years 1896 to 1902, inclusive, there was great activity in developing engine-driven generators; the size of the units increased by leaps and bounds. It became popular toward the end of that period to build the flywheel type. Considerable mechanical ingenuity was brought into play in designing some flywheels with rotor rims of laminations or riveted plates and others with steel castings in sections bound together by links, the entire rim mounted on a cast-iron spider. Stators usually were designed to have sufficient strength and rigidity to hold the airgap within allowable limits. Other stators were of the trussed type. These generators were made in sizes up to 5000 kw., 50 per cent overload—7500 kw. maximum—at 75 r.p.m., the overall diameter of such a generator being of the magnitude of 33 feet.

The scope of this article does not permit of any discussion of the problems that arose in connection with the production of suitable magnetic steels for cores, the insulating of the sheets, and the mechanical construction of armature and field cores; nor of the problems encountered in the development of suitable insulations for windings of low and high voltages, proper mechanical protection and supports for the windings, etc.

The author has confined himself to the consideration of the part played by the General Electric Company in the production of alternators.

Investigation of Water-air Radiators for Cooling Generators and Motors

By H. G. Reist
Alternating-current Engineering Department, General Electric Company
and
E. H. Freiburghouse
Turbo-alternator Engineering Department, General Electric Company

The satisfactory solution to the problem of ventilating large capacity electrical units in land stations, by means of ducts, air washers, etc., is not as readily applicable to the cooling of electrical apparatus where extreme compactness is essential—as for instance in the propelling machinery of a ship. The use of the customarily large ventilating air ducts would tend to offset one of the great advantages of electric marine drive; viz., the enlargement of the cargo carrying space. The following article reviews an investigation made to overcome the difficulty by applying a closed system of air ventilation with water-air radiators for removing the heat from the circulating system.—Editor.

Special Conditions of Ventilation

H. G. Reist

Under favorable conditions the common arrangement of ducts and air washers, which permits of a complete control of the ventilation for turbo-alternators and stations, is believed to be best. However, cases sometimes exist where it is very desirable to eliminate the numerous long air ducts of large cross-section. This is especially apparent in the case of electrically driven vessels where lack of space and other reasons make ducts objectionable. In order to meet such special conditions, it is essential that a closed system be employed for the circulation of the cooling air.*

Heat of Losses Must be Removed from the Air

E. H. Freiburghouse

For seagoing vessels, a closed system of ventilation is desirable. However, with such a system it becomes necessary to cool the circulating air through the same range of temperature

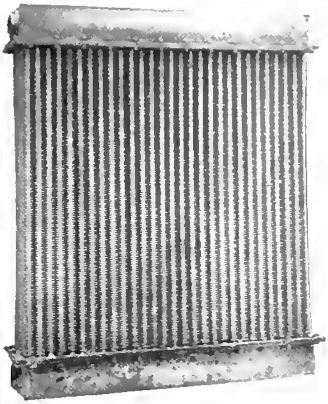


Fig. 1. Photograph of Truck Radiator Fitted with Special Header Tank for Test Purposes. For dimensions see Table 1

Fig 2. One of the Radiator Sections in the Air Tunnel Surrounded by Baffles. Baffles at front and sides of section not seen

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*See "Steam Turbine Generator Ventilation," by G. Monson, page 99 in this issue.

Fig. 3 Side View of Air Tunnel and Water Piping of the Radiators

that it is raised in passing through the generator or motor it cools.

The quantity of air which passes through a turbo-alternator is so related to the electrical and windage losses of the machine that the rise in temperature of the cooling air, or the range through which it must be cooled if used again, is approximately 20 deg. C. Assuming the standard temperature of the ingoing air to be 40 deg. C., as established by the Rules' Committee of the A.I.E.E., the temperature of the air which leaves the generator is 60 deg. C., and 50 deg. C. is the mean of the ingoing and outgoing air of any cooling device in the ventilating circuit.

Cooling Methods

The apparatus used for the removal of heat from the air will depend somewhat upon the character of the cooling water. Under most conditions, however, with a plentiful supply of fresh water, the air can readily be cooled by the use of the spray form of air washer now so generally employed for the cleaning and cooling of air. The cooling water in this case is discarded or, if necessary, recooled and used again. As the spray washer is an apparatus in which the air comes in contact with finely divided water particles, formed by spray nozzles, the character of the water supplied will determine whether an air washer would be applicable.

On ocean vessels, sea water is the only available heat conveyor from the cooling device of a closed system of ventilation. It is quite doubtful whether it is safe to have the cooling air pass continually through a spray of salt water, on account of the liability of small quantities of salt being carried into the windings.

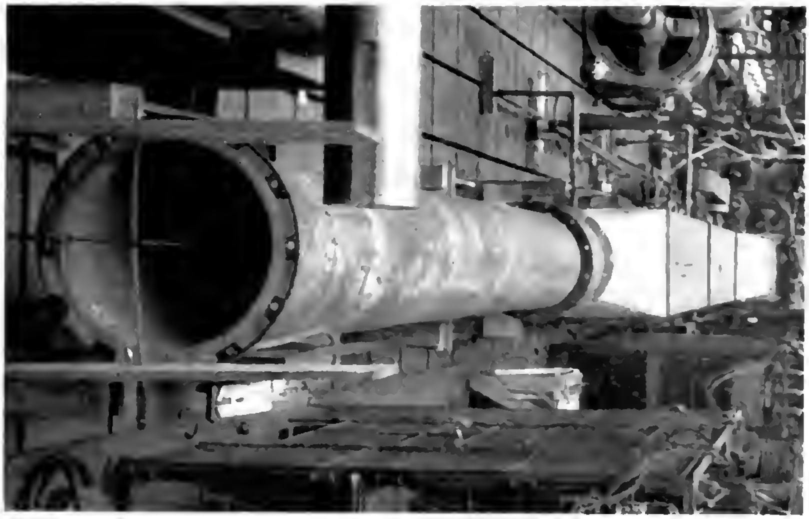

Fig. 4 End View of the Air Tunnel and Discharge Duct

In such cases two courses are open: either to recirculate a relatively small quantity of fresh water through the air washer and cool this water outside of the washer through the intermediation of a cooler, or to install some form of radiator in the ventilating air circuit and use salt water directly in the radiator tubes. This latter scheme was considered by one of the writers nearly one year ago as a feasible solution of a ventilating problem where it was very difficult to provide external ducts of sufficient size, and where an air washer was impossible because of the character of the cooling water. An investigation was started which led to tests from which the results given in this paper were obtained.

The function of the automobile radiator is to cool the circulating water and to heat the air passing through the radiator core or, in other words, to transfer heat from the water to the air. For the purpose under consideration, this heat transfer process would be reversed since the heat is to be transferred from the cooling air of the generator to the water in the tubes.

Selection of the Radiator

In those fields of service where radiators are given hard usage, the fin-and-tube type seems to be almost universally used. Clogging of irregular water channels by foreign matter is the most common cause of trouble in radiators. Obviously, the round tube offers the least trouble from clogging and, for given weight, is of the strongest construction as a conductor of water.

It was for these reasons that a small fin-and-tube type radiator was selected, and tests made to determine the rate of heat transfer as a function of the rates of flow of water and air.

Tests of Radiators

The tests conducted upon this small radiator having one quarter inch tubes confirmed the opinion that the scheme was feasible; in fact, they indicated results better than were expected. The reduction in the diameter of radiator tubes has a double effect in accelerating the transmission of heat, since it not only reduces the travel of the water particles between successive contacts with the tube wall, but also increases the area of contact surface of a unit weight of the water. Although it is beneficial to use tubing of small diameter for these reasons, it was nevertheless considered advisable to use tubing of larger diameter than one fourth inch in order to reduce the liability of clogging. This justified a more extensive series of tests which were made upon radiators having tubes of greater diameter and fins of different design.

TABLE I

Tanks were constructed of No. 18 B.&S. copper.	
Shaped $4\frac{15}{16}$ by 3 by $23\frac{1}{2}$ inches.	
Core had six rows of 29 tubes	174 tubes
Diameter of tube (outer)	0.375 in.
Diameter of tube (inner)	0.339 in.
Length of tube	$23\frac{27}{32}$ in.
Length of tubing per section	246 ft.
Fins outside	0.75 by 0.75 by 0.007 in.
Spacing of fins	0.165 in. pitch
Spacing of tubes front and back	0.8125 in.
External surface of tube per linear foot	13.55 sq. in.
Surface of fins (total per linear foot of tubing)	67.3 sq. in.
Total cooling surface per linear foot of tubing	80.85 sq. in.
Equal to	0.5615 sq. ft.
Free air section (between tubes and fins) of frontal area	2.02 sq. ft.
Frontal area of core	3.90 sq. ft.
Weight of core empty per cubic foot	37 lb.
Weight of core plus water per cubic feet	45.9 lb.

These tests were made to determine the relative dimensions of radiators, the heat transfer as functions of the speed of the air and the water, the amount of cooling surface for a given duty, and the resistance of the radiator to the flow of the air and the water.

Since the frontal area of a radiator within a restricted space would be limited, thus determining the minimum speed of the air through the core, it was realized that the practical application of radiators for this purpose greatly depended upon whether the air could be forced through the necessary depth of core without prohibitive pressure.

Five large radiators, intended for truck service and fitted with special headers, were obtained through the courtesy of the G. & O. Manufacturing Co., of New Haven, Conn. Fig. 1 shows one of these sections as described in Table I. The radiators were installed in an air tunnel in series with the air and water flow as indicated by Figs. 2 and 3. An end view of the entire testing equipment used is shown in Fig. 4.

Design of G. & O. Truck Radiator

The header tanks at each end of the core were specially designed for test purposes.

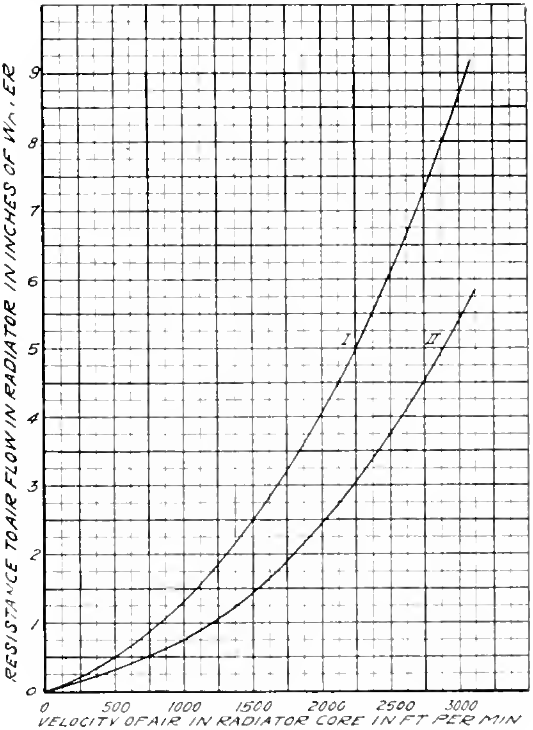

Fig. 5. Impact Pressure in Inches of Water to Force Air Through the Radiators as a Function of the Velocity of the Air in the Free Air Section of the Core

Curve I required by five sections in series
Curve II required by three sections in series

A motor driven blower of known speed, pressure, and volume characteristics delivered air through electrically heated grids to the radiators.

Air Flow

The air flow through the radiators was varied from 0.61 to 1.9 pounds per second per square foot of the frontal area of the core, which corresponds to a range in velocity of 930 to 2880 feet per minute through the minimum free air section of the core.

The quantity or mass flow was determined by means of a pitot tube and inclined manometer, also by the rise in temperature of the air and the electrical input as the air passed through the heating grid.

Air Pressure

Tests were made to determine the fan pressures required to deliver air through the five-section radiator. Ordinarily a radiator for service could be so designed that the depth need not exceed that equal to three of the sections tested, also the frontal area could be such as to limit the air velocity through the radiator core to less than 2000 feet per minute, which would add a resistance in the air circuit equal to about 2.5 inches of water.

If the speed of the fan and the resistance of the air circuit are fixed, the volume of the air and the air pressure developed by the fan are also fixed. Moderate increases in the resist-

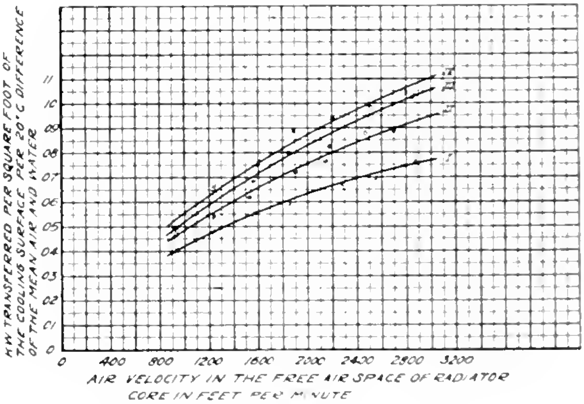

Fig 6. Rate of Heat Transmission as a Function of the Speed of Air Through the Free Air Section of the Radiator Core

Curve I. For an approximate speed of water in the tubing equal to 10 ft. per minute
Curve II. For 30 ft. per minute
Curve III. For 40 ft. per minute
Curve IV. For 50 ft. per minute

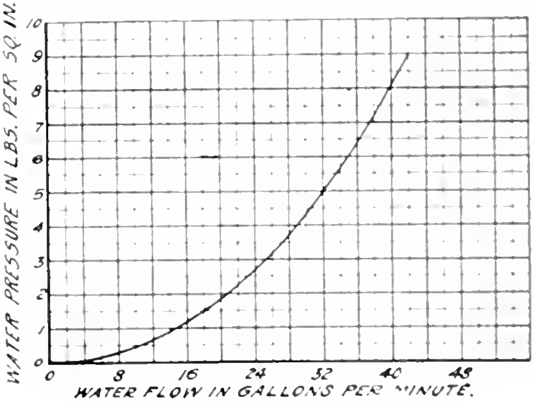

Fig 7. Difference in Water Pressure in Pounds Per Sq. In. Obtained on Four Sections of the Core as a Function of the Water Flow

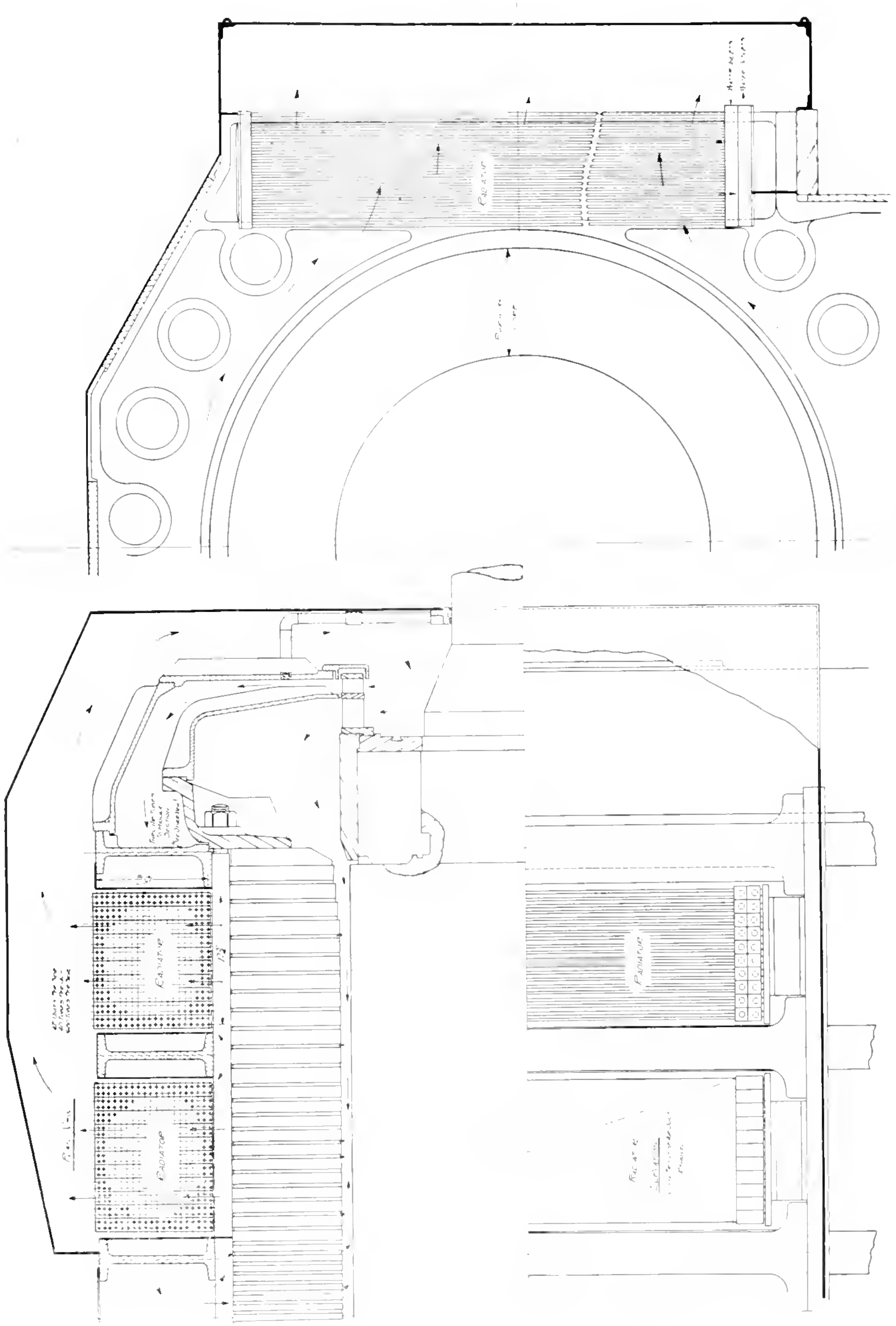

Fig. 8. Sectionalized Radiator Arranged Within the Frame of a Turbo-alternator

ance of the fan circuit do not appreciably affect the pressure developed by the fan as only part of the fan pressure is used in passing the air through this additional resistance. For moderate changes in resistance the volume of the air may be taken as proportional to the square root of the ratio of the pressure available to pass a given quantity of air through the generator alone under the two conditions. For instance, consider a case where a certain machine has no external duct and the fan produces a pressure of 13 inches of water while passing 60,000 cubic feet of air per minute through the machine. Assuming that an air duct and radiator are added in which the total head lost is three inches, then the quantity of air under the second condition is closely given by

$$Q = \sqrt{\frac{13-3}{13}} \times 60{,}000 = 52{,}700$$

cubic feet per minute.

Since long air ducts having numerous bends or changes in cross-section are eliminated by the use of the radiator and short ducts, it will be possible in many cases to obtain the necessary quantity of air without the use of external blowers.

The relation of air pressure to air velocity through the radiator cores is indicated by Fig. 5.

Beyond a certain air velocity the loss in air pressure required to force the air through

TABLE II

RADIATOR DESIGN ESTIMATED FROM INFORMATION SECURED FROM THE TESTS

(1)	Power dissipated..	600 kw.
(2)	Heat per minute dissipated.....	34,200 B.t.u.
(3)	Temperature of air into radiator.	55 deg. C.
(4)	Temperature of air out of radiator.	37 deg. C.
(5)	Temperature of air mean...	46 deg. C.
(6)	Temperature of air drop....	18 deg. C.
(7)	Temperature of water into radiator	25 deg. C.
(8)	Temperature of water out of radiator	28 deg. C.
(9)	Temperature of water mean........	26.5 deg. C.
(10)	Temperature rise of water ..	3 deg. C.
(11)	Mean air minus mean water	19.5 deg. C.
(12)	Velocity of water in tubes. .	50 ft. per min.
(13)	Velocity of air in free air area of core.	1200 ft. per min.
Cooling Surfaces		
(14)	External surface of tube per linear foot.	13.55 sq. in.
(15)	Surface of fins per linear foot of tube..	67.3 sq. ft.
(16)	Total surface per linear foot of tube..	80.85 sq. in.
(17)	Total surface per linear foot of tube...	.5615 sq. ft.
(18)	Total cooling surface per sq. ft. of frontal area in one layer of tubes.	8.3 sq. ft.
(19)	Total cooling surface required under conditions (12) and (13) is from S · 0.0614 = 600 kw.............. S	9770 sq. ft.
Estimated Weights, Volumes, and Surfaces		
(20)	Weight of air required per minute based upon (6) and (2)	4310 lb. per min.
(21)	Volume of air from (20)....	57,500 cu. ft. per min.
(22)	Free air area required from (20) and (13)........	47.8 sq. ft.
(23)	Weight of sea water based upon (2) and (10).....	6670 lb. per min.
(24)	Number of tubes required to carry water based upon bore of tube (0.083 sq. in. also (12) and (23)........	3602 tubes
(25)	Spacing tubes 0.8125 in. apart or....	11.75 per ft.

TABLE III

RADIATOR DESIGN FOR DIFFERENT CONDITIONS FROM THOSE OF TABLE II

(1)	Power dissipated..	600 kw.
(2)	Temperature of air ingoing. .	50 deg. C.
(3)	Temperature of air outgoing..	32 deg. C.
(4)	Temperature of water ingoing....	25 deg. C.
(5)	Temperature of water outgoing.....	27 deg. C.
(6)	Quantity of water at 50 ft. per minute	9800 lb. per min.
(7)	Width of core... ..	19.94 ft.
(8)	Height of core..	4.82 ft.
(9)	Volume of core...	117.5 cu. ft.
(10)	Weight of core empty...	4340 lb.
(11)	Weight of core plus sea water.. .	5400 lb.
(12)	Velocity of air in core........ .	1150 ft. per min.
(13)	Resistance to air flow in inches of water.	1.0 in.

the radiator makes the gain in heat transfer prohibitive.

Temperature of the Air

The temperatures of the air were obtained over the sections of air flow at the front and back of the heating grid and over each of the five sections of the radiator by means of extensive temperature coils and numerous thermometers. These furnished data for determining the mean temperatures of the air for the various sections of radiator.

Water Flow

The flow of water through the five sections of the radiator in series was varied from 8.25 to 40.5 gallons per minute, corresponding to a range in velocity of 10.1 to 49.6 feet per minute in the tubes. Entering at the bottom of the last or fifth section of the core, the water flowed upward in all of the 174 tubes of this section, then alternately downward and upward through the remaining sections, leaving the radiator from the top header tank of the first section. The air flowed through the cores of the five sections from front to back, thus moving through the core in the direction opposite to the progression of the water.

In determining the curves shown in Fig. 6, it is seen that the observed points for the higher flows do not lie as regularly on the curves as do those for the lowest flow. The curves were determined from the temperature rises of the water, which were lower for the greater quantities of water and thus made a greater percentage error in the observed temperatures. Nevertheless, it is shown that for an increase in the water flow up to a certain rate there is obtained an increase in the heat transfer for a fixed difference of the mean temperatures of the air and water, after which little benefit is secured by a further increase in the velocity of the water in the tubes.

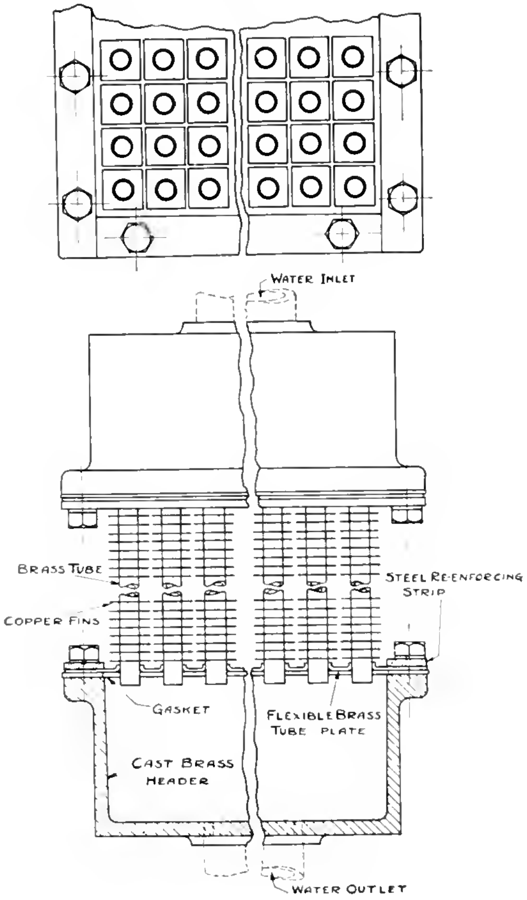

Fig. 10. Details of a Radiator Section

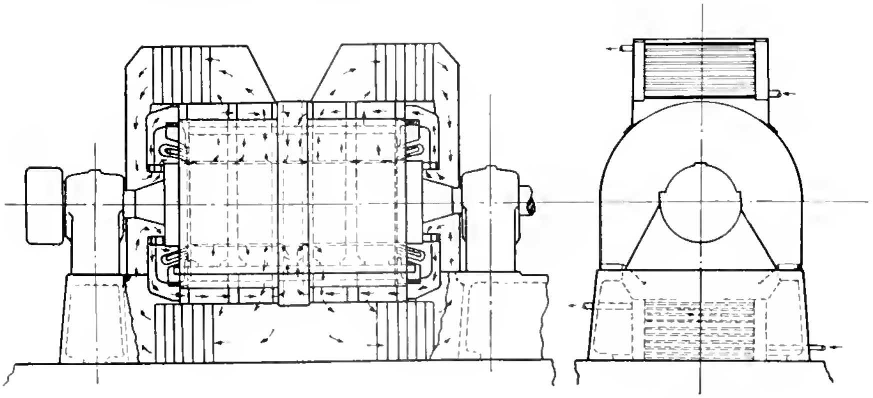

Fig. 9 Indicates the Ventilation System Obtained with a Turbo-alternator and a Radiator for Cooling the Air

Temperatures were obtained in the water circuit on each side of each of the five sections of the core, which made known the relative utility of the sections throughout the depth as a function of the air speed through the core. The curves shown in Fig. 6 were estimated from data taken on the first three sections of the core, since it was realized that this would be the approximate depth in the direction of air flow on most radiators.

The five sections of radiators were connected by 1.25-inch water piping provided with relief valves, pressure gauges, and U-tubes. Probably most of the drop in water head registered on four sections of the radiator was produced in the small connection piping. The curve shown in Fig. 7 obeys the "square law" approximately, and indicates turbulency of flow.

Arrangement of Radiators with Generator

Figs. 8 and 9 indicate possible arrangements of radiators between the sections of the stator frame, or entirely outside of it with the necessary inlet and discharge ducts for the air. As indicated by these diagrams, the radiator would be divided into a number of sections or units, thus facilitating handling or repairing a section while the remainder of the radiator was in service.

Fig. 10 indicates an arrangement of the tubes in a flexible tube sheet, to which is secured the header tanks. The flexible tube sheet has been found most satisfactory to prevent leaking tubes. Radiators intended for use with sea water should be constructed of the metal which will best resist the corrosive action.

In order to agree with the values of Table II, the width, height, and number of layers of tubes must be found by trial or by solving through simultaneous equations relating the unknowns.

Using the latter method:

Let x = width of core in feet.
Let y = height of core in feet.
Let z = number of layers of tubes from front to back of core.

Equations for:
Frontal area .... $47.8 = 0.518\ x\ y$
Surface .... $9770 = 8.3\ x\ y\ z$
Number of tubes .... $3602 = 14.75\ x\ z$

$x = 19.15$ ft. width permitting 283 tubes.
$y = 4.82$ ft. height.
$z = 12.75$ layers.

Anticipating a reduction of capacity due to clogging or higher temperatures of ingoing water, the radiator may be constructed with the front divided into 14 sections each having a width of 21 tubes, while in depth the core may be made in two divisons each having a depth of nine tubes. The frontal width will, therefore, be 294 tubes and the depth will be eighteen tubes or 5292 tubes total in core.

Substituting back through the above equations and computations there will be obtained the approximate relations shown in Table III.

Steam Turbine Generator Ventilation

By Geo. Monson
Alternating-current Turbine Engineering Department, General Electric Company

This article reviews the development of forced air ventilation for cooling large generators. On the early machines salient poles were used and these served to draw in the air and expel it through the ducts in the stator laminations. The next step was to provide passages through which air from the outside of the building could be obtained. The accumulation of dirt in the windings led to the introduction of air washers, which while removing the dirt, at the same time reduced the temperature of the air. As the size of generators increased, fans were introduced to increase the circulation of air. Separate blowers were used in some cases, but later designs embody the ventilating fans as part of the rotor structure. The latest system employs the closed air circuit and conserves space by mounting the humifying equipment and air dryers under the generator foundation. The advantages are the elimination of numerous station ventilating ducts and quantities of dirt that are always drawn in when outside air is employed.—Editor.

George Monson

Introduction

Many articles have been written on the necessity of ventilating turbine generators to remove the heat and to obtain increased output. It may, therefore, be of interest to review the progress that has taken place in the ventilation feature of these generators.

Review

About twenty years ago the General Electric Company entered the steam turbine business, and decided upon vertical type units. One of the first commercial machines designed was a two-stage 500-kw. four-pole 1800-r.p.m. unit. The generator was patterned in general after the then prevailing waterwheel and engine-driven types, having salient pole construction. The rotor body, with the field poles, was built of laminations riveted together in sections and forced on the shaft. This rotor had sufficient blower action to ventilate the generator in the following manner:

Air was drawn from the room through the top and the bottom of the generator into spaces between the poles, and then expelled directly into the room through the armature ducts and apertures cored in the frame for that purpose.

Several other units of different capacities were designed. Four-pole generators with a speed of 1800 r.p.m. up to 14-pole machines at 514 r.p.m. followed similar lines of construction and ventilation.

As the rotative speeds and capacities increased, the number of generator poles was correspondingly reduced and changes in the generator design were made to meet the new requirements of stresses, ventilation, etc. The principal departure was the inauguration of the cylindrical type of rotor having two or more field coils per pole. The rotor construction varied; some had laminated disk bodies with radial slots for receiving the field coils and others had parallel slots.

In generators of larger capacities than 5000 kw., laminated poles were dovetailed into steel plates which were shrunk on fluted cast-steel spiders, and these in turn were mounted on the shaft.

At first, the air was drawn in at both the top and the bottom of the generator by the action of the rotor spider and forced out through the rotor and stator ducts. Part of the ventilating air also passed through the end windings and then through apertures in the frame to the room. On later machines, the ventilating apertures in the stator frames were eliminated, the air being taken in at the top of the generator and expelled to the room through openings in the generator base. The ventilation for this type of generator was very easily accomplished; in fact, in many cases more air passed through the generator than was needed for good economy, hence baffle plates were inserted to reduce the quantity of air and thereby the windage losses.

Use of Hoods

It was found that in some stations the heated generator air exhausted from the base openings did not mix freely with the station air, but instead moved up along the stator frame and returned to the air inlet opening at the top of the generator, thereby causing undue heating in the generator. To prevent this a hood made either of steel plates or cast-iron was placed over the air intake shield. This hood had an opening which could be placed in any direction, e.g., could be turned toward the station windows which were kept open when the temperature inside the building was high. By this arrangement the air intake was further removed from the rising column of heated air, and cooler air was drawn into the generator. This hood served its purpose very well on those machines.

Innovation of External Ventilating Ducts

Up to that time air had been taken from and discharged into the engine room. The power stations had been originally laid out and built for a certain kilowatt output with a given number of units, but this output was soon outgrown and increased capacities were required. The simplest and cheapest scheme was to replace existing units with new units of increased capacity. In some cases, due to the substitution of new units, the amount of power was several times that originally contemplated. The increased quantity of heated air from the generators could not be removed from the engine room by the old method. Therefore, in order to keep the temperature of the generator within safe limits, and to secure a more comfortable room temperature, it became necessary to install ducts through which cool air could be drawn from outside the station building to the generator, and thence to the discharge outlet, also located outside.

Air Washers

It has always been more or less dangerous to allow dirt to accumulate on the windings, since it clogs the air passage and introduces a heat insulating material on the surface exposed to the air, thereby causing excessive heating. Yet it has been difficult to prevent such accumulation. Although only a very small percentage of dirt carried by the ventilating air may be deposited in the machine, the quantity of air passed through the machine is very large and therefore the amount of dirt deposited is considerable. Some conception of the magnitude of the quantities involved may be had from the fact that a 30,000-kw. machine requires approximately 6,000,000 lb. (81,000,000 cu. ft.) of ventilating air to pass through it during 20 hours of operation. The rapid deposit of dirt under such conditions makes frequent cleaning necessary. In order to reduce the frequency of cleaning, which is a slow, expensive process requiring the dismantling of the machine, air washers were installed in the air intake duct. In addition to removing a large percentage of the dirt, these washers also serve the purpose of cooling the air, thus permitting higher generator output, especially during hot weather. The problem was thus partially solved. A complete solution, involving a closed system of ventilation, is described later in this article.

First Use of Fans

The construction used in some of the earlier vertical alternators caused air pockets to be formed around the top and bottom ends of the windings, beyond the armature core. These produced eddies which prevented the proper flow of air. To overcome this difficulty a straight bladed fan was mounted on the top of the rotor for forcing part of the incoming cool air through, and also around the top end windings, thus overcoming the eddies. This fan directed the air downward between the stator core and frame to the outlet apertures in the base. In later designs most of the generators had fans mounted also on the bottom part of the rotor.

Dampers in the Air Ducts

It was recommended from the start that station air ducts be introduced, and that these be furnished with dampers for regulating the quantity of air. Later, doors were made in the ducts inside the station so that all the air, or part of it, could be taken from the room, or from outside the building, whichever was desired. Similar dampers were placed in the exhaust ducts, and in case of fire in the generator these dampers could be closed, thus impeding the progress of the fire.

Changing from Vertical to Horizontal Units

The largest vertical steam turbines built were 20,000-kw., 750-r.p.m., 25-cycle and 18,750-kw. (25,000-kv-a.) 720-r.p.m., 60-cycle units. With the demand for further increased kilowatt capacity and rotative speed, it soon became obvious that the limit was about reached in the design of the vertical machines. It was advisable from an engineering standpoint to change to the horizontal type of machine. This line of steam turbine generator sets was started at the Schenectady Works with the 300-kw., 4-pole, 1800-r.p.m., 60-cycle units and continued to date with capacities of units up to 30,000 kw., 1800 r.p.m., 60 cycles; 35,000 kw., 1500 r.p.m., 25 cycles; and 45,000 kw., 1200 r.p.m., 60 cycles.

The first horizontal sets up to 5000 kw., 1500 and 1800 r.p.m., had laminated cylindrical rotors with fluted shafts for blower action. The ventilating air was taken from the room through openings in the generator end shield, and discharged at the top of the stator frame to the engine room. Later machines were changed so that the discharge could be made upward or downward according to preference

Latest Construction of Generator

The turbine rotative speeds have now reached a maximum of 1500 r.p.m. for 35,000 kw., 25 cycles; 1800 r.p.m. for 30,000 kw.; and 3600 r.p.m. for 6000 kw., 60 cycles. The limit of output capacity with respect to speed is dependent upon the rotor stresses and the relation of the critical speed of vibration to the normal speed. To make such generators possible the solid forged rotor construction was adopted, and has proved satisfactory. With this construction, the ventilation became a still more difficult problem.

Fans Mounted on the Rotor

For ventilating some of the first of these generators separate blower outfits were used. In some cases blowers were mounted on the end of the rotor shaft; but this practice was later abandoned and since that time it has been standard practice to mount fans on each end of the rotor body. The fans force the air at both ends, around and through the end windings into the air gap, and from there along the rotor body, and out through the armature ducts and frame as already explained.

Double Air Flow System

With the ever-increasing capacity of units, it became necessary on account of stresses to build the larger machines with a relatively small diameter and a great axial length. With the air pressure available, the air gap in such machines did not afford adequate space for the passage of the large quantity of ventilating air required. A new departure in ventilation was therefore devised.

Double bladed fans were provided on each end of the rotor. Part of the air passes into the air gap in accordance with standard practice and part flows through tubes arranged outside the armature core leading to a central air pressure chamber where it passes through a number of armature core ducts radially inward toward the rotor and then axially along the air gap and out through the armature ducts, in the usual manner. By this arrangement it was possible to introduce air into the gap at four places and thereby force the necessary amount of air through the generator.

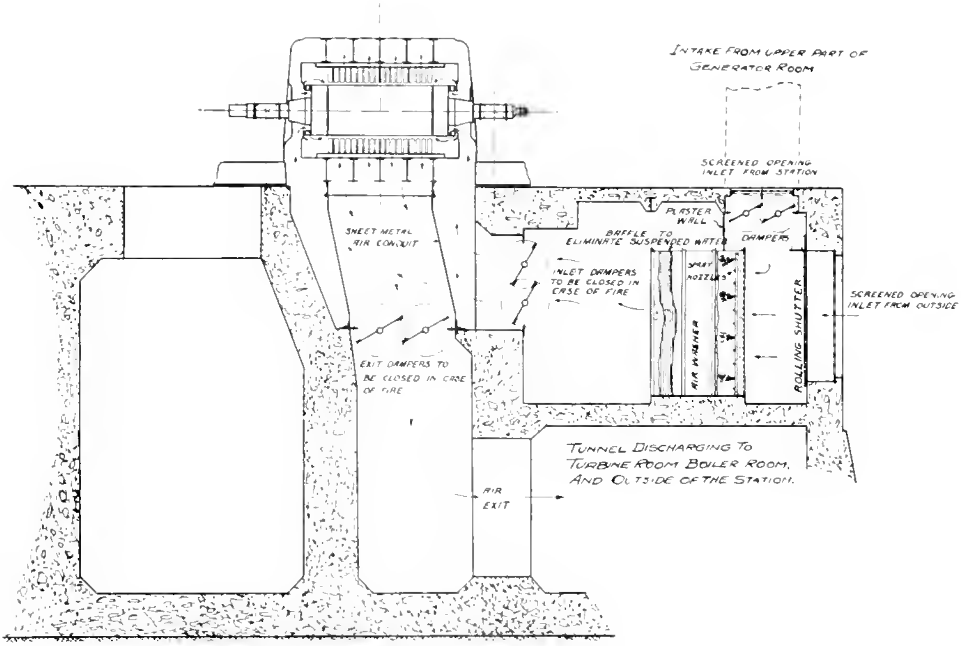

Fig 1. Diagram of the Ventilation System for Turbo-alternator

Exhausted Generator Air for Use Under Boilers

It seemed logical for power stations to use the exhausted generator air under the boilers for heat conservation. Ducts were therefore installed for the purpose, but this arrangement did not prove to be as successful as anticipated. During cold weather considerable condensation was caused in the engine room by air having high humidity coming in contact with the cold ceiling. Under unusually severe conditions fog would be present in the room, causing dampness and dripping of water from the ceiling. When this condition developed it became desirable to take air from the engine room through the air washer and to discharge it back to the room during cold and moist weather, and to regulate the room temperature by doors or openings to the boiler room. This arrangement is shown in Fig. 1. After the air passes through the generator and its temperature is raised approximately 20 deg. C., its ability to absorb moisture is greatly increased; and when discharged into the station toward the ceiling it reduces the relative humidity. The temperature of the station was regulated by opening the windows. This is the usual ventilating arrangement at the present time, but there are conditions where a closed air system is preferable as mentioned earlier in this article.

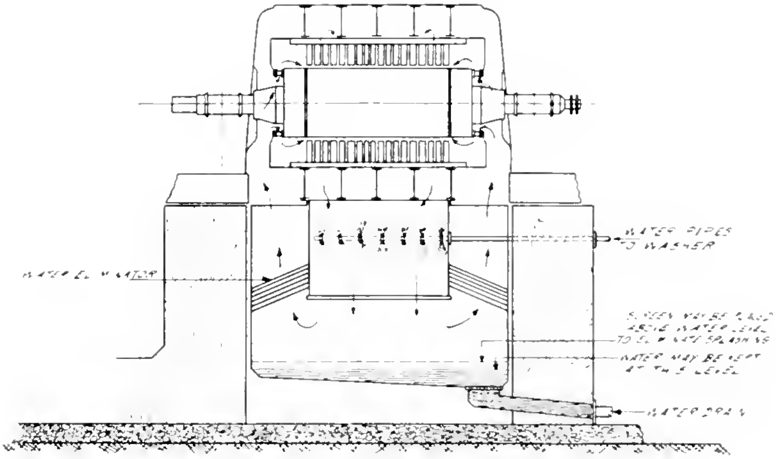

Fig 2 System of Ventilation in Which Inlet and Outlet Air Ducts and Air Rectifying Equipment Are Located Under Generator Foundation

Closed Air Circuit System

In some cases insufficient consideration was given to the installation of washers and they could not be operated in freezing weather. In other cases the washers were not kept in good condition and failed to clean the air properly. These conditions were detrimental to the generator and a better ventilation arrangement was desirable. It is believed that this has been found in the closed air circuit system.

The closed air circuit system operates in the following manner. The air enters the rectifier cooling chamber directly after leaving the generator, then flows to the speed reducing chamber where the water particles are segregated from the air flow, then through an eliminator chamber where the last vestige of water is removed from the air before it re-enters the generator. This system uses the same air continuously, and can be made to occupy a relatively small and compact space as compared with the present system.

The foundation directly under the generator is usually provided with a space which is occupied by the inlet and outlet air duct pipes. This space can be utilized to advantage for mounting the air rectifier as shown in Fig. 2. The cumbersome station ventilating ducts, including the room occupied by the air washing apparatus, will be eliminated, thereby simplifying the station construction considerably and saving space.

As stated before, the air washer is used for cleaning and cooling the incoming air. By using the same air continually, and without any possible way for it to mix with impurities, the problem of cleaning is eliminated.

Fig. 2 shows a view of the rectifier installed with a generator; the complete construction consisting of a steel tank having an inner compartment where the cooling water spray nozzles are located; a separating chamber where the heated water is collected from the air and discharged; and the eliminator compartment through which the air has to pass before re-entering the generator. The operation, simplicity in design, economy of space, and positiveness of action can readily be understood.

Noise

All high speed machines are more or less noisy when the air is discharged to atmosphere, but in the closed air system this should be reduced to an unobjectionable tone and volume.

Amount of Water

The necessary quantity of water for removing the generator losses from the heated air is approximately four gallons per kilowatt-minute for one deg. C. rise of water, and varies inversely as the allowed temperature rise of the water. Sufficient data are not now available to determine how many degrees centigrade the cooling water should be allowed to rise to obtain the best results from the generator; but there is a considerable saving in the quantity of water used, as compared with the present air systems, when the water from the washer is heated only about 2 deg. C.

Regulating the Generator Heating

As a rule turbine units are seldom operated at their maximum output and it would therefore be inefficient to operate the air rectifier continuously with the amount of water corresponding to the maximum load of the generator. Under such load conditions, and especially when water is scarce, an automatic water regulator should be installed for controlling the number of spray nozzles in operation. There are several ways to accomplish this: by electrical and mechanical arrangements for opening and closing the valves of the water supply pipes to the spray nozzles at prearranged temperatures; by the use of thermostats placed in the heated air leaving the generator, or in some other suitable location, etc. With such automatic regulation the generator will operate at practically constant temperature for different outputs and be entirely independent of surrounding atmospheric conditions. This cannot be accomplished with present systems because the air washers used are built for a combination of cleaning and cooling; i.e., any reduction in the quantity of water may adversely affect the cleaning of the air.

Air Free from Water

All the air washers the writer has seen in connection with turbo-generators have the flow of air through the washer in a horizontal direction so that the drops of water after leaving the nozzles must fall to drip-pans at right-angle to the air flow, which has a velocity of 500 to 1000 feet per minute. In some cases where the washers are not of liberal dimensions, small particles of water are carried along with the air flow and may enter the generator. In the system shown in Fig. 2 the air flow is vertically downward after leaving the spray chamber so that the water has to drop straight with the air flow. The direction of the air flow is then reversed to vertically upward at a speed of 300 to 500 feet per minute before it passes the eliminator plates. The low velocity, vertical flow, and eliminator plates effectively remove all particles of water from the air before it reenters the generator.

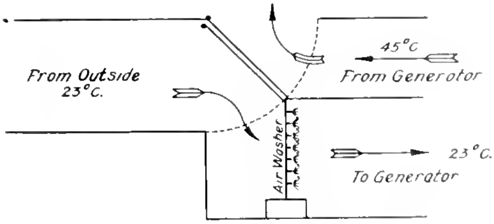

Fig. 3. Arrangement of Dampers Taking Air from and Discharging it to the Outside

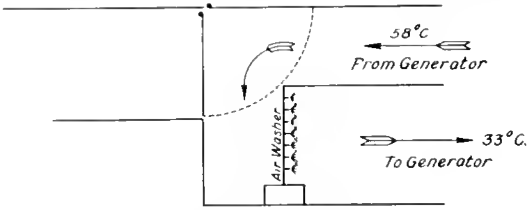

Fig. 4. Arrangement of Dampers Forming a Closed Circuit for Ventilating Air

Dampers and Fire Protection

In the present system, the air intake or outlet ducts or both are generally supplied with dampers installed for modifying the incoming air temperatures, and to prevent air circulation in case the armature winding should take fire. The object is to let the fire smother itself; but on account of the difficulty of preventing leakage past the dampers, this method has not been entirely satisfactory for the purpose.

In the closed system dampers are unnecessary since the amount of water controls the temperature. In case of internal fire the water valves may be closed which would prevent the air rectification and by this means the fire would be soon extinguished. In case a quicker action is desired, steam or pyrene may be injected in the system or water can be sprinkled directly on the windings by pipes installed for this purpose.

Danger Signal

The closed air system cannot operate without cooling water being supplied to the rectifier any more than bearings can operate without lubrication. It will, therefore, be prudent to install an alarm device which will announce danger in case the water cooler does not function properly, or stops entirely; and which will also serve as a tell-tale should the generator happen to operate above normal temperatures from other reasons such as heavy overloads, internal fire, etc.

Such an alarm system can be readily installed and may consist of a thermostat in the outgoing air duct, in connection with a bell that will ring at a predetermined temperature; or of an electric bell connected in circuit with one or more of the stator temperature coils; also temperature coils may be mounted in the outlet air duct in the same manner as the thermostat.

Other Applications of the Closed System

The closed air circuit system is useful not only for ventilating turbine generators and other electrical apparatus, but should prove of value in places where fumes from acids, carbon and steel dusts, or other injurious substances prevail as it will safeguard men and machinery from their effects.

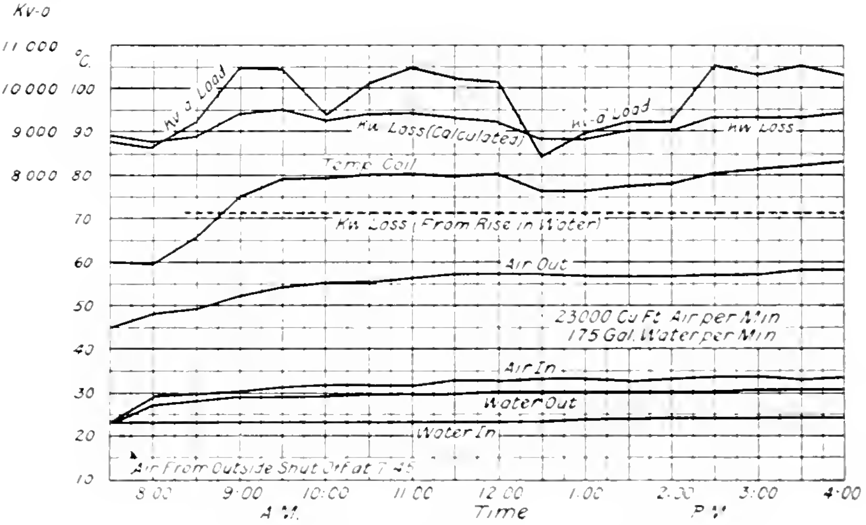

Fig. 5. Curve Showing Results of Test on 10,000-kv-a. Turbo generator Cooled by Ventilation from a Specially Designed System

Heat Run Made with Closed Circuit Ventilation System.

Tests have been made on a closed air circuit system utilizing the same washer as installed, which washer was designed for cleaning the air when it was taken from the outside atmosphere. The tests were made on a 10,000 kv-a. turbine generator unit that is fitted with a special design of air duct which, by means of dampers, permits of various schemes of ventilation. Air may be taken from out of doors and exhausted into the room, or the air may be circulated and used over and over, the heat being removed each time by means of water passed through an air washer.

At the time the test was started the machine had been running all night under approximately full load, with the dampers in the position shown in Fig. 3 (i.e., the air being drawn from the outside and discharged into the room) and the temperatures were constant with ingoing air at 23 deg. C. and outgoing air at 45 deg. C., or a rise of 22 deg. C. (for about 9000 kw.). The temperature coils and thermo-couples in the armature of the machine averaged 60 deg. C. actual, or 37 deg. C. rise.

At 7:45 a.m. the dampers were thrown to the position shown in Fig. 4, forming a closed circuit for the ventilating air, and a heat run lasting till 4 p.m. was made under these conditions to determine the efficacy of this ventilating system. During this time the load on the machine was maintained as nearly constant at 10,000 kv-a. as conditions would permit. Fluctuations in the load curve were caused by a variable demand made by the shops being supplied with power and by changes in steam pressure. Every half hour readings were taken of the load, temperature coils, air, and water. At the end of the run and at a load of about 10,000 kv-a., the temperatures were fairly constant with inlet air at 33 deg. C. and outlet air at 58 deg. C., or a rise of 25 deg. C. in passing through the generator and a corresponding drop of 25 deg. C. in passing through the air washer.

Water at the rate of 175 gallons per minute was passed through the spray nozzles of the air washer, with an average rise in temperature of 6½ deg. C. From these data the loss in the machine was calculated to be 302 kw. with a volume of air of 23,000 cu. ft. per min.

The discrepancy between this value of 302 kw. and the theoretically calculated loss, based upon the design, which averages about 340 kw., may be partly accounted for by radiation of heat from the generator and air ducts, and by small errors in reading the temperature of the cooling water.

Air temperatures, both ingoing and outgoing, were read very accurately by means of copper resistance coils wound on wooden frames in such a manner as to obtain the average temperature over the entire cross-sectional area of the air ducts. These temperatures were also checked by means of thermometers and thermo-couples. Thermo-couples placed in the armature of the generator checked the standard temperature coil within 2 deg. C. plus or minus.

A record of the entire run is shown by the curves in Fig. 5.

The air washer referred to is fitted with nozzles covering a cross-sectional area of approximately 36 sq. ft.

The results of the test indicate that the closed circuit system of ventilation is practical in every respect, and that the air washer installed at present is entirely adequate as regards size. Further tests will be made using varying amounts of water, and it may develop that by permitting a larger increase of temperature in the water the rate of flow can be reduced materially without seriously affecting the temperature of the generator.

Mechanical Design of Large Turbo-generators

By M. A. Savage

A-C. Turbo-generator Engineering Department, General Electric Company

The turbine generator of today is the essence of compactness. It is the result of a persistent effort to obtain the maximum usefulness from every pound of material employed in its construction. One pound of material in the present 5000 kw. turbo set does the work required of five pounds in the first 5000 kw. set built in this country. Stator construction has reduced itself to the simplest form, as the requirements of rigidity, light weight and flexibility of design are best fulfilled by such a design. However, high speeds and increased capacities have introduced real difficulties in the construction of rotors. The centrifugal stresses have necessitated the use of a solid forged rotor, and in the largest machines it has been desirable to use a three-piece rotor because of the great length and weight of a solid one-piece forging. Ventilation, which is of prime importance in the modern turbo generator, is briefly referred to in this article and is more fully discussed in other articles in this issue.—Editor.

M. A. Savage

THE early turbine generator design practice followed closely that of engine-driven machines with respect to large diameter and relatively low speed. As these generators were invariably built with salient poles and very little attempt was made to direct the air through different paths, they were extremely large and heavy for their output as compared with modern machines. For example, the first 5000-kw. turbine generator built in this country weighed 225,000 lb.; whereas the present 5000-kw. machine weighs approximately 47,000 lb. Most of this development has been along the lines of increased speed and better ventilation. Increased speed has made necessary the employment of better materials, and a more careful study into the duty to be performed by every element in the machine. Better ventilation has been brought about largely by a more complete knowledge of the source and location of the various losses, and a more careful direction of the air over the surfaces where these losses occur.

Stator Frame

The stator of these large units is made up of a number of annular "I" sections which are held together at the outer periphery by thick boiler plate and at the inner periphery by rolled steel ribs. Heavy steel foot plates along each side of the stator frame are bolted to feet cast integral with the circular "I" beams, as shown in Fig. 1.

This construction possesses a number of advantages.

(1) It is extremely stiff in the direction in which stiffness is required.

(2) It eliminates shrinkage strains in the castings, etc. It requires but simple and inexpensive patterns, and also it reduces the space required to store patterns.

(3) It permits of a large reduction in weight, and therefore results in lower shipping charges. It also makes possible the assembly of machines of larger capacity at the factory.

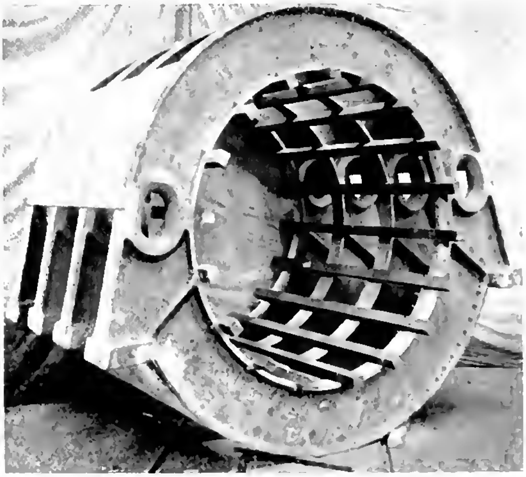

Fig. 1. Large Turbine Generator Stator Frame Built Up of Annular "I" Sections with Boiler Plate on the Outside and Rolled Steel Ribs Inside

(4) For a given diameter, the lengths can be increased or decreased within certain limits by adding or subtracting one or more annular "I" sections.

Electrical Characteristics

Due to the high rotative speed of this type of machine, the diameters are necessarily small and the axial length great. On the majority of machines of General Electric manufacture, the length is usually one and a half or more times the diameter. This proportion results in a relatively small number of slots. Naturally, the coils for such long cores are extremely heavy and present quite a problem in handling and assembling in the factory. The flux per pole of this type of machine is very large, consequently the number of turns to generate the required voltage is small In most of the later machines the number of turns rarely exceeds three.

Since the number of circuits in which the armature winding can be divided is limited by the number of poles, two circuits being the maximum for two poles, and four circuits for four poles, the current per circuit is extremely high and this results in very large conductors. Great care, therefore, must be exercised in the construction of these large conductors to keep down the eddy current losses (commonly called load losses). This is done by dividing the conductors into a number of thin, narrow strips, each strip being insulated from its fellows by a cotton covering. The coil thus formed is then twisted over at the V ends so that the strips which form the bottom layer in one slot will form an intermediate layer in the slot in which the other side of the coil is assembled. This gives a partial neutralization of the group eddies and is usually effective enough in the ordinary type of machine.

Fields or Rotors

The early type of rotors was made by assembling punchings on a shaft. Later, due to larger capacities, the stresses became so great that it was necessary to use a solid forging.

In the very largest six-pole machines the rotor is built up of three parts; the center part, forming the main field body, is shrunk on and bolted to two stub shafts which form the bearing portions of the rotor. This construction is illustrated in Fig. 2. The bolts holding these parts together are given an initial tension by heating them to some known temperature and then forcing them home. Ample keys are also provided for taking the torque from the prime mover. A rotor thus built up is as stiff as a solid structure. As no metal is needed at the center of these rotors for carrying flux, the rotor is cored out thus greatly reducing the weight on the bearings. This hole in the center increases the stress in the rotor body, but as the angular velocity is low when compared with a rotor operating at 3600 r.p.m. the body stresses do not become a serious matter.

In the two-pole machine the material at the center is needed for carrying flux. This is especially true in the 3600-r.p.m. machines where the diameters are small and the densities are often quite high.

Radial slots are milled in these forgings to receive the conductors.

The copper strips which form the field turns are wound on a machine which automatically changes the length of each strip for different radii encountered as the slots progress toward the center. The turns are insulated with mica tape and are then assembled by feeding turn by turn into the slots, which are insulated by a trough of tough insulation After the turns are once assembled they are cemented together by applying heat and pressure. This prevents the coils from moving in the slots when the machine is started and stopped. The end windings which project from the slots are taped with mica and asbestos and a ring insulation put over the whole.

There are certain points of superiority of this type of rotor which it might be well to mention briefly.

The first, and foremost, is ruggedness. Of the hundreds of rotors of this type which are constantly in operation there have been surprisingly few failures or faults of any sort. This is in part due to the solid structure surrounding the winding which resists any rapid change of flux through it and thereby resists any sudden rise in potential in the winding itself. Electrical failures in the rotor due to short circuits on the armature are therefore extremely rare.

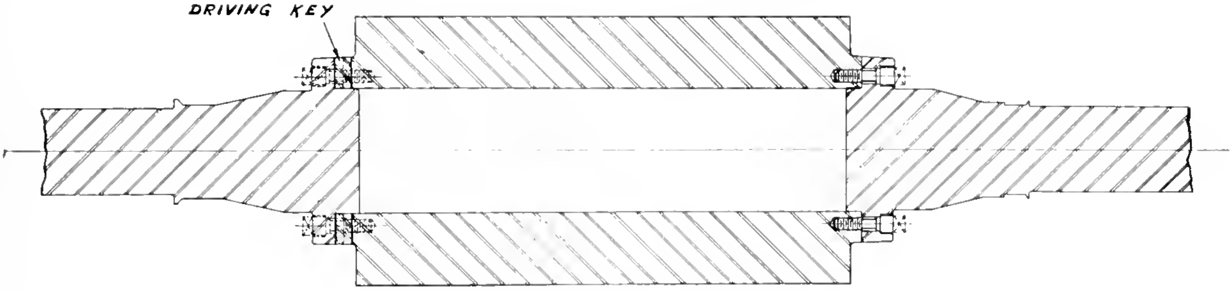

Fig. 2. Three-part Rotor Construction Employed in the Largest Six-pole Machines

Second, the solid structure of the rotor acts as a squirrel-cage damping device which reduces the danger of oscillations and greatly improves the parallel operation of the machine.

Third, the better control of the flux distribution. Since the slots for this type of rotor are milled from a template, it is no longer of manufacturing advantage to have the slots uniformly spaced. They can, therefore, be spaced to give the best electrical characteristics. These rotors when operating in an armature with three slots per pole per phase will give very nearly a perfect sine wave, a feature of great importance as it reduces the secondary losses and also the likelihood of interference where the power lines run near telephone or telegraph lines.

Fig. 3 shows the flux distribution of one of these rotors; Fig. 4, the resultant wave shape on the armature. This armature has five coils per phase per pole.

Ventilation

Sufficient ventilation has been and is the major problem in the design of the large turbine generator. More time probably has been spent on this subject than on any other in connection with turbine generator development. These machines are compactly built, the surfaces are small, and the heat loss is enormous when compared with the size of those surfaces. It has, therefore, been necessary to use forced ventilation at pressures and volumes which were never dreamed of for that purpose a few years ago. The quantity of air is based on the kilowatt loss in the generator and is usually so apportioned that the air rise through the machine will not exceed 18 or 20 degrees C. This condition makes necessary about 100 cu. ft. of air per minute per kilowatt loss and in the larger machines will necessitate some 60,000 to 70,000 cu. ft. of air per minute. Since the spaces through which the air is to be forced are relatively small, the velocity becomes extremely high. The air taken through the air gap very frequently reaches 12,000 ft. per min.

Probably the greatest problem of turbine generator ventilation is to keep the rotor cool. Attention has been previously called to the compactness of these rotors. The heat generated in the copper is first to be carried to the outside of the insulation, then through the iron forming the teeth, and to the air gap, thence dissipated into the air. This means that the drop in temperature between the rotor surfaces and the air has to be small or the temperature of the rotor becomes prohibitive.

The data which have been collected on the subject of ventilation give the designing engineer a feeling of certainty that the apparatus will meet the requirements for which it is designed. Much, however, depends upon the quality of the cooling air.

Quality of Ventilating Air

The quality of the air used in ventilation is a large factor in the operation of the machine. When it is remembered that one of the machines takes 70,000 cu. ft. of air every minute, even though the air may be relatively clean, it will in time pass a sufficient amount of dirt and foreign matter to completely clog the air passages. Air washers have therefore become almost universal for the larger machines. These washers, however, do not remove all the dirt from the air and their makers do not guarantee them to remove more than 98 per cent of it. Even with this small percentage passing through the generators, a number of machines which have been in operation a year or more have been found to contain a considerable amount of foreign material.

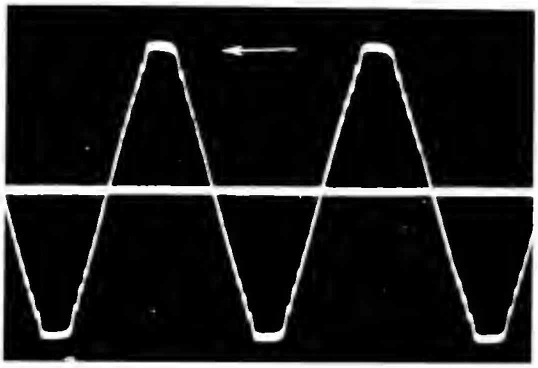

Fig. 3. Oscillogram of the Flux Distribution of a Five-coil-per-phase-per-pole Rotor

Humidity of the Air

The quantity of heat removed is very little affected by the humidity of the air in contact with it, but in passing the air through the washer the temperature is usually lowered from ten to fifteen degrees which means that the machine will run that much cooler.

Mechanical Stresses

The stresses to which these machines are subjected should be divided into two classes: First, the running stresses; second, the short-circuit stresses. The first are occasioned by centrifugal force; the second by accidental or intentional short circuit on the machine. As previously mentioned, the end windings of the field are held by steel retaining rings. When it is stated that these retaining rings on the higher speed machines have to hold a force of about 3,000,000 lb., it will be seen that both the quality of the material and the workmanship have to be perfect. These retaining rings are shrunk on the centering spider at a stress greater than that which is expected to occur in service, so that when the centrifugal forces are exerted on them they will still remain tight. The next limiting stress which occurs in the rotor is probably at the root of the teeth. This stress often limits the depth of the slot and, therefore, the output which can be obtained for a rotor of given dimensions.

Short-circuit stresses are more serious as regards the armature winding Enormous forces are exerted on the end portion of the coils, outside of the slot, which tend to distort them and if they are not sufficiently supported crack the insulation with the result that the machine subsequently breaks down. To overcome this, wooden blocks are inserted between coils and the coils are laced down to steel binding bands. Great care is exercised to see that the shaft and coupling bolts have sufficiently low stresses to withstand the shock of short circuits.

Capacity

In conclusion, it might be of interest to state that machines of 50,000 kv-a. operating at 1200 r.p.m. have been built and are operating satisfactorily. Machines of 38,889 kv-a. at 1500 r.p.m. have also been built and are in successful operation. In the 1800 r.p.m. class, there are a number of machines in commercial service with ratings of 31,250 kv-a. at 0.8 p-f., and 33,333 kv-a. at 0.9 p-f., while at the highest speed, viz., 3600 r.p.m., machines of 7500 kv-a. are in operation, and two of 9375 kv-a. are under construction.

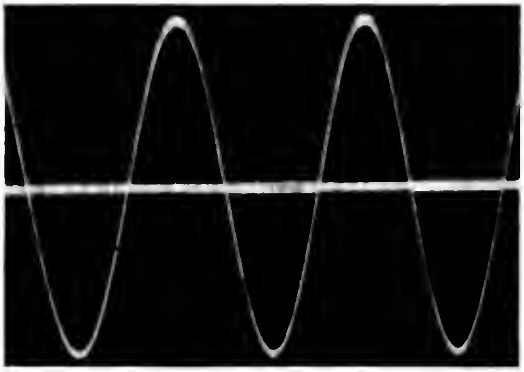

Fig 4. Oscillogram of the Wave Shape of the Armature Resulting from the Flux Distribution Shown in Fig 3

The Behavior of Alternating-current Generators When Charging a Transmission Line

By W. O. Morse

Alternating-current Engineering Department, General Electric Company

This article is a very interesting discussion of the effect of transmission line capacity on the behavior of alternating-current generators. When a generator is thrown on a transmission line of proper characteristics it is possible for the generator voltage to build up to a value considerably higher than normal without field excitation; while an alternator having different characteristics may be entirely unable to generate under the same conditions. Just what will take place when switching an alternator on a transmission line may be determined by plotting together the line characteristic and the alternator volt-ampere armature characteristic; if the armature characteristic lies above the line characteristic it is probable that the alternator will charge the line without field excitation, while if the alternator characteristic is below the line characteristic it will be impossible for the alternator to generate without field excitation. The effect of negative field excitation is also discussed.—Editor.

W. O. Morse

When a generator with a small amount of excitation is thrown on a dead transmission line of proper characteristics, it will build up in voltage until it ultimately reaches a point of stable operation. This phenomenon is caused by the transmission line acting as a static condenser and supplying leading or magnetizing current to the alternator; and if this magnetizing current causes the alternator voltage to build up to a value higher than the corresponding voltage of the line, the voltage and current will continue to increase until a value of current is reached at which, on account of the saturation of the generator the line voltage and the generator voltage are equal. This is the point of stable operation. It is quite possible that the residual magnetism of the generator will be sufficient to start the phenomenon.

The behavior of an alternator when charging a line cannot be determined from the generator characteristics alone; the line characteristics are also involved. Another point to be noted is that some generators when switched on a line of given characteristics will build up in voltage, whereas other generators switched on the same line will not. Whether the generator builds up depends upon the relative slopes of generator and line characteristics.

Before discussing the relation of these characteristics, their nature will be considered. The volt-ampere charging characteristic of a transmission line is a straight line; i.e., the charging current is directly proportional to the line voltage. This charging current is, of course, leading and practically wattless.

The alternator exciting volt-ampere characteristic for the armature has the shape o the ordinary saturation curve. It is, in fact, the saturation curve of the machine when excited by alternating current in the armature; but, due to the different disposition of magnetic flux in the iron circuits in this case, the knee of the curve occurs at a higher terminal voltage than in the case of the ordinary saturation curve. Under the conditions where the generator is excited by armature current, all the flux is effective in inducing voltage in the armature conductors; whereas if the generator is excited in the usual way, there is a certain amount of leakage flux between poles which does not interlink with the armature conductors and hence is not effective flux. However, it is essential at this point to have in mind only the shape of the curve; i.e., it is like the ordinary saturation curve.

By reference to Fig. 1, it is obvious that if the alternator characteristic lies above the line characteristic along the straight portion of the former, the leading charging current of the line, at any point in that range, will cause a higher alternator terminal voltage than is required to produce that current on the line. Hence the current and voltage will both continue to increase until, by saturation, the "volts per ampere" of the alternator become the same as that of the line; i.e., reach the point where the alternator characteristic crosses the line characteristic. This is designated "stable point" in Fig. 1.

It is equally obvious that if the alternator characteristic falls below the line characteristic the alternator will never build up without permanent field excitation.

However, if additional alternators are available for charging the line, the problem may be easily solved. Suppose two duplicate alternators, each having a characteristic as shown in Fig. 1, were switched on the line. This would mean that the line voltage per ampere for the pair would be one half that shown for the one alternator in Fig. 1. In other words, the combined alternator characteristic would now be a curve having ordinates one half of those of the single alternator curve, and would be as shown by the dotted curve in Fig. 1. The line characteristic, however, has not been altered by placing the additional generator on the circuit. Hence, since the combined alternator characteristic falls below the line characteristic, the pair of alternators will not build up without permanent field excitation.

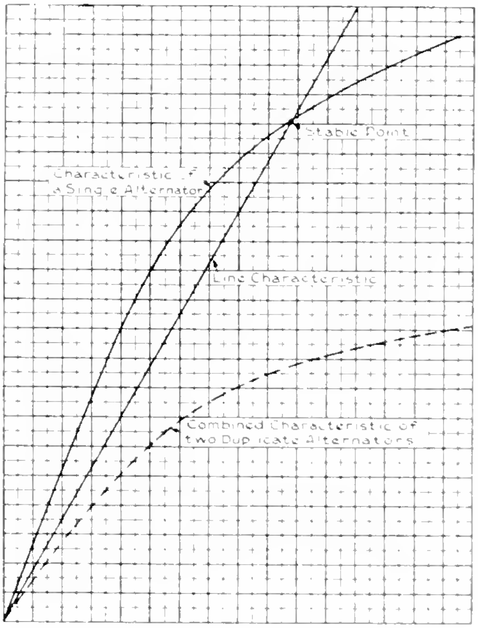

Fig. 1 Voltage-current Characteristics of a Single Alternator, of Two Duplicate Alternators, and of a Transmission Line

Likewise, any alternator or alternators whose combined characteristic falls below the line characteristic will not build up without permanent field excitation; and, conversely, if the combined characteristic falls above the line characteristic, the voltage will build up, once it is started by a momentary application of field excitation, or by the residual magnetism of the alternators. And in the latter case the voltage will rise cumulatively until, as already stated, the characteristic of the alternator, or alternators, bends by saturation until it crosses the line characteristic.

It should be noted that there is little relation in general between the alternator and the line characteristics, since the former is dependent largely upon the rating of the generator, and to some extent upon other considerations of design; while the line characteristic is roughly a function of its operating voltage and length. Therefore, we may find that a generator which requires permanent field excitation to charge one particular line may, on another line of different characteristics, build up in voltage and current to values far beyond the normal capacity of the machine. In such a case, the problem of charging the line without injury to the generator becomes a serious matter. It is not always feasible to obtain complete control by modifying the design of a normal generator. From the foregoing, however, it is clear that adding more alternators (if it is possible to keep them in phase during the process) will accomplish the desired result. In at least one instance, the paralleling of two alternators for the purpose of charging a line has been found practical. However, additional units are not always available.

There is another scheme involving the manipulation of the generators, which also has been confirmed by experience, but which is limited in application. It is the use of negative field excitation for neutralizing part of the charging current, thereby lowering the voltage and current. Its application is limited by the well-known fact that with increasing negative field current a point is soon reached where the machine slips a pole, thereafter intensifying what it is intended to diminish. There are two factors which fix this limit. One is the "reaction" torque of the machine; i.e., the torque which tends to hold the salient poles in line with the armature rotating poles when there is no excitation on the field, and which is of the same character as the force which tends to hold the poles of any two magnets in the position of minimum reluctance. In other words, it is due to the salient-pole construction and would not exist in a cylindrical rotor. It is this torque which makes it possible for a synchronous motor without field excitation, to carry some load in complete synchronism.

In the present problem it operates in the following manner. When the field is reversed the machine is equivalent to a synchronous motor which has slipped a pole. It is operating 180 electrical degrees from the normal no-load position. In other words, it is operating in an unstable position, the least displacement from which will produce greater synchronizing torque tending to produce still further displacement. This involves a shift of the flux relative to the pole and is therefore opposed by the "reaction" torque. Large negative field current means greater synchronizing torque. It also means less "reaction" torque because the voltage, and therefore the flux, is decreased. When equality is reached between these two opposing forces, the synchronizing torque pulls the rotor into the normal synchronous position and reverses the action; i.e., tends to increase the voltage instead of to decrease it.

The other factor which may limit the value of negative field current that can be applied is shown in Fig. 1. The two characteristics intersect at two points; viz., zero and the "stable point." The application of negative field current operates to shift the alternator characteristic to the right, as shown in Fig. 2 (since the voltage induced in the generator by the wattless charging current a is exactly neutralized; i.e., reduced to zero by the equivalent negative field excitation a_1). This causes the two intersections to approach each other, and ultimately they meet; i.e., the line characteristic is tangent to the alternator characteristic at this point. Any further increase in negative field will cause the machine to reverse, since now the alternator characteristic will be entirely below the line characteristic. This point can be predetermined with a fair degree of accuracy if the line and the alternator characteristics are known, because the negative field current a_1 is equal in ampere-turns to a. In this particular case a negative field excitation a_1 would reduce the voltage corresponding to the stable point to E, Fig. 2; i.e., to the neighborhood of normal magnetic densities.

Another interesting possibility is suggested by a study of Fig. 2. If it is required to hold the voltage at a still lower value, say e, it is obvious from Fig. 2 that a negative field current equal to two thirds of a_1 would cause the new displaced alternator characteristic shown in part by the heavy dotted line, to cross the line characteristic at two points; one at voltage e and another at voltage e_1. At e_1 the operation would be stable. At e the line and alternator each require the same current, but the condition is not stable. The least change of voltage, either way, causes a change in current which further augments the voltage change. Yet it may be possible, under favorable conditions, to operate at this point by the use of a voltage regulator. The line voltage might be started by a momentary application of positive field excitation, or by the residual magnetism of the alternator. Then the generator could be quickly thrown to the voltage regulator which would attempt to hold the generator voltage at the value e by applying negative field current. It is of course problematical whether the voltage regulator, working with an exciter, could respond quickly enough.

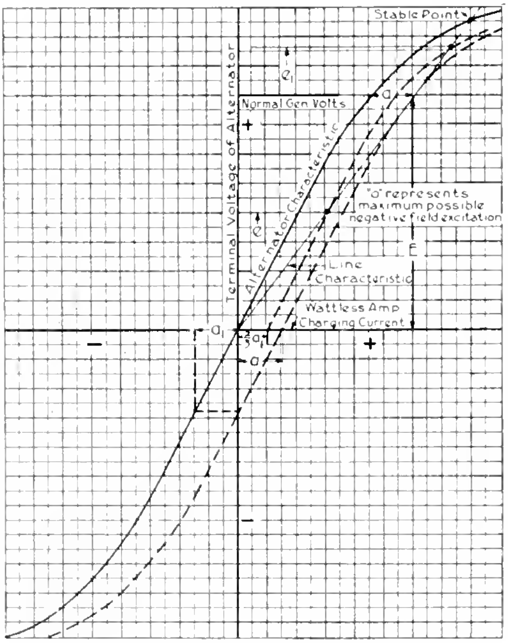

Fig 2. Diagram showing the Effect of Negative Field Excitation

Another important factor to be considered is the voltage at which it is necessary to charge the line; for while the charging kilovolt-amperes required at about normal voltage may not be larger than the generator rating, the line charging conditions may be such as to require a reasonably small kilovolt-ampere output, but at a low voltage and consequently high current; this is necessary in order to give normal voltage at the other end of the line, the voltage rising with the length of the line from the generator. This may be an impossible case to handle with the generator alone, but it may of course be met by the use of some transforming apparatus to obtain the proper ratio of volts to amperes, or by temporarily changing the connection of the generator. These artifices, however, are subject to the obvious limitations of complicated switching and high cost.

A scheme which has already been used for relieving the generator from excessive charging current is the use of shunt reactors across the line, which absorb a portion of the leading charging current. For normal operation of the system, the reactors are switched off the line. In order to avoid severe line disturbances which are incident to switching the reactors on or off the line, the use of saturated core reactors has been suggested. These reactors would be designed with a comparatively high reactance. When the cores are saturated by means of direct-current excitation, the reactance is reduced to a relatively low value, thus permitting a share of the charging current of the line to be absorbed. When the load is switched on the line, the direct-current excitation would be decreased gradually, thus minimizing the voltage fluctuations. Whether this device would be practicable in any particular case would have to be determined by a consideration of its cost and of the advantages to be gained.

Synchronous Motors

By W. T. Berkshire

Alternating-current Engineering Department, General Electric Company

Because it has been the usual practice to install induction motors wherever power was required from an alternating-current circuit, without regard to their collective effect on the power-factor of the circuit, many systems are today operating at low power-factor and consequently low efficiency. The judicious employment of synchronous motors in combination with the induction motors will correct the fault and thereby benefit both the distributing companies and the consumers. For the information of the latter, the following article describes the characteristics and qualifications of the synchronous motor for such applications.—Editor.


W. T Berkshire

THE desirability of using the synchronous motor as a synchronous condenser, and as the motor of a motor-generator set or frequency converter, for neutralizing low power-factor has been recognized for a long time by all users of electric power.

Within recent years, however, considerable impetus has been given to the general application of synchronous motor drive to all classes of industry because of certain advantages it has over other forms of drive. Heretofore, the induction motor has been more generally applied to all classes of industrial drive.

For various classes of service the synchronous motor has several advantages over the induction motor, the recognition of which has resulted in an ever increasing demand for motors of the former type. These advantages consist in better efficiency and power-factor, and, particularly for low-speed machines, lower first cost.

Efficiency

The efficiency of the synchronous motor is generally higher than that of the induction motor even when operating at leading power-factors as low as 0.8. Particularly is this true of the more modern synchronous motors designed for unity power-factor operation whose high efficiency is practically the same from full load to half load and is only slightly lower even at one quarter load.

Power-factor

The synchronous motor can be designed to operate at either unity or any leading power-factor, thus improving the power-factor of the system. With normal field excitation these machines will continue to improve the power-factor when underloaded. In this respect the induction motor is always at a disadvantage; its power-factor is always lagging and although this power-factor may be high at full load it becomes rapidly lower at partial loads; consequently an underloaded induction motor further impairs the power-factor of a system.

Dependability

From the standpoint of dependability of operation, the synchronous motor has a mechanical advantage over the induction motor by reason of its larger air gap which varies from five to eight times that of the induction motor. The operating characteristics of an induction motor may be seriously impaired by a slight change in air gap due to a little wear in the bearings. Due to the larger air gap of the synchronous motor, the same change on account of bearing wear will not materially affect its operating characteristics.

Starting Ability

In making a comparison of the relative starting ability of normally designed squirrel-cage synchronous and induction motors, the following points must be understood:

First: If a motor has a high initial starting torque it must also have a low pull-in torque, and vice versa. The high-resistance squirrel-cage winding, which is required for high initial starting torque, produces low pull-in torque; whereas the low-resistance squirrel-cage winding, which is required for high pull-in torque, produces low initial starting torque.

Second: The induction motor cannot use a high-resistance squirrel-cage winding on account of resulting high losses and low efficiency under normal operation.

Third: The synchronous motor can use a high-resistance squirrel-cage winding because, when operating in synchronism, there is practically no loss in this winding.

Therefore in cases where high initial starting with reasonably low pull-in torque is required, the synchronous motor has the distinct advantage that the high-resistance squirrel-cage winding, with its accompanying high starting torque and low kilovolt-ampere input, can be utilized.

In cases where the required starting and pull-in torques are about equal, but of a comparatively low value, the synchronous motor still has the advantage.

If, however, a high pull-in torque with a correspondingly low starting torque is required, then the induction motor has a slight advantage.

There are a few classes of service requiring both high initial starting and high pull-in torque. In such cases the double squirrel cage or other means is used to obtain the required torque; the double squirrel cage is also used on some of the larger induction motors. The starting of such loads by the synchronous motor, however, is usually attended by high current being drawn from the line. This is often objectionable both from the standpoint of the power company and the power consumer. This starting current can be more readily controlled by the use of the slip-ring induction motor, consequently this type of motor is better for driving loads requiring both high starting and pull-in torque.

Limitations

Owing to certain starting torque or speed requirements, there are three classes of service for which the normally designed synchronous motor is not suitable for direct drive. These are for service requiring the motor to start under full load; service requiring variable speed; and service requiring frequent reversals in the direction of rotation or requiring frequent starting and stopping.

The first class includes flour mills, grain elevators, or heavy line shafting where the torque required to overcome the static friction equals and often exceeds the full-load torque. In such cases the synchronous motor should be directly connected to the shaft through a clutch, thus permitting the starting and synchronizing of the motor before the load is applied.

Where the service requires a variable speed some mechanical means must be provided to obtain such variation.

Application

Synchronous motors have been successfully applied for driving the following:

Motor-generator Sets
Frequency Converters
Air Compressors
Ammonia Compressors
Pulp Grinders
Jordans
Stone Crushers
Centrifugal Pumps
Plunger Pumps
Screw Pumps
Blowers
Fans
Conveyors
Tube Mills
Flour Mills
Rubber Mills
Cement Mills
Line Shafting
Steel and Copper Rolls and
For Operationg and Synchronous Condensers

During the year 1918 alone, the General Electric Company built over 500 synchronous motors for various classes of service, having an aggregate capacity of over 300,000 horse power. This number does not include a large number of synchronous condensers. Of this number over 200 motors, having an aggregate capacity of more than 90,000 horse power, were built for air compressor drive alone.

The study of the synchronous motor, with particular reference to its application to various forms of industrial drive, has resulted in many improvements in design that have increased the efficiency of the starting elements, thus widening the field of application.

Inasmuch as the torque required at starting and pull-in varies with the class of service, whether it be for driving an air or ammonia compressor, pump, crusher, grinder, line-

Fig. 1 [illegible] kv-a. Synchronous Motor Driving Fan Blower

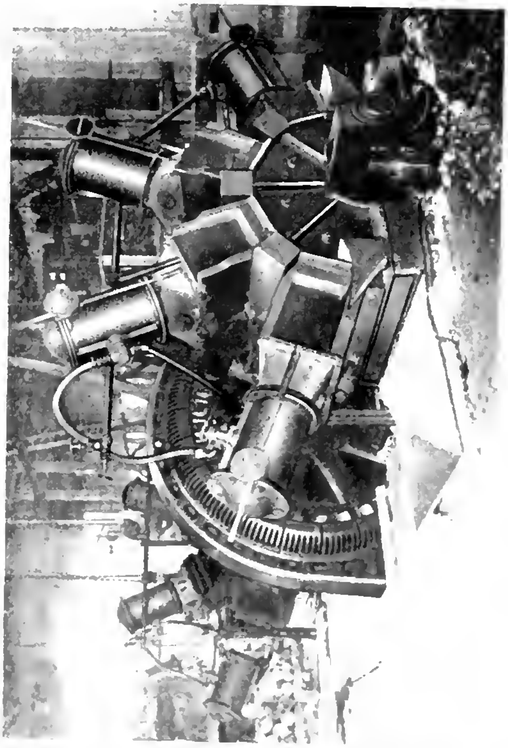

Fig. 2 Two 1200 h.p., 240 r.p.m. Synchronous Motors Driving Pulp Grinders

Fig. 3 600 h.p. Synchronous Motor and Rope Drive

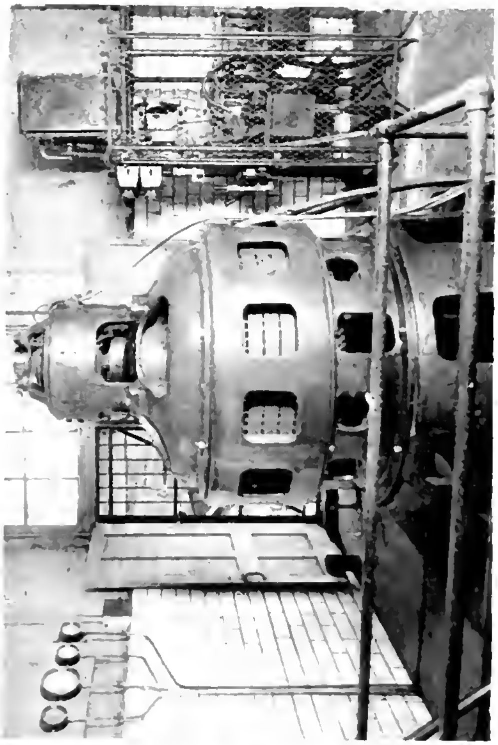

Fig. 4 400 kv-a. Vertical Shaft Synchronous Motor Driving Deep Well Pump shafting, motor-generator, etc. great care is given to the design of each motor in order that these various requirements may be fully met in each particular case.

The squirrel-cage winding, in each case, is very carefully designed, both as to the materials used and their mechanical arrangement, to meet the starting torque requirement for the class of service for which the motor is to be used.

The use of a fractional instead of an integral number of stator slots per pole in the design of synchronous motors eliminates the possibility of dead points during starting. It furthermore insures the maximum obtainable starting torque for every position of the rotor; i.e., the torque will not be low for one position of the rotor and high for another, but will be uniform and a maximum.

Torque

The solid curve in Fig. 5 represents the torque required during the starting of the average synchronous condenser, motor-generator set, or frequency converter. The dotted curve represents the torque developed by a synchronous motor normally designed for this service when starting at reduced voltage from a compensator as an induction motor, i.e., with no excitation on the field. Similarly Fig. 6 shows, by a solid curve, the torque required by an average centrifugal pump or blower during starting, the dotted curve again representing the torque developed by the synchronous motor normally designed particularly for this type of service. The shifting of the maximum torque point of the motor to different positions during starting, as required by the various classes of service, is accomplished by proper design as already described.

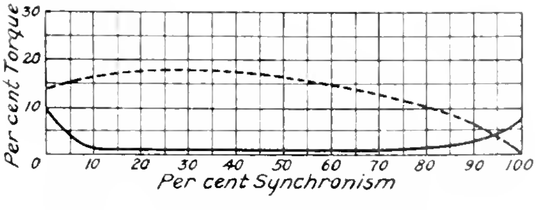

Fig 5 Dotted Curve Represents the Starting Torque of a Synchronous Motor Designed for Starting Torque Service Represented by the Full Curve

Referring again to Figs. 5 and 6, it will be noted that in one case the maximum torque required occurs near the initial start; in the other, it occurs near the synchronous speed. It will be further noted that there is a point where the curve representing the torque developed by the motor crosses that of the required torque. It is at this point that the machine reaches constant speed when operating as an induction motor. This point usually comes at approximately 95 per cent synchronous speed and it is here that the field excitation is applied, the motor thrown from the compensator directly on the line and the load pulled into synchronous speed; i.e., it is at this point that the motor begins to operate as a synchronous instead of an induction machine.

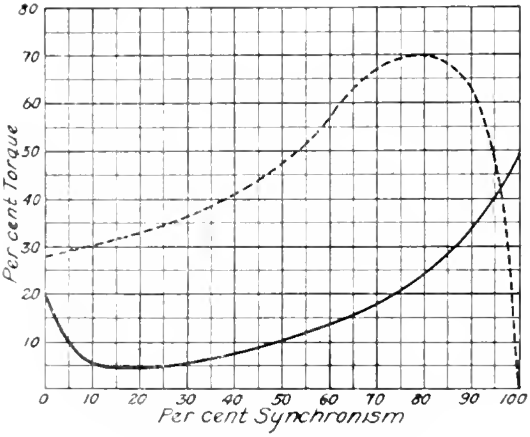

Fig 6. Curves Corresponding to Those in Fig. 5, but Applying to a Load of Different Character

The torque curves shown in Figs. 1 and 2 are representative of those of the various loads to which synchronous motors are direct connected or direct coupled. For properly by-passed air and ammonia compressors, the starting torque varies from 15 to 35 per cent and pull-in torque from 15 to 25 per cent. Some classes of pumps may also have similar starting characteristics. A pulp grinder may require a starting torque varying from 30 to 60 or 70 per cent of normal, the pull-in torque being approximately 15 to 25 per cent. All these starting requirements can be met with normally designed synchronous motors, starting at reduced voltage from a tap on the starting compensator.

For special service, synchronous motors have been built to develop 150 per cent normal torque at start and 75 per cent at pull-in, but such motors are of abnormal design.

Pull-out or Break-down Torque

The "pull-out" torque is an important factor in a synchronous motor. It varies in

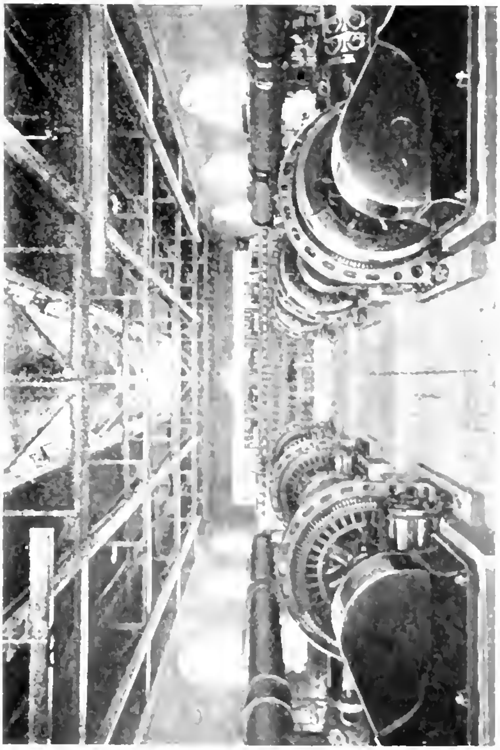

Fig. Eight 300 h.p., 440 volt Synchronous Motors Driving Compressors

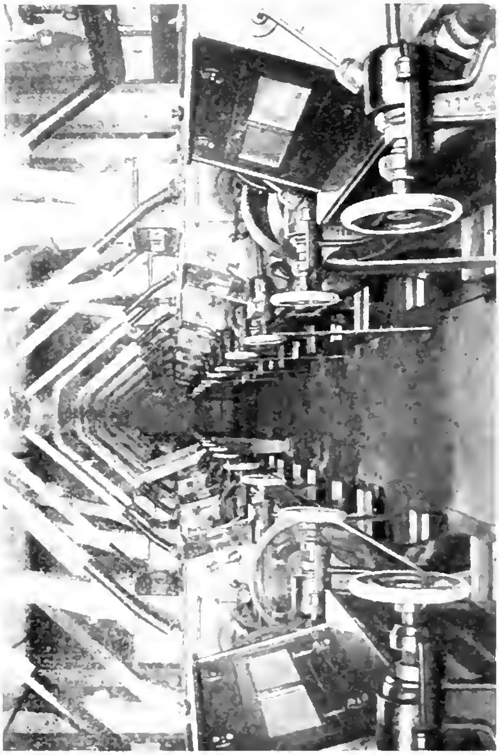

Fig. 8 Rolls Driven by 600 h.p., 2300 volt, 25 cycle Synchronous Motor

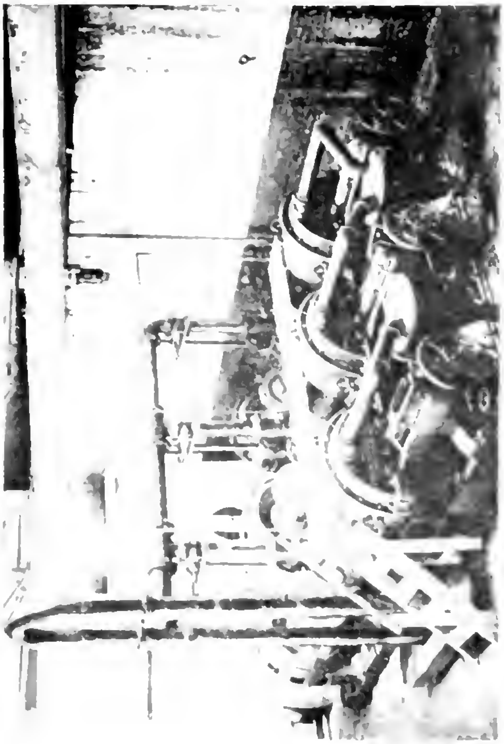

Fig. 9 Three 125 h.p., 900 r.p.m. Synchronous Motors Driving Jordan Engines

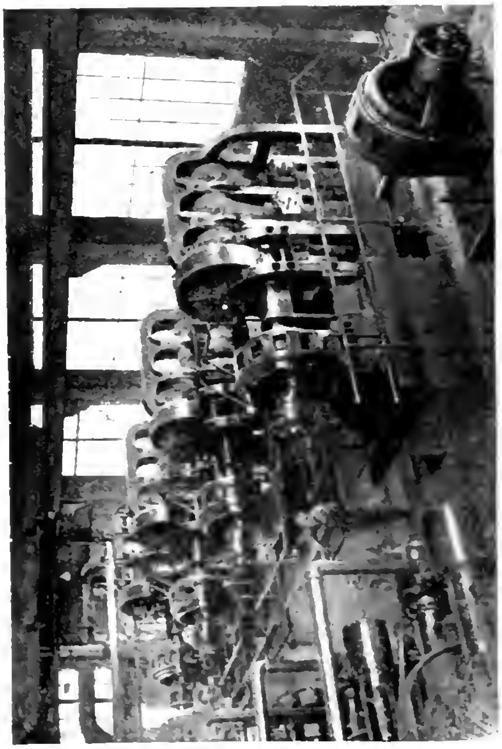

Fig. 10 Four 105 kv-a., 500 r.p.m., 2200 volt Synchronous Motors, with Direct-connected Exciters, Driving Triplex Pumps

different motors, of normal design, from 150 to 300 per cent of normal torque, depending on the particular class of service to which the motors are applied. Statements regarding the pull-out torque developed by a motor based on formula instead of fact may lead into difficulty where high pull-out torque is required. It is important, therefore, that the method of determining this torque should be understood.

This torque can be easily determined from standard test curves. In Fig. 11 are shown the no-load saturation curve and short-circuit characteristics; i.e., the "synchronous impedance" curve of a three-phase synchronous motor. The power delivered by the three-phase motor at "break-down;" i.e., the pull-out capacity at any terminal voltage e and any field current f is approximately

$$P\ max = \frac{\sqrt{3}\ e\ i_o}{1000} \text{ kilowatts}$$

where i_o is the current per armature terminal corresponding to field current f on the synchronous impedance curve. Therefore, the pull-out capacity varies directly as the terminal voltage and also directly as the field excitation.

It follows that at a constant normal terminal voltage E_n and a field excitation F_1 which corresponds to normal armature current I_n on the synchronous impedance curve, the pull-out capacity will be in kilowatts numerically equal to the normal kilovolt-ampere rating.

Hence if F_2 is the full-load excitation, the pull-out capacity for this excitation will be

$$\frac{\sqrt{3}\ E_n\ I_o}{1000} \text{ that is, it is equal to}$$

$$\frac{I_o}{I_n} = \frac{F_2}{F_1} \text{ times normal kv-a. rating.}$$

The short-circuit ratio is $K = \frac{F}{F_1}$ where

F = field current corresponding to normal voltage on the saturation curve and

F_1 = field current corresponding to normal armature current on the synchronous impedance curve.

$F_2 = F_1\sqrt{1+K^2}$ for 1.0 power-factor or

$= F_1\sqrt{1+1.3\ K+1.2\ K^2}$ (approximately) for 0.8 power-factor leading.

Therefore if the short-circuit ratio K is known, the pull-out capacity in kilowatts is approximately equal to the rated kilovolt-amperes multiplied by

$\sqrt{1+K^2}$ for a unity, or 1.0 power-factor motor or by

$\sqrt{1+1.3\ K+1.2\ K^2}$ for a 0.8 power-factor motor.

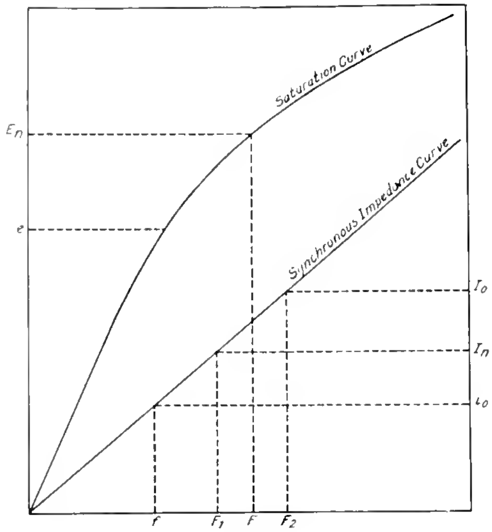

Fig. 11. Saturation and Synchronous Impedance Curves

For example, a 200-kv-a. synchronous motor having a short-circuit ratio of 1.41 would have a pull-out capacity of

$$200 \times \sqrt{1+1.41^2} = 200 \times 1.73 = 347 \text{ kw.}$$

If this were a 200-kv-a. 0.8 p-f. motor its pull-out capacity would be

$$200 \times \sqrt{1+1.3 \times 1.41 + 1.2 \times 1.41^2} = 200 \times 2.29$$

$= 458$ kw. While this method is approximate, its results are sufficiently accurate for checking pull-out torque guarantees.

The following formula, which may also be used in determining the pull-out torque, is slightly more accurate, providing it is correctly applied, but it is more complicated. The pull-out torque in "synchronous watts" is

$$T = 3\left(\frac{\sqrt{E_1^2+E_2^2}}{Z}\right)$$

$$E^2\ cos\left(180^\circ - tan^{-1}\frac{E_1}{E_2} - tan^{-1}\frac{X}{R}\right) \text{where}$$

X = *synchronous* reactance per leg of the armature winding

R = resistance per leg of the armature winding

$Z = \sqrt{R^2+X^2}$ = synchronous impedance

E_1 = applied voltage per leg of the armature winding

E_2 = nominal e.m.f. per leg of the armature winding.

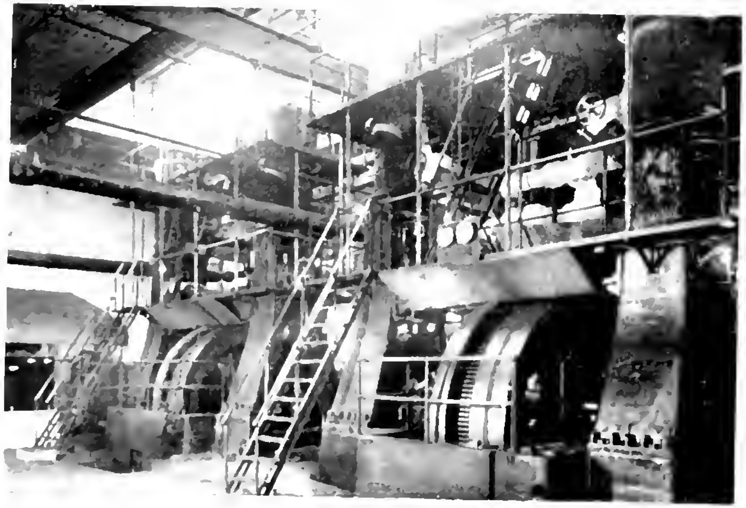

Fig. 12. Two 300 ton Refrigerating Machines Driven by Two 500 kv-a., 6600 volt Synchronous Motors

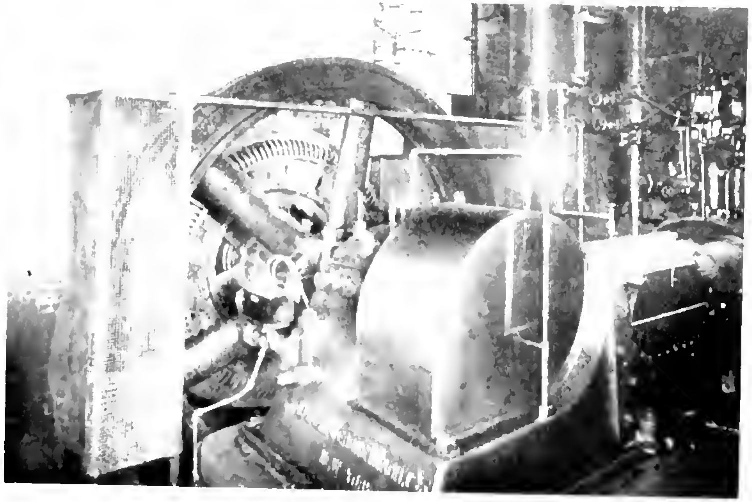

Fig. 13. 150 h.p., 214 r.p.m. Synchronous Motor Driving a 100 ton Ammonia Compressor

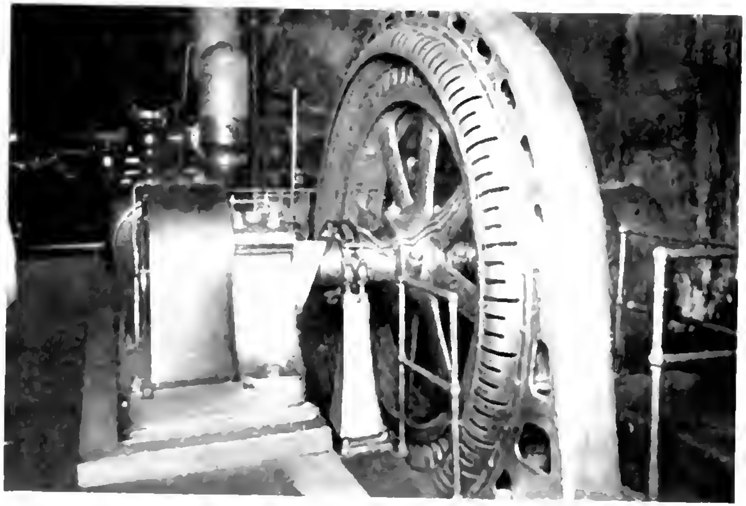

Fig. 14. 300 h.p., 120 r.p.m. Synchronous Motor Driving Reciprocating Pump Underground in a Mine

Fig. 15. Synchronous Motors Driving Air Compressors, U. S. Air Nitrates Corp., Muscle Shoals, Ala.

By an incorrect use of this formula, the self-inductive or *leakage* reactance of the armature may be substituted for the value of X, instead of the *synchronous* reactance, and the pull-out torque may therefore appear to be from 400 to 500 per cent when it really is only from 125 to 150 per cent of normal torque, since the value of the *synchronous* reactance is usually from four to five times that of the *leakage* reactance.

Unnecessarily high pull-out torque is not desirable as it usually impairs other operating characteristics of the motor.

Power-Factor

The disadvantages of low power-factor are generally known to most users of electric power. Low power-factor means unnecessarily large and more expensive generators and exciters with poor efficiency due to increased losses, increased cost of station, transforming and switching equipment, and increased cost of transmission line and distributing transformers. Furthermore, it may mean underloaded prime movers with decreased prime-mover efficiency. It results in poor voltage regulation. Because of these disadvantages, power companies are already beginning to charge higher power rates where the power-factor of the consumer's circuit is lower than a certain limit, consequently low power-factor means increased motor operating costs.

Low power-factor is due to the lagging current drawn from the line by inductive loads such as induction motors, series and multiple arc lamps, or even transformers supplying incandescent lamps.

For any given mechanical load on a synchronous motor the current in the armature is a minimum at a certain field excitation, this current being neither lagging nor leading, and the motor constitutes a unity power-factor load on the line. In this case all the current in the motor is energy current whose function is to drive the load and supply the losses of the motor. Now, if the field excitation is increased the motor will take a leading current from the line. This leading current may be separated into two components: first, an energy component as described, and, second, a magnetizing current; i.e., a current that tends to magnetize the generator fields and is the so-called "wattless leading component." This wattless leading component of the synchronous motor may be used to neutralize an equal amount of wattless lagging component due to induction load on the system. The excitation may be further increased until the motor current consists almost wholly o the wattless leading component; the energy component being only sufficient to supply the losses of the motor, none being available for driving mechanical load. The motor is then operating purely as a synchronous condenser.

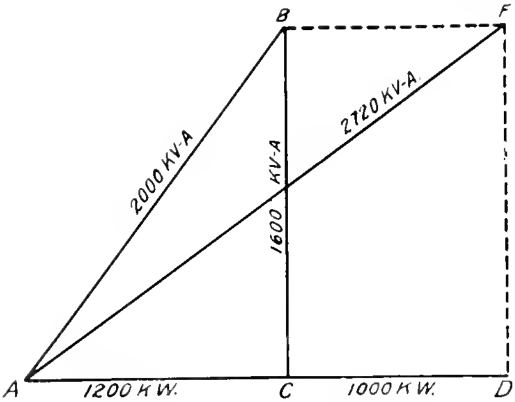

Fig. 16. Diagram showing the Improvement in Power-factor by the Addition of a 1000-kw. Unity Power-factor Motor

Improvement in power-factor can, therefore, be effected by the application of the synchronous machine in either one of three ways:

(*a*) As a unity power-factor motor; i.e., all the input being used for energy.

(*b*) As a power-factor motor; i.e., part of the input being used for energy and part for furnishing wattless leading current to the line.

c) As a synchronous condenser; i.e., all the input being used to supply wattless leading current to the line.

The following are examples of each of these uses:

Assume a load of 1200 kw. at 0.6 p-f. or 2000 kv-a. What will be the effect of adding a 1000-kv-a. synchronous motor to the system (*a*), at unity power-factor; (*b*) at, say, 0.8 power-factor, and (*c*) at zero power-factor, i.e., as a synchronous condenser?

(a) *As a Unity Power-factor Motor*

Referring to Fig. 16, the initial load of 1200 kw. at 0.6 p-f. is represented by the line AC, the kv-a. being $\frac{1200}{0.6} = 2000$ represented by the line AB.

The wattless lagging kilovolt-amperes represented by

$BC = \sqrt{AB^2 - AC^2} = \sqrt{2000^2 - 1200^2} = 1600$ kv-a. Now by adding a 1000-kv-a. 1.0 p-f. load, represented by the line CD, the total load becomes

$$AC+CD=AD \text{ or } 1200+1000=2200.$$

The wattless lagging kilovolt-amperes remain unchanged; i.e., 1600 kv-a. $=BC=DF$. The total kilovolt-amperes required, therefore, to deliver 2200 kw. energy load will be

$$\sqrt{AD^2+DF^2}=\sqrt{2200^2+1600^2}=2720 \text{ kv-a.};$$

and the new power-factor will be $\frac{2200}{2720}=0.81$.

With the addition of this unity power-factor motor it will be noted that two important things are accomplished, viz:

First, the power-factor is raised from 0.6 to 0.81. *Second*, the energy load has been increased from 1200 to 2200 kw., or 83½ per cent, with an increase of only 36 per cent in the generator capacity; i.e., from 2000 to 2720 kv-a.

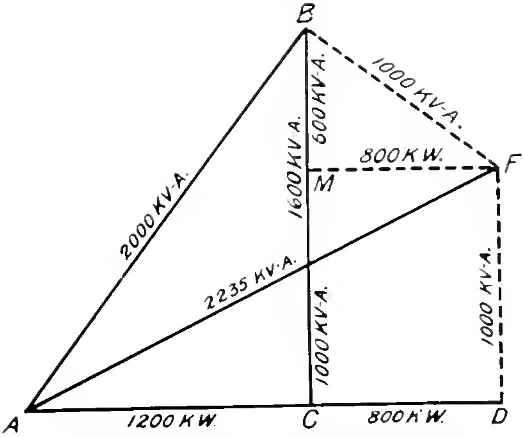

Fig. 17. Diagram showing the Improvement in Power-factor by the Addition of a 1000-kv-a 0.8 Power-factor Motor

(b) As a 0.8 Power-factor Motor

Referring to Fig. 17, the lines AC, AB, and BC represent the initial energy load, total kilovolt-amperes, and wattless lagging kilovolt-amperes respectively the same as in Fig. 16. A 1000-kv-a., 0.8 p-f. motor is now to be added to the system. This motor will deliver $1000\times0.8=800$ kw. energy load represented by the line $MF=CD$. It will also deliver a wattless leading kilovolt-ampere equal to

$$BM=\sqrt{BF^2-MF^2}=\sqrt{1000^2-800^2}=600.$$

This 600 wattless leading kilovolt-ampere will neutralize an equal amount of the 1600 wattless lagging kilovolt-amperes so that the wattless lagging kilovolt-amperes after the motor is added will be

$$DF=BC-BM=1600-600=1000 \text{ kv-a.}$$

The energy load will then be

$$AD=AC+CD=1200+800=2000 \text{ kw.};$$

the wattless lagging kilovolt-amperes $=1000$; and the total kilovolt-amperes required to carry this load will be

$$AF=\sqrt{AD^2+DF^2}=\sqrt{2000^2+1000^2}=2235 \text{ kv-a.}$$

The new power-factor, after the motor is added, will then be $\frac{2000}{2235}=0.895$ instead of 0.6.

It will be noted also that the energy load has been increased 66⅔ per cent with an increase of only 11¾ per cent in the generator capacity.

(c) As a Zero Power-factor Motor; i.e., a Synchronous Condenser

In this case the problem is: How much will the power-factor of the system be increased by the addition of a 1000-kv-a. synchronous condenser, it being the intention to keep the same energy load? Fig. 18, as Fig. 16 and 17, again shows the initial energy load, total kilovolt-amperes, and wattless lagging kilovolt-amperes by the lines AC, AB, and BC. The 1000-kv-a. synchronous condenser (neglecting the energy required to supply its losses which may be only 3 or 4 per cent) will supply 1000 wattless leading kilovolt-amperes $=BM$. The total wattless lagging kilovolt-amperes will then become $BC-BM=CM$ or $1600-1000=600$ kv-a. and the total kilovolt-amperes required to carry the same load will become

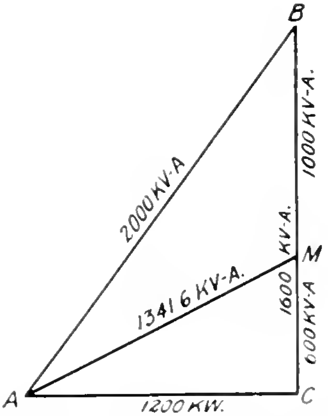

Fig 18. Diagram showing the Improvement in Power-factor by the Addition of a Zero Power-factor Motor or Synchronous Condenser

$$\sqrt{AB^2+CM^2}=AM \text{ or } \sqrt{1200^2+600^2}=1341.6 \text{ kv-a.}$$

The new power-factor will then be $\frac{1200}{1341.6}$ $=0.895$

Not only is the power-factor increased from 0.6 to 0.895, but it will be noted that, by the addition of this synchronous condenser, a generator of only about two thirds the former capacity is required to carry the energy load with a corresponding reduction in the capacity of all transforming and switching equipment, transmission lines, and exciters.

Unity Power-factor (1.0 p-f.) Synchronous Motor

Particular attention is drawn to the fact that the highest efficiency, in the driving of mechanical loads, can be obtained by the use of the unity power-factor motor. It requires less exciter capacity and has a considerably lower cost than a synchronous motor designed to operate at leading power-factors. Such a motor, of course, constitutes a non-inductive load on the line (i.e., it does not furnish any wattless leading kilovolt-amperes when operating at full load), but as shown in Fig. 16, it does improve the power-factor of the system to a considerable extent. If, however, it is under-loaded, with full-load excitation on the field, it always operates at a leading power-factor furnishing a certain amount of wattless leading kilovolt-amperes to the line depending on the degree of under loading. Fig. 19 shows the leading power-factor at which a normally designed unity power-factor synchronous motor will operate at partial loads with the normal full-load field excitation constantly maintained. It will be noted that at 50 per cent of the normal kilovolt-amperes input the machine will operate at 0.73 p-f. leading, and at about 33 per cent normal kilovolt-amperes input it will operate at zero power-factor; i.e., purely as a synchronous condenser. In the average motor this value of kilovolt-amperes input at zero power-factor will vary from 20 to 33 per cent.

Flywheel Effect

Synchronous motors driving air or ammonia compressors or other reciprocating apparatus embody, in the most essential respects, the same factors as engine-driven generators, so far as synchronous operation is concerned. Whether a synchronous machine is operating as a generator or motor, it behaves in the same manner as regards stability. That is, if its rotor is pushed or pulled away from the stable position in rotation—whether this be at no load or full load—there is a force opposing such displacement that is practically proportional to the displacement. Hence, if a variable torque is imposed upon the shaft, either positive or negative; i.e., either generator or motor operation, there will exist the tendency toward instability.

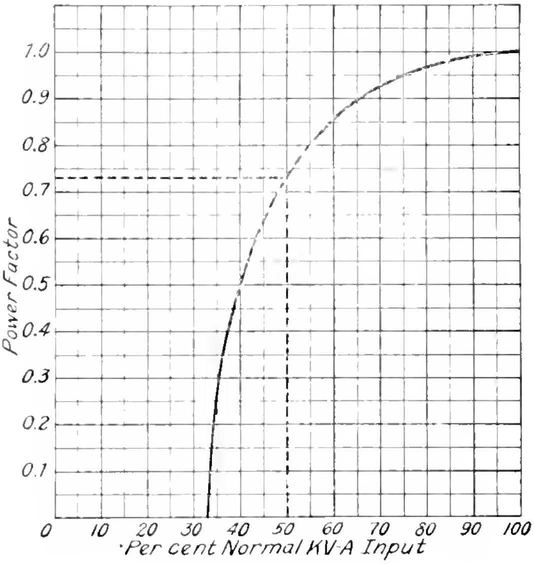

Fig. 19. Curve showing the Leading Power-factor at Which a Normally Designed Unity Power-factor Motor Will Operate at Partial Load with Normal Full-load Field Excitation

Now, the air or ammonia compressor is a reciprocating machine of relatively large mass, and therefore has a turning effort curve which in a general way resembles that of reciprocating engines. The variations are periodic and of sufficient magnitude to cause the motor to oscillate if proper precautions are not taken.

The precautions consist in the use of flywheel weight sufficient to limit the periodic angular deviation to 3½ electrical degrees, in either direction from the position of uniform rotation, and to fix the natural oscillating frequency at a safe distance from the frequency of the forced impulses of the compressor. The two most important impulses have frequencies equal to the revolutions and to the strokes of the compressor and it is considered desirable to keep the natural frequency of the motor away from the revolutions or strokes by 20 per cent.*

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* A complete discussion of this phase of the subject is given in the article, "Oscillating Frequency of Two Dissimilar Synchronous Machines," by R. E. Doherty, in this issue.

Magnetomotive-force Diagram of the Synchronous Motor

By E. S. Henningsen

Alternating-current Engineering Department, General Electric Company

The author shows that the magnetomotive-force diagram of the synchronous motor can be used to quickly determine, with a sufficient degree of accuracy for most cases, the operating characteristics of a given machine; for instance, the excitation required for any load, the phase characteristic curves, the pull-out torque and the wattless component for any excitation. The light errors in the method are due to the fact that the saturation curve is assumed to be a straight line. A concrete case is assumed as an example, and the method of applying the diagram to the determination of the several characteristics is worked out for illustration.—Editor.

E. S. Henningsen

All of the operating characteristics of a synchronous motor that can be determined from the complete excitation calculation can also be determined with reasonable accuracy, and in a fraction of the time, from the magnetomotive-force diagram. That is, knowing the field excitation required for normal voltage open circuit and that for normal current on short circuit, we can at once determine approximately the excitation required for any load, the phase characteristic curves, the break out capacity, and the wattless kilovolt-amperes for any excitation by combining these values in the proper phase relation. The method is of course not exact, since it assumes that the saturation curve is a straight line. Its inaccuracy therefore varies on different machines depending upon the reactance and degree of saturation. However, the magnetomotive-force diagram is a very useful tool because of the ease and speed with which the various characteristics can be obtained.

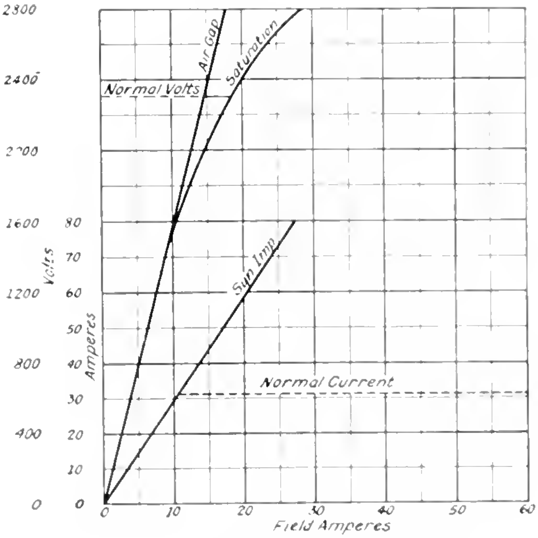

Fig. 1. Saturation and Synchronous Impedance Curves

Armature Reaction = 1790 ampere turns
Armature Reactance = 17.2 per cent
Armature Resistance = 1.0 per cent
Field Turns = 220

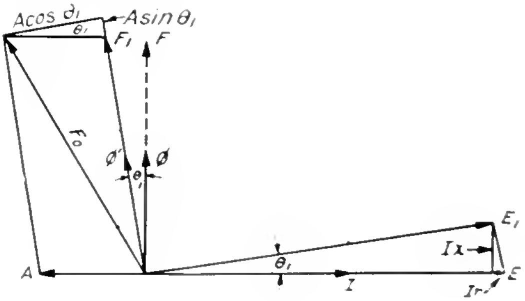

Fig. 2. Excitation Diagram, Unity Power-factor

For example, consider the field excitation required at unity and also at 0.8 p.-f. leading by a 125-kv-a. motor, the saturation and synchronous impedance curves of which are given in Fig. 1. This also gives the reactance, armature reaction and resistance, and field turns so that the complete excitation diagram as well as the magnetomotive-force diagram may be constructed.

Fig. 2 shows the excitation diagram for unity power-factor. The line current is I, the terminal voltage E, the internal induced voltage E, and the angle between I and E_1 is ϕ_1. From inspection $E_1=(E-Ir)+jIx$ where Ir is the resistance drop and Ix the self-inductive reactance drop through the armature windings. To produce the terminal voltage E requires a flux ϕ and a field excitation F. The internal voltage E_1 requires a flux ϕ, and field excitation F_1. This field excitation (F_1) can be obtained from the saturation curve corresponding to the voltage E_1. The armature reaction ampere-turns is A. Hence the full-load excitation $F_0 = (A\ cos\ \theta_1)$ $+j\ (F_1 + A\ sinc_1)$. Calculating F_0 from the data given in Fig. 1 gives 4750 ampere-turns.

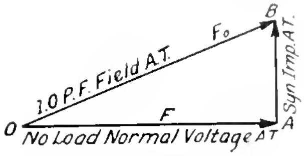

Fig 3 Magnetomotive-force Diagram, Unity Power-factor

Fig. 3 shows the magnetomotive-force diagram for unity power-factor load. Since increased saturation under load is to be neglected in the magnetomotive-force diagram, it is not necessary to separate the synchronous impedance into armature self-inductive reactance (which is treated as a voltage in the excitation diagram) and armature reaction. The field excitation required for normal voltage open circuit is OA, the field excitation for normal current from the synchronous impedance test is AB, and the field excitation for full load is OB. Constructing the diagram from the data given in Fig. 1 shows OB to be 4740 ampere-turns or practically the same as the excitation calculation. This is to be expected of course because the increase in saturation under load is slight for unity power-factor and the magnetomotive-force diagram differs from the excitation diagram only in the neglect of this factor.

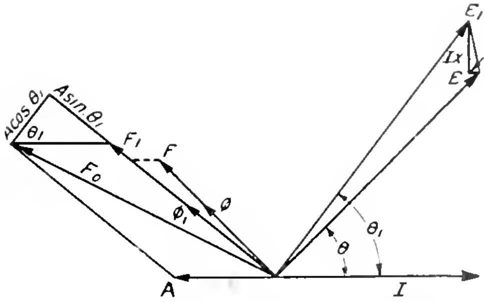

Fig 4. Excitation Diagram, Power-factor = Cos θ

Fig. 4 shows the excitation diagram for normal kilovolt-amperes at a power-factor of $cos\ \theta$. The vectors are the same as in Fig. 2, except that the terminal voltage E is ahead of the line current I by the angle θ. Calculating F_0 for $cos\ \theta = 0.8$ gives the load excitation as 6240 ampere-turns. Fig. 5 gives the magnetomotive-force diagram for the same condition, AB. The synchronous impedance ampere-turns, AB, has the same value as in Fig. 3, but is of course displaced from its unity power-factor position in Fig. 2 by the angle $cos^{-1} = 0.8$. Solving the triangle of Fig. 5 by graphical construction, using the values from Fig. 1, gives $F_0 = 5840$ ampere-turns or about seven per cent less than by the excitation calculation. For normal kilovolt-amperes zero power-factor, the excitation required is 6940 ampere-turns by the excitation diagram and 6450 ampere-turns by the magnetomotive-force diagram. A very close approximation can therefore be obtained if, when constructing the magnetomotive-force diagram for leading power-factors, the ampere-turns required for normal voltage no load are increased from 10 to 15 per cent to allow for increased saturation.

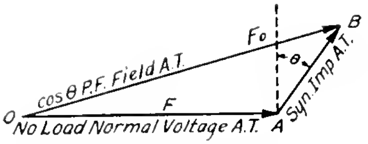

Fig 5 Magnetomotive-force Diagram, Power-factor = Cos θ

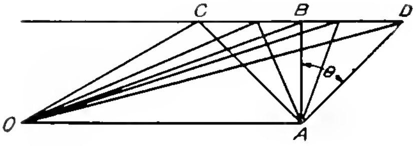

Fig 6 Magnetomotive-force Diagram for Load Phase Characteristics

To obtain the phase characteristic curves of a synchronous motor, it is only necessary to construct a magnetomotive-force diagram such as is shown in Fig. 6. The field excitation required for no-load normal voltage from the saturation curve is OA. The synchronous impedance ampere-turns corresponding to the line current at unity power-factor is AB for the load considered. The required field excitation is then OB. At any other value of field current such as OC the line current is AC/AB times the current corresponding to AB. Values of field less than OB mean an underexcited motor, therefore lagging armature current, and values greater than OB, leading current.

Fig. 6 also gives values of wattless kilovolt-amperes available for power-factor correction. For instance, suppose AB represents the synchronous impedance ampere-turns for normal load unity power-factor armature current, and that the field excitation on the motor is OD. There will then be a leading wattless current in the armature equal to DB/AB times normal. Or looked at another way, if OD is the total field excitation, and OA the field excitation corresponding to no-load normal voltage, the resultant AD must be balanced by a current in the armature large enough to require the field excitation AD to force it through the synchronous impedance. Hence, by finding the armature current corresponding to the field excitation AD on the synchronous impedance curve, and measuring the angle θ, cosine of which is the power-factor, the wattless kilovolt-amperes can be determined.

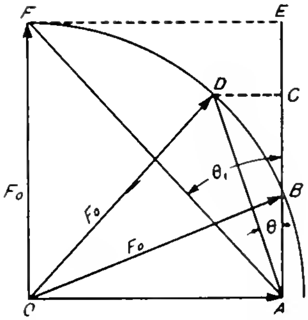

Fig. 7. Magnetomotive-force Diagram, Constant Field Excitation, Increasing Load

There are several methods of determing the break-out capacity of a synchronous motor; i.e., the load at which the motor will break out of synchronism. There is but a single principle however; viz., that a synchronous motor drops out of step when the watt-component of the synchronous impedance ampere-turns equals the ampere-turns on the field. Neglecting saturation, the break-out capacity varies directly with the field excitation. Fig. 7 shows the magnetomotive-force diagram, assuming constant excitation and varying load until the break-out point is reached. The full-load unity power-factor diagram is OAB identical with Fig. 3. If we assume the field excitation to be constant, F_0 must for any load terminate in the arc FDB of radius OB. Suppose the watt load to be doubled. Then the watt-component of the synchronous impedance ampere-turns, which was AB for normal load, becomes $AC = 2\,AB$ for double load. Since F_0 is constant there must be a wattless component of current corresponding to DC, or the magnetomotive-force diagram becomes OAD and the power-factor $\cos\ \theta$. Since by inspection, OD, the field ampere-turns is greater than AC, the watt-component of the synchronous impedance ampere-turns, the motor will still stay in step according to the principle stated above. If now the watt load is still further increased until the watt component of the synchronous impedance ampere-turns equals AE, the motor will break-out of step, because at this point AE equals the field excitation OF. The power-factor at break-out is $\cos\ \theta$, lagging, and the wattless component of armature current is proportional to EF. The value of load in kilowatts at which break-out occurs is AE/AB times normal load. The motor kilovolt-amperes at break-out is the kilowatts break-out load divided by $\cos\ \theta$. Applying this diagram to the motor previously considered gives the break-out capacity to be 250 kw. and the power-factor 0.76 lagging.

Oscillating Frequency of Two Dissimilar Synchronous Machines

By R. E. Doherty

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In operating two or more alternating-current generators driven by reciprocating engines it is important to avoid a condition that will produce "hunting," or a periodic oscillation of the revolving elements ahead of and behind the normal position. In cases where the natural oscillating frequency of the alternator is near the periodic variation in the torque of the driving engine, hunting may occur in such proportion as to throw the generators out of phase, or produce violent flickering of lamps or other trouble on the circuit. In a previous article published in this magazine the author discusses parallel operation of similar alternators with respect to hunting, and in the present article extends the discussion to parallel operation of two dissimilar alternators.—Editor.

R. E. Doherty

The natural oscillating frequency of a synchronous machine is like the oscillating frequency of a pendulum, or of a weight suspended by a spring, in this respect: if the rotor of the machine is momentarily displaced from its stable position[*] in space, it will oscillate at a definite frequency just as the pendulum or suspended weight. Within the range of ordinary loads, the synchronizing force acts upon the displaced rotor in the same way that gravity acts upon the pendulum, or that the stretched spring acts upon the weight. In the synchronous machine the "stretch" occurs in the magnetic field.

The natural oscillating frequency is an important factor in parallel operation where the synchronous machine is coupled to reciprocating apparatus. The periodic variations in the torque of such apparatus may cause "hunting," or oscillation, if the natural oscillating frequency happens to be nearly the same as the frequency of the torque variation. It is important, therefore, to prevent coincidence, or even proximity of these frequencies. This is done by choosing the proper flywheel effect. The formula[†] for calculating the oscillating frequency is

$$F = \frac{35{,}200}{N}\sqrt{\frac{P_o f}{WR^2}}$$

F = oscillations per minute
N = r.p.m.
f = electrical frequency, cycles per second
P_o = factor depending upon the synchronizing force
WR^2 = flywheel effect in lb. ft.^{2}

This formula, however, applies only to a single machine operating on a relatively large system, or to two duplicate machines alone in parallel. In this article equations are developed for the case of two dissimilar machines in parallel.

The principle underlying the theory of this case, as well as the previous one, is that the rotor field poles are locked to the rotating stator poles through the elastic medium of the magnetic field. It will be shown that if the rotor is displaced from its stable rotative position, it experiences a torque which is *proportional*[‡] *and opposite to the displacement.* This is the definition of harmonic motion—the motion of an oscillating weight or pendulum—hence the well known expression given in equation (1) for the period of harmonic motion can be applied.

It is necessary to inquire why in this case, as well as in the case of a single alternator connected to a large system, or of two duplicate alternators in parallel, the restoring force or the strain of the magnetic field is proportional to the displacement from the stable position; also why the two machines must oscillate at the same frequency. With these points established, the frequency of oscillation of either, and therefore of the system, easily follows.

Consider the spring-weight analogy. In Fig. 1 the weights or masses[**] M are suspended by very long cords so that the effect of gravity is eliminated and thus the only accelerating force is the spring tension, which in the analogy corresponds to the synchronizing force of an alternator. In Case A, Fig. 1, which corresponds to two duplicate alternators, if an oscillation is set up between the masses, it is obvious that the arrow a, attached to the

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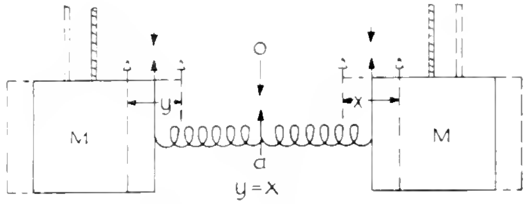
[*] The "stable position" is that position in rotation where the load torque on the shaft is just equal to the electrical torque exerted on the rotor, consequently where there is no acceleration.

[†] "Parallel Operation of Alternating-current Generators Driven by Internal Combustion Engines; Factors Affecting Generator Design," by R. E. Doherty, General Electric Review, March, 1915, Equation (14).

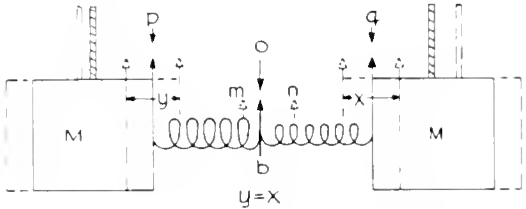
[‡] This proportionality does not hold for large displacement angles, just as it does not for large amplitudes in pendulum oscillation, but is practically correct for the angles involved in this problem.

[**] $\text{Mass} = \frac{\text{weight}}{\text{gravity}} = \frac{\text{weight}}{32.2}$.

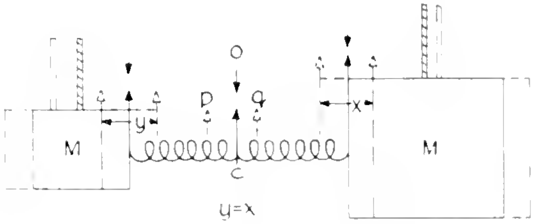
midpoint of the spring, or rather at the joint of the two equal springs, will be stationary. That is, the case is the same as if the point *a* were fixed; which would also represent the condition of a single alternator connected to an infinitely large system. In other words, the natural oscillating frequency of an alternator when operating in parallel with a duplicate machine is the same as when operating on a relatively large system. Obviously in Case *A* the restoring force, i.e. the spring tension, is by Hooke's Law proportional to the displacement of the weight and therefore the motion is harmonic.



Case A, equal weights, equal springs



Case B, equal weights, unequal springs



Case C, equal springs, unequal weights

Fig. 1. Three Diagrams Which Represent Two Weights or Masses Connected by Two Springs, and Which Are Analogous to Two Alternators in Parallel. The amplitudes of oscillation are indicated by *x* and *y*

In Case *B*, Fig. 1, two equal masses are connected by unequal springs. This corresponds to two alternators with equal moments of inertia, but unequal synchronizing forces. But two different springs in series can be replaced by an equivalent single spring, which would cause the two masses to oscillate in the same manner and through the same amplitude *x* and *y* as if they were connected by the two different springs. The only difference is that with the single spring the midpoint of the spring would be stationary; with the two, the arrow *b* would oscillate between *m* and *n*. This corresponds to the phase shift in the line voltage generated by the oscillating alternators. However, the accelerating force on each mass, i.e. the spring tension, is of course the same at all instants, and is proportional to the total stretch of the two springs in series. This in turn is equal to the sum of the displacement of the two masses from the positions of zero spring tension. Therefore if, as shown, the amplitudes *x* and *y* are equal and the force is proportional to *x* plus *y*, the force on either mass is also proportional to the displacement of that mass and the motion is harmonic.

Case *C*, showing unequal masses connected by equal springs, represents two alternators with unequal moments of inertia, but with equal synchronizing forces. Here also the force on each mass is the same at all instants, being the tension of the spring, and is proportional as in Case *B* to the total stretch of the springs. The motion of the masses is therefore harmonic. The arrow *c*, representing the terminal voltage, will obviously oscillate between the limits *p* and *q*, since with the same force acting on them the large mass will oscillate through a less amplitude than the small mass.

The foregoing considerations show that the oscillations of any such combination of two masses and two springs in series will be harmonic. It follows also that the frequencies of the two masses are the same; because if the accelerating force is the same on each mass at all instants, the momentum (mass × velocity = force × time = $\int f\,dt$) also must be the same for each at all instants. This means that the velocities are inversely as the masses, i.e., the ratio of the velocities is constant. Hence, when the velocity of one is maximum, the other will be also; when the velocity of one is zero, the velocity of the other will be zero, and so on. Thus by the spring-weight analogy, which is complete within practical limits, it is established that in two alternators of different capacities, i.e., different synchronizing forces, and of different moments of inertia, *the acceleration, velocity, and displacement of each rotor during oscillation is a harmonic function of time, and the oscillating frequency of each machine is the same.*

The following well known formula for the period of harmonic motion can therefore be used:

$$T = 2\pi\sqrt{\frac{I}{\sigma}} \text{ seconds} \qquad (1)$$

where, for linear motion

I = mass of oscillating body
σ = ratio of force to displacement = lb. force per foot displacement.

For rotation

I = moment of inertia
σ = lb-ft. torque per radian displacement.

The natural frequency is

$$F = \frac{60}{T} = 9.57\sqrt{\frac{\sigma}{I}} \text{ oscillations per minute.} \qquad (2)$$

The problem is to determine the value of σ and I for two alternators which are dissimilar in respect to speed, synchronizing force and moment of inertia. In relating the several factors involved, the ultimate reference for the determination of displacement will be taken as the "stable position" in rotation.

Consider the effect of different synchronous speeds. The power (involved in oscillation) which is given up by machine *A* as a generator is equal, neglecting losses, to the power consumed by machine *B* as a motor, the energy transfer causing *A* to decelerate and *B* to accelerate. The power being the same, it follows that the accelerating or decelerating torque produced thereby is inversely as the synchronous speed, hence directly as the number of poles. Therefore instead of the momentums of the two rotors being equal at all instants, which is true for machines of an equal number of poles, there is in this case a constant *ratio* of momentums. This ratio is obviously the inverse ratio of the synchronous speeds, or the direct ratio of the number of poles. There is, therefore, also a constant ratio of velocities and displacements.*

These relations may now be put in equations.

Let

θ_a = mechanical displacement angle of machine *A* at power p, measured in radians from the "stable position." See Fig. 2.
θ_b = corresponding simultaneous angle for machine *B*.
$\theta = \theta_a + \theta_b$
$n_2 = \dfrac{q_a}{q_b} = \dfrac{\text{poles on } A}{\text{poles on } B}$
$n_1 = \dfrac{I_a}{I_b} = \dfrac{\text{moment of inertia of } A}{\text{moment of inertia of } B}$

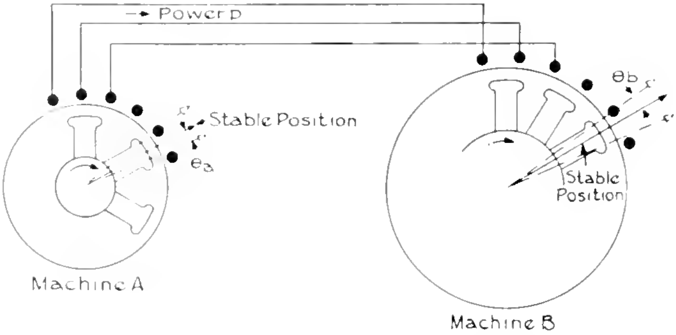


Fig 2 Diagram of Two Machines Having a Different Number of Poles. The dotted arrows indicate the limits of oscillation about the "stable position." The diagram shows the instant when *A* is ahead and *B* is behind the stable position; hence power flows from *A* to *B*

ϕ_a = phase angle, in electrical radians, between the mechanical and magnetic pole centers, i.e., the distortion angle of *A* corresponding to the power p (in kw.)
ϕ_b = corresponding simultaneous angle of *B*
$\phi = \phi_a + \phi_b$
ω_a = angular velocity (of oscillation) of *A*
ω_b = corresponding simultaneous velocity of *B*
P_{oa} = power in kilowatts of *A* corresponding to a distortion angle of one electric radian, i.e. ϕ_a = unity
P_{ob} = corresponding power for *B*
$n_p = \dfrac{P_{oa}}{P_{ob}}$
σ_a = lb-ft. torque, exerted on *A*'s rotor, per mechanical radian displacement, i.e., the ratio of torque to θ_a
σ_b = corresponding ratio for *B*
t = torque in lb-ft.
S_a = r.p.m. of *A*
S_b = r.p.m. of *B*
F = natural oscillating frequency in periods per minute
f = electrical frequency in cycles per second
g = gravity = 32.2 ft. per second^2
WR^2 = flywheel effect in lb-ft.$^2 = gI$

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*This refers to the velocities and displacement involved in the oscillation, not to the velocity and displacement of normal rotation.

The momentum of *A*, due to the velocity of oscillation, is

$$\omega_a I_a$$

Of *B*, it is

$$\omega_b I_b$$

The ratio of momentums is the ratio of the number of poles. Hence,

$$n_q = \frac{\omega_a I_a}{\omega_b I_b} = \frac{\omega_a}{\omega_b} n_I$$

Therefore,

$$\omega_a = \frac{n_q}{n_I} \omega_b \qquad (3)$$

Thus if *A's* angular velocity is always $n_q \div n_I$ times *B's*, then *A's* displacement will always be $n_q \div n_I$ times *B's*. Thus, considering both angles positive,

$$\theta_a = \frac{n_q}{n_I} \theta_b \qquad (4)$$

$$\theta_a + \theta_b = \theta = \theta_a \left(1 + \frac{n_I}{n_q} \right) \qquad (5)$$

It is now necessary to relate θ and ϕ. Both represent the distortion angle, i.e., the "stretch" in the magnetic field. They are different in two respects: θ_a or θ_b is expressed in mechanical radians, and measures phase displacement of the rotor pole from its "stable position;" whereas ϕ_a or ϕ_b is expressed in electrical radians,* and measures the phase displacement of the rotor pole from the magnetic pole, i.e., the time phase from the line voltage. The stable position may or may not correspond to the time phase of the line voltage; in other words, the zero reference for θ_a and ϕ_a may or may not be identical, depending upon whether the line voltage itself oscillates. In Fig. 1, it has been shown under what conditions the line voltage, represented by arrows *a*, *b* and *c* oscillates. For two two-pole similar machines, obviously

$$\theta_a = \phi_a$$

and

$$\theta_a + \theta_b = \theta = \phi_a + \phi_b = \phi$$

because electrical and mechanical angles are identical, and the line voltage does not oscillate. However, if the machines have different moments of inertia or different synchronizing forces, then θ_a and ϕ_a are no longer equal; but it is of course still true that for the same number of poles

$$\theta = \phi$$

because each measures the *total* distortion or "stretch" of the magnetic fields of the two machines. This relation obviously holds also for different numbers of poles provided the electrical angles ϕ_a and ϕ_b are reduced to mechanical angles. Thus

$$\phi' = \theta$$

where

$$\phi' = \frac{2}{q_a} \phi_a + \frac{2}{q_b} \phi_b$$

That is

$$\theta = 2 \left(\frac{\phi_a}{q_a} + \frac{\phi_b}{q_b} \right) \qquad (6)$$

The next step is to relate θ and the corresponding force. P_{oa} is the power which would be delivered by *A* at unit angular displacement ahead of the line voltage; or received at unit angular displacement behind the line voltage. Hence the power on *A* at any angle ϕ_a is

$$p_a = \phi_a P_{oa}$$

Likewise the power on *B* is

$$p_b = \phi_b P_{ob}$$

But p_a and p_b are identical during oscillation. That is, taking directions consistent with the assumption in equation (4),

$$p_a = p_b = p$$

whence

$$\phi_a = \frac{p}{P_{oa}} \qquad (7)$$

and

$$\phi_b = \frac{p}{P_{ob}} \qquad (8)$$

Substituting (7) and (8) in (6)

$$\theta = 2\, p \left(\frac{1}{q_a P_{oa}} + \frac{1}{q_b P_{ob}} \right)$$

or,

$$\theta = \frac{2\, p}{q_a P_{oa}} (1 + n_q n_p) \qquad (9)$$

Equating (5) and (9)

$$\theta_a \left(1 + \frac{n_I}{n_q} \right) = \frac{2\, p}{q_a P_{oa}} (1 + n_q n_p)$$

Hence, the power exchange per unit displacement of *A* from its stable position is

$$\frac{p}{\theta_a} = \frac{q_a P_{oa}}{2} = \frac{\left(1 + \frac{n_I}{n_q} \right)}{1 + n_q n_p} \qquad (10)$$

The general relation between power and torque is

$$2\pi St = \text{power} \qquad (11)$$

where

S = r.p.m.
t = torque in lb. ft.

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*That is, mechanical radians multiplied by one half the number of poles.

and power is in ft-lb. per minute. To express the power in kilowatts, (11) becomes

$$\frac{33,000}{0.746}p = 2\pi\ St$$

and

$$t = 7040\frac{p}{S}\text{ in lb. ft.} \qquad (12)$$

Solving for p and substituting in (10), the torque per mechanical radian displacement becomes,

$$\sigma_a = \frac{7040}{S_a}\frac{q_a}{2}P_{oa}\frac{\left(1+\frac{n_I}{n_q}\right)}{(1+n_q\,n_p)}$$

But,

$$q_a = 120\frac{f}{S_a}$$

Hence,

$$\delta_a = \frac{422,400}{S^2_a}f\,P_{oa}\frac{\left(1+\frac{n_I}{n_q}\right)}{(1+n_q\,n_p)} \qquad (13)$$

The moment of inertia of A is

$$I_a = \frac{WR^2_a}{g} = \frac{WR^2_a}{32.2} \qquad (14)$$

Substituting (12) and (13) in (2), the final equation for the natural oscillating frequency of A, and therefore of B, expressed in periods per minute is,

$$F = \frac{35,200}{S_a}\sqrt{\frac{P_{oa}\,f}{WR^2_a}\frac{\left(1+\frac{n_I}{n_q}\right)}{(1+n_q\,n_p)}} \qquad (15)$$

Example:

Machine A

400 kv-a., 150 r.p.m. 60 cycles
WR^2 generator = 90,000
WR^2 flywheel = 254,000
Total WR^2_a = 344,000
P_{oa} = 1000 kw.
S_a = 150 r.p.m.
f = 60 cycles

Machine B

200 kv-a., 720 r.p.m., 60 cycles
WR^2 generator = total WR^2 = 2765
P_{ob} = 410 kw.
f = 60 cycles
S_b = 720 r.p.m.

$$n_I = \frac{WR^2_a}{WR^2_b} = \frac{344,000}{2765} = 124$$

$$n_p = \frac{P_{oa}}{P_{ob}} = \frac{1000}{410} = 2.44$$

$$n_q = \frac{q_a}{q_b} = \frac{48}{10} = 4.8$$

$$F = \frac{35,200}{150}\sqrt{\frac{1000\times 60}{344,000}\frac{\left(1+\frac{124}{4.8}\right)}{1+4.8\times 2.44}}$$

$= 142$ periods per minute.

If machine A, with a speed of 150 r.p.m., were driven by a reciprocating engine, trouble from "hunting," or oscillation, could be expected, since there would be an engine impulse of 150 periods per minute acting upon a system whose natural frequency of oscillation is 142, i.e., a difference of only 5 per cent. In such a case the obvious solution would be to increase the WR^2 of B until there is a difference between frequencies of 20 per cent,* i.e., until F is reduced from 142 to 120. This means a 43 per cent increase in B's WR^2, or 3950 lb-ft.² instead of 2765.

It is obvious from equation (15), that if there is a large difference in the WR^2 of the two units and if n_I is greatly different from unity, as in the foregoing example, a given percentage change in the smaller WR^2 will result in a greater change in F than if that percentage change is made in the larger WR^2.

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*This percentage, based on experience largely, is generally accepted as the necessary difference to insure satisfactory operation.

Some Mechanical Features of Synchronous Machines

By A. P. Wood

Alternating-current Engineering Department, General Electric Company

The immediately following pages are devoted strictly to a description of the mechanical features of the present day design of synchronous machines. Illustrations are given of the improvements which have been made in design and construction by the introduction of arc welding and spot welding. Descriptions are given of the oil starting system and the oil circulating system, the coreless and the cored box type of stator frame, and the rotor spiders of various types and speeds.—Editor.

A P Wood

If one would take time to look at more than the surface of one of our latest machines, he would discover those many features of present day design which have improved the efficiency and reliability of the machine's performance. He would find that electric arc and spot welding have played an important part in producing a better machine.

In the smaller or belt-driven generators a further step is taken by having the pole tips indexed for future operation as synchronous motors. All that is necessary for such use is to insert an amortisseur winding. This feature is desirable where a larger machine replaces a smaller one, thus allowing the use of the smaller machine as a condenser. The field coils having been originally insulated in accordance with the A. I. E. E. Rules for motor operation, no trouble would be experienced from this source.

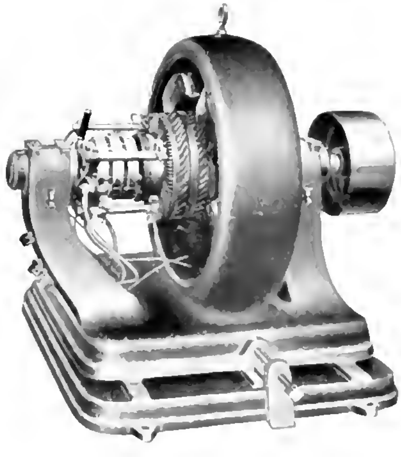

Fig 1 7.5-15 and 25 kv-a Self-excited Generators

Should the operator desire a direct connected exciter at some future time, he will find machined lugs on the bearing bracket and a proper shaft extension to accommodate the exciter.

As to size of alternators the limiting feature seems to be shipment, tunnel clearances, etc. Quotations have been given on waterwheel generators as large as 45,000 kw. and there is now installed a 32,500-kw. waterwheel-driven unit. By sectionalizing the stator and rotor, pieces 14 feet across have been transported across the United States.

In general, the alternator design should be as compact as possible, especially as to elevation, because each foot in height entails a considerable extra outlay in the cost of the station to house the machine.

Recently a large number of proposals have been made to use outdoor generators. A large unit has already been installed in the West without any station over it. To protect the generator from the elements, a temporary wooden structure is erected over it. In case of trouble or where inspection is necessary, a gantry crane moves over the generator.

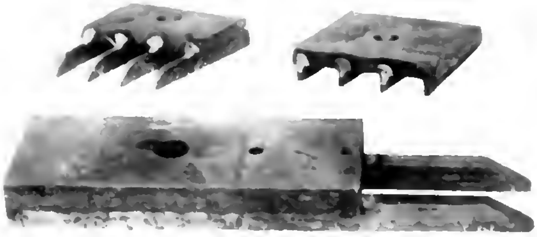

Fig 2 Stator Core Clamping Flanges and End Fingers Combined by Arc Welding

Sixty-cycle synchronous machines ranging from 7.5 to 25 kv-a. are of the self-excited type and embody two machines in one. The revolving armature has both the multiphase winding and an independent direct-current exciter winding in the same slots. Figs. 1 and 3 show a photograph and wiring diagram of one of these machines. The stator laminated field poles have the cast-iron frame, standards, and base cast around them in one piece to reduce the machining operations to a minimum.

No external excitation is required.

The exciter winding, therefore, is not similar to that of a synchronous converter where taps are taken off the main armature winding, nor does it depend on rectifying commutators or series transformers for stepping down part of the armature current. This arrangement has been thoroughly tried out, both in test and practice, and has proven thoroughly reliable in every way.

When operated as synchronous motor, grids are placed on the poles which have been punched to accommodate them.

Arc Welding

The combined clamping flanges and end fingers used to secure tight stator cores consist of pieces of sheared machine steel arc welded together. Fig. 2 shows a perfect ventilating path between the flange and the punchings that is not obtained in any other type. The punchings can be tightened in sections at any time without stopping the machine by removing shims placed beneath the flanges

This type of flange entirely supersedes the old heavy cast-iron sectional flanges and is fast taking the place of the combination segmental cast-steel flange and end fingers. The delays in production due to making expensive patterns, as well as the foundry loss which runs as high as 25 per cent, have been eliminated.

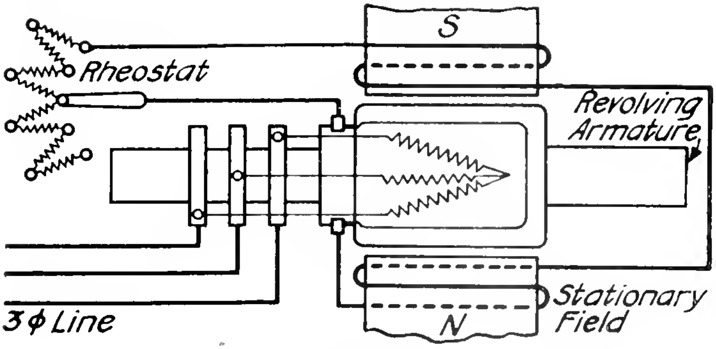

Fig. 3. Diagram showing Electrical Connections of Three-phase Self-excited Generators

Many large castings are being reclaimed by the use of arc welding.

Rotor spiders which have too large a bore can be used without a bushing by slightly increasing the shaft diameter by arc welding.

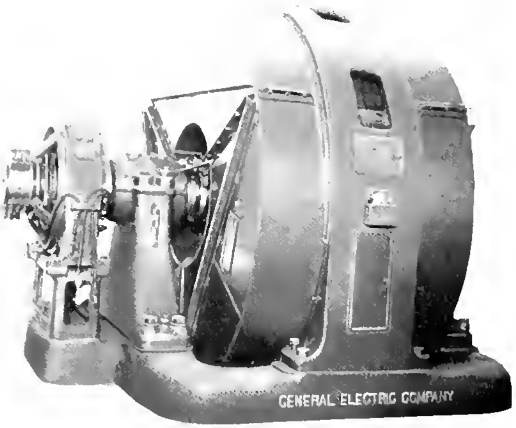

Fig. 4. 3000-kv-a. Synchronous Condenser, the Enclosing Ventilating Shields of Which Are Constructed of Sheet Iron and the Seams Arc Welded

The tool expense for machining generators has been greatly reduced by welding high grade steel cutting ends to cheaper grades of body stock.

When positive ventilation is required, the enclosing shields consist of arc welded pieces of sheet iron as shown in Fig. 4. A more finished appearance is now obtained by flanging over the corners, thus doing away with the square appearance. A set of enclosing shields can be produced in a few days. In the case of castings an expensive pattern is required which sooner or later becomes obsolete, and the foundry is fortunate in obtaining 75 per cent good castings.

The danger of damaging the stator windings when removing cast-iron end shields is eliminated by the use of light sheet-iron shields. The absence of heavy machine work such as the truing up and facing required by large cast shields facilitates production. Being much lighter and made in either 90 or 120-deg. sections, the operator can readily remove them for inspecting or repairing the field or stator coils.

The stairways for large vertical machines are now being arc welded and present a finished appearance.

Laminated field spiders where bolts are to be tapped in the periphery have the separate laminations are welded together.

Fig 5. Stator of a 1400 kv-a. Synchronous Motor Showing the Construction of the Cold Rolled Steel Spot-welded End Shield

Experiments are now being made to extend the use of arc welding.

Spot Welding

For several years the lengthy job of riveting has been superseded largely by spot welding. The open-type shields consist of strips of cold rolled steel held in jigs and spot welded. Fig. 5 shows the finished appearance of such an end shield. This shield also can be produced in a few days. It appeals strongly to the operator as it is unbreakable and does not require removing when shifting the stator. The expensive pattern shop work and foundry breakage always present where castings are used has been done away with.

Where large machines are boxed for shipment, the welded shields do not have to be removed as is the case where cast-iron ones are used. Also, if the welded shields do become damaged they can be easily straightened.

The space blocks for ventilation between the stator punchings are pieces of I-beam section cold rolled steel, spot welded to the laminations. This method eliminates the chance of space blocks becoming loose, dropping out, and damaging either the rotor or stator. These straight beam space blocks allow a greater volume of air to pass through the core than would be possible with blocks of rectangular shape, which in most cases are curved or bent to keep them from turning over.

Advantage of this welded space block is being taken to replace various types of clamping flanges for retaining the punchings in small stator frames. Should a loose core develop, the end fingers would still remain in place which would not be the case were friction depended upon.

Amortisseur Winding for Synchronous Motors

In recent years the use of tin and solder have been replaced by a method of making better joints between bars and end rings. Fig. 6 shows an amortisseur winding which is practically indestructible. Fig. 7 shows a method of increasing the cross section where the bar enters the end ring. This construction has been used for several years with perfect results. Brass, copper or monel metal is used according to the class of service the motor has to perform.

Synchronous motors have been made with multiple amortisseur windings and in some cases with cast windings.

Fig. 6. Synchronous Motor Rotor Having the Amortisseur Winding Before the Laminated Poles Were Riveted

The amortisseur winding shown in Fig. 6 was assembled before the laminated pole was riveted, thus eliminating the drifting of the slots where the windings are assembled after the poles are completed.

Oil Starting Systems

For many years hand operated or motor-driven high-pressure oil pumps have been available for reducing the kilovolt-amperes required to start heavy rotating elements. A film of oil is forced beneath the shaft until the oil rings become effective, after which the pump is shut down. A motor-driven outfit for this purpose is shown in the lower right-hand corner of Fig. 8. The saving in kilovolt-amperes is obtained by using a lower tap on the starting compensator than would be required were it not for the high-pressure oil starting system.

The oil for lubricating the rotating element is obtained from an equalizer pipe which parallels the two bearing standards and flows into the pump plunger chamber. After the pump is started and the bearings are lubricated under pressure, and the rotating element is receiving oil from the bearing oil rings, the pump is shut down. The pump plungers act as check valves, otherwise the rotating shaft would build up a back pressure and drain the bearings.

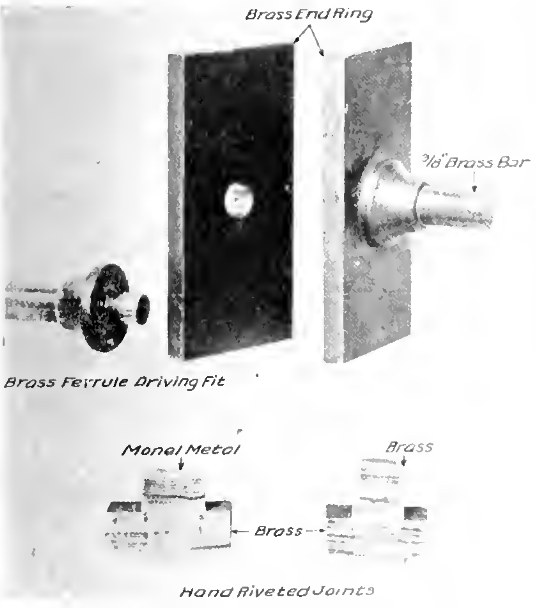

Fig. 7. Photograph showing the Method of Connecting Amortisseur Winding Bars to the End Rings and showing the Enlargement of the Bar at the End Ring

Oil Circulating Systems

A pump has been developed to replace the gears and gear pump, Fig. 11, common to oil circulating systems now in general use. The expensive split driving gears, so hard to assemble on vertical machines, and the inefficient check valves with screw adjustments are all eliminated. The oil pan shown in Fig. 11 is designed so that the pump can be completely assembled on one half of the pan. This arrangement allows for easy inspection without interfering with or disconnecting the piping system.

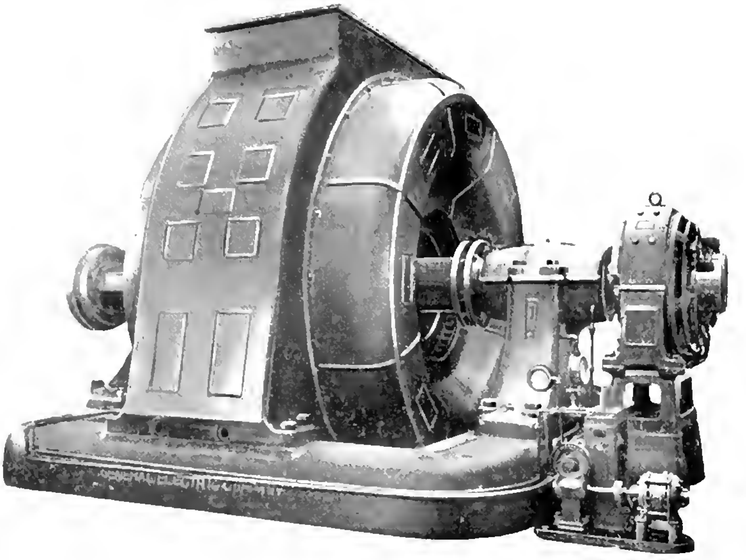

Fig. 8. Motor-driven, High-pressure Oil Pump at the Lower Righthand, Used to Facilitate Starting the Large Horizontal Machine by Forcing Oil Beneath the Bearings

The piping is arranged to take oil from the bottom of the oil pan to a point above the lower guide bearing outside of the stator frame, through a flow indicator, then to the top of the guide bearing and after filling the grooves in the guide bearing it overflows back into the oil pan.

The lower guide bearing has an independent oiling system on the smaller vertical machines. The upper guide bearing and spring thrust bearing are designed as a unit, are self oiling, and require no attention whatever.

Stator Frames

The old, familiar, heavy skeleton type stator frame has been replaced with the present box type. This latter frame is not only stronger and lighter mechanically, but eliminates the errors in air gap which resulted from improper alignment of the cross ribs in the old type.

The stators are made of cast-iron and consist of two types. One requires cores in casting and the other does not. Due to its unique design the coreless type, Fig. 9 (used on smaller machines) when assembled acts the same as clamping flanges to retain the laminated punchings in place. The cored type, Fig. 10, has separate clamping flanges for retaining the punchings and is superior for larger stator frames as any looseness in punchings can be taken up by removing shims from beneath the flanges.

Fig. 9 Coreless Box Type Stator Frame Used for the Smaller Machines

Cast-iron is the most economical material since steel castings cannot be obtained thin enough to take advantage of the increased strength.

The deflection allowed in calculating the stiffness of frames varies with the diameter, and the allowance, say for six feet in diameter, is increased by increments for larger diameters. In single-phase machines there is a pulsating flux and consequently the stiffness of the frames has to be increased considerable. In all cases the frame must be stiff enough to prevent undue distortion in shop handling, turning over, or boring mill work.

It is essential to have the stator cores tight and this is obtained by the use of individual combination clamping flanges and end fingers, the result being a very tight core.

Field or Rotor Spiders

The larger percentage of the cast-steel rotor spiders have been replaced by a laminated type which cuts down the time of production from weeks to days. These spiders are produced by interchangeable dies that supersede the expensive old combination method wherein one set of dies was required for each particular size of machine.

Very few cast-iron field spiders are used now on account of the improved magnetic circuit obtained by the use of steel. The excitation required to give full voltage no load has been decreased by replacing cast-iron with cast-steel.

Rotor spiders are so proportioned that shrinkage strains may be avoided, these being overcome in steel castings by annealing.

For securing the poles to the spiders the simple construction of putting bolts through the rim into the poles is used on rotors having speeds up to approximately 225 r.p.m. For higher speeds dovetails are used.

Fig. 10 Cored Box Type Stator Frame Used for the Larger Machines

The V or wedge dovetail was used for many years until the size and speed of machines rapidly increased; then the T dovetail took its place. As the neck of the V dovetail is increased to cover tension stresses and the depth is increased to overcome bending (this also applies to the rotor dovetail), we soon come to a point where the laminations of the pole dovetail will buckle, thus preventing its use. The ordinary T dovetail has some bad features, such as keying up the pole and field coil, also introducing the reluctance of an air gap between the pole and rotor. This T type dovetail has been improved so that the objectionable features have been removed.

The stresses are calculated so that at double speed of the rotor no stress will exceed half the elastic limit of the material. Supporting brackets are placed between the poles where higher stresses of pole and copper winding are encountered.

Some of the rotors are of too high speed to depend upon a pressing fit on the shaft. They must be shrunk on, otherwise at double or runaway speed they would float on the shaft.

Shafting

Carbon steel with a tensile strength of approximately 75,000 lb. per square inch is generally used. At maximum power transmitted, a stress of 7000 lb. per square inch is not exceeded. On special shafts nickel steel is used. Shafts are designed so that the deflection will not exceed a certain percentage of the air gap when the rotor is assembled in the stator.

Bearings

With ball-seat self-aligning bearings lubricated by oil rings, pressures are used as high as 130 lb. per square inch projected area.

Ventilation

The rotating field poles are purposely designed to overhang the field spider, and for peripheral speeds of approximately 8000 or 9000 ft. per minute the pole pieces themselves act as natural fans and have sufficient blower effect to ventilate the stator. Holes are also placed in the rotor rim between the poles and are of great assistance in distributing the air properly. Bafflers are also placed between poles in some cases to stop air from passing directly through the rotor poles, the result being a more even distribution through the stator and a considerable reduction of temperatures.

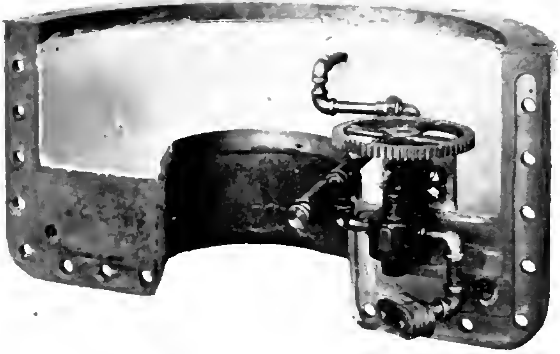

Fig. 11. Gear-driven Oil Circulating Pump Now in Common Use on Large Vertical Machines

The tendency is for higher speeds for large output alternators and where the peripheral speed exceeds 9000 ft. per minute, enclosing shields are used, producing a much quieter running machine. In many large installations, especially where more than one machine operates in the same room, ducts are furnished to carry cold air to the machines and other ducts to allow the heated air to be led away.

Vertical machines present more difficult problems in ventilation than horizontal machines. Fresh air is generally taken from the wheel pit. Approximately three cubic feet per kilowatt rating is required.

Parallel Operation and Synchronizing of Frequency Converters

By O. E. Shirley

Alternating-current Engineering Department, General Electric Company

The operation of a single frequency converter between two systems is comparatively simple. However, when more than one converter is used the phase angle between the incoming generator and the bus introduces a factor which must be provided for. The author gives a very clear explanation of the reasons for this phase displacement between loaded and unloaded converters trying in the same systems. In modern frequency converter sets the difficulty introduced by this condition is taken care of by means of a motor-operated screw which shifts the stator of the motor or generator in its cradle to the required position.—Editor.

O E. Shirley

The use of frequency converters has become of considerable importance since power systems have expanded and overlapped. Thus, systems of different frequencies have come together and it has been necessary to connect them through frequency converters. As the size of the systems has increased, it has followed that the size of the converters has also increased and these converters can now be built in capacities as high as 15,000 kw. The operation of a single converter between two systems is comparatively simple, for it is only a matter of synchronizing the generator with its system. When more than one converter is operated in parallel between two systems, the matter of proper paralleling becomes of importance.

The present-day design practice is tending toward machines of higher regulation, with resulting higher efficiencies, lower short-circuit stresses, and cheaper costs. These characteristics, which are somewhat different from those of the units of older design, are liable to introduce operating difficulties unless proper attention is given to the conditions of operation and design when installing new units. Conditions of load division are quite important in some cases, especially where reversible operation is required, and an understanding of the behavior of alternators under load is quite necessary to insure satisfactory operation.

Lag Angles

The power output from an alternator operating in parallel with other synchronous apparatus is dependent only on the power input from the prime mover, and does not depend on the field adjustment. The changing of the field current will change the reactive component, but does not affect the energy component of the armature current.

It is now quite generally known that the rotor of an alternating-current generator moves forward from its no-load synchronous position as the load increases. In the same way, the rotor of a synchronous motor drops back from the no-load position. That is, if the rotor of the generator is at a certain place when the voltage of one phase reaches a maximum with no load on the machine, it will be several electrical degrees ahead of that position when the voltage of that same phase reaches a maximum with the machine under load. Similarly, the rotor of the motor is behind the no-load position when the machine is loaded. This angle varies for different designs, but the usual value at full load is from 20 to 40 electrical degrees. The value of the angle depends on a number of different design factors and is rather difficult to calculate from the design of the machine. Some of the most important factors are the ratio of pole arc to pole pitch, the variation of the air gap from the center to the edge of the pole tip, the relation of the air gap to the pole pitch, the relative values of field and armature magnetomotive forces, and the value and power-factor of the load.

In the case of frequency converters, the angle to be considered is the resultant for the two machines, referred to one or the other of the units. Assume that the converter is a 25-to-60-cycle set, and the full-load lag angle of the 25-cycle unit is 20 electrical degrees, while that of the 60-cycle unit is 25 electrical degrees. The pole pitch of the 25-cycle unit is 2.4 times that of the 60-cycle unit, hence one electrical degree on it is equal to 2.4 degrees on the 60-cycle unit. When the converter is transferring power to the 60-cycle system, the angle by which this system is behind its position at no load is the sum of the two angles of the machines, allowing for the factor 2.4. That is, the electrical lag angle of the 60-cycle system will be 25 deg. plus 2.4 times 20 deg. or 73 deg. Similarly, if the converter is operating with the 60-cycle unit as a motor, the lag angle of the 25-cycle end will be 20 deg. plus 25 deg. divided by 2.4 or 30.4 deg.

It should be noted that with a 10-and-24-pole combination, such as is required for a 25-to-60-cycle converter, it is possible on starting from the 25-cycle end to come into step on any one of ten positions depending on the pole that happens to be at the reference position when the motor comes into synchronism. The rotor may be caused to drop back a pole pitch by reversing the field. This means that the 25-cycle unit will drop back 180 deg. and the 60-cycle unit will drop back 2.4 times 180 deg. or 432 deg. This is equivalent to one complete cycle and 72 deg. more. On the fifth reversal of the field the rotor will be back one complete cycle on the 60-cycle end and the last five poles will simply repeat the cycle of the first five. From this explanation it can be seen that the motor may come into synchronism so that the generator voltage will have any one of five different angles.*

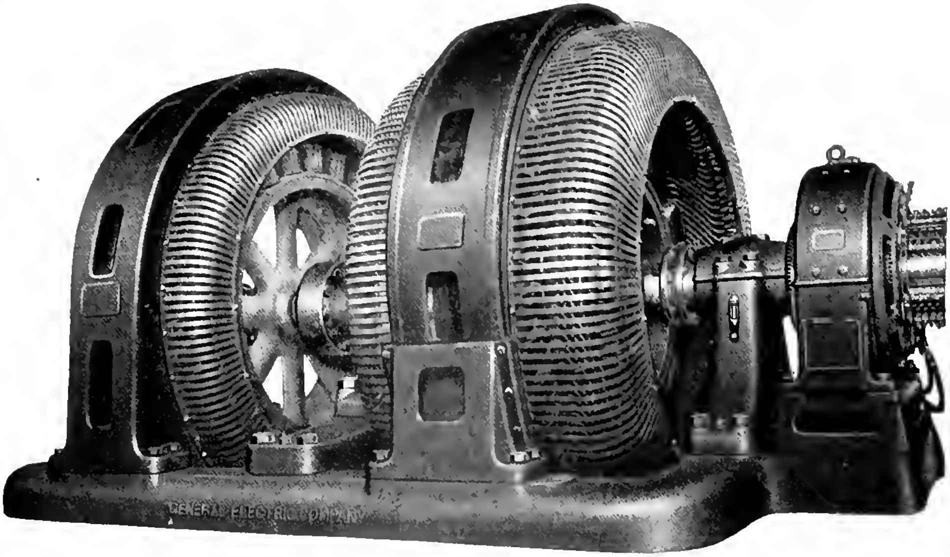

Fig. 1. Frequency Converter with Exciter. To permit of adjustment for parallel operation with another frequency converter, the stator of the near unit is mounted in a cradle to which it can be clamped after the load adjustment has once been made

Parallel Operation

The parallel operation of frequency converters made by different manufacturers or of different dates of manufacture by the same company may introduce some little difficulty, but if the stator frame of all the units, or all except one, are made adjustable it is usually quite easy to get satisfactory operation by shifting the frames of the various units until the proper load division is obtained. This adjustment may be made once for all when the sets are first installed after which the setting of the frames need not be changed.

When the converters are operated to transfer power always in one direction, that is non-reversible operation, it is not necessary that the lag angles of the sets be equal, as the frames can be adjusted so that all the units will take the maximum load for which they are designed for continuous operation, and the load division may come what it will at the lighter loads. With sets of different design characteristics this condition may result in a pump back between them at no load; but, when the load is light enough for this to be objectionable, all but one or two of the converters may be shut down so no trouble will be experienced from this cause. It is quite important to note that for non-reversible

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* For a more complete discussion of this feature of parallel operation, covering the more common combinations of frequencies aside from the example given above, refer to "Some Features Affecting the Parallel Operation of Synchronous Motor-generator Sets," by J. B. Taylor, A.I.E.E., 1906, Vol. XXV, Page 113.

operation with converters of older design it is usually not advisable that the new converters be designed to divide the load proportionately to their rated capacities. To produce this condition may necessitate a higher cost and result in other disadvantages without any real gain in operating characteristics.

Reversible Operation

There are a few cases where it is desirable to operate the converters in parallel throughout the entire range of load in both directions, and then it is desirable that the load division be proportional to the rated capacities throughout this entire range. This condition requires that the full-load lag angle of the converters be the same or very nearly the same. The use of the motor-operated phase-adjusting device described later will usually be the most satisfactory method of operation under these conditions.

Synchronizing

When only one converter is used between the two systems, it is only necessary to start the motor and throw it on the line in the ordinary way for starting synchronous motors. Then the generator is synchronized with the second system by changing the speed of one or the other of the systems until the generator runs at approximately the same speed as the system to which it is to be connected and then closing the switch when the synchronism indicator shows that the two are in phase. If the converter is used to supply power from the generator without operating in parallel with any other generator, it is not necessary to have any synchronizing devices at all. Adjustment of the stator frame need not be provided where only one converter is to be used, but it is usually advisable to have the stator frame made adjustable as the future installation of other sets for parallel operation may make this feature very convenient.

It is evident from the preceding discussion of load angles that when an unloaded converter is to be paralleled with sets that are carrying load the incoming generator will be ahead of the bus voltage by the load angle of the converters already operating. The synchroscope needle will not rotate as the converters already tied in will hold both systems at a ratio of frequencies corresponding to the ratio of the number of poles, and the incoming set will be held at exactly the same speed as the others by the synchronous motor. The angle between the needle and the in-phase position will be the load angle of the converters already operating when the incoming converter is on the proper pole for synchronizing. This angle may be from 30 to 75 deg., depending on the load and which unit is operating as a motor, being greater for the higher frequency generators. As the change in the angle indicated by the

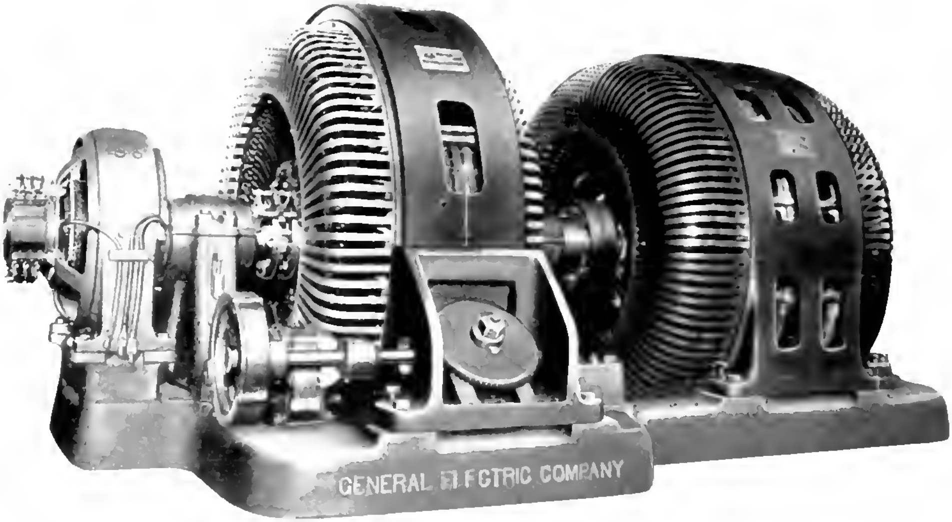


Fig. 2. A Frequency Converter similar to the one in Fig. 1, except that the stator of the near unit can be shifted by an auxiliary motor-driven device. This arrangement readily permits of synchronizing with other sets without disturbance and of adjusting the load while the set is in operation

synchroscope due to slipping a pole is relatively large, it is very easy to determine the proper position for synchronizing. The synchroscope dial may be calibrated to indicate this position for various values of load on the sets already operating.

The operations necessary for synchronizing a converter with sets already loaded are as follows:

(1) Start the converter from the motor end and operate from the line with full field.

(2) Adjust the voltage of the incoming generator to approximately the bus voltage.

(3) Slip poles on the motor by reversing the field until the generator is ahead of the bus voltage by the load angle of the sets already operating.

(4) Close the generator on the bus and adjust the field until the proper reactive current is taken by the incoming generator.

Methods of Phase Adjustment

The usual standard method of adjusting the phase angle of frequency converters to secure proper load division is to mount the stator of one unit in a cradle rigidly secured to the base. The stator may be securely clamped in this cradle when the required load adjustment is obtained. With the frame once set it is unnecessary to change this adjustment. A converter equipped with this type of cradle is shown in Fig. 1.

The synchronizing of converters equipped with this type of adjustment requires that the generator be put on the line when its voltage is out of phase with the bus by an angle of 30 to 75 deg., which will cause some little disturbance when the switch is closed and there will be some swinging of the load between the converters before they settle down to stable operation. This may be objectionable especially if the converters are of large capacity, and to eliminate the action a motor-operated phase-shifting device may be used. This device enables the stator frame to be shifted while under load. When synchronizing with this device, the stator frame is shifted until the generator voltage is in phase with the bus voltage, and the switch closed. There will then be no disturbance on closing the switch, but the converter will not take any load until the stator frame is shifted. This shift may be adjusted until the desired load is taken by the incoming set. The converter may also be unloaded before taking it off the line, and there will be no disturbance on opening the generator switch. It should be particularly noted that this device is of use only where two or more converters are to be operated in parallel.

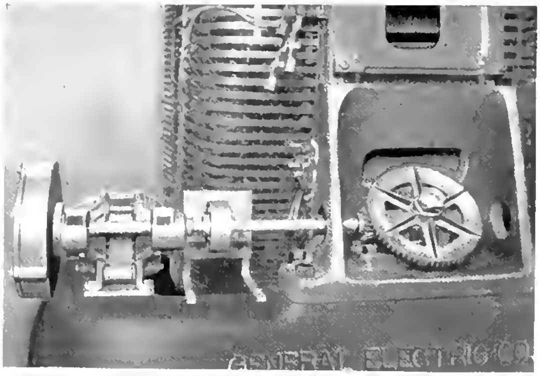


Fig. 3. Close-up View of a Motor-driven Phase-shifting Device Similar to That Shown in Fig. 2

This shifting device is very useful where reversible operation of sets of recent design is required with sets of the older types. The recent designs will very likely have larger load angles than the older ones, unless larger and more expensive machines are used; and they will therefore have a tendency to take less load than they should unless a shifting device is employed.

A converter equipped with this type of adjustment is shown in Fig. 2, and a more detailed view of the device itself is given in Fig. 3.

Motor-generator Sets

By G. H. Tappan

Alternating-current Engineering Department, General Electric Company

In the smaller motor-generator sets an induction motor is usually employed on the alternating-current side, while in the larger units the synchronous motor is found more desirable. Sometimes the field of the synchronous motor is excited from the direct-current generator and in other cases a separate exciter is provided. With frequency converter sets either a single exciter may be used for the two field windings, or a separate exciter for each, depending upon the service for which the set is intended. The author briefly describes the basis on which motor-generator sets are rated. Provision for heavy overload is often required and a method of compounding the exciter to automatically take care of such conditions is mentioned.—Editor.

G. H Tappan

MOTOR-GENERATOR sets in which one or more of the machines are of the synchronous type may in general be divided into two classes; those converting alternating current to direct current, and those converting alternating current at one frequency to alternating-current at a different frequency.

Machines of the first class are commonly known as motor-generator sets; while those of the latter, although properly motor-generator sets also, are now known as frequency converters.

Those which convert alternating current to direct current are the more numerous of the two classes.

There are many conditions of service where the rotary or synchronous converter is not quite as suitable as the motor-generator set. Often a direct-current supply is desired where the voltage can be varied or controlled over a considerable range. Also, the synchronous motor may be built for higher voltages than the rotary converter, thus doing away with the necessity of using transformers. Such sets are used for electrolytic work, battery charging, mining, railway, lighting and power service, etc. Motor-generator sets which convert alternating current to direct current and which are of less than 100-kw. capacity are usually built with an induction motor as the driver, while those above 100 kw. are driven by synchronous motors. Of the two methods of driving, the synchronous motor has some advantage. This motor runs at constant speed and may be used for correcting the power-factor of the system on which it operates. The desirability of this latter feature is being more and more emphasized inasmuch as public service companies are beginning to place a premium and give a bonus on this type of load.

The majority of synchronous motor-generator sets are built for operating from a 60-cycle circuit, although there are many operating from 25-cycle circuits and some at other frequencies such as 50, 42, 40, 30.

The present day tendency is to build motor-generator sets to run at as high a speed as practicable because of the smaller space required for the same kilowatt output and the lower cost.

There is also a tendency to enclose machines and obtain a greater output from them, with the same heating, by the addition of forced ventilation or improved natural ventilation. Also, since enclosure reduces the noise it is permissible to design motors for higher peripheral speeds than is practicable with the open type of machines.

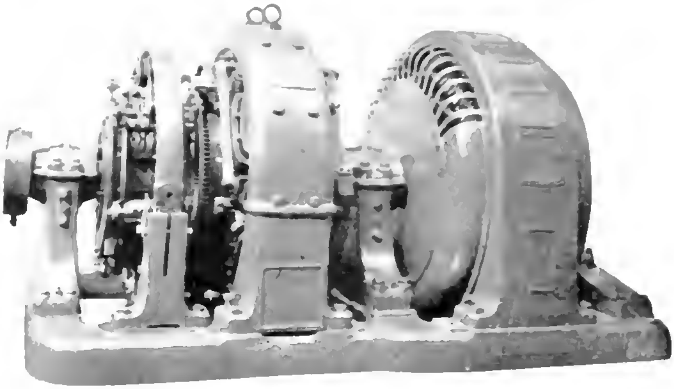


Fig. 1 Motor generator Set 900 r.p.m., Consisting of an 800 kv-a., 2300-volt Synchronous Motor and a 600-kw., 250-volt Direct-current Generator

Small size 60-cycle motor-generator sets, such as 300-kw. or less, are not usually built for voltages higher than 4000. Larger sets are built for voltages up to 13,200.

Where the voltage of the direct-current generator is fairly constant and not over 275 volts, the field of the synchronous motor is usually excited from the generator end of the set; but where the voltage of the generator is greater than 275 volts, or where the service required of the generator necessitates a greatly varying or fluctuating voltage, separate excitation for the synchronous motor is required. For this case a direct connected exciter is generally used with the set.

The ratings given to the synchronous motor-generator sets which have been standardized by the General Electric Co. are those recognized by the A.I.E.E. These are the "nominal" rating and "continuous" or 50-degree rating.

Following the demand for the power-factor correction feature, the synchronous motors of the standard sets are designed for operation at a leading power-factor. In the case of the nominal rated sets, the motors are designed for 80 per cent power-factor; and for the continuous or 50-degree rated sets, the power-factor chosen usually is 85 per cent.

There are frequently cases where a greater corrective effect is desirable, which conditions require a motor having a much lower power-factor rating and approaching very close in design to a synchronous condenser. Quite a number of such sets have recently been built with synchronous motors designed for 70, 60 and 30 per cent power-factor.

The character of the average load and the conditions of momentary overloads are taken into consideration in designing the synchronous motors. Thus the motors of the nominal rated sets are designed to withstand a momentary overload of 100 per cent, while the motors of continuous rated sets are designed for a momentary overload of 50 per cent.

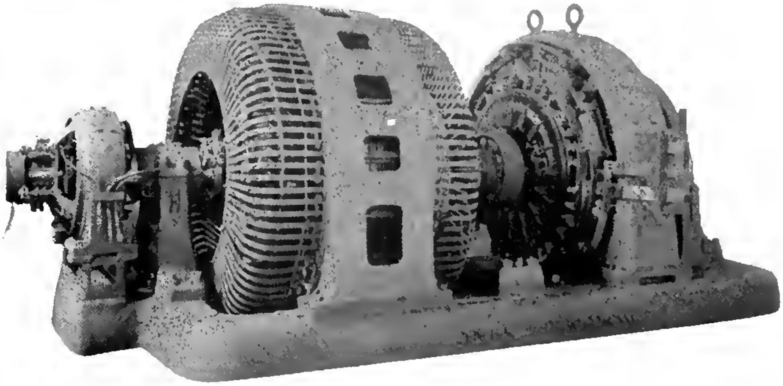


Fig 2. Motor-generator Set (720 r.p m.), Consisting of a 1600-kv a., 12,500-volt Synchronous Motor, a 1000-kw., 600-volt Direct-current Generator and an Exciter

The nominal rating is based on a certain normal load maintained continuously until the temperatures have become constant, and this followed by a 150 per cent overload for two hours on the generator. Under these conditions the maximum temperature rise is guaranteed not to exceed a specified value.

This rating is generally applied to the motor-generator sets for mining and railway service. The synchronous motors of the sets in this case are generally designed to operate at 80 per cent power-factor at normal load, and the same field strength which is necessary for normal load is maintained on all loads above the normal full rated load.

The continuous or 50-degree rating is the load which the set will carry continuously without exceeding a temperature rise of 50 degrees. The momentary overload is the only overload guaranteed in this case.

Sometimes the severity of the conditions, with respect to the nature of the overload peaks, requires even a greater margin of safety. This is especially true in railway service. For such cases the motors are designed for an overload as great as 200 per cent, i.e., capable of withstanding a momentary load of three times normal without the synchronous motor dropping out of step.

However, another method of taking care of this condition is sometimes used where the motor line conditions permit; viz., that of compounding the direct-connected exciter which excites the field of the synchronous motor. This compounding is done with the direct-current generator line current or a part thereof being passed through the series field of the exciter. The adjustment can be so made that, with a certain direct-current generator load, the field current of the synchronous motor will be of the proper value to give the desired kilovolt-amperes input and power-factor. It will also be so adjusted that the field strength for a peak load will be sufficient to keep the motor from dropping out of step.

When a momentary heavy load occurs on the generator, the increase in current in the series field of the exciter will cause a corresponding increase in the exciter voltage, which in turn will result in a motor field current of sufficient value to hold the motor in step. This method usually increases the size of the exciter due to the large series field, or due to the higher insulation required on the series field, as the sets where this method is used may have a generator voltage much higher than that of the exciter. Also, the design of the exciter for the heavy peak duty requires a larger exciter than otherwise would be necessary. On the other hand, it allows the use of a smaller synchronous motor, inasmuch as the momentary overload can be taken care of and the size of the motor be determined by the heating at the normal or average speed.

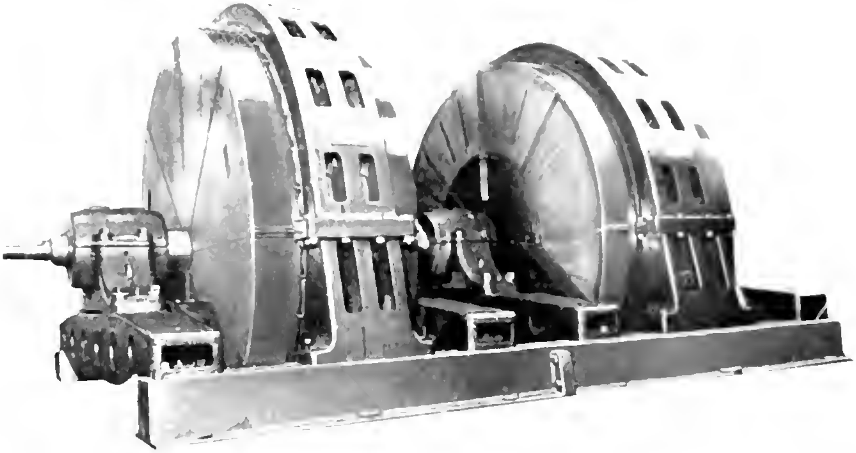


Fig. 3. Enclosed Frequency Converter of 10,000 Kw., 60/25 Cycles, 300 R.P.M. and 13,200/11,000 Volts

Motor-generator sets are started from either end, but the general practice is to start from the synchronous motor end using an auto transformer or low-voltage taps on the transformers. Due to the high induced voltage in the field coils of the motor during the starting period, it is the common practice on synchronous motors forming part of alternating current to direct current sets, to start with the field closed through a resistance.

The voltage required to start the motors varies considerably with the design. As a general rule, 25-cycle motors will start on a lower voltage than 60-cycle motors. Thus, the 25-cycle motors of motor-generator sets require approximately 20 to 30 per cent normal voltage, while the 60-cycle motors will average approximately 35 to 45 per cent.

The other class of motor-generator sets, properly known as frequency converters, is used to convert power at one frequency to power at another frequency. The most usual application is in converting 25-cycle power to 60-cycle power for tying two systems together.

Very little choice is possible in the matter of the speed of these sets as the maximum speed for which 25-cycle to 60-cycle converters may be designed is 300 r.p.m., and this is low enough for any capacity so far demanded.

The size of the standard line of frequency converters ranges from 300 kw. to 3000 kw., the smaller sets being standard for 2300 volts and the larger sets for 2300 to 13,200 volts. Sets are built also for 4000 kw., 5000 kw. and larger, there being a 10,000-kw. set now in process of manufacture.

The usual power-factor for which the 25-cycle motor is designed is 90 per cent, and for the 60-cycle generator 80 per cent.

When conditions of service permit of raising the 60-cycle frequency to 6.25 cycles (and this may ordinarily be done if the prime movers of that system allow it and the system is not already tied to the 25-cycle system by a 25-cycle to 60-cycle converter), a speed of 750 r.p.m. may be used, converting the 25-cycle power to 62.5-cycle power or, if operating reversed converting the 60-cycle power to 24-cycle power. The higher speed allows the use of smaller machines for the same capacities, therefore smaller space is required and the cost is less.

The bulk of the frequency converters manufactured are for the two conversions of frequency mentioned, although several other conversions are common, such as 40 cycles to 60 cycles, 42 cycles to 50 cycles, the latter being frequently used in Europe.

The frequency converter is usually built with one direct-connected exciter for exciting the fields of both units, but when a voltage regulator is used on the generator it is usually customary to have a direct-connected exciter for each unit, one being placed on each end of the frequency converter.

One of the units of the frequency converter is built with adjustable feet, so that the stator may be rotated to get the correct phase relation for synchronizing. A complete explanation of this arrangement is given in the article, "Parallel Operation and Synchronizing of Frequency Converters," by O. E. Shirley, in this issue.

Synchronous Condensers

By E. B. Plenge

Alternating-current Engineering Department, General Electric Company

As a means of controlling voltage on high potential long distance transmission lines, the synchronous condenser is an absolute necessity. It is also an economical investment for users of large quantities of power at low power factor, as it is now common practice for central stations to make a charge for supplying wattless current. Greater latitude in the electrical characteristics is permissible in the design of synchronous condensers that are not intended to carry mechanical loads. In most applications a synchronous condenser is required to carry leading currents, but occasionally, as for example when the load is removed from a transmission line, it may be necessary to operate the synchronous condenser with a lagging current. The requirements of machines for such service are shown vectorially. Starting characteristics, ventilation and prevention of noise are also briefly referred to.—Editor.

E. B. Plenge

THAT the economies effected in the operation of generators, transformers, and transmission lines by the use of synchronous condensers are now generally appreciated is evident by the rapidly increasing number of applications of these machines for power-factor correction. The higher rates charged for loads of low power-factor by many power companies is undoubtedly partly responsible for this increase. The use of condensers on long transmission lines for voltage control is a practical necessity. This article will be confined to the design and characteristics of the condensers themselves, as other articles have dealt at length with the determination of the capacity required to attain certain results.

In general, the design of a synchronous condenser differs little from that of a synchronous motor, but the fact that the condenser runs idle; i.e., with no mechanical load and at approximately zero power-factor, permits of certain modifications which result in a less expensive machine than a motor or generator of the same kilovolt-ampere capacity.

Speed and Capacity

A reduction in cost is obtained by an increase in speed, up to the point where the greater mechanical stresses necessitate a more expensive type of construction or where a change is required in the electrical loading (such as lower armature reaction) to relieve the duty on the field. As the speed of the condenser is usually left to the choice of the manufacturer, it is made as high as possible with a salient pole type of rotor. This construction has been found best suited for condensers and is now used almost exclusively. The mechanical design is therefore the same as for high-speed waterwheel-driven generators with the added problem of designing an amortisseur winding to withstand the high stresses. Fig. 8 in the article entitled, "Large Horizontal Alternating-current Waterwheel-driven Generators and Synchronous Condensers," page 151, illustrates the rotor of a 12,500-kv-a., 500-r.p.m. condenser and is typical of the construction used. Small capacity condensers have been built with speeds as high as 1800 r.p.m. The most economical speed will, of course, be lower as the capacity is increased, so moderate size 60-cycle machines are built to operate at speeds of from 900 to 720 r.p.m. and the largest sizes at 600 r.p.m.

The size of individual units has followed the increased capacity of generating stations and transmission lines. At present, there are a considerable number of machines in operation with capacities ranging from 5000 to 15,000 kv-a. and a 50-cycle condenser of 30,000-kv-a. capacity at 600 r.p.m. is now under construction.

Electrical Design

As a condenser runs with little or no mechanical load, it can be designed without consideration of the breakdown torque. The armature reaction can therefore be made higher and the no-load excitation lower than in a synchronous motor. The reduction in the length of air gap is limited principally by the heating of the pole faces and the increase in the leakage reactance.

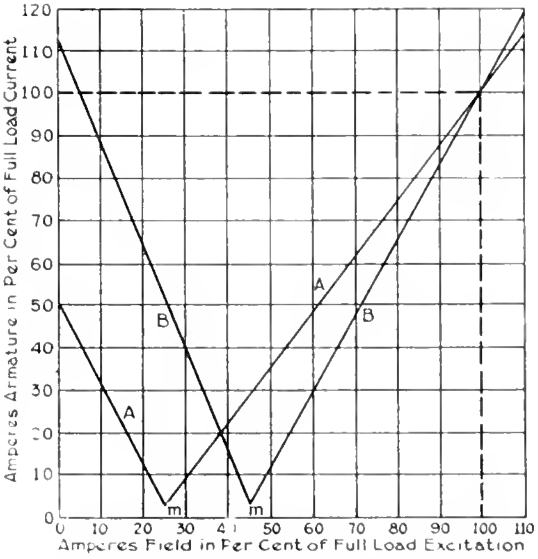


Fig. 1. Comparative Phase Characteristic Curves for Two Values of Armature Reaction and No-load Excitation

Taking advantage of these factors and also the fact that the mechanical parts, such as the base, shafts, standards, and bearings can be made lighter than for a motor or generator, results in a compact and efficient machine requiring comparatively little floor space and having excellent starting characteristics.

A machine designed with a large ratio of armature reaction to no-load excitation, however, will have a very flat phase characteristic or "V" curve with the minimum input point *m* near the origin, curve *A*, Fig. 1. With no excitation whatever it will operate at a lagging power-factor at only 40 or 50 per cent of its rated capacity and will require a range of approximately 30 to 125 volts across the collector rings from the minimum input point *m* to full capacity leading power-factor. This is not objectionable when the condenser is used solely for raising the power-factor and is not required to operate at lagging power-factors, since automatic regulators can be built for this range in excitation voltage.

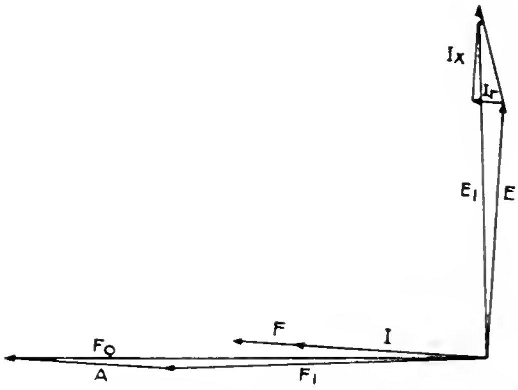


Fig. 2. Vector Diagram of Current, Voltage, and m.m.f. Relations at Zero Power-factor Leading

The reasons for this wide range in excitation will probably be most readily understood by a consideration of the vector diagrams. Fig. 2 illustrates the current, voltage, and m.m.f. relations at zero power-factor leading. E is the terminal voltage and E_1 the internal voltage. Ir is the resistance drop at right angles to the voltage and is of so little effect that it can usually be neglected. Ix is the reactance drop which adds directly to E. F and F_1 are the ampere-turns required to produce the fluxes corresponding to E and E_1 respectively. A is the armature reaction.

It will be noted that, in addition to the ampere-turns on the field required for the voltage E_1, there must be added an amount equal to A as the armature reaction is entirely demagnetizing at zero power-factor leading. The total ampere-turns required for excitation is represented by F_0.

At the minimum input point m, F is approximately the same as F_1 since both Ix and Ir are small under this condition. An inspection of Fig. 2 will show that if the armature reaction is increased and the no-load excitation reduced, there will be a rapid increase in the range of excitation required from minimum input to full capacity leading power-factor. This range is represented approximately by the ratio $\frac{F_0}{F}$.

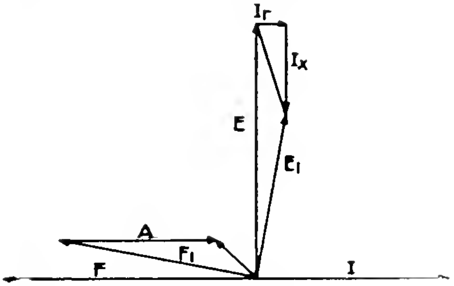


Fig. 3. Vector Diagram of Current, Voltage, and m.m.f Relations at Zero Power-factor Lagging

Fig. 3 shows the relations at zero power-factor lagging. In this case Ix subtracts from the terminal voltage E, and as the armature reaction A is magnetizing it also subtracts from F_1. The resultant excitation F_0 thus becomes very small.

When a condenser is used at the end of a long transmission line having considerable capacity, it often becomes necessary to operate at lagging power-factors when charging the line or during periods of light load in order to reduce the voltage at the receiving end. In certain instances it is necessary to hold the voltage constant on the high-tension side and the requirements on the condenser then become even more severe as the reactance of the transformers adds to E_1, Fig. 2, at leading power-factors and subtracts from E_1, Fig. 3, at lagging power-factors.

It is evident from Fig. 3 that a condenser will not operate at full capacity lagging if the armature reaction A exceeds F_1, the ampere-turns corresponding to the internal voltage E_1. Theoretically, the proper relation between A and F_1 can be obtained by lengthening the air gap and thus increasing F_1 but this results in a proportionate increase in the full-load excitation F_0. The reactance is slightly less with the longer gap, but this is offset by the increased leakage between poles. It is seldom that the additional excitation can be provided on the field on account of the limitations as to space and heating. The armature reaction must therefore be reduced at the same time that F_1 is increased, in order to keep the full-load excitation approximately the same. The effect is that the angle of the phase characteristic curve is accentuated and the minimum input point m is moved away from the origin, as shown by curve B, Fig. 1. This results in a larger and more expensive machine. For example, a 2000-kv-a. condenser to operate at leading power-factors only can be built with a core length of say 20 inches. To operate at full capacity at both leading and lagging power-factors, and still keep the excitation voltage within the range of a voltage regulator, it is necessary to increase the length to say 30 inches. The cost, however, is not increased in the same proportion.

If separate excitation is provided for the voltage regulator, it will operate from practically 0 to 125 volts and a considerable saving can be effected in the size of the condenser. This excitation can be supplied by

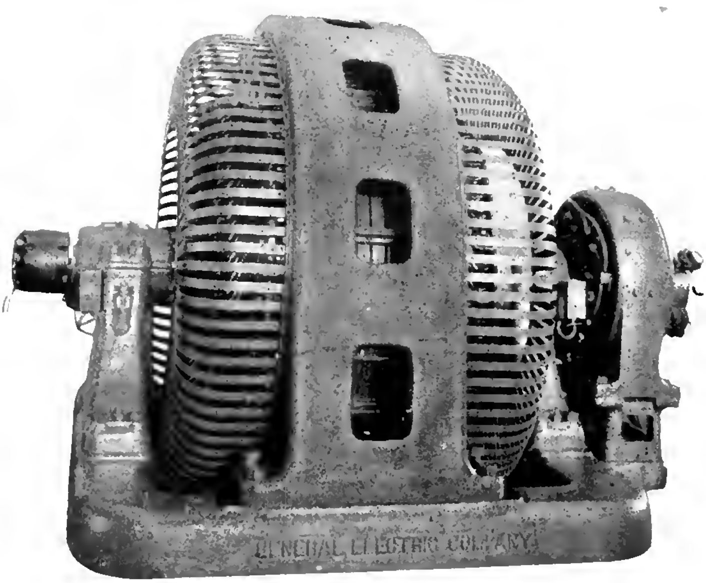


Fig. 4. A Synchronous Condenser with Direct-connected Exciter for the Main Field and Small Exciter for the Regulator

storage batteries or any other fairly constant source. Fig. 4 illustrates a condenser furnished with a direct-connected exciter for the main field and a small exciter for the regulator.

It is realized of course that by reversing the field of the condenser the lagging kilovolt-amperes can be increased, but behavior under this condition is uncertain, and no attempt has so far been made to operate in this manner commercially, although it is done in the Testing Department of the Company. If the negative excitation is increased beyond a certain point the machine will slip a pole and continue to operate, but the kilovolt-amperes will drop to the amount corresponding to the same positive excitation.

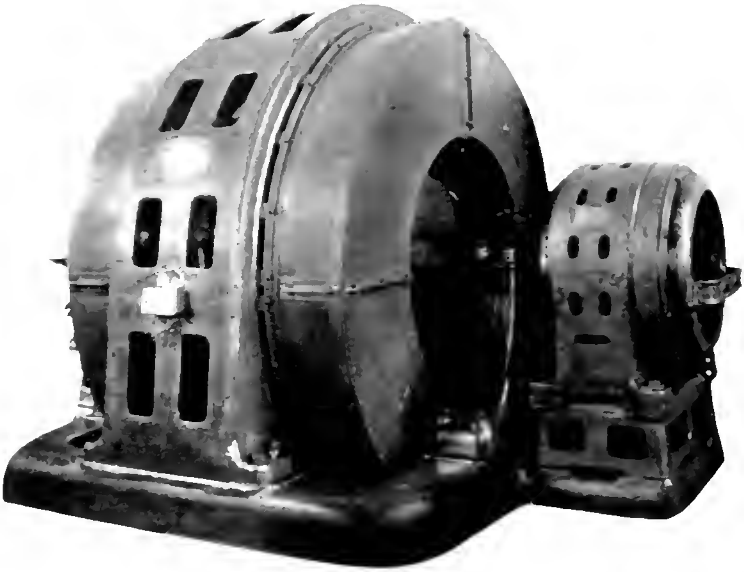


Fig. 5. Synchronous Condenser Eqxipped with an Induction Starting Motor to Reduce to the Minimum the Line Disturbance at Starting

Starting

These machines are provided with high-resistance amortisseur windings and are usually started as induction motors by means of compensators or low-voltage taps on the transformers. In general, the starting kilovolt-amperes do not exceed 50 per cent of the rated capacity and are usually much less. In some cases where it is particularly important to start with the minimum disturbance to the line, starting induction motors have been applied as shown in Fig. 5. Motor-driven pumps for supplying oil to the bearings at a sufficient pressure to lift the rotor and thus reduce the torque required to break the machine from rest have also been used.

Ventilation and Noise

The problem of ventilation is the same as for generators with the exception that condensers are more often in rooms by themselves. The smaller sizes are entirely open, the moderate sizes semi-enclosed; i.e., these draw air in around the shaft and discharge it into the room through holes in the stator frame. The largest sizes are completely enclosed, air being drawn in and discharged through ducts especially provided for the purpose. All the condensers are self ventilating, air being circulated in the larger machines by means of fans attached to the rotor

Condensers are occasionally installed in residential sections and it then becomes necessary to take special precautions to make the operation as quiet as possible. This is accomplished by either partially or totally enclosing the machine.

Large Horizontal Alternating-current Waterwheel-driven Generators and Synchronous Condensers

By M. C. Olson

Alternating-current Engineering Department, General Electric Company

In the November, 1919, issue of the Review the writer dealt with designs of large *vertical* waterwheel-driven generators. In the article below some features of large *horizontal* waterwheel-driven generators and synchronous condensers are considered. The importance of these subjects is emphasized by the fact that the number of waterpower installations is constantly increasing and yet only 16 per cent of the latent waterpower resources of the world has so far been utilized. More and more synchronous condensers are being used on power circuits; the writer describes the largest condenser ever designed and also the highest voltage condenser built.—Editor.

M. C. Olson

The trend in the design of waterwheel-driven generators and synchronous condensers is continually toward higher speeds and larger capacities. As a rule, the higher the speed the lower is the cost of the waterwheel, as well as the generator or synchronous condenser.

There are cases, however, where higher speed machines may be more expensive than those of a lower speed, due to the special and more expensive design of rotor occasioned by the overspeed requirement of the waterwheel. The poles on the high-speed machines become large and heavy, and consequently require special construction for attaching them to the field rim. Two or three supporting brackets between poles are sometimes required to prevent the heavy field winding from bulging out.

The rotors of high-speed machines are balanced with extreme accuracy, so that when running no vibration is transmitted to the bearings.

Fig. 1 shows one of the highest speed generators. It is rated 10,500-kv-a., 0.75-p-f., 6600-volt, three-phase, 42-cycle, 630-r.p.m., and two of them were built for the Breda Power Company, Milan, Italy. Each unit has a 40-kw., 250-volt, compound-wound, direct-connected exciter. These machines are located at an altitude of 5610 feet and are to operate at any voltage between 6000 and 6600 volts. The guarantees under these conditions are 50 deg. C. by thermometer on all parts.

The machines are totally-enclosed and are of the self-ventilating type, the air for ventilation being supplied through ducts in the foundation and being drawn into the rotor at each side by the poles and by fans which are attached to the rotor rim. After passing through the machine the air leaves through a duct located at the bottom of the stator frame. The amount of ventilating air required is approximately 30,000 cu. ft. per min. Around

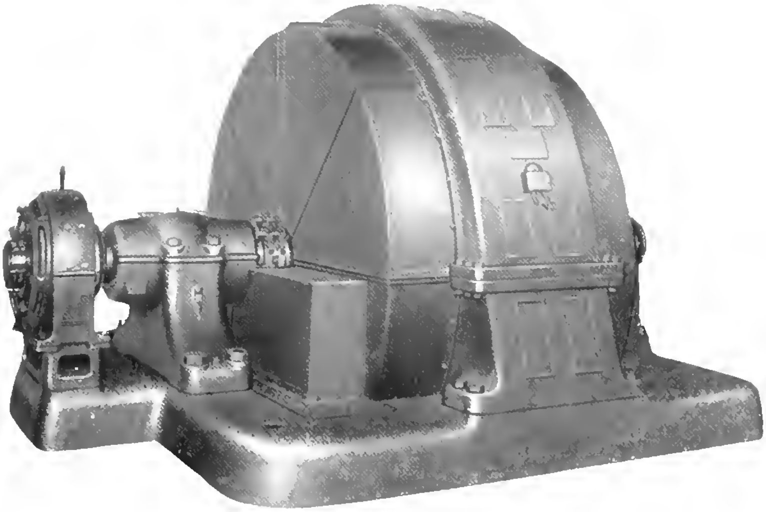


Fig. 1. A High-speed, (630 r.p.m.) Totally-enclosed, Self-ventilating, 10,500-kv-a., 6600-volt, Three-phase, Waterwheel-driven Generator

the periphery of the stator frame there are several holes which are closed by small sheet-iron covers that may easily be detached if the operator desires to allow the warm air from the machine to escape into the room in cold weather. The enclosed shield on

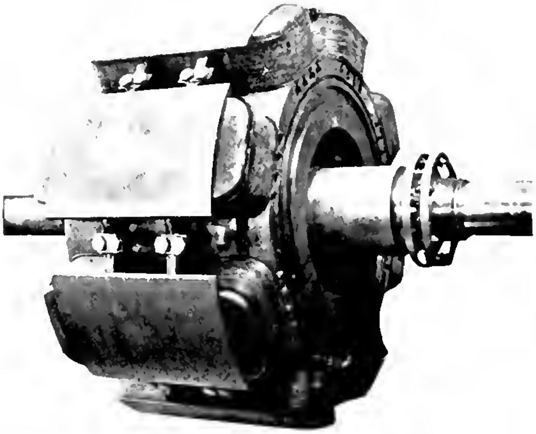


Fig. 2. Rotating Field of the Generator shown in Fig. 1
This photograph was taken before the ventilating fans were assembled on each side of the rotor rim

each side also has several covered openings through which to inspect the inside of the machine. In addition to obtaining a definite flow of cooling air through the machine, these enclosing features reduce to a minimum the noise occasioned by the revolving parts.

The rotor is shown in Fig. 2. The field spider consists of two cast-steel wheels. The poles are attached to the field rim by four T-dovetails, as the rotor must be capable of withstanding an overspeed of 80 per cent above normal. The rotor has fans at each side of field rim, but these are not shown in the illustration. The WR^2 of this rotor is 120,000, this being the amount required by the waterwheel makers for proper speed regulation.

Six leads, that is, the ends of each phase, are brought out to the terminal board of this generator for use in connection with current transformers and relays for protective devices. The reactance is approximately 13 per cent, and the test efficiency at 10,500 kv-a., 1.0 p-f. is 97.3 per cent, and at 10,500 kv-a., 0.75 p-f. is 96.3 per cent.

A generator of similar design and ventilation of lower speed and larger diameter is shown in Fig. 3. Its rated output is 7050 kv-a. at 0.85 p-f., 6600 volts and 375 r.p.m. Two of these generators were built for the Tasmanian Government, Australia, and two more are now being built. The rotor is designed to withstand a runaway speed of two times normal without distortion of any of the parts.

Machines of different capacities and speeds require different methods of construction and ventilation. Waterwheel-driven generators are, in most cases, self contained; i.e., they are supplied with shaft, bearings, and base or foundation caps. The flywheel effect required is usually embodied in the rotor of the generator. In some cases the waterwheel is overhung on the generator shaft, which makes it necessary to design the shaft and bearings to take care of the weight of waterwheel and water thrust, if any.

A somewhat unusual design is shown in Fig. 4, a 10,000-kv-a., 5000-volt, three-phase, 50-cycle, 300-r.p.m. generator, six of which were built for the Andhra Valley Power Supply Company, India. As it was required to provide for moving the stator in the direction of the shaft to facilitate repairing and to utilize the space thrust required, the ventilating hoods were so designed as to take in all the air from one side instead of from both sides of the generator

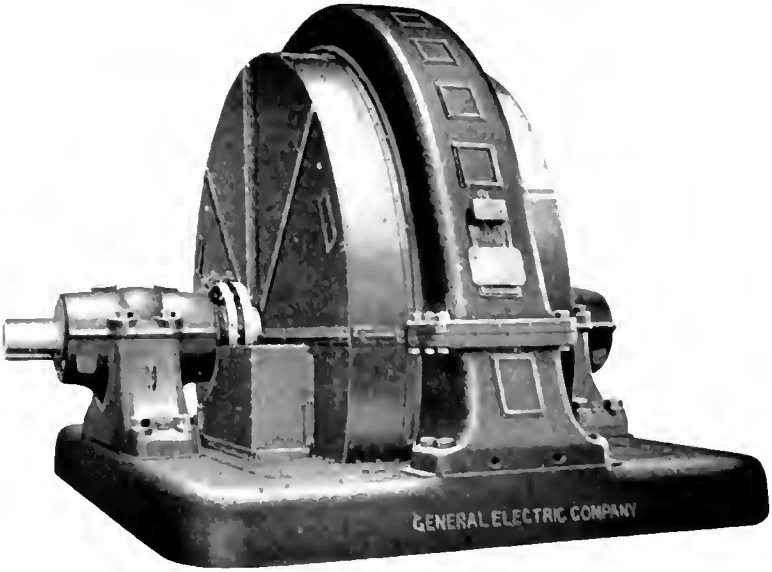


Fig. 3. A Generator of Larger Diameter and Lower Speed Than That Shown in Fig. 1, but of Similar Design and Ventilation

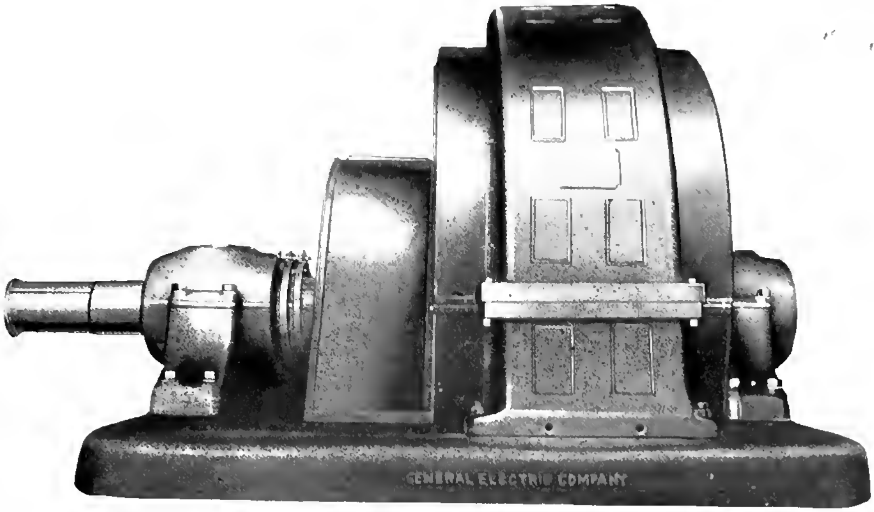


Fig. 4. A 10,000-kv-a. Generator of Somewhat Unusual Design, in That All the Ventilating Air is Drawn in from One Side

This design has the further advantage that it relieves the weight on the bearing, due to the overhung Pelton waterwheel, which in this case is opposite from the usual side. The center line of the overhung waterwheel is 32 in. from the outside of the bearing housing.

The machine is entirely enclosed. All the cooling air is taken in through a duct below the generator on one side, the duct being 4 by 6 ft., and is discharged into another duct 6 by 12 ft. 4 in. through the bottom of the stator frame. Air dampers, made of steel plate, are located in the air inlet and outlet to regulate the amount of air and to prevent air entering when the machine is not in use. Underneath the feet of the stator are rollers so arranged that, after the ventilating hoods have been removed, the armature can be easily moved along the shaft for repairs.

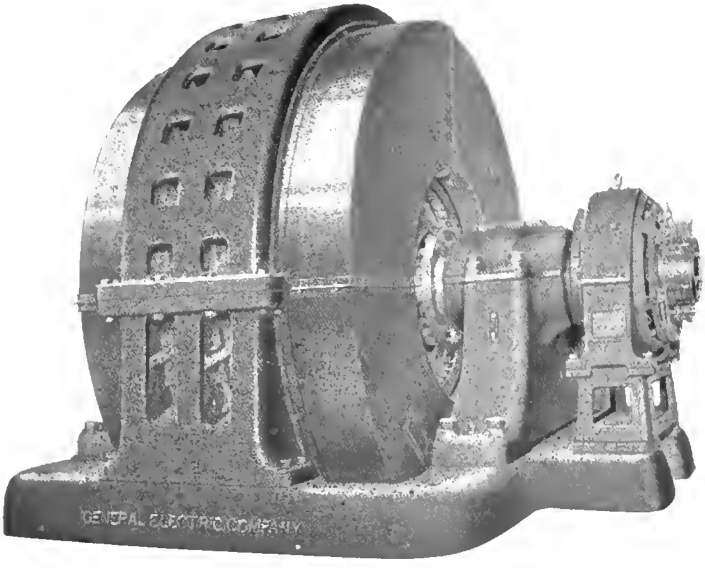


Fig. 5. An 8,750 kv-a., 500 r.p.m., 6000-volt, Waterwheel-driven Generator of the Usual Construction, Wherein the Ventilating Air is Drawn in Around the Shaft and Expelled Through Openings in the Stator

The bearings of this machine are cooled by water circulating through copper coils imbedded in the babbitt. On all horizontal machines the bearing pedestals are insulated from the base to prevent circulating currents that may be produced by unbalanced magnetic conditions, from flowing through the shaft and bearings.

The rotors of two of these machines were run in a testing pit at 80 per cent above speed for fifteen minutes without any distortion of field coils or poles. The temperature guarantees on the generators are 60 deg. F. rise by thermometer for continuous operation at 10,000 kv-a., 0.8 p-f. and 80 deg. F. rise on a rating

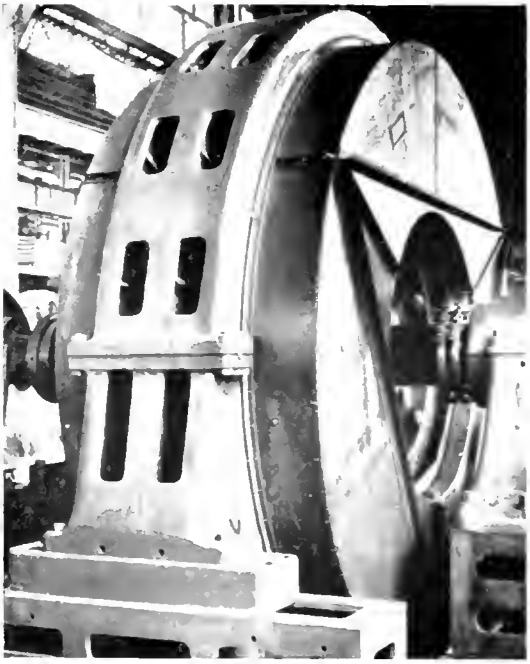


Fig. 6. A 10,000-kv-a., 300-r.p.m., 6600-volt Generator of the Same General Construction as That Shown in Fig. 5

of 12,000 kv-a., 0.8 p-f. for ten hours based on a room temperature of 110 deg. F.

Figs. 5 and 6 show the usual construction of waterwheel-driven machines, with sheet-iron enclosing shields. The air for ventilation is drawn into the machine around the shaft and expelled into the room through openings in the stator spider. This last machine has water-cooled bearings designed to carry one half of the weight of a 15-ton flywheel at the coupling end.

Synchronous condenser designs are very similar to waterwheel-driven generators both in mechanical arrangement and ventilation, except the poles are equipped with a squirrel-cage winding for stability of operation and for self starting. The number of slots in the stator and the size of the rotor bars and end rings are so proportioned as to require the lowest amount of kilovolt-amperes at starting.

A sectional view of the largest capacity condenser under construction is shown in Fig. 7. It is a 30,000-kv-a., 6600-volt, 50-cycle, 10-pole, 600-r.p.m. machine, and will be capable of operating at 20,000 kv-a. lagging. The machine is arranged with hoods for the intake of approximately 83,000 cubic

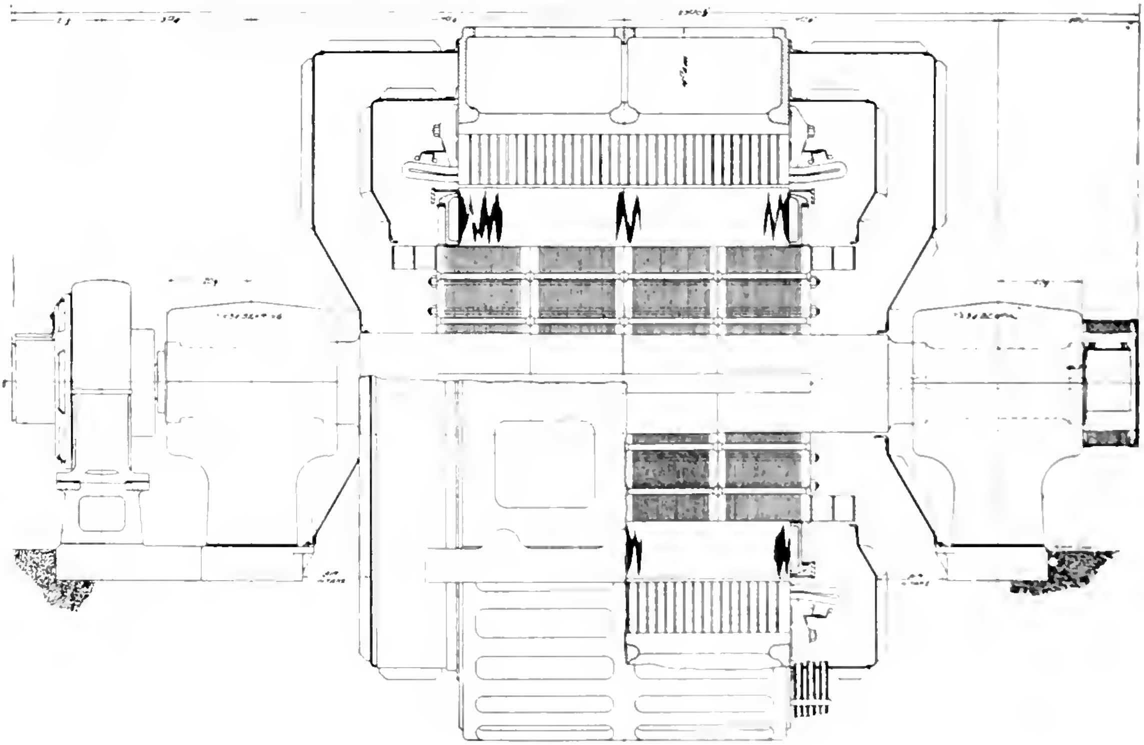


Fig 7. Sectional Drawing of a 30,000-kv-a., 6000-volt, 600-r p.m., Totally-enclosed Synchronous Condenser

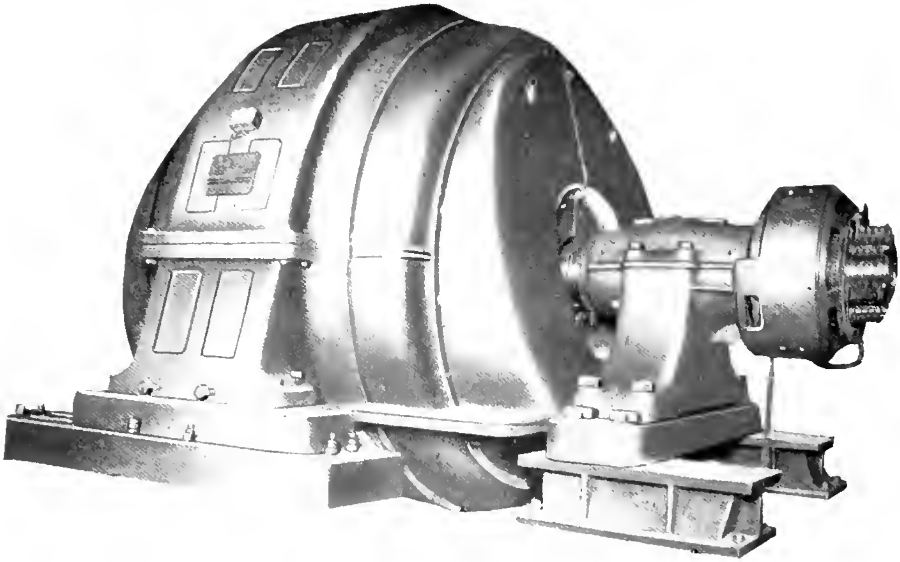
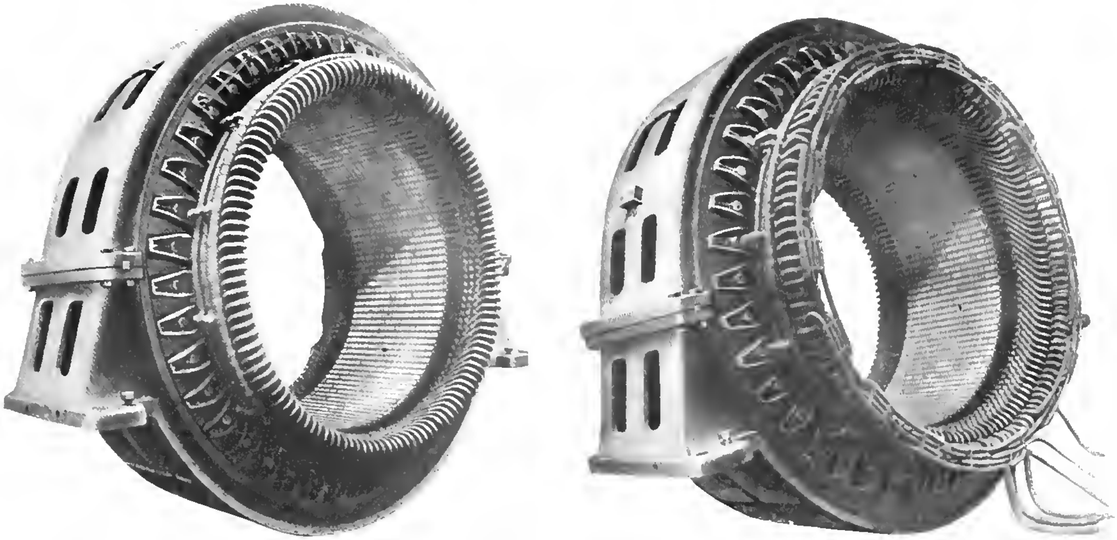


Fig. 8 A 12,500-kv-a., 22,000-volt Synchronous Condenser

feet of air per minute and is designed to exhaust the air vertically at the top. A special double ventilating hood is provided for admitting this amount of cooling air which is drawn into the rotor by the poles and fans. On account of the very long stacking of this machine and the amount of air required for cooling, the fans at each end of the rotor are double and have curved blades. The guarantees on this condenser for continuous operation are 50 deg. C. by thermometer and 60 deg. C. rise by temperature coil, except the field which will be 80 deg. C. rise by thermometer. Special attention has been directed to the elimination of those harmonics in the wave shape that would produce inductive interference with communicating lines.

The rotor, instead of being built in the usual way of steel castings, is built of steel plates in four sections. Each section consists of a number of $\frac{1}{2}$-in. plates and 2-in. plates riveted together and shrunk on the shaft. The rotor center is heated to approximately 80 deg. C. above the room temperature for



Figs. 9 and 10. Stator Coils of the Condenser shown in Fig. 8, showing the method used to support them at the ends of the windings

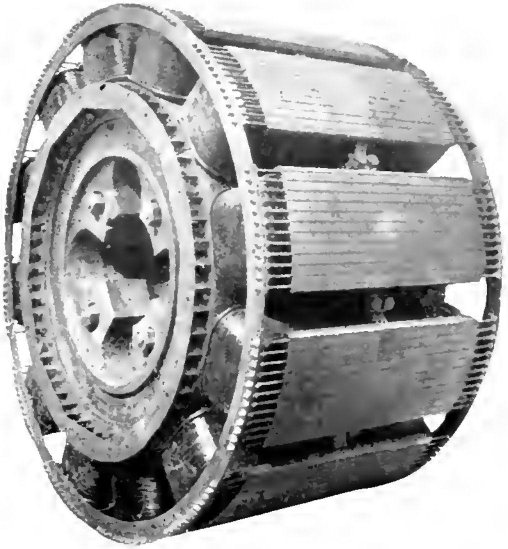


Fig. 11. Rotor with Squirrel-cage Winding for the Condenser shown in Fig. 8

assembling on the shaft. The rotor spider and shaft are to be shipped assembled. The bearings are arranged for water cooling and oil pressure will be used when starting. The direct-connected exciter is 150-kw., 250-volt, and is compound wound. The exciter armature has a stub shaft with forged coupling and is bolted to the end of the condenser shaft. The magnet frame of the exciter is supported by the bearing housing.

The condenser is to be started by a compensator in connection with a 50 per cent tap in the transformer. The potential taps available for starting will be 30, 37½, and 45 per cent of the normal voltage.

The highest voltage condenser built is shown in Fig. 8, being 22,000 volts, 12,500 kv-a., 500 r.p.m., three-phase, 50 cycles, two of which were constructed for the Andhra Valley Power Supply Co., Bombay, India. The temperatures are guaranteed not to exceed 80 deg. F. on the armature and 100 deg. F. on the field when operating continuously at 12,500 kv-a. leading, based on a room temperature of 110 deg. F. (43½ deg. C.).

On account of the very high voltage and great expense involved in making up the armature coils, unusual precautions have been taken in making the coils and assembling them in the stator. The projecting ends of the armature coils are laced to three steel binding bands firmly supported from the stator.

Figs. 9 and 10 show the stator coils and their method of support at the ends of the windings. These windings were given a high-potential test of 50,000 volts for one minute, between phases and between phases and frame.

The ventilation of this condenser is the same as that for the machines shown in Figs. 1 and 3, the air being taken in at each side of the ventilating hood and expelled at the bottom of the stator frame through an opening 3 ft. 9 in. by 10 ft. 5 in. In order to protect the high-voltage coils from handling as much as possible in erection, the stator without ventilating hoods, but with punchings and windings, is to be shipped completely assembled. The rotor complete with its squirrel-cage winding is shown in Fig. 11.

Fig. 12 shows a 6500-kv-a., 50-cycle, 6300-volt, 750-r.p.m. condenser, with direct-connected exciter at one end and starting induction motor at the other end.

The design of the stator and rotor of water-wheel-driven generators and synchronous condensers are so proportioned that the wave form follows very closely a sine wave.

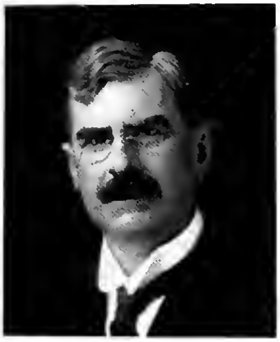
Fig. 12. A 6500 kv-a., 6300-volt, 750-r.p.m. Condenser, having a direct-connected exciter at the near end and a starting induction motor at the far end

Measurement of Losses and Efficiency by Temperature Rise of Ventilating Air

By Wm. F. Dawson

Turbo-Generator Department, Lynn Works, General Electric Company

The determination of the losses and efficiency of a machine by measuring the temperature rise of its ventilating air possesses many advantages which will undoubtedly make this type of test popular. Two methods are applicable; first, measure the average inlet and outlet temperatures and the volume of the ventilating air, assuming the specific weight and heat of the air; second, measure the average inlet and outlet temperatures, pass the discharged air through an electric heater of known capacity and measure the average temperature of the air from the heater. Both methods are described and discussed in detail below, and several actual tests are included for the purpose of illustration.—Editor.



Wm. F. Dawson

During the discussion of a group of papers on "The Method of Determining Losses," before the American Institute Electrical Engineers in 1913, H. M. Hobart made a strong plea for this method of determining losses.* The author had previously made some experiments and since then has followed the subject with considerable success. An important contribution to the subject is contained in the paper by S. F. Barclay and S. P. Smith, entitled, "Determination of the Efficiency of the Turbo-alternator."†

The A.I.E.E. papers referred to and their discussion made it plain that, with the methods available at that time, an accurate determination of full-load efficiencies was practically impossible without the great expense of making special input-output tests, in conjunction with calibrated loss supply apparatus.

Load losses cannot as a rule be measured directly and can be determined only by subtracting known losses from a reasonably accurate determination of all the losses made either by the input-output method or by the method described herewith. Obviously, the latter system can be used only where the arrangements for ventilating the machine under test are such that there is a distinct path for the ventilating air, and where it is possible to measure accurately the average temperature of the inlet air and the average temperature of the outlet air at such points in the air path that the temperature difference is affected wholly and only by the losses of the machine. Such losses as those of the bearings and those by convection must be determined in a different manner and care must be exercised to insure that extraneous heat such as that from steam pipes, etc., is not added to the discharged air before its temperature is measured.

There are two methods of determining the losses by the air method: The first is by measuring the average inlet and outlet temperatures, and the volume of air passing through the machine; assuming the specific weight of the air and its specific heat. The second method, and apparently the more satisfactory one, necessitates the measurement of average inlet temperatures and average outlet temperatures; the passing of the discharged air through a suitable tunnel or duct in which is placed an electric heater that supplies a known quantity of heat during the test; and the measuring of the average temperature of the air as it is discharged from the heater.

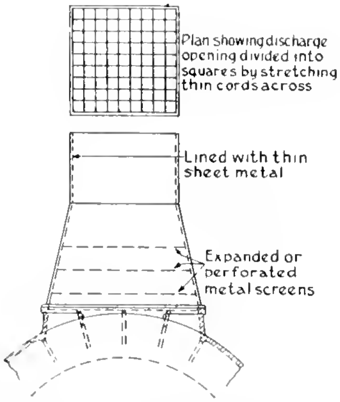


Fig. 1. Temporary Discharge Trunk to Facilitate the Accurate Measurement of Air Volume and Temperature †

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* Transactions A. I. E. E.; Vol. 32, Pt. I, Page 645.
† Journal I. E. E. (London), Vol. 57, April, 1919.

Measuring of the Air Volume

Barclay and Smith* describe the testing and calibration of anemometers for this work. They also describe the Pitot tube, Ventur tube, and electrical methods. Their choice was the anemometer and this was applied opposite the end of a discharge trunk arranged as shown in Fig. 1. It will be noted that this discharge trunk was fitted with expanded or perforated metal screens to level out differences in velocity otherwise due to the direction of rotation of the machine. Fig. 2 shows the variation in velocity across the opening, curve *A* with the expanded metal baffler and *B* with baffle plates omitted. Our own earliest experiments were made without baffle plates by dividing the cross-section of the discharge opening into equal squares and measuring the velocity of each square by means of a "hook" gauge. An example of the variations over the discharge area is indicated graphically by the readings shown in Fig. 3 and taken on a 1563-kv-a., 3600-r.p.m. turbo-alternator. It will be noted that the hook gauge readings vary from a minimum of 0.05 in. of H_2O (water) to a maximum of 0.154 in. The lower value represents a velocity of 15 ft. per sec. and the higher, 26.3 ft. per sec. Other careful tests, where the average velocity was about the same, actually show some negative readings. These data are given to indicate the extreme care necessary for this method of testing. The mean of repeated tests when carefully worked out check with reasonable accuracy, but the labor involved in determining the square of the average of the square roots is considerable.

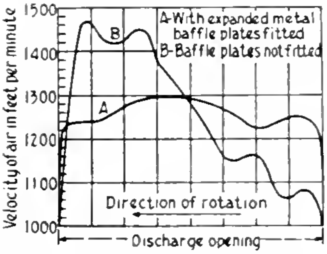


Fig. 2. Curves Plotted from Pitot Tube Readings, Taken Over the Opening of a Temporary Discharge Trunk to Show the Effect of Baffle Plates on the Uniformity of the Air Velocity*

35"

Top

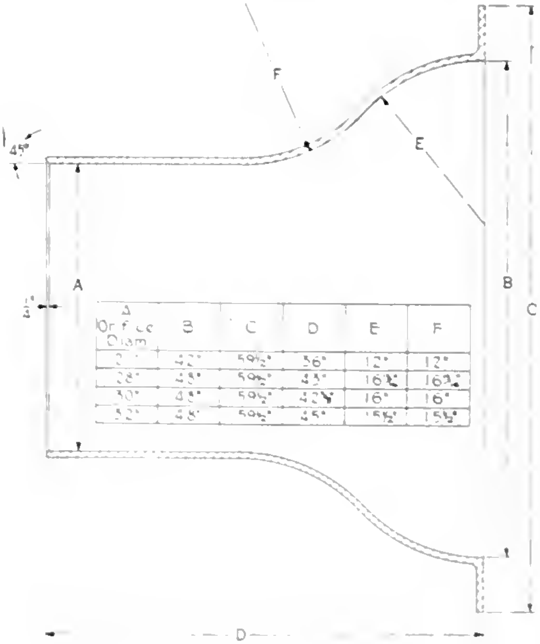
.118	.137	.136	.138	.145	.145	.140	.142	.139	.146	.146	.154	.142
.120	.122	.122	.130	.138	.148	.152	.159	.137	.128	.130	.150	.150
.129	.125	.107	.092	.095	.114	.141	.132	.102	.093	.094	.106	.127
.125	.120	.090	.082	.093	.102	.122	.100	.093	.060	.055	.063	.091
.106	.090	.070	.066	.074	.085	.110	.110	.083	.050	.050	.062	.085
.114	.090	.079	.084	.084	.100	.108	.144	.096	.064	.065	.079	.101
.109	.101	.098	.101	.109	.117	.121	.121	.117	.115	.098	.090	.096

19¼"

Bottom

Fig. 3. Diagram showing the Variation of Hook Gauge. Readings expressed in inches of water Over the Area of a Discharge Trunk Not Having Baffle Plates

Fig. 4 Orifice and Impact Tube



A Orifice Diam	B	C	D	E	F
[illegible]	42"	59½"	36"	12"	12"
28"	43"	59½"	43"	16¾"	16¾"
30"	45"	59½"	42¾"	16"	16"
32"	48"	59½"	45"	15½"	15½"

Fig. 5 Dimensions of Some Measuring Orifices

Tests of this sort had been resorted to more as a means of measuring the volume of ventilating air to check fan calculations than to measure the losses of the machines. Even for the former purpose, however, the measurements were cumbersome and arrangements

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* Journ. I. E. E. London, Vol. 57, April, 1919, Page 291.

were therefore made to make future tests by means of a calibrated orifice, such as is shown in Fig. 4. This latter method has been described in detail by Dr. S. A. Moss.*

These tests demonstrated not only the accuracy and accessibility of this method, but also the effect on the quantity of air by restrictions in the outlet ventilating ducts, as shown in Fig. 6. These curves show the effect of external restriction on the volume of ventilating air and the effect of volume on static pressure in the generator casing.† The apparatus required for this test consisted of a wooden elbow, a wooden pipe connecting the discharge under the generator base to an 18-foot straight length of 42-in. pipe, and standardized orifices of the general shape shown in Fig. 4. These were respectively of 21, 28, and 32-in. orifice diameter and produced restrictions at 3600 r.p.m. (see Fig. 5) of 0.844, 0.314, and 0.189 in. of H_2O respectively. Fig. 6 also demonstrates that with machines fitted with fans, which give practically constant pressure independent of the volume, the external restriction may approach 10 per cent of the static pressure without reducing the air volume an objectionable amount. The rotation losses indicated by the zero-field test were 24,100 watts at 3600 r.p.m. and 20,300 watts at 3000 r.p.m. or 1 per cent of the kilowatt rating.

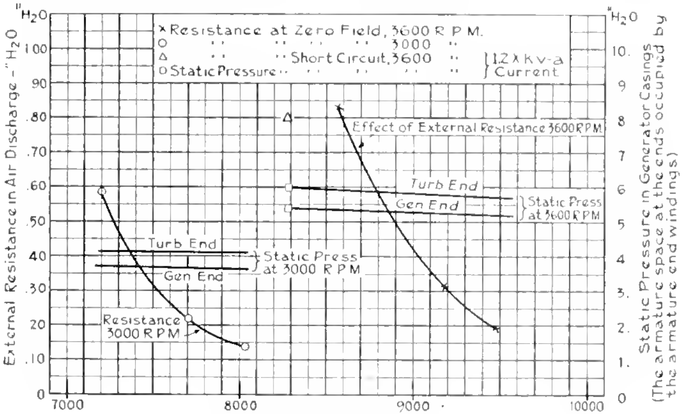

Fig. 6 Curves of Static Pressure in Turbine Generator Casing *vs.* Quantity of Standard Air

This method of measuring the volume of ventilating air is much more satisfactory than either of the methods described previously. Its only disadvantage is the necessity of providing a sufficient length of straight discharge pipe and the calibrated nozzles; but, when these are available, the quantity of air can be measured to within about 2 per cent.

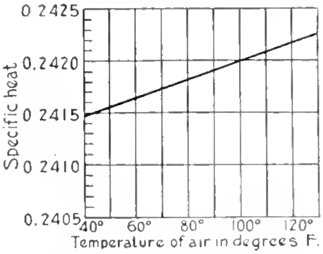

Fig. 7. Curve showing the Variation of the Specific Heat of Dry Air with Variation of Temperature. (From values determined by W. F. G. Swann.)

All measurements of air volume require correction to "standard air" which is defined as air at 60 deg. F. (15.55 deg. C.), having a barometric pressure of 14.7 lb. per sq. in. (29.92 in. mercury). The weight of such air is 0.0764 lb. per cu. ft. and its specific heat at constant pressure is 0.2416, as shown in Fig. 7.‡ Obviously the specific weight varies directly with the barometric pressure and inversely as the absolute temperature (60 deg. F. equals 519.5 deg. F. absolute), as shown by Fig. 8.

There is still another source of error, this being due to the moisture content as shown in Fig. 9, but it will be noted that even with 90 deg. F. inlet air, saturated, the correction is less than 1 per cent. Hence, this correction has not been included.

In the following formula for calculating the velocity and quantity of air through the discharge orifice:

α = inches of water shown by the hook gauge

β = inches of mercury (barometer)

27,700 represents the height in feet of a column of air having a pressure of 14.7 lb. per sq. in. and a uniform density of 0.0764 lb. per cu. ft.

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*"The Impact Tube," read before the American Society of Mechanical Engineers, Dec. 5, 1916.

† The annular spaces which are occupied by the armature end windings and into which the fans at the ends of the rotor discharge.

‡ Most tables and text books give this value as 0.237, but the values shown on the curve by W. F. S. Swann are considered more reliable.

27.7 represents the height in inches of a water column for one lb. per sq. in.

459.5 deg. F. is the absolute temperature of zero deg. F.

29.92 is the barometric reading corresponding to 14.7 lb. per sq. in.

$$\text{Velocity (Ft. Sec.)} = \text{Orifice Coeff} \sqrt{2gh}$$

$$= 0.99\sqrt{\frac{64.34\times 27.700\times \alpha}{14.7\times 27.7}}$$

$$= 0.99\sqrt{4375\times\alpha} = 65.6\sqrt{\alpha}$$

The above is correct only for "standard air."

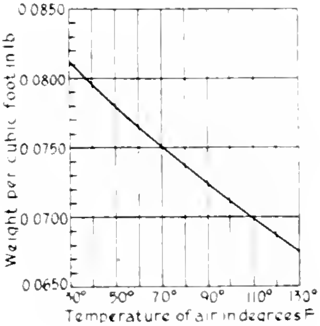

Fig. 8. Curve showing the Weight of a Cubic Foot of Dry Air at Various Temperatures (Barom 29.92 inches of mercury)*

Actual velocity of non-standard air

$$= 65.6\sqrt{\alpha\times\frac{459.5+T_3}{459.5+60}\times\frac{29.92}{\beta}}$$

$$= 65.6\times 0.24\sqrt{\frac{\alpha\times(459.5+T_3)}{\beta}}$$

$$= 15.72\sqrt{\frac{\alpha\times(459.5+T_3)}{\beta}}$$

Quantity (Cu. Ft. Min.) of "standard air" from measurements of non-standard air

$$= 60\times 15.72\times$$

$$\sqrt{\frac{\alpha\times(459.5+T_3)}{\beta}}\times\frac{519.5}{459.5+T_3}\times\frac{\beta}{29.92}\times\text{Sq. Ft.}$$

$$= 60\times 15.72\times 17.38\sqrt{\alpha}\times\sqrt{\frac{\beta}{459.5+T_3}}\times\text{Sq. Ft.}$$

$$= 16{,}380\sqrt{\alpha}\times\sqrt{\frac{\beta}{459.5+T_3}}\times\text{Sq. Ft.}$$

The heat carried off by one cubic foot of standard air per minute for one deg. C. rise equals:

$$\frac{\text{lb. per cu. ft.}\times\text{Sp. ht.}\times\dfrac{\text{Deg. F.}}{\text{Deg. C.}}\times\text{Ft. lb. in one B.t.u.}}{\text{Ft. lb. in one Watt-minute}}$$

$$= \frac{0.0764\times 0.2416\times 1.8\times 778}{\dfrac{33000}{746}} = 0.585$$

Second Method

It is obvious that if the inlet temperature and outlet temperature of the ventilating air are accurately recorded after having reached a steady value, and that if after the outlet air has passed the thermometers, an electric heater be introduced with sufficient energy to raise the temperature an amount equal to that caused by the losses of the machine, the energy dissipated in the heater will equal the losses. In practice, it is more convenient to supply a heater of fixed resistance with a constant input from a constant potential supply; the input being as large as possible, preferably equal to the full-load losses of the machine. In this case the following simple formula applies

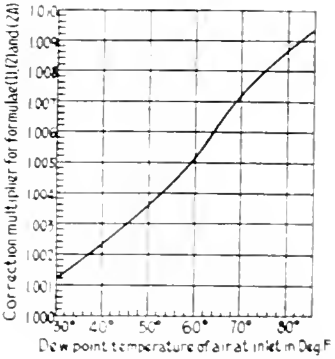

Fig. 9. Correction in Respect of Variation of Air Density and Specific Heat with Humidity. (This correction may be ignored for commercial work and is not taken into account in any of the formulæ.)*

$$\text{Loss in watts} = H\frac{T_2-T_1}{T_3-T_2}$$

wherein

T_1 = Inlet temperature
T_2 = Outlet temperature
T_3 = Temperature after passing the heater
H = Heater watts

This method has the advantage that cumbersome and expensive air flues and hook-

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* Journal I. E. E. (London) Vol. 57, April, 1919

gauge readings with awkward fluctuations are avoided. Also, there can be no dispute as to the specific heat of the air, the effect of humidity, or the corrections for temperature and barometer. The volume of standard air can be quickly computed from these tests:

$$\text{Volume} = \frac{\text{Heater watts}}{(T_3 - T_2) \times 0.585}$$

Tables I and II give data on air tests of a 3750-kv-a., 2300-volt, 3600-r.p.m. turbo-alternator. Mercurial thermometers were used for measuring the temperatures of the inlet air and outlet air in these tests,* and the volumes of the air were measured by a discharge pipe with calibrated orifice and "hook gauge." The tests indicate a considerable variation in the quantity of ventilating air. It is hard to explain why test No. 8 should show only 7850 cu. ft. of standard air while tests No. 11 should show 8750 cu. ft., but in spite of this apparent discrepancy, the load losses worked up as 5.32 kw. and 6.82 kw. respectively—a discrepancy of only about one per cent of the total losses.

One difficulty experienced was caused by the shape of the discharge elbow creating a centrifugal swirl which, impressed upon the discharged air was sufficient to give decidedly uneven readings across the calibrated orifice.

TABLE NO. I

Air Readings

3750 Kv-a. 2300 Volt, 3600 R.P.M. Turbo-Alternator.

28 in Orifice = 4.28 Sq. Ft.

Test Number	Hook Gauge Inches Water	Barometer Inches Mercury	Air Temperature at Nozzle T_3 in Degrees F.	Velocity (Ft. per Sec) reduced to "Standard Air" = $273\sqrt{''H_2O} \times \sqrt{\frac{''Hg}{459.5+T_3}}$
1	0.309	30.15	94.5	273 X 0.555 X 0.233 = 35.3
2	0 288	30.39	95.5	273 X 0.537 X 0.234 = 34.4
3	0 321	30.354	100.7	273 X 0.567 X 0.233 = 36.05
4	0.315	30 078	102.0	273 X 0.561 X 0.231 = 35.4
5	0.308	30.354	103 0	273 X 0.555 X 0 232 = 36.4
6	0 329	30.14	106 0	273 X 0.582 X 0.231 = 36.7
7	0.330	30.15	120.0	273 X 0.575 X 0.228 = 35.8
8	0.239	30 384	122.0	273 X 0.489 X 0.229 = 30.6
9	0.305	29.97	112.0	273 X 0 552 X 0.229 = 34.5
10	0.317	30.36	116.5	273 X 0.563 X 0.230 = 35.4
11	0 300	30.35	124.0	273 X 0 548 X 0.228 = 34.1

TABLE NO. II

Losses and Efficiencies By Air Tests

3750 Kv-a., 2300 Volt, 3600 R.P.M. Turbo-Alternator

Calibrated Orifice

Test Number	Kv-a. Load	Power Factor	Volts Arm.	Amp Arm	Volts Field	Amp Field	Air Degrees C. T_1	Air Degrees C. T_2	Cu Ft./Min Stand Air	Kw. Loss	Arm Rise Deg C.	Field Rise Deg.C.
1	Zero	Field	——	——	——	——	26.7	35.7	9070	47.7	7.4	7.6
2	Zero	Field	——	——	——	——	27.5	36.8	8840	48.2	10.0	7.7
3	100%	O.C	2300	——	38.5	850	25.3	40.0	9250	77.2	19 2	16.6
4	110%	O C.	2530	——	45.9	99 0	23.0	38.9	9100	85 0	20.0	28.2
5	100%	S.C.	——	941	53 7	111 5	24.5	41.0	9350	90 2	42.0	36.4
6	120%	S.C.	——	1140	67.0	133 6	23.2	43.0	9410	110.0	44.8	63 0
7	3770	100%	2270	960	73.0	141 8	29 0	53.3	9200	113.0	51 0	51 0
8	3760	80%	2260	960	100 6	180 4	29 0	54.0	7850	115 0	44 3	73.5
9	3700	100%	2280	935	70.0	140.0	28 0	48.0	8870	98.5	41.5	43.3
10	3900	100%	2200	990	75 0	142.0	Hg 31.2 El 27.8	50.0 47.3	9100	96.7	39.2	57.3
11	4020	82%	2260	1035	104.5	192 0	Hg 30.0 El 31.0	55.5 56.0	8750	121.3	47.0 46.0	77.0

Losses

Test Number	Convection *	Bearing Friction	Windage	Core Loss	I^2R Arm.	Load Loss	I^2R Field	I^2R Rheo	Total Loss	Per Cent Loss Full Load	Per Cent Loss ¾ Load	Per Cent Loss ½ Load	Kw Loss at Zero Load Normal Voltage
1	0 993	10.00	47.70	——	——	——	——	——	58.69	——	——	——	——
2	0 943	10.00	48.20	——	——	——	——	——	59.14	——	——	——	——
3	1.490	10.00	47.95	25.53	——	——	3.27	——	88.69	——	——	——	——
4	1.610	10.00	47.95	32.51	——	——	4.54	——	96.61	——	——	——	——
5	1 675	10.00	47 95	——	17.30	18.97	5.48	——	101.17	——	——	——	——
6	2 000	10.00	47.95	——	21 20	31.90	8.95	——	122.00	——	——	——	——
7	2 460	10.00	47.95	25 53	18.00	11 15	10.37	7.40	132.86	3.42	3.97	5.40	96.56
8	2 540	10.00	47.95	25.53	18.00	5.32	18.20	4 40	131.94	4 20	4.92	6.55	96.60
9	2 030	10 00	47.95	25 53	17.00	-1 78	9.80	7.70	118.23	3 10	——	——	——
10	1.910	10.00	47.95	25 53	19 10	-6 53	10.65	7 10	115.71	2.88	——	——	——
11	2.380	10.00	47.95	25 53	20.90	6.82	20.10	3 93	137.61	4 02	——	——	——

* Convection Surface = 180 X 45 = 8100 sq. in.

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* Electric thermometers were inserted as a check in tests Nos. 10 and 11, but the results are not tabulated.

Under more favorable conditions, the readings across the calibrated orifice vary less than one per cent from a single reading taken at the center. A wooden cross of boards, having an axial length equal to about twice the diameter of the discharge pipe, was placed at inlet of the pipe and eliminated the difficulty.

Another source of perplexity was the fact that on some readings, at least, there was a greater variation between the maximum and minimum readings of the inlet air than between the average of these readings and the average discharge temperature.

An insurance against errors due to improperly averaged air readings seems to lie in the use of electric resistance thermometers, either as a substitute or as a check to the mercurial thermometers. Very satisfactory results were obtained by plotting the complete cross section of both the inlet and outlet air with standard ten-ohm resistance coils arranged four in series and four in parallel, thus giving the average of 16 readings with what was in effect a ten-ohm coil. A specialized application of this principle, consisting of wooden frames exactly fitting the air inlets and air discharge pipes was made as follows: Wooden pegs were fitted to peripheries of these wooden frames and at approximately equal intervals. No. 24 (0.020-in.) copper wire was zigzagged around the wooden anchor pins, vertically on one side and horizontally on the other side of the wooden frame; in sufficient quantity to provide the standard resistance. Ten ohms (25 deg. C.) were provided in the discharge pipe and five ohms in each of the two inlet areas; the latter coils being connected in series. Actual temperatures, T_1, T_2 and T_3, were read on a standard temperature indicator wherein a standardized ten-ohm manganin wire resistance forms one arm of the Wheatstone bridge and the heated ten-ohm copper wire, under observation, forms the other arm of the bridge. A refinement of this method would be to substitute the ten-ohm coil T_2 for the constant resistance manganin coil of the instrument and to read T_1 and T_3 as differences instead of as actual temperatures. Besides automatically averaging the temperatures, the electric thermometer has the advantage that it can be placed sufficiently close to the machine to insure against any appreciable change in the air temperature between the source of energy loss and the thermometer. Also, the instrument for indicating the temperature is always visible and is fully accessible, while mercurial thermometers if properly placed are inaccessible.

It is natural to suggest that all of the generator losses are not indicated by the temperature rise of the ventilating air, particularly in respect to the heat radiated from the generator casing. Data vary as to the convection loss which ensues from a given area at a measured difference in temperature between the exposed surface and the room. Some data are available indicating that there is only $\frac{1}{140}$ of a watt dissipated per square inch for each degree centigrade difference in temperature. The writer, however, has noted a loss of approximately $\frac{1}{80}$ of a watt for each degree centigrade difference per square inch of black surface. This figure is used by the author in his computations and it appears that there is rather less than 5 per cent of the total loss radiated from the shell of a 500-kw. 3600-r.p.m. turbo-alternator and that the value drops to approximately two per cent in the case of a 3000-kw. machine. Certainly a fairly close approximation can be made by computing the area (in square inches) of the stator frame exposed on the inside to the heated air from the core, and on the outside to the room temperature, and assuming a loss of $\frac{1}{80}$ of a watt per square inch per degree centigrade temperature difference. Other losses consist of those in the bearings and in the field rheostat, where these are chargeable to the turbo-generator. Bearing losses can be computed from the bearing reactions and curves of co-efficient of friction, provided these factors are known. Where these data are not available, it is quite accurate to assume the loss equal to one third of one per cent of the kilowatt rating; where the generator is "maximum" rated, 3600 r.p.m. and 0.8 p-f.

The rheostat losses will be:

$$(\text{Fld. amp.}) \times (\text{Exciter volts} - \text{Collector ring volts}).$$

In respect to hand-wound electric resistance thermometers, it is important to guard against long spans of fine wire. There appears to be good evidence that these may be stretched sufficiently, by the pressure of rapidly moving air, to increase their resistance and impair their accuracy as much as one or two degrees. Where the span is great, it is best to wind the resistance wires as helices on glass or wooden rods, to mount these in the outside frame, and to connect the helices together. The supports of the helices must be thin enough and be spaced sufficiently far apart to prevent undue obstruction to the air flow.

Electric Heater

It seems advisable to utilize heaters specially built for the air tunnels employed, in order that the air be heated uniformly across the duct section. Excellent results were obtained from 0.015 by 1.5-in. German-silver ribbon having a resistance of about 150 ohms per square mil-foot. The ribbon was corrugated by being run through loosened gears having about ⅜-in. pitch. This provided sufficient resilience to prevent any slackness when heated and also increased the radiating surface for a given span. The strip was zigzagged vertically on one side and horizontally on the other side of a steel frame provided with pins having porcelain insulator supports and the ends were provided with ample terminals. Each frame was arranged to carry about 25 kw. and the frames were set in the discharge duct about eight inches apart. Due advantage was taken of the fact that, when in use, these heaters would be subject to a strong blast of air. A temperature rise of about 85 deg. C. was considered satisfactory and the expected heating was based on the formula:

$$\text{Deg. C. rise for one watt per sq. in.} = \frac{896}{\sqrt{\text{Air velocity, ft. per min.}}}$$

TABLE NO. III

Losses and Efficiencies By Air Tests

1250 Kv-a., 2300 Volt, 3600 R. P. M. Turbo-Alternator

Electric Heater Method

Test Number	Kv-a. Load	Power Factor	Volts Arm.	Amp. Arm.	Volts Field	Amp. Field	Air Degrees C.		Heater T_3-T_2	Heater Watts	Kw. T_2-T_1
							T_1	T_2			
1	Zero Field		—	—	—	—	Hg 29.4 E 131.5	33.2 36.0	15.5 14.5	48.670	12.0 15.1 Avg. = 13.55
2	110%	O. C.	2530	—	51.8	59.5	Hg 27.7 E 131.5	38.7 41.5	15.9 16.0	51.500	35.6 32.2 Avg. = 33.9
3	120%	S. C.	—	377	68.5	72.3	Hg 36.8 E 140.7	46.8 52.0	16.4 14.1	50.400	40.3 30.7 Avg. = 35.5
4	100%	80%	2300	314	110	102	Hg 33.1 E 137.2	47.2 52.8	16.3 14.4	50.030	43.2 54.2 Avg. = 48.7

Losses

Test Number	Convection *	Bearing Friction	Windage	Core Loss	I^2R Arm.	Load Loss	I^2R Field	I^2R Rheo.	Total Loss	Per Cent Loss			Kw Loss at Zero Load Normal Voltage
										Full Load	¾ Load	½ Load	
1	0.197	⅓% 3.333	12.00 13.55 15.10	—	—	—	—	—	15.53 17.08 18.65				
2	0.504	3.333	12.00 13.55 15.10	20.51 17.25 14.00	—	—	3.09	—	39.43 32.73 36.03				
3	0.508	3.333	12.00 13.55 15.10	—	12.08	10.52 4.19 -2.15	4.95	—	44.10 39.33 34.54				
4	0.720	3.333	12.00 13.55 15.10	16.90 14.20 11.50	8.90	-6.05 -6.32 7.5	11.20	1.53	48.53 53.11 59.76	5.03	5.88	7.60	38.35
5+	0.720	3.333	12.00 13.55 15.10	16.90 14.20 11.50	8.90	—	10.00	1.40	52.2	4.00	4.68	6.27	38.35

*Convection Surface = 3840 Sq. in. +Computed at 1.00 Power-Factor, 100% Kv-a.

A current of 139 amp. for each 0.015 by 1.5-in. ribbon gave 3.57 watts per sq. in. and consequently (with an air velocity of 1500 ft. per sec.) an expected rise of 82.5 deg. C. The current density was 6170 amp. per sq. in. Repeated heat runs of 3½ to 4 hours gave wholly satisfactory results, but due to the difficulty of placing thermometers no temperatures were taken. That the temperatures were conservative is shown by the fact that, on the initial tryout, the heater ribbon was zigzagged around wire nails driven into a

TABLE NO. IV

Losses and Efficiencies By Air Tests
3750 Kv-a., 3000 Volt, 3000 R.P.M. Turbo-Alternator
Electric Heater

Test Number	Kv-a Load	Power Factor	Volts Arm	Amp. Arm.	Volts Field	Amp Field	Air Degrees C		Heater	Heater	Kw	Arm Rise	Field Rise
							T1	T2	T3-T2	Watts	T2-T1	Deg. C	Deg. C
1	Zero	Field	—	—	—	—	Hg 297 El 30.7	34.5 36.8	11.3 12.7	49.5	21.10 23.80 Avg.= 22.45	11.3	12.2
2	110%	O.C.	3300	—	55.3	129	Hg 280 El 315	44.5 50.0	15.0 11.0	49.7	54.60 83.50 Avg.= 69.05	25.0	39.1
3	120%	S.C.	—	867	58.5	129	Hg 270 El 300	42.0 47.0	14.5 12.0	49.6	51.30 70.20 Avg.= 60.75	44.0	57.3
4	100%	80%	—	—	96.0	200	—	—	—	—	—	—	—

Losses

Test Number	Convection *	Bearing Friction	Windage	Core Loss	I^2R Arm.	Load Loss	I^2R Field	I^2R Rheo.	Total Loss	Per Cent Loss			Kw Loss at Zero Load Normal Voltage
										Full Load	¾ Load	½ Load	
1	0.573 0.850	10.0	21.10 23.80 Avg.= 22.45	—	—	—	—	—	31.67 34.65 Avg.= 33.16	—	—	—	
2	1.970 2.210	10.0	21.10 23.80 Avg.= 22.45	26.35 52.55 Avg.= 39.44	—	—	7.15	—	66.57 95.71 Avg.= 81.14	—	—	—	
3	1.790 2.030	10.0	21.10 23.80 Avg.= 22.45	—	22.0	0.65 16.85 Avg.= 8.81	7.55	—	63.09 82.23 Avg.= 72.66	—	—	—	
4	2.300	10.0	22.45	32.60	15.2	6.12	19.20	5.8	113.67	3.62	4.25	5.65	80.32

* Convection Surface = 180 X 53 = 9550 Sq. in.

TABLE NO. V

Losses and Efficiencies By Air Tests
4375 Kv-a., 3600 Volt, 3600 R.P.M. Turbo-Alternator
Electric Heater

Test Number	Kv-a Load	Power Factor	Volts Arm.	Amp. Arm.	Volts Field	Amp Field	Air Degrees C.		Heater	Heater	Kw	Arm Rise	Field Rise
							T1	T2	T3-T2	Watts	T2-T1	Deg. C.	Deg. C.
1	Zero	Field	—	—	—	—	Hg 24.0 El 26.5	33.0 35.5	9.6 10.0	49.3	46.2 44.4 Avg.= 45.3	12.5	6.03
2	110%	O.C.	3960	—	56.2	131	Hg 21.5 El 24.0	41.5 46.0	11.0 10.0	50.1	91.0 110.0 Avg.= 96.0	29.5	34.6
3	120%	S.C.	—	867	58.4	129	Hg 22.5 El 25.0	40.0 44.0	12.6 10.0	50.2	69.7 95.5 Avg.= 82.6	48.0	61.0
4	100%	80%	—	—	97.0	202	—	—	—	—	—	—	—

Losses

Test Number	Convection *	Bearing Friction	Windage	Core Loss	I^2R Arm	Load Loss	I^2R Field	I^2R Rheo	Total Loss	Per Cent Loss			Kw Loss at Zero Load Normal Voltage
										Full Load	¾ Load	½ Load	
1	1.070 1.070	12.0	46.2 44.4 Avg.= 45.3	—	—	—	—	—	59.27 57.07 Avg.= 58.37				
2	2.385 2.150	12.0	46.2 44.4 Avg.= 45.3	38.44 57.24 Avg.= 47.33	—	—	7.360	—	105.38 123.15 Avg.= 114.26				
3	2.090 2.260	12.0	46.2 44.4 Avg.= 45.3	—	22.0	6.08	7.540	—	85.79 109.76 Avg.= 96.77				
4	2.500	12.0	45.3	39.00	15.2	5.4	19.60	5.65	134.7	3.61	4.28	5.83	120.3

* Convection Surface = 180 X 53 = 9550 Sq. in.

frame of soft wood and there was no signs of charring after the experiments.

A few examples of air measurements, illustrating the different methods outlined in the foregoing and the results obtained, are given in Tables I, II, III, IV, and V.

The tests recorded in Table III were made by using the electric heater in the air discharge directly after the air had passed the thermometer indicating outlet temperatures (T_2). The air temperature was measured by both mercurial thermometers (H_g) and electric thermometers (E1). The results averaged from the two methods are also indicated.

It is difficult to reconcile some of the discrepancies observed, but the author favors the results from the mercurial thermometers in this particular test. He feels that the accuracy of the electric thermometers was impaired by the stretching and vibration of the unsupported resistance wires. It is hoped that this difficulty will be considerably reduced by winding the resistance wires as helices upon suitable supports.

As indicated in Table IV, no tests were run under energy load but efficiency at full load of 3000 kw. and 80 per cent power-factor was computed from the three tests made at zero field, 110 per cent voltage open circuit, and at 120 per cent kv-a. current short circuit. These tests were duplicated at 3600 r.p.m., Table V The open-circuit heat run was here made at the same flux as previously, the short-circuit heat run at the same current and the efficiency computed at a rating of 3600 kw., 80 per cent power-factor.

The tests were made by introducing an electric heater of approximately 50-kw. capacity just outside the thermometers measuring the discharge air. The tabulations indicate the H_g readings averaged from the mercurial thermometers, the E1 readings averaged from the resistance thermometers, and the average of these.

The efficiencies were computed from the average of the two methods.

It is interesting to note that, in spite of some apparent discrepancies, the full-load losses at the two speeds check within 1/100 of one per cent and that the losses at fractional load also agree very closely.

This machine shows the remarkably high efficiency of 96.4 at full load, 80 per cent power-factor.

As measured by mercurial thermometer, the short-circuit test run at 3600 r.p.m. shows a negative "load loss" of 6 kw. This is undoubtedly due to some error in the test.

The procedure in making such tests should be as follows wherever possible:

(1) Zero-field heat run. This will indicate the windage friction of the machine plus the power required to drive the self-contained rotor fans.

(2) Open-circuit heat run at normal voltage and also, if possible, at 110 per cent normal voltage. This will indicate the core loss by subtracting the windage loss and the loss occurring in the fields.

(3) Short-circuit tests at normal kilovolt-ampere current.

(4) Short-circuit tests at 120 per cent kilovolt-ampere current.

The load-loss can be obtained from test (3) by subtracting the windage loss, the I^2R loss of the armature, and the field loss (volt-amperes at the collector rings). The test at 120 per cent kv-a. current is used as a check. This load loss will include the short-circuit core loss, the loss due to the circulation of idle currents in the armature conductors, and whatever losses are induced in the pole pieces and the retaining rings by induction from the armature windings.*

(5) Full-load unity power-factor test.

(6) Full-load fractional power-factor (usually 80 per cent) test.

(7) Tests at full kilovolt-amperes and zero power-factor can sometimes be taken when (5) or (6) are not available on account of insufficient power. Such tests are valuable but (5) and (6) are preferable.

It is obvious that, to be reliable and to be in accordance with contract requirements, tests of this class should be continued long enough to insure constant temperature in the various parts of the machine as well as in the rise of the ventilating air. Our experience in this line of apparatus indicates that constant temperatures will be attained in from three to four hours.

Acknowledgment is made to the Turbine Department of the West Lynn factory for permission to publish the results of tests, and also to the Turbine Research Department for guidance and assistance in making the air tests and checking the formulæ.

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* It is important to observe that the load losses which exist on short circuit are often very greatly reduced when the machine is running at full voltage and rated power-factor, see Tables I and II. The A. I. E. E. Standardization Rules, 1918, page 458, provide that the load losses measured on short-circuit tests shall be charged against the efficiency of the machine. Our air tests have demonstrated that, in certain machines, this is a reasonable rule; but there are sufficient tests on other machines to show that load losses which are of considerable magnitude when measured on short-circuit test are practically eliminated at rated load and power-factor. Dr. S. F. Barclay pointed this out in his paper on "Mechanical Design of Turbo-alternator Rotor," page 482, Journal I. E. E. (London), Vol. 56, July, 1918.

Bearings and Lubrication for Vertical Shaft Alternators

By T. W. Gordon

Alternating-current Engineering Department, General Electric Company

We have published several articles in the Review on the new type of spring thrust bearing that has been developed for large vertical shaft machines. These articles dealt chiefly with the design of the bearing and the success that it has attained in actual installation. The present contribution discusses methods that have been adopted for lubricating and cooling this type of bearing. On some of the larger units a central station oiling system connecting with all main bearings is found to be necessary, and in such systems the arrangement of piping may be greatly simplified by careful study. In the smaller units a self-contained oiling system is often provided, which gives excellent results and requires very little attention.—Editor.

T. W Gordon

The usual vertical shaft alternator is equipped with a thrust bearing and two guide or steady bearings. The thrust bearing supports the weight of the rotor and is of first importance because of the very heavy loads often imposed upon it. The duty required of the guide bearings is less severe. Many conventional designs of horizontal journal bearings, with suitable changes in the oil grooves, may be used for vertical shafts.

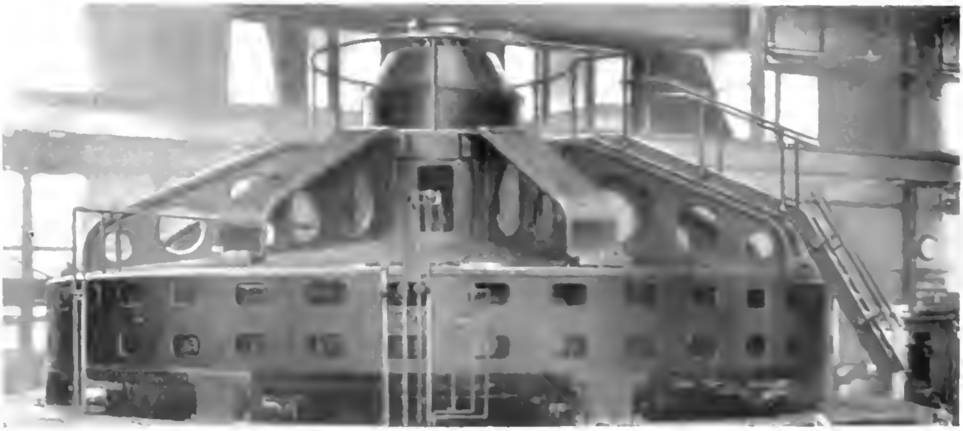


Fig 1 Modern Type of Large Vertical Waterwheel-driven Generator The thrust bearing is located at the top and supports the weight of the entire revolving element plus the water thrust

In the design of hydro-electric generating stations, the early practice of supporting the rotating parts of the generator and waterwheel on a step bearing below the generator has been discontinued. Now the combined weight of the generator rotor and turbine runner is suspended from a bridge or bearing deck, over the generator, on which the thrust bearing is located at the upper end of the shaft. Fig. 1 shows a standard type of vertical waterwheel-driven 2857-kv-a. 55.5-r.p.m. generator. The thrust bearing is located in the housing at the top and carries the entire weight of the revolving parts and the water thrust. The total load or downward thrust is 340,000 lb.

Fig. 2 shows a spring thrust bearing built for large vertical shaft hydro-electric generators. The rotating ring (standing on its edge) has radial oil grooves in the rubbing surface. This part is made of a special grade iron, and the bearing surface is ground and polished to a high degree. The stationary bearing ring (which is raised to show the springs and dowel pins) is made of steel with a babbitted rubbing surface. It is a continuous ring, but it has a saw cut in one oil groove to prevent any tendency of the plate to "dish" with a change in temperature. The total thickness of the babbitt is small as

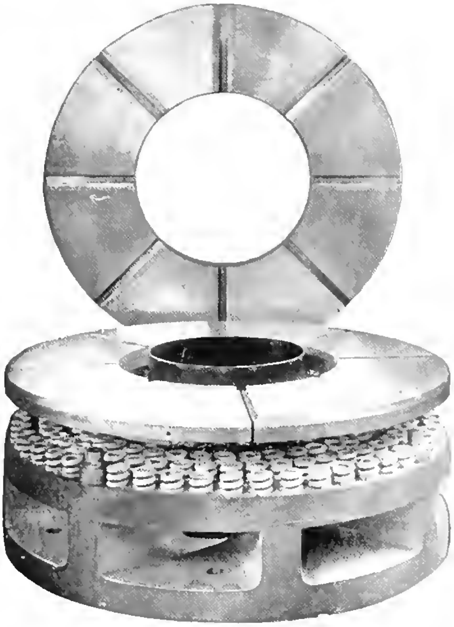


Fig. 2. Spring Thrust Bearing with Babbitted Stationary Ring Raised to Show Springs and Dowel Pins

compared with the diameter. This flexible ring rests on a multiplicity of steel springs, which press the babbitted surface against the rotating ring with approximately the same intensity at all points.

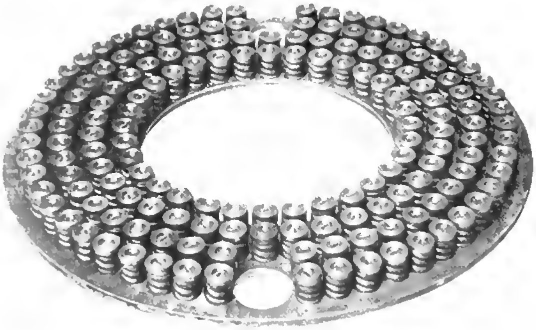
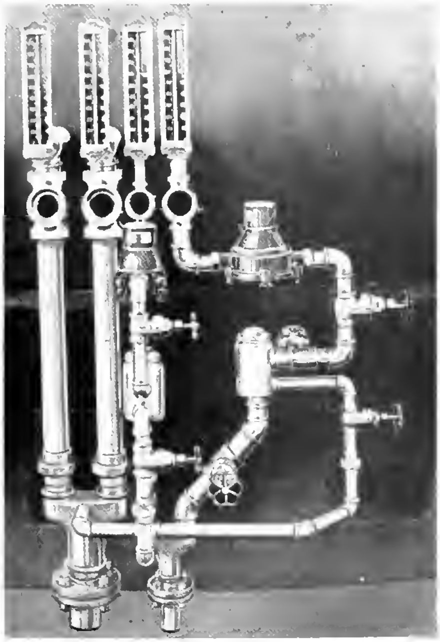
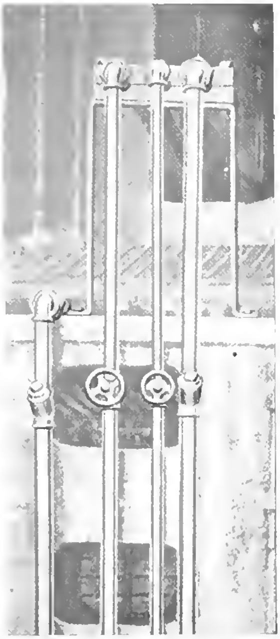


Fig. 3. Plate with "Compressed Springs" Used in Thrust Bearings for Machines Having Small Clearances

Heretofore, the aim of bearing designers has been to provide a very rigid support for the rotating part. Such bearings must be carefully fitted to the running surface in order to have the load well distributed. With an oil film of only about three ten-thousandths of an inch in thickness between the rubbing surfaces, it is quite evident that





Figs. 4 and 5. A comparison of these illustrations shows the extent to which oil piping may be simplified even with good machining and erection very severe conditions may exist in a rigidly supported thrust bearing. The spring supported thrust bearing furnishes the runner with a flexible support which will automatically adjust itself, while in operation, to any tendency toward unequal distribution of the load, caused by inaccuracies in workmanship or alignment. This flexibility is particularly advantageous in connection with large generators, which cannot be constructed as accurately as small ones. With the ever increasing size of hydro-electric units, the thrust bearing with a flexible support will be found superior to any of the rigid types.

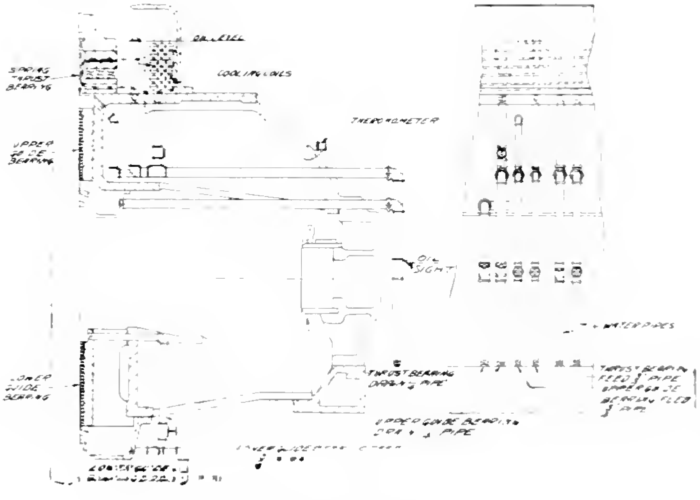


Fig. 6. Arrangement of oil and water pipes on large vertical-shaft generators when connected to a station oiling system

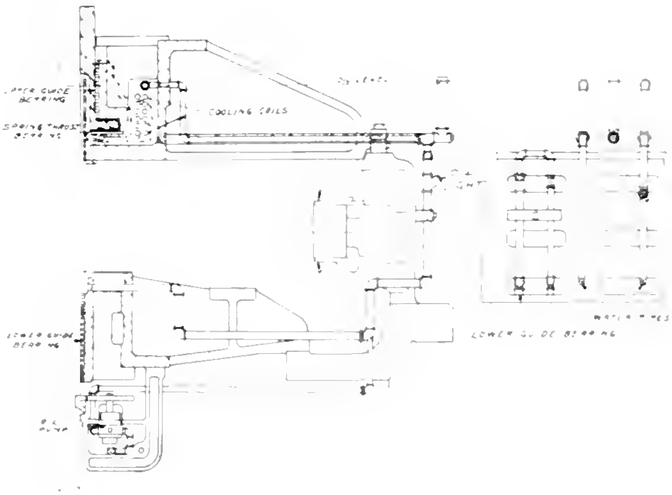


Fig. 7. Arrangement of oil and water pipes for self-oiling vertical-shaft generators having a combined thrust and upper bearing

Some of the smaller waterwheels have very little vertical clearance between the runner and the stationary parts. In such cases, it is sometimes desirable for convenience in erecting to precompress the springs to a position corresponding to full load on the bearing. This is accomplished by the use of washers and clamping screws. Fig. 3 shows a set of "compressed springs." When a bearing with compressed springs is installed there is no further deflection of the springs as a whole while the weights of the generator and waterwheel rotors are being placed on the thrust bearing. If, however, there are high local pressures on any part of the babbitt surface, the springs directly below will be further compressed and the pressure at these spots will be relieved before it reaches a value that will cause "wiping" to the babbitt.

Many power plants containing vertical shaft alternators have elaborate central station oiling systems for furnishing large quantities of oil for cooling the thrust bearings. These systems include an extensive equipment of large filters, tanks, pumps and pipe lines, together with thermometers, meters and any other devices which might aid in insuring a continuous supply of clean, cool oil to the generators. The installation of water cooling coils in the thrust bearing housing to remove a part or all of the heat from the bearing will allow of a considerable reduction in the capacity and cost of the lubricating system. Fig. 4 shows a typical installation of thermometers, integrating flow meters, oil sights, strainers, and large return pipes, such as has often been used on generators in the past. In addition to these thermometers, there is a recording thermometer on the thrust bearing housing with its bulb in the oil bath near the bearing. Thermometers in return pipes as here shown are apt to be unreliable because these pipes do not run full and the bulb of the thermometer is often not covered by the oil. On account of the small stream of oil passing through a guide bearing, there will be a considerable drop in the temperature of the oil before it reaches the thermometer at the outside of the machine. Oil sights in both feed and return pipes are not necessary and the records of the meters showing the amount of oil pumped per day are of little value.

The oil piping seen on the generator in Fig. 1 is sufficient to meet the requirements for successful operation of all bearings. The water pipes to the cooling coils in the thrust bearing housing are seen at the left of the photograph, and the valve connected to three small pipes at the right controls the operation of the brakes. The oil pipes are shown to better advantage in Fig. 5. A comparison of the equipments seen in Figs. 4 and 5 indicates the extent to which the oil piping may be simplified and the reduction in the size of pipes for the thrust bearing when cooling coils are used. The drain pipes have openings for observation of the oil flow. A mercury actuated indicating dial thermometer is mounted in a conspicuous place on the bearing bracket arm and is connected by a capillary tube to its bulb, which is in the oil bath near the thrust bearing. Thermometers for the guide bearing are not considered necessary.

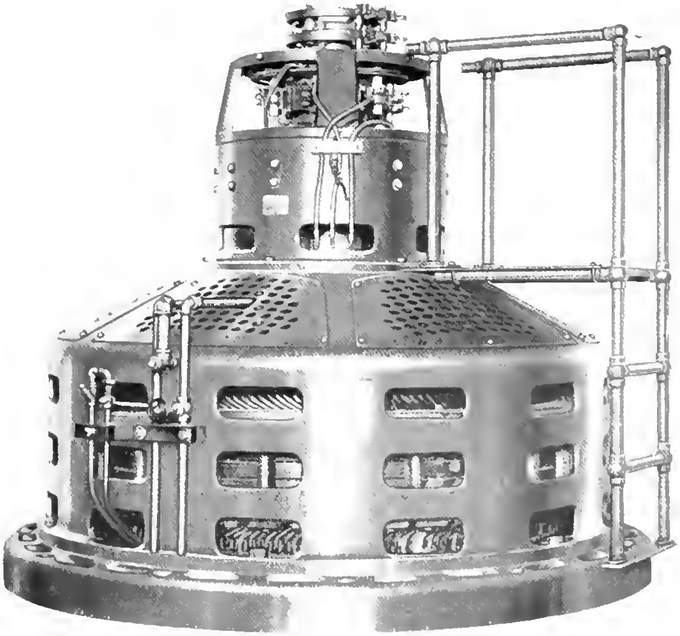


Fig. 8. A 1000-kv-a., 360-r.p.m. Waterwheel-driven Generator with Direct-connected Exciter. All bearings are self-oiling and a station oiling system is not required

Fig 9. Pump in Oil Pan of Lower Guide Bearing on Vertical Generators. One-half of pan removed for inspection of pump

Fig. 6 is a sketch showing the arrangement and size of pipes for a large high-speed generator connected to a station oiling system. All thrust bearing pipes pass under the platform and up to the oil space. With this arrangement the platform is free from obstructions. By using cooling coils in the thrust bearing housing, the oil required in one case was reduced from sixty gallons to five gallons per minute. Such a reduction in the oil for each generator makes possible a corresponding reduction in the size of the station oiling system.

It is very desirable to make the smaller units self-oiling and thus eliminate a central station system. Fig. 8 shows a 1000-kv-a. 360 r.p.m. generator which is self-oiling. The upper guide bearing is above the thrust bearing and runs in the same oil bath, from which the heat is removed by the water cooling coils. Fig. 7 shows the arrangement of bearings and oil piping on this self-oiling unit. There are radial grooves in the rotating surface of the thrust bearing which pump oil from the thrust bearing up through the upper guide bearing. The oil for the lower guide bearing is pumped up to a convenient height where the operator on the generator floor can regulate and observe the flow to this bearing. In the right-hand view the small pipe at the left comes from the pump and returns to the lower bearing. The pipe between the water coil connections is for filling and draining the thrust bearing housing. An oil pump is located in the drain pan of the lower guide and circulates the oil for this bearing. The pump is geared to the generator shaft and is mounted so that one half of the oil pan may be removed without disturbing either the pump or the discharge pipe leading to the floor above. Fig. 9 shows this arrangement. The oil in these generators is removed occasionally and the housings refilled with new or filtered oil.

Large generators, having the upper guide bearing below the thrust bearing, as in Fig. 6, are sometimes equipped with unit oiling systems. This is done by the addition of a pump located in the lower drain pan, as in Fig. 7. The returns from all bearings are taken to a small filter 30 by 15 by 30 inches deep mounted on the wall of the pit below the generator. The oil is pumped from the clean oil compartment of this filter to the bearings.

A Unique Design of Waterwheel-driven Alternator

By A. E. Glass

Alternating-Current Drafting Department, General Electric Company

The waterwheel-driven alternator described in this article is one of three which are being built to operate in a powerhouse hewed out of the solid rock of a mountain in Norway. The conditions which prevail in this most unusual installation have necessitated the adoption of a unique design for the generating units. These features of design are clearly explained and illustrated by the author. Editor.

A E. Glass

THE increasing demand for large waterwheel-driven alternators of high speed has led to the design of some rather unusual units, especially those of the 25-cycle type. These alternators are novel, not only in the method of ventilation, but in the construction of the revolving element or the "revolving field" as it is commonly called. Alternators of high rotative speed necessarily have high stresses. The unit is liable to an overspeed of from 80 to 100 per cent in case the electrical load is suddenly removed and the waterwheel governing mechanism fails to function. In order that no failures occur at this overspeed the rotors should be so designed that the stresses at the overspeed will not exceed one half the elastic limit of any of the material. These considerations lead to the use of as small a diameter as is consistent with other factors in the design. Therefore the core length of the alternator must be necessarily long for units of large capacity; and it is at once apparent that, with small diameter and long core length, ventilation becomes one of the most difficult problems. The location and layout of the power house is also a determining factor of design with respect to ventilation. The General Electric Co. has under construction three 25-cycle, 11,000-volt, 750-r.p.m. horizontal shaft generators for the Aktieselkabet, Saudefaldene, Norway, to be direct driven by waterwheels built by A S. Myrens Veakted, Christiana, Norway.

Generating Unit

Each unit consists of a generator, flywheel, direct-connected exciter, and waterwheel. The electrical part of the set consists of an alternator mounted between two bearings and an exciter overhung at one end. The mechanical part of the set consists of a flywheel mounted between two bearings with the waterwheel overhung. The generator, flywheel, and exciter are mounted on a common base. The bearing which supports the weight of the waterwheel runner must carry in addition a force of 2000 lb. due to water thrust Fig. 2 shows the general design of the unit. It is unusual to equip a unit of this design with a separate flywheel, but as a total WR^2 of 146,000 was required, and the generator WR^2 was but 84,000, the flywheel was necessary to make up the additional WR^2 of 62,000.

Construction Features of the Stator

The construction of the stator core is not novel, the usual ducts are provided for the passage of air through the core to the stator frame. The inside of the stator frame at the top is free of ribs to facilitate the passage of air through the frame to the exit. The stator coils are of the usual barrel type, connected one circuit Y for 14,000 volts, and are well supported from the stator frame to prevent vibration or distortion due to short circuits. The stator frame is split into two parts; and as there is no provision made for repairing the stator or rotor coils by sliding the stator along the base, the top half of the stator must be unbolted and some of the coils removed in case repairs to the stator winding are necessary.

Construction Features of the Rotor

Due to the small diameter of the rotor, and to the high peripheral speed of the poles, the usual definite pole construction could not be used. Instead of a laminated pole keyed directly to a spider, the loose or removable tip construction was adopted

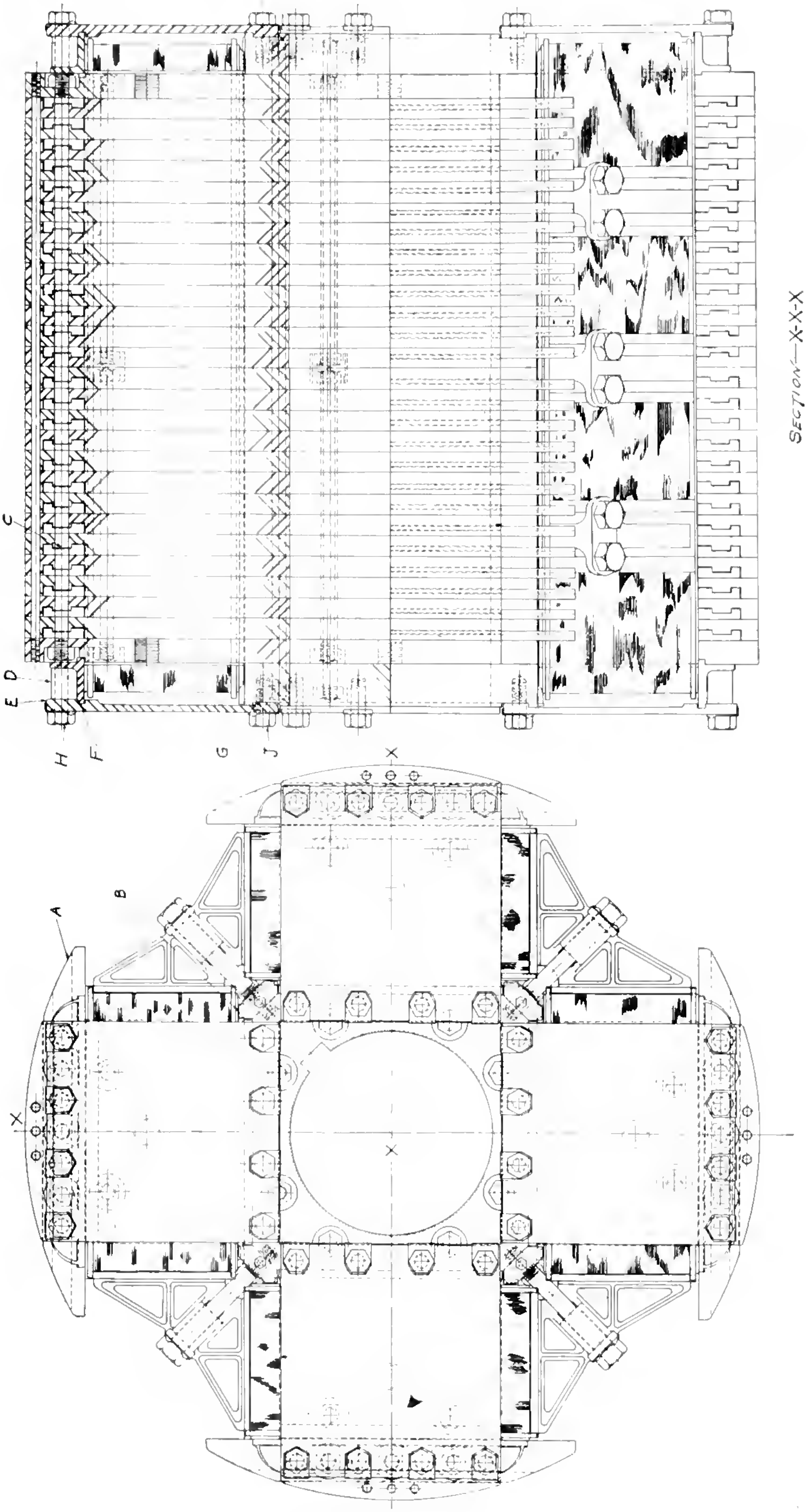


Fig. 1. Rotor Assembly of the 7000-kv-a., 750-r.p.m., 14,000-volt Alternator

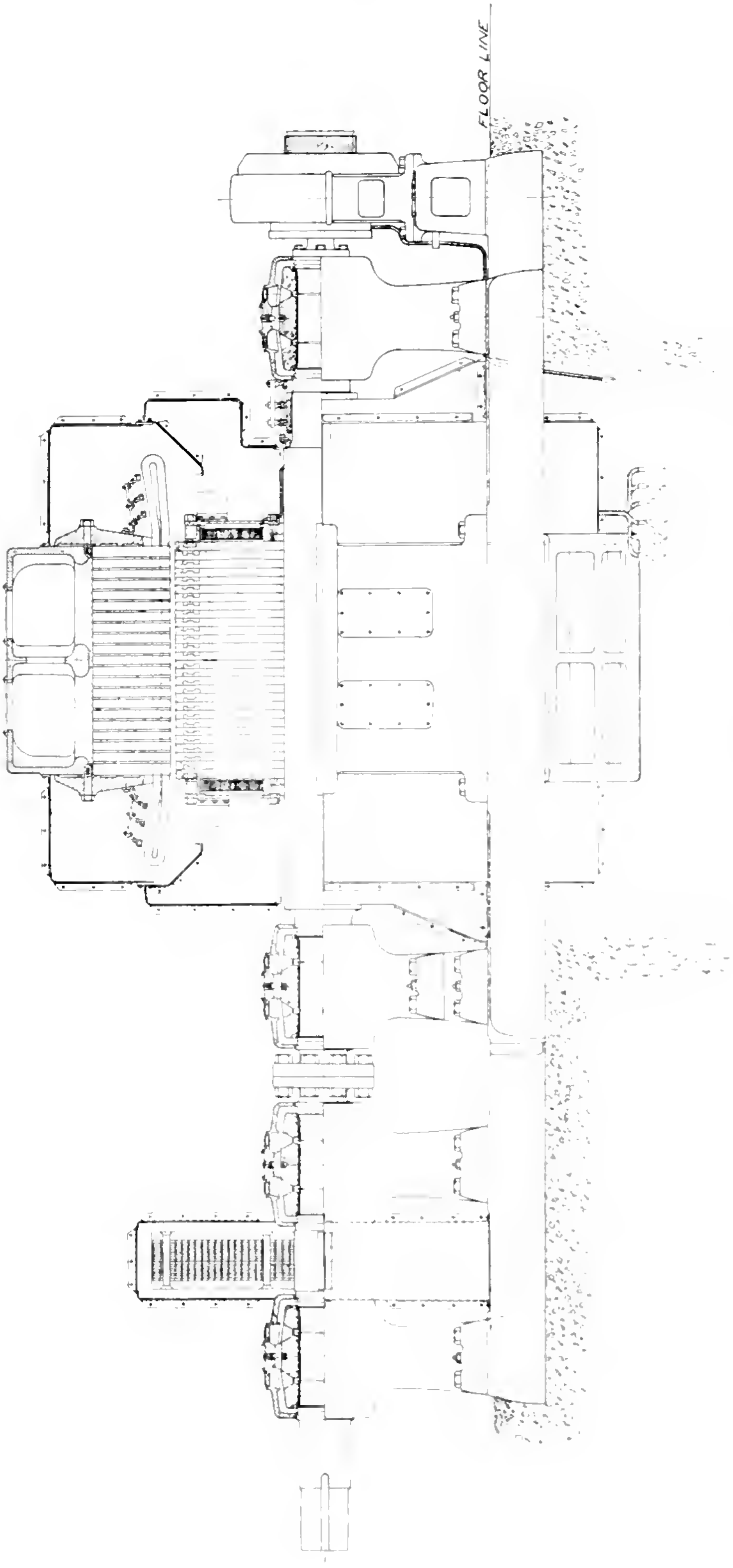


Fig. 2 General Arrangement of the Alternator, Exciter, Bearings, and Flywheel. The overhung waterwheel is not shown

in order that the rotor coils could be wound on a form and assembled separately or disassembled readily when making repairs. Fig. 1 shows the general design of the rotor.

The rotor body and poles consist of a series of steel plates machined to shape; each plate is slotted across the pole face at right angles to the shaft axis to receive the pole tip, which is a separate steel bar machined to the shape of a pole tip as shown at *A* in Fig. 1. After machining and drilling the individual plates, they are bolted together in two sections and these sections are again bolted together with through-bolts, the whole forming the revolving field without coils. The rotor complete is then shrunk onto the shaft; the shrink fit is required so that there will be a tight fit between rotor and shaft at the runaway speed of the rotor.

Rotor Coils

The rotor coil is of the usual ribbon type, wound edgewise on a form, furnished with top and bottom insulating collars and a metal retaining collar at the bottom of the coil. This retaining collar is slotted to receive keys for tightening the coil on the pole as shown at *B* in Fig. 1.

Rotor Coil Assembly

Each coil is well insulated and mounted directly on the pole body. The pole tips are inserted in the slots in the pole body, as shown at *C* in Fig. 1. Long bolts are then driven through holes provided in the pole body and pole tip to definitely lock the pole tips into position.

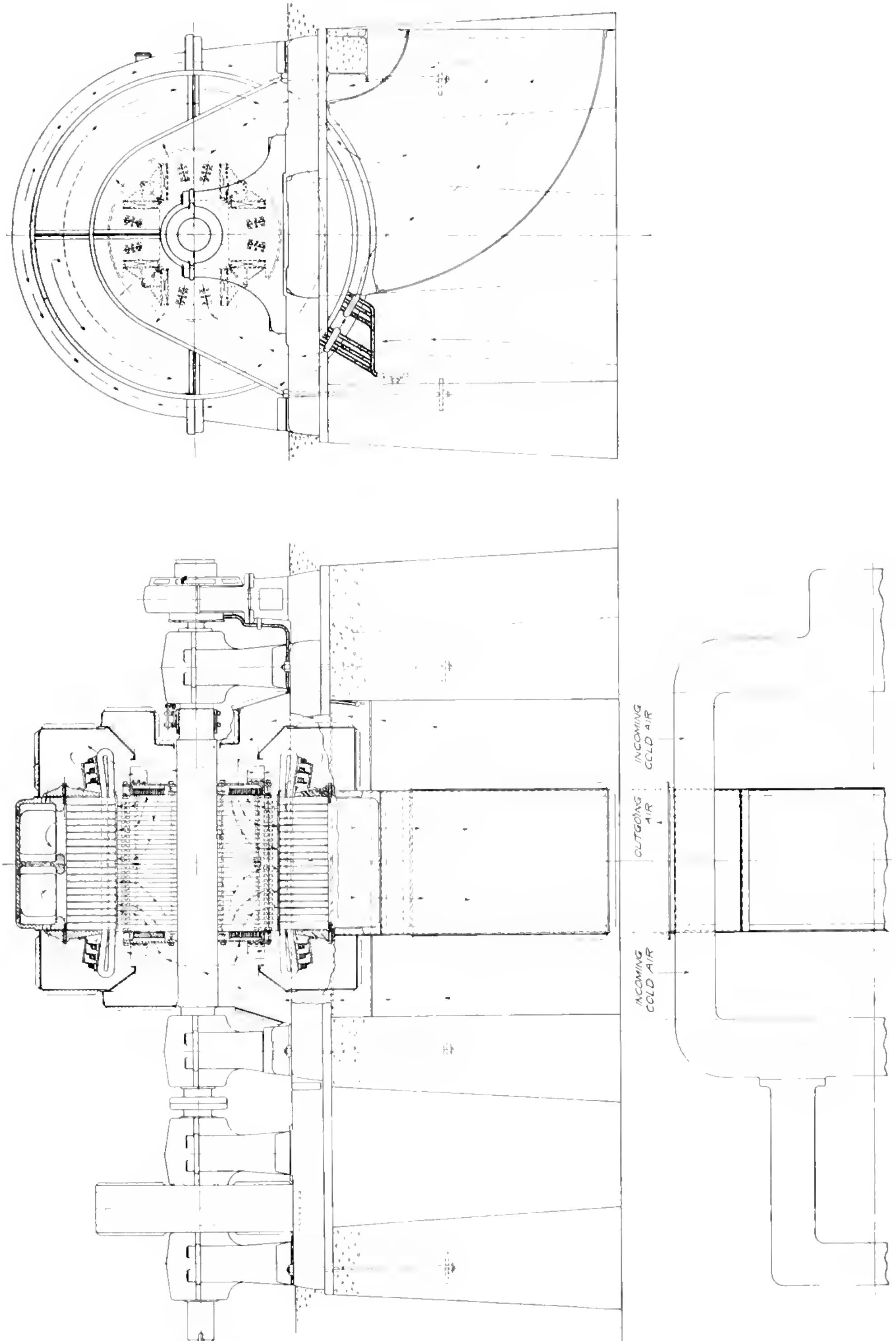


Fig. 3. Scheme Employed to Ventilate the Totally Enclosed Alternator

The distance piece, as shown at *D* in Fig. 1, is placed on top of the coil end. This distance piece is held and locked by a retaining plate shown at *E*, Fig. 1, this plate being rabbeted to the distance piece at *F* and to the lower coil support at *G* previously built up as part of the pole body. After the distance piece and retaining plates are assembled, bolts are inserted through the distance piece and plate at the top of the pole as shown at *H* and screwed directly into the pole body, and bolts are also inserted through the retaining plate at the bottom of the coil and screwed into the lower coil support as shown at *J*. All bolts are then carefully locked to prevent backing off.

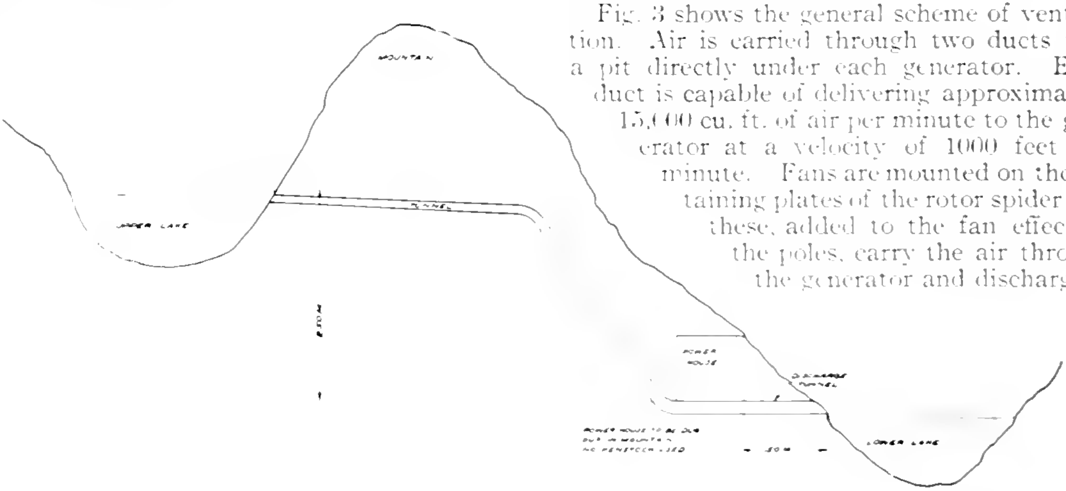


Fig 4 Sectional Elevation Showing the Unique Location of the Power House and Its Hydraulic Connections

Supporting brackets, well insulated from the coils, are then placed between adjacent coils and bolted directly to the pole body to prevent distortion of the coils due to the side strain produced by the large centrifugal forces in the rotor coils.

Balancing

Drilled and tapped holes are provided in the pole tip for the insertion of weights to balance the rotor. Each rotor is given a static and running balance after assembly, and a high-speed or runaway-speed test is then made after which all parts are carefully inspected.

Shipment

Due to the comparative inaccessibility of the power house and the mountainous nature of the country, the unit had to be so designed that no one part boxed for shipment would exceed 16,000 lb., hence the unit is split into a larger number of sections than is usual.

Ventilation

A glance at Fig. 4, representing the location and design of the power house, will show that the ventilation problem of the generator was a peculiar one. As all the air for the generators had to be taken into the station and discharged from it, the incoming and outgoing air ducts were located on the "down stream" side of the power house. The sheer rock of the mountain forms the other three walls of the power house; in other words, the power house is gouged out of the solid mountain rock.

Fig. 3 shows the general scheme of ventilation. Air is carried through two ducts into a pit directly under each generator. Each duct is capable of delivering approximately 15,000 cu. ft. of air per minute to the generator at a velocity of 1000 feet per minute. Fans are mounted on the retaining plates of the rotor spider and these, added to the fan effect of the poles, carry the air through the generator and discharge it into the stator frame, thence to an outgoing central duct directly under the stator frame and expel it outside the station. The generator is entirely enclosed above the floor line to prevent the escape of the ventilating air into the station. Ventilating hoods, attached to the stator frame, guide the air into the rotor.

Summary

The following figures give the relative weights and size of one of these units exclusive of the waterwheels. The length given includes the waterwheel shaft extension and exciter.

Stator weight complete (two halves)	70,000 lb.
Rotor, exclusive of shaft (two halves)	31,000 lb.
Flywheel	13,500 lb.
Total weight	150,500 lb.
Length overall	24 ft. 7½ in.

Belted Alternating-current Generators

By A. L. Hadley

Engineering Department, Fort Wayne Works, General Electric Company

This article describes the principal features in the construction of a line of small alternating-current generators ranging from 37½ kv-a. to 300 kv-a. These generators are used principally on lighting circuits, but also find a wide field of usefulness in supplying power to induction motors, heating devices, welding machines, etc. The machines are built according to the best practice in alternator design and require the minimum amount of attention in service.—Editor.

A. L. Hadley

THE advent of the high-efficiency tungsten and nitrogen-filled lamps has created an unusual demand for lighting generators. A 30-kw. generator using tungsten lamps will supply as much light as a 90-kw. generator using carbon lamps. Also, on the same basis, a 240-kw. machine equals a 720-kw. machine in lighting capacity. The substitution of nitrogen lamps for carbon lamps makes a 240-kw. generator equal to a 1200-kw. machine.

To meet this demand, a standard line of small belted generators is being built, in sizes ranging from $37\frac{1}{2}$ to 300 kv-a., 0.8 p-f., 50 deg rise (maximum rating) or rated in kilowatt sizes from 30 to 240 kw. These machines are built standard both for 60 and 50 cycles in the following voltages: 240/480 (same windings used by reconnecting), 1150/2300 (same windings used by reconnecting) and 600 volts. They are equipped with either three-phase or two-phase windings. Special machines of higher voltage are frequently built, up to 6600 volts. For 6600 volts, special stator punches and dies have been developed to provide for the extra insulation required. The kilowatt ratings, however, are reduced 20 per cent.

These machines although used in a large measure for lighting purposes are also used for supplying power to induction or synchronous motors, heating devices, welding machines, etc. For lighting purposes the generators may be belted to steam engines, gas engines, counter-shafts, or used as parts of motor-generator sets. Also they may be belted or direct connected to waterwheels of the vertical as well as the horizontal type. Fig. 1 shows a vertical-shaft alternator for direct coupling to a waterwheel; this unit has a direct-connected exciter mounted above the thrust and upper guide bearings.

These generators are frequently used for butt welding and spot welding, in which case the load is approximately 0.7 power-factor. Standard 125-volt fields are used but the excitation is taken from a 250-volt circuit with a large resistance in series. A special control is provided for short circuiting part of this resistance at the time the weld is made, thus rapidly boosting the field current and maintaining the generator voltage.

Fig. 1 Vertical Alternating-current Generator with Exciter Arranged for Direct Coupling to a Waterwheel

Fig. 2 shows a standard belted generator with belted exciter, and Fig. 3 a generator

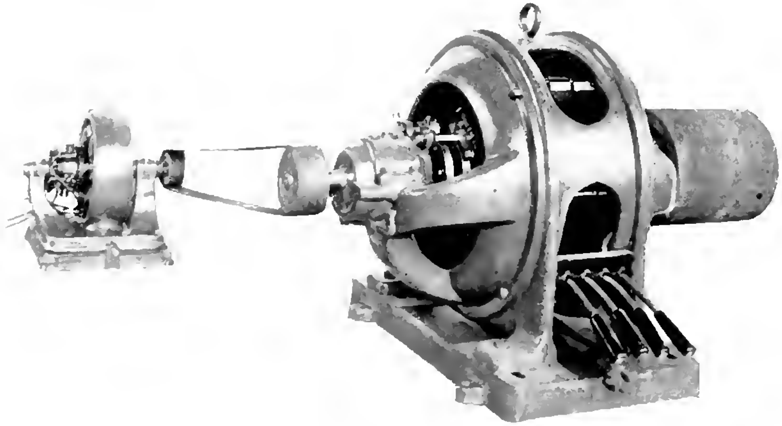


Fig. 2. Standard Belted Alternator and Exciter

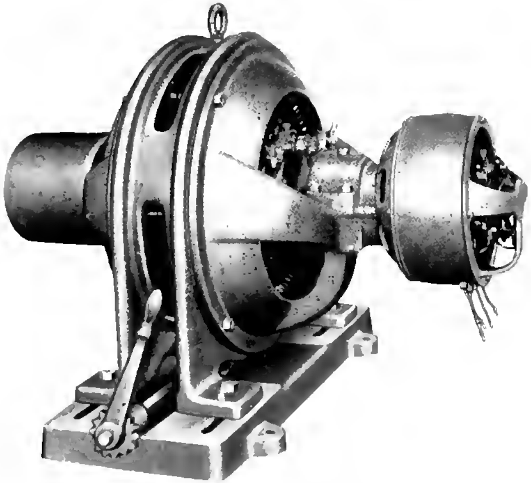


Fig. 3. Belted Alternator with Direct-connected Exciter

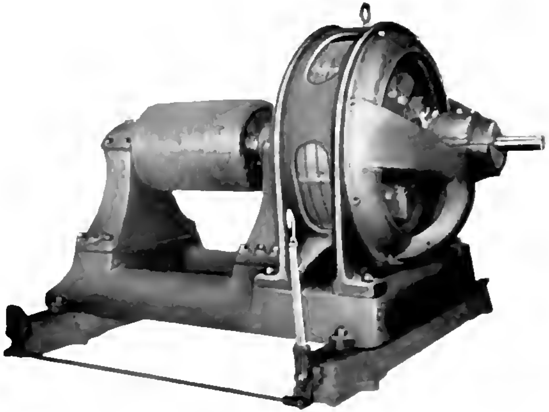


Fig. 4 Three-bearing Alternator Mounted on Slide Rails

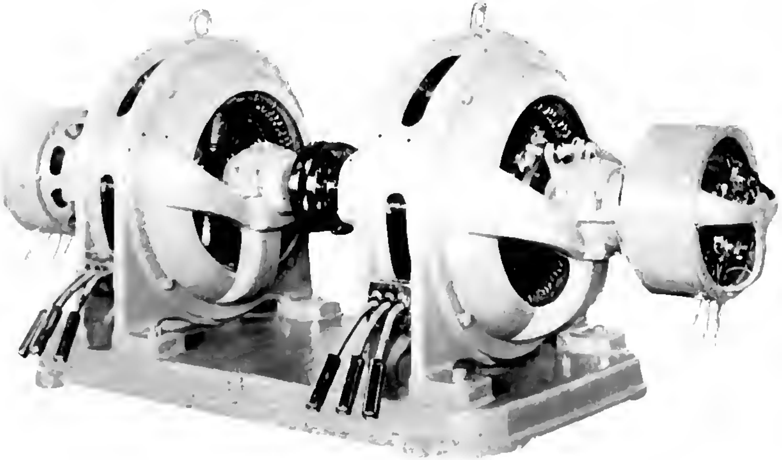


Fig. 5 Alternating Current to Alternating-current Motor-generator Set with Two Exciters

with direct-connected exciter. Fig. 4 shows a three-bearing 240-kw. generator with slide rails.

These machines have been used largely in motor-generator sets, transforming from direct current to alternating current; also from alternating current to alternating current for special applications where special control of the voltage was required, Figs. 5 and 13. These machines are also used in motor-generator sets, to transform from alternating-current to direct-current, the alternating-current machine being equipped with an amortisseur winding and being operated as a synchronous motor.

Stator

The stator frame consists of two castings made from the same pattern, split at right angles to the shaft, fitted together by an accurately machined rabbet joint and fastened together with heavy bolts extending through openings in the outer edge of the laminations outside the magnetic circuit; the two halves of the stator frame serve also as clamping rings for the stator laminations. This is illustrated by the laminations shown in Fig. 6.

The stator coils are machine wound, using rectangular wire, and are insulated and treated with tape and varnish to make them thoroughly moisture-proof. The stator core is made of thin sheets of electric steel punchings built up with generous air ducts for ventilation; the air passes freely through and around the ends of the core between the core and the stator frame castings. The air ducts are formed by I-beam separators spot welded to the laminations; these I-beams extend one against each tooth, thus making a very rigid, uniform construction. The stator frame castings are made with openings so that air can freely circulate through and around the core, providing exceptional means for ventilation.

End-Shield Bearing Brackets

The end shields are heavy castings each provided with three arms for supporting the bearing. They also have heavy flanges which extend over the ends of the stator coils, to serve as a protection against injury from the outside. These end flanges are bolted into recesses machined into the stator frame, and form a very rigid construction. The top half of the bearing housing consists of a cap which can be removed readily, thus facilitating inspection or removal of the split bearing without dismantling the remainder of the machine, Fig. 7. The bearing cap on the collector end has two cast-on lugs for supporting the brush studs that carry the brushes for the collector. Each bearing cap has two hinged oil hole covers which provide a ready means for inspecting the oil rings. The housing is made with a generous reservoir for oil, the lower portion of the housing being tapped with two holes, one on each side, so that the sight feed overflow oil gauge may be installed on either side. A pipe plug, in the side opposite the oil gauge, can be readily removed for draining the oil.

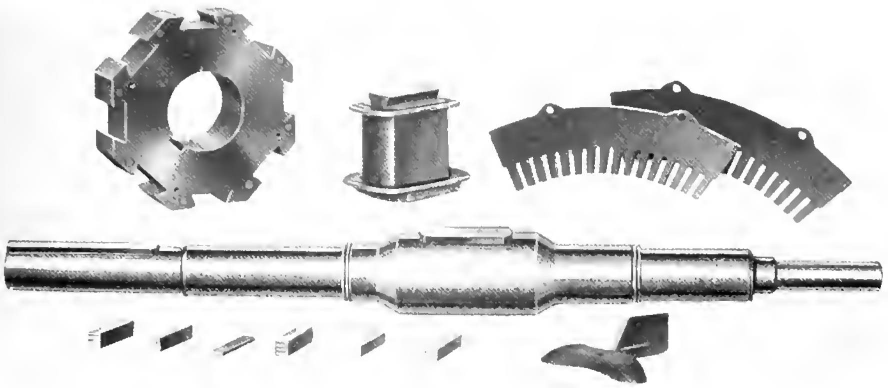


Fig. 6 Rotor Shaft, Spider, Pole, and Stator Laminations

Bearings

The bearings are split horizontally and are liberally designed for a large diameter shaft. They are of cast-iron, babbitt lined, and have two oil rings, Fig. 7. The collector-end and pulley-end bearings have the same diameter for each size of machine, the ratio of length

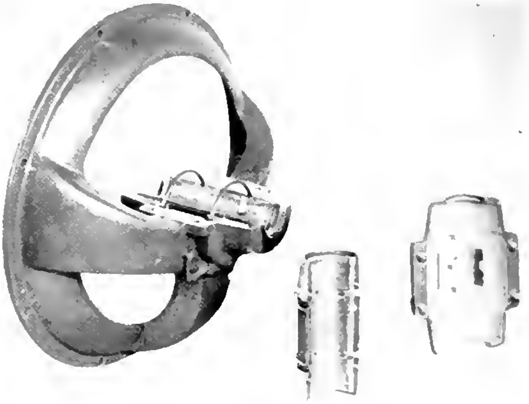


Fig. 7. End Shield showing the Ease with which the Bearing Can be Dismantled

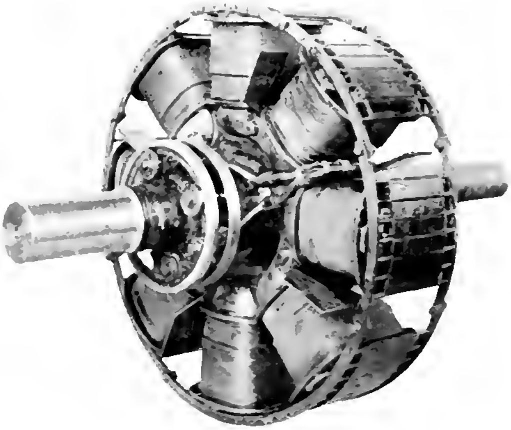


Fig. 8. Rotor with Amortisseur Winding for Synchronous Motor Operation

to diameter of the collector-end bearing being two to one, and that of the pulley-end bearing being three to one. Space is thus provided for the collector without detracting from the symmetrical appearance of the machine.

Rotor

The rotor spider is built up of $\frac{1}{16}$-in. thick laminations riveted together. These laminations have punched dove-tail openings for receiving the laminated pole pieces. Each pole piece is held in place by two small taper wedges driven in from opposite sides, to make a good mechanical and magnetic joint.

Pole Pieces

The pole pieces are made of $\frac{1}{16}$-in. thick laminations held together by heavy rivets through cast steel flanged end plates, the flanges being so made and located as to serve also as a support for the outer veneer board insulating washers. Each pole piece is carefully insulated, and together with the two veneer board washers, one at each end, serves as a form over which the field wire is wound and anchored. All rotor coils of each machine are alike, no rights and lefts, the leads being brought out between the coils from the end next the spider. This construction has several distinct advantages: (1) the wire is wound tight to the pole piece, making a better mechanical construction than if the coils were wound separately and afterwards placed on the pole, (2) the coils being wound tight to the poles, the heat is largely conducted through the pole piece, thus reducing the coil temperature, (3) the increased space between coils permits of better ventilation, (4) the losses are less due to the shorter mean length of turn, (5) all the coils being alike, fewer spare coils and pole pieces need to be carried in stock by the operator, and when ordering new coils there is no question as to what is wanted, and (6) the making of all the coil connections at the inner end of the poles next to spider, where the speed is less,

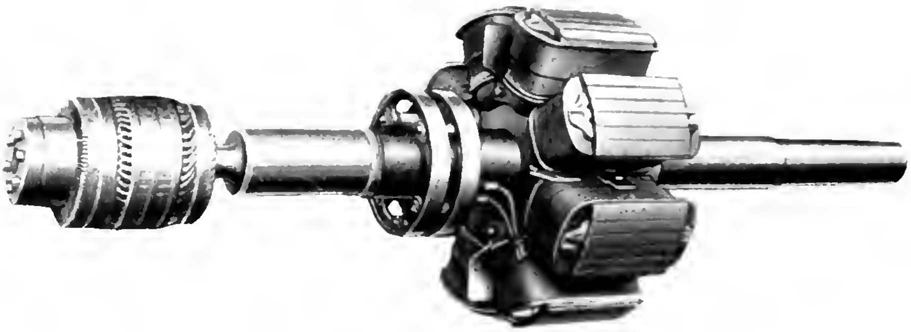


Fig. 9. Alternating-current Generator Rotor with Exciter Armature

insures against vibration and breakage of leads, and throwing out into the air gap. After the coils are wound on the pole pieces they are baked to expel moisture, and then filled with varnish and baked to make them moisture-proof. All pole pieces are built to permit of the use of an amortisseur winding for the synchronous motors of motor-generator sets, to facilitate parallel operation with other generators, for generators driven by gas engines, or for single-phase machines.

Collector Rings

The collector rings consist of two heavy cast-iron rings insulated from and mounted upon a cast-iron spider pressed on the shaft, as shown in Figs. 8 and 9. The rotor in Fig. 8 is equipped with an amortisseur winding, that in Fig. 9 has no such winding but has an exciter mounted on the same shaft. Both illustrations show the cast ventilating fans which are part of the end plates used for carrying balance weights and for covering the dove-tail joints between the poles and spider, to give the rotor a finished appearance.

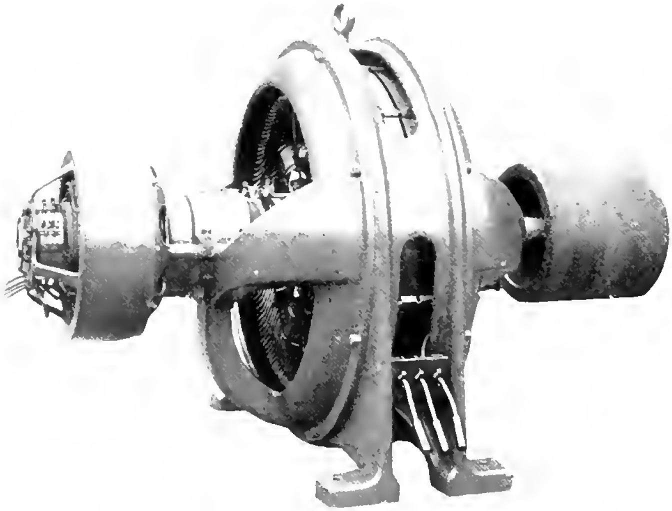


Fig 10. A Direct-connected Exciter and Its Alternator

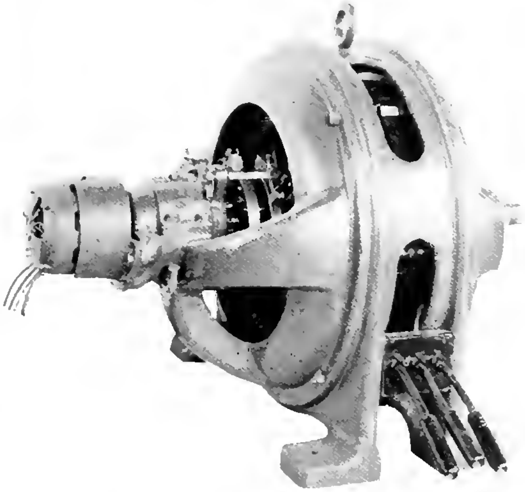


Fig 11 Alternator and Direct-connected Counter-electromotive-force Generator

Brush Holders

The brush-holders and brushes are liberal in size, there being two brushes for each ring, mounted in one holder in tandem. The use of two brushes per ring permits the removal of either brush without interfering with the operation of the machine. Furthermore, there is less likelihood of sparking in case

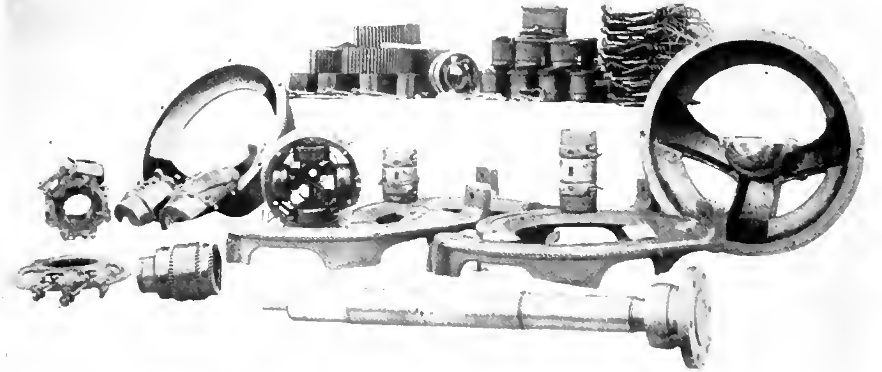


Fig 12. The Machine shown in Fig 10 as Dismantled for Mule Back Transportation

dirt or some foreign particle becomes lodged on the collector ring and lifts one brush at a time.

Shaft

The shaft is made of forged steel, is finished to size by grinding, and is equipped with heavy shoulders for taking the end thrust. A key is sunk in the shaft for driving the rotor spider which is pressed on by hydraulic pressure, Fig. 6.

Exciters

The exciters may be belt-driven or direct-driven. A belt-driven unit is shown in Fig. 2 and a direct-driven unit in Fig. 10. The direct-connected exciter is the more commonly used. Its exciter frame is mounted on the collector-end bearing housing, being held by means of a heavy cast-iron ventilated bracket which is fitted into a groove of and bolted to the bearing housing. The same shaft extension on the collector end may be used either for carrying the driving pulley for a belted exciter, or for carrying the armature of a direct-connected exciter. The direct-connected exciter armature is overhung, and does not have any outboard bearing. This construction is very simple, and for these belted alternators of comparatively high speed the size exciter is such that it costs very little if any more than the ordinary belted exciter which has to be equipped with sliding base, pulley, exciter belt, and exciter drive pulley. This combination of alternator with direct-connected exciter is usually used, one of the principal advantages being that it occupies less floor space.

Fig. 12 shows the various parts of the machine dismantled for mule back transportation, where the weight must be kept down to a certain minimum.

Fig. 11 shows a generator for a special application where the voltage control is effected by means of a small counter-electromotive-force generator mounted on the collector-end bearing.

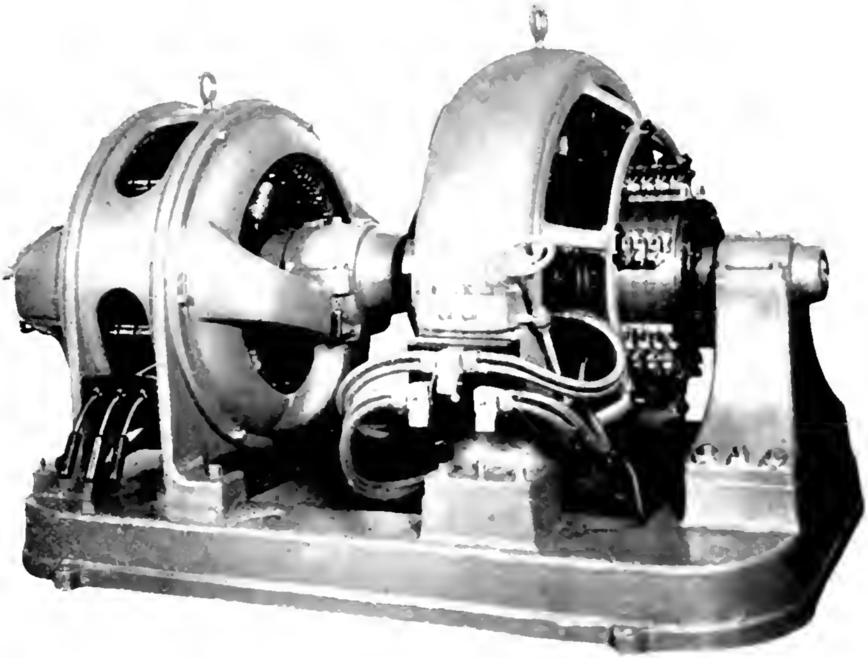


Fig. 13 Alternating-current to Direct-current Motor-generator Set

Sine Wave Testing Sets

By E. J. Burnham

Alternating-current Engineering Department, General Electric Company

There are many uses in the laboratory and in schools and colleges for a sine wave generator, and in response to this demand the sets described in this article have been developed. Oscillograms and test data show that the generator maintains practically a true sine wave of voltage from no load to full load unity power factor and full load zero power factor. The generator is specially useful for testing the magnetic properties of iron and for meter testing.—Editor.

E J Burnham

BECAUSE the sine wave is the ideal or standard form of voltage wave, a generator that will produce this wave under different load conditions is desirable in many kinds of electrical testing.

In iron testing, for example, it is very essential that the variation of the flux in the iron take the form of a sine wave and this can be obtained only by the use of a sine wave voltage. Meter calibration and testing are other applications which require a sine wave voltage. Schools and universities also are often in need of sine wave generators for use in their testing and laboratory work.

Development and Description of Generator

After careful study and investigation a special generator has been developed to meet these needs and any others that require an expectionally good wave form. This generator is made small and compact, is three-phase, four-pole, and of the revolving field type. At 1800 r.p.m. or 60 cycles it has a capacity of 5 kv-a. at 220 or 110 volts; and at 750 r.p.m. or 25 cycles it has a capacity of 2.1 kv-a. at 110 volts. The good wave form is in part due to the use of a large number of stator and rotor slots and to the use of a cylindrical rotor on which the exciting coils are displaced in phase. In addition, the rotor is enclosed in a magnetic sheath which maintains a sine-wave distribution of flux under the most severe conditions.

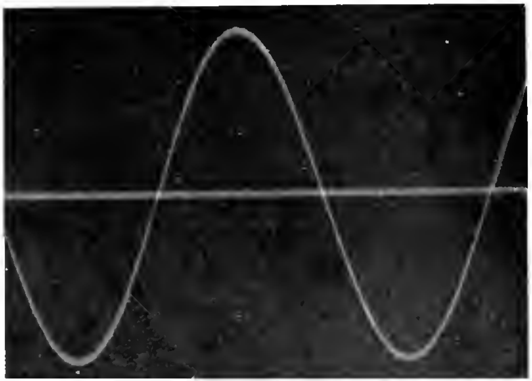
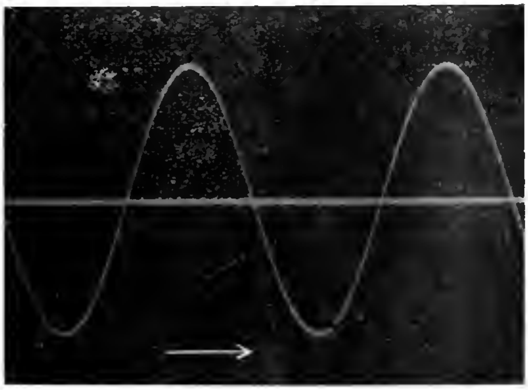


Fig 2 Full-load Unity Power-factor Voltage Oscillogram of the Sine Wave Testing Generator



[Fig 1 No-load Voltage Oscillogram of the Sine Wave Testing Generator

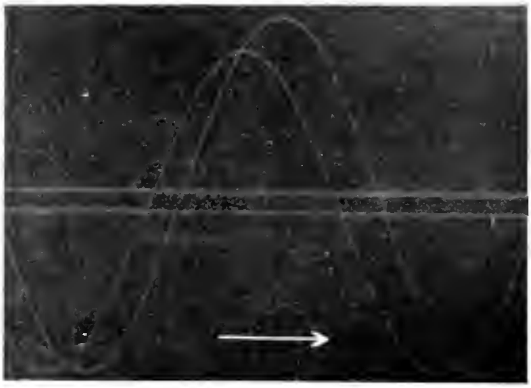


Fig 3 Full-load Zero Power-factor (leading Voltage Oscillogram lower curve of the Sine Wave Testing Generator

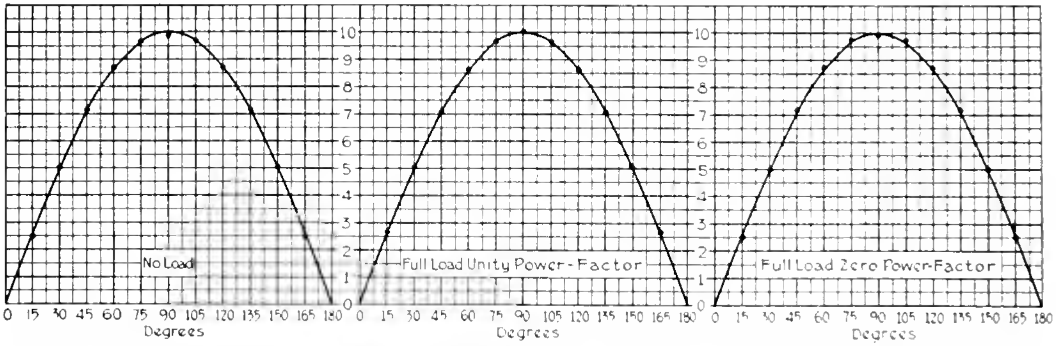


Fig. 4. No-load and Full-load Normal Voltage Waves of the Sine Wave Machine Compared with an Equivalent Sine Wave
The full line is the Equivalent Sine Wave; the dots are points plotted from the Machine Voltage Wave
For a tabulur comparison see Table II

If a phase displacement between voltage and current is desired, as in meter testing, one of the generators can be furnished with a special device for shifting the stator.

The generator is capable of operating under a wide range of load conditions. Many different voltages may be obtained by connecting the leads of the stator windings in Y or delta, and for either one or two circuits per phase. A total of 13 leads as shown in Fig. 5 are brought out from the machine, one of which is for a special connection to be used in iron testing. The frequency may be varied between 60 and 25 cycles by varying the speed of the generator between 1800 and 750 r.p.m.

Mechanical Arrangement of Sets

In order to meet the different uses and driving requirements, arrangements have been made so that the generator may be used alone as a single unit or with a driving motor in either a two-unit or a three-unit set.

Single-unit Set

The single-unit set is mounted on a sliding base and has a driving pulley.

Two-unit Set

Fig. 5 shows a standard two-unit set in which the generator is direct connected to an 8-h.p., 1800 750-r.p.m. direct-current driving motor. If alternating current only is available, an induction motor may be substituted for the direct-current driving motor. In such a case speed variation cannot be obtained.

As it is often convenient to use the machine as a single-phase generator, Table I is given to show its capacity single-phase and three-phase for both 60 and 25 cycles.

TABLE I

SINGLE-PHASE AND THREE-PHASE, 60 AND 25-CYCLE CAPACITY OF THE SINE-WAVE TESTING GENERATOR

Phases	Cycles	Kv-a.
3	60	5.0
3	25	2.1
1	60	3.5
1	25	1.47

A comparison of the no-load and full-load voltage waves of the machine with an equivalent sine wave is given in Fig. 4 and Table II. The deviation from a sine wave, as given

TABLE II

NO-LOAD AND FULL-LOAD NORMAL VOLTAGE VALUES OF THE SINE WAVE TESTING GENERATOR COMPARED TO THOSE OF AN EQUIVALENT SINE WAVE

Degrees	NO-LOAD			FULL-LOAD UNITY POWER-FACTOR			FULL-LOAD ZERO POWER-FACTOR		
	Ordinates		Per Cent Deviation from Sine Wave	Ordinates		Per Cent Deviation from Sine Wave	Ordinates		Per Cent Deviation from Sine Wave
	Voltage Wave	Equivalent Sine Wave		Voltage Wave	Equivalent Sine Wave		Voltage Wave	Equivalent Sine Wave	
0	0	0	0.0	0	0	0.0	0	0	0.0
15	2.50	2.58	0.8	2.67	2.58	0.9	2.50	2.58	0.8
30	5.02	5.00	0.2	5.03	5.00	0.3	5.00	5.00	0.0
45	7.12	7.07	0.5	7.08	7.07	0.1	7.18	7.07	1.1
60	8.70	8.66	0.4	8.62	8.66	0.4	8.72	8.66	0.6
75	9.66	9.66	0.0	9.65	9.66	0.1	9.75	9.66	0.9
90	9.85	10.00	1.5	10.05	10.00	0.5	9.90	10.00	1.0

in Table II, is found according to the A.I.E.E. Standardization Rules; i.e., by placing the equivalent sine wave on the actual wave so to give the least difference between ordinates, and then determining the deviation by dividing the maximum difference between corresponding ordinates by the maximum value of the sine wave.

It will be noticed in Table II that the maximum deviation of the voltage wave from the equivalent sine wave is only 1.5 per cent. In fact, the deviation is so small that when points from the voltage wave are plotted, as in Fig. 4, they apparently fall on the equivalent sine wave.

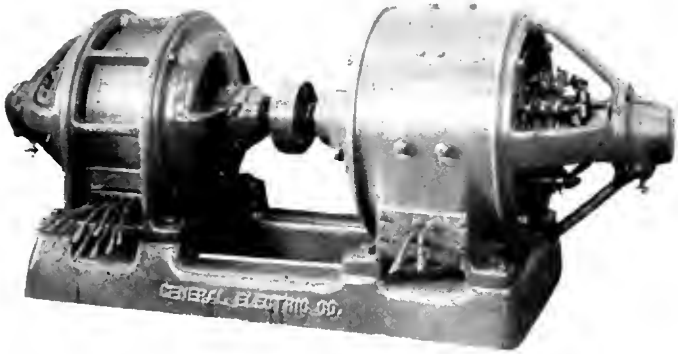


Fig. 5. Two-unit Sine Wave Testing Set: Sine Wave Generator at left, and Direct-current Driving Motor at right

Three-unit Set

The standard three-unit set is shown in Figs. 6 and 7, in which two of the sine-wave generators are direct connected to a 16-h.p., 1800/750-r.p.m. direct-current driving motor. The inner bearing bracket has been omitted on one of the generators so that the machines may be assembled closer together, thereby minimizing floor space. The

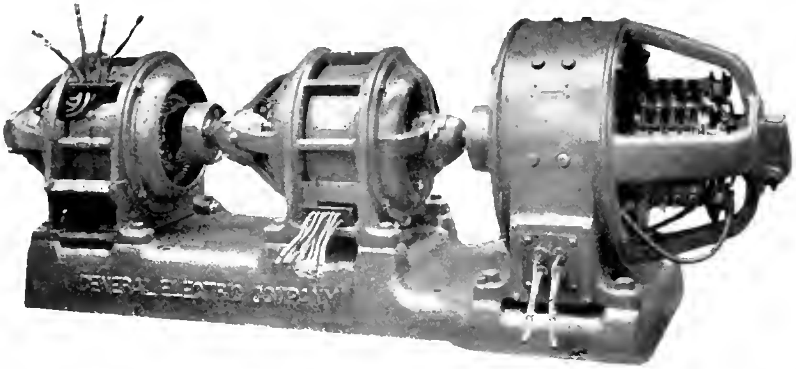


Fig. 6. Front View of the Three-unit Sine Wave Testing Set, Driven by the Direct-current Motor on the right. The machine in the center is a High-voltage Low-current Stationary-frame Sine Wave Generator. The machine at the left is similar to the one in the center except that it is wound for Low-voltage High-current, and its Stator is adjustable

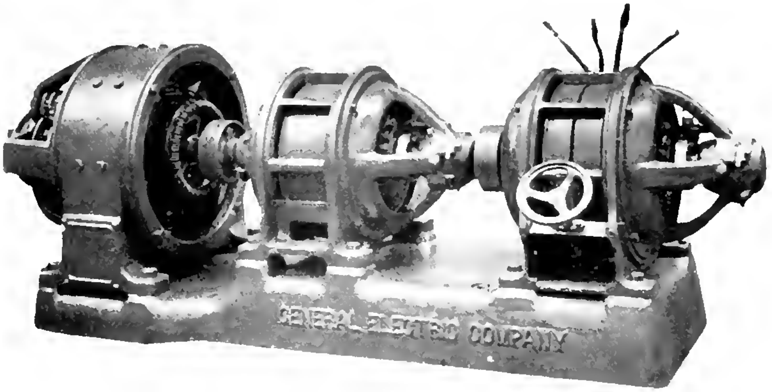


Fig. 7. Rear View of the Three-unit Sine Wave Testing Set Shown in Fig 6 The hand wheel on the right-hand Generator is used to adjust the Stator in its cradle

base is strong and self-supporting, so the assembled set can be easily lifted from one place to another. Fig. 7 shows the phase-shifting device, which consists of a hand wheel, worm, and worm segment for shifting the stator frame of one of the machines.

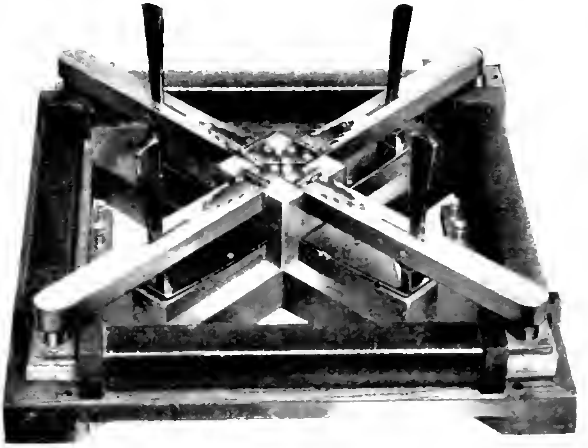


Fig 8. Apparatus for Testing the Magnetic Properties of Sheet Iron

The worm segment is of sufficient length for rotating the frame 50 mechanical or 100 electrical degrees in either direction from the neutral position. The armature windings of the two generators are different because one of the generators is used for current and the other for voltage, hence one is designed for low voltage and high current while the other is designed for low current and high voltage. Fig. 6 shows the adjustable frame 20-volt generator used as the high current low-voltage machine. The four leads from the stator windings, one of which is the netural, are brought out near the top of the machine as shown so they will not interfere with the rotation of the frame.

Iron Testing

The sine-wave generator either as a single-unit or as part of a two unit set is extensively used for testing iron. For testing sheet iron conveniently and accurately the use of the (General Electric) Epstein Tester in connection with the sine wave generator is recommended. Fig. 8 shows the essential part of the Epstein tester with sample sheet iron held in place in the coils by clamps. Fig. 9 shows the diagram of connections to be used in making the tests. Fig. 10 shows that the form factor of a sine wave, namely, 1.11, is practically maintained under the severe distorting effect of the magnetizing current in the testing of iron.

Meter Testing

The three-unit set described is very useful for calibrating and testing wattmeters and also for many other kinds of work where it is necessary to make tests at different power-factors. In wattmeter testing, the 20-volt or high-current generator is used to excite the current coil of the wattmeter and the 220/110-volt or high-voltage generator is used to excite the voltage coil of the wattmeter. The desired power-factor setting is then obtained by mechanically shifting the stator of the adjustable frame machine.

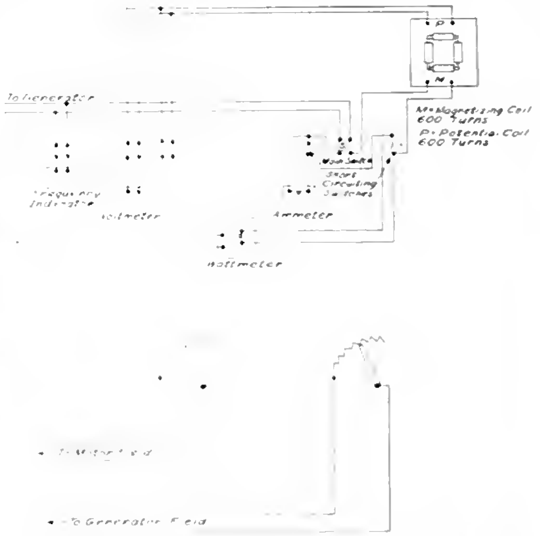


Fig 9 Diagram of Connections for Testing the Magnetic Properties of Sheet Iron by the Use of the Sine Wave Generator and the Apparatus Shown in Fig. 8


Fig 10 Voltage and Exciting Current Wave of the Sine Wave Testing Generator While Testing Iron Sample by Method Shown in Fig 9 Form Factor 1.115

IN MEMORIAM

T S. EDEN

Timothy Sharpe Eden, Engineer in Charge of the Generator and Synchronous Motor Division of the Alternating Current Department of the General Electric Company, died on Wednesday morning, October 1, 1919, following a brief illness. To those who knew Mr. Eden best, his passing came with the force of a personal grief.

Mr. Eden was born on the island of Jamaica, W. I., where he received his early education in a private high school. On coming to the United States in 1892, he entered Lehigh University. After graduating from Lehigh in 1896, he was employed by the Bethlehem Steel Company at Bethlehem, Pa., as an assistant metallurgical engineer. In September, 1897, he entered the Drafting Department of the General Electric Company, and in January, 1900, was transferred to the Alternating Current Engineering Department, where he remained until his death.

In the death of Mr. Eden, the General Electric Company has lost a faithful and able engineer. He possessed, to an unusual degree, the qualifications of the ideal designing engineer—a good sense of proportion, a well trained mind of mathematical bent, great care in the consideration of alternatives, patience in working out details, a good memory, sound and sober judgment. He seemed to delight to be in close touch with his machines as they came through the shops, the test, and the installation, and after they were put into service by customers. He was respected by his fellow workers who accepted his opinion in engineering matters with great confidence.

Mr. Eden was indeed much beloved by his friends and associates for his amiable qualities of mind and heart, never sparing himself when he could be of service to others. He won his way to their hearts where he will long be held in esteem.

Besides his wife, Mr. Eden is survived by his mother, a stepfather and three half sisters, Alice, Elsie and Winnie, all of Jamaica; one brother, Alfred, of East Orange, N. J., two half brothers, Dr. Arthur Henderson, of Montreal, and Brooke Henderson, of New York City.

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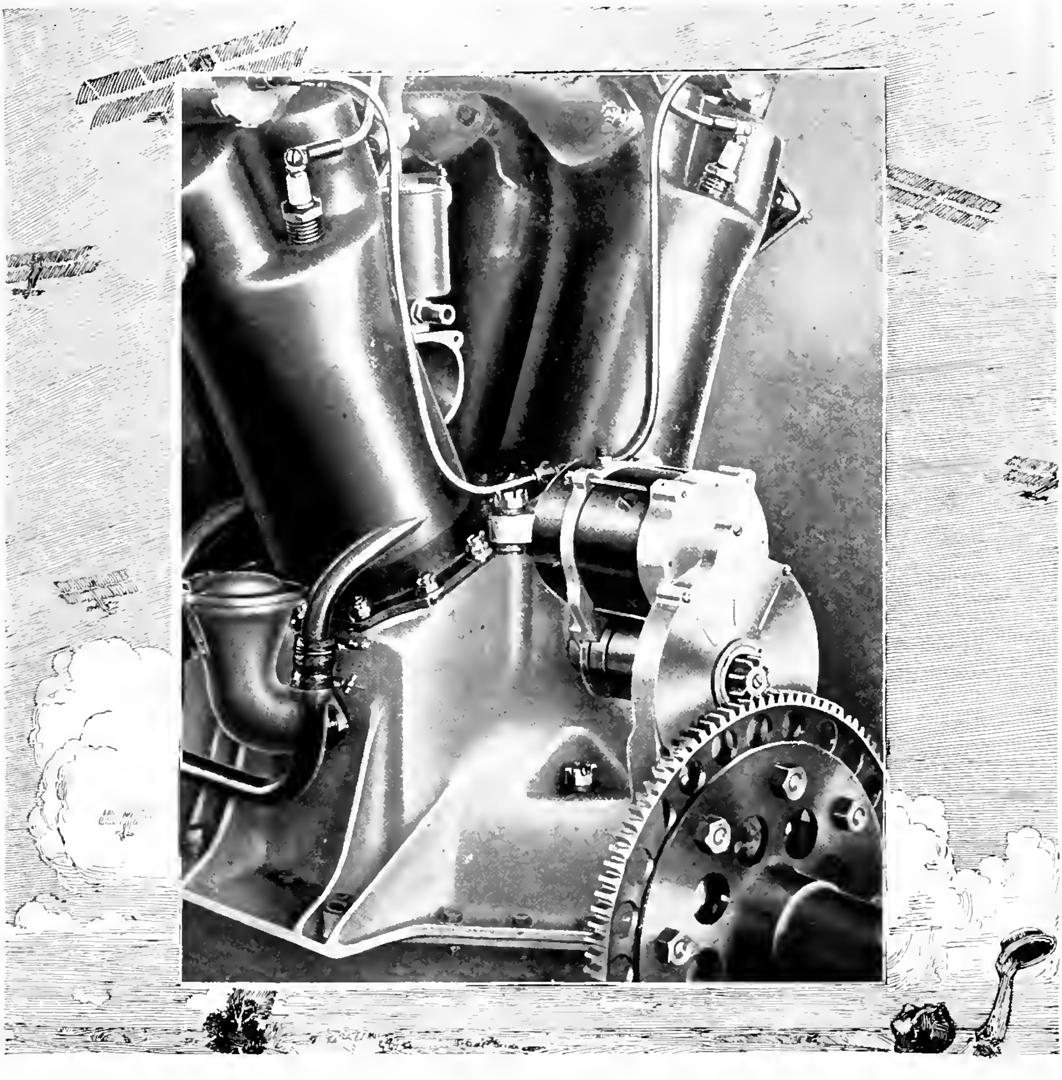

ELECTRIC STARTING MOTOR AS APPLIED TO A 12-CYLINDER LIBERTY AIRPLANE ENGINE
(See article, "Electric Starting Systems for Automobiles," page 186)

GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

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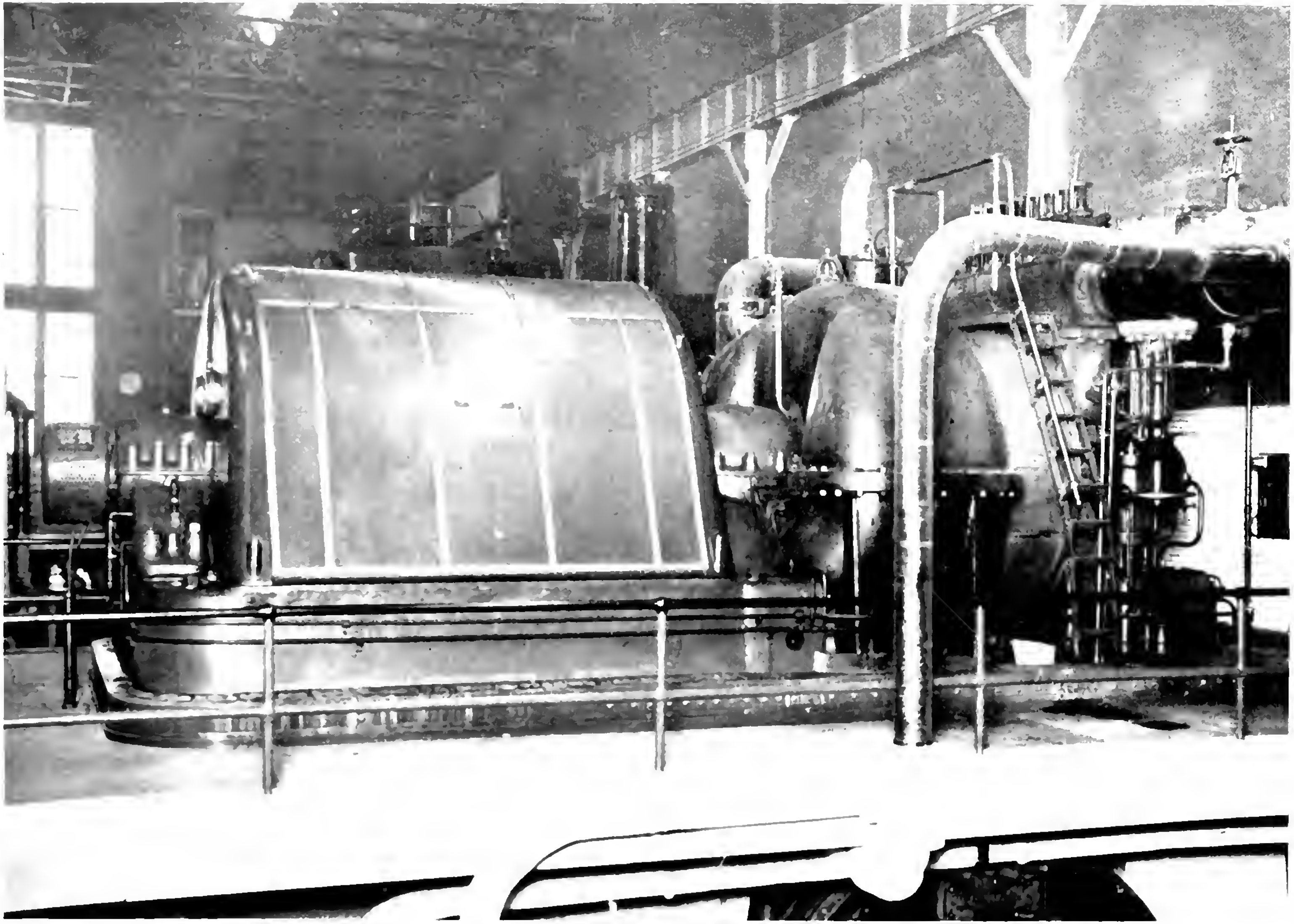


This is the 10,000-kv-a Turbo-alternator on which the short-circuit tests described in the article, page 214, were made

GENERAL ELECTRIC
REVIEW

ELECTRICITY ON THE AUTOMOBILE

For a number of years the inability of the internal combustion engine to be self-starting plainly militated against its use as the motive power of the ultra popular self-propelled vehicle. The woman who had the courage to drive the stalling, balky automobile was a rarity. The condition today is wholly changed and we observe a goodly percentage of women drivers, even in the densest city traffic. We must attribute this rapid change to the development and application of the electric starting system.

When we review the state of development of electric motors and storage batteries as early as 1905, we are caused to wonder why a satisfactory electric starting equipment did not sooner present itself. The first starting motors differed but little from existing series motors for other applications; and the storage batteries, while being subjected to unusually severe service, resembled in all essential respects storage batteries for electrically propelled vehicles. It would seem that the application of the electric motor to starting the internal combustion engine awaited the development of a satisfactory method of connecting the two—an arrangement foolproof, simple, and sturdy. A form of shift which automatically meshes the motor pinion with the flywheel teeth immediately the motor is connected to the battery, and throws it out of mesh and holds it there as soon as the engine begins to fire, is now almost universally used on American built cars.

To one who has experienced the back-breaking job of cranking a cold engine it is incredible that a motor only 4½ inches in diameter can perform the work twice as fast and for an indefinite period. All the credit, however, does not belong to the creators of this small motor; the battery manufacturers have accomplished wonders in providing such a bountiful reservoir of electric energy in so small a space. Discharge rates on starting and lighting batteries range from an ampere or two for lighting to three or four hundred amperes for starting in cold weather.

The principles of the electric starting system for gasolene engines are described at length in the article by Mr. F. C. Barton in this issue.

Electricity was first used on the automobile for igniting the gas in the cylinders, and in this capacity it is indispensable to the operation of the gas engine. Other means of ignition were attempted in the early stages of gas engine development, but they were crude and woefully inadequate. True, the Diesel engine dispenses with electric ignition, but this high compression engine as at present developed is out of the question for automobile propulsion.

With electric starting systems incorporated as standard equipment on practically all cars, electric lighting exists as a matter of course. Now, instead of insufficient light for safe driving, the injudicious use of the brilliant miniature Mazda lamps has effected the opposite extreme, and has provoked restricting legislation in many states.

The electric generator-motor system of transmission and speed reduction has met with favor. With this arrangement the clutch and transmission gears are replaced by a generator-motor set, the armatures of which are mounted on a common shaft intervening between the engine crank shaft and the driving shaft. Speed reduction is effected by increasing or decreasing the magnetic pull between field and armature. The generator also serves as a starting motor; and on long down grades is made to act as an electromagnetic brake.

Further uses for the electric current are found in the electro-magnetic gear shift; a method of heating the mixture in the intake manifold to facilitate starting in cold weather; electrically heated hand grips for the steering wheel; and cigar lighters. There has been some application of electrically operated brakes by means of a motor driving a drum on which is wound a cable connected with the brake bands. A motor-operated jack would be a boon to the tourist.

A consummation devoutly to be wished is an electrically propelled automobile having a radius of operation comparable with that of the gas engine driven car, and as readily replenished. Its realization is contingent only on the appearance of a suitable accumulator for the magic "juice."—B.M.E.

Electric Starting Systems for Automobiles

By F. C. Barton

Lighting Department, General Electric Company

After briefly describing the straight mechanical, compressed air, and acetylene methods which were used to some extent years ago for starting internal combustion engines and detailing the reasons for abandoning such methods, the author confines his description of starters to the various electric types. The design, characteristics, and operation of the single-unit, two-unit, and combination-unit types of starting and lighting equipment are discussed in great detail. Description and examples are also given of the methods employed in selecting the size of units for assumed requirements. The conclusion of the article relates what has been done by the Society of Automotive Engineers in standardizing the mountings of starting motors and lighting generators.—Editor.

Ever since the early development of the explosion or internal combustion engine, it was realized that the inherent drawback to the use of this type of prime mover lay in its inability to be started by energy stored within itself. The problem of starting the engine with the least expenditure of human energy has therefore occupied a large place in the minds of designers, with the result that various forms of starters were devised.

There were straight mechanical devices employing springs or their equivalent to give the initial impulse; then, too, there were devices in which the internal combustion engine by the use of special distributor valves was converted into a compressed air engine, taking air under pressure from a storage flask. This flask was in turn charged by some form of pump connected to the engine and driven by it during periods of normal operation. There were gas devices in which an explosive charge of acetylene, or other gas, was introduced through suitable distribution valves directly into the cylinders and was there exploded by the usual electric ignition.

Almost without exception these devices lacked reliability. The springs did not store enough energy to make second and third attempts at starting in case the first failed. The air starters developed leaks and pump troubles which resulted in the slow discharge of stored air with attendant loss of starting ability. The gas starters were always "touchy" and frequently the mixture introduced for starting would not ignite when the spark was applied, and, when it did ignite, the resulting explosion was apt to be of greater violence than is desirable from a mechanical standpoint.

There were also electrical starters, which took energy from a storage battery to drive an electric motor mechanically connected to the engine, the battery being recharged by an electric generator driven by the engine during normal operation. Other things being equal, the type of starter using electrical energy acquired a tremendous advantage over all others by reason of the possibility of combining starting with the most satisfactory form of lighting, viz., that employing Mazda electric lamps. Furthermore, it might be combined to furnish energy for the now extensively used battery ignition. Hence, electric systems always include starting and lighting, and, frequently, starting, lighting, and ignition.

It is not the purpose of this article to discuss either lighting or ignition systems, but to give a brief outline of the various ways in which electric motors and generators are employed in modern automobile design and construction.

Electric starting and generating sets may be divided into three general classes, as follows:

First: The single unit system in which the same electrical machine acts as both motor for starting and generator for charging the battery.

Second: The two unit system in which the motor is employed for starting only, and is not in use for any purpose except during the starting period. The generator is used only for charging the battery, and is an entirely separate unit driven independently by some means from the engine during normal operation.

Third: A combination of the two systems already mentioned. This system usually includes a single field structure and an armature having two windings and two commutators, one being employed when the machine is operating as a motor, and the other when operating as a generator.

The single unit system requires an electrical and mechanical compromise. The mechanical reduction ratio between the armature of the machine and the engine crank shaft must be such that the speed of the armature will not be dangerous when the engine is driven at speeds equalling maximum car speeds. These engine speeds may be in the neighborhood of 3000 r.p.m. or above. It is therefore advantageous, from the generator standpoint, that the driving ratio be as low as possible but, from the motor standpoint, where a high torque is required at the crank shaft, it is desirable to keep this ratio as high as possible, as the lower the ratio the larger must be the electrical machine to accomplish a given result. The electrical compromise lies between the speed at which the machine will crank as a motor and that at which it will charge the battery as a generator.

The combination-unit system employs a single field structure and a double wound armature. In this system the armature shaft is usually extended through both ends of the machine, the rear end being connected through suitable gearing to the engine flywheel (upon the periphery of which gear teeth are cut) during starting operations. After starting, the mechanical connection to the engine flywheel is disconnected, and the armature of the machine is then driven by means of the forward shaft extension from a suitable power take-off on the engine arranged to drive the armature as a generator at a suitable speed.

To accomplish the change-over from motor action to generator action, various automatic or semi-automatic mechanical devices are necessary. These usually consist of a manually operated gear shifting device and switch, for engaging the motor reducing gears with the flywheel gear and completing the electric circuit to the motor winding, and an over running clutch on the generator drive which permits the armature to rotate free from the generator drive while it is running as a motor cranking the engine, but which will cause the armature to be driven by the engine when the starting gears are disengaged and the motor circuit broken. This arrangement permits the motor ratio to be selected independently of the generator ratio.

The two-unit system employs a motor and a generator, the generator being driven through an ordinary coupling, or by chain or gear by the engine, and the motor being connected automatically, or by a manual shift, to the flywheel gear ring during starting operation.

The means employed for making the mechanical connection between the motor shaft and the engine flywheel has been the subject of a great deal of engineering development. At this date, by far the greatest number of devices make this connection and disconnection automatically. These automatic "shifts" consist, in almost all cases, primarily of a pinion connected by some means to, or made part of, a nut which runs on a screw thread mounted on, or cut in, an extension of the motor armature shaft. When the motor circuit is closed, the armature starts to rotate, but the pinion and nut, because of their inertia, remain almost stationary. This causes the lead screw on the motor shaft to propel the pinion forward toward the flywheel in a direction parallel to the axis of the shaft until it encounters and engages with the flywheel teeth. Contact between the edges of the flywheel and pinion teeth checks any tendency the pinion may have had to acquire the rotative action of the armature, thereby causing the lead screw to propel the pinion positively to the limit of its travel. It then can travel no farther axially and must, therefore, either stop the armature or rotate with it, and, being in mesh, if it rotates, it must also rotate the flywheel and thereby crank the engine. As soon as the engine commences to run by its own power, its speed is sufficiently great, with relation to that of the motor, that the pinion is driven by the engine faster than the screw shaft is driven by the motor. This causes the action of the lead screw to be reversed, and the pinion is therefore propelled by the engine back along the motor shaft to the out-of-mesh position. At this point the motor circuit should be broken. If it is not, it merely continues to accelerate until free running speed is reached, but as the pinion is then running at approximately the same speed as the armature, there should be little tendency on its part to re-enter the flywheel gear.

The foregoing merely outlines the fundamental actions of engaging and disengaging. A description of details, such as the method of absorbing shock, and the prevention of re-entry, and the obtaining a correct angle of entrance follow.

Shifts

Generally speaking, there are two types of automatic screw shifts in extensive use. One transmits the torque developed by the motor to the pinion through the medium of a coil spring wound around the shaft. The other delivers the motor torque to the pinion through a self-tightening friction clutch.

The object of either the spring or the clutch is to minimize the shock that would take place when the pinion reached the end of its travel on the lead screw on the motor shaft, or the point at which its axial motion is translated into rotative motion. It must be remembered that the rate of acceleration of the motor armature is very high, and by the time it has rotated the necessary one or two revolutions, which carries the pinion into mesh, its angular velocity is great enough to damage the gear teeth or armature shaft if the shock at the instant of starting to crank is not cushioned in some way.

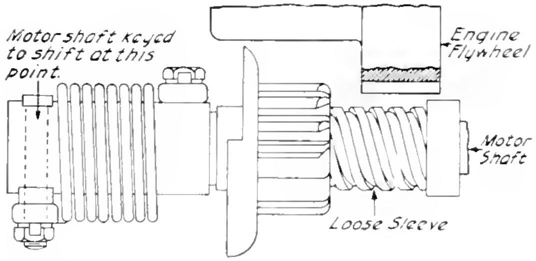


Fig. 1. Spring Drive Automatic Shift (Inboard Shift)

These devices are also designed to minimize the liability of encountering what is known as a "butt." This means a condition where the flywheel teeth and the pinion teeth are not so lined up that they can slide directly into mesh. In other words, a pinion tooth may strike end on against a flywheel tooth, and, without some flexibility in the drive, will not be able to enter, and the two will then lock tight in what is commonly known as a "jam."

To reduce further the possibility of a "jam," the front end of the pinion teeth are chamfered to produce the smallest frontal area, and still maintain a liberal mechanical margin of safety against breakage. This chamfering is very similar to that used on transmission gear teeth, where it is done for the same purpose.

The flexibility of drive also provides against another condition known as "hunting." This condition is particularly in evidence with four cylinder engines, and is a result of the reaction of gases compressed in the combustion chambers of the cylinders by the pistons on their compression strokes. The expansion of each compressed charge, on what would be the working stroke of the cycle if the charge were fired, causes the engine to tend to over-run the starting motor, which in turn tends to run the motor pinion out of mesh. The two factors which prevent this from actually taking place are the flexibility of the drive and the high rate of acceleration of the motor, which enables it to keep up with quite violent changes in angular velocity. The tendency to "hunt" decreases as the number of cylinders is increased, until, with a twelve-cylinder engine, the torque required by the engine for starting is, due to overlapping of power impulses, almost uniform throughout a revolution.

When the engine fires, causing its sudden acceleration from cranking speed to running, the motor pinion, as previously explained, is run back along the lead screw to the out-of-mesh position. This throw-out is frequently quite violent; therefore, some form of cushion stop or detent is provided at the out end of the screw to prevent the possibility of a rebound of the pinion, which might bring it into contact with the flywheel again, and, due to the relatively high speed of the latter, might cause serious damage to the gear teeth.

Another point, which is given consideration in "shift" design, is "angle of entrance." Normally, the pinion is approximately 3/8 of an inch away from the flywheel when out of mesh. While travelling this 3/8 of an inch along the lead screw, and being restrained from turning only by inertia, a certain amount of rotative movement is acquired. Experiment has demonstrated that a definite amount of rotative movement is desirable, and reduces the liability of "butt," and that this amount is usually in excess of that which would be normally acquired; therefore, some form of friction clutch, or loading device, is provided to give "initial" friction between pinion and lead screw to give the desired number of degrees of rotation.

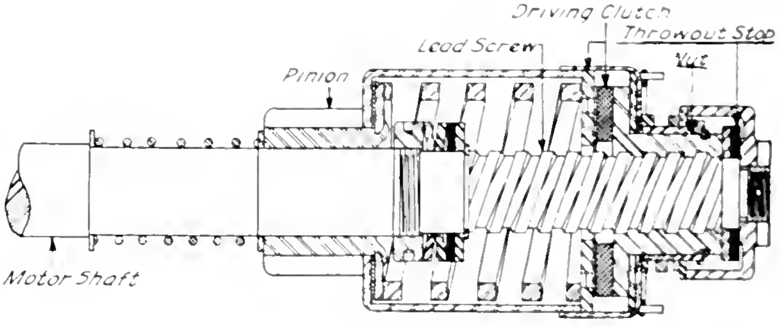


Fig. 2. Clutch Drive Automatic Shift (Inboard Mesh)

Two forms of each type of automatic shift are used; that in which the pinion is propelled rearward away from the starting motor when going to mesh, this being known as "outboard" mesh, and that in which the pinion in normal position is to the rear of the flywheel gear, and is therefore propelled forward toward the starting motor into mesh. This latter is known as "inboard" mesh.

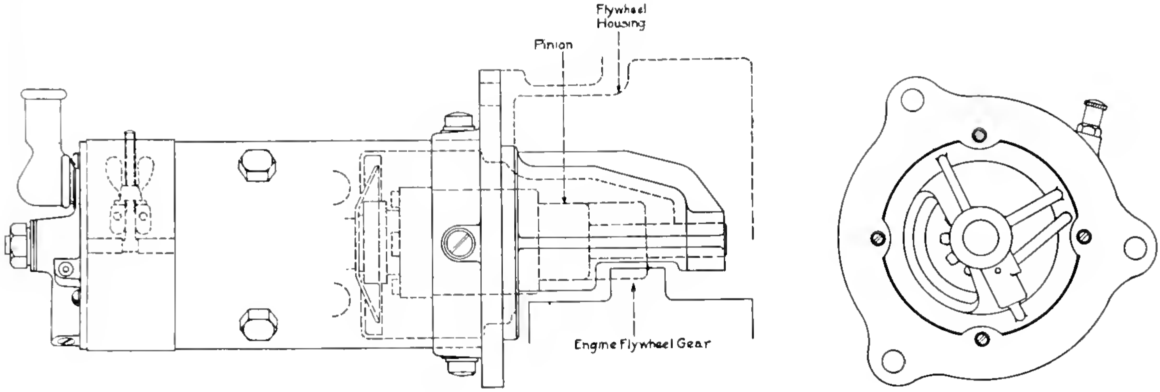


Fig. 3. Starting Motor for Outboard Shift

Car builders who manufacture their own engines and clutch housings usually provide for inboard shift, as such changes as are necessary are purely internal matters with them, and can be easily provided for. But manufacturers of assembled cars purchasing engines and gear sets, which usually include clutch housings, almost invariably use the outboard form of shift.

The shift description has been carried out to some length, as it is a very vital part of the whole system, and, while fundamentally simple, has undergone much re-design and development to bring it to the present position of reliability and sturdiness.

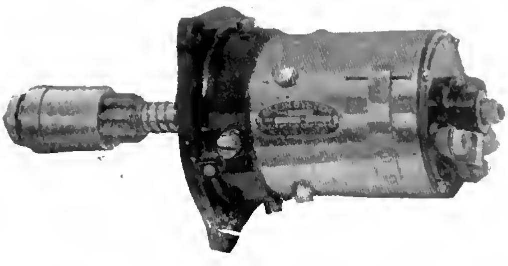


Fig. 4. Starting Motor Flange Mount (Inboard Shift)

Motors

Starting motors are always straight series wound and of very low internal resistance, both as to windings and brushes. This is necessary to meet cold weather conditions when the battery voltage is low and the current demand is high. Under these conditions the current necessary to turn over a stiff engine may be three or four hundred amperes, which means only 3.5 to 4 volts at the motor terminals. This voltage is used up in two ways: first, in overcoming brush and brush contact drops and winding resistance, and, second, in the production of useful work. So whatever fraction is saved from the former is available for the latter, thereby improving the performance of the motor.

The conditions outlined in the preceding paragraph will be found only in extremely cold weather, but they must be met if the starting is to be successful at all times.

Fig. 5 gives characteristic horse power, speed, and torque curves of a $4\frac{7}{16}$-inch diameter Bijur motor. With this curve as a base, the most desirable ratio of pinion to flywheel to give the most satisfactory cranking can be determined. It is of course to be desired that when conditions are adverse, viz., when the engine is cold, the motor speed shall be such that it will operate as nearly as possible at the peak of its horse power curve, that being the point at which it will do the most useful work.

Take, for example, a six cylinder engine of a size suitable for the moderate sized car. This engine will have a displacement of 303 cubic inches or cylinders $3\frac{1}{2}$ by $5\frac{1}{4}$ inches, and a flywheel having 126 teeth. We know that this engine will require about 30 lb.-ft. torque at the crank shaft to crank when hot, and that it will need three to four times that torque to crank at zero or below, and that under this severe condition the cranking speed must not fall below 50 r.p.m.

By a cut-and-try method it will be found that a nine-tooth pinion will be suitable.

The ratio will be 126:9 or 14:1, or at 50 r.p.m. crank shaft will give a motor speed of 700 r.p.m. 700 r.p.m. = 8.6 lb-ft. torque or 120 lb.-ft. at engine crank shaft will take 400 amp. and deliver 1.2 h.p. which is near the peak of the horse-power curve, and, therefore, at the most desirable point. This is satisfactory for cold performance.

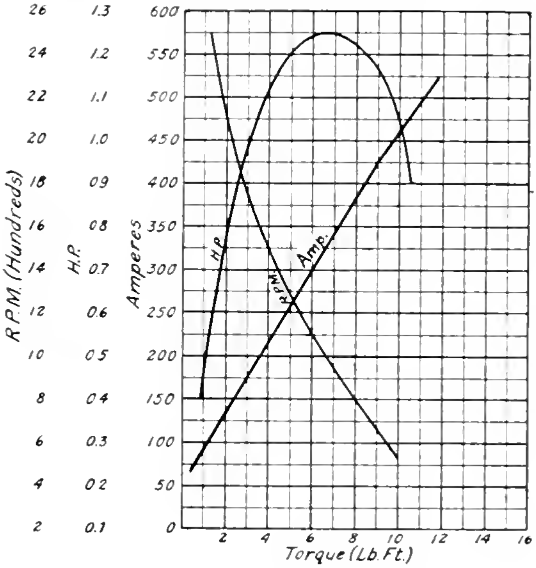


Fig. 5. Starting Motor Characteristic Curves

To find what will happen with a warm engine requiring only 30 lb-ft. at the crank shaft or 2.12 lb-ft. at the motor shaft, read straight up from the 2.1 torque point. It equals 135 amp., 2080 r.p.m. or 147 r.p.m. crank shaft and 0.82 h.p. which is satisfactory.

Generators

The principal factor in determining the size of generator suitable for a given car is the ratio between the driven speed of the generator and the miles per hour of the car. This factor is usually given in terms of revolutions per minute of the generator per mile per hour of the car. This is affected by:

First: the road wheel diameter.
Second: the rear axle ratio.
Third: the ratio of the generator drive to the crank shaft.

This last ratio is usually determined by the number of engine cylinders, as the generator drive is in almost every instance made to run at a speed suitable for magneto drive. This would be 1:1 for four cylinders and 1.5:1 for six cylinders.

For example: A four cylinder car having 33-inch wheels and a 4:1 rear axle ratio and a 1:1 generator to crank shaft ratio would have a generator speed of 41 r.p.m. at 1 m.p.hr. If this happened to be a six-cylinder car and the generator to crank shaft ratio was 1.5:1, the generator speed would be 61.5 r.p.m. at 1 m.p.hr.

Experience has shown that a generator to meet average conditions should deliver 10 amp. at a car speed not much in excess of 14 m.p.hr. and should give maximum output at some speed between 20 and 25 m.p.hr.

The choice of a generator, therefore, is merely a matter of selecting a standard machine which will fulfill the current output conditions outlined above at the speed available at 14 m.p.hr.

Take the six-cylinder example for illustration. A generator having an output like the curve Fig. 6 would be satisfactory. This machine delivers 10 amp. at almost exactly 860 r.p.m., which equals 61.5×14, or 14 m.p.hr. car speed. It reaches a maximum of between 16 and 17 amp., at 1400 r.p.m., equaling 23 m.p.hr.

After the maximum output has been reached a further increase in speed causes the current rate to fall off. This falling off of the charging rate at high speeds is a most desirable feature of a generator employing the third brush type of regulation, as it means that the average city driver, who operates at low speeds but who uses the greatest amount of current for lighting and starting, gets the highest charging rate, whereas the tourist or country driver, operating over longer periods of time and at higher average speeds than the city man, gets a lower rate of charge which

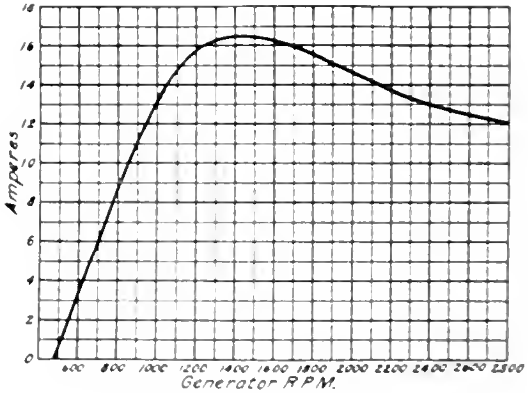


Fig 6. Battery Charging Curve, Third Brush Generator

saves his battery from heating and loss of electrolyte due to the decomposition of the water when gasing.

The foregoing remarks on charging rates relate to the current regulated or third brush type of machine. This is the type most extensively used on moderate and low-priced cars. One other system of regulation is in fairly extensive use, especially among the higher-priced cars. It is the system employing voltage control. The feature of this method of control is that it supplies a high current when the battery is low, and a low current when it is high. It approximates what is known as a "taper" charge or one in which the generator if connected to a discharged battery will deliver a high rate at the start of the charge, but as time progresses the rate will gradually fall until, at the end of the charge, it is down almost to zero.

This system usually includes a straight shunt-wound generator which builds up to a voltage equal to that necessary for the maximum charging rate at comparatively low speed and some form of vibrating voltage regulator whose function is to hold constant generator voltage. This is done by alternately cutting an external resistance in and out of the shunt field circuit. Its rate and period of vibration depend upon the speed at which generator is being driven and the battery current requirements.

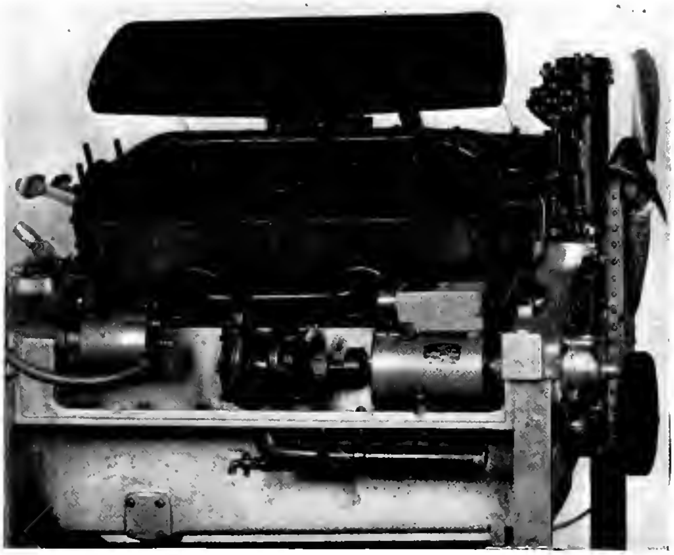


Fig. 8. Starting Motor and Voltage Regulated Generator

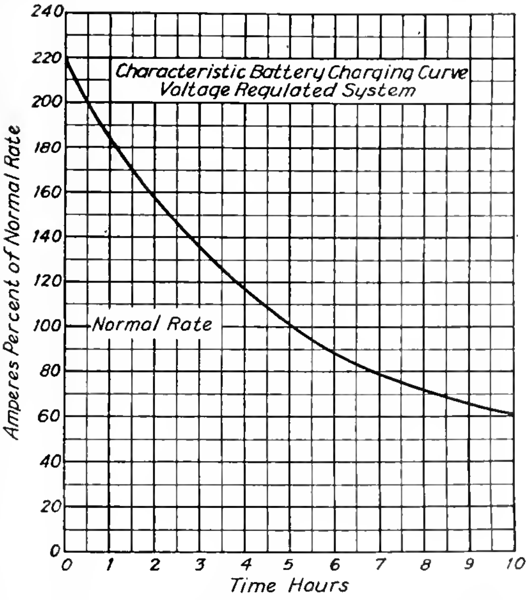


Fig. 7. Characteristic Battery Charging Curve, Voltage Regulated System

Taper Charging

The voltage regulated or constant potential system of battery charging, which gives a tapering charge, Fig. 7, is based on the fact that the counter electromotive force or opposing voltage of a battery is lower when the battery is discharged than when it is charged. The difference will be in the order of 0.6 volts per cell, or for a 3-cell 6-volt battery will be 1.8 volts. Therefore, if the generator is set to hold 7.8 volts, equalling a fully charged battery, it will have, with a discharged battery having a counter electromotive force of only 6 volts, 1.8 volts available for forcing the charging current through the battery; consequently, the charging rate will be high. Leaving the regulator and generator characteristics out of consideration, the high current rate will be determined by Ohm's law, where E or voltage is the difference between generator voltage and battery counter electromotive force and R or resistance equals the sum of the battery and external circuit resistances. If $E = 1.8$ and $R = 0.06$, then the charging rate to the battery will be $1.8 \div 0.06 = 30$ amp. at the start. The rate will taper to zero when the charge is complete, at which point the battery counter electromotive force equals the generator voltage.

In actual practice this condition is only approximated, that is, the regulator or generator, or both, may be so designed that the initial rate will be lower than the rate indicated by the foregoing formulas, and the final rate will not be zero, but rather something of the order of 5 or 6 amp. This is done to prevent the generator from being excessively overloaded during the first part of the charge, and to insure the battery receiving a low rate overcharge after completion of the regular charge.

Fig. 9. Starting Motor for Sleeve Mount (Outboard Shift)

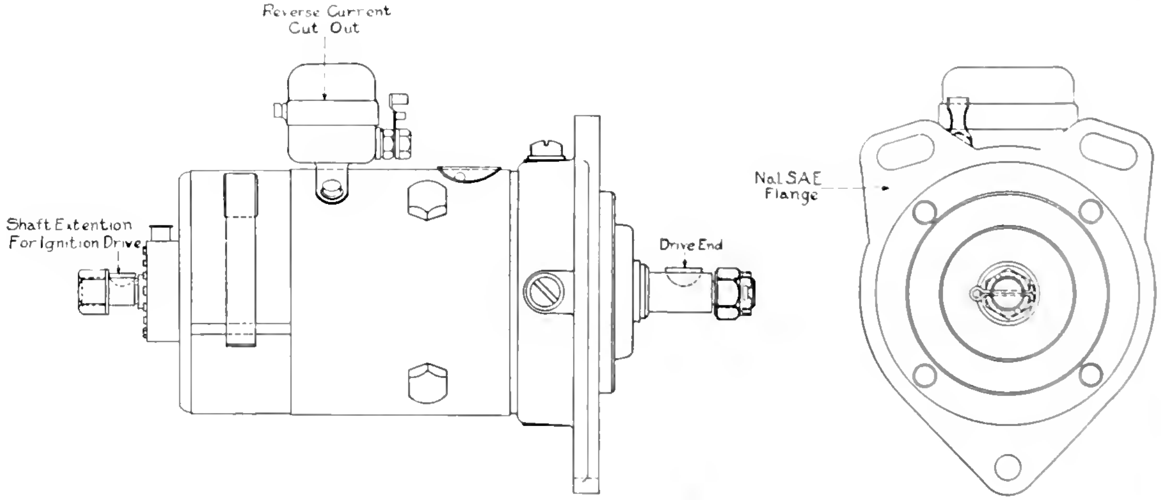


Fig. 10. Generator for Flange Mount

Terminals

Car builders in many instances do not give the subject of connections and terminals the consideration that it should have. Terminals should be rugged to withstand vibration, and should so hold the cable that the effects of vibration at the point they are attached will also be minimized. Terminals should always be soldered to cables, but the solder should never extend beyond the last point of support of the cable; in fact, it is preferable that the terminal be so designed as to support the cable by means of a clamping band which encircles the insulation at a point beyond the bared portion to which the solder is applied. Above all, terminals should be tight on connection boards, as loose terminals mean extra resistance, and extra resistance in the lamp or ignition circuits means decreased brilliancy of lights or unreliable ignition. In the generator circuit of a third brush machine, extra resistance means increased generator voltage with attendant heating of the generator; and in the generator circuit of a voltage regulated machine means decreased current output to the battery.

Society of Automotive Engineers

The work of the Society of Automotive Engineers toward the standardization of all parts of the automobile has been of great value in simplifying and standardizing the mounting of electrical apparatus. The Society through the medium of its standards committees has recommended for adoption by manufacturers: three methods of mounting starting motors; two methods of mounting generators; one form of pinion and gear tooth.

The three mounts are:

First: for inboard flange mount with three sizes of flange.

Second: for outboard flange mount with three flange sizes.

Third: for outboard sleeve mount. This in only one size.

In each of these, all dimensions which affect both motor and engine manufacturers are given. Roughly, these are: flange bolt drilling and location of holes; diameter of pilot; distance from flange face or dowel screw to flywheel teeth; and height of flywheel teeth above flywheel proper.

The gear and pinion tooth selected is of standard 8-10 pitch 20 deg. pressure angle.

The generator mounts are:

First: flange with two sizes to accommodate large or small machines.

Second: bracket with but one size laid out to accommodate the largest generator that may reasonably be encountered.

The flange method of mounting is employed when the generator is driven direct by a gear or sprocket running in the engine timing gear case. The engine half of the flange mount is then machined on the rear face of the gear case. The bracket mount is used where a separate shaft is brought out of the timing gear case for driving the water pump, ignition apparatus, or generator, or sometimes two or all three of them. In this case, the generator is mounted on the engine bracket and driven by means of a flexible coupling.

In these layouts, as in the motor layouts, all common dimensions are given, including shaft and sizes, coupling fits, and height of shaft above bracket, and in the case of the flange mount, shaft end sizes for gears or sprockets and drilling and shape of flange.

Fig. 11. Generator for Bracket Mount

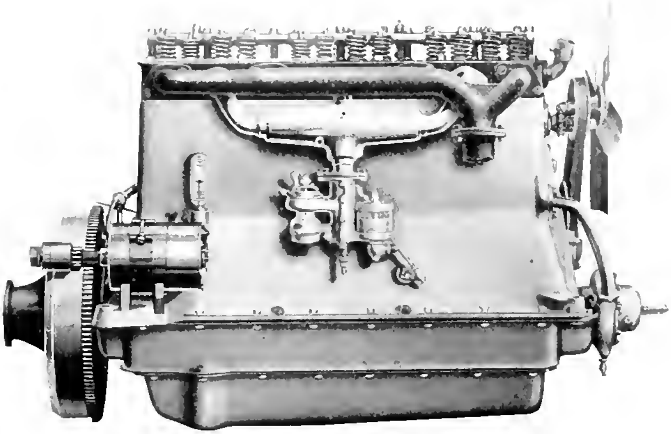


Fig. 12. Inboard Mesh Starting Motor

The Outdoor Generating Station

By H. W. Buck

Vice-President, Viele, Blackwell and Buck, Engineers

That a power plant must be sheltered by a "house" has become a habit of mind in engineering design. In the opinion of the author it is now time to analyze the situation and to determine whether there is really any need for the expensive buildings that have always been erected for housing hydro-electric generating equipment. In the final analysis it would seem that the function of such a structure is to house the station operators and switchboard panels and to provide favorable conditions for initial installation work and subsequent repairs. Drawings are shown of an outdoor generating station which was designed and submitted to the War Department for a development at Muscle Shoals, Alabama. It is shown that a plant of this kind is entirely feasible and offers decided advantages from the standpoint of economy in construction.—Editor.

The installation of electrical apparatus in the open air without the protection of a housing structure is of increasing importance, due to the constantly increasing cost of building, and also to the increasing cost of construction funds.

The installation of small transformers out of doors is as old as the electric lighting business, since such apparatus has always been considered intrinsically weather-proof. In recent years other types of apparatus, such as oil switches, disconnecting switches, lightning arresters, busbars and other substation apparatus have been forced out of doors for economic reasons on account of their increasing size with higher voltages, and the high cost of housing.

Thus far, however, little progress has been made on the out-door installation of generating and other rotating electrical machinery, for such apparatus has been regarded as more or less perishable. There have been some isolated cases of outdoor installation of generators, such as some mining power plants in the arid regions of Arizona and Mexico, where boilers, engines and generators have been installed in the open. There is also a modern installation of a waterwheel-driven generator on one of the power systems in Utah. The question, however, has been under discussion by engineers for a number of years, but prejudice has worked against it. That a power house must have a "house" in order to be a workable combination has become a habit of mind in engineering design.

The time has now come, in the opinion of the writer, to analyze the situation and to determine whether there is a basis of justification for the large investment required in the construction of the modern and expensive power house superstructure in connection with hydro-electric plants. The economic situation at the present time forces this question prominently to the front.

In the steam driven generating plant the annual cost of power is largely a matter of operating expense and thermodynamic efficiency. In this respect there is still hope for improved economy and lower generating cost. In the hydro-electric plant, however, there is little to be expected in the way of lower operating expense, which is already very low. Water turbines have now reached an efficiency of about 94 per cent, so that there is small hope for improvement in this respect. The large item of annual cost of power from the water power plant is the interest charge, and this can only be reduced by reducing the capital cost of construction. The most hopeful field for saving in this part of the account lies in simplifying the power house construction, particularly by eliminating the costly super-structure now universally built to house the hydro-electric generators.

The modern vertical shaft internal revolving field generator is essentially a waterproof structure. The vital parts of the machine are all on the inside protected by a massive casing of cast-iron, and the openings in the upper spider are usually plated with steel for purposes of ventilation so that the top is naturally protected. With slight modifications in its design, the standard vertical shaft alternator can be made absolutely proof against all stresses of weather. The waterwheels themselves naturally need no housing, since they are imbedded in the concrete substructure of the power house and are designed to run in water.

Thrust bearings are housed in heavy steel or iron casing and need little protection from weather. The various auxiliaries, including governors, connected with an hydro-electric plant can easily and advantageously be installed under the main generator floor, in the various compartments naturally existing in the substructure of such a plant and there protected from the weather. It is therefore interesting to inquire why millions of dollars are expended to house machinery which really does not need housing at all.

In the last analysis it appears that the function of the hydro-electric superstructure

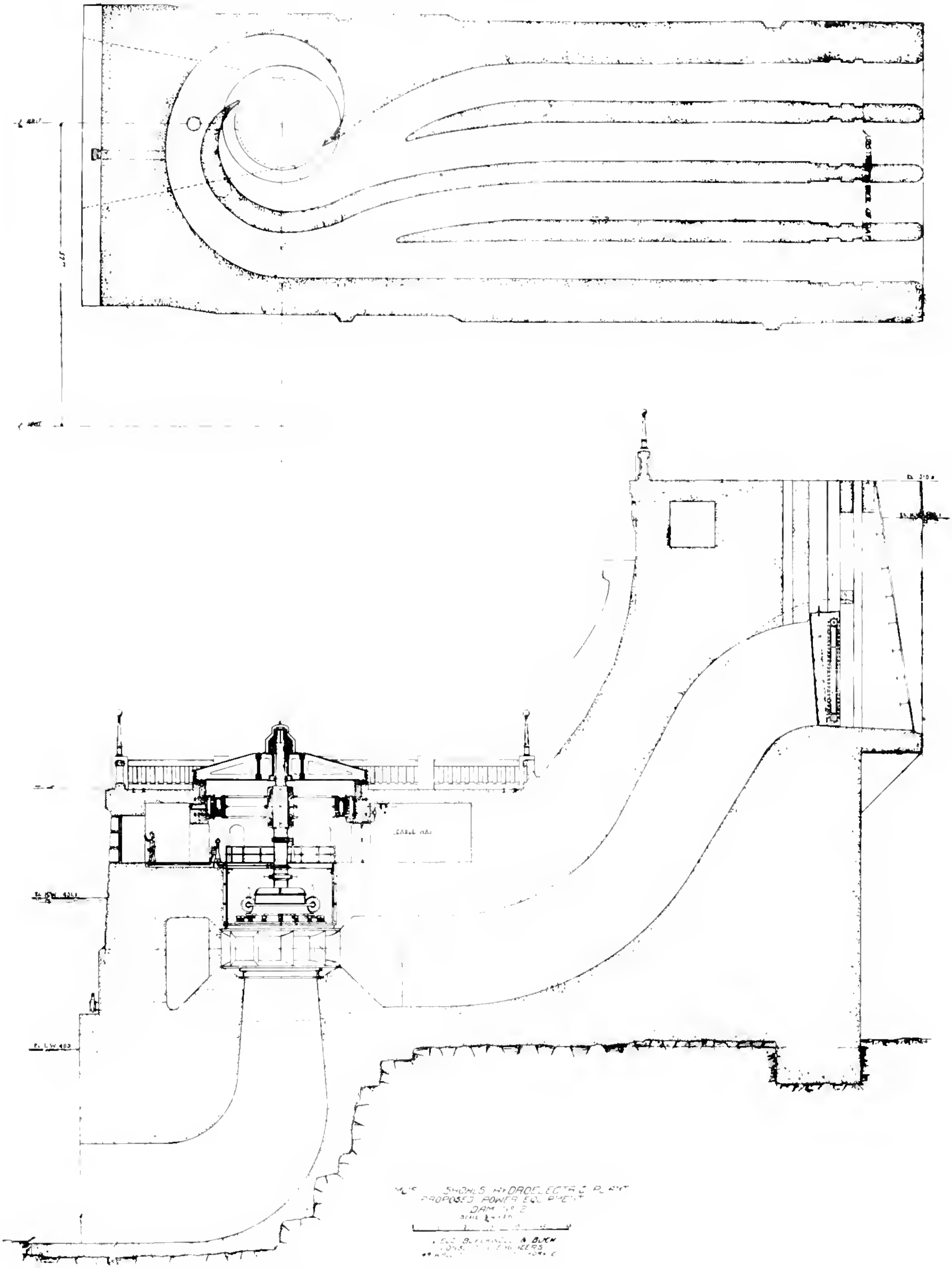


Fig 1. Cross Section of a Generating Unit in the Outdoor Station Proposed for the Muscle Shoals Development in Alabama

is to house two or three station operators, to house the switchboard panels, and to produce conditions favorable to original installation work, and for repair work required from time to time thereafter.

In regard to the switchboard panels, there is apparently no reason why they should not be housed in a small pilot house of a size not over five per cent of the size of the total power house superstructure required.

The drawings, Figs. 1 and 2, show a general design of the Muscle Shoals Development prepared for the War Department by Viele, Blackwell & Buck in August 1918. The design, as shown, comprises the outdoor installation of fifteen 20,000-kw. generating units. The situation at Muscle Shoals is very favorable for such an outdoor generating station. The climate in Alabama is mild, and the number of generating units in the plant is large, which gives a maximum of saving from eliminating the superstructure. It was proposed to install within the generating structure itself only the water turbines, generators, exciters, governors and the various pumps. The switchboard panels were to be located in a relatively small "pilot house" on the bluff overlooking the generating structure, which would also contain the low voltage oil switches and busbars. All of the transformers and high tension equipment would be installed in the open, adjacent to the pilot house. In this arrangement, the switchboard operators would be housed and the generator attendants also protected in the substructure. The plant auxiliaries would also be housed. All of the vital parts of the alternators could be inspected from below the machines. Only the occasional inspection of thrust bearings would have to be made in the open. In this connection it should be remembered that sailors are not housed in the work which they are obliged to do, and there is no reason why some of the operators of a power plant should not perform some of their duties in the open air.

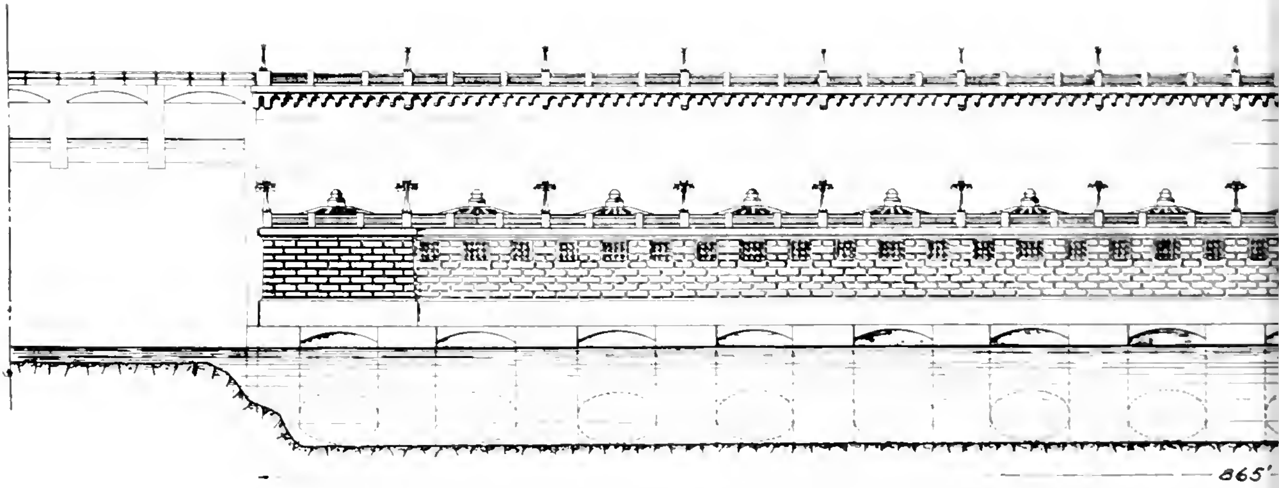


Fig. 2. General Design of the Outdoor Generati

In order to perform, under protection from the weather, the work of installation and repair on the generating units of this outdoor Muscle Shoals plant, it was planned to install a housed-in traveling gantry crane of sufficient length to cover a single unit, which would travel on rails the total length of the generator structure. In this way it would be available for any one of the units. The crane could be placed over any desired unit, and, with the various openings in the ends and sides of the gantry closed with adjustable panels, the unit could be completely protected from the weather for handling and repair work.

In the case of this Muscle Shoals plan tthe saving in construction cost by omitting the superstructure was very large. Approximately 3000 tons of steel for superstructure columns and roof trusses would be saved, and after paying for the "pilot house" and gantry crane, the net saving would amount to over $700,000.

It will be noted from the cross section of the plant, Fig. 1, that the generator assembly is of a somewhat novel type. The usual iron frame of the stationary armature is omitted, and the armature laminations and coils are attached to the surrounding concrete. The only function of the armature frame of a standard generator is to provide general stability, and this can be provided by the surrounding concrete, which must be there in any case for supporting the weight of the machine. By this arrangement approximately 70,000 lbs. of iron per generator can be saved in the plan shown. It is also possible by this design to save a large amount of boring mill work on the armature frame at the factory, which is apt to be the limiting element in production in most machine shops. This method of construction was first suggested, in the knowledge of the writer, by H. G. Reist. It is mentioned here because it is admirably adapted for the outdoor installation of generators.

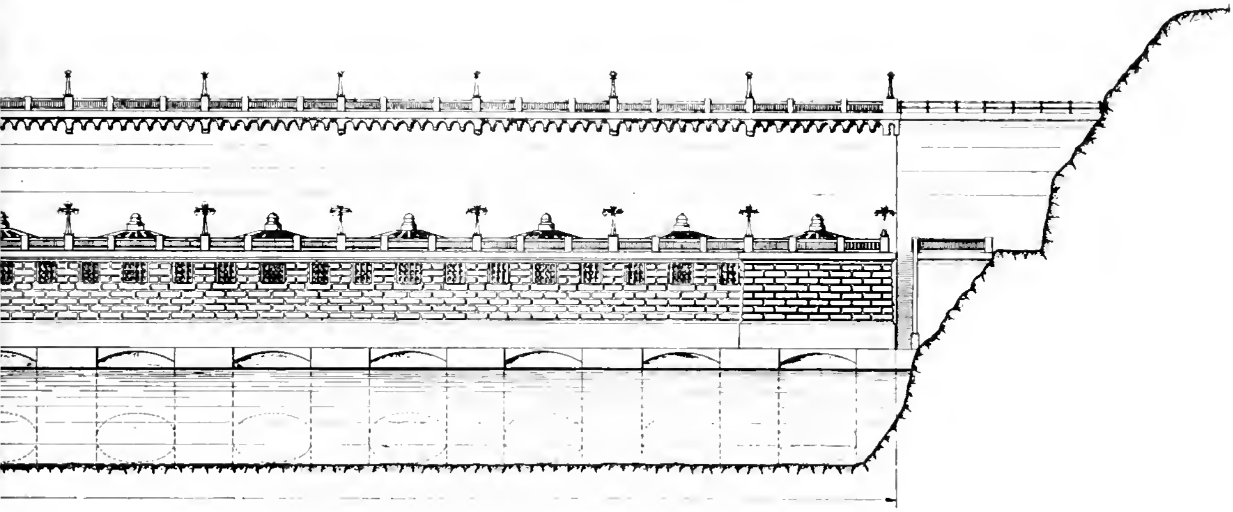
It may be argued that an outdoor generating station, which would be successful in the mild climate of Alabama, would not be practicable in an installation where severe winters are experienced. There does not appear, however, to be much weight in this argument. An outdoor generator can be made snow-proof as well as rain-proof. The operator would be normally housed, in any case, in the pilot house or between decks in the substructure, and would be required to go on deck at occasional intervals only.

In cold climates it would probably be necessary to make some special provision against freezing, where water-cooled bearings are used, and it might be necessary to use a specially light oil in the upper bearings in cold weather on an outdoor machine.

The saving in the construction cost of a power house superstructure is not the only saving resulting from the outdoor construction. The annual maintenance of such a building is a considerable item, which would be entirely eliminated.

The advantage in cost of eliminating the power house superstructure will increase, of course, in proportion to the number of generating units in the plant. In a single unit plant, for instance, it might be a fact that a housed crane for handling the unit would prove almost as expensive as an enclosed fixed superstructure; but with, say three or more units installed, there should be no doubt of a large saving in cost of plant construction. In such plants as Muscle Shoals, Keokuk, Cedars and Niagara Falls, where there are large numbers of units installed, the possible saving is very large.

Whether the outdoor plan can be applied to steam turbine driven plants must be decided by future development. Some complications might be encountered from freezing in idle steam pipes, valves, water pipes, etc. It does not appear impossible, however, to install turbo-generator units, and also the boilers, etc., in the open, if special protection can be worked out for certain parts of the equipment. Such an installation would afford an opportunity for a very large saving in the construction cost of such plants.


on Proposed for the Muscle Shoals Development

Methods for More Efficiently Utilizing Our Fuel Resources

PART XXXI. PETROLEUM*

By Chester G. Gilbert and Joseph E. Pogue

Division of Mineral Technology, United States National Museum

In this series of articles we are at present reviewing the fuel resources of the Western Hemisphere. Previous installments have described the fuel resources of Canada and Alaska; also the coal and natural gas resources of the United States. The present installment is the first of a group which will treat of the petroleum resources of the United States. It is introductory in character and treats of the nature and occurrence of petroleum and the essential features of the petroleum industry, including production, transportation and refining, as well as the distribution of the products. The next installment will treat of the petroleum reserve and its limitations. Then the conservation of petroleum will be taken up.—Editor.

Petroleum is of peculiar value to society because it is the sole source of gasolene, the dominant motor fuel; provides kerosene, the most important illuminant outside of cities and yields lubricating oil, upon which the wheels of industry revolve. In addition, it has come to be an essential fuel in the Southwest and on the Pacific coast, where coal is lacking; is requisite to the operations of an oil-burning navy; and forms the starting point for an oil by-products industry, a branch of chemical manufacture still in its infancy and offering unlimited possibilities of development.

The liquidity of the crude product makes petroleum unique among mineral raw materials, contributing wide commercial availability through the ease with which the substance may be mined and handled; while the magnitude of the resource has given confidence for the extensive mechanical developments essential to its use. As the petroleum deposits of the United States have been drawn upon with extraordinary rapidity and the supplies have already suffered serious depletion, the matter of their approaching exhaustion assumes the light of immediate importance. The comfortable assertion that such considerations may be safely left to future generations does not apply to petroleum.

Nature

Crude petroleum, as the raw or unrefined product is often termed, is an oily liquid varying considerably in appearance according to the locality from which it comes. It is an extremely complex mixture of organic compounds, chiefly hydrocarbons, but substances containing sulphur, oxygen, and nitrogen are also present in small amounts.

If exposed to the air, it gradually thickens until a solid residue is left. The first product given off is natural gas; then liquid components evaporate in the order of their lightness; and the final residue is composed largely of either paraffin wax or asphalt. Petroleum is thus seen to be a mixture of different liquids dissolved in one another and holding in solution also natural gas and solid substances. This conception correlates natural gas as a by-product of petroleum and affords a simple epitome of the changes more rapidly induced when petroleum is subjected to refining. The asphalt lake of Trinidad and the ozokerite deposits of Galicia and Utah represent natural residues from the prolonged evaporation or natural distillation of petroleum.

While petroleums vary considerably in character, they fall chiefly into two classes according to whether the residue yielded is predominantly paraffin wax or asphalt. The first are said to have a *paraffin base;* the second, an *asphaltic base,* or called merely asphaltic petroleums. There are also intermediate oils with almost equal proportions of paraffin and asphalt. This broad distinction is of great economic significance, because the paraffin petroleums, occurring chiefly in the eastern part of the country, came first into use and therefore determined the current refining practice and the existing demand for petroleum products; while the asphaltic petroleums, exploited later in the Gulf region and California, found their immediate commercial outlet in the form of fuel. The higher gasolene content of paraffin oils, coupled with the distance of coal from the Californian region, gave free scope to the economic differentiation of the two types.

Occurrence

Because of its liquidity, petroleum differs markedly in geological occurrence from all other minerals. It appears on the surface in some localities in the form of oil seeps, but

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*Extract from Bulletin 102, Part 6, U. S. National Museum, "Petroleum: A Resource Interpretation."

commercial quantities of petroleum are found only at depth inclosed within the rocks of the earth's crust. Its occurrence is very similar to that of artesian water, with which, indeed, it is frequently associated. It saturates certain areas of porous rocks, such as beds of sand or sandstone, tending to accumulate where such strata occur beneath denser, impervious layers. Occurring in this way under the pressure that obtains at depth, carrying immense quantities of natural gas in solution, and almost invariably associated with water, petroleum is capable of movement and in general migrates upward until it encounters a layer of impervious rock so disposed in structure as to impede further progress and impound the oil into a "reservoir" or "pool," Fig. 1.

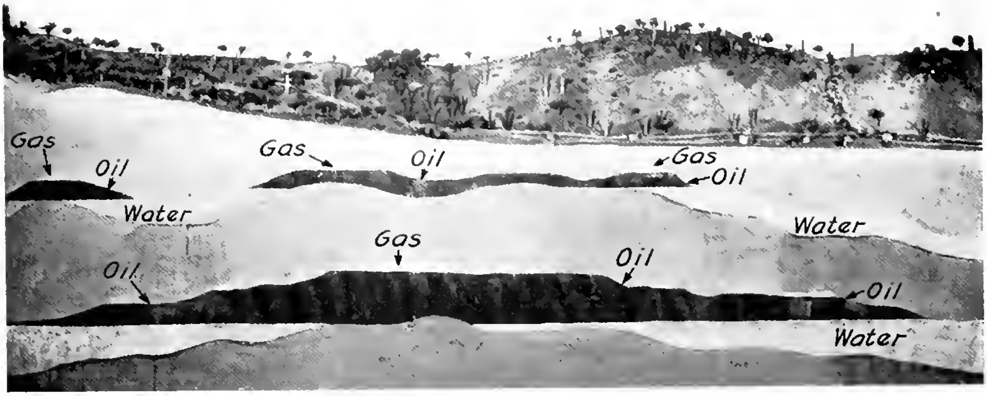

Fig. 1. View of the Occurrence and Mining of Oil and Gas

The geology of petroleum, therefore, is the geology of rock structures, and the skillful mapping of the surface disposition of rock formations gives the means for determining the structure at depth and hence the position of structural features favorable to the accumulation of oil. When this information is supplemented by careful records of the rock layers encountered as wells are drilled, a three-dimensional knowledge of the earth's crust is obtained, remarkable for its detail and accuracy. Thus by the aid of geological methods the development of petroleum fields may be changed from a gambling venture to an exact science, and, if the scale of operations be sufficiently large, it may be figured rather closely how much oil can be obtained from a given expenditure of money. Instead of representing the most uncertain venture in the world, therefore, oil production can now be made as definitely an engineering project as the mining of a clay bank.

The migratory character of petroleum, coupled with the general tendency of stratified rocks to occur in broadly undulating folds and shallow domes, gives peculiar significance to the underground disposition of the oil deposit. Thus the process of winning the oil consists in puncturing the structural feature that holds it so as to give free scope to a movement upward to the surface. Accordingly the position of the oil grows highly unstable as soon as the deposit comes under exploitation and this affects the entire geological unit or pool. In consequence the joint ownership or joint exploitation of a single pool results in the inability to apportion the product on any arbitrary basis of vertical boundary planes, and the oil, therefore, is practically no man's property until it is got above ground. This circumstance is almost invariable and the customary method of exploiting the single oil pool by a series of small, independent holdings has cost an inordinate toll of waste and loss. The economics of oil production is out of adjustment with the geological occurrence of oil.

Origin

Few questions in geologic theory have met with more discussion than the origin of petroleum. It is reasonably certain, however, that petroleum in the main is of organic origin and represents the natural distillation products of plants and animals buried in the muds and oozes of ancient swamps and seas.

Vast rock formations, indeed, are known which are nothing more than the accumulated debris of innumerable organisms, compressed, hardened, and changed into rock. Fossiliferous limestones, phosphate rock, and coal seams are familiar examples which underlie thousands of square miles of the earth's surface. It would be strange, in fact, if in the process of formation oils were not produced, when organic products today, subjected to heat and pressure, yield oily substances not unlike petroleum. Sediments carrying organic remains are sufficiently abundant and wide spread to account for all the petroleum that the oil fields of the world give promise of producing.

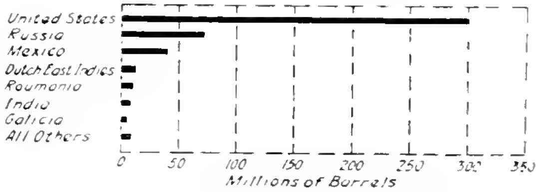

Fig. 2. World's Production of Petroleum in 1916

Distribution

While petroleum is of very common occurrence in traces, areas underlain by commercial quantities are somewhat restricted and fields of great importance are few. Thus in spite of an intensive search for new oil regions and vigorous campaigns of development carried on in all parts of the world, the entire supply comes largely from three countries, as shown in Fig. 2.

In the United States the output is derived from a number of widely scattered regions known as "fields." In a broad way, these fields fall into two groups—those of the eastern half of the United States, bound into a single unit by an extensive system of pipe lines, and those of California, connected with the rest of the country by railroad transportation only. The intermediate fields of Wyoming do not come within this rough geographic classification, but with further development they will presumably be joined by pipe lines with the group of the eastern half of the country. The Kansas-Oklahoma field of the eastern group and the California field are about equal in production and dominate the petroleum output of this country, together contributing over two thirds of the total supply.

The development of petroleum production in the United States from 1881 to 1917, is indicated graphically by Fig. 3. From the situation there depicted, two features of particular significance stand out—the slow increase in domestic production up to 1900, less marked than the increase in the corresponding foreign production, and the rapid domestic growth between 1900 and 1917, contrasted with a nearly constant production for foreign countries during that period. This emphasizes the fact that since the beginning

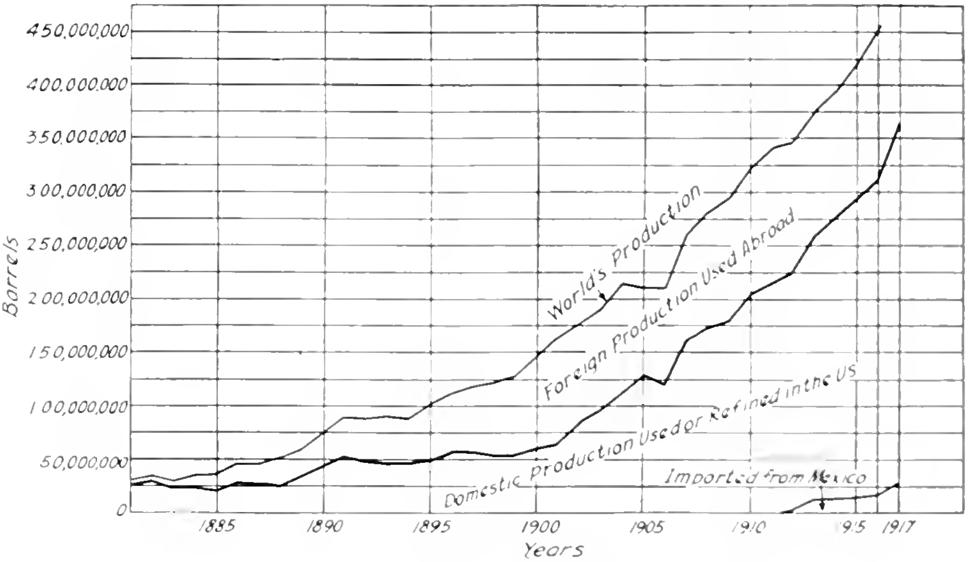

Fig. 3. Chart Showing Petroleum Used in the United States and the Rest of the World from 1880 to 1917

of the twentieth century, the rapidly increasing use of petroleum throughout the world has been met largely through the intensive exploitation of American deposits. Thus the United States has assumed a dominant position in respect to this commodity, producing now two thirds of the world's supply.

THE INDUSTRY

The activities concerned with the production, transportation, refining, and distribution of petroleum constitute the petroleum industry. In quantity, value, and importance of production, this industrial field stands among the foremost in the country. It is notable, especially, for the scope of its operations, which embrace diverse activities usually the function of separate industries—a characteristic arising from the peculiar nature of petroleum. In most other industries, to cite the most striking distinction, transportation over alien lines separates the producing activity from the manufacturing activity, creating a break between continuity of operations; in the case of petroleum, however, the liquidity of the crude product adapts it to specialized transportation through pipe lines, themselves a part of the resource development. In consequence, the petroleum industry in its ideal form represents a type of industrial activity more highly coordinated than other industries of the present day, affording, therefore, an important object lesson for constructive consideration.

The petroleum industry, in point of fact, however, is not coordinated throughout, but at present breaks into two portions, by no means in complete adjustment—the production of petroleum and the handling of petroleum with its threefold aspect of transportation, refining, and distribution. The conditions of producing crude petroleum are wholly different from those involved in its treatment after it is above ground. This is reflected in the circumstance that over 15,000 individual companies are engaged in the mining of petroleum, while the organizations concerned with the handling of the product are numbered by a few hundred. About 80 per cent of the crude production appears above ground through the efforts of a great many small operators, while the bulk of the transportation, refining, and distribution is taken care of by a very few large organizations.

Production

Petroleum is won in commercial quantities through wells drilled to varying depths into the crust of the earth. The drilling is commonly done by means of a heavy string of tools suspended at the end of a cable and given a churning motion by a walking beam rocked by a steam engine. This method is known as the standard or percussion system of drilling. The steel tools, falling under their own weight, pulverize the solid rock encountered and literally punch their way to the depth desired. To prevent the caving in of the hole, but especially to avoid the inflow of water from water-bearing formations, the well is lined or "cased" wholly or in part with iron piping, which is inserted in screw-joint sections at intervals during the drilling and forced down to positions needful of such protection. The well does not taper, but if deep changes to successively smaller bores at several points, resembling in section a great telescope.

Another method of drilling, known as the rotary system, is also in common use, being particularly adapted to regions where the sides of the well tend to cave badly, as in California and some other localities. This system requires more elaborate machinery than the standard, as the drilling and insertion of the casing is simultaneous. The iron casing, indeed, is tipped with a steel bit and rotated so as to bore its way downward like a great auger.

The oil well is marked by a tall wooden framework called a derrick, which permits the string of tools and the casing to be inserted or withdrawn when necessary. It is the presence of derricks that gives the characteristic appearance to an oil field landscape Oil wells vary from a few hundred feet or less in depth, requiring a few weeks only to drill, to those thousands of feet deep and demanding months of continuous labor before production starts. The deepest wells are slightly over 7000 feet, but such depths are exceptional. The cost of drilling, before the war, ran from $1 up to $15 and more a foot, while the rate of progress, except for shallow wells, ranges from about 60 down to 10 feet a day, slowing, of course, with depth. It is apparent, then, that oil-well drilling is a slow and costly process and makes a heavy draft upon the iron and steel industry, consuming, indeed, about one twelfth of its output in ordinary times.

A well favorably located eventually penetrates an oil-bearing bed, and the petroleum may spurt forth in a lavish stream under the influence of the natural gas held in solution under pressure. Such wells are called gushers and some pour forth prodigious quantities of oil. Other wells flow with less violence, and many, lacking in notable quantities of natural gas, yield only under the inducement of pumping. All wells, however, soon reach a maximum production, after which they pass into a period of decline, and eventually become extinct. So inexorable is this procedure that a curve may be plotted in advance depicting the future behavior of a given group of wells. Wells during decadence are spurred into temporary renewals of activity by the explosion of charges of nitroglycerine at their bottoms. The life of an oil well varies from a few months to twenty years or more. The average life of Pennsylvania wells is estimated to be seven years.

When a gusher is struck, adequate facilities are often lacking for catching and storing the product, so that veritable lakes of oil gather between quickly thrown-up earthen embankments. Quantities, in such instances are dissipated through seepage and evaporation, while disastrous fires of spectacular nature are not uncommon. With more careful development, however, field storage tanks shaped like huge cheese boxes are in readiness to receive the oil and prevent the glaring waste inherent in more hasty operations.

Turning attention from the single well to the oil field, we observe that in petroleum mining sustained production depends upon an unbroken campaign of drilling operations. Thus the producers must not only draw oil from existing wells, but at the same time must persist in the drilling of an *increasing*[1] number of new wells and in locating promising territory in advance of drilling. Any factor that retards any one of these three related activities quickly reacts to cause a falling off in production.

Fig. 4 Model of an Idealized Petroleum Refinery

When an oil well becomes extinct, its nonproductiveness does not signify that all the oil is exhausted. On the contrary, current practice in general leaves over half of the oil underground still clinging to the pores and capillary spaces in the rock. To obtain a greater yield from productive ground constitutes a problem of the first magnitude, and promising results have been obtained by forcing compressed air into some of the exhausted wells of a group, with the result that the laggard oil is swept to the neighborhood of other wells from which it may be pumped.

Output, development, and exploration, therefore, must go hand in hand. In a general way, this threefold activity of production is carried on either as a large scale engineering procedure or as a composite of small, individual operations. Large oil companies engaged in production naturally adopt what

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[1] As an oil field ages, new wells yield less than the initial yields of the earlier wells, hence a growing number of new wells is necessary to maintain production.

might be called the engineering procedure, while small companies and individual operators tend more to follow what is picturesquely termed "wildcat"[2] operations. Thus the production of oil is in part dependent upon stable conditions, but in larger part is still a type which operates in considerable measure as a gambling venture. This is why oil mining is generally looked upon and commonly described as hazardous from a financial standpoint. The hazard is inherent only in small-scale operations.

The engineering type of production makes use of skilled geological knowledge in its campaign of oil production. The modern oil company employs a large geologic staff, which determines by detailed field surveys the most promising spots for drilling. The growth of oil geology has been rapid and while, of course, geologic science can not strike oil with every drill, it does multiply by many times the chances of each drilling operation. It has been stated that "the operator who plays geology has a fifty times better chance of striking oil than he who does not."

But in spite of numerous highly organized production activities, the fact remains that the petroleum production of the United States is in considerable measure dependent upon a hit-or-miss plan of exploitation. Were it not for the wildcatter, who stakes his all (sometimes borrowed) on the chance that a random hole drilled in the general vicinity of productive territory will yield the hoped-for return, the output of petroleum in a country which produces two thirds of the world's supply would fall to an utterly inadequate figure. The gambling instinct is still the prime motive power that lifts most of the oil produced in this country.

It is not intended, of course, to throw oil production into an unfavorable light by thus focussing attention upon its gambling aspect; to exert onerous effort (such as oil field development demands) under the incentive of rich possibilities of reward is a straightforward and legitimate business activity. It is frequently questioned whether oil development could be sustained without prospect of large pecuniary gain. The point is merely made that under present circumstances petroleum production is dependent upon this psychological aspect, acutely developed, which is both subtle and intangible, yet profoundly important in conditioning the output; this factor must be reckoned with in contemplating the course of the resource development.

Production and consumption, of course, can not coincide in amount; hence, of necessity, there are reserves of petroleum above ground which serve as an expansion and contraction joint, so to speak, between supply and demand. When there is an overproduction in respect to current needs, the reserves or, as commonly termed, the stocks increase conversely, with industrial expansion or lessened output, drafts are made upon the stocks, which then decrease. The condition of the stocks, therefore, is a sort of pulse to the crude-oil market, since prices, under the influence of the same factor of supply and demand, fluctuate in like manner. The stocks, under conditions of unorganized production, have come to be unusually great during the past few years, representing roughly in 1916 a six-months' supply. Under war conditions, the stocks were rapidly depleted to meet a consumptive demand which was greater than the productive capacity of the country.

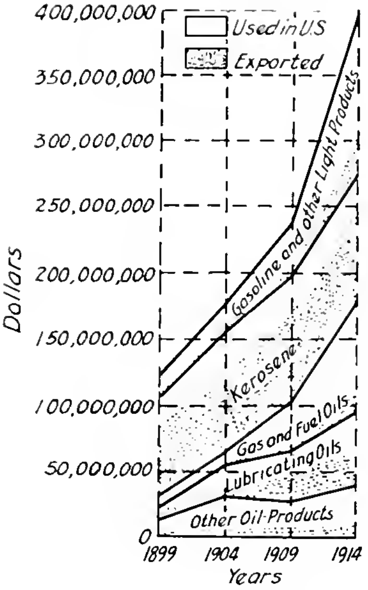

Fig. 5. **Chart Showing the Relative Values of the Principal Petroleum Products Manufactured in the United States from 1899 to 1914**

The price of crude petroleum at the well varies considerably according to quality, distance from market, and other factors. The paraffin oils of light gravity, such as those produced in Pennsylvania, are the most valu-

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[2] In strict oil-field parlance, to *wildcat* is to drill a well where oil has been proven not to exist, as opposed to drilling a well in the midst of producing wells. Thus both large companies and small may alike engage in *wildcatting*, although, as a matter of course, most of the *wildcatting* is done by small operating units.

able because they yield the largest percentage of products in demand, while the asphaltic oils of heavy gravity, such as those of California and part of the Gulf region, command a price roughly a fourth of that which the best oil enjoys. Thus the Pennsylvania crude commenced 1915 with a price of about $1.50 a barrel and ended 1917 at about $3.75, while during the same period California crude climbed from about 35 cents to practically $1. These two types of oil represent the extremes of quality, with the factor of distance from markets nearly the same in the two instances. Between these limits range the prices of all the other oils of the country, the quotation at any given time and location being a complex of quality and of balance between supply and demand, with all the qualifications that the latter expression involves. The wide range in prices for a single raw material, with the utmost concession to differences in location and composition, suggests an undue discrepancy to be credited against the conditions under which oil is produced.

The dependence of sustained production upon an unbroken campaign of drilling exploration, and the extent to which such a campaign is carried on by "wildcat" operations on the part of small companies and individuals, lead to many perplexing legal and economic difficulties. Land, of course, is rarely owned by the operator, so that he must ordinarily either purchase or lease the oil (and gas) right. The laws connected with oil lands have not been modernized, but are confusing and in part conflicting, so that the operator is put to undue trouble and expense in meeting the legal requirements of his holdings. Moreover, the method of leasing under small unit operations leads to a wasteful competition between neighboring wells in their race to secure a maximum production within the period of the lease—haste, with waste, being an economic necessity in such instances. In regard to lands owned by the Government, the legal regulations are so ill-adapted to progress that R. H. Johnson and L. G. Huntley in their "Principles of Oil and Gas Production," remark: "Most of the public lands which seem promising for oil and gas have been withdrawn, since there is universal agreement by both Government and producers that the present law, by which oil and gas lands are taken as placer claims, is utterly unadapted to the industry. The development of the lands which are not withdrawn would best be postponed until a new oil and gas prospecting permit and leasing law is passed, and the oil placer claim law revoked except where work is already started."

Transportation

One of the remarkable and impressive features of the petroleum industry is the fact that the crude product is transported through a system of pipe-lines that connect the points of production with refineries, markets, and seaports. This method of handling is natural and inevitable with a liquid product consumed in bulk, as evidenced by a somewhat analogous method of transportation adopted for the municipal water supply. While petroleum shares with coal the main responsibility for energizing the mechanical acitivities of the country, it is interesting to note that crude oil, unlike raw coal, imposes normally no appreciable burden upon the railroads.

The pipe lines of the United States, comprising those of the subsidiary companies of the Standard Oil and a number of independent companies, aggregate thousands of miles in length and form a network spread over much of the country. They consist of trunk lines, the longest of which connects Oklahoma with the Atlantic seaboard by way of Illinois, and gathering lines leading into the main channels. The approximate mileage of the principal lines of the United States amounts to 28,995 miles. The total length of all the pipe lines is much greater.

The pipes vary in diameter from 2 to 12 inches, but 6 to 10 inches represent the common sizes. The piping is made of iron plate and is ordinarily placed below the surface of the ground. At intervals of from 15 to 30 miles, according to the viscosity of the oil, there are pumping stations. In the case of heavy, viscous oils, such as those of California, it becomes necessary to heat the product at each pumping station to facilitate its progress. Unlike a railroad, the pipe-lines, in general, follow a direct course, uphill and down. An 8-inch pipe weighs 28 pounds per foot, and its cubic capacity is about 328 barrels of oil a mile. This means that millions of barrels of oil are required merely to keep the pipe lines of the country active. The pipe-line facilities of the country are ample to handle the normal distribution of the current production.

The significance of the pipe line in the development of the petroleum industry has been great. It has made crude petroleum independent of the railroads and through cheapness of operation has lowered the cost of petroleum products; it has freed the refineries from geographic allegiance to areas of production and permitted their establishment at strategic points in respect to consumption of products; it has permitted and induced integration of activities, with marked advantage to the consuming public, but not unaccompanied by hardships and abuses falling upon small units of the industry itself; and by stretching out to meet a growing area of exploitation it has unified widely separated fields and enabled production to grow to its present imposing size. The pipe line has woven the scattered strands of adventurous exploration into a steady flow of bulk raw material.

Some crude petroleum is transported in tank cars, but most of the 60,000 tank cars in operation in this country are engaged in moving petroleum products—gasolene, kerosene, and fuel oil chiefly. For transportation by sea, steel tankers and towing barges, fitted with non-communicating compartments, are employed for both crude petroleum and its bulk products. The development of the tank steamer has been an important factor in building up an important foreign trade in petroleum products, is responsible for a considerable coastwise movement of crude and fuel oil, and has opened the oil fields of Mexico to the United States and other markets.

Refining

Crude petroleum may be burned as fuel and nearly a fifth of the domestic consumption is utilized in this way. But most of the petroleum is manufactured into a series of products which have wider usefulness and higher value than the crude oil, and it is upon this dominant part that the petroleum refining industry depends.

At the present time petroleum yields, when completely refined, four main products—gasolene, kerosene, fuel oil, and lubricating oil—and a large number of by-products, of which benzine, vaseline, paraffin, road oil, asphalt, and petroleum coke are well-known examples. These are commercial terms and therefore carry no exact meaning in a chemical sense. Since the products merge one into the other, there can naturally be between them only an arbitrary line of demarcation. Gasolene, as here used, covers those products of crude oil which are more volatile than kerosene; the term therefore embraces some benzine and naphtha. Kerosene, as here used, is the common type of illuminating oil representing the distillate heavier than gasolene, but lighter than fuel oil. Fuel oil is used as a broad term, including all distillates heavier than illuminating oils and lighter than lubricating oils; it includes so-called gas oil—a high-grade fuel oil used in the manufacture of gas—as well as fuel oil proper, used largely for steam raising. The term lubricating oil includes a variety of heavy oils used for lubricating purposes. Most of these products in turn may be broken up into other substances, each the starting point of further refinements. Under present practice petroleum yields only a few hundred substances of commercial value, but the mind can set absolutely no limit to the number of useful materials that chemical research may still wrest from this raw material.

While refinery practice is a highly technical matter and varies both according to the chemical nature of the oil and the local demand for products, we may, for the sake of simplicity, ignore all details[3] and note merely that there are three main types of refineries. The first of these is called a "skimming" or "topping" plant, because the light oils, gasolene and kerosene, are removed from the rest of the products, which are left behind as a residual oil and sold in this semicrude condition for fuel purposes. The "skimming" plant, as its name implies, make an incomplete recovery of products, suppying only those in greatest demand or easiest to make; most of the plants of this kind are situated west of the Mississippi River.

The second type of refinery may be termed the "straight-run" plant; this produces all four of the main products—gasolene, kerosene, fuel oil, and lubricating oil—together with by-products, the process separating the crude oil into its natural components with the minimum of chemical change. The "straight-run" refinery lacks flexibility, because it has no power of producing, for example, more gasolene than the crude oil naturally contains. Such plants are situated in the East and other parts of the country where the demand, especially for lubricants, justifies the expense of the practice.

The third type of refinery is of recent birth, but has made rapid strides toward a great future; it employs the so-called "cracking" process, which yields, like the "straight-run" plant, a full set of products, but a greater percentage of gasolene than the crude oil gives upon ordinary distillation. This is accomplished at the expense of the heavier component oils, whose molecules are broken or "cracked" into lighter molecules, which constitute just so much additional gasolene.

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[3] See Part VIII of this series, Dec. 1917. [Ed.]

It is obvious that cracking has developed in response to a growing demand for gasolene; its significance is apparent in the fact that it permits the production of a more valuable product from one less valuable. With an increasing call for gasolene and a decreasing supply of petroleum, cracking may be called the hope of the future as regards refinery advance.

If we pause for a moment to contemplate the consumption of petroleum in the crude condition, and then the three types of refining—skimming, straight-run, and cracking—it becomes evident that each treatment represents a step in advance over the preceding, and that, while all four prevail today, the cracking refinery is in line with true progress and will eventually dominate the situation.

Refineries, whatever the type, employ the principle of distillation in their operations. The petroleum is heated in stills and the products vaporize, pass off, and are condensed in fractions, representing roughly the materials in demand. These products are then purified by chemical treatment or transformed by chemical means into a series of secondary products. The production of the various kinds of lubricating oils needed for diverse uses represents an intricate, yet single, part of petroleum refining; and is merely one aspect of the many ramifications found in refinery technique. The refining of petroleum makes heavy drafts upon other chemical industries—for example, in normal times, about one tenth of the sulphuric acid produced in the United States goes into petroleum refining—but the refinery in turn contributes many essential products to other chemical manufacturing activities. These industrial interrelationships, ofttimes overlooked, are of the utmost significance—a fact strikingly brought out when one activity is called upon to expand more rapidly than some other activity with which it is geared.

The refining of petroleum, requiring elaborate plants, is by nature a large-scale enterprise; hence such activities in the main have naturally come under the control of a few large organizations. While several hundred individual refineries are in operation, the bulk of the output is due to the efforts of less than 10 companies. The refining of petroleum, therefore, is largely an integrated activity, in close alliance with transportation of crude, on the one hand, and distribution of refined products on the other. It has already been pointed out that the development of pipe-line transportation has permitted the establishment of refineries at points distant from oil fields, but convenient to centers of consumption and to seaports.

With the broad outlines of refinery technique in mind, it will be of interest to observe the shifting focus of development that has characterized the production of petroleum products in America. When the famous Drake well struck oil on Oil Creek, Pa., in 1859, an illuminating oil distilled from coal and called "coal oil" was in general use throughout the country. Petroleum, therefore, found a market already established for its illuminating constituent, which it usurped at once, quickly supplanting the coal-oil industry with a production of *kerosene*. Although other products were also produced, and lubricating oils made from petroleum found quick favor in connection with a growing application of mechanical energy, kerosene became the chief petroleum product and for over 40 years its use expanded until this illuminant penetrated literally to the uttermost corners of the globe. It would be difficult, indeed, to estimate the value to the world at large of this cheap and convenient source of light, which has been aptly termed "one of the greatest of all modern agents of civilization." During this period there was little demand for the light products of distillation, the liquids now sold under the commerical name of gasolene, which were, therefore, largely waste products in an economic sense, and even in some instances physically destroyed for want of any adequate demand for their utilization. Gasolene for a long time, then, was a by-product of little value turned out in the manufacture of kerosene.

Toward the close of the nineteenth century, however, the commerical application of the incandescent mantle in gas lighting and the development of the electric light introduced types of illumination so superior to the kerosene lamp in convenience that the use of the latter was gradually relegated, in large part, to the small town, the country, and foreign regions, where gas and electricity had not been introduced. Accordingly, in spite of a most aggressive campaign for foreign trade on the part of the petroleum industry, the refinery faced the restrictions of a slowing demand for kerosene which presaged a limit to the output of the whole set of petroleum products. But the menace of this limiting circumstance was destroyed, before it became effective, by the introduction and rapid advance of the internal-combustion engine. The phenomenal growth in the use of the automobile built up such a heavy demand for gasolene that this product came into the lead and took up the burden of justifying the increasing refinery consumption of crude petroleum—a burden which kerosene, even with the aid of a growing market for fuel oil, lubricants, and other oil products, was scarcely longer able to sustain. Gasolene, now, is the main prop to the whole cost structure of petroleum refining.

With the industrial quickening due to the entrance of the United States into the world war, the demand for fuel oil became so insistent that the complexion of the oil situation again changed and the emphasis fell upon fuel oil. And as the production of crude petroleum was not able to keep pace with the attempted consumption of fuel oil, a serious shortage of this product resulted; even while the supplies of gasolene were ample to maintain the activities of war, business, and pleasure.

If the course of development, as indicated by this broad survey of refinery evolution, be projected into the future, we may foresee a time when the petroleum industry will yield a range of fuels for the internal combustion engine only; illuminating kerosene in quantity narrowing to that desirable for country use and export trade; lubricating oils adjusted to the growing demands of mechanical power and an ever-widening range of chemical products supporting a great oil by-products industry, rivalling if not exceeding the coal-products industry in importance. In respect to the last, it should be emphasized that the United States today faces an opportunity similar to that which 20 years ago confronted both Germany and the United States as regards the manufacture of dyestuffs, explosives, fertilizers, drugs, and other chemicals from the non-fuel components of coal.

Distribution

Many industries terminate their activities with the manufacture of commercial products, turning these over to independent agencies for distribution. With the petroleum industry, however, distribution forms an integral division of the industrial activity, a carefully planned out construction of markets as part of the resource development being substituted for a demand ordinarily left to natural growth or maintained by costly advertising. Thus, once the oil is produced, it passes through the various stages of transportation, refining, and distribution under the influence of a highly organized economic machine, a coordinated industrial unit, engaged not merely in adapting a crude material to diverse uses, but also in shaping and developing latent needs the world over into a demand which will sustain a balanced output of products.

We have already seen how the pipe line and to a less extent the coastwise tanker, brings the crude petroleum to the refineries which are favorably located in respect to distribution. From the refineries the gasolene, kerosene, fuel oil, lubricating oil, and other petroleum products are sent forth to supply the needs of surrounding territory, while refineries near seaboard furnish heavy contributions to foreign trade. As distribution is a diverging process, and, moreover, the crude petroleum is broken into numerous products requiring separate handling, the pipe line is not broadly adapted to this diverse haulage. Railroad tank cars,and barges (where water transportation is advantageously available), therefore, receive the bulkier products and carry them to distributing depots, where storage tanks release the railroad carriers and supply tank wagons that radiate to fill the local needs. In this way the entire country is covered by a network of specialized transportation, each step employing a bulk carrier best adapted to its particular purpose both as to size and mechanical facility, the whole involving the maximum of expedition and simplicity. Without this highly organized system, with its far-reaching ramifications, the present widespread use of gasolene and kerosene would not be possible. From the oil field to the consumer, the handling of petroleum is remarkably efficient.

The arrangements whereby a foreign trade has been built up and sustained are no less elaborate. Fleets of tank steamers and freighters carry the products in bulk or in suitable containers to all parts of the world. Fuel oil, gasolene, and lubricants go in greater measure to industrial countries, but kerosene penetrates to every corner of the globe, a system of depots and distributing lines adapting the product to the needs of the most out-of-the-way regions. The care that has been bestowed upon the extensions of the market for kerosene, against every conceivable obstacle of climate, topography, and racial prejudice, is a striking example of industrial foresight; yet without this policy, the whole oil industry would have been unable to expand to its present proportions.

Professor Elihu Thomson's Early Experimental Discovery of the Maxwell Electro-Magnetic Waves

By Prof. Monroe B. Snyder
Philadelphia Observatory

It must be borne in mind that this very early and very remarkable investigation of the electro-magnetic waves by Professor Elihu Thomson was quite incidental to an investigation intended to set aside a claim then made by a famous inventor for the existence of an alleged Wetheric force. It is not possible here to reproduce the relentless logic of description of special experiments made to prove the fallacy of the claim. But it is very clear how Professor Thomson was led by his mode of testing for "induction" effects to the far more extensive testing for the æther waves produced, and thus to the tests which Professor Snyder has so definitely described as performed by his former colleague. It was indeed a misfortune for American science, as Professor Snyder indicates, that Professor Thomson could not then continue his investigations in the incidental field. And this very clearly appears from the ingenious use then made in the Thomson experiments, as described in the *Franklin Institute Journal* cited, of "balanced circuits" and of other devices thoughtfully dealing with the æther waves concerned. It is indeed gratifying that these notable tests of the electro-magnetic waves by Professor Elihu Thomson in 1875 have now been so specifically and reliably placed on record by one appreciating their significance. The story was originally published in the Central High School *Mirror*, Philadelphia.—Editor.

In the annual lectures to my classes in astronomy on the vast electro-magnetic spectrum of radiation of more than 50 gamuts, and in which the interesting visible light occupies but a single gamut, I have again and again been reminded of the fact that my former colleague, Professor Elihu Thomson, had already in 1875 experimentally discovered the long electro-magnetic waves first announced in the mathematical theory of Clerk Maxwell in 1873, and later concretely revealed by the experimental work of Hertz in 1887.

One day in 1875, while busily engaged in some work in the old Central High School Observatory, at an elevatorless height that usually obviated intrusion, I was surprised by a bustling visit from my associate, Professor Elihu Thomson. He was bent, as I soon found, on testing whether the æther disturbance, which he was exciting by means of a Ruhmkorff coil in the Physical Room of the first floor of the building, could be observed in the observatory hallway on the sixth floor. Applying the sharpened point of a short lead pencil near the brass knob of the observatory library door, Thomson called attention to the delicate sparks that were passing between the pencil point and the door knob. With due elation over the success of the test, he then told me that he had similarly traced the æther disturbance all through the building; in the Lecture Hall on the first floor at a distance of about 60 feet; at the room of the professor of mathematics on the third floor at a distance of about 80 feet; and now at the door knob of the observatory library, distant perhaps over 100 feet from the experimental apparatus.

It is interesting to know what odd electric radiating system was at that time kept in action in the Physics Room. In an effort to magnify the electrical oscillations, then being studied for another purpose, Thomson had connected one terminal of that famous induction coil to the water pipe and the other terminal to a large metallic still, which stood at hand, and which he duly insulated by placing it on a glass jar. Vigorous sparks of a few inches were then passed, and the unique radiating system produced results that soon induced the professor to widen the area of his observations in the manner mentioned.

The invisible long electro-magnetic waves were thus definitely and repeatedly traced by Professor Elihu Thomson in 1875 to the distances and effects stated, and through five intervening floors, by a means much simpler than the detector of Hertz, and yet 12 years prior to Hertz's celebrated verification of the Maxwell theory. The insight and the accuracy of the conception of Professor Thomson as to what was really happening, so clearly reflected in an article on the same experiments undertaken for the purpose of correcting a misconception of Edison's (*Journal of Franklin Institute, April, 1876*), show how unfortunate it was that Professor Thomson was then diverted from a continuance of the study of those æther waves, observed so many years before their elucidation by Hertz. Elihu Thomson's demonstration of 1875 seems, beyond doubt, to have been the very first discovery, by means of repeated tests at large and varying distances, of the transmission of the invisible electro-magnetic waves through the æther, the first experimental discovery of what are generally known as the Hertz-Maxwell waves, now so widely and triumphantly used in wireless telegraphy and wireless telephony.

Effect of Color of Walls and Ceilings on Resultant Illumination

By A. L. Powell

Edison Lamp Works, General Electric Company

The color of walls and ceilings plays a very important part in the illumination of interiors, and architects and others who are responsible for systems of interior illumination should make a special study of the reflecting powers of different colored walls and ceilings with special reference to the qualities of paints and other pigments. The author outlines briefly some color schemes for walls, ceilings and fixtures that have been found to give good results in industrial plants, offices, schools, stores, and residences. Some valuable information is given on the reflecting power of several different kinds of paint, both when new and after ageing one year. Some helpful suggestions as to the best methods of applying paint to secure satisfactory reflection are also offered, and a method is described for determining the coefficient of reflection of any surface.—Editor.

No matter how carefully designed a lighting system may be with respect to lamps, reflectors, spacing, height, etc., if the surroundings are not adapted to reflecting such light as strikes them an inefficient system may result. The proper painting of walls and ceilings is therefore of great importance.

The ceiling and wall surfaces in a room are secondary sources of light—receiving and reflecting light from the lamps. Merely increasing the reflection coefficient of the ceiling a slight amount may greatly increase the effective illumination.

It is therefore very important to see that the ceilings are as light in color as possible. Pure white is usually to be preferred, although if a tint is demanded for artistic effects it should be a light cream rather than gray or some similar tone. Not only is the color of the ceiling important, but the actual finish must also be considered. A glossy surface reflects images of the lamp filament and introduces glare causing eye strain. A flat or matt finish is therefore essential. A thin coating of white paint through which a dark surface may be seen has the same effect as a thin coating of enamel on a reflector. In other words, unless this surface is thick the light gets through the surface and becomes absorbed.

It is safe to say that well painted white ceilings give an increase of between 20 and 30 per cent in illumination over ordinary light buff or similar colored ceilings where semi-indirect or similar lighting systems are in use. This is really a conservative figure.

Industrial Plants

Efficiency of utilization of light is highly important in the industrial plant, and pillars, walls and ceilings should be pure white. Any light striking these surfaces is reflected in a degree depending upon the color. If dark brown or smoke covered, possibly only 5 per cent will be reflected; if pure white the reflection coefficient may be as high as 70 per cent. Even the floors should be kept as light as possible, for a portion of the flux which strikes this is reflected to the ceiling and then back to the work.

A recent test in a new factory building with white ceiling, light wood floor and light colored side walls showed more units of light reaching the working planes than were generated by the lamps themselves. This paradox is explained by a consideration of the multiple reflection. Of course the extremely high value would not have been obtained if machinery were installed.

The lower part of the side walls is of less importance in reflecting light, and for purposes of appearance it is often desirable to have a dado of dark green or some neutral color, as finger marks and other disfigurements are not so noticeable. This treatment of the walls also reduces the brightness of the background in the field of view—a desirable feature.

In many instances the painting of certain parts of a machine white or a lighter color will materially soften the shadows and improve working conditions, eg., on a large vertical slotter the surface which faces the table, or on a lathe the area surrounding the work.

High grade oil painting, as discussed later, is most desirable, but where whitewash is absolutely necessary frequent cleanings will speed production and keep the lighting bills at a minimum. A clean, bright shop has a decided effect in improving the morale of the workmen.

Offices and Schools

Because of the justly wide-spread use of the indirect lighting systems and the likelihood that they will be installed at any time, the ceilings should always be light in color.

With most systems of lighting a considerable portion of the flux strikes the upper part of the walls; for these surfaces, a soft pale olive green with a light blue cast in north rooms and a yellow cast in south rooms is recommended. However, this question of wall tint is largely a matter of personal preference. Some individuals prefer a greenish tint which is soft and restful, while others, for artistic reasons, prefer a light buff or cream. It is recognized that it is often worth while to sacrifice lighting economy for artistic effect. The lower surfaces can well be of a darker neutral color to provide space on which the eye can rest in comfort.

A light-colored room is decidedly more cheerful than one finished in dark colors. In many cases dark surroundings have given the impression of bad lighting, while in reality there was a sufficiently high intensity on the desks. The psychological effect of gloomy interiors is well known, and it is, of course, desirable to keep the clerks or pupils buoyant and cheerful.

In general, light surroundings reduce the conditions of glare. An artificial light source viewed against a bright ceiling is less annoying than in another position. Light-colored walls diffuse the light back toward the window sides of the room and thus lessen the contrast between the bright sky and adjacent walls.

As has been mentioned before, glossy wall surfaces should not be used, and even the furniture and trim should not be highly varnished. In this connection close cooperation between the builder and lighting engineer is essential.

Light buff window shades are desirable, and if these are drawn at night they materially assist in reflecting the light rather than allowing it to escape to the street. If these shades are slightly translucent they are very useful in the daytime in cutting down the direct sunlight, diffusing the light which passes through them and preventing a sharp line of shadow demarkation which may result if opaque shades are used. The Code Lighting School Building issued by the Illuminating Engineering Society gives some interesting data on this subject as well as the question of design of blackboards.

Stores

A pure white finish throughout is most universally applicable to stores, not only for its effect on the amount of light utilized and general bright appearance desired, but for the color result secured.

White light striking a colored surface will have some of its rays absorbed and be reflected as colored rather than white light. (This property is that which makes the surface colored.) Hence, if an illuminant approximating daylight is used, and all of the reflected light is tinted, the resulting light will be of a different color from that given out by the lamp. A practical illustration of this undesirable condition will be seen where daylight lamps are used in semi-indirect units in a room with a yellow ceiling. White surroundings do not modify the color of the reflected light as do colored surroundings.

Residences

It is true that efficiency of light utilization is not at all important in the home, yet the color of walls and ceilings, particularly the former, has a remarkable bearing on the pleasing appearance of the room.

If these are of such colors that they do not reflect the light satisfactorily, no matter how much light is supplied the room will never appear bright and cheerful. Dark green wall paper, for example, reflects very little light, and a room finished in this way frequently is dull. A room finished in deep brown woodwork and side walls is often uncomfortable when lighted by ordinary methods of illumination. With general lighting systems no matter how much precaution is taken to shield and diffuse the light, the lamp and its accessories show up in contrast to the dark background and become annoying bright spots. The only satisfactory method of lighting such an interior is by the use of table or floor lamps giving spots of fairly bright illumination, around which the occupants are grouped and the attention concentrated, allowing the room as a whole to be comparatively dark or in shadow.

Light-colored wall paper and paint are therefore generally to be desired if the room is to be cheerful at night. An object or an interior looks cheerful and bright in proportion to the amount of light it reflects back to the eye, although pure white finishes are not to be desired from an artistic standpoint. The study of the psychological effect of the different colors is most interesting, but space does not permit a discussion of this phase of the subject.

Permanency of Various Wall Finishes

The freshly scraped surface of a block of magnesium carbonate reflects more light than any other object, 88 per cent of the light falling on it being sent back. We cannot expect as good results from ordinary painted surfaces, because the usual mediums, including even zinc white, are quite gray compared with magnesium carbonate. A paint made with magnesium carbonate as a pigment more nearly approaches this value and is desirable from a standpoint of light reflection. As comparative average values for properly prepared and freshly mixed samples, the following figures apply:

Paint	Coefficient of Reflection	
	New	After Ageing One Year
White lead and oil	0.85	0.67
Lithopone	0.77	0.72
Calcimine type	0.74	0.67
Flat enamel (magnesia bearing)	0.76	0.73
Gloss enamel	0.75	0.75

There is comparatively little choice between any good white paints when fresh. The story is different, however, after being exposed to normal daylight conditions.

It is seen from this table that the enamels have held their own very well. The lithopone paint has fallen off by 6 per cent of its initial value. Calcimine and white lead have fallen off about 10 per cent. The falling off of calcimine is due largely to its porous nature, which permits it to absorb dirt readily. The falling off in white lead and calcimine is progressive and does not decrease in rate. Numerous observations on lead and oil paint in use for two years indicate a falling off of about 20 per cent. The slight falling off of flat enamel occurred in the first month, no further decrease being observed. The coefficient of reflection of the gloss enamel was constant throughout the test.

These tests were all made under constant laboratory conditions and must serve only as a guide for judgment. They form a starting point for observation and practice.

Method of Applying Paint

Now as to the actual painting itself: What conclusions do we draw from the data presented? It is obvious that a gloss enamel will not fulfill one of our initial conditions, due to its high value of specular or image reflection. We are therefore reduced to the use of some form of what we have called flat enamel. This paint must contain no lead and probably no linseed oil. It must be composed of chemically inert white substances ground exceedingly fine (to produce density) and mixed in an inert vehicle which is impervious and non-porous when dry. It must dry flat and be washable.

The most permanent and highest practical coefficient of reflection and diffusion can be obtained with plaster surfaces treated as follows:

First coat.—Good impervious surface.
Second coat.—Straight lithopone paint.
Third coat.—Gloss enamel and lithopone mixed equal parts.
Fourth coat.—Flat enamel (magnesium bearing flowed on).

For metal surfaces, after the usual preparation apply a first coat of red lead thinned with raw linseed oil drier and "turps" to give an eggshell finish. Over this a coat of lithopone paint, mixed one gallon to one quart of good varnish; then the second, third and fourth coats as applied to plaster.

From an illuminating standpoint the walls of a room are not as important as the ceilings, and they should be less bright. A simple painting formula will apply. It is in brief: First coat, good impervious surfacer mixed with equal part lithopone paint; second and third coats, straight lithopone paint, the last tinted with japan tint thinned with "turps."

If it is necessary for any reason to use a gray tint it should never be obtained by mixing lamp black in the paint. This is the substance having the lowest known coefficient of reflection. To obtain the gray it is desirable to mix vermilion and emerald green to get black and then thin out with white. This produces what is known as a warm gray and has a reasonably high coefficient of reflection.

In any painting, the surface on which it is applied should be properly prepared and nonporous so that it will not absorb any of the vehicle of the final coat. It must also be chemically inert with respect to this final coat.

A number of paint manufacturers have investigated the subject of "painting for light" and have produced pigments which give results comparable with those specified above. Any of the prominent paint manufacturers will gladly furnish detailed information on their product upon request.

Economics of Situation

It is true that it is somewhat more expensive to paint the surroundings correctly than to apply calcimine, mill white, or some other paint which depreciates quite rapidly, yet the economics of the situation well warrant this expenditure. For example, the following calculation applies:

If we consider a room in which the ceiling is painted with white lead and oil, as described in the test quoted above, we may expect at the end of two years that the illumination efficiency has decreased not less than 15 to 20 per cent, due alone to the reduction in coefficient of reflection of the ceiling, other conditions being constant. But in actual work other conditions are not constant; for one thing the coefficient of reflection of the paint on the wall also undergoes a decrease. It is probably safe to say that the use of lead and oil (or calcimine) as an interior paint entails a progressive loss of light amounting to 15 per cent at the end of the first year. Thus a room of 400 sq. ft. floor area, so painted and initially lighted by four 100-watt lamps, will require an additional 100-watt lamp at the end of two years to bring the illumination back to what it was in the beginning—an increase of 25 per cent in energy consumed and lamp renewals. Surely this figure is striking enough to warrant the necessary expenditure. The writer is indebted to an article by Mr. Bassett Jones, Consulting Engineer, on "The Characteristics of Interior Building Finishes as Affecting Illumination," for many of the figures presented in connection with painting.

Measurement of Reflection Factor

There are a number of laboratory methods of obtaining this value, some of which employ elaborate apparatus and which take into account with a high degree of accuracy the direction of the incident light, color of incident light, and similar features. A complete description of these methods will be found in the technical press, references to which are given in the bibliography which follows the article.

Fig. 1 Determining by Means of Portable Photometer the Reflection Factor of a Wall Surface

The practical determination of the coefficient of reflection of a wall or ceiling (diffuse reflection) is quite simple indeed, and can be made by anyone familiar with the operation of a portable photometer employing a detached test plate. The standard on which reflection factors are based is a freshly scraped block of pure magnesium carbonate. One of these standards can be secured at any drug store. A block approximately four inches square and two inches thick can be purchased for a few cents. The first step in the determination is to scrape the surface of this and place the block in any convenient position relative to an artificial light source.

The photometer is then pointed at the block from some angle not too far from the normal and a reading taken and recorded. A secondary standard, or working standard, such as a sheet of blotting paper, is next calibrated. This is substituted for the magnesium block, and with the same illumination incident on it as with the previous reading, a second reading is taken and recorded. We then have the following proportion applying: Reading *A* is to 88 per cent as reading *B* is to the coefficient of reflection of the blotting paper.

Taking care that the blotting paper or secondary standard does not become dirty, it is placed at a convenient position on the wall or ceiling the reflecting factor of which is desired, and a reading taken of the blotting paper with the normal illumination received on the wall incident on the paper. The paper is now removed and a reading taken of the wall surface. We have already determined the coefficient of reflection of the blotting paper, and the following proportion applies: Reading on blotting paper is to the coefficient of reflection of blotting paper as reading on wall is to coefficient of reflection of wall.

If the surface to be tested is polished or has a considerable element of specular reflection, the determination of the coefficient is more complex, and several readings at different angles should be taken to insure a fair average value.

No difficult mathematical equations are involved in this determination. Simple readings of the photometer and a proportion are all that is necessary. Example calibration: Magnesium carbonate block, apparent foot-candles 10.5; white blotting paper, apparent foot-candles 9.1. Then.

$$\frac{10.5}{0.88}=\frac{9.1}{x}$$

Coefficient of reflection of blotting paper is 76 per cent.

Test of wall surface: Apparent foot-candles, white blotting paper in place, 3.7; apparent foot-candles of wall, blotting paper removed, 2.6. Then

$$\frac{3.7}{.76}=\frac{2.6}{x}$$

Coefficient of reflection of wall is therefore 53 per cent.

Coefficient of Reflection (Reflection Factors)

The following table indicates in general the amount of light reflected by the different colors. It will be noted that there is a considerable variation in percentage for any particular color. This is necessary, as we do not have any means of specifying the exact shade or tint of the various colors. The figures presented are the result of a considerable number of tests by different authorities and are representative average values. We believe them to be fairly typical within reasonable limits.

Color	Percentage of Light Reflected
White—new	74 to 80
White—old	67 to 76
Cream	56 to 72
Buff	44 to 59
Ivory	66 to 70
Gray	15 to 57*
Light green	43 to 67
Dark green	10 to 22
Light blue	31 to 55
Pink	32 to 55
Dark red	12 to 27
Yellow	55 to 67
Dark tan	27 to 41
Natural wood brown stain	15 to 26
Light wood varnish	38 to 44

* Grays vary remarkably, depending on the way they are prepared. A gray made by mixing lamp black with white paint has a low co-efficient of reflection. A gray made by mixing red and green paint with white base has a relatively high co-efficient of reflection. It is known as a warm gray.

BIBLIOGRAPHY

Effects of Reflection from Floors. J. R. Cravath, Electrical World, October 28, 1911.

Reflection Co-efficients. Paul Bouder, I. E. S. Transactions, Vol. 6, p. 85.

Determining the Reflecting Power of Opaque Bodies. P. G. Nutting, I. E. S. Transactions, Vol. 7, p. 412.

Reflecting Properties of Painted Interior Walls. C. W. Jordan, I. E. S. Transactions, Vol. 7, p. 529.

Influence of Colored Surroundings on the Color of Useful Light. M. L. Luckiesh, I. E. S. Transactions, Vol. 8, p. 62.

Reflection from Painted Surfaces. Louis Bell, Electrical World, Jan. 22, 1915.

Air Shaft Illumination as Studied by Models. C. H. Sharp, I. E. S. Transactions, Vol. 9, p. 598.

Report of Committee on Glare—Diffusing Media VI Interior Furnishings, I. E. S. Transactions, Vol. 10, p. 397.

The Light Reflecting Values of White and Colored Paints. W. S. Gardner, Journal Franklin Institute, January, 1916.

Effect of Interior Colors and Finishes Upon the Lighting of Rooms. S. G. Hibben, Electric Journal, July, 1916.

Measurement of Reflection Factors. M. Luckiesh, Electrical World, May 19, 1917.

Effect of Wall Colors on Lighting Requirements. Electrical World, Aug. 16, 1919.

Short-circuit Tests on a 10,000-kv-a. Turbine Alternator

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The series of tests described in this article were made for the purpose of rounding out the data that has been compiled on the behavior of alternators under short circuit. The performance of definite pole machines under short circuit had previously been analyzed by means of extensive tests, but the characteristics of the alternator with smooth core rotor were not so well known. The tests were carefully conducted under numerous conditions of short circuit, with various arrangements of reactors in circuit and with no reactors in circuit. Special precaution was taken to eliminate errors and meter readings were taken as a check on oscillograph records. The results of tests are shown in tabular form and by means of curves plotted from the table values. The deductions that may be drawn from this series of tests are stated in a series of concluding paragraphs.—Editor.

The question of predicting the amount of current that will flow when an alternator is short circuited under various conditions has been widely discussed, particularly in the past few years. Although not a new problem at all, its importance has increased with the increase in size of central stations and transmission systems. While the theory underlying the phenomena of short circuits is now well established, the weight to be given certain factors in the theory can be determined only by actual tests on a variety of types of machines under different conditions of load, voltage, etc. As there seems to be less accurate data on large turbine alternators than on definite pole machines, an elaborate series of short-circuit tests were made some time ago on a 10,000-kv-a., 10,000-volt, 2400-r.p.m. turbine-driven alternator installed in the power house of the Schenectady Works of the General Electric Company. The results of this test are briefly described in this article.

The armature leakage reactance of this generator as calculated from saturation and synchronous impedance curves was 12.5 per cent. The three-phase synchronous impedance from test was 130.2 per cent and single-phase synchronous impedance 87.5 per cent. For the tests with external reactance in the circuit, standard current limiting reactors were used. Fig. 1. These were wound with 270 turns of copper wire in eighteen layers of fifteen turns per layer. The resistance of each reactor was 0.292 ohms and the ohmic impedance as obtained from an average of some fifty volt-ampere readings was 4.96 ohms, which corresponds to 49.6 per cent reactance three-phase and 28.7 per cent single-phase on the basis of the generator.

Three oscillographs were used in the test: one to record the three currents, another the three voltages and the third the field current and voltage and the voltage across one external reactor. The voltages were read from the secondaries of potential transformers, but the currents were read by means of direct-current shunts instead of current transformers, so that no distortion or inductance due to transformers would be recorded on the films.

Saturation and synchronous impedance tests were made and are recorded in Fig. 2. The short-circuit tests were made as follows:

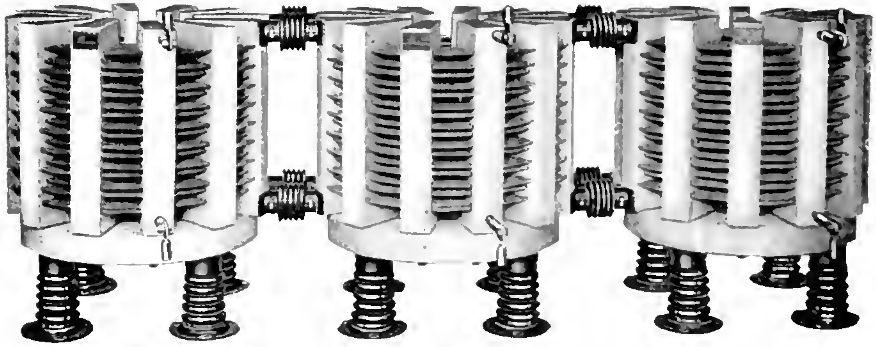

Fig. 1 Group of Current Limiting Reactors Arranged for Three-phase Operation

Starting with initial conditions of 5000 volts, 10,000 volts and 12,000 volts open circuit, the generator was short-circuited three-phase with, first, one reactor in each leg; second, two reactors in parallel in each leg; third, three reactors in parallel in each leg, and fourth, four reactors in parallel in each leg. Fig. 3 shows the connection employed for one reactor in each leg.

These same tests were then repeated for single-phase short circuits at the same voltages and various numbers of reactors in the line. Fig. 4 shows the connections for the one reactor test.

An automatic voltage regulator was then wired in and the 10 000-volt condition for all the foregoing tests was repeated. These tests represent as nearly as possible the actual operating conditions when the generator is being regulated. On these tests records were also obtained showing how rapidly the regulator opened and closed and how soon after the short circuit came on the regulator contacts closed to put full field on the exciter.

Short circuits were made under 10,000 and 12,000 volts full load zero power-factor, the load being obtained by means of reactors in series. These tests were made with and without external reactance, Figs. 5 and 6.

The generator was dead short-circuited at the three voltages with zero reactance in the line and also dead short circuits were thrown on when the machine was carrying practically full load unity power-factor, Figs. 5 and 6.

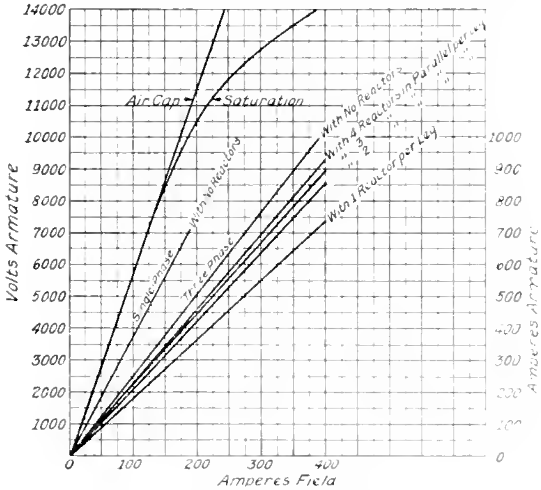

Fig. 2. Saturation and Synchronous Impedance Curve on 10,000-kv-a., 10-000-volt Alternating Current Generator, with and without current limiting reactor in circuit

The oscillograph films were run at a speed that would allow a record of the phenomena from approximately one second before the short circuit came on to about eight seconds afterward. Meter readings were also taken as a check on the oscillograph records. More than 150 oscillograms were taken and therefore it is not practical to include copies of the films in this article. Figs. 7 and 8, however, are typical of the current records. Fig. 8 is particularly interesting in that it shows the operation of the automatic voltage regulator contacts controlling the current in the exciter field. One vibrator of the oscillograph was connected in series with the regulator contact for the purpose of observing how quickly, after the short circuit came on, the contacts would close. As shown, the action is very rapid.

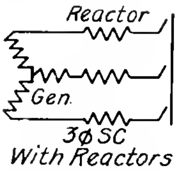

Fig. 3. Three-phase Short Circuit on A-C. Generators with Reactors in Each Phase

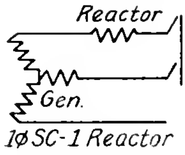

Fig. 4. Single-phase Short Circuit with One Reactor in Circuit

It was not considered necessary to take into account the resistance of the armature circuits in calculating the results because from test the reactance and impedance were practically identical. Likewise the spacing of the reactors (approximately four feet between centers) was considered sufficient to disregard any effect of mutual inductance between them.

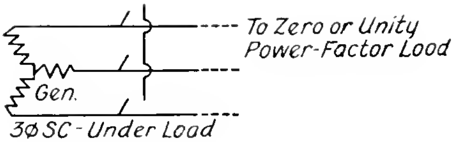

Fig. 5. Three-phase Short Circuit, No Reactors

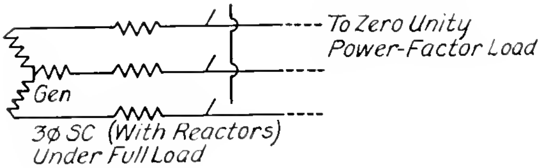

Fig. 6. Three-phase Short Circuit with Reactor in Each Phase

Measurements were made of the current films on the basis of a symmetrical current. Lines were drawn through the tops and bottoms of the current waves and the instantaneous values obtained by measuring the distance between these lines, and dividing by two times the square root of two to obtain the effective symmetrical current.* Readings were taken at the following points: the instant the short circuit occurred, which assumes that the current could rise instantly and is the value used as the instantaneous short circuit current; the first peak; second peak; fourth, eighth, twentieth, fortieth and eightieth cycles; the point where the current waves become symmetrical; and the sustained value. The duration of the armature and field transients, and the time from zero to the first peak were also recorded. The duration of the armature transient was also found from the field current film, using the arbitrary rule of taking the number of cycles from the instant of short-circuit until the ripples in the field current show an amplitude equal to twice (approximately) the thickness of the light line as the duration of the armature transient.

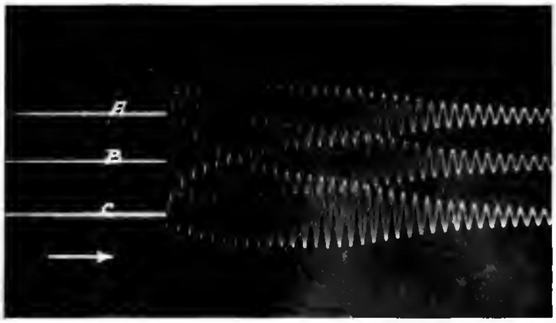

Fig. 7. Oscillogram of 3-phase Short Circuit. Reactor in each phase

Particular attention was given to the elimination of errors and all precautions were taken to obtain as consistent results as possible. Meter readings were taken as a check on the oscillograms just before the short circuit was thrown on, and as soon after as conditions again were steady. The meter readings are a little more consistent than the values obtained from the oscillograms; and while many of the oscillograph records are within one to two per cent yet, in the aggregate, it is believed that the error in the values at the instant of short circuit are of the nature of five per cent. However, for practical considerations this is negligible. In reading sustained values from the films, the amplitude of the waves is so small that these readings are not closer than ten to twenty per cent; but for all sustained conditions, synchronous impedance curves were taken using standard meters.

Table I gives a summary of results of a few of the oscillograms taken. The values of voltage and current given are effective values. The meter readings recorded were taken just before the short circuit came on, and after sustained conditions were reached, as a check on the values obtained from the oscillograms. The calculated values of reactance do not include the field leakage reactance which must be included to obtain the true value of the transient reactance limiting the current at short circuit. However, the field leakage reactance on this machine is very low.

Fig. 8. Single-phase Short Circuit, Alternator Controlled by Automatic Regulator. Lower curve shows the rapidity with which regulator contacts close to increase excitation

The values of transient reactance obtained from these tests are tabulated in Table II. Where duplicate tests showed varying values of reactance, the several values obtained are given so that the accuracy of the results may be judged.

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* "Analysis of Short-circuit Oscillograms," by O. E. Shirley, GENERAL ELECTRIC REVIEW, Feb., 1917, page 121.

TABLE I

		VOLTS AT TIME OF SHORT CIRCUIT		FIELD AMPS.							SUSTAINED AMPERES	
Test	Per Cent External Reactance	Meter Reading	Oscillograph Reading	Meter Reading	Oscillograph Reading	Average Inst. Effect Symmetrical S-c. Current	Per Cent Calc. Inst. React.	Per Cent Test Inst. React.	Duration Arm. Transient, Cycles	Duration Field Transient, Cycles	Meter Reading	Oscillograph Reading
1	0	10040	10200	180.6	180	4320	12.5	13.4	21	135	440	466
2	12.4	10000	10380	180.6	171.5	2160	24.9	26.8	17	230	410	435
3	16.5	10020	10150	181.8	182.7	1820	29.0	31.8	18	220	412	404
4	24.8	10000	10000	183.6	181	1390	37.3	41.6	16	202	428	448
5	49.6	10000	10000	182.4	183.8	842	62.1	68.5	11	310	339	336
6	0	10000	9920	281	351	3780		15.3	23	81	772	820
7	0	10030	9900	315	430	4760	11.1	12.1	24	110	1060	1180
8	49.6	10000	9970	92.8	90	980	61.20	59	13		612	570
9	12.4	10000	9910	183.3	173	2040	24.9	28.4	18		952	1060
10	49.6	10000	9960		154.5	826	62.1	70	11		928	883
11	0	10000	10000	312.5	337.4	4420		13.1	27	155	575	776
12	0	9360	9260	291.5	293	3630		15.9	24	110		760
13	0	12000	12100	246.3	227	5280	10.4	10.95	21	107	616	683
14	41.4	12000	12040	222.3	250	965	51.8	59.8	12	200	466	451
15	0	11680	11680		261.6	5760	9.3	10.0	22	90	1480	1442
16	41.4	11980	11890			1118	51.0	51.9	9	205	820	800
17	0	5020	5090		80.8	3510	25	38.2	24	135		262
18	99.2	5000	4980	83.7	83	412	124.2	140	12	340	152	152
19	7.2	10000	10100	181.8	178.8	2370	19.7	24.4	15	216	652	661
20	9.6	10000	9940	183.6	182	2300	22.1	25.1	16	221	620	656
21	14.35	10030	10050	179.7	169	1760	26.85	32.8		205	600	614
22	28.7	10000	10110		188.4	1230	41.2	47	9	250	552	552
23	23.9	12020	12000	225	247	1460	34.3	39.6		222	784	704
24	28.7	5000	5100	84	77.4	895	53.7	64.6	11	230	260	307

Tests 1, 2, 3, 4, 5, 13, 14, 17, 18. 3ϕ short circuit, no load, no voltage regulator.
Tests 9, 10. 3ϕ short circuit, no load, with voltage regulator.
Tests 6, 11, 12. 3ϕ short circuit, 1.0 p-f. full load, no voltage regulator.
Tests 7, 8, 15, 16. 3ϕ short, circuit 0. p-f. full load, no voltage regulator.
Tests 18, 19, 20, 21, 22, 23, 24. 1ϕ short circuit, no load, no voltage regulator.

TABLE II

PER CENT REACTANCE OF GENERATOR FROM SHORT-CIRCUIT TEST

	THREE-PHASE						SINGLE-PHASE		
	No-load			Full-load			No-load		
Ohms External React-ance	10000 Volts	12000 Volts	5000 Volts	0 P-F. 12000 Volts	0 P-F. 10000 Volts	1.0 P-F. 10000 Volts	10000 Volts	12000 Volts	5000 Volts
0	13.4	10.25	38.2	10	12.1	15.3			
		10.95				15.9			
1.24	16 0	13.2	29.4				17.0		
	16.0	12.7					17.2		
	14.4								
	17.4								
1.65	15.3	12.9	38				15.4		
	16.5	13.3					17.5		
	14.8								
2.48	16.0	14.0	39.4				18.3		35.9
	16.8						18 4		
4.96	18.9	18.4	39.8	10.5	14.5		18.3	15.7	42.5
	20.4				9.4		18.3	15.7	45.5
								16.5	

Values of currents at various intervals of time from the instant of short circuit were scaled off and are plotted in Fig. 9 without the automatic voltage regulator and in Fig. 10 with the automatic voltage regulator connected in.

DISCUSSION OF RESULTS OBTAINED FROM THE TESTS

Sustained Short-circuit Current

In speaking of instantaneous short-circuit current it is common practice to refer to per cent leakage reactance as it is generally understood what is meant. There is, however, more or less confusion when speaking of the synchronous reactance that limits the sustained value of short-circuit current. In order to have as logical a means of expressing synchronous reactance as there is for dealing with leakage reactance, Mr. R. E. Doherty has proposed that the voltage consumed by the synchronous reactance be expressed as a percentage of the normal open-circuit voltage.

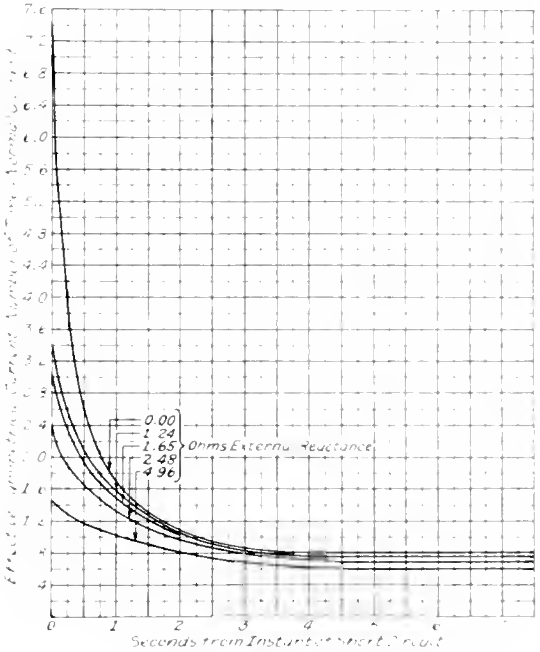


Fig. 9. Three-phase Short Circuit Test at 10,000 Volts, no Regulator. Curves show values of armature current from the instant of short circuit until sustained values are reached

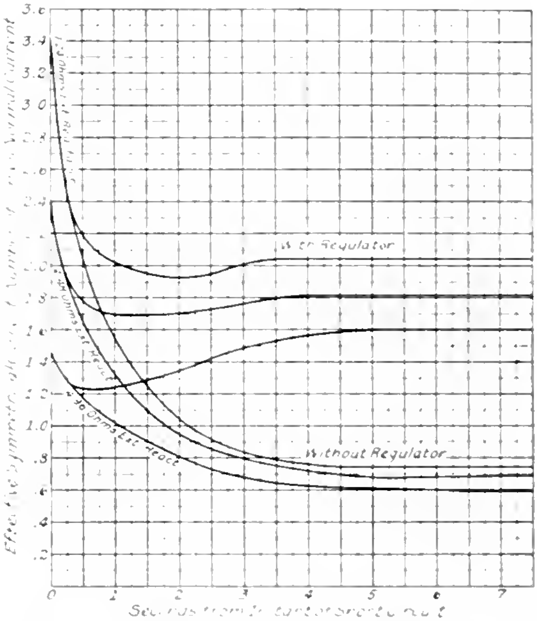
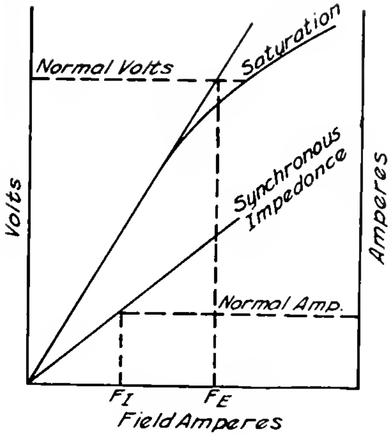


Fig 10. Tests Made at 10,000-volt, Three-phase, with External Reactance, with and Without Automatic Voltage Regulators. Curves show values of armature current from instant of short circuit until sustained values are reached

Since the actual flux in the machine under normal sustained short-circuit current is only from five to forty per cent of the flux at normal voltage, saturation need not be considered. In other words, if F_I in Fig. 11 is the field current required to force normal current through the synchronous impedance of the machine, and F_E the field current to give normal voltage, assuming the saturation curve to be a straight line, then the per cent synchronous impedance is $F_I \div F_E$. The value of F_E must also be given when specifying per cent sustained reactance in order that correction may be made for whatever field current is being held on short circuit, since the sustained current will be directly proportional to the field current. By using this value of per cent synchronous reactance, external reactance expressed in per cent may be added directly to the generator reactance and the sustained short-circuit current calculated. For example, in Fig. 2 the field current for normal voltage no load with straight line saturation is 175 amperes; that required to give normal current on synchronous impedance test is 228 amperes. Hence the per cent synchronous or sustained reactance is $(228 \div 175) \times 100 = 130.2$ per cent at 175 amperes field. The per cent reactance of one reactor is 19.6. Therefore with one reactor in each phase the total sustained reactance is $130.2 + 19.6 = 179.8$ per cent at 175 amperes field, and with this vaule of field current the sustained short-circuit current would be (100÷179.8)×578 (normal current of the generator is 578) = 321 amperes. Reference to the test results in Fig. 2 shows that exactly this value was obtained. At any other value of field current (until saturation is approached) say F_c amperes, the sustained value would be $(F_c \div 175) \times 321$ amperes. Table III shows how closely the test values check the amperes calculated by this percentage method.



The prediction therefore of the sustained short-circuit current of a generator is a simple matter when all phases are short-circuited. It can be determined of course from the synchronous imepdance curve, or can be calculated on a new design on which no test data are available, with the same degree of accuracy that the saturation curve is predicted. However, the sustained current that results when a polyphase machine is short-circuited single-phase is not so easily calculated. The single-phase armature reaction, pulsating from zero to $\sqrt{2}NI$, where I is the armature current and N the armature series turns per phase, is opposed by the field current and also by the eddy currents induced in the pole-pieces, damper windings, etc., which are most difficult of calculation. In most cases it matters little whether we can calculate this, since a single-phase synchronous impedance test will give the necessary data and is easily made.

Instantaneous Short-circuit Current

At Normal Voltage No Load Zero External Reactance

The almost universal method of calculating the initial short-circuit current of a generator is as follows: Calculate, estimate, or obtain from the saturation and synchronous impedance tests the per cent leakage reactance of the generator. The instantaneous symmetrical short-circuit current will then be approximately 100 divided by the per cent reactance, times the normal current. The total current with the wave completely offset may be two times the above value. This of course neglects the field reactance, but so far as present tests have determined it does not seem necessary to add the field leakage reactance of modern turbine generators to the armature leakage reactance in the determination of the transient reactance limiting the current on instantaneous short circuit. This is not the case with definite pole machines where the field leakage reactance may be from 30 to 60 per cent of the value of the armature leakage reactance.*

At Other Voltages

It is of course well known that at voltages higher than normal the per cent reactance limiting the instantaneous short-circuit cur-

TABLE III

	PER CENT REACTANCE			SUSTAINED SHORT-CIRCUIT CURRENT	
	Generator	External	Total	Calculated	Test
3-phase, 1 reactor...........	130.2	49.6	179.8	321	321
3-phase, 2 reactors...........	130.2	24.8	155.0	372	370
3-phase, 3 reactors...........	130.2	16.5	146.7	394	390
3-phase, 4 reactors...........	130.2	12.4	142.6	405	403
1-phase, 1 reactor...........	87.5	28.7	116.2	497	504
1-phase, 2 reactors...........	87.5	14.3	101.8	568	568
1-phase 3 reactors...........	87.5	9.6	97.1	594	593
1-phase, 4 reactors...........	87.5	7.2	94.7	611	625

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*"Reactance of Synchronous Machines and Its Applications," by R. E. Doherty and O. E. Shirley, Proc., A.I.E.E., June, 1918.

rent decreases, and that it increases at lower than normal voltage. Furthermore, as a general rule, the reactance at half voltage is higher in proportion to the reactance at normal voltage on turbine generators than on definite pole machines. However, basing conclusions on all the data available, it does not appear that any great error will be introduced if between 50 and 120 per cent of normal voltage the per cent reactance at normal voltage is assumed to vary in inverse proportion to the terminal voltage. Practically, of course, machines are seldom operated at other than normal voltage, consequently approximations are sufficient for these conditions.

With External Reactance

External reactance has the same effect as partial voltage in increasing the apparent reactance. The reason for this is that since part of the voltage is consumed outside of the generator, the reactive voltage within the machine must counterbalance only a part of the total voltage. Due to the decrease in saturation accompanying the low voltage, proportionately less current through the internal reactance is required to generate a reactive voltage equal to the partial voltage. Placing an external reactance of value equal to the internal reactance of the machine in circuit when short circuiting has the effect of increasing the generator reactance from ten to thirty per cent or increasing the total reactance from five to fifteen per cent. Since in practice the external reactance is seldom if ever more than the internal reactance of the generator, it does not seem that any correction for this increase in reactance is necessary.

Under Load Conditions

When a generator is operating under full load, the flux in the machine is that necessary to maintain normal voltage plus the reactive flux due to normal current flowing in the armature windings added in the proper phase relation. This reactive flux is x per cent of the normal flux where x is the armature leakage reactance of the armature. At zero power-factor, these two fluxes are in phase and at unity power-factor at right angles to each other. Since on short circuit there must be enough current in the armature to maintain the total flux that existed in the machine prior to short circuit, and since normal current in the armature will cause x per cent of normal flux to flow in the leakage paths, it follows that on sudden short circuit under full load zero power-factor the initial current will be $\left(\frac{100}{x}+1\right)$ times normal and on full load unity power-factor $\sqrt{\left(\frac{100}{x}\right)^2+(1)^2}$ times normal current. The tests made on open circuit and on full load zero power factor confirm the above theory. It is not known why the tests at unity power factor full load do not check unless it is due to an error in test.

On Single Phase

The single-phase tests agree with those made on other machines showing that the reactance limiting a single-phase short circuit is somewhat higher than the corresponding three-phase reactance. The difference, however, is small and may just as well be due to inaccuracies in the results as to any actual difference. There seems to be no reason why it should be different except that there may be some slight effect of mutual reactance between phase belts in the one case that is not present to the same extent in the other.

Effect of Automatic Voltage Regulator

In this particular case, the automatic voltage regulator had no effect on the short-circuit current until one quarter of a second after the short-circuiting switch was closed. This time was the same for various amounts of external reactance also. Oscillograph records were taken which show the action of the contacts of the regulator; Fig. 8 shows one of these records. Full field was put on the exciter in approximately one and three quarter seconds and the generator current reached its sustained value in from three and one half to five and one half seconds.

CONCLUSIONS

While there is not yet enough data at hand to decide finally the various points brought out in these tests, yet the following conclusions are apparently well established.

1. Within all practical accuracy the effective symmetrical initial short-circuit current I (effective amperes) of a turbine generator equals:

(*a*) $I=\frac{100}{x_g}\times I_n$ on no-load normal voltage with no external reactance.

(*b*) $I=\frac{100}{x_g\times x_e}\times I_n$ on no-load normal voltage with external reactance.

(*c*) $I=\left(\frac{100}{x_g}+1\right)I_n$ on full-load zero power-factor and with no external reactance (*d*) $I = \left(\frac{100}{x_g + x_e} + 1\right) I_n$ on full-load zero power-factor and with external reactance.

(*e*) $I = \sqrt{\left(\frac{100}{x_g}\right)^2 + (1)^2}$ on full-load unity power-factor with no external reactance

where

E = normal voltage per phase of the generator

I_n = normal current per phase of the generator

X_e = per cent external reactance

$$= \frac{\text{ohms external reactance} \times I_n \times 100}{E}$$

X_g = per cent transient reactance of the generator.

II. Percentage synchronous reactance X_s of the generator equals:

$$X_s = \frac{F_I}{F_E} \times 100 \text{ per cent at } F_E \text{ amperes,}$$

where

F_I = field current required to give normal current on synchronous impedance tests, and F_E = field current no-load normal voltage assuming a straight line saturation (i.e., air gap amperes). Then the sustained short-circuit current with external reactance and F_S amperes field is I_S

$$I_S = \frac{100}{x_s + x_e} \times I_n \times \frac{F_S}{F_E}$$

That is, external reactance is added directly to the internal reactance of the generator in the same way as for the instantaneous values.

III. It is close enough for practical purposes to consider that the per cent leakage reactance varies inversely with the voltage.

IV. As far as the first quarter second after short circuit is concerned, it makes no difference whether the generator is regulated by hand or by means of an automatic voltage regulator.

V. Adding external reactance in a generator circuit equal to the internal reactance of the machine reduces to one half the instantaneous short-circuit current. At the end of one second, however, the current is practically the same whether the external reactance is connected in or not, if the leakage reactance of the machine is small compared with the synchronous reactance.

VI. All of the foregoing conclusions apply to definite pole generators as well as turbine generators except that in definite pole machines it is very essential that the field leakage reactance be included in the transient reactance, while on this machine, neglecting the field reactance did not introduce any appreciable error.

The Engineer Can Do More About It Than Pay and Grin

By Calvert Townley

President, American Institute of Electrical Engineers

In this address, which was prepared for presentation to the Schenectady Section A.I.E.E., Mr. Townley discusses the pressing question of why prices are high. The analysis discloses that prices are high because costs are high, and costs are high largely because wages have increased. The whole structure of costs and wages has shaped itself according to the law of supply and demand. An increasing scarcity of materials and labor since the beginning of the war, first in Europe and then in this country, has acted to bring about the vicious circle of mounting prices. The problem of greatest moment is to foresee what will be the ultimate outcome of the situation. Will prices continue at their present level? Will they rise still higher or descend to their pre-war basis? History gives us a precedent, and it is almost certain that supply will eventually catch up with demand, and if prices have not by then adjusted themselves gradually and orderly they will come down with a thump which will be heard around the world. The engineer can do much to prevent the disaster and hardship that would result from such a course of affairs.—Editor.

The purchase prices of most essentials—not to mention luxuries of life—are now abnormally high. Can the engineer do anything about it except pay and grin? George F. Swain of Boston, says that the engineer is the antithesis of the idealist and that the idealist is a most dangerous individual The engineer approaches a problem with an open mind; first obtains all the available facts and then reaches his conclusion and bases his action on those facts. The idealist, on the contrary, first pictures the ideal result which he would like to obtain and then proceeds to make his facts fit; if they do not, so much the worse for the facts.

In discussing higher prices, let me see if I can qualify under Professor Swain's definition of an engineer. The first question that arises is, "Why are prices high?" And the answer to this question is almost, if not quite, obvious. Prices are high because costs are high and costs are high because wages have gone up. Of course material as well as labor goes into cost, but material in the last analysis is very largely labor, because coal, iron, copper, lumber and other raw materials forming the bulk of those used are governed as to their cost by the wages paid to produce them. It is also alleged, and with reason, that prices of some commodities are higher than the increased costs justify because their distributors have taken advantage of existing conditions to reap abnormal profits. This no doubt is so to a limited extent. It can hardly be claimed to be true in general and certainly not to such an extent as to disprove the statement that prices are high because costs are high.

Following the analysis, if prices are high because costs are high and costs are high because wages have increased, the next question is, "Why have wages increased and in what way, up or down, may wages be expected to change in the future?" We have all heard much about the "awakening" of labor and its determination to hereafter demand and obtain a greater "share in the reward of its products." Our recent history is not lacking in examples of efforts on the part of workmen to benefit through organization and collective bargaining, efforts crowned with no mean measure of success; but of catch phrases and slogans it perhaps may be said that they lack a sufficiently definite meaning to be interpreted alike by all. A catch phrase can frequently be made to mean whatever its user wants it to mean over wide limits. Let us therefore adhere to a terminology of which the meaning is understood by all and which is always the same.

First of all, what do we mean by "labor" and "capital?" Perhaps we all ought to understand what these words mean, but do we? If we say that "labor" is the performance of manual work and "capital" is accumulated money, it can be pointed out that many are classed with labor who do no manual work, while a large number have accumulated money who are not capitalists. Possibly the walking delegate's definition would be that a laborer is one who works all the time for pay but never has any money and a capitalist is one who has money all the time but never does any work. Both of these are manifestly incorrect definitions. For the purpose of avoiding misleading terms perhaps we can dodge the issue by not using them in the present discussion and instead of referring to capital and labor speak of the "employer" and the "employee" although even then it becomes necessary to expand the term "employer" to include not only him who pays for the services of others with his own money but also him who directs the work of others while himself employed, and also to limit the term "employee" to those who do not direct the work of others.

Is there any good reason to believe that a "new order" of things has been created that the working man or employee will hereafter "demand" and what is more to the point obtain a greater share of the reward of his labor, and that therefore wages and consequently the cost of everything into which labor enters will stay up and may even go higher? Has there been anything which may properly be called an "awakening" of labor? The only evidence that I can find to support such an idea is the undeniable fact that beginning in 1914 the employee has demanded and has obtained a greatly increased wage, and of course we know it is human nature to get all we are able and to keep it if we can. But these plain facts do not prove the reasons why. The working man like every other man has in the past always wanted all he could get and human nature today has neither gained nor lost cupidity. There is no indication of a "new order" in these facts.

It is conservative to look for ordinary and natural causes before evolving new theories, so before wondering whether there is or is not any "new order" of things, suppose we examine the old order and see what would be naturally expected under it. Before the war the country was prosperous, general business was good, the employees if not contented and happy were at least much less discontented and unhappy than they are today, and with wages very much lower than they now receive. Then came the war. The men of both sides threw down their tools and took up arms. The productive capacity of every warring nation was at once greatly reduced, but their needs were not—they were greatly increased—and naturally the United States was called upon to help supply them. We were by no means the only, but we were certainly by far the largest, source of supply in the world and our productive capacity was immediately speeded up to meet the new and unusual demand made upon it. All this was natural, ordinary, and logical and its analysis so simple as to seem very obvious.

Then what happened? The business men of this country—the employers—those in command of industry saw their chance. They had, if not exactly a monopoly or corner in the supply market, at least something very like it and they promptly took advantage of the situation and boosted their prices. Higher prices for export to Europe soon reacted to cause higher prices at home and the complaint of profiteering started and spread. It reached such proportions as to influence the government, and action was taken to curb the business man's cupidity and make him loosen up. To a considerable extend he did it; sometimes with not very good grace, but nevertheless as a class he recognized the logic of events and acquiesced.

Then we got into the war ourselves and we likewise took several million men out of our shops to fight and in turn we increased our demand for manufactured goods and decreased our productive capacity. You will note that I say "productive capacity" not our output. That our actual output was greatly increased in spite of the reduction in capacity is history but the reasons for it were improved efficiency, concentrated effort, etc., and do not contradict nor weaken the preceding statement. Well—what happened then? Why the workman—the employee—waked up. He began to do what the business man—the employer—did when the war began and which caused the hue and cry against profiteering. He saw a diminishing supply of men and an ever increasing demand for work and he cornered his market. He put up the price of his services and having got the new price easily he put it up again and so on. You know the rest. Now all this seems to be natural, simple, logical, and so obvious as not to need argument, but it is all based not on any "new thought" or on the "awakening of the proletariat" or any other new ideas or theories but on the plain old-fashioned simple law of supply and demand, a law as old as the hills and just as immutable.

I do not lose sight of the fact that the organization of labor played a conspicuous part in bringing about increased wages. Many people no doubt honestly believe that organization did it all. Well, organization did a great deal of course. The organization was the machine tool or weapon which the employees used to get quicker and greater results. It is pertinent to remember, however, that the organization of workmen is not new. They have been organized for years. There is no essential difference between the way in which nor the extent to which they are organized now, and what they have been for many years past. And ever since employees began to organize they have been trying to get higher wages by identically the same methods they've been using during the war period. But organization never before accomplished anything like the results which latterly have been brought about, and it seems clear therefore that we must seek the cause for the great wage advances not in some old condition, like organization which existed long before the war, but in some new condition that has been created since the war began. That new condition is obviously a change in the relation of supply and demand and we get back to our first conclusion again as to why wages have so greatly increased.

Another contributory cause is the decreased efficiency of the workmen. Employees—as a class—do less work, produce smaller results per day's work than formerly. There seems to be abundant evidence of this condition, enough to warrant our accepting it as a fact. One reason, of course, is that the employers had to use "seconds." Just as a builder in times of stress will put into a house lumber that he would ordinarily reject, because he cannot get enough first class lumber and he *must* have the house, so employers were forced to hire men in war time that ordinarily they wouldn't have about the place; there weren't enough others. Then of course there is the matter of fewer hours per day and a reluctance to work continuously through the week. These features materially affect the increase in cost. They affect it tremendously, but while in fact they may be important they nevertheless are not causes at all but merely results incidental to the working out of the law of supply and demand. They are superimposed upon and do not underly the existing condition which we are analyzing.

Some say that a change in the value of the dollar has caused the increased cost. On all sides we hear and read the statement that the dollar is only worth 50 cents, or some other small fraction of its face, and that prices and wages are really no higher than they used to be because the dollar is now worth much less. Well, suppose we briefly examine that statement. What is a dollar worth anyhow—by itself? Why a dollar isn't worth anything—by itself. You can't do anything with it—by itself. A dollar is simply and solely a convenient medium of exchange. It has become valuable just to the extent that men want it and will give up something which they have to get it. When we set out to place a definite value on the dollar in commodities or labor, it isn't sufficient to take into account the conditions in one place only; in Schenectady for example or in a dozen or in 50 places, or even in any one entire country. The dollar has value all over the world, but when our economists insist that the value of the dollar has fallen permanently they are evidently thinking in terms of conditions in the United States only. Abroad the situation is very different. A dollar will buy about six shillings in London, one and one half times its old rate; 15 francs in France, three times its old rate; 100 marks in Germany, 24 times its old rate, and the end is not yet. Travellers returning from Europe bring back specific information of how much more than formerly can now be bought with a dollar. Not only is foreign money cheaper but things are as well. For example, in November last the rate at the best hotel in Vienna, Hotel Bristol, for a big room with three beds and a bath, occupied by three, was the equivalent of 62 cents a day American money. Does that look like a depreciated dollar? And if it be said that this comparison is misleading because European exchange is only down for awhile and the condition is therefore temporary, the answer is how do we know, how does anybody know that the values in the United States are any more stable or permanent?

Instead of theorizing, why not look to history for real information? The best indication of what will happen in the future is what has happened in the past. We have had wars before, not so big, not so many men were killed, but those that were killed were just as dead, and a very similar condition as to the supply of and demand for labor was created. This same condition of inflated values that confronts us now existed right after our Civil War and it seems reasonable to attribute it to the same causes. In any event the high cost of living after the Civil War was not due to the activities of labor organizations because they didn't exist then. The more we examine the cause for the abnormal advance in wages from different angles the more it seems evident that the fundamental underlying and controlling cause has been an increased demand and a decreased supply. Now if the law of supply and demand has controlled the wages of workmen in the past and through them the cost and therefore the price of commodities, this same law is very likely to exercise this same control over the same conditions in the future. In other words, prices will stay up, go higher, or fall according as the supply of labor is equal to, less than, or greater than the demand.

You will have noted, I hope, that I have tried to discuss facts and conditions and have not referred to the so-called "rights" of the interested parties, the employer, the employee and the public. That is another part of the story, but it is my conception that the economics of industry will continue to be governed by economic laws which are just as immutable as is the law of the attraction of gravitation and other physical laws, albeit not so generally understood and acknowledged; and that any so-called "rights" of the different elements of society, no matter how skilfully or persistently asserted, must give way absolutely before the inexorable operation of economic laws. The question of "rights" is further one into which opinion enters more than demonstrable facts and no opinions of any party to such a discussion have received particular credence, much less acceptance from any opposing party. It would be profitless therefore in the present discussion to diverge into any attempted examination of this phase of the subject.

If now prices were raised to their present level because the war required greatly increased production and at the same time withdrew from productive occupations so large a number of workers, how will prices be affected by the operation of economic laws in the future? The war is over. War material is no longer demanded. Its production has ceased. The men who fought have been released to pursue again their pre-war vocations. Yet prices are still up where they were. If my reasoning is correct, why has the law of supply and demand not reversed its effect and operated to restore pre-war conditions? That question has to be asked to follow the analysis logically but its answer seems fairly obvious. Pre-war conditions have not been restored because there hasn't been time.

In this country during the war we couldn't and didn't produce what was needed. We produced all we could, selecting the things most essential—war material. Industrial needs had to wait. Now the country is catching up. Our stimulated productive capacity has been diverted from war to peace channels and a booming business still struggles to meet the demand made upon it. In Europe the conditions are similar but more acute. Industry was put out of joint there worse than here. It will take Europe longer to recover and readjust, meanwhile some of their immediate needs must be supplied from this side and this requirement puts an added demand on us and still further defers our return to a pre-war normal status. New nations have been created, financial and many other problems demand solution, all taking time and yet more time and keeping the United States still working extra hours. Although the supply of workmen has been greatly augmented by demobilization, the peace demands have absorbed this supply and as yet there is no surplus.

Many people say there never will be a surplus; that the United States has taken up a new place in the world's industries and henceforward will be expected to produce and will supply a so much larger share of the total world's commerce than ever before that our industries will be kept going at top speed and every workman be busy. This is certainly an optimistic picture. It is worth examining. Europe owes a lot of money. Some of their men have been killed. In the war zone the country was laid waste. These are the only real differences between then and now. Their abilities are no less, their natural resources are intact, their morale is good. Europe competed with us before the war and although we set up a tariff wall around our own country and successfully protected our domestic business she captured most of the world's trade against our best efforts. Of course we now have certain advantages we did not possess before. We are a creditor nation and can exert the influence attaching to that position. We have made tremendous inroads into Europe's foreign commerce while she was down and out commercially and we have thereby established relationships and gained an entree previously denied to us and which if judiciously followed up should produce results of great value. But the European nations are not out of the running permanently. They must recover a large volume of trade or go bankrupt. They are diligent and by nature and training thrifty. They will work under the spur of necessity. We are naturally spendthrifts and are inclined to overconfidence. When the world's productive capacity shall have caught up with the industrial shortage occasioned by the great war and the demands of commerce shall have again become normal, and when Europe's industries are once more functioning properly, it seems reasonably certain that there will be an excess of production over consumption and some nations will lack a market. Translated to workmen this means that the supply will be greater than the demand and some must go hungry. It will be then that the test will come. If the United States shall have used the prosperous period to prepare for it by reducing the costs of production and by teaching its people economy and thrift, the readjustment may come perhaps without any serious disturbances and we may save a good share of what we had gained by our running start. But if we sail serenely on ignoring the possibility of a coming storm, if we continue the policy of working less and less and of paying more and more while Europe buckles to, the resulting depression with its period of unemployment, suffering, and possible panics is appalling to contemplate. Then prices and wages will come down suddenly and with a thump, such a thump as the country has never known. The inexorable law of supply and demand is no respecter of people or of nations and its deadly work will be deadly indeed.

We now come back to the question I asked in the first place: "Can the engineer do anything about it except pay and grin?" I think he can. An engineer is by training taught to think straight and to speak clearly. Further it is a fixed tenet of his faith to tell the truth and fear none. People know that and believe him. If I have been fortunate enough to have made my views clear to you and if you agree with me, say so and keep on saying it as you go about your daily tasks. Do what you can to show up the idiocy of dwelling in a fool's paradise and preach the gospel that industrial prepaerdness is as essential to commercial safety as military preparedness is to national safety. Dispel the bogy of class control. Brains always have ruled the world and brains always will. Show that we are dealing with a perfectly normal problem which must be solved in conformity to well known natural laws and not with any mysterious unknown or novel principles or with newly discovered rules of life. No organization of a minority created for the avowed purpose to taking from the majority some of its property or just rights can long prevail. Witness organized Germany's effort to subjugate the world. The laws of supply and demand will ultimately just as surely bring down the cost of living and the wages paid employees as it put these items up. The only uncertain features are the time when the changes are to occur and whether these costs and wages shall be brought down in an orderly and gradual manner so that the readjustment shall be made without disturbance and with lasting benefit to all, or whether they shall come down with a thump, heard around the world, amid disaster and distress.

This is one of the most important problems confronting our great nation today. As citizens, it concerns us all. As members of the A. I. E. E. who have enjoyed the privilege of special training and of valued association with our fellows, we have each a duty to perform. It is perhaps as well stated as may be on the old familiar railroad crossing sign,

"STOP, LOOK, LISTEN."

Helium, the Substitute for Hydrogen in Balloons and Dirigibles

By W. S. Andrews

Consulting Engineering Department, General Electric Company

The successful transatlantic round trip made by the dirigible R-34 attracted attention again to the capabilities of heavier-than-air machines for freight and passenger air traffic. One drawback to this mode of travel however has been the fire danger inherent in the use of hydrogen as the buoyant gas. It has long been known that this danger would be eliminated if the light and incombustible gas, helium, could be discovered in sufficient quantity for use in place of hydrogen. Only recently has this welcome discovery been made. Mr. Andrews, who has made a considerable study of this remarkable gas, describes below its historical features and physical properties, one of which is that its lifting power is 92.6 per cent that of hydrogen.—Editor.

Introduction

A considerable amount of public interest has been recently focussed on the rare gas helium on account of its proposed use in dirigible and observation balloons instead of hydrogen, thus absolutely eliminating the constant danger of fire that is connected with the use of the latter gas. It is true that helium is a little heavier than hydrogen, but both of these gases are so light in comparison with air that there is actually not much difference in their volumes for equal lifting power; and the total elimination of the constant fire hazard connected with hydrogen far overbalances the disadvantage. Moreover, on account of helium being a little heavier than hydrogen, it does not diffuse so readily through the thin covering of a balloon and is therefore less subject to waste.

Helium is one of the so-called noble gases; it makes no chemical combination with any other element, and therefore is absolutely inert and incombustible under all conditions. The great and hitherto insurmountable drawback to its use in balloons has been its extreme scarcity, its only known source until recently being the atmosphere and certain rare minerals and mineral waters, from which it has been extracted only in small quantities by refined methods involving much time and expense.

Within the past year or two, however, it has been discovered that the natural gas found in Kansas and elsewhere contains sometimes as much as 2.5 per cent of helium, and that the latter can be extracted and purified in large quantities at a comparatively small expense.

If, therefore, the present promise for the cheap production of helium holds good, it is reasonable to hope that its application to aeronautics may almost revolutionize this important branch of scientific and commercial development.

Historical

It is stated that a brilliant yellow line was first seen by Janssen in the spectrum of the sun's photosphere in 1868. This remarkable line has a wave length of 5876.6 Angstroms; and, being up to that time unknown, it was considered good evidence of a new element existing in the sun but foreign to the earth. Frankland and Lockyear therefore named this new element "Helium," from the Greek word "Helios," the sun.

Great interest was excited in the scientific world by this discovery, and numerous investigators began to search diligently for further evidence of helium. As time went on, the yellow spectral line of helium was discovered in the spectra of some stars and in 1882 it was observed by Palmer in the spectrum of flames issuing from Mount Vesuvius, thus proving the actual presence of the element on the earth.

Later on in 1895, Ramsay while investigating the properties of gas obtained from certain rare minerals such as clevite, uranite, etc., submitted it to spectrum analysis, and once more the bright yellow line of helium became apparent, thus showing the new element to be at length actually within our grasp.

A practical, though very limited source of this new gas being thus discovered, it was soon produced in sufficient quantity for the examination of its physical and chemical properties.

Up to quite recently, however, the term *rare* was applied to it with good reason, for only a few years ago the price of pure helium was quoted at from $1700 and upwards per cubic foot, whereas, according to recent estimates, it can now be produced from the Kansas natural gas, before referred to, for about 10 cents per cubic foot.

Physical Properties

One of the most interesting physical properties of helium is that it is the most difficult of all gases to liquify and for a long time resisted all efforts. At length, however, in 1908, Onnes succeeded in condensing it to a liquid, by means of liquid hydrogen and pressure, and by its rapid evaporation he obtained a temperature within two degrees of absolute zero.

The boiling point of liquid helium is −268.7 deg. C. Its specific gravity in liquid state is 0.15 and it is therefore the lightest of all known liquids.

Helium gas is generally believed to be monatomic, although some physicists consider the possibility that its molecules consist of two atoms so firmly bound together that they have never yet been separated. It is present in the air at ordinary levels to the extent of two to three parts by volume in a million but at higher altitudes it is probably more abundant.

As previously stated, helium is heavier than hydrogen, which latter is the lightest of all known gases its molecular weight being 2.016. The molecular weight of helium is 3.99 or practically twice that of hydrogen, but, owing to the wide difference between the weights of air and hydrogen, helium has only about 7.5 to 8 per cent less lifting power than hydrogen, and this may be deemed an insignificant feature in consideration of the perfect safety from fire hazard which results from its use.

Ordinary dry air at zero deg. C. and at 760 m.m. pressure weighs 1.293 grams per litre, but this weight is naturally subject to variation under changing conditions of humidity and altitude. However, assuming the above figures to be correct for all practical purposes, the difference in lifting power between hydrogen and helium may be figured thus:

Dry air weighs about 1.2933 grams per litre.
Hydrogen weighs about 0.089 grams per litre.
Helium weighs about 0.178 grams per litre.

Therefore

$$\frac{1.2933-0.178}{1.2933-0.089}=92.6=\text{the lifting power of}$$

helium in air as compared with that of hydrogen taken at 100; or, in other words, a given volume of helium will lift 7.4 per cent less weight than the same volume of hydrogen under similar conditions.

According to a statement in the U. S. Government Bulletin 178 C (p. 76), issued by the Bureau of Mines, about 15 per cent of hydrogen may be mixed with 85 per cent of helium without imparting any dangerous inflammable feature. This mixture would have 93.4 per cent of the lifting power of hydrogen and its use is proposed for dirigible balloons.

The Spectrum Lines of Helium

Helium shows a remarkable and beautiful spectrum when excited by electricity, consisting principally of eight lines which include the colors red, yellow, green, blue, and violet, the yellow line, as before referred to, being especially brilliant.

The most remarkable feature connected with helium is that although it is unquestionably an element yet it is one of the disintegration products of another element as discovered by Ramsay and Sody in 1903. When the life cycle of a radium atom is completed it breaks up into two elementary atoms, one of which, the helium atom, is permanent, while the other, the niton atom, proceeds through a cycle of changes, until it is believed to assume finally a stable form in the shape of lead. Other atoms of helium are also ejected at the instant of some of these changes.

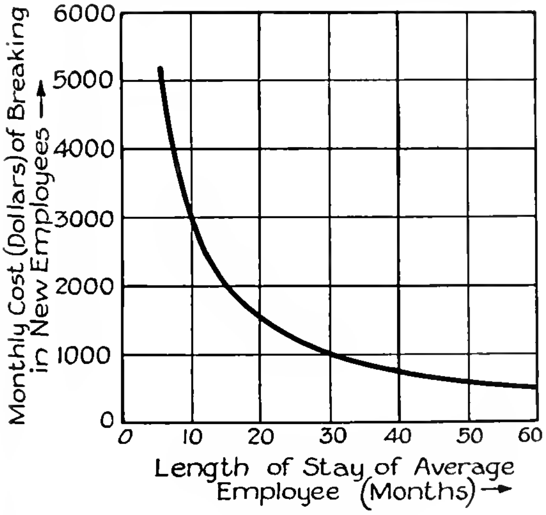
These elemental changes are due to intra-atomic action for they can be neither hastened or retarded by any known external means. The forces which maintain the integrity of the atoms of radium and all other elements appear to be almost inconceivably more powerful than any disintegrating force that we are able to apply from the outside.

Silent Spokesmen in the Factory

By Roscoe Scott
National Lamp Works of General Electric Company

The problem of labor turnover is of great importance to the employer. Not only is it expensive to break in many new men each month in proportion to the average number of employees on the payroll, but the manufactured product is naturally not up to standard where a great share of the work is performed by inexperienced help. Many employees will make a change without giving a single thought to the matter of living conditions. Good wages, good hours, good treatment and good working conditions would be supposed to create a feeling of contentment, but it has been found that unless some special means are taken to focus employees' attention on these advantages they are prone to make frequent changes in employment. This article shows that a judicious use of "Silent Spokesmen"—placards and cards posted in conspicuous places in the factory—will serve to make the employee appreciative of the advantages that have been provided for him by the management, hence contented with his lot and reluctant to make a change without mature thought.—Editor.

In one of the General Electric Company's factories in Providence, R. I., there is an employee who has been with that particular plant, and its predecessor, for forty-five years. If every industrial worker were of his type, the much-discussed problem of labor-turnover would not exist—unless it existed as a problem of getting "new blood" into the works without bidding farewell to a band of white-haired but devoted employees of half a century's standing.



Expense of Training New Employees

It is hardly likely that a condition of general labor stagnation, such as that just suggested, will ever be found in the electrical industry. The person who stays with his or her job only forty-five weeks is met a thousand times more often than the one who sojourns forty-five years. Accordingly, we find a widespread anxiety among superintendents and employment managers that the percentage yearly turnover,

$$\frac{200\,(a+c-b)}{a+b}$$

may be brought as low as possible, so that the continual expense of training new employees to fill the places of those who leave may be brought within reasonable limits. (In the above expression, a stands for the number on the payroll at the beginning of the year, b the number at the end, and c the number hired during the year.)

Many employers have had the notion that good wages, good hours, good treatment and good working conditions—important as they unquestionably are—would solve every difficulty with labor, and have been disappointed to find that all of these helps combined did not produce the immediate results expected. They did not create a "company feeling," nor did they deter employees from throwing up their jobs with disturbing frequency.

The Company may spend $20,000 on a special ventilating and air-conditioning system, to eliminate unpleasant working conditions in certain departments, but does Sally Smith give the fact a moment's thought before taking it into her head to "lay off a few weeks?" Perhaps she does; perhaps she considers the efforts that have been made in her behalf and decides that she, in turn, should do the square thing by her employer. But if she does thus take the company's efforts into account, it is probably because she has been *told about them, and from time to time reminded of them.*

Only a constant presentation of the facts in their proper light can keep even the most intelligent of us from occasionally viewing our work through colored spectacles that distort the good and make mountains out of molehills. In the case of an operator at the bench or machine, who has formed the mental habit of looking at his work as meaningless and at the quitting-time whistle as his best friend, we should not blame him for the human tendency to overlook shower-baths, bonuses and other benefits, but should, rather, blame ourselves for not having tried to direct his thoughts along the proper lines. How, then, shall this be done?

First and foremost, the personal contact of the superintendent with his foremen, and through them with his people, can do wonders towards promoting an atmosphere of harmony and co-operation, if systematic effort along this line is made. But there are limits to what can be done by personal contact. Some foremen are ill adapted to explain the company's policies to employees; others are too busy, or take no interest in that sort of thing. Right here is where the "Silent Spokesmen in the Factory," referred to in the title of this article, play their part.

The "spokesmen" in question consist of printed messages, systematically posted throughout the plant, reminding the people of facts they would otherwise overlook, and in this way molding their attitude towards the institution with which they are connected.

In the incandescent-lamp factories and lamp-parts factories of the Edison and of the National Lamp Works of the General Electric Company, "silent spokesmen" have been put to work to build up goodwill among some 15,000 employees. A three-fold system of placarding was started over two years ago, comprising:

(1) Permanent signs, 15 in. by 11 in., protected by glass in green wooden frames.

(2) Smaller placards 11 in. by 8½ in., protected by celluloid in slotted frames. These placards are changed at six-week intervals, the plan being to put up new copy before the old copy has entirely lost its interest.

(3) 5½-in. by-3½ in. cards (postcard size), distributed in large numbers in suitable holders of three specially-designed types, throughout the factory. These cards also are changed at six-week intervals.

The purpose of the large permanent signs is to advertise certain definite working conditions, or beneficial features of the plant, to those who benefit by them. One sign, for example, reads:

"HEALTH = $$$$$$

"Your health is priceless.

"You value it—we value it, too.

"We value it so much that we have put in a special ventilating plant, costing many thousand dollars, to change the air in here completely every few minutes and prepare it for your lungs. The air is purified, then moistened so as not to be harmfully dry, heated or cooled (as needed), and forced into this room by a powerful fan.

"No poor air conditions for our people—not if the management can help it!"

Among other points similarly featured are pure drinking water, large windows, fireproof doors, "panic" doors, oily-waste cans, clothing lockers, protective conduits for electric wires, toilet-room facilities, fire extinguishers, sand and water pails, and guards on machinery. The simple facts are stated, and the reader left to draw his own conclusions.

The 11-in. by 8½-in. changeable placards carry goodwill messages suited to special seasons of the year, or deal with special conditions that may arise, such as an epidemic of tardiness (these frames, by the way, are located near the time-clocks and building entrances). It is felt that the requirements of promptness and regularity can be presented in such a way as to create goodwill. Among the seasonable placards posted are those relating to Christmas, vacations, lectures at the factory, precautions against influenza, etc.

The small cards (5½ in. by 3½ in.) are more general in tone. The goodwill messages which they bear relate not only to the employee's work, but to the spirit of the institution; sometimes epigrams and quotations regarding qualities that foster or hinder success are given, for example:

"*The Most Contagious Disease in the World is Not the Grippe—it's the Grouch.*"

"*A Slap on the Back Beats Two in the Face.*"

"*There's one sure way of getting more money—and that's to do more and better work each day.*"

Most of the cards are attractively illustrated in colors. Some are designed simply to provoke a smile that will relieve the tension of prolonged application to an exacting operation. Others point out the usefulness and importance of the work in supplying the world's needs, or dwell on the greater earnings that the employee can make by guarding against breakage and shrinkage. Good suggestions are very frequently furnished by the factory executives and foremen.

A census taken in one of the lamp factories showed that out of 417 people engaged in making electric lamps in this particular plant, only 189, or 45 per cent, had electric light in their homes. This fact served as a basis for a series of cards of which the following is a sample:

"For home lighting, electricity costs much less than many people think. You can burn a 15-watt Mazda lamp seven minutes *for less money than it costs to light a match.* And think how much safer, cleaner and more convenient!

"If renters would only insist on living in wired houses, landlords would quickly wire them."

"Do they pay?" is a question that naturally suggests itself regarding the "silent spokesmen in the factory." The answer, viewing the matter from either the theoretical or the practical standpoint, is "Yes." The accompanying diagram, indicating the great saving of expense in "breaking in" new employees, through lengthening the average term of employment, shows one reason why it pays. A numerical example will show even more clearly what is meant.

Assume that the average cost of "breaking in" a new employee is $100, which is a conservative figure in many industries when all factors are taken into consideration. In a shop containing 300 employees, whose average length of stay is 10 months (which is a typical condition in industries where female operators are in the majority), the monthly cost of "breaking in" new operators will be $3000. A little figuring will show that on any plan which will increase the average period of service by even 2 per cent, the management will be justified in spending $58 per month. The cost of the placarding system, when conducted on a large scale and spread over a large number of factories, is much less than this.

A test of this advertising service was made in a certain department employing over 100 male (union) operatives, with the object of reducing, if possible, the number of unexplained absences from work. Placards were featured in which the subject was tactfully handled, with the idea of goodwill uppermost. A check-up of time-cards for the month preceding and the month following the installation of the advertising showed a drop of over 25 per cent in the percentage of absences.

Placards and posters are not the only mediums of internal information that can be used to good purpose. The fact that they are kept in sight of the operator more continuously than other mediums, such as pay-envelope enclosures, is one strong point in their favor. The employees' house-organ, particularly if it be carried into the homes, can be made very effective.

While we engineers are improving the efficiency of machinery and mechanical equipment of all kinds, we shall do well to recognize the importance of promoting mutual understanding and goodwill with the people in our plants—the human element on whom we depend for the translation of engineering into commercial output.

A Biographical Sketch of the Late William Olney Wakefield

William Olney Wakefield was born on the 2nd of January, 1841, in the town of Gardiner, Maine. In his youth he had a varied experience in different trades, from shoeing horses (his father being a blacksmith) to working in the local paper mills, and the building of boats, which was then an important industry on the Kennebec River.

William Olney Wakefield

He finally was apprenticed as a millwright, which in those days embraced nearly every phase of the mechanical trade from patternmaker to tinsmith.

After serving his apprenticeship he entered business in Boston as a hydraulic engineer and also operated a machine shop for several years. It was there in 1876 that he invented, patented and manufactured the first water motor, which was installed to operate a large coffee-mill in the window of Cobb, Bates & Yerx's Boston store. This red coffee mill was for years a landmark at the corner of Kneeland and Washington streets. He also designed a hydraulic engine on which he secured a patent in 1877.

A further development of his water motor resulted in its application to blowers for church organs, many being installed by Mr. Wakefield throughout New England; notably those in Trinity Church, and the Holy Cross Cathedral, Boston.

It was while engaged in this business that he became acquainted with the late Henry A. Pevear, which acquaintance resulted in his going to New Britain, Conn., in 1882, where in the pioneer days of electrical development he worked with Professor Elihu Thomson and Mr. E. W. Rice, Jr. Thus he became the first draftsman employed by the Thomson-Houston Electric Company now known as the "General Electric Company." In the year 1883 the Thomson-Houston Electric Company moved to Lynn, Mass., with Mr. Wakefield as the chief and only draftsman. It is interesting to note that he personally made Drawing No. 1, which is still in the files of the Company.

Mr. Wakefield was a man of keen perception and always ahead of the times. He foresaw with remarkable accuracy the great future before the infant electrical industry, and laid the foundation upon which was built the Company's present system of making, numbering and cataloging drawings. Through his persistence a standard nomenclature was adopted for the parts of machines as well as the machines themselves. The whole system, a revolution from general practice, has since marked in a peculiar way the Company's drawings, resulting in a standard known the world over as "General Electric."

In 1894 Mr. Wakefield came to the Schenectady Works and although relieved of many of the onerous duties of Chief Engineer of the Drafting Department, retained the position and title of Chief Draftsman until his death. In recent years he had his own machine shop in Building No. 4, where every opportunity was afforded him to develop his mechanical ideas. In this work he seemed to specialize in machines for the Blueprint Department, which department under his supervision grew rapidly from the day he made the first blueprint to the day of his death, November 4, 1919, on which day 10,835 prints were produced.

Mr. Wakefield was an American patriot, a "down East Yankee" of the old-fashioned type. As an abolitionist, he enlisted in the

War of the Rebellion and became a private in the 16th Maine Infantry. He was severely injured on the field of battle and crippled for some years. He was reticent, however, about relating his war experiences and very few except his closest friends knew of the resultant physical infirmities, which deprived him of the sight of one eye and left one side of his body nearly paralyzed.

Not only was Mr. Wakefield a mechanic and a soldier, but he was also a deep student of political economy. Of a literary turn of mind, he numbered among his acquaintances such men as Sylvester Baxter, the American poet and author; Robert Creelman, of newspaper fame, and Arthur Brisbane, the great editorial writer. He also enjoyed the personal friendship of Edward Bellamy.

Mr Wakefield for a number of years was a member of the one-time famous "Cold Cut Club" of Boston, which numbered among its membership some of New England's most noted men of science, art and literature.

Mr. Wakefield was active in politics, invariably leaning to the progressive and even the radical theories.

His religion was that of the "Brotherhood of Man and the Fatherhood of God." He took a deep interest in the personal welfare of his associates and was often a last resort in counsel. He had little patience with orthodoxy, although numbering many of the clergy among his circle of friends. His intimates recognized in him a character of rare achievements, a philosopher, a man wonderfully versatile, in a word "unique."

He was a member of the Bay State Lodge, Independent Order of Odd Fellows of Lynn, Mass., and the General Electric Quarter Century Club. His remains are interred in the beautiful Forest Hills Cemetery, a suburb of his beloved city, Boston.

Edison's Birthday Comments on Work

In celebrating his 73rd birthday, February 11th, Thomas A. Edison made some comments on the value of work that all of us could cogitate to advantage. Mr. Edison's capacity for work has been the subject of wonder the world over; and while he is not opposed to the eight-hour day for his fellow workers, imagine how he would have chafed had the working of such a ruling restricted his activities in his younger days! He does not believe that a young man should tie his hands by limiting his efforts by the time clock. Mr. Edison's birthday comments follow in part:

"I'm glad that the eight-hour day had not been invented when I was a young man. On my birthdays I like to turn for a moment and look backward over the road I have traveled. Today I am wondering what would have happened to me by now if fifty years ago some fluent talker had converted me to the theory of the eight-hour day and convinced me that it was not fair to my fellows to put forth my best efforts in my work.

"This country would not amount to as much as it does if the young men of fifty years ago had been afraid that they might earn more than they were paid. There were some shirkers in those days, to be sure, but they didn't boast of it. The shirker tried to conceal or excuse his shiftlessness and lack of ambition.

"I am not against the eight-hour day or any other thing that protects labor from exploitation at the hands of ruthless employers, but it makes me sad to see young Americans shackle their abilities by blindly conforming to rules which force the industrious man to keep in step with the shirker. If these rules are carried to their logical conclusion, it would seem that they are likely to establish a rigid system of vocational classes which will make it difficult for the workingman to improve his condition and station in life by his own efforts.

"Of course, I realize that the leaders of union labor have their political problems and that they must appeal to the collective intelligence of their followers, which is lower than the average individual intelligence of the same men, but there ought to be some labor leader strong enough and wise enough to make trades unions a means of fitting their members for better jobs and greater responsibilities. I wonder if the time will ever come when the unions, generally, will teach their members how to be better workmen, and train the ablest and the most ambitious to become bosses and employers. If that time ever does arrive trade unionism will be one of the world's greatest forces in social progress, and I think there will be a much better understanding between capital and labor.

"I hope I may have enough birthdays to enable me to witness something of that kind. I feel like it now. Inasmuch as the prohibitionists have buried Johnny Walker under the Eighteenth Amendment and he has no further use for his trade mark in this country, I'll borrow it and say 'I'm still going strong.'"

Question and Answer Section

Beginning with the May issue, we will resume the Question and Answer Section of the GENERAL ELECTRIC REVIEW, which was discontinued in 1917, at the commencement of war.

This section provides a valuable service to our readers in making available to them the consulting service of a large corps of engineering experts, and in publishing Questions and Answers of general interest and educational worth.

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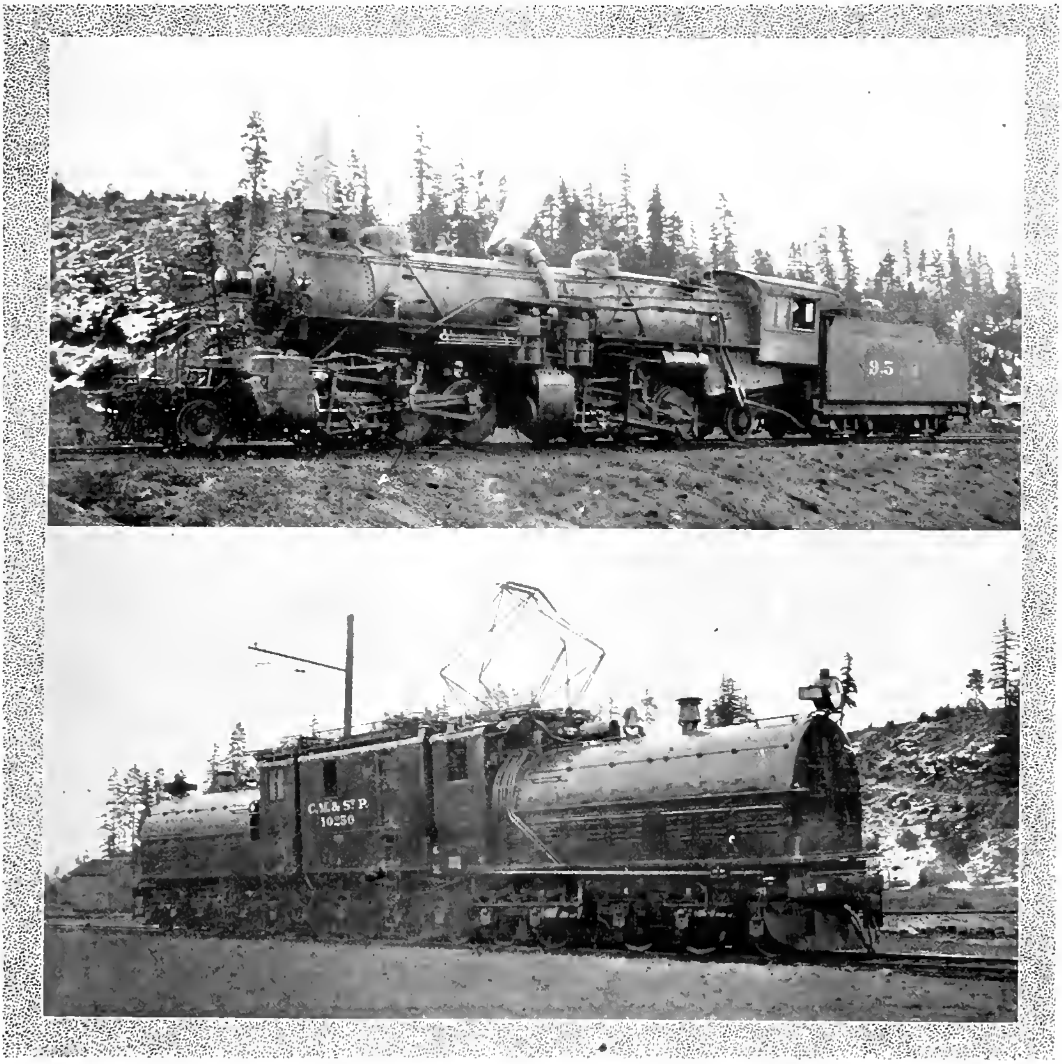

Mallet Type Freight Locomotive Formerly Used on the Mountain Divisions of the C., M. & St. P. R. R. and the New Electric Passenger Locomotive for the Cascade Division of the same Railroad

A SPECIAL ISSUE ON

ELECTRIC TRACTION

GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

Manager, M. P. RICE
Editor, JOHN R. HEWETT
Associate Editors, B. M. EOFF and E. C. SANDERS
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APRIL, 1920

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THE SPEED KING OF THE RAILS

The New 3000 volt Direct current Passenger Locomotive Hauling the Olympian over the Cascade Division of the C., M. & St. P. Rwy.

GENERAL ELECTRIC REVIEW

ELECTRICITY OPENS WIDE THE DOOR TO ADVANCEMENT

Electrification is the open sesame to better performance and to achievements otherwise unattainable. Upon its ability to open the door to these accomplishments, we wish to lay particular stress in introducing this special electric railway issue of the REVIEW.

Electricity for traction purposes made its debut when it displaced the horse car and the cable car. Even in those early days, when comparatively little was known of its workings and the equipment was crude, electricity rendered a better performance than did the motive powers it replaced. Its promise of a brilliant future attracted engineering talent which, in the years that followed, has so developed our city trolley system that its service is no longer capable of duplication by any non-electrical method.

When the increasingly heavy traffic in our larger cities outgrew the capacity of surface lines, on account of the limited space available in the streets, the elevated railway came into being as a parallel transportation system. In the earlier of these installations, steam locomotives were employed. This method of operation was comparatively short lived, however, because rapid progress in the development of electric traction equipment made evident the advantages of electrification in this new field. The resulting electric operation produced not only an improved service but one incapable of accomplishment by steam. The same characteristics are true of electrification in subways.

The interurban trolley system was designed to furnish a service where none existed before. Its electrification was therefore a feature of installation—not one of substitution for prior motive power. The development of this type of transportation has been so successful as to discourage any ambition of the steam engineer to produce an equivalent service in this field.

The initiation of electrification in the steam traction field took place at railroad tunnels and terminals. Increasing traffic had resulted in the steam locomotive smoke becoming so dense as to limit operation in tunnels and to be declared a public nuisance at terminals. In both these locations, the limitation of trackage had resulted in such congested traffic conditions as could be relieved only by a radical change in the motive power employed. Electrification was the logical solution to these difficulties; and the record made by all the resulting installations has unequivocally established the fact that electricity is the only tractive power capable of meeting all the requirements.

The experience gained in the operation of this type of electric traction paved the way for the next progressive step—the electrification of main line divisions. When congested traffic conditions demanded the actual taking of this step, mountain divisions were the first to be electrified because the long grades and sharp curves in these sections had already taxed steam locomotion about to the limit of its capacity. The operation of the equipments developed for this service has conclusively demonstrated that the performance of electric traction is better than that of steam under these exacting haulage requirements. In fact, the operating data of the later installations indicate that the art of electrification has already entered the stage wherein its applications produce results impossible of attainment by steam motive power.

Now that the substitution of electricity for steam has surmounted the greatest difficulties experienced in heavy traction, namely, the handling of traffic at terminals and the haulage through tunnels and over mountains, there no longer remains any engineering obstacle to the electrification of entire steam railway systems. E. C. S.

A Close up View of the New 3000 volt Direct current Passenger Locomotive of the C., M & St P Rwy.

Summary of French Mission's Report on Railway Electrification*

By A. Mauduit

Secretary of the Mission and Professor of the Faculty of Science of the University of Nancy (France)

Destruction of French coal mines by the invading Germans and intensified production during the war so depleted the coal resources of France as to force the Government to take active steps toward providing for future requirements. Because electrification of the steam railroads would relieve the situation immensely, a commission of experts was sent to America for the purpose of studying our systems of railroad electrification, comparing them with those employed in Europe, and making recommendation as to the best system to install on French railroads. The commission has completed its work; and M. Mauduit, Secretary of the Mission, has prepared the following summary of its activities. It is of particular interest to note that he states that he "does not hesitate to formally conclude in favor of the adoption of this [high-voltage direct-current] system, and he believes it to be actually the only system suitable for the electrification of heavy traffic lines."—Editor.

The Minister of Public Works (France) formed, by the resolution of November 14, 1918, in accordance with the upper chamber of Public Works, a commission of students charged to examine the propositions submitted by the railway systems of the Paris-Lyons-Mediterranean, the Orleans, and the Midi for the electrification of approximately 10,000 kilometers of the lines of their systems.

This committee, composed of the most qualified technical men of the administration and of the railway systems, believed that it was necessary to propose to the Minister to send to the United States a commission of engineer specialists, instructed to obtain all information relative to the recent progress of electric traction.

Organization and Composition of the Mission

The mission was comprised of thirteen members as follows:

Major D'Anglards, and Professor A. Mauduit of the faculty of Sciences of the University of Nancy, attached to the Administration of Railways, delegates of the Ministry of Public Works and Transports.

M. Pomey, Chief Engineer of the Post and Telegraph, and M. Lecorbeiller, Engineer, delegated by the Administration of the Post and Telegraph.

M. Debray, Chief Inspector, and M. Barillot, Inspector, delegates of the State Railways.

M. Sabouret, Chief Engineer, attached to the Administration, M. Balling, Principal Maintenance Engineer of the line, and M. Parodi, Chief Engineer, all three delegated by the Orleans Railway.

M. Japiot, Chief Engineer of material, and M. Ferrand, Chief Engineer of the central maintenance service, both delegated by the Paris-Lyons-Mediterranean Company.

M. Bachellery, Chief Engineer attached to the Administration, and M. Leboucher, Principal Engineer of Motor Power, delegates from the Midi Railway Company.

The greater part of the members of the Commission left Paris the 15th of April for America and returned to Paris the 22nd of July, 1919.

Itinerary and Work of the Mission

Arriving at New York on April 25th, we got in touch with the representatives of different construction companies, manufacturing companies, and railway companies, and visited the following electric railways:

New York Central; direct current 600 volts with third rail.

New York, New Haven & Hartford; single-phase, at 11,000 volts, 25 cycles.

Pennsylvania Railroad and Long Island; direct current, 600 volts, with third rail.

Suburban Lines; that carry a considerable freight traffic.

We also visited a certain number of steam central stations for electric power; the Interborough Rapid Transit Company and the New York Edison Company, together with the Hydro-electric Central Station of Niagara and Steam Central Station at Buffalo.

From May 8th to 10th we made a visit to the works of the General Electric Company at Schenectady, New York, and discussed with the principal engineers of that Company questions concerning railway electrification in general and particularly the electrification with high-tension direct current (3000 volts) of the Chicago, Milwaukee & St. Paul (710 kilometers in operation) installed by the General Electric Company.

From the 11th to the 25th of May, we visited the following installations:

Electrification of the Norfolk and Western Railway; single-phase, 11,000 volts, 25 cycles, from Bluefield to Vivian, Virginia.

Electrification of the Pennsylvania Railroad; single-phase, 11,000 volts, 25 cycles, from Philadelphia to Paoli.

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* Translated from the *Journal Officiel De La Republic Francais*, August 13, 1919.

Washington, Baltimore and Annapolis Electric Ry.; direct current, 1200 volts (Interurban).

The Baldwin Locomotive Works at Philadelphia.

The repair shops and factory of the Pennsylvania R. R. at Altoona.

From May 25th to 28th we visited the factory of the Westinghouse Mfg. Co., at Pittsburgh, and discussed with their engineers the subject of electrification in general, and particularly the single-phase and single-to-three-phase systems installed by that Company and also the new direct-current 3000-volt locomotives for the extension of the electrified portion of the Chicago, Milwaukee & St. Paul Rwy.

From May 29th to June 4th different visits were made to the electric locomotive factory of the General Electric Company at Erie, Pa., to automatic railway substations for 600-volt direct current, both of Westinghouse and General Electric designs, and to the Chicago, Lake Shore, and South Bend Electric Railway single-phase 6600 volts 25 cycles.

From June 5th to June 14th a complete study of the Chicago, Milwaukee & St. Paul Railway was made, including the sections in operation from Harlowton to Avery (710-kilometers, Rocky Mountain and Missoula Divisions), the section in the course of construction from Othello to Tacoma and Seattle (360-kilometer Cascade and Coast Divisions) all direct current at 3000 volts, and the repair shops and supply depot at Deer Lodge, Montana.

A visit was made to the three hydro-electric stations of the Montana Power Company, which furnish the three-phase 100,000-volt 60-cycle current to the electric railroad. The stations were the Rainbow (35,000 kw.), the Great Falls (48,000 kw.), the Holter (48,000 kw.) all three on the Missouri River.

The following installations were also studied:

Central California Traction Company; the line from Stockton to Sacramento (72 kilometers) in California, equipped with the inverted third-rail for 1200 volts direct-current, a unique American example of the application of the third rail to rather high voltage.

The Pacific Electric Railway system; suburban and interurban lines around Los Angeles, from 600 to 1200 volts direct-current.

The hydro electric station of the Puget Sound Light & Power Company on the White River, near Seattle, Washington; 48,000 kw., 55,000 volts with a head of 130 meters.

The principal incoming substation of the Utah Power & Light Company at Salt Lake City, Utah; outdoor substation at 120,000 volts 25,000 kw. with a regulation by synchronous condensers (located inside a small special building).

The Great Western Power Company of San Francisco, California; their hydro-electric plant at Los-Plumas, California, on the Feather River with a head of 138 meters, 65,000 kw., 115,000 volts and a double line on unique poles for 246 kilometers to the incoming substation at Oakland.

The oil burning steam central station of the Pacific Gas and Electric Company at San Francisco; 57,000 kw.

The Southern California Edison Company of Los Angeles; the two hydro-electric plants nearby at Big Creek in the Sierra-Nevadas, each of 25,000 kw., 600 meter head, 150,000 to 160,000 volts and the two 400-kilometer lines made of aluminum and steel on separate towers; the incoming substation at Eagle Rock, near Los Angeles, 150,000 volts, with regulation by synchronous condensers.

Apart from the general duty of the Mission, consisting of collecting all useful documents on the electrification of railways and the distribution of electric energy at high tension, the principal duty was to find out, on summing up all the information gained by the study of the Swiss and Italian Electric Railways on one side and the American on the other, if a system of electric traction existed for large systems distinctly superior to all others and able to be adopted to the exclusion of all others by all the different companies interested for the projected electrification in the center and the south of France.

From the four systems of electric traction actually in operation on great lines of the world, that is, the single-phase, three-phase, single-to-three-phase, and high-tension direct-current, the three-phase has already been studied in detail in Italy, where it is largely used, while it is not used to any appreciable extent in any other country, and the single-phase has been equally studied in operation in France on the Midi Railway and in Switzerland on the Loetchberg Lines and in construction on the Swiss Federal Railways which have adopted this system for the gradual electrification of all their systems, the electrification actually intended and even in the course of construction for the Gothard Railway.

The single-to-three-phase, and the high-tension direct-current systems are used only in America, and so became the principal object of the work of the mission. At the same time, the examination of American single-phase installations (25-cycle, while the analogous French installations are 16-cycle,) allowed the completion of the study of monophase installation.

The total information of all kinds gathered in America forms the subject of a detailed report by M Mauduit. This report was submitted at the October, 1919, meeting of the Technical Sub-Commission in order to serve as a basis for the discussion of a proposition tending to make a choice of a traction system, different for the individual companies but following a general formula established by this Sub-Commission with the approval of the whole committee.

The purpose of this summary of the report is to give only the most important results and the principal impressions obtained from the American experience, together with the personal conclusions of the writer. The documents have been gathered by all members of the commission, perhaps together and perhaps separately, but the opinions expressed in this article, while they are in general the concensus of the general impressions of the Mission, are personal opinions and only bind the writer, since they have not been approved by the technical sub-commission in the presence of all the members of this commission, called before this commission to complete and discuss them.

Monophase Electrification

The principal lines equipped with monophase current are the New York, New Haven & Hartford Railroad and the Pennsylvania Railroad, from Philadelphia to Paoli. Although these lines are suburban lines, they are interesting to study since the system of traction employed is applicable to larger lines, and the same as that of the French Midi road save that the frequency is 25 cycles instead of 16.

New York, New Haven & Hartford Railroad

The electrification of this system was decided upon in accordance with the order of New York State; it has a total of 102 kilometers electrified and takes in a part of the direct-current inverted third-rail system in the common terminal with the New York Central Railroad, when leaving New York.

The outlying part is 11,000 volts single phase, with an overhead trolley wire. The necessity of operating partly on 600 volts direct-current and partly on 11,000 volts single-phase greatly complicates the equipment of the locomotives which must run into the city of New York.

The traffic is important and the technical operation adequate after many difficulties of the first years were surmounted. These difficulties mainly consisted in struggling against accidents due to the frequent short circuits on the trolley wire, or on the power feeders, and against the interference set up in the telegraph and telephone lines adjoining and belonging to different companies.

The solution of these problems has been found, but at the price of complicated organization, delicate and costly to install and maintain. The telephone lines have been put underground in lead covered cables; the distribution of power has been made at 22,000 volts by means of 30 compensating auto-transformers, spread over the 102 kilometers of the road to lessen the height of the voltage surges in the line, and to reduce the interference on the telegraph and telephone lines. This installation is in place of the transformers for this work on the Midi road with the additional advantage of the reduction of the voltage.

The equipment includes 103 locomotives and 26 motor cars; the cost of maintenance is comparatively high and the personnel of the repair shops quite numerous. The single-phase motors are very delicate and require very careful watching of the commutator.

Pennsylvania Railroad

The lines from Philadelphia to Paoli are 32 kilometers with four tracks and from north Philadelphia to Chestnut Hill are 20 kilometers with two tracks.

The equipment includes only motor cars, not locomotives, and the service varies from suburban type to heavy traffic. The technical operation is good, the motors are not required to operate on both direct current and monophase current, are of a more modern type, and possess better commutation.

Special precautions have been taken to prevent short circuits, and the struggle against interference on the telegraph and telephone lines has been solved after a fashion: (1) by placing these lines in lead covered cables underground; (2) by the use of frequent feeder transformers (5 for the 52 kilometers of road); and (3) by the use of track transformers placed along the track at very short distances, approximately one kilometer.

Under normal conditions, the operation of the signal lines is adequate, but short circuits although rare produce important disturbances. A very interesting preparatory register connected on an extra wire, placed in a cable, permits the control at any moment of the interference voltage induced in the telegraph and telephone lines.

The American monophase traction installations, especially on account of the high frequency adopted (25 cycles instead of the 16 cycles in Europe) a frequency which was imposed by the local conditions in order that the numerous distribution systems at this frequency might be directly utilized, and the employment of motors often not quite so good as those which have been found on the Midi and in Switzerland, showed an installation less perfected than the similar installations in Europe.

At the same time the struggle against interference with telephone and telegraph lines has been carried to a considerable perfection and there will certainly be a considerable discussion in the large report of this system of traction in France, if it is adopted. On the other hand, the trolley lines with catenary suspension are remarkably well made.

If we assemble now the experience of France, Switzerland and America, we are forced to conclude that the monophase system is still far from the point of presenting the solution to a number of problems insufficiently solved in actual practice, notably the production of a motor capable of exerting a heavy torque for a considerable time without rotating, in order to be able to start heavy trains on the important grades, and of regenerative braking.

Furthermore, this system leads to complicated equipment for the protection of the neighboring telephone circuits, which considerably augments the cost of installation. Without this consideration the cost would be distinctly less than similar costs with the three-phase and high-tension direct-current systems.

The expenses of maintenance of the rolling stock are always higher than in the latter two systems and the motors are less rugged and capable of less overload.

Single-to-three-phase Electrification

In the single-to-three-phase system which the American calls split-phase, the power is furnished to a single contact wire as in the monophase with the return by the rails as in the single-phase form, but it is transformed in the locomotives by means of a special converter to three-phase power and the motors used with this last locomotive are three-phase induction motors. The aim of this installation is to profit from the single-contact wire of the monophase system (while the Italian three-phase requires two trolley wires in addition to the rail serving as a return) and from the three-phase induction motor, rugged and economical and capable of exerting heavy torque for several minutes without rotation and of pulling the heaviest trains which, up to now, has not been obtained with the ordinary commutator monophase motor.

There only exists at this time one line operating with this system. It is the line from Bluefield to Vivian of the Norfolk & Western Railway, in the Appalachian Mountains in Virginia and West Virginia, for a length of 48 kilometers with two or three tracks, and numerous curves and grades reaching 20 millimeters per meter.

These locomotives are flexible and robust, but their operation brings out different mechanical and electrical faults which have not been corrected up to this time in an adequate fashion and, on account of which, this installation may be considered to be as yet only in the test period, and the maintenance expense of the rolling stock is greater than that of the other systems.

From the mechanical point of view the transmission of motion from the motors to the axles, which is made by "jack shafts" and horizontal cranks, occasions rapid wear of the bearings, and even a dislocation of the frame or the breaking of the cranks, on account of enormous forces developed at the time of the vertical displacement of the frame.

From an electrical point of view the principal inconveniences are the following: The three-phase power produced by the converter actually is not perfectly symmetrical, and the phases do not have equal currents. Furthermore, the rotors of the motors are connected to different liquid rheostats, and the loads are not always equally divided between the different motors, very often with considerable differences. A regulation of loads by the engineer has been provided but the latter, very busy, can only make sure of a very imperfect adjustment, and the motors consequently often deteriorate rapidly. The power-factor is very low, on account of the presence of the induction converter which adds its magnetizing losses to those of the motors.

To remedy these defects, with the exception of the distribution of the load between the motors, the manufacturer is taking up at this moment the use of a synchronous converter to give a good power-factor and to make the three-phase current more symetrical; but no practical application of this new apparatus has been made yet, and it must be feared that there will be very great instability on the occasion of breaks in the trolley wire.

On account of the numerous repairs in progress and of the lack of electric locomotives due to the war, the operation of this portion from Bluefield to Vivian still requires many steam locomotives. The Pennsylvania Railroad is taking up on its own account a single-to-three-phase application on the four track line from Altoona to Johnstown on the road from Philadelphia to Chicago. A test locomotive is in the course of being tried out, but no permanent installation has been started on the road.

In conclusion, the single-to-three-phase system, in which the principle at first glance seems very interesting, and which supplies an effectual assistance to the monophase system by the employment of locomotives or motor cars with monophase only for the express trains or light trains, and of locomotives single-to-three-phase for the heavy and slow trains, all these locomotives being supplied by the same trolley wire with monophase current, is found to present in practice numerous faults which have not yet been corrected, and on account of which this system has not come up to the hopes with which it was regarded when started.

High-tension Direct-current Electrification

Already the 600-volt direct-current system has been utilized for a long time, in a standard method for city and suburban electric railways, either with a trolley wire for the tramways, or with a third rail for the suburban railways (the line of the Invalides to Versaille and from Paris to Juvisy, of the Metropolitan).

In the United States, the greater part of the interurban lines operate at 1200 volts direct current with an overhead trolley wire. A considerable number of these lines are really railroads with both passenger and freight traffic, and attain speeds of 60 to 80 kilometers per hour. Many of them were originally equipped with single-phase current, at voltage varying from 3000 to 6600 volts, but have been made over for direct current at 1200 and 1500 volts. The equipment for this latter voltage is now as standard as that for tramways at 600 volts.

Encouraged by the excellent operation of these installations the Americans have tried, with like success, to raise the direct-current voltage to 2400 volts, and have equipped in this manner the mining line from Butte to Anaconda of the Butte, Anaconda & Pacific Railway (Montana), 53 kilometers of main track. Following this they have executed, at 3000 volts, the electrification of the world, from Harlowton to Avery, 710 kilometers, main track across the Rocky Mountains and the Missoula region on the Chicago, Milwaukee & St. Paul Railway.

The electrification of the second section of 360 kilometers, between Othello and Tacoma, Seattle, as far as the Pacific, is in the course of construction*, and that of the portion comprised between Avery and Othello, about the same distance, has already been decided upon.

We studied with particular care this installation of the Chicago, Milwaukee and St. Paul, and all the members were unanimous in considering that this electrification, by far the most important in the world, was at the same time greatly superior to all the others on account of the excellence of its technical operation from all points of view.

The electric power is furnished by the Montana Power Company and is three-phase 100,000 volts. It is transformed to direct current in rotary substations consisting of motor generator sets, which are composed of a synchronous motor and two generators for direct current, mounted on the same shaft and coupled electrically in series in such a manner that each produces only 1500 volts on the commutator.

These substations are the most delicate and most expensive part of this traction system, but they are only to the number of 14 for the 710 kilometers (about 1 every 50 kilometers) and operate very excellently. They require only a personnel of three men each, a chief and two aides for continuous operation with a power from 4000 to 6000 kw. By the use of flash barriers on the commutators, and of extra fast circuit breakers† in the main line, accidents resulting from the most redoubtable phenomenon of direct-current circuits, namely, the flash of fire on the commutators (flash over) in the case of short circuit, have been eliminated.

The excellence of the installation of these substations counts for a great deal in the success obtained by the high-tension direct-current project.

At the relatively low tension, 3000 volts on the trolley wire (in place of 11,000 to 15,000 volts for single phase) gives a correspondingly great volume of current to obtain the pull on heavy trains. Experience has shown that with a double trolley wire

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* This second section of the C., M. & St. P. Ry. will have been placed in electric operation before this article is printed.—Ed.

† These breakers are described in the article "High-speed Circuit Breakers for the C., M. & St. P. Electrification," by C. H. Hill, General Electric Review, September, 1918, and also in the article, "A New Type of High-speed Circuit Breaker," by J. F. Tritle, in this issue.—Ed.

and a pantograph trolley with a double shoe and quadruple contact a current of 1500 to 2000 amperes is easily obtained at a speed of 80 to 96 kilometers per hour, and 4000 amperes at a speed of 25 kilometers per hour, which is more than sufficient for the heaviest trains and the greatest powers.

The locomotives are very easy to run and operate perfectly, the series direct-current motor being of all others the ideal motor for traction work as has long been shown by the experience of tramways and suburban railways. They are capable of regenerative braking, marvellously regulated, which assures the most flexible progress on down grades and occasions an important economy of the power, the tires of the wheels, and the brake shoes. A single armature winder with an assistant assures the operation of the 336 motors of the 42 locomotives in the service, while the former storage of steam locomotives at Deer Lodge, corresponding to 360 kilometers of line, is sufficient for the installation of the storage of the electric locomotives and the repair shops for the total distance electrified, which is 710 kilometers.

A single locomotive is sufficient to pull passenger trains of 900 to 1000 tons American, even on grades of 20 millimeters per meter. Freight trains of 2800 American tons are pulled by a single locomotive on grades of 10 millimeters (the tractive effort is then 32.8 metric tons) and by two locomotives on greater slopes. The average weight carried by freight trains is about 1900 American tons. In trains pulled by two locomotives, the second machine is placed in the middle of the train and not at the end. It must be said furthermore that the break-up of a train is not feared in America as all the freight trains, like the passenger trains, are provided with an automatic air brake on every car.

A considerable advantage of the direct-current system is that it does not seem to have any but the slightest interference with the telegraph and telephone lines, in fact insignificant. We are well able to report that one may telephone very easily on the service lines of the railroad placed all along the tracks on an aerial wire without any protection.

A multiplex printing apparatus for the telegraph service, worked between Spokane and Helena with an earth return, was diverted especially for us in such a fashion as to use a wire placed on the poles of the electric railroad for a distance of 270 kilometers. This operated perfectly during eight days without even being troubled by three short circuits made very complete intentionally between the trolley wire and the rail in the course of the telegraph wire.

In spite of the loss of energy due to transformation of three-phase current to direct current in rotary substations, operating continuously, and although the load is comparatively light, that is, two passenger trains and three to four freight trains in each direction per day, the efficiency of the system is good; 27 watthours per metric ton kilometer which corresponds to an over-all efficiency of 50 per cent from the point of purchase from the producer up to the point of consumption.

Conclusions Relative to the Choice of an Electric Traction System

On account of the remarkable results obtained by the Chicago, Milwaukee & St. Paul Rwy. with 3000-volts direct current, the writer does not hesitate to formally conclude in favor of the adoption of this system, and he believes it to be actually the only system suitable for the electrification of heavy traction lines.

It is possible that with the single-phase system, which at the first glance shows the advantage of lending itself to a great variety of combinations, satisfactory operation may some day be obtained, but it is, without doubt, the fact that the actual practice is far from being desirable at this time.

Direct current presents the inconvenience of being a little more expensive in first cost, on account of the rotary substations required to transform the 50-cycle three-phase current generally produced in the (French) central stations. Nevertheless, it must be said that to obtain economy in this regard with the monophase installation, it is necessary to generate directly the single-phase current at a low frequency (16 cycles) by means of special electric generating groups, so that if it is wished to utilize the current produced normally by the central station (three-phase at 50 cycles) it is necessary to go back to the rotary transformation, the same with the single phase as with the direct current. From this point of view, the direct current offers the advantage of being able to use the current of any station under the same conditions.

So far as the expense of operation is concerned, the complete and exact calculations compiled by the engineering services of the different companies could only show the comparison between the different systems; the writer, nevertheless, estimates that the difference would not be great, and would not come into consideration in the choice of the system.

The almost complete absence of interference on the telephone and telegraph lines constitutes for direct current a very considerable superiority over the other systems.

We have not spoken of the three-phase system, which, in America, has only an insignificant local application. Dispite certain advantages obtained by the Italians, we are of the opinion that it should be rejected especially in consequence of the complexity and of the high price of installation and maintenance of the two trolley wires.

Economic Considerations of Electric Traction

From the economic point of view, the papers which we brought back from America are much less complete and less accurate than the technical information.

On the other hand it is necessary, in judging from the American experience the future economy of European electric traction, to make considerable modifications in the figures in the case of two principle items, which differ in the American installation from the European installation.

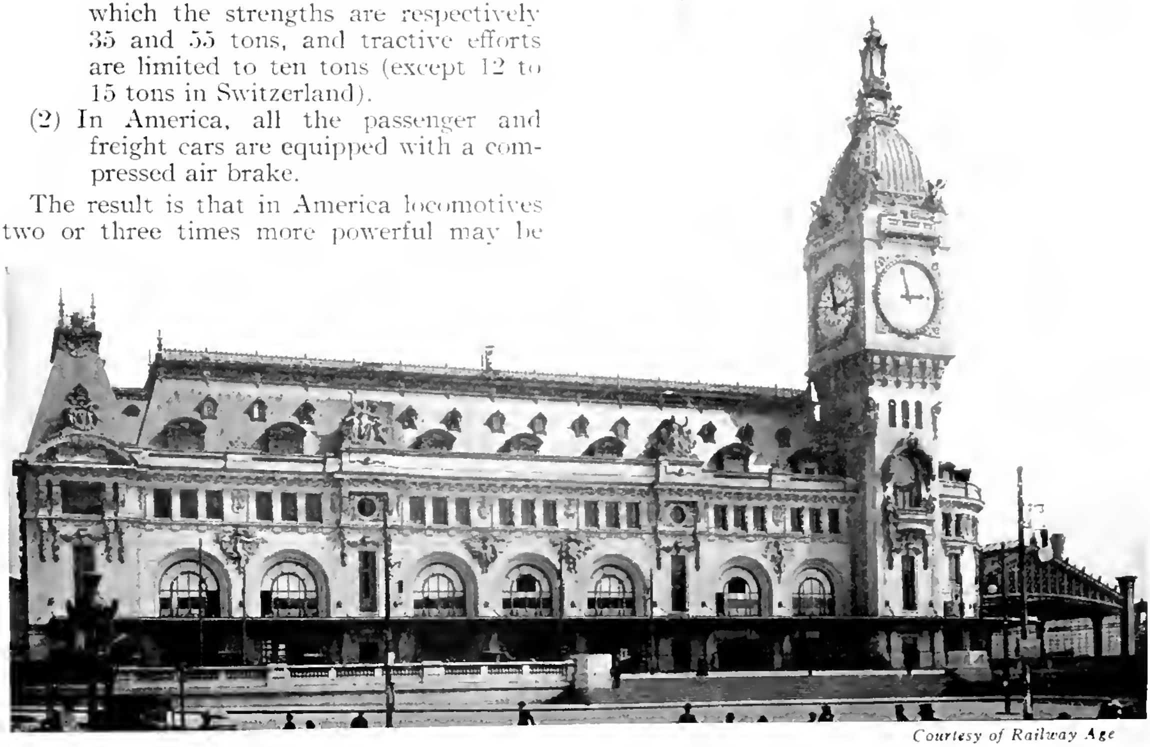
(1) In America, the coupling employed has a strength against breaking of about 135 tons, and the tractive efforts are allowable up to 40 tons. In Europe, the draw bars are of two models of which the strengths are respectively 35 and 55 tons, and tractive efforts are limited to ten tons (except 12 to 15 tons in Switzerland).

(2) In America, all the passenger and freight cars are equipped with a compressed air brake.

The result is that in America locomotives two or three times more powerful may be employed, with freight trains two or three times longer and heavier than in Europe, and that the personnel on these trains is relatively much smaller which completely changes the expense of operation.

The accurate calculations made by the Companies, and above all the results of the first electrifications installed and the consideration of the exact prices of coal, can alone show under what conditions electric traction will be more economical than steam traction. It is known, however, from another source, that the economy will be mostly felt on the lines having steep grades and heavy traffic; and it is probable that for many lines differing too greatly from these conditions, electric traction will be more expensive than steam traction.

Nevertheless the necessity, more and more important, of economizing coal, and the great advantages, which, it is well known, are linked with electrification, render it necessary that the most rapid construction of the first works be carried out in view of the gradual electrification of the most interesting lines of the systems of the Paris-Orleans Railway, the Paris-Lyons-Mediterranean Railway, and the Midi Railway.



Courtesy of Railway Age

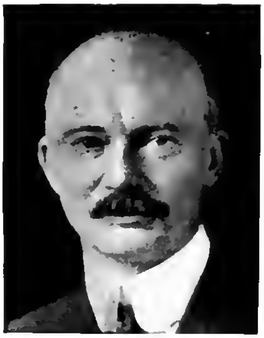
La Gare de Lyon, Paris

Railway Electrification in the Super-power Zone

By W. B. Potter

Engineer Railway and Traction Department, General Electric Company

The proposal that a Super-power Zone be created in the section of the Atlantic seaboard lying between Boston and Washington, and extending 100 to 150 miles inland, calls for the electrification of the railroads and industrials in this congested district and for the installation of a comparatively few exceptionally large electric generating stations of the most modern type to furnish the necessary power. At the Midwinter Convention of the A. I. E. E., New York, February 19, 1920, Messers. W. L. R. Emmet, J. F. Johnson, H. G. Reist, F. D. Newbury, W. B. Potter, P. Torchio, P. H. Thomas, W. D. A. Peaslee, and A. O. Austin, all experts in their fields, contributed to a symposium on the subject of the Super-power Zone. Under the leadership of Mr. W. S. Murray, Chairman of the Traction and Transportation Committee, truly astonishing facts were brought out. For example, the electrification of this district would raise the load-factor from 15 to 50 or possibly 60 per cent, would enable one ton of coal to do the work of two, and would produce a 25 per cent saving annually on the Zone investment cost. The following article is Mr. W. B. Potter's contribution to the symposium. His figures for this district and those of Mr. Armstrong for the entire United States clearly demonstrate the advisability of the Government, railroad operator, and electric locomotive manufacturer taking immediate steps toward the general electrification of our railroads.—Editor.



W. B. Potter

THE suggested economic system of interconnected power generation and distribution throughout the proposed Super-power Zone, Fig. 1, should adequately and advantageously provide for the electric operation of the railways within this zone, as well as for the power required for industrial and other purposes. The electrification of these railways would insure not only a substantial reduction in the amount of coal otherwise consumed by the steam locomotives but also a material reduction in the cost of maintaining the motive power units. Electrification would also provide a more reliable service for all classes of traffic and would be a welcome improvement to the traveler as passenger trains would be less frequently late, especially during the winter. The colder the weather the greater is the reserve power of the electric locomotive, which is a much better characteristic than that of the steam locomotive whose power under similar conditions is correspondingly diminished.

There are numerous illustrations of electric operation which are comparable to the service within the zone under consideration, as well as many other examples of railway electrification throughout the country and abroad, which afford conclusive evidence as to the successful operation of railways with electric power. In fact, a large number of railway electrifications are already embraced within the limits of the proposed zone, and while they do not represent a large proportion of the total mileage, their traffic statistics are available and can readily be studied as a basis for determining the demands of the whole area. A tabulation of these electrifica-

TABLE I

STEAM RAILROAD ELECTRIFICATION IN THE SUPER-POWER ZONE

Railroads	Date of Electrification	Route Miles	Total Mileage of Track	No. of Locos.	No. of Motor Cars
Baltimore & Ohio R. R.	1895	3.6	8.	9	0
Long Island R. R.	1905	88.63	218.	0	477
N. Y. C. & H. R. R. R.	1906	54.00	268.	73	221
W. J. & Seashore R. R.	1906	74.60	150.26	0	109
N. Y., N. H. & H. R. R.	1907	81.63	527.49	106	27
Penn. R. R. (New York)	1910	18.73	97.49	33	8
Boston & Maine R. R.	1911	7.97	21.50	7	0
N. Y., West & Boston	1912	18.23	54.41	1	40
Penn. R. R. (Phila.)	1915	30.5	116.3	0	115
Totals	....	377.89	1461.45	229	997

tions shows that in this area there are already three hundred and eighty (380) miles of electric route, embracing 1450 miles of single track and operating 230 electric locomotives and about 1000 motor cars for multiple unit suburban service. Table I shows the data of the various roads embraced in this statement.

In order to obtain a general picture of the railroad traffic which would be affected by the power supply of the Super-power Zone, a study was made of the traffic conditions of the territory covered by the Zone. In making this study, data were taken from the operating reports of the United States Railroad Administration, extending over the months of 1919 for which comparable figures are available.

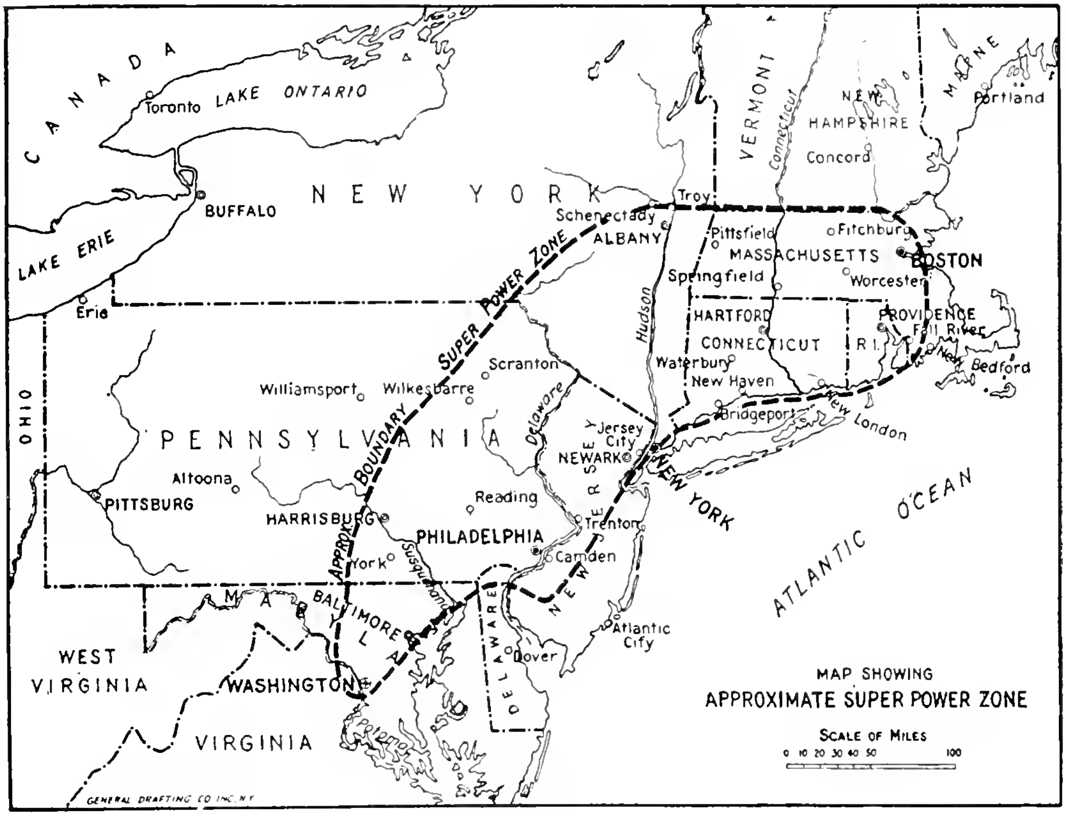


Fig. 1. Map Showing the Proposed Super-power Zone

The reports of the Railroad Administration do not give separate traffic statistics of the various divisions of the roads which are embraced in their report, and there is necessarily some uncertainty in estimating the portion of each road and the traffic which would be embraced in the Zone. For the purpose of the investigation, the mileage of those divisions of each road which would presumably be included in the proposed Super-power Zone has been tabulated, thus determining the percentage of the total mileage of each road lying within the Zone. This percentage, or ratio, has been applied to all other data of the road in order to determine the traffic within the zone. This factor, therefore, determines the number of locomotives, the amount of traffic which would be handled electrically instead of by steam, and the tonnage of coal which would be replaced by electric power. In view of these assumptions as to the probable area of the Super-power Zone and the amount of included traffic, the estimate as given can only be an approximation.

As the detailed figures obtained from the operating reports do not apply to switching service, 20 per cent has been added to the mileage and tonnage to cover this service; and as the power requirements per ton mile for switching are approximately double those for main line service, 40 per cent has been added to cover the coal consumed in switching.

On this basis it is estimated that the railroad traffic in the region covered by the zone can be approximately represented by Table II.

TABLE II

RAILROAD TRAFFIC IN THE SUPER-POWER ZONE

(Passenger, Freight and Switching)

Miles of route...	12,000
Miles of single track.	30,000
Locomotives in service..	8,100
Locomotive miles annually.	185,000,000
Gross ton miles annually, including main line and switching movements of passenger trains, freight trains and locomotives....	170,000,000,000
Tons of coal consumed annually....	21,000,000

Considering railway electrification broadly throughout the whole country and including only those lines which handle freight and passenger service with electric locomotives, there are found to be about 700 electric locomotives operating over 5000 miles of route.

There has been some data published on the results of heavy electrification.

From data available,* it would appear that the ton-miles moved by 6½ lb. of coal in a steam locomotive is approximately equal to that which can be moved by one kilowatt-hour delivered from the power station. Applying this ratio to the last item in Table II, the electric energy which would be required to handle the traffic now handled by the 21,000,000 tons of coal in steam locomotives is approximately 6,500,000,000 kw-hr.

If we assume 40 watt-hours per ton mile at the power station, which checks fairly well with the records of a mixed service of main line and switching, the total energy for moving the assumed traffic of 170,000,000,000 ton miles would be approximately 6,800,000,000 kw-hr.

The actual requirements would, however, be something less. It has been estimated that of all the tonnage moving over the railroad, approximately 12 per cent is taken up with the movement of railroad coal to points of distribution, including a second movement of the same coal in the locomotive tenders. Making an allowance for railroad coal that would still be required, a reduction of 10 per cent would seem a fair estimate. This would correspondingly reduce the yearly power requirements to about 6,000,000,000 kw-hr. On the basis of probable load-factor, this load would call for about 1,250,000 kw. of power station equipment.

The conclusions to which this analysis points may be summarized as follows:

(*a*) Of the whole mileage included in the Zone, not a very large proportion has been electrified, but main line electrifications now in operation are of sufficient extent and carry tonnage of such character to present data which can be applied to the traffic of the whole district.

(*b*) The traffic within the Zone now handled by steam locomotives, if handled electrically, would require an average output of less than 750,000 kw. and if produced entirely by coal-burning electric power stations would reduce the coal requirement for transportation purposes from 21 to 7 million tons annually.

(*c*) As a certain proportion of the electric power will be produced from hydraulic power stations, this coal requirement will be reduced in proportion as advantage is taken of hydraulic operation.

(*d*) The reduction in cost of maintaining the motive power units would be a large amount which estimated from the locomotive mileage would be in the order of $15,000,000 or more, annually.

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* Particular reference was made to the following papers:

"Electrification Analyzed and Its Practical Application to Trunk Line Roads," by W. S. Murray, A. I. E. E., Vol. XXX, 1911.

"Electrical Operation of the Butte, Anaconda & Pacific Railway," by J. B. Cox, A. I. E. E., Vol. XXXIII, Sept., 1914.

"Operating Results from the Electrification of the Trunk Line of the C., M. & St. P. Ry.," by R. Beeuwkes, New York Railroad Club, March 16, 1917.

The Last Stand of the Reciprocating Steam Engine

By A. H. Armstrong
Chairman Electrification Committee, General Electric Company

The reciprocating steam engine is gradually disappearing from the industrial field, and indications point to a similar movement in the propulsion of ships. The author foresees an era of electrification in the steam road field, as the trend of real progress. The remarkable success of the C. M. & St. P. electrification warrants the belief that this method of haulage could be used to advantage, beginning with terminals, mountain grades, and congested districts. Although treated in a broad way, the recommendations may well be applied to specific cases, where roads are confronted with heavy expenditures for improvement of existing facilities. The article was originally presented as a paper before the Schenectady Section of the A.I.E.E., Feb. 20, 1920.—Editor.

A. H. Armstrong

During the year 1920 the people of the United States will pay out for automobiles, not commercial trucks or farm tractors, but pleasure vehicles, a sum of money considerably greater than the estimated requirements of our steam railways for that year. The railways, however may find it very difficult and perhaps impossible to secure the large sums needed without government aid, notwithstanding the fact that the continued operation and expansion of our roads is of vital necessity to the welfare and prosperity of the country and all its industries. The will of the American public has always been constructive and undoubtedly, in due time, its voice will be heard and properly interpreted by its representatives in Washington with the resulting enactment of such laws as will permit our railways again to offer an attractive field for the investment of private capital.

The purpose of this article is not to discuss the politics of the situation nor any necessary increase in freight rates that may be required to make our roads self-sustaining, but rather to offer certain suggestions as to the best manner of spending the sums that must ultimately be provided for new construction and replacements.

During the war period many lessons were most clearly brought home to us and not the least of these is that there is something inherently wrong with our steam railroads. During the three generations of its development, we have become accustomed to look upon the steam engine as properly belonging to the railway picture and have given little thought to its wastefulness and limitations. It is around the steam locomotive that railway practice of today has gradually crystallized.

During the winter of 1917-18 our railways fell down badly when the need for them was the greatest in their history. It is true that the cold weather conditions were unprecedented and the volume of traffic abnormal, but the weaknesses of steam engine haulage were disclosed in a most startling and disastrous manner. Delayed passenger trains in cold weather can be endured by the traveling public in suffering silence or voluble expression, according to temperament; but the blocking of our tracks with frozen engines and trains, resulting in a serious reduction of tonnage in cold weather and a prohibitive delay in transportation of freight in times of great stress, is quite another thing and plainly indicates the inability of the steam engine to meet overloads and adverse climatic conditions.

In marked contrast to the adjoining steam engine divisions, the 440-mile electrified section of the Chicago, Milwaukee and St. Paul Railway continued to do business as usual all through that trying winter of 1917-18. The electric locomotives brought both freight and passenger trains over the electrified tracks in schedule time or better; in fact, it was quite customary to make up on the 440-mile electric run fully two hours of the time lost by passenger trains on adjoining steam engine divisions. While the results obtained upon the Chicago, Milwaukee & St. Paul were perhaps more spectacular due to the greater mileage electrically equipped, other electrified roads contributed similarly attractive records. The reliability and permanency of the comparison between steam and electric locomotive haulage is sufficiently guaranteed, therefore, by the results of several years' operation, to justify drawing certain conclusions regarding the merits of the two types of motive power. The following analysis of the railway situation is therefore offered for the purpose of exposing the fact that railroading today is in reality steam engine railroading and the general introduction of the electric locomotive will permit fundamental and far reaching changes being made in the method and cost of hauling freight and passenger trains.

The writer is not proposing the immediate electrification of all the railways in the United States, as many roads of lean tonnage would render no adequate return upon the large capital investment required, but is offering the following table of total operating statistics simply as a measure of the magnitude of the problem confronting us in the future. In this country it should be noted, however, that we have during the past thirty years installed electric power stations equal to twice the estimated capacity required for the electrical operation of every mile of our tracks today.

The tonnage passing over the tracks of our railways may be subdivided in a most interesting manner as shown in Table I. The first four items, representing 85.56 per cent of the total ton-miles made during the year 1918, may be regarded as fundamentally common to both steam and electric operation. By introducing the electric locomotive, however, the last four items are reduced to the extent of completely eliminating items (6) and (7), reducing item (5) by possibly 80 per cent and item (8) by one-half. Of the total of 14.44 per cent affected, therefore, it may be assumed for purposes of comparison that

TABLE I

TOTAL TON-MILE MOVEMENT

All Railways in United States—Year 1918

	Per Cent	Ton Miles
1—Miscellaneous freight cars and contents	42.3	515,000,000,000
2—Revenue coal cars and contents	16.23	197,000,000,000
3—Locomotive revenue, driver weight only	10.90	132,300,000,000
4—Passenger cars, all classes	16.13	196,000,000,000
Total revenue, freight and passenger	85.56	1,040,300,000,000
5—Railway coal	5.00	60,600,000,000
6—Tenders, all classes	6.50	78,800,000,000
7—Locomotive railway coal	0.39	4,700,000,000
8—Locomotive, non-driving weight	2.55	31,000,000,000
Total non-revenue	14.44	175,100,000,000
GRAND TOTAL (All classes)	100	1,215,400,000,000

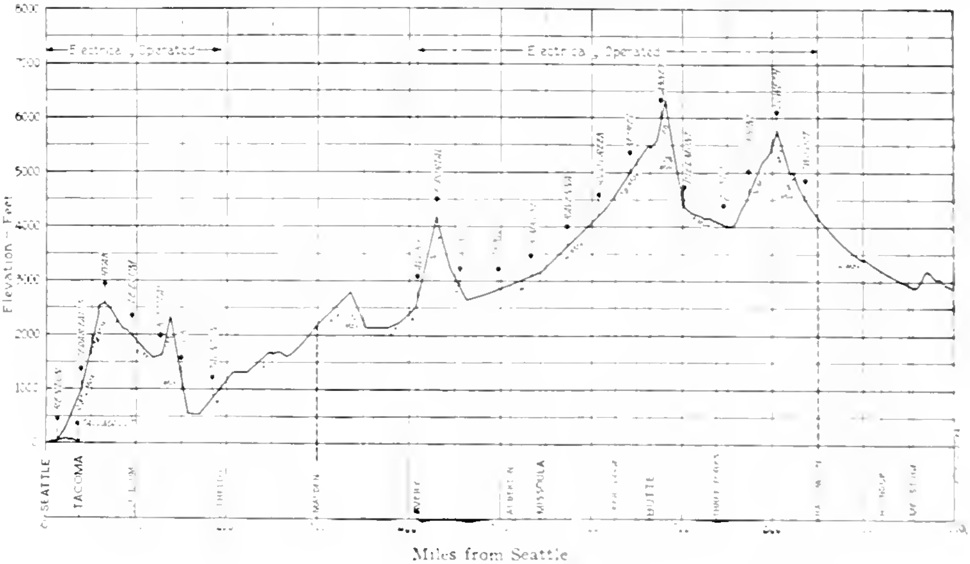

Fig. 1. Profile of Electrified Lines of the Chicago, Milwaukee and St Paul Railroad

approximately 12 per cent or 146,000,000,000 ton-miles at present hauled by steam engines over our roads will be totally eliminated with electric locomotive haulage. This ton-mileage eliminated is equal to over 20 per cent of items (1) and (2) representing the revenue producing freight traffic on our railways. In other words, if all our railways were completely electrified they could carry one fifth more revenue producing freight tonnage with no change in present operating expenses or track congestion.

It is evident that the greater part of the tonnage reduction effected by electrification is included in items (5) and (6), representing the railway coal movement in cars and engine tenders. The steam engine tender will of course entirely disappear, while the railway coal haulage will be largely curtailed by utilization of water as a source of power and the establishment of steam power houses as near the coal mines as an abundant supply of good condensing water and load demand will permit. While water power should be utilized to the fullest economical extent, the greater portion of the railway power must undoubtedly be supplied by coal, due to the unequal geographical distribution of water power available.

Even with coal as the source of power, it may not be fully appreciated just how enormous is the saving made by burning fuel in large modern power stations under the most efficient conditions possible, instead of under the boilers of 63,000 engines which by necessity must be designed and operated for service rather than for fuel economy. During the year 1918 the fuel used by railways is reported to be as shown in Table II.

TABLE II

RAILWAY FUEL 1918

Total coal production (all grades)	678,211,000 tons
Used by steam railways	163,000,000 tons
Percentage of total	24 per cent
Total oil marketed in U.S.	355,927,000 bbl.
Used by steam railways	45,700,000 bbl.
Percentage of total	5.8 per cent
Coal equivalent of oil at 3½ bbl.	13,000,000 tons
Total equivalent railway coal	176,000,000 tons

A quarter of all the coal mined in the United States is consumed on our railways and the following analysis will point out some features of this extreme wastefulness which are inseparable from steam engine operation.

During the year 1910, exhaustive tests were made upon the Rocky Mountain Division of the C., M. & St. P. Ry. to determine the relation existing between the horse-power-hours work done in moving trains and the coal and water consumed on the steam engines in service. Table III gives the results of these tests:

TABLE III

C., M. & ST. P. RY.; ROCKY MOUNTAIN DIVISION

Coal and Water Used

	Water per H.p.-hr.	Water per Lb. Coal	Coal per H.p.-Hr.
Three Forks-Piedmont	39.6	5.08	7.75
Piedmont-Donald	35.4	4.70	7.54
Deer Lodge-Butte	39.7	4.85	8.31
Butte-Donald	40.4	4.86	8.74
Harlowton-Janny	38.0	4.09	8.90
Janny-Summit	44.2	4.65	9.48
Three Forks-Piedmont	41.4	6.51	6.37
Piedmont-Donald	40.2	5.63	5.78
Average of eight tests	39.86	5.04	7.86

The records were obtained during the portion of the runs that the engines were doing useful work in overcoming train and grade resistance, that is, all standby losses were excluded. The through run, however, included such losses in the magnitude shown in Table IV:

TABLE IV

STANDBY LOSSES

	Coal per hour
Fire banked in roundhouse	150 lb.
Cleaning fires for starting	800 lb.
Coasting down grade	950 lb.
Standing on passing track	500 lb.

Adding standby losses to the average of 7.86 lb. per h.p.-hr. obtained in the preceding eight tests, the total actual coal consumed under the engine boiler in twenty-four hours divided by the actual work performed by the engine is found to be 10.18 lb. per h.p.-hr. at the driver rims.

As the result of this particular series of tests it was determined that the coal consumed while doing useful work was raised 30 per cent by standby losses. It should be appreciated in this connection moreover that this value was obtained on through runs with no yard switching service or adverse climatic conditions. It may be concluded, therefore, that under all conditions of service fully one third the coal burned on our steam engines today is absolutely wasted in standby losses of the general nature indicated above.

Supplementing these tests, a 30-day record was kept of all coal used on the entire Rocky Mountain Division and the total engine, tender, and train movement reduced to horsepower-hours, resulting in a value of

10.53 lb. coal consumed per horsepower-hour at the driver rims. Both the above values were based upon constants of 6 lb. per ton train resistance at all speeds and 0.7 lb. per ton per degree of curvature as determined in part by dynamometer car tests and representative of general railway operation. Reducing the average coal values of the test runs and the 30-day record per horsepower-hour to electrical constants, we arrive at the data shown in Table V:

TABLE V

COAL EQUIVALENT PER KW-HR.; STEAM OPERATION

Coal per h.p.-hr. at driver rims	10.27 lb.
Coal per kw-hr. at driver rims	13.75 lb.
Coal per kw-hr. at power supply on basis 55 per cent efficiency	7.56 lb.

It is this last figure of 7.56 lb. of coal burned on steam engines to get the equivalent tonnage movement of one kilowatt-hour delivered from an electric power station that is of special interest to this discussion. Comparing coal and electrical records on the Butte, Anaconda & Pacific Railway before and after electrification results in arriving at a value of 7.17 lb. of coal previously burned on the steam engines to equal the same service now performed by one kilowatt-hour input at the substations, a figure comparing favorably with 7.56 lb. above arrived at by an entirely different method.

TABLE VI

ANALYSIS OF ROUNDUP COAL USED

Fixed carbon	49.26 per cent
Volatile carbon	38.12 per cent
Ash	7.74 per cent
Moisture	4.88 per cent
B.t.u.	11,899

Making due allowance for the fact that roundup coal is somewhat low in heat units, it is nevertheless within the limits of reasonable accuracy to assume that the steam engines operating over all our railways are consuming coal at a rate closely approximating 12.75 lb. per kilowatt-hour of useful work done, as measured at the driver rims or 7 lb. per kilowatt-hour as measured at a power station and including for convenience of comparison the transmission and conversion losses inherent to electrical operation.

An electric kilowatt can be produced for so much less than 7 lb. of coal that we are now in position to finally forecast the approximate extent of the coal economy that would result from electrification.

All power values in Table VII are given at the point of supply from the Montana Power Company at 100,000 volts and include deductions made for the return of power due to regenerative braking of the electric locomotives on down grades, amounting to approximately 14 per cent of the total. Owing to the excessive rise and fall of the profile of the electrified zone of the C., M. & St. P. Ry., its operation is materially benefited by regenerative electric braking and the value of 33.2 watthours per ton mile for combined and passenger movement should possibly be raised to the round figure of 40 to make it apply more nearly to conditions universally obtaining on more regular profiles.

Hence referring again to the ton-mile values of Table I:

Total ton-miles, 1918	1,215,400,000,000
Watthours ton mile	40
Kw-hr. total movement	48,700,000,000
Coal required at 7 lb. per kw-hr.	170,000,000 ton

TABLE VII

RELATION BETWEEN KW-HR. AND TON-MILES CHICAGO, MILWAUKEE & ST. PAUL RAILWAY

Avery-Harlowton—Year 1918

	Passenger	Freight
Average weight locomotive	300 ton	284 ton
Locomotive miles,	651,000	1,431,500
Locomotive ton-miles	195,000,000	407,000,000
Trailing ton-miles	434,406,000	2,903,099,000
Total ton-miles	629,406,000	3,310,049,000
Kilowatt-hours	24,890,000	105,287,000
Watthours per ton-mile	39.6	31.9
Ratio locomotive to total	31 per cent	12.3 per cent
Watthours per ton-mile combined movement	33.2	
Ratio locomotive to total combined movement	15.25 per cent	

The actual equivalent coal consumed on our steam railways for the year 1918 is given as 176,000,000 tons, closely approximating the figure of 170,000,000 tons estimated from the operating results obtained on the C., M. & St. P. electrified zone. These several values check so closely as to justify the completion of the fuel analysis of the railways as shown in Table VIII.

TABLE VIII

COAL SAVING BY ELECTRIFICATION

Total ton-miles steam	1,215,400,000,000
Reduction by electrification	146,000,000,000
Total ton-miles electric	1,069,400,000,000
Kw-hr. electric at 40 watts	42,776,000,000
Coal on basis 2½ lb. per kw-hr.	53,500,000 tons
Equivalent railway coal 1918	176,000,000 tons
Saving by electrification	122,500,000 tons

The startling conclusion arrived at is that approximately 122,500,000 tons of coal, or more than two thirds the coal now burned in our 63,000 steam engines, would have been saved during the year 1918 had the railways of the United States been completely electrified along lines fully tried out and proved successful today. This vast amount of coal is 50 per cent greater than the pre-war exports of England, and twice the total amount consumed in France for all its railways and industries. Moreover, the estimate is probably too conservative as no allowance has been made for the extensive utilization of water power which can be developed to produce power more cheaply than by coal in many favored localities.

Perhaps no nation can be justly criticised for lavishly using the natural resources with which it may be abundantly provided. In striking contrast with the picture of fuel waste on the railways in this country however is the situation presented in Europe at this writing.

Faced with a staggering war debt, with two millions of its best men gone and an undetermined number incapacitated for hard labor, and with so much reconstruction work to do, France has to contend also with the destruction of half its coal producing capacity. Before the war, France imported twenty-three million of the sixty-five million tons of coal consumed. It is estimated that the full restoration of the coal mines in the Lens region will take ten years to accomplish, which means materially increasing the coal imported into France if pre-war consumption is to be reached, as the relief rendered from the Saar District will not compensate for the loss in productivity of the mines destroyed by the Germans. This situation is being promptly met in part by France in the appointment of a Commission* to study the feasibility of the general electrification of all its railways with special reference to immediate construction in districts adjacent to its three large water-power groups, the

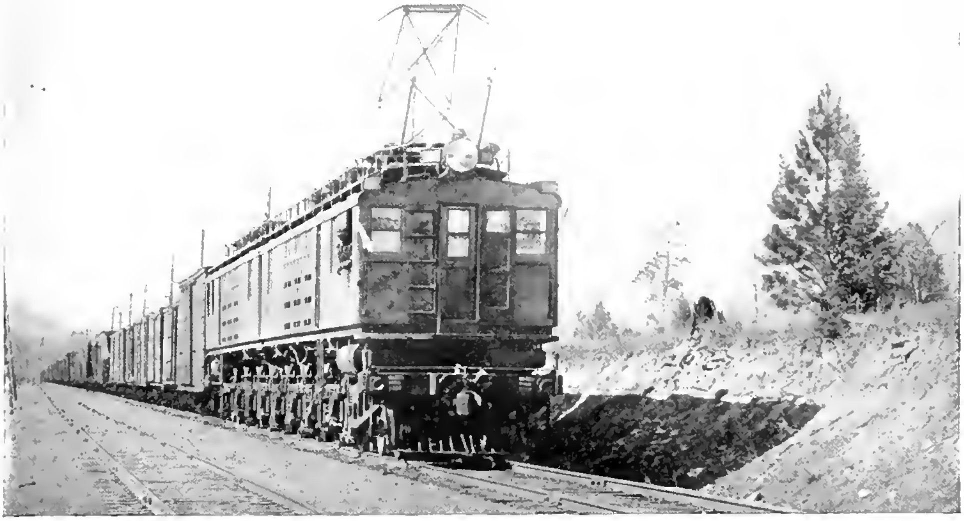

Fig. 2. 5000-ton, 100-car Freight Train on the Missoula Division, Chicago, Milwaukee & St. Paul Railway

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* See article by M. Mauduit in this issue.

Alps, the Pyrenes, and the Dordoyne or Central plateau region. It is proposed to electrify 5200 miles of its total of 26,000 miles of railways during a period covering twenty years. If this work is accomplished at a uniform rate of 260 miles a year, it is a most modest program, considering the extreme necessity for the improvement.

In even worse plight is Italy with practically no coal of its own and compelled to import its total supply of 9,000,000 tons. The war has brought home to these countries what it means to be dependent upon imported fuel for their very existence and both Italy and Switzerland are also proceeding with extensive plans for railway electrification. Contrary to general understanding, the mines of Belgium are not destroyed, but the need of fuel economy is very acute and this country also has broad plans for railway electrification with immediate construction in view.

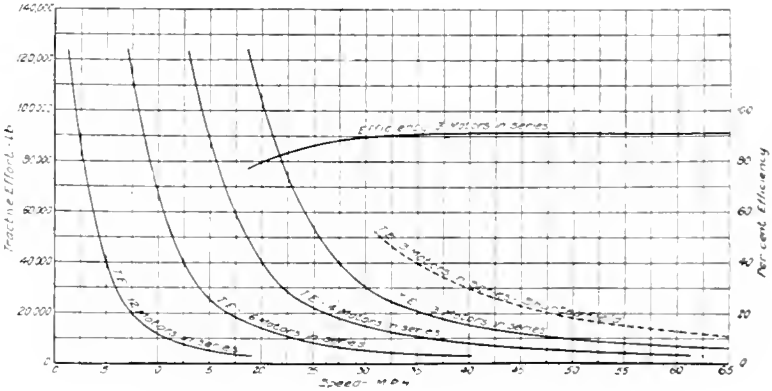


Fig. 3. Characteristic Curves of Gearless Passenger Locomotive

Recognizing the many advantages of electric operation of its railways, Europe furthermore considers this a most opportune time to start the change rather than to spend its limited funds in replacing worn out and obsolete steam equipment in kind. Also in marked contrast to the American attitude is the sympathetic interest and constructive assistance rendered by the Governments abroad in regard to the vital matter of rehabilitation of its railway systems. It would not be without precedent if the next decade witnessed England and the Continent outstripping this country in the exploitation of another industry which, while possibly not conceived here, has certainly been more fully developed and perfected in America than elsewhere.

From figures given, the conclusions in Table IX are arrived at in the matter of power station capacity required for complete electrification of the railways in the United States.

TABLE IX

RAILWAY POWER REQUIRED

Kw-hr. electric operation, 1918	42,776,000,000 kw-hr.
Average load, 100 per cent load-factor	4,875,000 kw.
Power station capacity at 50 per cent load-factor	9,750,000 kw.

It appears therefore that approximately 10,000,000 kw. power station capacity would have been sufficient to run all the railroads for the year 1918, or one half the station capacity which has been constructed during the past thirty years.

TABLE X

ESTIMATED POWER STATION CAPACITY UNITED STATES—YEAR 1918

Central stations	9,000,000 kw.
Electric railways	3,000,000 kw.
Isolated plants	8,000,000 kw.
Total	20,000,000 kw.

In the order of magnitude, therefore, it is not such a formidable problem to consider the matter of power supply for our electrified railways and it becomes evident also that the railway power demand will be secondary to industrial and miscellaneous requirements.

Such being the case, the question of frequency of electric power supply becomes of great importance, if full benefit is to be obtained from extensive interconnected generating and transmission systems covering the entire country. Indeed with the full development of interconnected power systems supplying both railway and industrial load from the same transmission wires, the above assumption of 50 per cent load-factor for the railway load can be materially bettered.

In this connection a method of limiting the troublesome peak load hitherto considered inherent to railway power supply has been in successful operation on the electrified C., M. & St. P. zone for the past year. With unrestrained peaks, the load-factor was approximately 40 per cent, but this low value has been raised to nearly 60 per cent by the installation of an inexpensive and most satisfactory device known as the power limiting and indicating apparatus.

TABLE XI
LOAD-FACTOR RECORDS
C., M. & ST. P. RY.
1919

	Per Cent Duration of Peak	Per Cent Load-Factor
April	6.4	59.3
May	4.6	56.1
June	1.6	56.5
July	0.7	55.6
August	4.1	54.7
September	9.5	58.8

The readings in Table XI cover the performance on the 220 miles of the Rocky Mountain Division supplied by seven substations controlled as a unit. A load-factor of nearly 60 per cent brings the electric railway within the list of desirable customers and makes it possible for power companies to quote attractively low rates for power.

Returning again to the question of power supply, it is instructive to note the general trend toward a higher frequency as evidenced by the turbine and transformer sales of the General Electric Company during the past decade.

It is quite evident that 60 cycles is rapidly becoming the standard frequency in America; and many instances are on record where it has replaced lower frequencies, principally 25 cycles. This fact in no manner handicaps the future development of electric railways, as entirely satisfactory power can be obtained from 60-cycle transmission lines through rotary converters or synchronous motor-generator sets, depending upon the direct-current trolley voltage desired. Indeed a growing appreciation of the declining importance of 25-cycle power generation in this country contributed largely to the demise of the single-phase system, as its chief claim for recognition is wiped out with the introduction of the motor-generator substations required with 60-cycle supply.

While America apparently has adopted 60 cycles as its standard frequency and can look forward to unlimited interconnection of

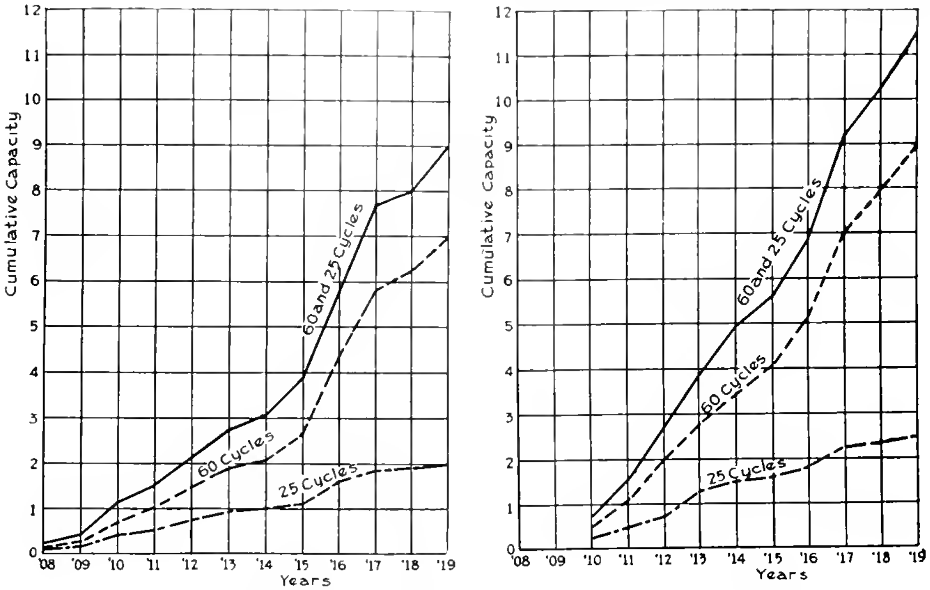


Fig. 4. Comparative Sales of 25 and 60-cycle Transformers and Steam Turbines

its large power systems, European practice is evidently crystallizing on 50 cycles. The situation abroad is as yet, however, not clearly defined. In such a small compact country as Switzerland for instance, where so much electrical development is taking place, there is much conflict of frequencies. Apparently there is little appreciation of the advantages resulting from interconnected power stations; in fact the Loetschberg Railway is supplied with power from 15-cycle waterwheel-driven generators placed in the same power station with 42-cycle units supplying industrial load while in the same immediate district there is a 50-cycle transmission line and no tie-in frequency changer sets as yet installed to interconnect any two frequencies. The power company, power consumer, and electrical manufacturer pay heavily for the complication imposed by maintaining three frequencies where only one is needed, and growing appreciation of this fact may lead to the standardization of 50 cycles in Switzerland and thus swing that country in line with its neighbors and ultimately bring about a more economical ratio of installed generator capacity to average load demand for the country as a whole.

A good example of the necessity for improvement in power distribution conditions in Switzerland is provided in the supply of power to the Loetschberg Railway as illustrated in Table XII:

TABLE XII
POWER SUPPLY TO THE LOETSCHBERG RAILWAY
March, 1919

Total for month	540,180 kw-hr.
Average of six 15 min. peaks	3,489 kw.
Load-factor, basis 24 hours	20.8 per cent

Fig. 5. General Views of Grand Central Terminal Area from 50th Street Before and After Electrification

As the railway was operating for only seventeen hours per day, the load-factor during actual operation is somewhat better than 20.8 per cent. On the other hand, the actual momentary peak load greatly exceeded 3489 kw.; and this very fluctuating railway load furnishes a good illustration of the need of combining it with other diversified loads, in order to keep down the fixed investment of power station equipment now set aside for this isolated railway load. For example, the 60 per cent load-factor of the C., M. & St. P. power demand is the ratio of average to momentary peak while the Loetschberg Railway peak load is determined by six 15-min. peaks with momentary peaks greatly in excess of this figure.

Apparently the adoption of a standard frequency of 50 cycles would meet all general requirements in Switzerland, but would necessitate the installation of frequency changing substations to meet the demands for 15-cycle single-phase railway power. If the electrified railways are to benefit, therefore, from the establishment of a common generating and transmission system in Switzerland, the choice of the single-phase railway system might possibly be considered unfortunate, viewed in the light of modern development in power economics and the successful adaptation of the less expensive and more flexible direct-current motor to high trolley voltages.

From the power station standpoint, the electrification of our railways admits but one conclusion. We have some 63,000 engines now in operation and their average combined load amounts to approximately four million horse power at the driver rims, or only an insignificant total of 65 h.p. for each engine owned. It is true that, owing to shopping and for one cause or another, a large proportion of these engines are not in active service at all times, still the average twenty-four hour output of each engine is less than ten per cent of its rating. In the case of the C. M. & St. P. electrification, the average load of each individual electric locomotive is only 15 per cent of its continuous rating, but by supplying power to 45 electric locomotives from one transmission system, the average combined load-factor is raised to nearly 60 per cent, a figure which could even be surpassed on roads of more regular profile. Furthermore, when the railway load is merged with the lighting and industrial power of the district and the whole diversified load supplied from the same 60-cycle transmission and generating system, it is quite evident that all the conditions are most favorable for the efficient production of power. In this country such an achievement will probably be governed by the laws of economic return upon the capital required because our vast natural fuel resources are popularly regarded as inexhaustible, but in Europe there is the compelling spur of stern necessity behind the movement to utilize economically the water powers they possess in place of the coal they cannot get.

Fig. 6. **High Speed Gearless Passenger Locomotive for the C., M. & St. P. Rwy. 3000-volt Direct-current Electrification**

While the much discussed subject of power generation and transmission is a very vital part of the railway electrification project, chief interest centers in the electric locomotive itself. Few realize what a truly wonderful development has taken place in this connection in a comparatively few years and how peculiarly fitted this type of motive power is to meet the requirements of rail transportation. Free from the limitations of the steam boiler, and possessing in the electric motor the most efficient and flexible known means of transmitting power to the driving axles, the electric locomotive gives promise of revolutionizing present steam railway practice when its capabilities become fully recognized.

The only limits placed upon the speed and hauling capacity of a single locomotive are those imposed by track alignment and standard draft rigging Only questions of cost and expediency control the size of the locomotive that can be built and operated by one man, as there are no mechanical or electrical limitations that have not been brushed aside by careful development. Just what this means in advancing the art of railroading is as yet but faintly grasped, any more than the boldest prophet of twenty years ago could have fully pictured the change that has taken place at the Grand Central Terminal as the result of replacing steam by electricity.

Progress in utilizing the capabilities of the electric locomotive has been slow. It is hard to break away from life-long railway traditions established by costly experience in many cases. In consequence the electric locomotive has thus far simply replaced the steam engine in nearly similar operation. Even under such conditions of only partial fulfillment of its possibilities, the electric locomotive has scored such a signal operating success as to justify giving it the fullest consideration in future railway improvement plans.

On the C., M. & St. P. Ry. 42 electric locomotives have replaced 112 steam engines and are hauling a greater tonnage with reserve capacity for still more. On this and other roads, electrification has set a new standard for reliability and low cost of operation. In fact, although no official figures have yet been published, it is an open secret that the reduction in previous steam operating expenses on the C., M. & St. P. Ry. are sufficient to show an attractive return upon the twelve and a half millions expended for the 440 miles of electrification, without deducting the value of the 112 steam engines released for service elsewhere. As the electric locomotive is destined to leave its deep impression upon the development history of our railways, it is fitting that the remainder of this paper should be devoted to its consideration.

Our steam engine construction is unsymmetrical in wheel arrangement, must run single ended, and is further handicapped with the addition of a tender to carry its fuel and water supply. The result has been much congestion at terminals; and the necessary roundhouses, always with the inevitable turn tables, ash pits, and coal and water facilities, have occupied much valuable land; and in addition steam operation has greatly depreciated the value of neighboring real estate. The contrast offered by the two large electric terminals in New York City is too apparent to need more than passing comment, and similar results may be expected on the fulfillment of plans for electrifying the Chicago terminals.

While it has been a simple matter to design electric locomotives to run double ended at the moderate speeds required in freight service, the problem of higher speed attainment, exceeding 60 miles per hour, has presented greater difficulties. The electric motor is however so adaptable to the needs of running gear design that electric locomotives are now in operation which can meet all the requirements of high-speed passenger train running. These results, also, are obtained with less than 40,000 lb. total weight. and 9500 lb. non-spring borne or "dead" weight on each driving axle, and finally, but not least, with both front and rear trucks riding equally well, a success never before achieved in locomotives of such large capacity.

In connection with the riding qualities of electric locomotives, it is of interest to note the conclusions that the Committee of the American Railway Engineering Association, F. E. Turneaure, Chairman, reached in their report of 1917:

> "From the results of the tests on the electrified section of the Chicago, Milwaukee & St. Paul Railway, the tests made in 1916 on the Norfolk and Western, and the few tests made in 1909 at Schenectady, N. Y., it would appear to be fairly well established that the impact effect from electric locomotives is very much less than from steam locomotives of the usual type. Comparing results obtained in these tests with the results from steam locomotives, it would appear that the impact from electric locomotives on structures exceeding, say, 25 ft. span length, is not more than one third of the impact producted by steam locomotives."

There is as yet no general acceptance of a standard design of electric locomotive. Geared side-rod construction for heavy freight service and twin motors geared to a quill for passenger locomotives appear to find favor with the Westinghouse-Baldwin engineers, while the General Electric Company goes in for the simple arrangement of geared axle motors for freight and gearless motors for passenger locomotives. In both Switzerland and Italy the side-rod locomotive enjoys an almost exclusive field. How much of this preference for side-rod construction is due to the restrictions imposed by the use of alternating-current motors is hard to determine, but the facts available indicate both in this country and abroad the uniformly higher cost of repairs of this more complicated form of mechanical drive.

Fig. 7. Armature and Wheels of 3000-volt Direct-current Gearless Locomotive

The electric railway situation in Italy is further complicated by the employment of three-phase induction motors with all the attendant handicaps of double overhead trolleys, low power-factor, constant speeds, and overheating of motors resulting from operation on ruling gradients with motors in cascade connection. In many respects the non-flexible three-phase induction motor is poorly adapted to meet the varied requirements of universal electrification; and in consequence Italian engineers are still struggling with the vexing question of a system, which may, however, be in fair way of settlement through the adoption of a standard of 50 cycles as the frequency of a nation-wide interconnected power supply, thus throwing the preponderance of advantages to high-voltage direct current.

The extreme simplicity of the gearless motor locomotive appeals to many as does its enviable record of low maintenance cost, reliability, and high operating efficiency, as exemplified by its unvarying performance in the electrified zone of the New York Central for the past twelve years. Table XIII shows that the high cost of living did not appear to have reached this favored type of locomotive until the year 1918.

The records on the C., M. & St. P. locomotive are equally remarkable when considering their greater weight and more severe character of the service.

TABLE XIII

MAINTENANCE COSTS NEW YORK CENTRAL

	1913	1914	1915	1916	1917	1918
Number locomotives owned	48	62	63	63	73	73
Average weight, tons	118	118	118	118	118	118
Cost repairs per locomotive mile	4.32	4.03	4.45	3.78	4.01	6.26

TABLE XIV

LOCOMOTIVE MAINTENANCE COSTS CHICAGO, MILWAUKEE & ST. PAUL RAILWAY

	1916	1917	1918
Number locomotives owned	20	44	45
Average weight, tons	290	290	290
Cost repairs per loco. mile	8.21	9.62	10.87

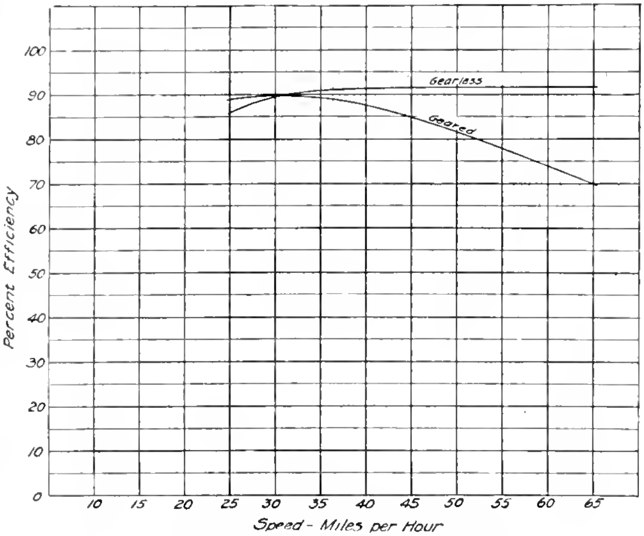


Fig. 8. Comparative Efficiencies of Original Geared and New Gearless C. M. & St. P. Rwy. Passenger Locomotives

In both these instances the cost of repairs approaches closely to three cents per 100 tons of locomotive weight. Giving due credit to the excellent repair shop service rendered in each case, it is instructive to note that three cents per 100 tons maintenance cost of these direct-current locomotives is less than half the figures given for any of the alternating-current locomotives operating in the United States or in Europe.

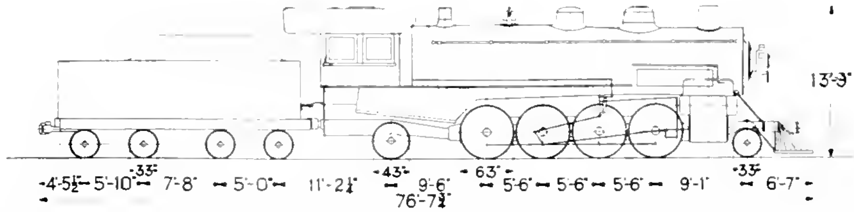
Compared with the cost of repairs for equivalent steam engines, the foregoing figures for electric locomotives are so very favorable as to justify the general statement that electric motive power can be maintained for approximately one third the cost of that of steam engines for the same train tonnage handled. As locomotive maintenance is a measure of reliability in service and in a way expresses the number of engine failures, it is quite in keeping with the records available to state also that the electric locomotive has introduced a new standard of reliability that effects material savings in engine and train crew expense as well.

While the first cost of electrification is admittedly high, it may in certain instances be the cheapest way to increase the tonnage carrying capacity of a single track especially in mountain districts where construction is most expensive and steam engine operation is most severely handicapped. In this connection a comparison of steam and electric operation on the C., M. & St. P. Rwy. may be summarized as follows:

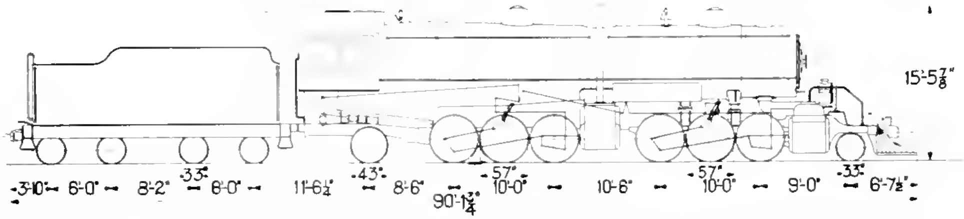
For the same freight tonnage handled over the Rocky Mountain Division, electric operation has effected a reduction of 22½ per cent in the number of trains, 24.5 per cent in the average time per train, and has improved the operating conditions so that nearly 30 per cent more tonnage can be handled by electric operation in about 80 per cent of the time it formerly took to handle the lesser tonnage by steam engines. This means a material increase in capacity of this single-track line which may be conservatively estimated in the order of at least 50 per cent and probably more. In other words, on this particular road, electrification has effected economies which sufficiently justify the capital expenditure incurred and furthermore has postponed for an indefinite period any necessity for constructing a second track through this difficult mountainous country.

A careful study of the seriously congested tracks of the Baltimore and Ohio Railroad between Grafton and Cumberland disclosed vitally interesting facts. Company coal movement in coal cars and engine tenders constituted over 11 per cent of the total ton-miles passing over the tracks. In other words, due to the very broken profile of this division, the equivalent of one train in every nine is required to haul the coal burned on the engines. Taking advantage of this fact and the higher speed and hauling capacity of the electric locomotive and its freedom from delays due to taking on water and fuel, it is estimated that the three tracks now badly congested with present steam engine tonnage could carry 80 per cent more freight with electric locomotive operation. The coal output of the Fairmont District is largely restricted by the congestion of this division of the B. & O. R. R. and it is probable that

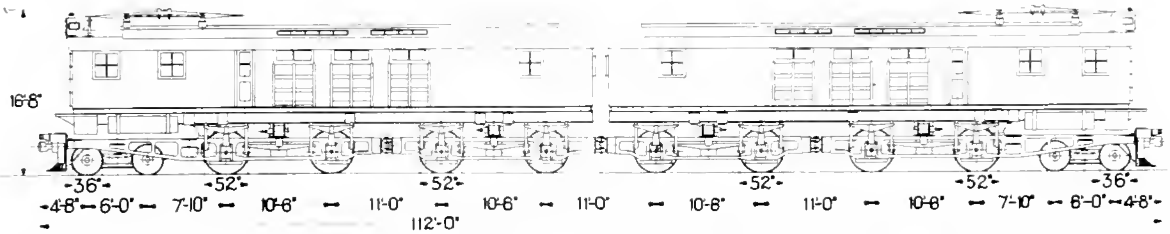
Fig. 9 Latest Type Gearless Passenger Locomotive in Service in the New York Central Electric Zone



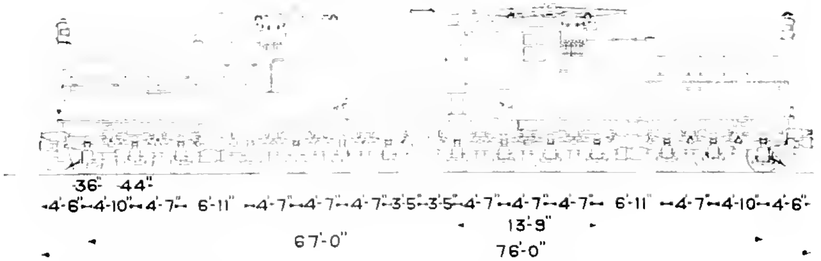
WEIGHT-LOCOMOTIVE & TENDER	414,500 lb.	STEAM PRESSURE	200 lb
WEIGHT OF TENDER	154,000 "	HEATING SURFACE	3614 SQ FT
WEIGHT ON DRIVERS	201,000 "	GRATE AREA	48.8 " "
CYLINDERS	24"×30"	TRACTIVE EFFORT	46,630 lb.



WEIGHT-LOCOMOTIVE & TENDER	555,700 lb.	STEAM PRESSURE	200 lb.
WEIGHT OF TENDER	165,700 "	HEATING SURFACE	6554.6 SQ FT
WEIGHT ON DRIVERS	323,500 "	GRATE AREA	72.4 " "
CYLINDERS	23½" & 37"×30"	TRACTIVE EFFORT	76,200 lb.



WEIGHT OF MECH. EQUIPMENT	328,000 lb.	MOTORS	8
WEIGHT OF ELEC. EQUIPMENT	248,000 "	TYPE OF MOTOR	GE 253, 1500/3000 VOLTS
WEIGHT-TOTAL	576,000 "	GEARING	82-18 RATIO 4.55
WEIGHT ON DRIVERS	450,000 "	TRACTIVE EFFORT	1 HOUR 85,000 lb.



WEIGHT OF MECH. EQUIPMENT	295,000 lb.	MOTORS	12
WEIGHT OF ELEC. EQUIPMENT	235,000 "	TYPE OF MOTOR	GE 100, 1000/3000 VOLTS
WEIGHT-TOTAL	530,000 "	GEARING	GEARLESS
WEIGHT ON DRIVERS	458,000 "	TRACTIVE EFFORT	1 HOUR 46,000 lb.

Fig. 10. Principal Types of Steam and Electric Locomotives on the Chicago, Milwaukee and St. Paul Railway, Puget Sound Lines

equal relief with continued steam engine operation could not be secured without the expenditure of a much larger sum for additional track facilities than would be needed to put electric locomotives upon the present tracks.

Further instances could be cited where the benefits of electrification are badly needed and many of these are coal carrying roads among which the Virginian Railway stands out conspicuously as a good opportunity to make both a necessary improvement and a sound investment.

securing increased track capacity and improved service than by laying more rails and continuing the operation of still more steam engines in the same old wasteful way.

To conclude the startling picture of our present railway inefficiency, we are today wasting enough fuel on our steam engines to pay interest charges on the cost of completely electrifying all the railways in the United States,—fuel that Europe stands in sad need of and which England and Germany, the pre-war coal exporting countries, cannot now supply. With operating expenses mounting to 82 per cent of revenue, inadequate equipment and congestion of tracks, what we need, in addition to constructive legislation and real co-operation on the part of the Government in the matter of rates and safeguarding invested capital, is wise direction in the expenditure of the large sums that must speedily be found and used to bring our railways abreast of the times. Accord full honor to the reciprocating steam engine for the great part it has played in the development of our railways and industries, but complete the work by replacing it with the electric motor and enter upon a new era of real railroading, not restricted steam engine railroading.

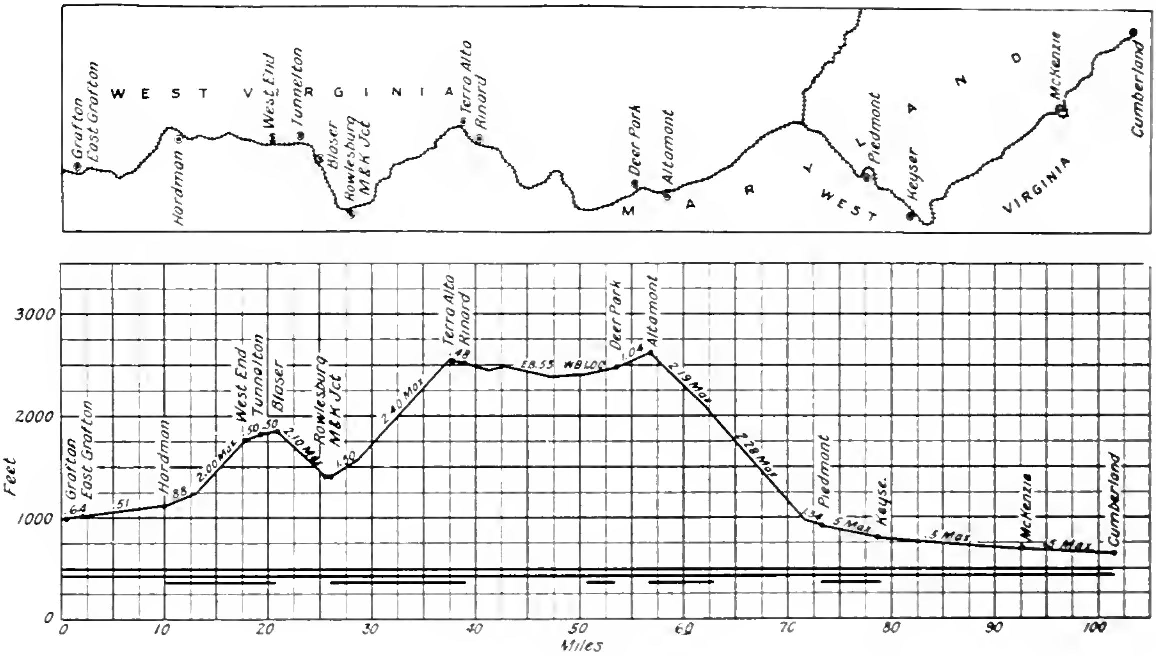


Fig. 11 Map and Profile of West End Cumberland Division, Baltimore & Ohio Railroad

Reviewing the progress made in a short twenty-year period, we have seen the steam turbine and electric generator drive the reciprocating engine from the stationary power field. The same replacement is now taking place on our ships, big and small, notwithstanding the fact that the marine reciprocating engine is a very good engine indeed and operates under the ideal conditions of steady load and constant speed. And now the steam locomotive must in turn give way to the electric motor for the same good reason that the reciprocating steam locomotive has become obsolete and fails to respond to our advancing needs. Electrification affords a cheaper and better means of

Electrification of the Coast and Cascade Divisions of the C., M. & St. P. Ry.

By E. S. Johnson

Railway and Traction Engineering Department, General Electric Company

A convincing testimonal as to the excellence of the system of electrification employed on the C. M. & St. P. Ry., and of the performance of the apparatus, is disclosed by the fact that the equipment for the newly electrified Cascade and Coast Divisions differs but little from that which for four years has been operating on the Rocky Mountain and Missoula Divisions. The principal feature of difference lies in the new passenger locomotives. These are designed especially for passenger service, while the original passenger locomotives were in reality freight locomotives temporarily geared for higher speed until such a time as they would be put in freight service and replaced by genuine passenger locomotives. The adoption of bi-polar gearless design for the new passenger locomotives marks a distinct step towards simplicity and low maintenance cost of motive power equipment. Advancement in the art of railroading has been very much speeded up by the successful application of the many new features of this electrification, summarized in the conclusion of this article.—Editor.

E. S. Johnson

The original 3000-volt electrification of the Chicago, Milwaukee & St. Paul Ry., from Harlowton, Mont., to Avery, Idaho, a distance of about 440 miles, comprising the Rocky Mountain and Missoula Divisions was described in the General Electric Review, November, 1916. Other articles calling attention to the phenomenal success of this great undertaking have appeared from time to time in the technical press. The section from Seattle and Tacoma to Othello, Wash., a distance of 208 miles, including the Coast and Cascade Divisions, is now being placed in operation.

This electrification in the main is a duplication of the original undertaking, differing only in various minor details which will be pointed out later.

The electrification of the C. M. & St. P. Ry. differs from practically all other work of this kind in that it was undertaken for reasons of economy and for the purpose of increasing the tonnage capacity rather than the elimination of smoke in tunnels or at terminals, the taking care of suburban traffic or other local conditions. The results of operation for the past four years have thoroughly demonstrated the reliability of electric operation as compared with steam, the increase available in the tonnage capacity, and the reduction possible in operating costs. Preliminary figures indicate that the economies effected more than justify the capital expenditure and that the tonnage capacity is practically doubled, which is of very great advantage at certain times of the year. Furthermore, during the past four years the entire amount of coal that would have been used for steam operation has been saved and made available for other purposes, which has helped in a small way to relieve the coal shortage that has been so serious, as the total electric power used has been obtained from the waterpower plants of the Montana Power Co. The comfort in traveling the mountainous regions resulting from the elimination of cinders, smoke, grinding and jarring due to air brakes, and the saving in running time have been very much appreciated by the travelling public as shown by the increase in passenger traffic over these lines.

The reliability of electric operation under the very severe weather conditions such as prevail in this part of the country has demonstrated the fitness of the electric locomotive to meet the most severe service requirements. It is the opinion of engineers who have studied electrification for the past several years that it will supplant steam operation in the very near future where it is necessary to increase the tonnage capacity and where economical operation and conservation of the world's fuel resources are the watchword.

The service on this section is very similar to that on the sections previously electrified, consisting principally of the two all-steel elegantly equipped trans-continental passenger trains Olympian and Columbian in each direction per day, a local passenger service between Cle Elum, and Seattle and Tacoma, and four to six through freight trains each way per day. The freight trains are made up of all types of cars varying in weight from 25 to 70 tons loaded, and thus the importance of careful handling can be fully appreciated only by the train crews having charge of this

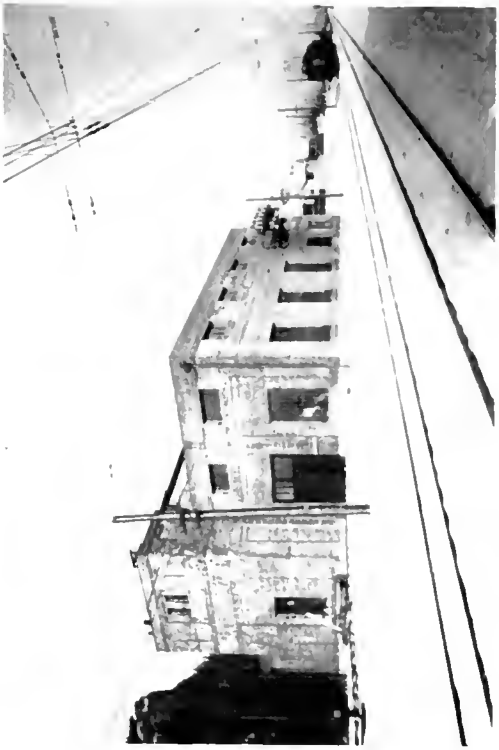


Fig. 1 Cedar Falls Substation and Bungalows

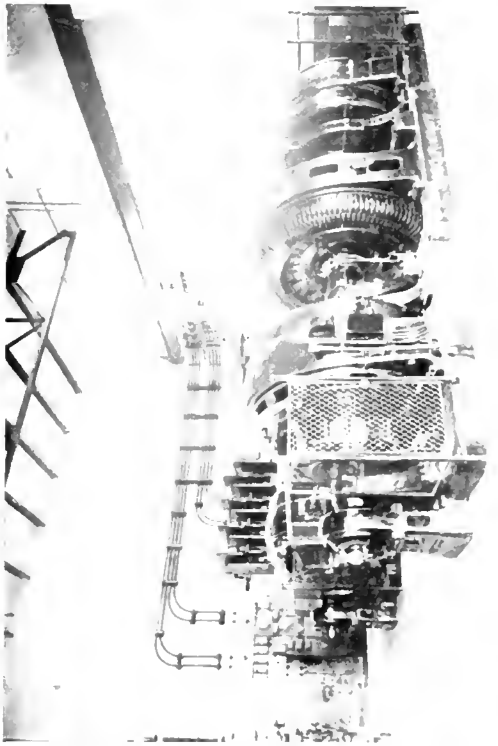


Fig. 2. 2000 kw Synchronous Motor-generator Sets and Switchboard, Tacoma Substation

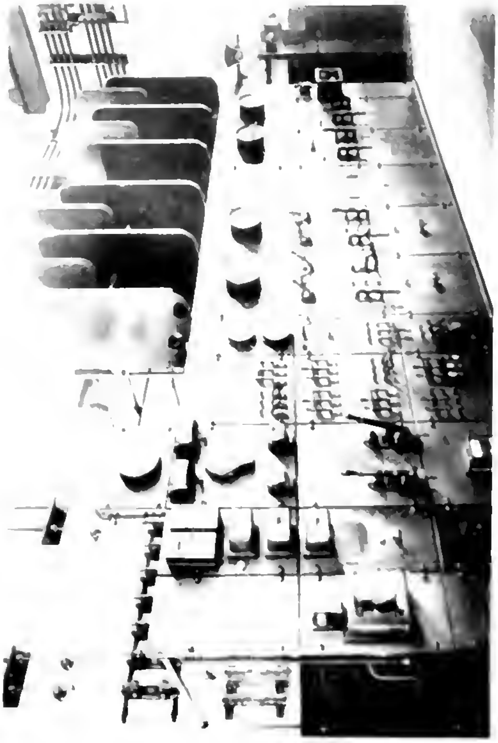


Fig. 3 Direct-current Switchboard, Cedar Falls Substation

Fig. 4. 265-ton, 3000-volt Direct-current Gearless Passenger Locomotive

work. Trains of 3000 tons are now handled with far greater ease at approximately twice the speed on grades, and with less damage to rolling stock, especially the pulling of draw bars, than 2000-ton trains were handled with steam operation.

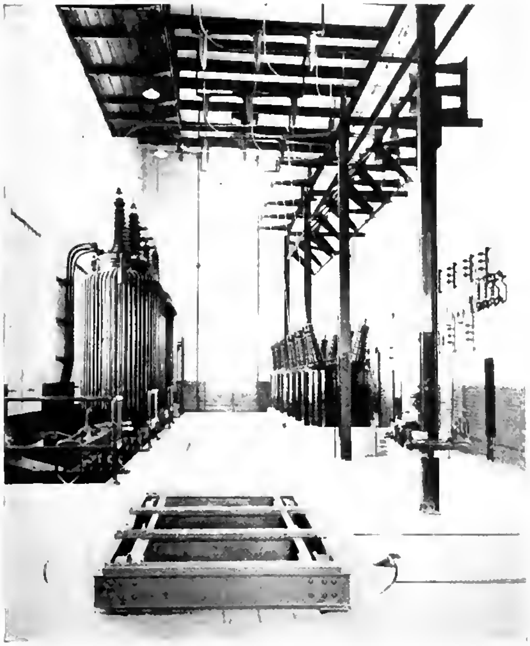


Fig. 5. High-tension Room, Showing 2500-kv-a., 100,000-volt Transformers and Oil Circuit Breakers, Tacoma Substation

The motive power equipment assigned to these divisions consists of five bi-polar gearless passenger, twelve geared freight, and two switching locomotives, all of which were furnished by the General Electric Co. The geared freight and switching locomotives were described in the REVIEW, October, 1916. The two switching engines are duplicates of those previously furnished and the geared freight locomotives are those originally used in passenger service on the Harlowton-Avery electrification, the gear ratio having been changed to make the locomotives suitable for freight service. (The original passenger and freight locomotives were duplicates, except as to their gear ratio.)

The bi-polar gearless locomotives are designed especially for high-speed passenger service and tests have demonstrated that their riding and tracking qualities are superior to any double-ended locomotives built. The running gears consist of two three-axle trucks, one at each end, and two central four-axle

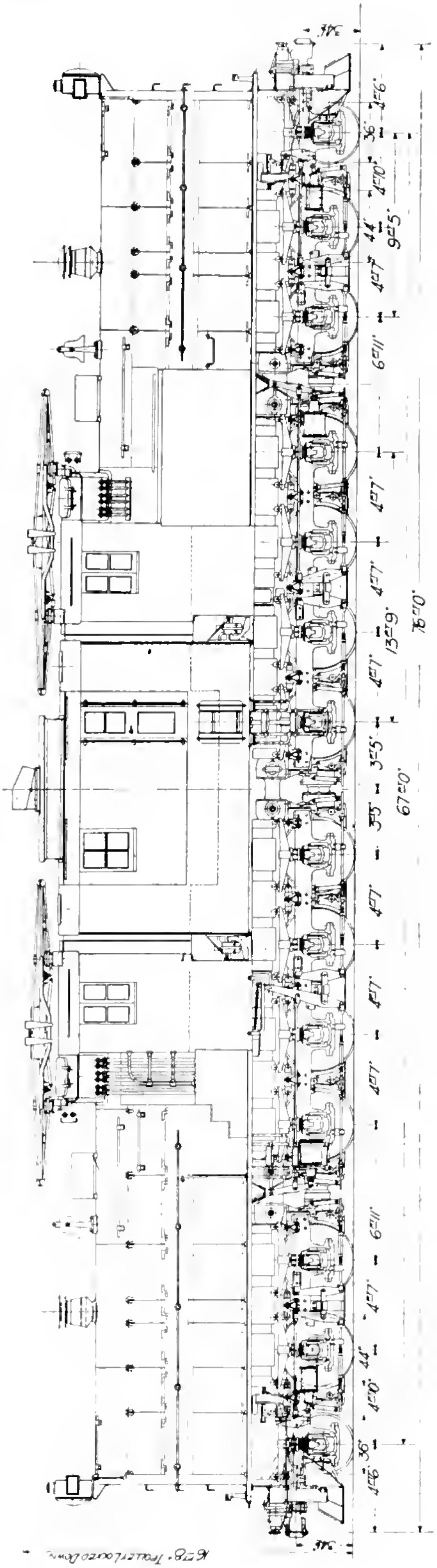


Fig. 6. Dimension Outline 265 ton Gearless Passenger Locomotive

trucks, all of which are articulated together and equalized in such a manner as to give approximately the same weight per driving axle and to insure proper tracking at high speed. These important features received much favorable comment from prominent railway engineers on the occasion of the exhibition tests at Erie, Pa., November 7, 1919. The leading wheels on each of the three-axle trucks are not equipped with motors, and by a special arrangement of the journal boxes are free to move axially a certain amount without movement of the entire truck, thus assisting in a more gentle turning of the trucks on curves and a reduction of flange wear.

Fig. 6 gives the general dimensions and Fig. 4 is a photograph of one of the locomotives, which was described in the REVIEW, December, 1919. They are now in service on the Rocky Mountain and Missoula Divisions, while the geared passenger locomotives are having their gearing changed for freight service preparatory to being transferred to the new electrification.

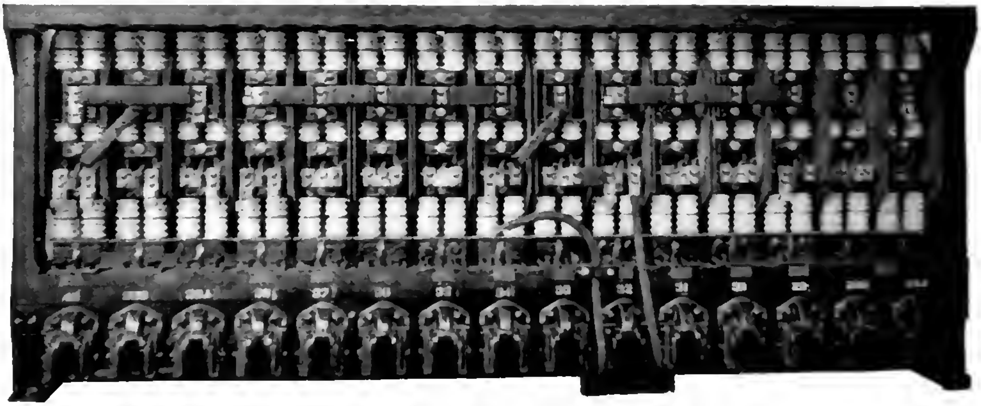


Fig. 7. Rear View of 3000-volt Contactor Group

Each of these locomotives is equipped with a high-speed circuit breaker* to prevent damage to the electrical apparatus due to short circuits. Repeated tests under the most severe conditions and actual operation have shown this feature to be a distinct advance. These breakers are duplicates of those installed in the substations for the protection of the generators of the motor-generator sets. With the protection thus afforded to both locomotives and substation apparatus, all damage due to short circuits is eliminated and thus the dream of engineers for decades has been realized.

The general arrangement and installation of the electrical control apparatus is the same as that used in the construction of the geared locomotive. The contactors and other parts are assembled on supports when built and the work of installing them in the locomotives consisted only in bolting the supports in place and connecting on the proper cables. Back view of the rheostatic contactor group is shown in Fig. 7. With this type of construction the apparatus can be more systematically arranged and provision made for easy inspection and maintenance. These equipment groups, together with the major portion of the other electrical apparatus, are installed in the two end cabs, with an aisle through the center, and hatches are provided on either side of the locomotive so that all parts can be readily inspected without the necessity of removing any apparatus. Fig. 8 is of a cross section through the locomotive showing the arrangement.

The profile of the entire electrification extending from Harlowton, Mont., to Seattle and Tacoma, together with the 212 miles remaining under steam operation, is shown in Fig. 9. This illustration also shows the location of the 22 substations which have a total installed capacity of 91,500 kw. This equipment consists of 39 2000-kw. and 9 1500-kw. synchronous motor-generator sets with transformers and switching equipment. The substation spacing averages approximately 30 miles.

The maximum grades on the new section are the 17 mile 2.2 per cent grade from the Columbia River west and the 19 mile 1.7 per cent grade from Cedar Falls east to the summit of the Cascades.

The 3000-volt power for the operation of this section is supplied from eight substations located as shown in Fig. 10. This illustration

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* A view of this circuit breaker is shown in Fig. 1 of the article by Mr. J. F. Tritle in this issue.

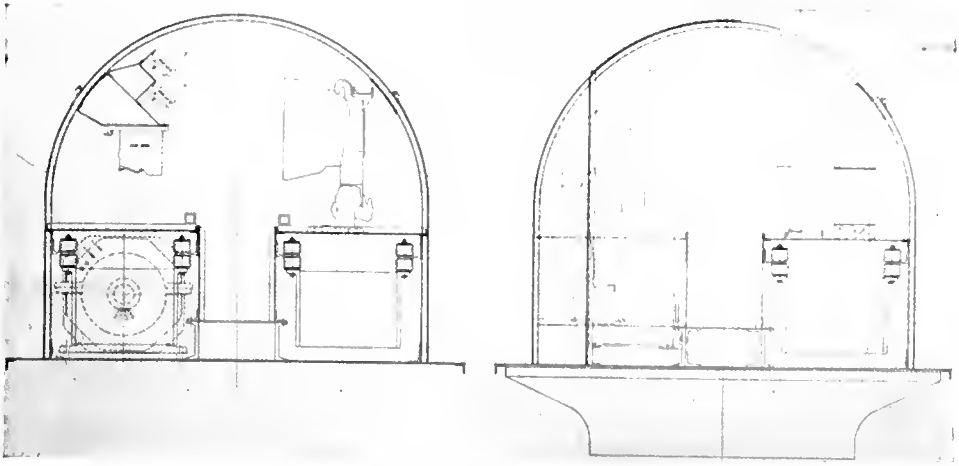


Fig. 8. Apparatus Compartment 3000-volt Direct-current Gearless Locomotive

also shows the present and ultimate capacity of each of these substations, the sizes of the feeders and the tonnages of the freight trains on which the feeder sizes were determined.

The lay-out arrangement of the substations is the same as that of the original substations, except that the synchronous motor starting and running oil circuit breakers are installed in cells in the basement instead of in the dividing wall between the motor-generator and transformer rooms, in order to afford greater space in the motor-generator room and greater reliability, and the direct-current feeder disconnecting switches are installed on framework outside the building instead of on the walls inside the station. The installation of these switches outside the buildings was desirable, as practical operation had demonstrated that it was necessary that they be of a design that could be opened under load at times of emergency. Their mechanisms are so arranged that they are operated from within the buildings. They have been thoroughly tested under the conditions that will exist in actual operation and they meet every requirement, being capable of opening a current from 7000 to 8000 amp. successfully.

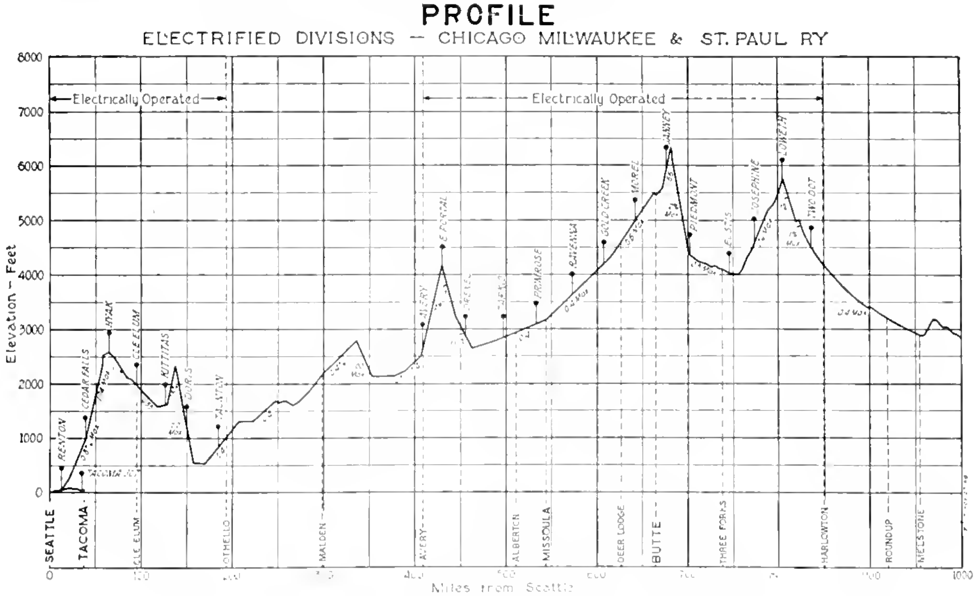


Fig. 9. Profile, Harlowton, Montana to Seattle and Tacoma, Washington

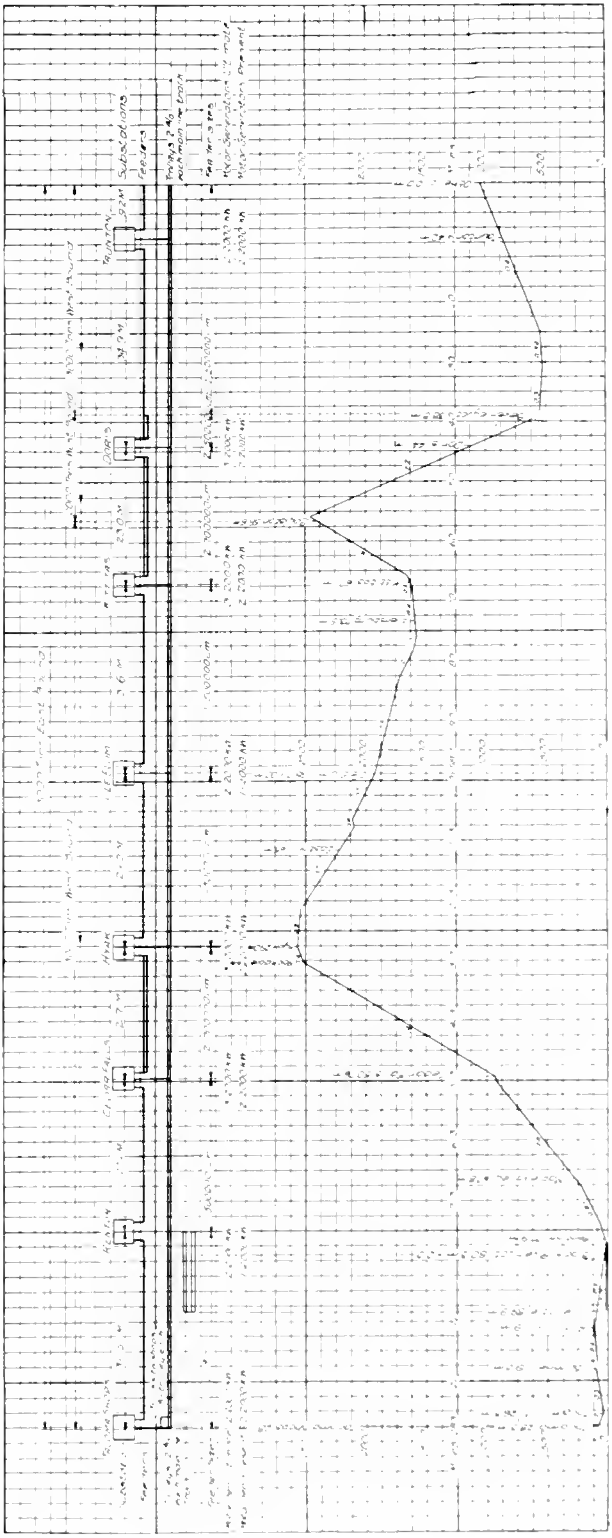
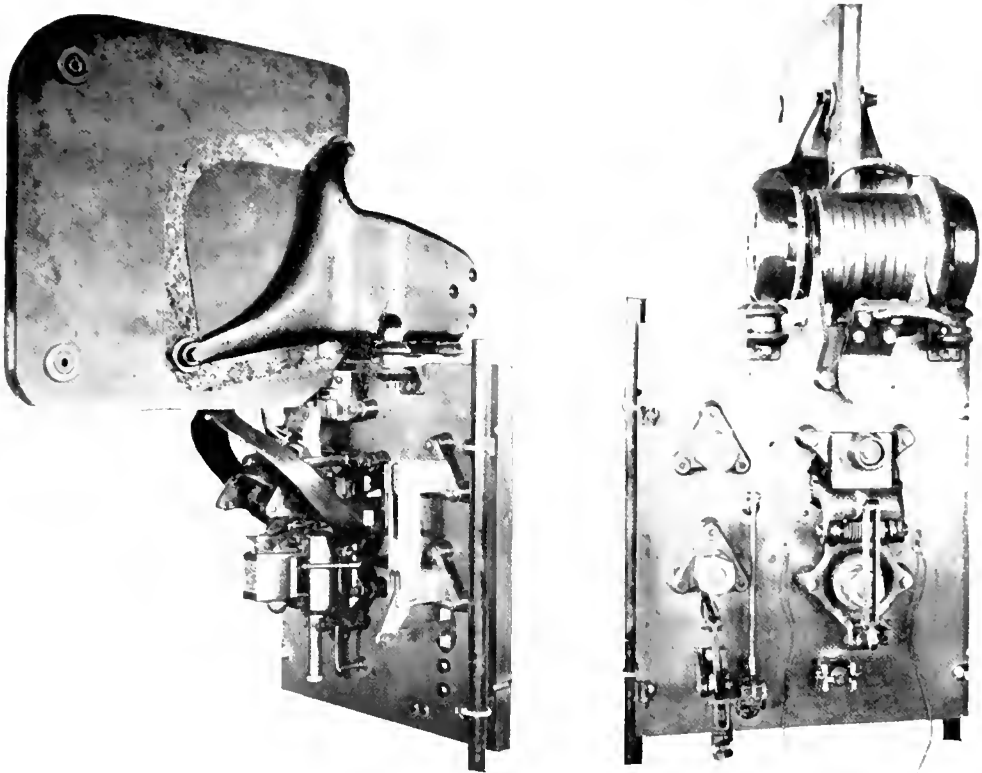


Fig. 10 Profile Cascade and Coast Divisions

It is of particular interest to note that all of the substation apparatus for the Cle Elum, Hyak, Cedar Falls, Renton and Tacoma substations is a duplicate of that in the substations on the Rocky Mountain and Missoula Divisions except for the high-speed circuit breakers and the direct-current feeder disconnecting switches. One high-speed circuit breaker is used per motor-generator set instead of one per station, which somewhat simplifies the arrangement of connections. The high-speed circuit breakers are of a more simple design than those originally furnished and are interchangeable with those used on the locomotives. The contacts are held closed magnetically, eliminating the use of any latches or toggles. The operation is effected by a shifting of the flux upon an increase in the main current, and the operating arm when released is moved quickly by a heavy coiled spring. They will thoroughly protect the direct-current generators from damage due to a short circuit by preventing the current from exceeding 6000 amps. This avoids excessive strains in the armature windings, which eventually might weaken the insulation and result in the burning out of an armature.

The motor-generator sets are of 2000 kw. capacity each, consisting of two 1000-kw. compound-wound 1500-volt direct current generators connected in series for 3000-volts and flat compounded from no load to 150 per cent load, driven by one 2500-kv-a. 2300-volt three-phase 60-cycle synchronous motor, and two direct-connected direct-current exciters, one of 12 kw. capacity for exciting the fields of the two generators and the other of 30 kw. capacity at 125 volts for exciting the fields of the synchronous motor. The synchronous motor exciter is compounded by the line current of the generators in order to provide the most economical excitation for the synchronous motor over the wide variation in the load. This compounding also helps in the regulation of the alternating-current line, to compensate for drop in voltage due to load, as it is arranged so that the motor operates at a lagging power-factor on light loads and at a leading power-factor on heavy loads.

The sets are cooled by external automatic blower equipments which are not started until the load reaches a value sufficient to produce a predetermined heating. The blowers are again shut down as soon as the load is reduced to an amount that will produce a temperature below this value. This arrangement materially increases the all-day efficiency, as the average load will probably be slightly below that necessary for the blower equipments to operate.



Figs. 11 and 12. Front and Back Views 3600-volt Direct-current 1500-ampere Circuit Breaker

These sets are designed to carry 300 per cent load for five minutes when operating either as straight synchronous motor-generator sets or inverted. The operation of some twenty sets of exactly the same design on the Harlowton-Avery electrification for the past four years has been very successful.

The transformers are of 2500 kv-a. capacity each, oil insulated, self-cooled, wound for 102,000 volts Y primary and 2400 volts delta secondary with one half voltage starting taps. They are of the circular-disc core-type design with the windings mounted on three vertical members of the core. The high-tension winding is divided into 44 sections per leg insuring a low voltage between sections and thorough ventilation of the coil stack. Taps on the low-tension winding give the desired range of voltage in the high-tension winding from 92,400 volts Y to 102,000 volts Y.

The transformer tanks use external tubes for circulating the cooling oil, which is the same construction as was used on the transformers previously supplied. The high-tension bushings are of the oil filled type and the low-tension bushings of the solid type. Both bushings have their ground sleeves extended from the cover beneath the oil level to obtain an electrically neutral atmosphere in the chamber above the oil. This construction eliminates the possibility of an explosion due to static discharge.

The main circuit breakers have combined series and shunt blowout coils with a large magnetic circuit suitably proportioned and an improved narrow arc chute which insures the circuit being opened under all conditions of operation. At the same time a gradual reduction of the current is effected so as to keep the potential strains of the various parts at a comparatively low value. The design of the breaker is very rugged and great care was exercised in proportioning the various parts in order to insure obtaining the desired operating characteristics.

Protection from lightning and surges on the transmission line is taken care of by one aluminum-cell lightning arrester per substation, connected to the high-tension bus with choke coils installed in the high-tension leads of each transformer. The horn gaps in the case of the flat roof substations, which are used where there is very little snow, are installed on the roof; and in the case of the hip-roof stations used in the snow belts they are installed inside the station. The protection afforded by those in operation for the past four years has been remarkable, as very little if any trouble has been experienced from lightning.

Great care was taken in the selection of the protecting scheme of the high-tension transmission system to insure continuity of service, in order that when trouble occurs on the high-tension line the power would be cut off from only the section in trouble. In order to meet the selective protection necessary under the various conditions of operation, three main types of relay are used; viz., an induction relay, an induction three-phase reverse-power relay, and an inverse time-limit relay. The first two types of relays have been in use for several years and do not need further comment. The inverse time-limit relay, however, is a new device developed specially to meet the requirements of selective protection for this particular system. It has a truly inverse time-limit curve and its construction is such as to insure that the adjustment will remain permanent for a long time. The working elements consist of two parts, one of which is to all intents and purposes an ammeter element, and the other a definite time element.

Fig. 13. Main Line, showing Overhead Construction Looking East from Cedar Falls Substation

The overhead construction is of the modified flexible catenary type using two-4/0 copper trolley wires flexibly suspended side by side from the same steel messenger by independent hangers alternately connected to each wire. Forty-foot wooden poles suitably guyed and spaced are used except in crossing the Columbia River and on other special work where steel construction is used. Bracket construction is used wherever the track alignment will permit, and cross-span construction on passing tracks and in yards. The length of the trolley poles is sufficient for two cross-arms at the top on which are carried the direct-current feeders, the 4400-volt signal wires, and the power limiting and indicating system wires. A supplementary 4 0 negative feeder, which is tapped to the middle point of every second reactance bond, is carried directly on top of the poles without the use of an insulator. The positive feeder is tapped to the trolley wire at every seventh pole, or approximately every 1000 feet.

Power for the operation of this division is supplied by the Inter-Mountain Power Co. which in turn purchases its energy from the Washington Water Power Co., and the Puget Sound Traction Light and Power Co., both of which have large waterpower developments. Thus the change to electric operation saves the coal and oil previously used for steam operation.

The power supplied by the Washington Water Power Co. is furnished from its Long Lake Plant northwest of Spokane by a 113-mile transmission line to the Taunton Substation. The power supplied by the Puget Sound Traction Light & Power Co. comes over a ten-mile transmission line from its Snoqualmie Plant to the Cedar Falls and Renton Substations. Power to the other substations is supplied by the Railway Company's own high-tension transmission lines which connect between all of the eight substations except the Cedar Falls and Renton Substations. The construction of this line is similar to the line which has been in service on the Rocky Mountain and Missoula Divisions, practically the only difference being that there are a number of transpositions in order to reduce as far as possible any inductive interference on the neighboring telephone and telegraph lines. The transmission construction, except where special construction is necessary, such as on curves, etc., consists of 45 and 50-foot Idaho cedar poles with two cross-arms, on which are carried the 100,000 volt lines on suspension type insulators and an uninsulated ⅜-inch steel ground wire. The high-tension conductors are 2/0 stranded copper, with a with a hemp core.

The work undertaken by the Chicago Milwaukee & St. Paul Railway has been notable for the development in electric traction brought forth, and as these developments have been in successful operation for some time, they are here summarized.

(1) Commercial application of Electric Regeneration by which power is generated by trains on descending long grades and is returned to the line for use on other parts of the system.

(2) Development of a Power-Limiting Indicating System by which the power supplied to a system at a number of points can be totalized at one point and the maximum power available for operation at all times can be controlled.

(3) Development of the High-Speed Circuit Breaker by which commutating apparatus including locomotives can be protected from injury due to short circuits.

(4) Development and successful application of the Twin Trolley Wire by which the operation of the heaviest freight trains can be accomplished at 3000 volts without any sparking at the trolley wire at any speeds within safe operating requirements. The wear on the trolley wires which have been in service for the last four years is inappreciable.

(5) The development of the Slider Pantograph in connection with the adoption of the twin trolley wire has been as notable as the adoption of the twin trolley wire itself.

(6) The introduction of the compounding of the synchronous motor exciter of a motor-generator set used for supplying the high-voltage direct current, by means of the main direct current so that the synchronous motors operate economically under all conditions of load and at the same time compensate in a measure for the drop in line voltage due to load.

(7) Development of a High Speed Passenger Locomotive especially adapted to trans-continental service over heavy mountain grades and severe curves.

Fig. 14. Overhead Construction Looking East Toward Cedar Falls Substation

Passenger Locomotives for C., M. & St. P. Rwy.

By A. F. Batchelder
Engineer Locomotive Department, General Electric Company
and
S. T. Dodd
Railway and Traction Engineering Department, General Electric Company

The Chicago, Milwaukee & St. Paul Railway since 1915 has been operating electrically over the mountain ranges of Montana. The results of this operation have convinced the directors of the railroad of the marked advantages of electrification; and, as a consequence, they have extended the electrification over the Cascade Range. When placing orders for locomotives for this extension, the railway company proposed to purchase locomotives designed strictly for passenger service, their characteristics and equipment to be those most suitable for this purpose. In the following article the authors discuss the details of the electrical and mechanical construction of the new passenger locomotives, five of which were completed last year at the Erie plant.—Editor.

A. F. Batchelder

S. T. Dodd

December 9, 1915, may be considered the date of the initial electrical operation over the electrified lines of the Chicago, Milwaukee & St. Paul Railway. During the following winter the electrification was extended over 440 miles of route from Harlowton, Montana, to Avery, Idaho, a section which crossed the Belt, the Rocky, and the Bitter Roots Mountains. The locomotives for this initial electrification were of the geared type, designed and built especially with a view to the most economical operation of the freight service. The locomotives for passenger service differed from the freight locomotives only in the details where it was absolutely necessary to meet the operating requirements, such as changing the gear ratio to increase the speed and providing each with heating and lighting equipment.

Three years later, in 1918, the successful operation of the original equipment had convinced the railroad company's officials of the economical advantages of electric operation, and they decided to equip an additional section extending over the Cascade Mountains between Othello, Washington, and Tacoma, Washington, a distance of 212 miles. In choosing the equipment for the new extension, it was decided to give special emphasis to the requirements of passenger service and to purchase locomotives which were primarily

Fig. 1. Three-quarter View of New Direct-current Electric Locomotive

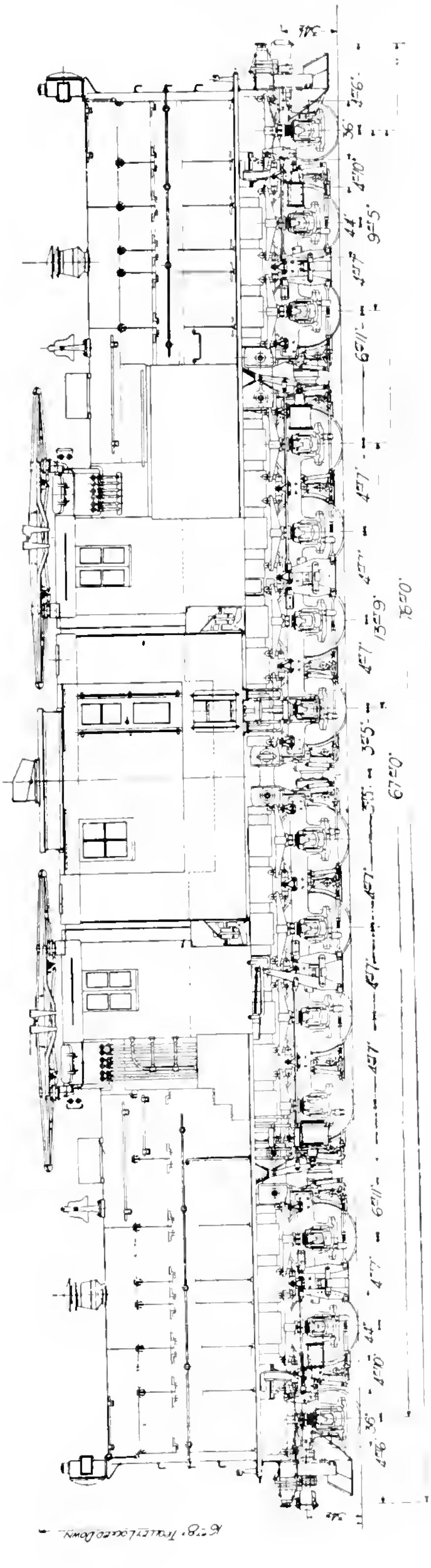


Fig. 2. Outline Drawing and Dimensions of New Direct-current Electric Locomotive

designed with this in view, taking advantage of any details which would assist in the proper and economical operation of passenger trains. For the freight service it was decided to retain the geared locomotives that were in use on the Harlowton-Avery Division, changing the gear ratio where necessary to meet freight conditions, and using only locomotives of the new design for passenger service.

To meet the specifications for the passenger locomotives, the General Electric Company has designed, completed, and tested a locomotive which appears to embody the necessary qualifications and to successfully fulfill the requirements, both from electrical and mechanical standpoints. In designing the locomotive, particular attention has been given to the features affecting safety, reliability, efficiency, convenience of operation, effect on track, and cost of maintenance. The locomotive has especially good riding qualities; it has no apparent effect on the alignment of the track, and to a marked degree it is free from transverse movements or oscillation which would tend to create lateral pressure against the rails.

It is the intention of this article to give a description of this locomotive, which differs in many ways from the locomotives that are now in operation on the Harlowton-Avery Division, to indicate the reason for choosing this design, and to call attention to some of the principal features which differ from usual practice. Briefly stated, the service requires the locomotive to haul a 950-ton passenger train over the mountain divisions of the Chicago, Milwaukee & St. Paul Railway at 25 m.p.h. up 2 per cent grades, with a maximum operating speed of 60 m.p.h. on the level, and to provide regenerative braking on the down grades at speeds consistent with safe operation. Fig. 1 shows a view of the completed locomotive and train. Fig. 2 is an outline drawing of the side elevation, giving the general dimensions. Fig. 3 is a section through the apparatus cab, showing the location and arrangement of the principal pieces of apparatus.

It will be seen that the running gear is composed of four individual trucks, two end trucks having three axles each, and two center trucks having four axles each. These trucks are connected together by special articulation joints. The motor armatures are mounted on the axles and the motor fields are carried on the truck frames.

The superstructure is made in two sections of similar design with a third section between them The third or central section contains the train heating equipment, which consists of an oil fired steam generator together with water and oil tanks. This unit is complete in itself, and is carried over supports attached to the two middle trucks. It can be readily removed for repairs without interfering with any other part of the locomotive. It is placed between the two operating cabs in order to be easy of access to the engineers' helper, or fireman, from either end location.

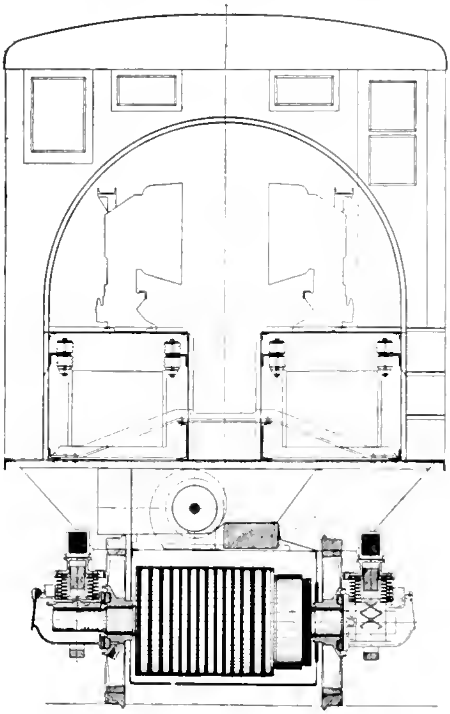


Fig. 3. Cross-Section of Apparatus Cab

The two end sections are similar to each other in appearance. The operator's cab in either section is on the inner end next to the heater cab just described, in order that the operator will be convenient to the heater and in order to allow a maximum space for apparatus in the apparatus cab or outer end section. Another advantage of this arrangement of cabs is that the operator can have access to any section of the locomotive requiring his presence without passing through a section containing high-tension apparatus. The engineer's or operating cab contains a main or master controller, the air brake valves and handles, and an instrument panel containing air gauges, ammeters, and speed indicator. The engineer uses either of the two operating cabs according to the direction in which he is running.

A door gives access from the operating cab to the apparatus section, which extends with a cylindrical top to the extreme end of the locomotive. The cylindrical construction naturally adapts itself to the protection of the apparatus included; and, in addition, it has the advantage of allowing a clear vision for the operator from his normal operating position. Contained in this apparatus section are the resistors and contactors to control the power circuits of the locomotive. The starting resistors are placed in two rows on each side of the central passage just above the floor of the superstructure, and they are covered at the sides by removable covers which when opened allow the separate resistor boxes to be slid out upon the longitudinal running board outside of the apparatus cab. The air compressor for the air brakes, the motor-generator set for train lighting, and the storage battery for marker lights and emergency control stand upon the same level as the resistors and can be removed or replaced in a similar manner. Above the resistors are located the contactors with their arc chutes facing a central aisle two feet wide. This arrangement allows ample arcing space and room for inspection of the contactors. Above the contactors is the cylindrical roof of the locomotive with trap doors for inspection of the back connections and insulation, and for removing the contactors in case replacement is necessary. The whole design and arrangement of this apparatus cab lends itself to a maximum economy of cost and material, as well as to convenience of inspection and repair of apparatus.

Motors

The motors are of the well known bi-polar gearless design which was adopted by the New York Central Railroad fourteen years ago. The continuous operation of these motors since that time, in hauling heavy passenger trains between the Grand Central station and Harmon, proves them to be of a design well suited for the service. This motor has demonstrated its remarkable reliability and low cost of maintenance.

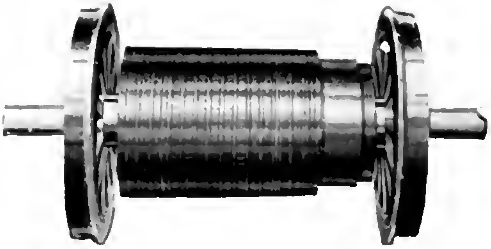


Fig. 4. Bi-polar Gearless Armature and Wheels

To insure light weight per axle, flexibility in control, good truck arrangement for curving as well as for high-speed running, 12 motors were chosen, each of relatively small capacity. They are especially designed to withstand high temperature, being insulated with mica and asbestos.

Fig. 4 shows the motor armature complete, built directly on the axle with the wheels pressed and keyed in place. The continuous rating of each motor at 1000 volts and with 120 degrees rise by resistance is 266 h.p., corresponding to 3500 lb. tractive effort at the rim of the drivers at a speed of 28.4 m.p.h. Forced ventilation is employed for cooling. The armature core is provided with holes for the passage of the ventilating air. Blowers are located above each motor armature and deliver air at the commutator end of the motor where it divides, part passing through the armature and part back through and around the field coils where it escapes upward and is afterwards used for ventilating the starting resistors.

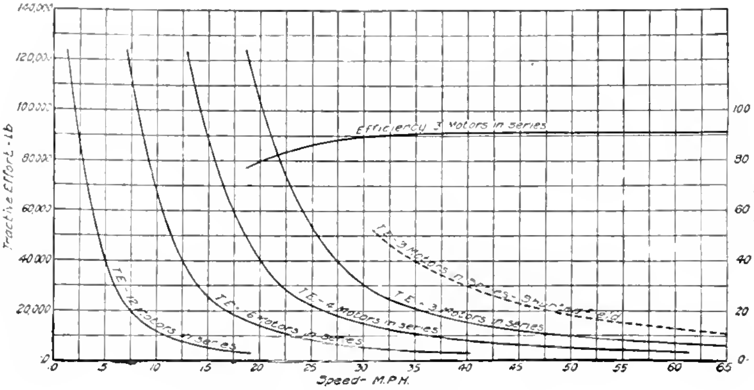


Fig. 5. Locomotive Characteristics

This type of motor gives very high efficiency in average operation, it having no journal bearings or gearing. It lends itself nicely to simple and compact locomotive design as the frame is made use of to furnish the entire path for the magnetic flux. The pole pieces and field coils are fastened to the cross transoms of the trucks and the magnetic flux passes horizontally in series through all twelve motors, finding a return path through the locomotive frame. The articulated joints between the trucks are made in such a manner that large surfaces are in contact to provide a low reluctance path for the flux. The pole faces are made flat in order to prevent them from coming in contact with the armature during the vertical movement of the truck frame on its springs, or when removing or replacing the armatures. A minimum clearance of ⅛ inch on each side is allowed between the armature and the pole piece tips. The brush-holders are bolted to the transom, an arrangement which permits the brushes to move up and down with the fields as the frame rides on the truck springs.

Control

In choosing the control apparatus special care has been taken to use those individual pieces of apparatus best suited to the particular requirements. Where single independently operated switches are necessary, as on the resistance notches, electro-magnetic control is used. Where several switches are required to operate at one time, as in changing from series to parallel motor connections, banks of switches with electro-pneumatic cam control are used, thus insuring positive operation, eliminating interlocks, and simplifying the wiring.

The control for motoring is arranged for four motor combinations.

The first combination has 9 rheostatic steps, one full-field step, and one tapped-field step, with twelve motors in series across 3000 volts.

The second combination has 6 rheostatic steps, one full-field step, and one tapped-field step, with six motors in series and two sets in multiple.

The third combination has 8 rheostatic steps, one full-field step, and one tapped-field step, with four motors in series and three sets in multiple.

The fourth combination has 8 rheostatic steps, one full-field step, and one tapped-field step, with three motors in series and four sets in multiple.

These combinations result in a total of 39 control steps with a choice of eight operating speeds, exclusive of the resistance steps. The locomotive characteristics on the various steps are clearly shown in Fig. 5.

The regeneration of power for braking is accomplished in a simple manner by using some of the motors for exciting the fields of the others, which in turn are used as generators to return power to the line.

As a provision against short circuits, or extreme overloads, there is provided in the apparatus cab a quick acting circuit breaker which will protect the circuit in less than 1/100 of a second.

Mechanical Construction

For flexibility in curving, the running gear is made up of four trucks, each of a relatively short wheel base. The two middle trucks have four driving axles each; and the two end trucks, two driving axles and one guiding axle each, making a total of 14 axles. The trucks are connected together with articulated joints which allow of no relative lateral movement between them, so that each truck positively leads the following truck. This is for the purpose of reducing flange wear on curves and lateral oscillation on tangent track.

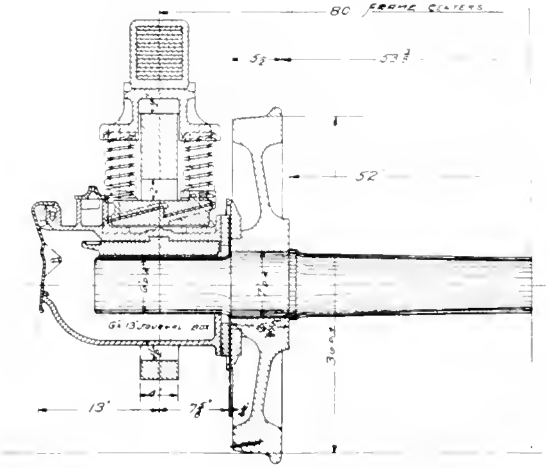


Fig. 6. Centering Device of Leading Axle

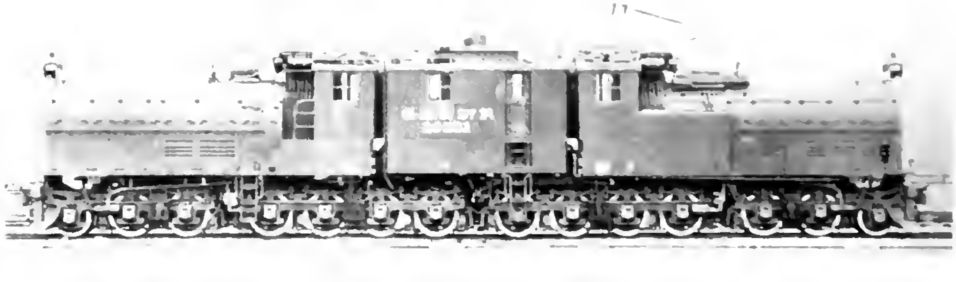


Fig. 7. Side View of Locomotive

The most important problem that has to be faced in the design of a locomotive for high-speed passenger service is the problem of limiting the lateral oscillations of the locomotive structure, which tend to distort the track, and of minimizing the effect on the track of such oscillations as occur. If a locomotive were built with a rigid wheel base as long as the total wheel base of the present locomotive (67 feet), the lateral oscillations could not reach any large angular value. However, on account of the long wheel base, such a locomotive would be incapable of taking curves. By articulating the wheel base the locomotive is capable of accomodating itself to track curvature; and, at the same time on account of this articulation and the consequent guiding effect of one truck on another, the lateral oscillations on tangent track are minimized in the same manner as would be done by the use of a long rigid wheel base.

To soften any lateral blow that may be given against the rail, the leading and trailing axles are allowed a movement of one-half inch, relative to the truck frame, either way from their central position. This movement takes place against a resistance introduced by wedges above the journal boxes which tend to hold the box in its central position and to give a dead beat action opposing the motion. This wedge construction is illustrated in Fig. 6. To further protect the track from lateral displacement on the ties, the outer end of the superstructure is carried on rollers, bearing on inclined planes upon the truck frames; while the inner end of the superstructure is rigidly bolted to one of the middle trucks. This construction tends to hold the leading and trailing trucks in their central position. When a blow is delivered by the leading or trailing truck against the rail head, the superstructure is displaced laterally across the outer trucks. In such a sideways displacement, the weight of the superstructure rolls up on the inclined plane on that side, and thus transfers weight to the rail that is affected, thereby increasing adhesion of the rail to the tie. This action really has two results: It not only increases the holding power between rail and tie at that point, but it introduces a time lag and increases the time and distance during which the pressure is delivered to the rail head.

As a matter of record, it should be said that the first of these new locomotives was delivered to the railway company at Deer Lodge, Montana, on December 14th, 1919, and was put in operation handling passenger trains between Deer Lodge and Avery.

For convenience of reference, Table 1 gives a summary of the principal dimensions and characteristics of this locomotive.

TABLE 1

LOCOMOTIVE DIMENSIONS

Total weight	521,200 lb.
Total weight on drivers	457,680 lb.
Weight per driving axle	38,140 lb.
Dead weight per driving axle	9,590 lb.
Weight per idle axle	31,750 lb.
Dead weight per idle axle	3,560 lb.
Length overall	76 ft. 0 in.
Width overall	10 ft. 0 in.
Height over cabs	14 ft. 11$\frac{5}{8}$ in.
Height over pantograph, locked down	16 ft. 8 in.
Total wheel base	67 ft. 0 in.
Maximum rigid wheel base	13 ft. 9 in.
Diameter of driving wheels	44 ft.
Diameter of idle wheels	36 ft.
Size of journals	6 ft by 13 ft.
Dimensions of operator's cab	5 ft. by 10 ft.
Dimension of heater cab	14 ft. 11 in. by 10 ft.
Heater capacity	4000 lb. steam per hour
Water capacity	30,000 lb.
Oil capacity	6,000 lb.
Compressor capacity	150 cu. ft. per min.
Number of motors	12
Type of motor	(Bipolar-) GE-100
Diameter of armature	29 ft.
Clearance between bottom plate and top of rail	5$\frac{1}{4}$ in.
Working range of pantograph	9 ft. 0 in.

Locomotive Rating	Tapped Field	Full Field
Total horsepower, one hour motor rating	3,480	3,380
Total tractive effort one hour motor rating	36,000	46,000
Speed, m.p.h.	36.2	27.5
Total horsepower continuous	3,200	3,200
Total tractive effort continuous	32,000	42,000
Speed, m.p.h.	37.8	28.4

Control Equipment of the New Locomotives for the C., M. & St. P. Rwy.

By F. E. Case

Railway Equipment Department, General Electric Company

Power not under control would be useless—in fact would be destructive in most instances. Control is, therefore, a vital factor in the production and application of power. Since the difficulty in designing control equipment for a machine increases with the variety of the conditions under which the machine is to operate, the control of an electric locomotive employing regenerative braking probably presents the most complex problem. That a satisfactory solution has been arrived at is evidenced by the successful performance record of the earlier C. M. & St. P. locomotives. The new locomotives are equipped with essentially the same system of control, the principal modifications being along the line of simplification.—Editor.

F. E. Case

The five new passenger locomotives which were recently delivered by the General Electric Company to the Chicago, Milwaukee and St. Paul Railway differ materially in appearance from the original type* and the arrangement of electrical apparatus has also been somewhat changed. The adoption of twelve bi-polar gearless motors per locomotive instead of eight geared ones, as on the earlier locomotives, resulted in a different electrical grouping of the motors, and further development of regenerative electric braking permitted a simplifying of the method of control.

The motors are air blown and each has a continuous rating of approximately 250 h.p. and a one hour rating of 270 h.p. The use of a larger number of motors made it possible to provide a greater variety of groupings for motor operation with a corresponding increase in the number of running speeds.

Motoring

There are four motor combinations, the motors being connected 12, 6, 4 or 3 in series, and the fields may be weakened with each grouping to secure four additional running speeds. This field weakening is obtained by tapping or cutting out a portion of the winding.

The number of accelerating steps for each of the four motor groupings, and the speeds at continuous capacity with full and tapped field, are shown in Table I.

TABLE I

Motors in Series	Number of Groups	Accelerating Steps	SPEED AT CONTINUOUS RATING	
			Full Field	Tapped Field
12	1	10	5.0	8.0
6	2	7	12.3	18.7
4	3	9	20.0	29.0
3	4	9	27.0	40.0

Regenerative Braking

Broadly speaking, the system of regenerative braking is similar to that on the previous locomotives, in that the series motors when regenerating have their fields separately excited to a density higher than would be obtained for motoring at corresponding speeds. In consequence, the combined armatures generate a higher voltage than that of the line and return power to it. The main difference is the source of energy for exciting the motor fields and the consequent arrangement of the motor circuits. In the original equipments a separate motor-generator was used for exciting these fields, but in the new ones part of the motors are employed as exciters for the fields of the other motors and no separate machine is required.

The motors are connected in two virtually independent groups for regeneration and these groups may be connected either in series or parallel, depending upon the train speed desired. Each group consists of four motors which generate the power returned to the line, and two which generate current for exciting the fields of all six motors. When the regenerated current returned to the line is of the same value as the exciting current in the fields and is also equal to the continuous rating of the motors, the locomotive speed is about 11 miles per hour for the series connection of the regenerating groups and 23 for the parallel connection.

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* A full description of these earlier locomotives appeared in the General Electric Review, November, 1916.

The amount of regenerated current required to maintain any constant speed is dependent upon the train weight and grade, and it is necessary to vary the field excitation to secure the proper loading of the motors.

Above about 22 miles per hour it is desirable to have the two regenerating groups connected in parallel in order to make the armature and field currents as nearly equal as possible. With these connections power can be returned to the line at speeds up to more than 60 miles per hour.

The control is so arranged that it is possible to start regeneration without first passing through the motor running positions.

With the pantograph lowered, or power off the line, it is possible in an emergency to make all the regenerating connections by means of a storage battery provided on these locomotives. The braking effort obtained keeps the train bunched and the current generated may be used for operating the main air compressor so that the air brakes can be employed on the train.

Main Circuit Apparatus

The principal pieces of apparatus in the main circuit are:

2 sliding contact pantograph trolleys.
3 knife blade disconnecting switches.
1 magnetically operated high-speed circuit breaker.
2 magnetically operated line contactors.
4 groups of magnetically operated resistor contactors.
5 groups of electro-pneumatically controlled, cam operated contactors for series-parallel and regenerating motor connections.
2 electro-pneumatically controlled, cam operated motor reversers.
2 electro-pneumatically controlled, cam operated field tappers.
43 cast grid resistors.

Most of the apparatus is essentially the same as that used on the earlier locomotives.

Pantograph Trolleys

The pantograph trolleys are the same as those of the previous equipment, long continued operation in very exacting service having shown that they needed no important change. Although there are two trolleys on each locomotive, one is of ample capacity for collecting the current, the other being held in reserve.

The two sets of lubricated copper strips, which are mounted on the top of the pantograph for making a sliding contact with the two trolley wires, have given remarkably long service, many of them lasting for more than 10,000 miles.

In both installations the trolleys are raised by admitting compressed air to two pistons, which extend the elevating springs, and are lowered by exhausting the air. On the new locomotives the raising and lowering is controlled by means of a small switch, in either end cab, which operates an electrically actuated air valve located close to the trolley. This arrangement permits a quicker operation in an emergency than the manually operated valve, owing to the shorter distance between valve and trolley.

With the pantograph down, the storage battery provides a source of energy for controlling the raising valve and for operating

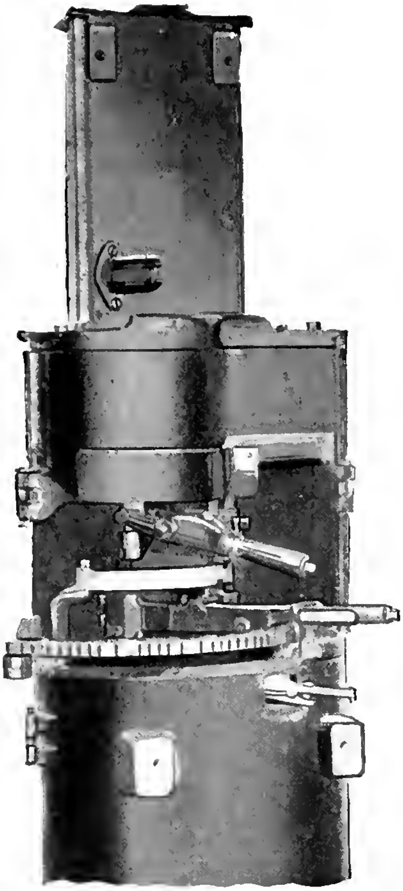

Fig. 1. Master Controller. The master controller provides for 8 motoring speeds and 2 combinations of motors for regeneration. During motoring the locomotive may be operated with 12, 6, 4, or 3 motors in series and the motor fields may be tapped in each combination. During regenerative braking the motors may be operated either 8 or 4 in series

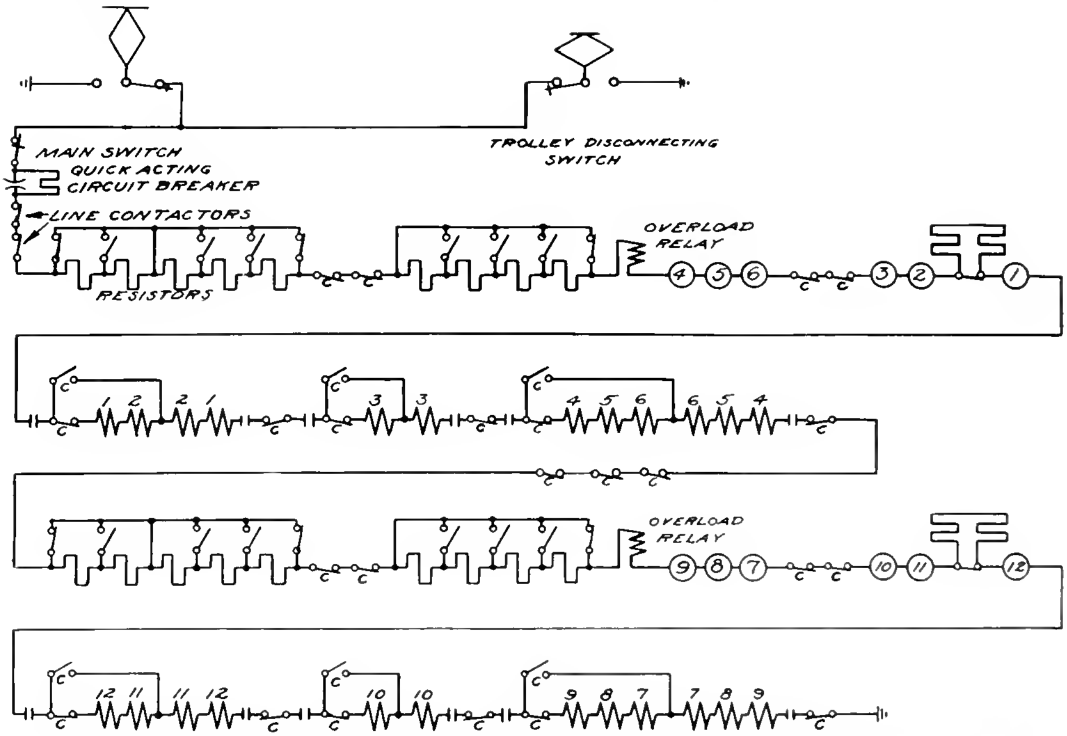

Fig. 2. First Running Position for Motoring with 12 Motors in Series. Contactors Marked "C" are Cam Operated and the Remaining Ones Magnetically

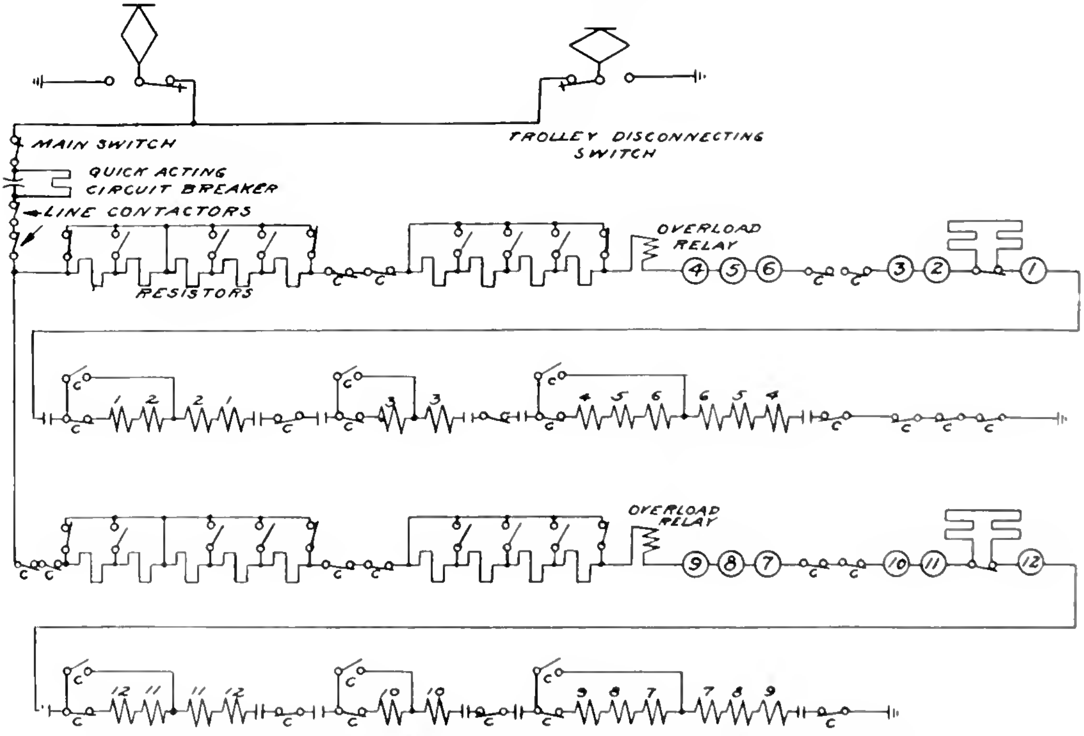

Fig. 3. Second Running Position for Motoring with 2 Multiple Groups of 6 Motors in Series in Each Group

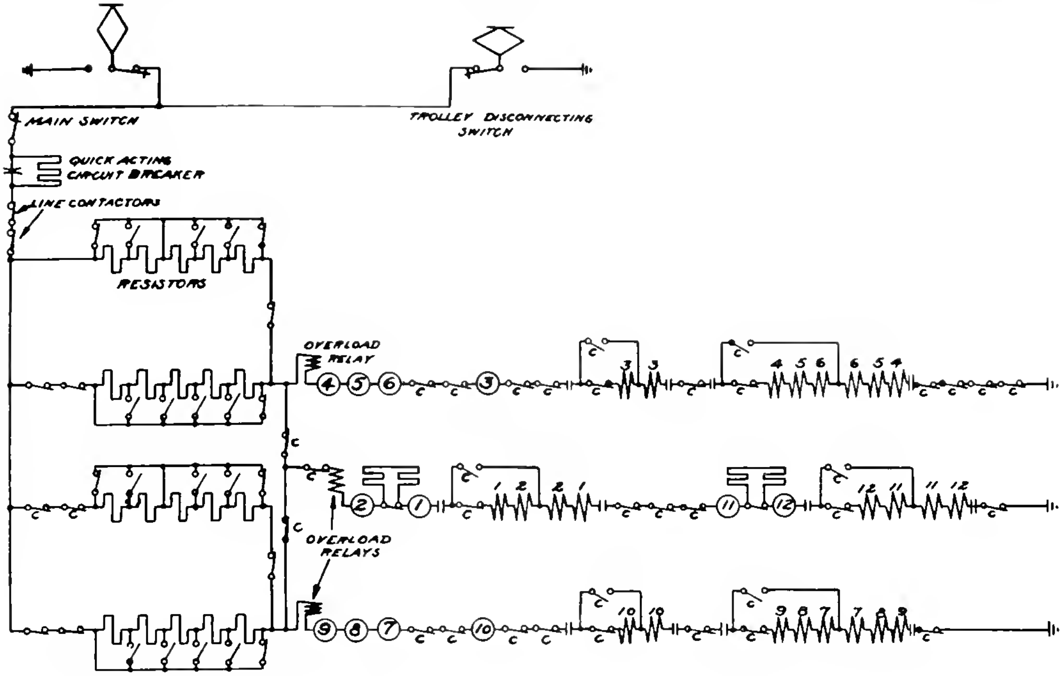

Fig. 4. Third Running Position for Motoring with 3 Multiple Groups of 4 Motors in Series in Each Group

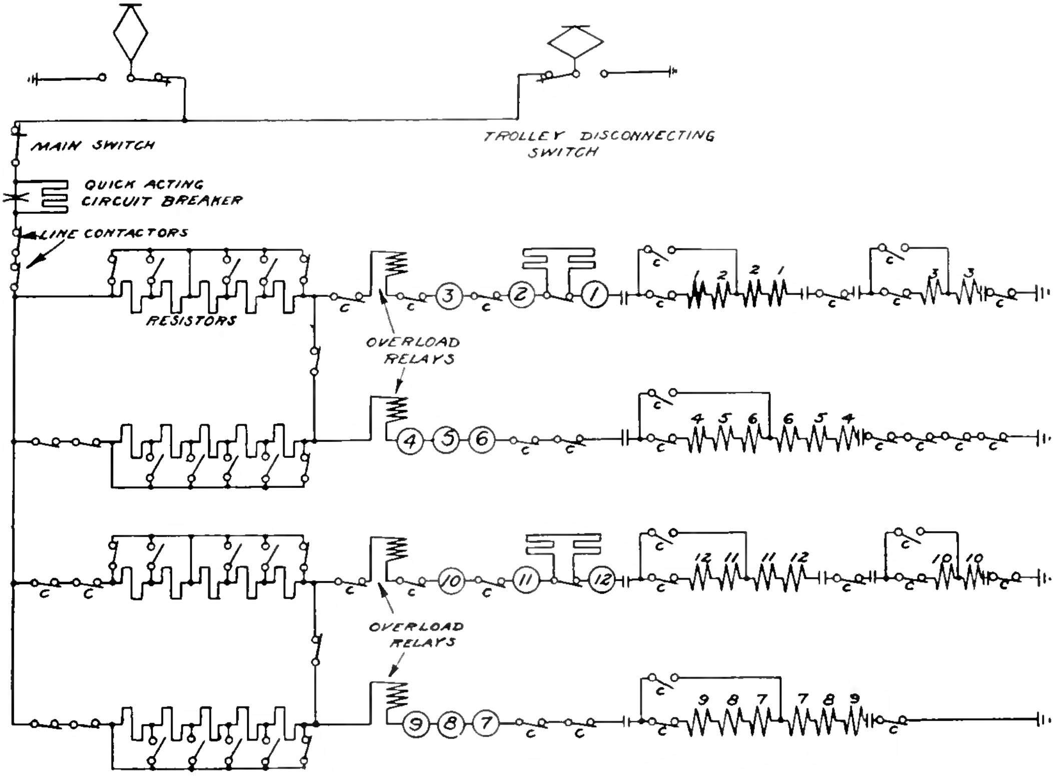

Fig. 5. Fourth Running Position for Motoring with 4 Multiple Groups of 3 Motors in Series in Each Group. Overload Relay is Placed in Each Group.

a small auxiliary air compressor which produces a supply of air for raising the trolley if the pressure in the reservoir is inadequate.

On the previous locomotives an auxiliary base with pole is used for making contact with the trolley wire when the locomotive has been idle so long that the air pressure in the reservoir falls below the amount required to raise the pantograph trolley. After the air compressor has produced a pressure of about 50 pounds in the reservoir the pantograph trolley may be put up and the pole trolley lowered.

Fig 6. Disconnecting Switch and Line Contactors. The knife blade switch makes it possible to test the control apparatus without applying power to the motors. The magnetically operated line contactors break the motor circuit both when the master controller is turned off and when an overload occurs

Knife Blade Disconnecting Switches

A knife blade switch, mounted in a weatherproof sheet-steel box, is located in a convenient place near each trolley for disconnecting it from the main lead to the interior of the locomotive in case of damage or during inspection. The switch is of the double-throw type and is so connected tha when a trolley is cut out it will be grounded for safety during inspection.

The switch shown in Fig. 6 is provided for disconnecting the main circuit from the trolley. It is used when it is desired to test out the functioning of the different pieces of apparatus without applying power to the motors. In the *down* position of the switch, connection is made to a coupler contact at the side of the locomotive. When it is desired to move the locomotive into a round house or repair shop where there is no overhead trolley wire, a cable leading from a low-voltage supply may be attached to this contact.

High-speed Circuit Breaker

This protective device for the main circuit is fully described in another article* appearing in this number of the Review. Its operation is much more rapid than anything previously used for the purpose on locomotives and in consequence the damage resulting from a motor flashover, or ground, will be greatly decreased.

Fig. 7. Magnetically Operated Contactors. These contactors short circuit the accelerating resistors. They are assembled in groups as shown in another cut. Similar contactors, except that they are closed and opened by cams operated pneumatically, are used in the groups for transposing motor circuits

When a short circuit or other overload occurs and the circuit breaker opens, it introduces a resistance in the circuit which limits the current to a normal amount. A small switch, which is directly operated by the breaker, simultaneously opens the control

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* "New Type of High-speed Circuit Breaker," p. 286.

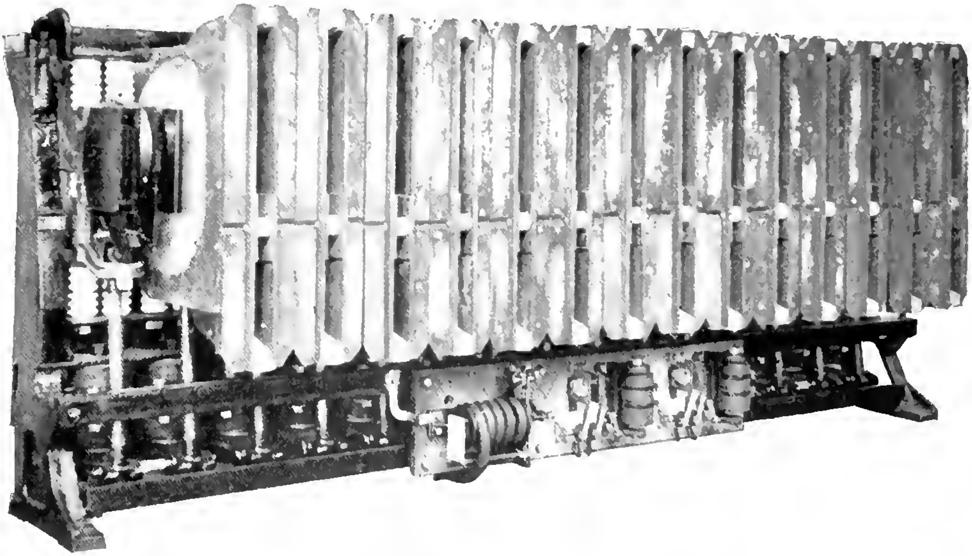

Fig. 8. Magnetically Operated Contactor Group. These contactors are mounted in conveniently handled groups on steel supports An overload relay and two other control relays are shown installed below the contactors

circuit of those contactors which cut out the accelerating resistors and the latter are introduced in the circuit to reduce the current still further. The main circuit is then broken by the line contactors. This sequence of operation permits of opening the overloaded circuit with a minimum disturbance.

The circuit breaker is adjusted to carry the total current for all four motor circuits in multiple. In order still further to limit the current in the individual motor circuits an overload relay, which opens the holding coil circuit of the quick acting circuit breaker, is placed in series with each combination of motors. On the geared locomotives the main circuit is protected by a magnetic blowout copper ribbon fuse and the individual motor circuits are provided with overload relays which open the contactor circuit in case of overload.

The circuit breaker is automatically reclosed by a solenoid when the master controller is turned to the first point. A lever is also provided for closing the circuit breaker manually. Opening the main control switch permits the circuit breaker, as well as other apparatus operated magnetically, to open.

Contactors

The line contactors are mounted on the same frame as the main circuit disconnecting switch and, aside from the magnetic blowout

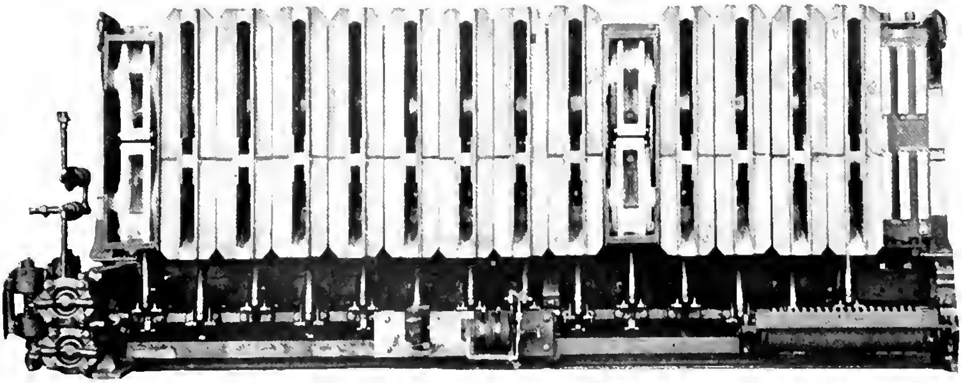

Fig. 9. Cam Operated Contactor Group. The various motor combinations for motoring and regenerating are effected by these pneumatically operated contactor groups. The above illustrates one which has three positions; one for 6 motors in series, one for 4 motors in series, and the third for regeneration

and arc chutes, are similar to the contactors for cutting out the accelerating resistors. Both forms of contactor are directly operated by means of electro-magnets from the low-voltage circuit.

The series-parallel and regenerating contactors are composed of main circuit parts which are the same as in the resistor contactors but they are operated by a set of cams moved by air cylinders. The air cylinders are controlled by electrically operated valves.

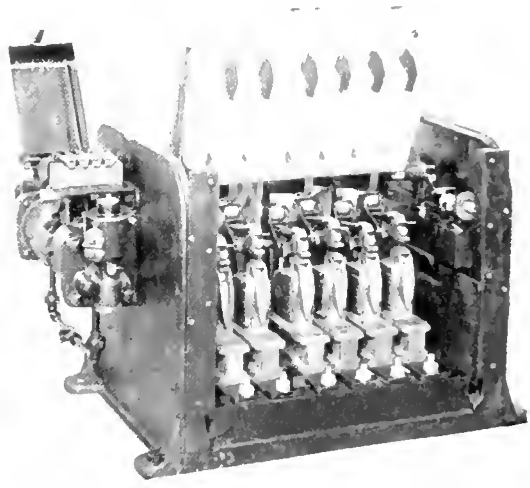

Fig. 10. Field Tapper. A section of each motor field winding is cut out of the circuit by two of these pneumatically operated field tappers and additional speeds for motoring are thereby obtained.

This arrangement of contactors was used with great success on the previous locomotives. It permits of the simultaneous operation of a considerable number of contactors with a minimum of magnets, valves, or air cylinders. Also in making transitions from one grouping of motors to another, a perfect sequence of contactor opening and closing is assured.

Auxiliary Apparatus

The following are the principal pieces of auxiliary apparatus:

- 6 blowers.
- 1 main air compressor.
- 1 auxiliary air compressor.
- 1 motor-generator set for charging the storage battery.
- 1 storage battery.
- 1 lightning arrester.

Blowers

The locomotive is provided with six double blowers for cooling the main motors, each half being capable of delivering approximately 3500 cu. ft. of air at 2-in. pressure. Each blower is driven by a 12-h.p. series motor. The circuits are so connected by four magnetic contactors that the motors may be operated six in series or in two groups of three each in series on 3000 volts. The motors are connected directly across the line voltage when starting without any resistance in the circuit.

Air Compressors

The main air compressor has a capacity of 150 cu. ft. of free air per minute and it is driven by a 3000-volt motor requiring a current of 10.5 amperes when the compressor is operating at a pressure of 135 lb. per sq. in. It is started by connecting it across the line by a magnetically operated contactor with a starting panel in series. The panel consists of a resistor and a series contactor which automatically closes and short circuits the resistance when the current through the compressor motor has dropped to a predetermined value. The coil of the contactor is energized by a standard air compressor governor when the air pressure drops to 123 lb. or below, and is de-energized when the pressure reaches 135 lb.

The auxiliary compressor which provides a supply of compressed air, in an emergency, for the pantograph trolley and other pneumatically operated control apparatus, has a capacity of approximately 10 cu. ft. of free air per minute. It is operated from the storage battery and requires about 25 amperes when compressing at 70 lb. per sq. in.

Motor-generator

The motor-generator consists of a compensated shunt motor of approximately 40 h.p. at 3000 volts and a shunt generator rated at 25 kw. 80 volts. This set provides a low-voltage source from which the various pieces of control apparatus may be operated, and for charging the lighting storage batteries located on the various cars of the train and the auxiliary storage battery on the locomotive. The generator voltage is held constant by means of a single vibrating regulator relay with its coil across the generator terminals and its contacts acting to short circuit the field of a very small generator, the armature of which is in series with the shunt field of the main generator. This small generator armature is mechanically connected to the shaft of the generator which it regulates.

The set is controlled by a magnetically operated contactor. When starting, the motor of the set is thrown directly across the line with two starting panels consisting of a resistor and series contactor connected between the low side of the armature and ground. As the shunt field is tapped from between the two commutators to ground it has practically double excitation when the set starts, and it is connected across the low commutator when the series resistance is short circuited. The two panels are so connected that when the current through the set is reduced to the value for which the series contactors are adjusted, one of them closes, short circuits one section of the resistance, and connects the series coil of the second contactor into the circuit. The second contactor closes when the current has again dropped to the proper value. With the control arranged in this way the set automatically starts up when power has been returned after an interruption.

Storage Battery

The storage battery is composed of 36 cells rated at 95 ampere-hours, based on a 4½ hr. discharge rate. It is automatically connected to and disconnected from the generator terminals by a reverse current relay. It is used for operating the auxiliary air compressor and other pieces of apparatus requiring low-voltage current when the pantograph trolley is not raised.

Lightning Arrester

The arrester comprises twelve standard direct current cells of the liquid type connected in series. Each cell is composed of a glass jar containing aluminum plates which are submerged in a liquid electrolyte. Balancing resistances of a high ohmic value are used to equalize the potentials across the cells.

The Long Lake Station of the Washington Water Power Company located on the Spokane River, Washington. This system is interconnected with that of the Puget Sound Traction, Light & Power Company and furnishes energy to the Cascade Division of the C., M. & St. P. Rwy.

New Type of High-speed Circuit Breaker

By J. F. Tritle

Railway Equipment Engineering Department, General Electric Company

The higher the voltage for which a direct-current generator is designed the greater is the likelihood that the machine will flash over and become damaged on short circuit. The problem of protection did not reach an acute stage, however, until the advent of our latest high-voltage direct-current railway electrifications. The generators for such systems require a degree of protection far greater than it is possible to secure by good commutating characteristics alone and consequently an auxiliary device was developed for the purpose. This first took the form of a special circuit breaker employing the fundamental principle of a standard breaker but capable of operating at 15 times higher speed by reason of powerful springs held in leash by a train of latches. The article below describes a new type of high-speed circuit breaker that operates on an entirely different principle nad is far superior to the older type.—Editor.


J. F. Tritle

THE problem of protecting direct-current generators, particularly high-voltage generators, from flashover, has received a great deal of attention in recent years. Various improvements have been made in the commutating characteristics of the machines, but as yet no commercial machine has been built which is immune from flashover under the most severe short-circuit conditions unless it is protected by some external device, such as a high-speed circuit breaker.

Standard circuit breakers operate much too slowly to prevent flashover on heavy short circuits. Repeated tests have indicated that to prevent flashover a circuit breaker should operate, stop the current rise, and reduce it below the flashing value in something less than the time required for a commutator bar to pass from one brush-holder to the next. On a 60-cycle machine, this means a speed of approximately *eight one-thousandths* of a second. As the standard circuit breaker operates in about eight to fifteen one hundredths of a second, it has less than one tenth the required speed.

A high-speed breaker using a refinement of the principles of a standard breaker was developed to protect the 3000-volt generators that supply power to the Rocky Mountain division of the Chicago, Milwaukee and St. Paul Railway.* One was installed as part of the equipment in each of the 14 substations. These breakers have the required speed of operation and have demonstrated quite conclusively that direct-current machines can be made practically immune from flashovers and damage from excessive overloads and short circuits. These breakers, however, are rather large and expensive; and the tripping mechanism, which holds the breaker closed against very powerful operating springs, and which consists of a train of latches and levers actuated by a solenoid, requires great accuracy in manufacture and adjustment.

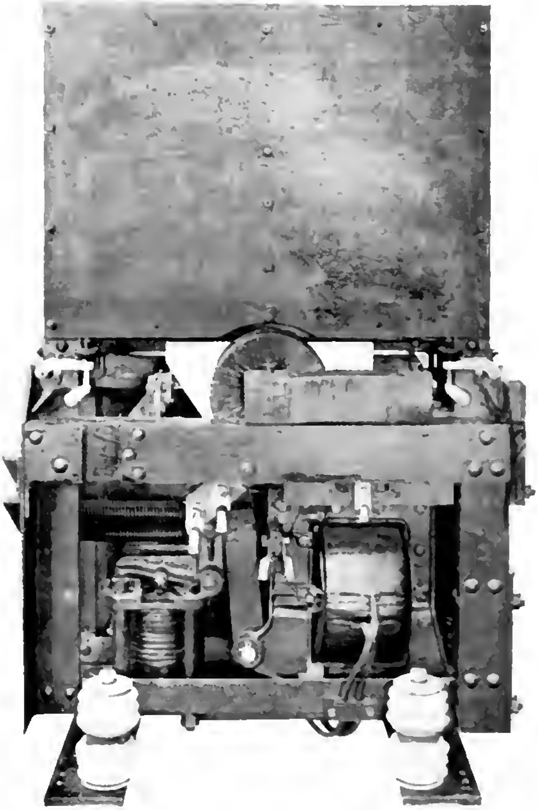
Fig. 1. 1500-ampere 3000-volt Direct-Current High-speed Circuit Breaker with Covers Removed

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* "High-speed Circuit Breakers for Chicago, Milwaukee & St. Paul Electrification," by C. H. Hill, G. E. Review, Sept., 1918.

A new type of high-speed circuit breaker has recently been developed which operates on entirely different principles from the original, particularly in regard to the method of tripping and the arrangement of the magnetic blowout. All mechanical latches and triggers have been entirely eliminated. The breaker is tripped electro-magnetically instead of electro-mechanically. The spring power necessary to operate the device has been greatly reduced. The magnetic blowout has been improved and has a combination of two powerful magnetic fields and a narrow arc chute, which increases the speed of blowout and reduces the arcing space required. The breaker is, therefore, very simple and rugged in construction and is much reduced in size, weight and cost.

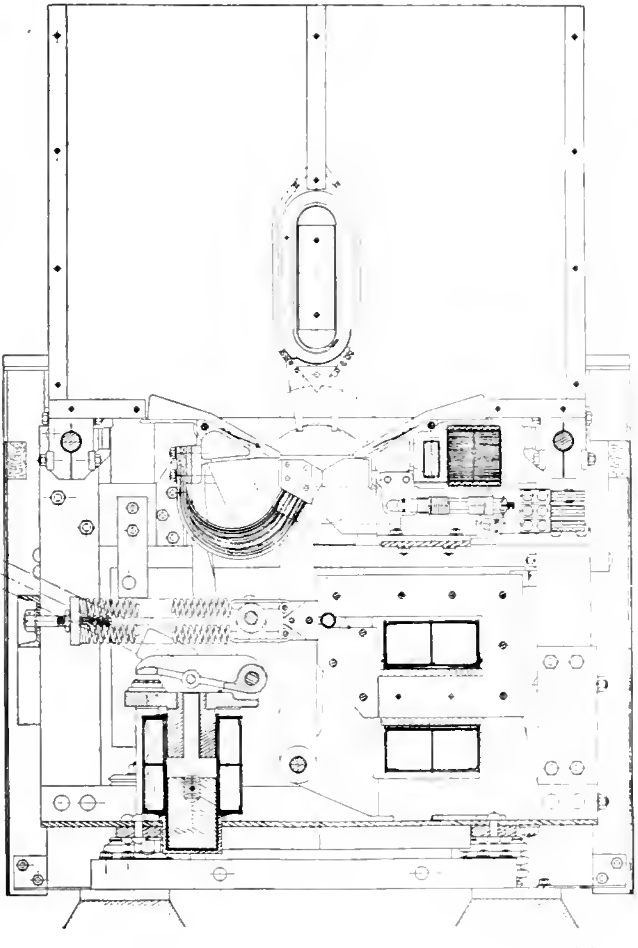

Fig. 2. Cross Sectional View of 1500-ampere 3000-volt High-speed Circuit Breaker

One of these new type breakers is installed in series with each of the eight 3000-volt 2000-kw. motor-generator sets in the substations supplying power for the electrification of the Coast and Cascade Division of the Chicago, Milwaukee and St. Paul Railway.

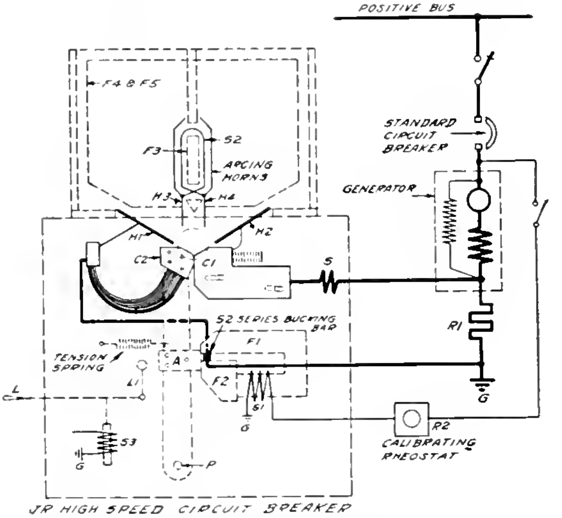

Fig. 3. Schematic Diagram of the High-speed Circuit Breaker and the Connections for Installing It in the Negative Side of a Generator

A similar breaker is also installed on each of the five new bi-polar gearless type passenger locomotives.

Fig. 1 shows a side view of this new type of breaker with the covers removed, and Fig. 2 shows a cross-sectional view. Fig. 3 shows its principle features, together with the connections for installing it in the negative side of a generator.

In this latter illustration, *F1* and *F2* represent a laminated field structure something like that of an ordinary alternating-current magnet. The poles of *F1* and *F2* are bridged by a very light armature *A* pivoted at *P* and held in contact with the poles by a shunt coil *S1* energized from any convenient constant voltage source, such as the exciter circuit or the main bus. A series bucking bar *S2*, which electro-magnetically trips the breaker, is located between the poles of the field magnet and in close proximity to the armature. Thus the current flowing in the bar produces the maximum change in the armature flux, with the minimum change in the flux interlinking the shunt winding *S1*. The bucking bar simply shifts the flux from the armature to the air path at the right of the bucking bar, thus causing the armature to release as soon as its flux is reduced a predetermined amount.

The tension spring attached to the armature gives the high-speed opening of the contacts and also provides a means of adjusting the breaker. On account of the relatively light armature and the fact that it is not necessary to trip any latches to release the breaker, a pull of less than 800 lb. is required of this spring for the 2500-ampere capacity breaker, which is far less than that required in the original type.

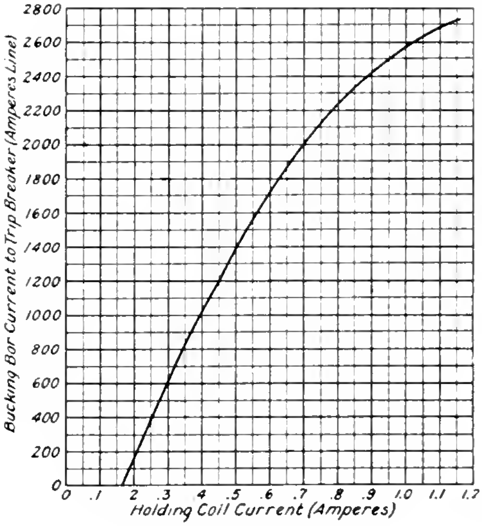

Fig. 4. Calibration Curve for 1500-ampere 3000-volt High-speed Circuit Breaker

The main contacts *C1* and *C2* are of the solid copper type used so successfully on railway contactors. Contact *C1* is materially heavier than *C2* and, when the armature is released, *C1* follows *C2* for a predetermined distance, but at a much lower rate of speed, so that *C1* and *C2* begin to part practically simultaneously with the beginning of movement of the armature.

The blowout coil *S* is in series with the main circuit and is designed to give a very intense field but of comparatively small area around the main contacts *C1* and *C2*. An additional blowout coil, *S2*, is provided in the auxiliary arc chute and is automatically cut into the circuit during the time the arc is being ruptured. When the tips *C1* and *C2* begin to part, the series coil *S* blows the arc upward off the tips onto the arcing horns *H1* and *H2*. As the arc moves further upward, it comes in contact with the ends of the arcing horns *H3* and *H4*, between which is connected the blowout coil *S2*. This inserts the coil in the circuit and divides the arc into two parts, one of which is blown upward through the left-hand side of the chute between the arcing horns *H1* and *H3* and the other through the right-hand side of the chute between the arcing horns *H2* and *H4*. The coil *S2* surrounds the iron core *F3* to which is connected the field pieces *F4* and *F5* which cover practically the entire area of the auxiliary chute. The auxiliary arc chute is hinged at both ends so that it can be easily swung out of place for ready inspection of the main contact tips. The sides of the arc chute are also arranged in a novel way to provide an arc chute materially narrower than the contact tips, thus increasing the resistance of the arc stream for a given length and giving the maximum cooling effect to the vapors.

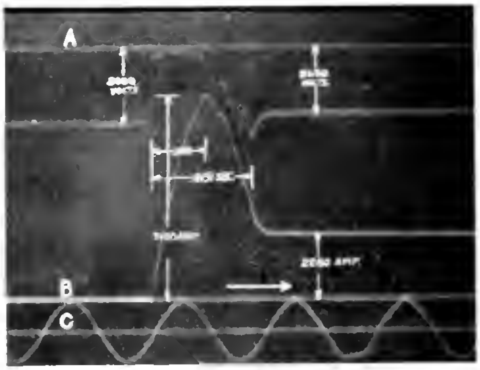

Fig. 5. Short Circuit on 2000-kw. 3000-volt Motor-Generator Set Protected by High-speed Circuit Breaker and Flash Barriers. Line Resistance, 0.0 ohms; Limiting Resistance 1.2 Ohms. Tripping Point, 2250 Amperes. *A*, line voltage; *B*, line current· *C*, 59.5 cycle Timing Wave

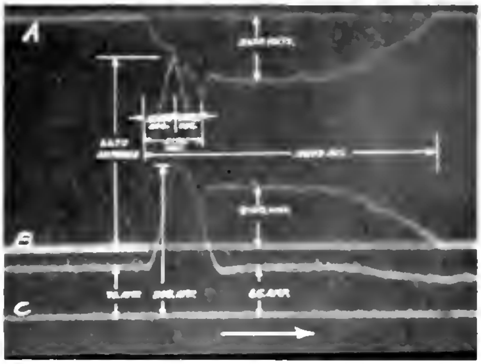

Fig 6. Short Circuit on 2000-kw. 3000-volt Motor-generator Set Protected by High-speed Circuit Breaker and Flash Barriers. Line resistance, 0.0 ohms, limiting resistance, 1.2 ohms. Tripping point, 2550 amperes. *A*, voltage across contacts and generator series fields. *B*, Line current; *C*, Current in generator shunt field

Means are provided for closing the contacts either manually by means of the handle *L* or remotely from the station switchboard through the solenoid *S3*, the plunger of which engages with the lever *L1*.

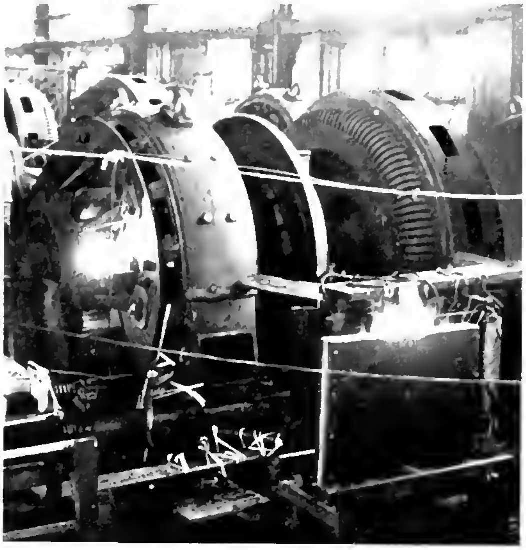

Fig. 7. High-speed Circuit Breaker and 2000-kw. 3000-Volt Motor-generator Set Under Short Circuit. Record in Fig. 6

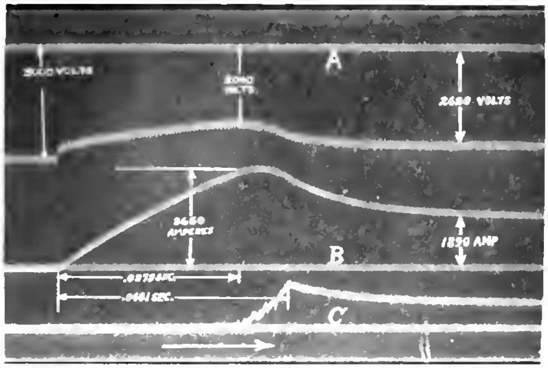

Fig. 8. Short Circuit on 2000-kw. 3000-volt Motor-generator Set Protected by a High-Speed Circuit Breaker, a Resistor, a Reactor and Flash Barriers. Line resistance, 0.175 ohms; line reactance, 21.6 milli-henrys. Limiting resistance, 1.2 ohms. Tripping point 2470 amperes. *A*, line voltage; *B*, line current; *C*, voltage across breaker

Fig. 4 shows a typical calibration curve for the high-speed breaker shown in Fig. 1. From this curve it will be noted that it requires a current of 0.17 amperes to hold the armature closed with zero current in the bucking bar. If it is desired to have the breaker trip at 2000 amperes load, it is merely necessary to adjust the holding current of *S1* to 0.7 amperes by means of the calibrating rheostat *R2*. The main current may rise to the trip value slowly as in the case of overload, or rapidly as in the case of short circuit. In either case the armature of the breaker starts to move the instant its flux is reduced to normal drop-out value by the bucking bar current. On short circuit, the current will rise to several times the normal tripping point and the flux in the armature will be reduced to a very small value or even reversed. This condition, however, gives the maximum speed of operation, as the armature starts to move the instant the flux is reduced to normal drop-out value, and by the time the flux reaches zero, the armature is moving at a fairly high rate of speed. On account of the high speed and steep pull characteristics of the armature, it is not possible for the bucking bar current to rise rapidly enough to build up sufficient reversed flux in the armature to hold it closed.

The connection shown in Fig. 3, with the circuit breaker installed on the negative side of the generator and operating to introduce a limiting resistance *R1*, gives the maximum protection against flashovers. With this connection any possible flashover current from the positive stud to frame has to pass through the limiting resistance to return to the armature. Tests have demonstrated that the breaker will successfully open the circuit completely instead of only inserting the

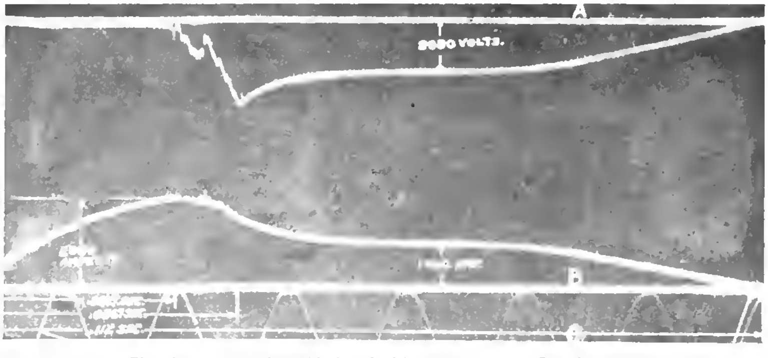

Fig. 9. Short Circuit on 2000-kw. 3000-volt Motor-generator Set, Protected by a High-speed Circuit Breaker, a Resistor, a Reactor and Flash Barriers. Line resistance, 0.455 ohms; line inductance, 11.1 milli-henrys. Limiting resistance, 1.2 ohms. Tripping point, 2580 amps. *A*, voltage across contacts and generator series fields: *B*, line current; *C*, 59.5 cycle timing wave. Current rupture completed by air circuit breaker

limiting resistance; but it has been found in practice that better protection is afforded the machine if the current is ruptured in two steps.

Figs. 5 and 6 show oscillographic records of dead short circuits on one of the 3000-volt 2000-kw. direct-current motor-generator sets built for the Chicago, Milwaukee and St. Paul electrification; and Fig. 7 shows the performance of the machine and the breaker during one of the tests. For these tests the positive terminal of the generator was connected to ground through a circuit closing contactor and a high-speed circuit breaker by means of a 1,000,000 cir. mil cable so that the total resistance in the circuit including the resistance of the generator was approximately 0.095 ohms. Fig. 5 shows that the current rose to approximately 7100 amperes, that it reached its maximum value and started down in 0.008 seconds and was down to normal in 0.015 seconds.

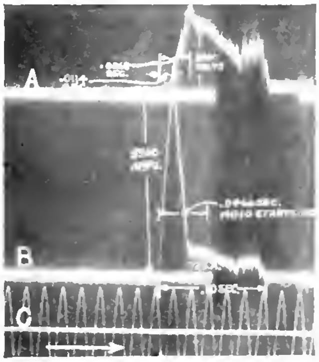

Fig. 10. Short Circuit on C. M. & St. P. Locomotive No. 10250, When Protected by high-speed Circuit Breaker on Locomotive Only. *A*, Voltage across high-speed circuit breaker and line contactors; *B*, Line current; *C*, 60-cycle timing wave

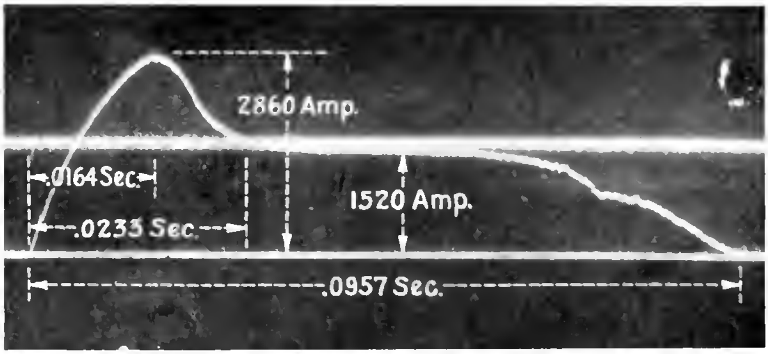

Fig. 11. Short Circuit 9600 Feet from Substation on 1500-kw. 3000-volt Motor-generator Set Protected by High-speed Circuit Breaker and Flash Barriers. Single track road, 100 pound rails, two 4 0 trolleys

Figs. 8 and 9 show oscillograph records of 3000-volt short circuits through various amounts of resistance and reactance. While the speed of the breaker on these tests was necessarily lower than in the tests without reactance in circuit, on account of the lower rates of current rise, the flashing at the commutators was practically negligible, as the current peaks were much lower.

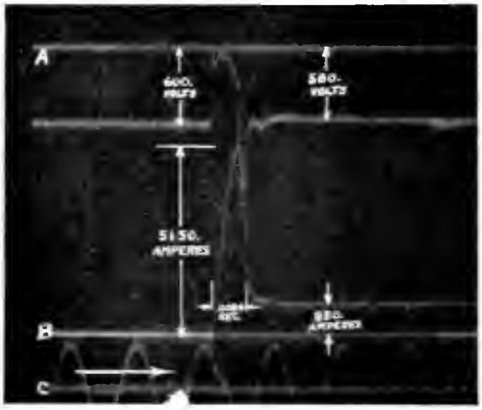

Fig. 12. Short Circuit on 600-volt, 300-kw. 60 cycle Synchronous Converter Protected by High-speed Circuit Breaker and Flash Barriers. Line resistance, 0.0033 ohms. Limiting resistance, 0.666 ohms. Tripping point, 1500 amps. *A*, Line voltage; *B*, Line current; *C*, 60 cycle timing wave

Very extensive tests under every conceivable operating condition were made on the breaker in connection with the Chicago, Milwaukee and St. Paul motor-generator sets. The acceptance tests alone required approximately 65 successive short circuits of various degrees of magnitude. Five dead short circuits were thrown on the set inside of 10 consecutive minutes at the conclusion of the acceptance tests without any flashovers. No attention was given the brushes or commutator during any of these tests.

Fig. 10 shows a dead short circuit on locomotive No. 10,250 standing at the Erie substation. In this case the high-speed breaker in the station was not in use and the short circuit was easily cleared by the breaker and the line contactors on the locomotive.

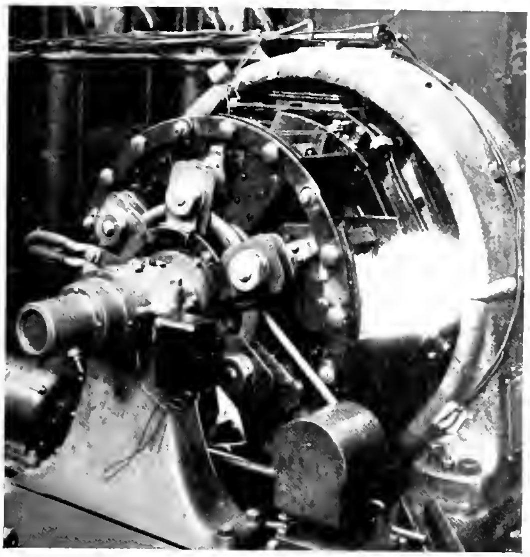

Fig. 13. 600-volt, 300-kw. 50-cycle Synchronous Converter Under Short Circuit. Record in Fig. 12

Fig. 11 shows a dead short circuit 9600 feet from the substation.

Fig. 12 shows a typical oscillograph record of a short circuit on a 600-volt 300-kw. 60-cycle rotary converter; and Fig. 13 shows the performance of the machine when protected with barriers and the high-speed circuit breaker. Heavy short circuits on 60-cycle machines usually cause a slight amount of arcing at the brushes, but not enough to cause the machine to flashover. It should be noted that the short circuit causes only a momentary drop in the machine voltage, and that the voltage is very stable after the high-speed breaker removes the short circuit and reduces the current to normal.

Fig. 14 shows the plot of an oscillograph record of a dead short circuit on a 3000-volt 2000-kw. machine protected by the high-speed circuit breaker and the regular 3000-volt magnetic blowout circuit breaker, and also shows the theoretical curve for a similar short circuit, with only the regular circuit breaker in service. The areas enclosed by the two curves indicate 184 ampere-seconds with the high-speed circuit breaker in service and 615 ampere-seconds without, which values in a measure show the relative punishment of the generator under the two conditions.

The simplicity, ruggedness and reliability of this new type of breaker opens for it a wide field of application in the protection of direct-current apparatus. The magnetic blowout and arc chute are particularly effective and insure the successful rupture of practically any direct current and voltage which it is possible to obtain from modern commercial generators. In combination with the flash barriers, this breaker insures practical immunity from flashovers under the most severe short circuit conditions. There are no latches, triggers, etc., to get out of adjustment; and, as the tripping mechanism is simply a straight copper conductor carrying the main current, the breaker may be expected to duplicate its performance many times in succession. It may also be used for the protection of feeders and other circuits, as well as main generators.

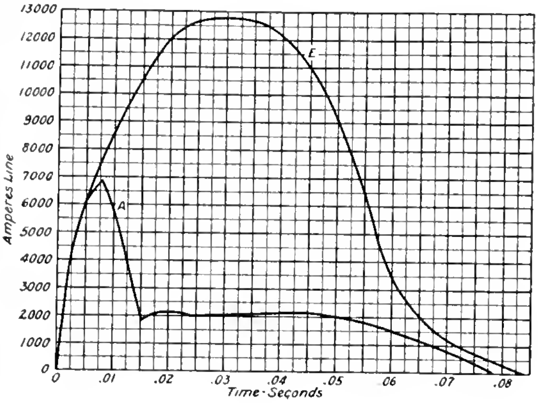

Fig. 14. Short Circuits on 2000-kw. 3000-volt Motor-generator Set. *A*, Line current with high-speed circuit breaker in operation. Plotted from Fig. 6. *B*, Theoretical line current with regular 3000-volt magnetic blowout circuit breaker in operation

One particular advantage of the protection afforded by this type of breaker is that it can be applied to old or new direct-current generators, or synchronous converters of any type or voltage, with no change whatever in the machine itself.

Power-limiting and Indicating System of the C., M. & St. P. Rwy.

By J. J. Linebaugh

Railway and Traction Engineering Department, General Electric Company

The power limiting and indicating system employed on the C. M. & St. P. Rwy. is one of the unique features of this electrification. As its name implies, it is designed for two purposes: the first to limit the peak load demands made upon the Power Supply Company, the second to facilitate the determination of the amount of power used. The first function results in a high operating load-factor, with mutual benefit to the Power Supply Company and the Railway Company; and the second produces on a single meter a reading which is the total resultant of the power supplied to the railway system at five widely spaced feeding points minus the power returned by regeneration of the railway locomotives. In addition to the metering system canceling out the interchange of power within the railway distributing lines, it furnishes the train dispatcher with a continuous indication of the amount of power his operations are drawing from the Power Supply Company. In the initial stages of the development of this system very careful investigations were made of the possibilities of various other schemes. However, eloquent testimonal as to the excellence of the scheme selected is furnished by the record of its three years of successful operation.—Editor.

J. J. Linebaugh

The Power Limiting and Indicating System constitutes one of the many new and novel features developed and installed as part of the original equipment furnished by the General Electric Company to the Chicago, Milwaukee and St. Paul Railway for the electrification of its Rocky Mountain and Missoula Divisions. This system has overcome so many difficult problems and performs so satisfactorily it is believed a detailed description will be of interest.

Several different schemes were proposed and investigated, such as increasing the frequency of the circuit proportional to the power input, adding electrical impulses of different kinds, etc., but the system which was finally adopted and which will be described was found to be the simplest, to require the least number of pilot wires, and to necessitate very little apparatus in either the substations or the dispatcher's office.

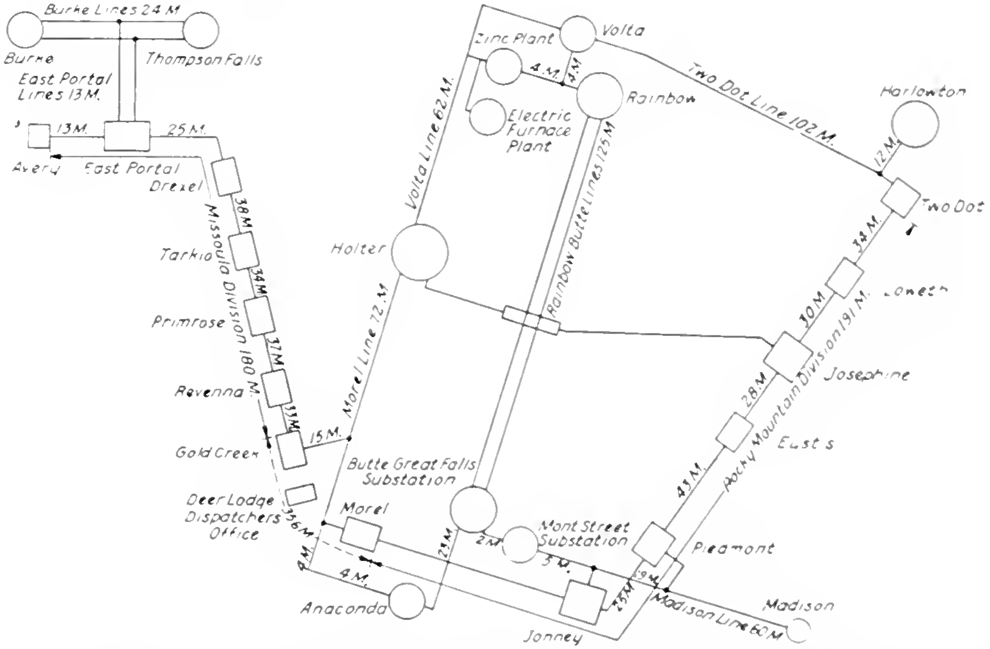

Fig. 1. General Connections of the 100,000 volt System of the Montana Power Company and Transmission Line of the Chicago, Milwaukee & St. Paul Railway, Including Location of the 3,000-volt d-c. Railway Substations

The general requirements specified by the railway were based on its desire to obtain an equipment which, with heavy trains comparatively few in number, would give the highest load-factor consistent with good railroading; and on the part of the Montana Power Company to prevent excessive peaks which might cause serious voltage variations and require the installation of excess generating apparatus to take care of the railway load. The power company was also very desirous of obtaining means by which the total power supplied to the railroad transmission line at a number of different points, over a distance of 220 miles, could be accurately recorded at one place and on one meter; to replace the former practice of having laboriously to add up records of as many as five curve-drawing meters, which are somewhat difficult to synchronize as to time, in order to obtain proper peak load data upon which to base the price of power. It is, therefore, very evident that the accomplishment of these results is of great mutual advantage and benefit to the railway company and the power company.

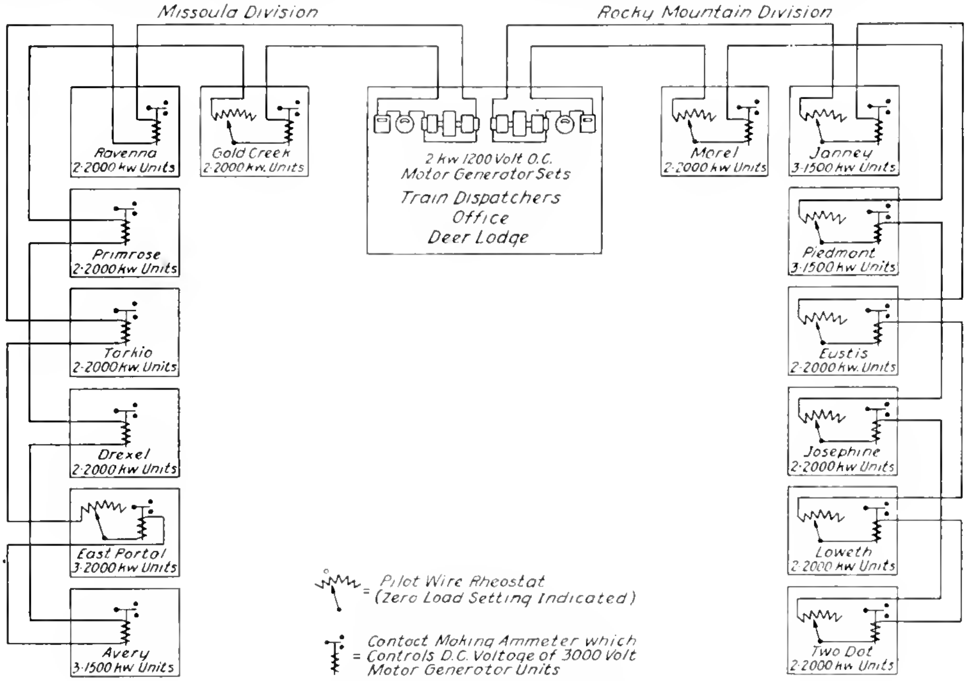

Fig. 2. Diagram Showing General Connections of the Pilot Wire Circuit and Location of the Contact-making Wattmeters for the Rocky Mountain & Missoula Divisions

The 220-mile Rocky Mountain Division was selected for the first installation as being the most difficult section due to the five feeding points and the heavy grades with regenerative braking. The apparatus described was designed, built, installed, and tried out in service on this section before going ahead with similar equipment for the 220-mile Missoula Division which has only two feeding points.

The equipment for the Rocky Mountain Division as first installed was based on metering the power at the five feeding points (Two Dot, Josephine, Piedmont, Janney, and Morel Substations), but was later changed to meter the power at the low-tension side of the motor-generator set step-down transformers. This change was decided upon by the two companies concerned as it was found impossible to prevent the transfer of very large blocks of power from one of the power company's lines to the other lines through the railway company's transmission line at times of switching or line troubles with resultant losses not correctly chargeable to the railway company, added duty to the metering equipment due to the necessity of adding and then subtracting this power, excess meter capacity, etc. The Missoula Division with only two feeding points did not have these objections and power for this division is metered on the high-tension side.

The main features of the power company's transmission line, railway company's transmission line, feeding points, location of substations and train dispatcher's office is shown in Fig. 1. The dispatcher's office is located at Deer Lodge, Mont., the center of the 440-mile electrification, and all the indicating and recording apparatus for both divisions is installed at this point.

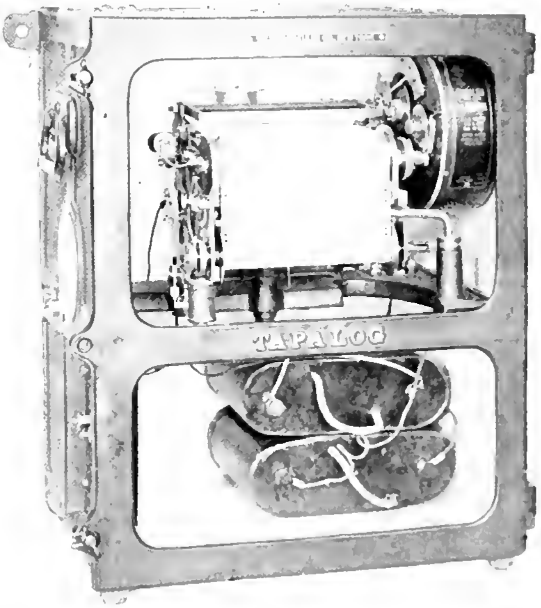

Fig. 3. Curve Drawing Kilowatt Totalizing Wattmeter. Dispatcher's Office

The complete system comprises the two separate and distinct functions of limiting the maximum power demand at the will of the train dispatcher and of indicating and recording the total net power at all times. The combination of these two functions accomplishes the following remarkable results:

(1) Independent of the number of feeding points, it indicates to the train dispatcher at all times the total net amount of energy being delivered to his division and it makes a permanent record for future study and as a basis for power bills.

(2) It automatically deducts regenerated power if returned to the power company's lines or transfer of power from one line to another over the railway company's transmission line.

(3) It automatically limits the amount of power supplied to the division by lowering the trolley voltage and slowing down the trains so that the peak load on the system cannot exceed a certain predetermined maximum.

(4) Its maximum limit can be changed instantly, easily, accurately, and directly by the dispatcher at any time without any necessity of notifying substation operators.

(5) It is capable of reducing the peak power demand by 30 per cent.

(6) If desired, the equipment can be adjusted so that the lightly loaded substations will not be affected, thereby providing the highest possible voltage for the operation of passenger trains.

(7) If desired, the equipment can be adjusted to reduce the voltage on the heaviest loaded substations at the time of peak demand (above the maximum limit) slightly in advance of the other stations, thereby tending to equalize the load on all the stations.

(8) If an excessive demand for power occurs near any one substation, the voltage of the nearest substation is automatically lowered without affecting the voltage of the other substations, dividing the load between this substation and the stations on either side.

Fig. 4. Indicating Kilowatt Totalizer. Dispatcher's Office

(9) The total power fed in at any point or transferred from one power line to another or the amount returned due to regeneration can be easily taken care of by a change in the ratio of the current transformers, or by an adjustment of the wattmeter rheostats.

Preliminary negotiations between the railway company, the power company, and the manufacturer were completed in November, 1915; the equipment was completed and installed for the first division in 1917, and has been in successful operation since that time. The equipment for the second or Missoula Division has been installed and is now in operation.

The system is essentially an ohm-meter on a large scale; consisting of a pilot wire circuit extending the length of the division, connecting in series all of the substations, and the train dispatcher's office with contact-making wattmeters and suitable rheostats at the incoming power points, and contact-making ammeters with voltage lowering generator rheostats in each substation.

As each of the divisions was about 220 miles in length, No. 8 B & S. copper wire was selected as being the smallest wire that for mechanical reasons should be used. To give the utmost reliability, a two-wire pilot circuit was installed in each instance. This pilot wire is placed on the trolley poles beneath the 3000-volt direct-current feeders, Fig. 18. It is very probable that one wire with a good ground return would be satisfactory, but as this was the first installation it was thought best not to take any risk of such an arrangement being unsatisfactory and therefore a complete non-grounded metallic circuit was installed. The insulators were selected after a very extensive investigation of the comparative merits of porcelain and glass, leakage constants, etc., a special attempt being made to obtain an insulator which would give a minimum surface leakage under all atmospheric conditions. A 6600-volt porcelain insulator was chosen. The leakage under the most severe conditions has been so slight that the accuracy and operation has not been affected. No. 4 B & S. wire is used at all crossings.

A constant source of direct-current potential is applied across the two ends of the pilot wire loop at the dispatcher's office, power being obtained from a 2-kw. 1200-volt direct-current motor-generator set, the voltage of which is held constant by a standard voltage regulator. The voltage applied to the pilot wire is determined by the length of the division, the resistance of the pilot wire, the number of substations, and the power feeding points. The equipment as finally worked out only requires a maximum of 1200 volts direct current for the 220-mile division, or 440 miles of pilot wire.

The indicating and limiting feature is obtained by inserting or removing a certain number of ohms or resistance for a definite change in the kilowatt demand which causes a definite decrease or increase in the current flowing in the circuit when a constant voltage is held across the pilot wire.

The contact-making wattmeter resistances and the pilot wire contact-making ammeters are connected in series with the pilot wire as shown in Fig. 2, which shows connections for both divisions. As the Rocky Mountain Division has the greatest number of feeding points, and maximum regeneration, the equipment of this division will be described in detail.

Due to the necessity of accounting for the regenerated power from the locomotives, or the transfer of power through the 100,000-volt 60-cycle three-phase transmission line of the railway company, it was necessary to provide a so-called Zero Center Meter, which made necessary having either the resistance for the total power or the regenerated and transferred power always in circuit at the no-load position. The total amount of power in both directions, for which it was necessary to provide resistance, is shown in Table I. It will be seen that it would have been necessary to provide resistance for a total power input of 70,000 kw. and 21,000 kw. for regeneration. In order to obtain greater accuracy it was therefore decided to insert resistance for increase of power and to have

TABLE I

MAXIMUM KILOWATT CAPACITY FOR INCOMING POWER AND REGENERATION AT EACH SUBSTATION

Substations	Maximum Incoming Power in Kw.	Maximum Regeneration in Kw.
Morel	10,000	1,000
Janney	10,000	6,000
Piedmont	10,000	6,000
Eustis	10,000	1,000
Josephine	10,000	3,000
Loweth	10,000	3,000
Two Dot	10,000	1,000

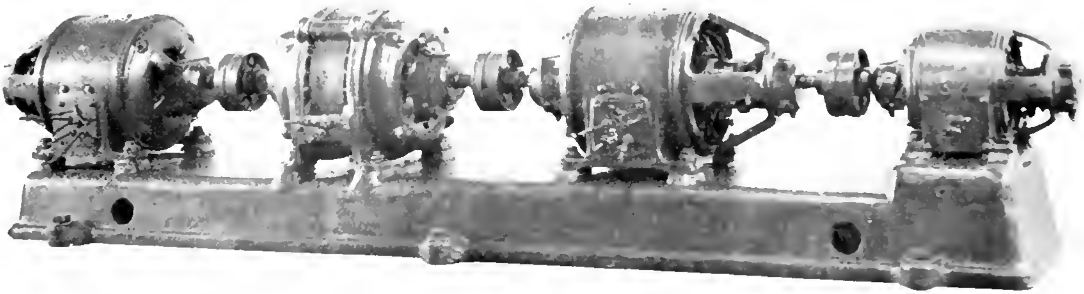

Fig. 5. 2-kw., 1200-volt Motor-generator Set. Dispatcher's Office

the contact-making ammeters arranged to make contact at minimum instead of at maximum current.

This arrangement makes it necessary to have only the resistance for regeneration in the line permanently, while the resistance for power input has to be available only at each wattmeter. This arrangement gives a much smaller total meter scale with greater accuracy at the loads usually obtained.

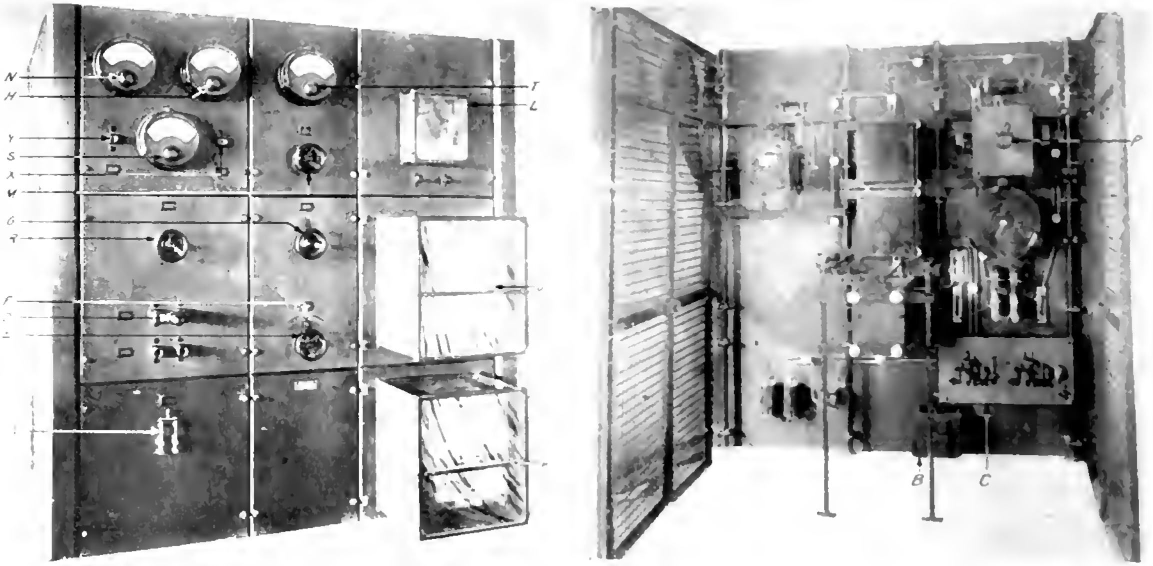

Fig. 6. Switchboard. Dispatcher's Office

A, induction motor switch; **B**, motor starting resistance; **C**, induction motor control panel for 2-kw. pilot wire set; **D**, plus switch for pilot wire connections; **E**, hand wheel of kilowatt limit adjusting rheostat; **F**, kilowatt limit scale marked from 10,000 to 25,000-kw. as noted in Fig. 4; **G**, hand wheel of rheostat for fine adjustment of regulator voltage; **H**, pilot wire indicating voltmeter; **K**, curve drawing voltmeter; **L**, pilot wire voltage regulator; **M**, rheostat for calibrating pilot wire for change in resistance (due to temperature); **N**, pilot wire ammeter; **P**, resistance used when testing out pilot wire for grounds; **R**, rheostat for hand adjustment of pilot wire voltage when regulator is not in use; **S**, milliammeter used to test for leakage; **T**, indicating kilowatt totalizer; **U**, curve drawing kilowatt totalizer; **X**, plug to short circuit ammeter when testing for possible grounds. **Y**, plug to connect the milliammeter between middle point of the two generators and ground.

The total length of the No. 8 B & S. pilot wire loop from the dispatcher's office at Deer Lodge to the farthest substation near Harlowton is approximately 434 miles, with a total resistance at 75 deg. F. of approximately 1450 ohms.

After careful consideration of all the different factors, the equipment was designed on the basis of 15 kw. for each ohm resistance and 125 kw. for each step on the wattmeter rheostats, giving a resistance per step of 8⅓ ohms. The kilowatt settings, pilot wire voltage, current in the pilot wire, and resistance are given in Table II, from which it is noted that there are 0.237 amp. flowing in the pilot wire at the peak kilowatt setting.

The contact making ammeters are designed to make contact at this current. The apparatus is designed to hold certain definite peak limits in 2000 kw. steps from 10,000 to 25,000 kw. as indicated.

The power-indicating apparatus, with exception of the contact-making wattmeters in each substation, is all installed in the dispatcher's office. The equipment in the dispatcher's office consists of a 2-kw. motor-generator set, a milli-ammeter calibrated in kilowatts, a curve-drawing ammeter also calibrated in kilowatts, a curve-drawing voltmeter to give a permanent record of the pilot wire voltage, and suitable indicating instruments and switchboard to control the motor-generator set.

On account of the very small amount of power available for the operation of the curve-drawing totalizing wattmeter, a special meter had to be developed and both the wattmeter and voltmeters are based on the well-known Tapalog principle. These meters were built by the Wilson Maeulen Company, New York, and one is shown in Fig. 3. The curve-drawing voltmeter and wattmeter are exactly alike with exception of the meter element.

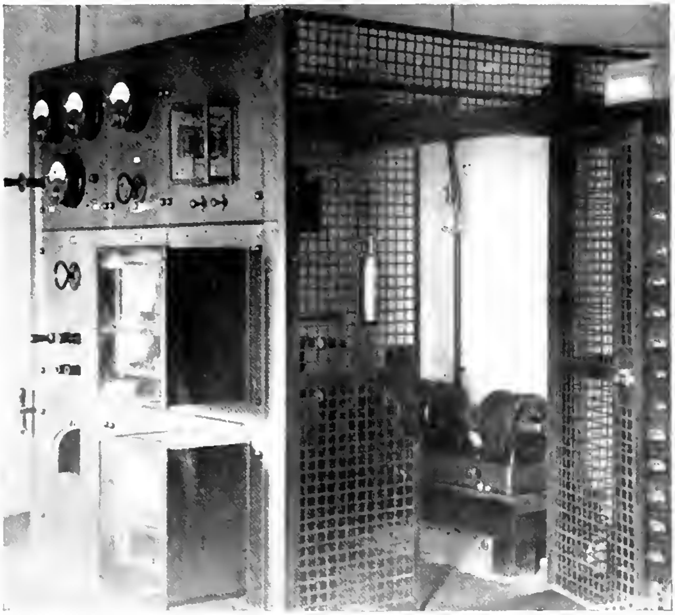

Fig. 7. Photograph of Complete Installation in the Dispatcher's Office, Deer Lodge, Mont.

The meter element is a standard Weston direct-current ammeter for the wattmeter, and a standard Weston voltmeter for the voltmeter. A tapping bar actuated by clockwork and dry batteries, in connection with an ink ribbon and paper roll, taps the meter needle at intervals of 5 seconds making a small dot on the paper at the point where the needle happens to be at that time. The totalizing wattmeter and the indicating wattmeter work between limits of 0.190 and 0.353 amp., calibrated for the correct kilowatts. The doors of the meter cases are equipped with switches so that voltage is removed when the door is open. These meters produce a very satisfactory record and have given very successful operation.

Due to the reasons explained, the indicating wattmeter reads a maximum at the lowest amperes and is therefore off scale above 25,000 kw. or when no current is flowing.

The motor-generator set consists of two 1-kw. 600-volt generators connected in series for a maximum of 1200 volts direct connected to a 3-h.p. 1800-r.p.m. 110-volt 60-cycle induction motor with 1/3-kw. 125-volt exciter, Fig. 5. Power is supplied by a 3-kw. 2300/110-volt transformer. Separate excitation at 125 volts is used with a standard regulator to obtain very close regulation. The automatic control of this regulator is somewhat special as the voltage variation covers a range from 964 to 1200 volts and must be changed at the same time as the connections of the wattmeters.

The front and back views of the switchboard with notations giving the function of most of the devices are shown in Fig. 6. The general connections are shown in Fig. 8. A view of the complete switchboard as installed in the dispatcher's office is shown in Fig. 7.

Due to the simplicity of the indicating wattmeters, two of these meters have been installed for each division, one on the switchboard and the other in front of the trick train dispatcher as shown in Fig. 9. With this arrangement the dispatcher can tell at a glance the exact amount of power being taken by his division at any instant and also can watch the power demand resulting from his orders to the train crews in charge of trains ascending or descending the mountain grades.

Variation in resistance of the pilot wire due to change in temperature is taken care of in the dispatcher's office by a rheostat which can be easily inserted and the total resistance adjusted to 2000 ohms, the approximate resistance of the pilot wire loop and the coils of the contact-making ammeters, by holding 1200-volts and adjusting the rheostat for 0.6 amp.

The adjustable wattmeter resistances in the substations are automatically short circuited during this operation by reversing the current through the pilot wire, which action short circuits the resistance by means of a polarized relay near the top of the contact-making wattmeter unit, Fig. 11.

The equipment for each substation at which power is supplied is exactly the same on the Missoula Division, only the wattmeters being omitted from the other substations; while the equipment for the seven substations on the Rocky Mountain Division is identical.

The contact-making wattmeter equipment consists of a contact-making wattmeter built along standard meter lines, Fig. 13, with an indicating pointer equipped with contacts moving between the two stationary contacts. The spiral spring of the pointer is connected to the shaft of the pilot wire rheostat located immediately above the wattmeter. This shaft is driven by the motor-driven clutch mechanisms at the top of the supporting framework, as shown in Fig. 11. When contact is made on one side,

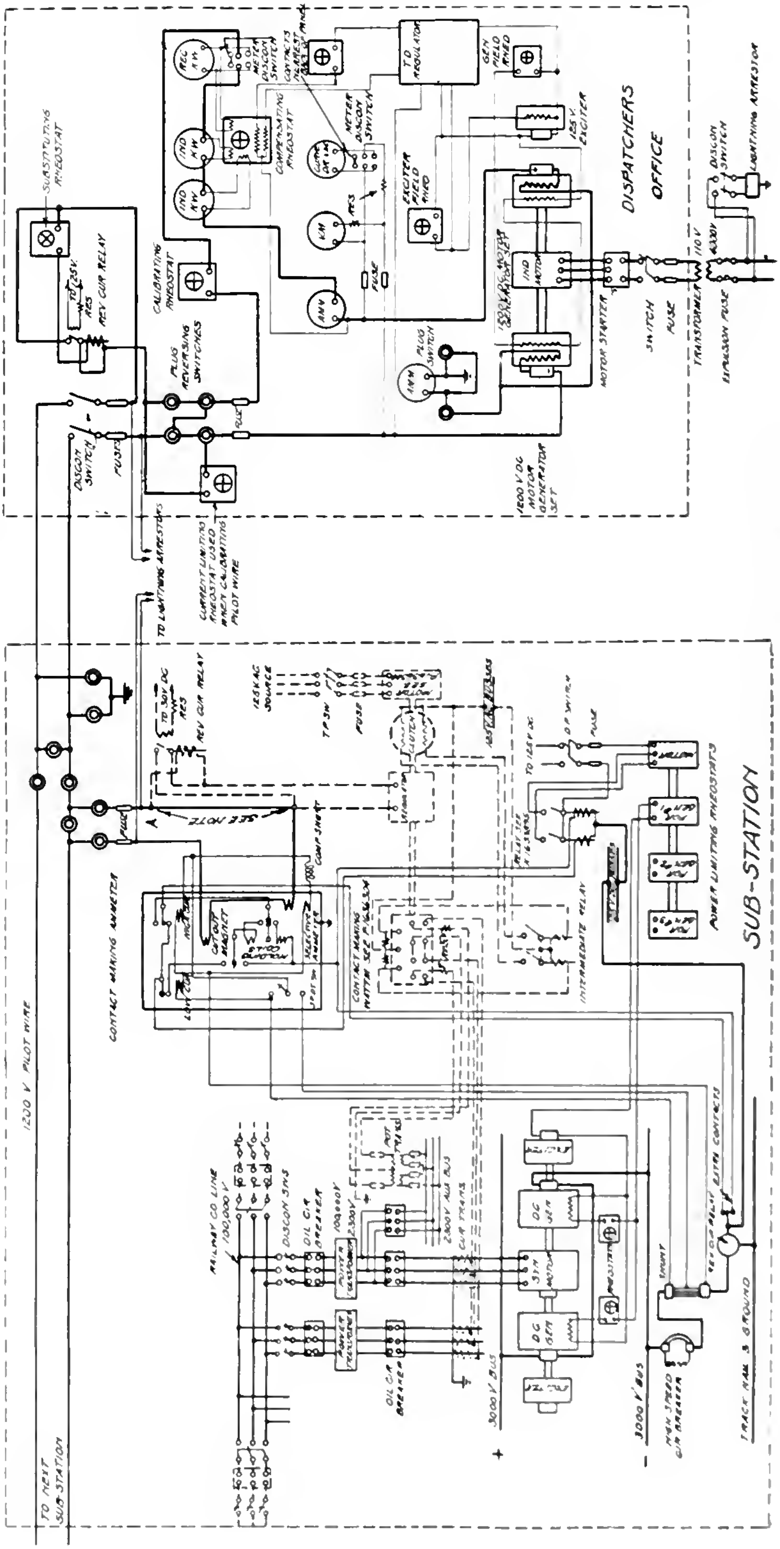

Fig. 8. General Wiring Connections, Dispatcher's Office, and Typical Substation

Fig. 9. Photograph Showing Indicating Kilowatt Totalizer in the Trick Dispatcher's Office

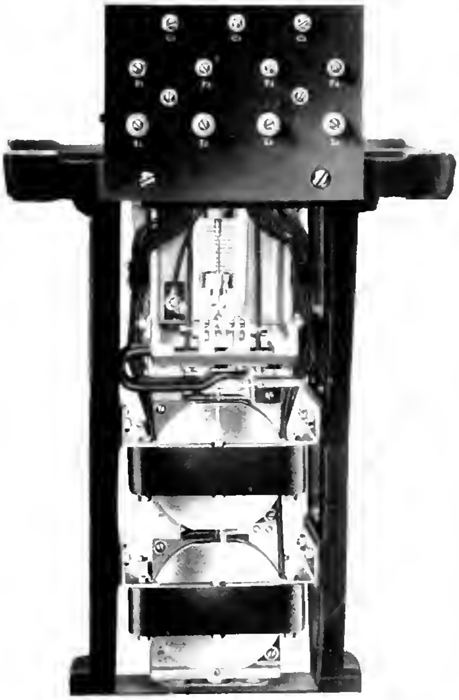

Fig. 10. Contact Making Wattmeter Forming Part of Complete Unit Shown in Fig. 11

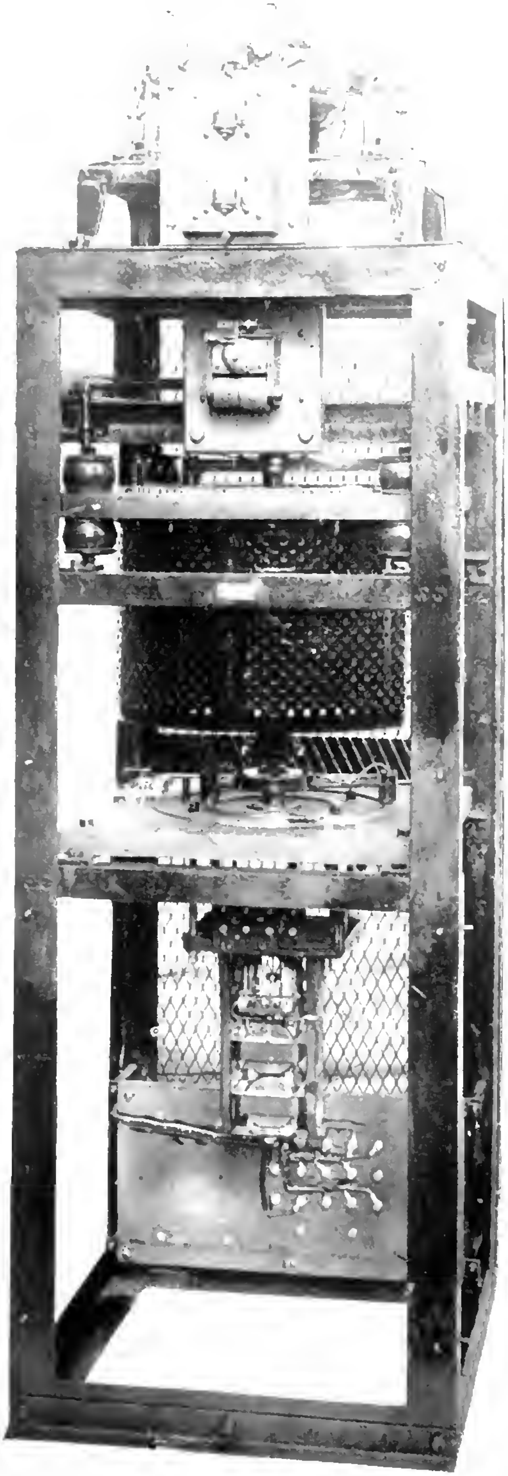

Fig. 11. Complete Motor Operated Clutch Driven Contact Making Wattmeter with Covers Removed

due to an increase in incoming power, the circuit is completed through the clutch coils causing the clutch to engage the rheostat gearing and insert a certain amount of resistance in the pilot wire. At the same time the wattmeter spring is wound up due to the movement of the shaft. This action continues until the torque of the wattmeter is offset by the torque of the spring when a balance is obtained and the clutch circuit interrupted thereby causing the rheostat to come to a standstill. This operation is continued for any increase or decrease in the incoming power.

Fig. 12. Complete Motor Operated Contact Making Wattmeter Unit and Motor Operated Generator Voltage Lowering Rheostats Located Above the Wattmeter in the Janney Substation

The rheostats forming part of this unit have the same number of buttons with $8\frac{1}{3}$ ohms between each button, a sufficient number of buttons being used to take care of the power requirements as specified in Table I

The complete motor operated clutch contact-making wattmeter resistance unit is shown in Fig. 11 with the protecting covers removed, while Fig. 12 shows one of the meters installed in the Janney Substation. The generator field rheostats which are used to lower the substation voltage are shown in this photograph located above the wattmeter unit.

The power-limiting scheme in connection with the indicating equipment consists of a contact-making ammeter, Fig. 14, for each substation with its coil connected in series with the pilot wire circuit so that when the current in the pilot wire decreases to a certain predetermined point, 0.237 amp., contact is made and resistance inserted in the exciter circuit supplying excitation to the separately excited direct-current generators by means of a motor operated rheostat, Fig. 12. These rheostats have sufficient resistance to lower the substation voltage to a minimum of 2100 volts. When contact is made by the contact-making ammeter, the voltage of the

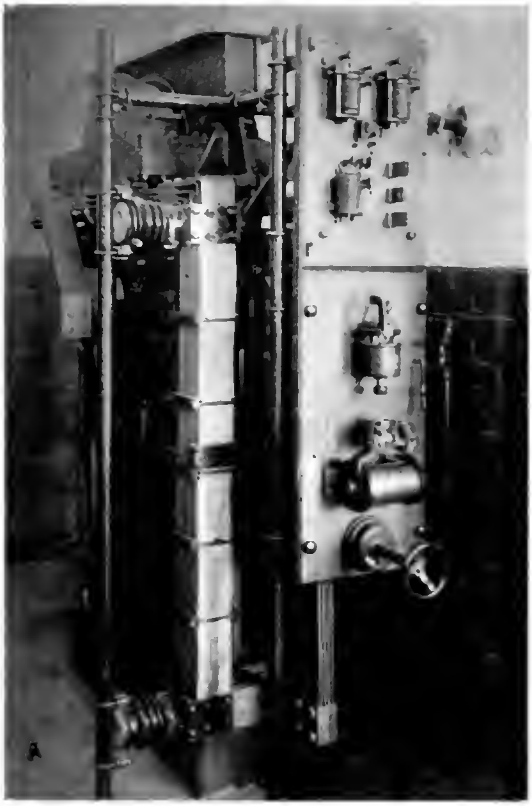

Fig 13. Main Negative Shunt Used with Relays Shown in Fig 14

substation is decreased and the resulting slowing down of the trains reduces the total input of the substation to a value below the predetermined peak setting. When the total load becomes less than the peak setting, the contact-making ammeter will make contact on the other side and bring the voltage of the substation back to normal. A secondary current coil forms part of the contact-making ammeter and is energized with current from a direct-current shunt, Fig. 13, in the ground or negative side of the 3000-volt substation, so that the heavily loaded substations have their voltage decreased slightly before those with lighter loads. If the total alternating-current input is beyond that covered by the power contract, or the limit determined by the train dispatcher, the voltage of all of the substations will be decreased until the total input reaches the amount decided upon.

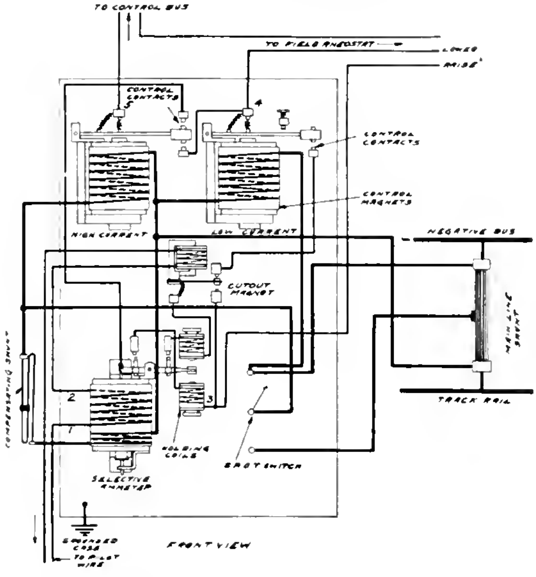

Fig. 14. Connections of Contact-making Ammeter Panel

An overload and an underload relay are also connected across the current shunt. The underload relay is calibrated to make contact at about one-half load on a substation so that the limiting equipment is inoperative until the load is greater than this amount. The overload relay is set to take control of the motor-operated rheostats at three times load and prevents the load going above this amount by lowering the voltage independently of the power-limiting equipment which transfers some of the load to the substations on either side.

If the power demand should be greater than the peak limit while a locomotive is regenerating through a substation, the reverse-current relay, at the bottom of the panel, Fig. 13, in each substation (primarily used to give correct field connections of the synchronous motor exciter) is also arranged to open one of the control circuits so that the voltage lowering rheostats are inoperative.

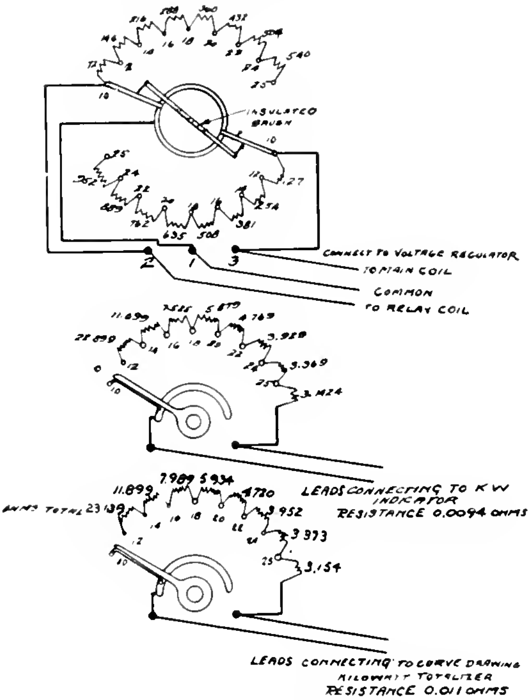

Fig. 15. Connections of Complete Kilowatt Limit Adjusting Rheostats

With this arrangement the potential is held constant at 3000 volts. If the voltage should be below normal, due to operation of the power-limiting equipment, and regeneration should occur, the voltage is automatically brought back to 3000 volts and held at this value.

The shunt for operating the underload and the overload relays, and the selective coil of the contact-making ammeter is also shown in Fig. 13.

The maximum kilowatt peak limit or kilowatt setting can be changed at any time by the train dispatcher to take care of unusual congestion or other requirements by simply varying the voltage across the pilot wire in the definite steps shown in Table I by means of the handwheel *F*, Fig. 6. The simplicity of this arrangement is due to the fact that the higher the voltage the greater the number of ohms which must be inserted to reduce the pilot wire current to 0.237 amp. This is clearly shown in Table II.

The different kilowatt settings are therefore obtained with certain definite voltages which must be held accurately by the voltage regulator. This is accomplished by the rheostat handwheel *F*, Fig. 6, and the connections, Fig. 15, which change the setting of the voltage regulator. If the voltage held should vary slightly, closer adjustment can be made with rheostat *G*. These main voltage points are marked in red on the scale of the indicating voltmeter to assist in obtaining correct setting.

Due to the necessity of reducing the pilot wire current to the same value, the kilowatt totalizing meters, which are ammeters calibrated in kilowatts, must record correctly the total kilowatts although finally carrying the same amperes, i.e., 0.237. This is accomplished by gearing the several rheostats together with a common rheostat handwheel *F*, Figs. 6 and 15. This handwheel which changes the voltage through the regulator by definite steps also changes at the same time, by definite increments, the resistance across the coils of the two kilowatt meters, thus altering the current required to give any definite scale indication in the ratio of the change made at the same time in the pilot wire voltage. By this means 0.237 amp., which is the point at which the contact-making ammeter makes contact, can be made to represent 10,000 kw., 12,000, up to 25,000 kw. by simply turning the rheostat handwheel to definite points plainly marked on the escutcheon, correctly connecting the three different circuits.

TABLE II

CURRENT IN PILOT WIRE CORRESPONDING TO VARIOUS POWER LIMITS

Kilowatt Peak Limit	Volts Across Pilot Wire	KILOWATT SCALE													
		0	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000	22000	24000	25000
		Milliamperes													
25000	1200	353.0	339.5	327.2	315.8	305.1	295.0	285.5	277.0	268.5	261.0	253.5	246.5	240.0	**237.0**
24000	1184	348.5	335.0	323.0	311.6	301.0	291.0	282.0	273.3	265.0	257.5	250.0	243.0	**237.0**	233.7
22000	1152.5	339.0	326.5	314.5	303.5	293.0	283.5	274.5	266.0	258.0	250.5	243.5	**237.0**	230.5	227.5
20000	1121	330.0	317.5	306.0	295.0	285.0	275.6	267.0	259.0	251.0	244.0	**237.0**	230.5	224.0	221.0
18000	1089.5	320.5	308.5	297.0	287.0	277.0	268.0	259.5	251.5	244.0	**237.0**	230.5	224.0	218.0	215.0
16000	1058.5	311.0	299.5	288.5	278.5	269.0	260.0	252.0	244.0	**237.0**	230.0	224.0	218.0	212.0	209.0
14000	1027	302.0	290.5	280.0	270.0	261.0	252.0	244.5	**237.0**	230.0	223.0	217.0	212.0	205.5	203.0
12000	995.5	293.0	281.5	271.0	262.0	253.0	244.7	**237.0**	230.0	223.0	216.0	210.5	205.5	199.0	196.5
10000	964	283.5	272.5	263.0	253.5	245.0	**237.0**	230.0	222.5	216.0	209.5	204.0	198.0	193.0	190.5
Resistance (ohms)		3400	3533	3667	3800	3933	4067	4200	4333	4467	4600	4733	4867	5000	5067

It was thought that it might be necessary actually to calibrate the kilowatt meters on the ground after being installed by means of the standard curve-drawing meters in the different circuits but this was found unnecessary as the check readings, taken with all the equipment installed exactly as laid out, indicated that these meters are as accurate if not more so than the standard meters. Table III gives a record of a large number of readings taken before the contact-making wattmeters were changed to the low side of the step-down transformers. These readings show remarkable accuracy as no special pains were taken to synchronize the clocks of the different curve-drawing meters which probably accounts for some of the greater variations. It should be kept in mind that this record was made when equipment was first placed in operation and that the four feeding points were located along the railway line over a distance of more than 200 miles, being the first time that power supplied by more than one line was added and recorded on one meter over such a great distance. It is therefore evident that the power supplied by any number of transmission lines over practically any reasonable distance can be accurately indicated and recorded in this manner.

The curve-drawing kilowatt totalizing meter reaches correct readings more quickly than the standard curve-drawing switchboard-type wattmeters in the substation and consequently gives a better detailed record of the load.

The lowering of the trolley voltage in the substation is accomplished slow enough, by proper speed of the motor-operated field rheostat, as not to affect the operation of the trains objectionably, the only result being a gradual slowing down of the train.

Additional power limiting is also obtained by instructing the freight engineers to drop back to the series connection of the locomotive motors if very low trolley voltage is indicated by the voltmeters in each locomotive cab.

Several different peak settings have been tried out from time to time during the last two years to ascertain the correct peak limit for different service conditions. Some of the lower settings slowed down the trains to such an extent as to be objectionable on account of overtime of train crews or delay in passenger trains. It was found that peak settings could be obtained which would prevent excessive peaks and still maintain good operating voltage practically all the time, giving load-factors which have never before been obtained for similar service in electric

TABLE III

COMPARISON OF CURVE-DRAWING KILOWATT TOTALIZING METER INDICATION WITH SUMMATION OF READINGS OF THE SUBSTATION CURVE-DRAWING WATTMETERS, APRIL 16, 1918

Time	Morel	Piedmont	Josephine	Two Dot	Summation Curve Drawing Meters	Curve Drawing Kilowatt Totalizer
8:00 a.m.	0	1000—	2500—	5800	2300	2100
8:30	200	200—	3400—	5800	2500	2800
10:00	0	1500	2800—	10000	7700	7750
10:30	1000	800	2800—	9000	8000	8000
11:30	2800	1000	2400—	10500	11900	11800
11:30	3000	1600	2600—	10000	12000	11800
12:00 noon	4000	3000	2800—	9600	13800	13300
12:30 p.m.	1000	2000	2600—	9000	12000	11700
1:00	1500	1600	2800—	10800	11100	11700
1:30	2600	1800	2500—	9800	11700	11300
2:00	5400	3000	3000—	11700	17100	17500
2:30	2800	0	3200—	10800	10400	10900
3:00	0	500—	2600—	11000	7900	7800
3:30	400—	500—	3200—	7900	3800	3500
4:00	1500	500—	3000—	5900	3900	3900
4:30	1500	500—	2400—	6900	5500	6200
5:00	1700	0	2200—	8100	7600	7500
6:30	4000	1500	2600—	10100	13000	13500
7:00	1000	1600	2800—	7100	6900	7600
7:30	3100	500	2200—	7000	8400	6600
8:00	4000	0	2600—	7000	8400	8500
9:00	4000	400—	3000—	7900	8500	9000
10:00	4000	0	3000—	7500	8500	9000
11:00	2000	0	2200—	8900	8700	7000
11:30	3200	0	2000—	8700	8900	9400
12:00	3600	0	3000—	7500	8100	8000
Average.....	....	......	....	......	8792	8775

—Indicates power fed back to the power company.

TABLE IV

SUMMARY OF PERFORMANCE OF POWER-LIMITING AND INDICATING SYSTEM FOR SIX MONTHS—ROCKY MOUNTAIN DIVISION

Date 1919	Time Peak Limit Hours	Per Cent Peak Time of Actual Running Time	Load-factor
April	43.6	6.4	59.3
May	32.6	4.6	56.1
June	6.1	1.6	56.5
July	4.6	0.77	55.6
August	26.7	4.1	54.7
September	65.8	9.5	58.8
Average	....	....	56.8

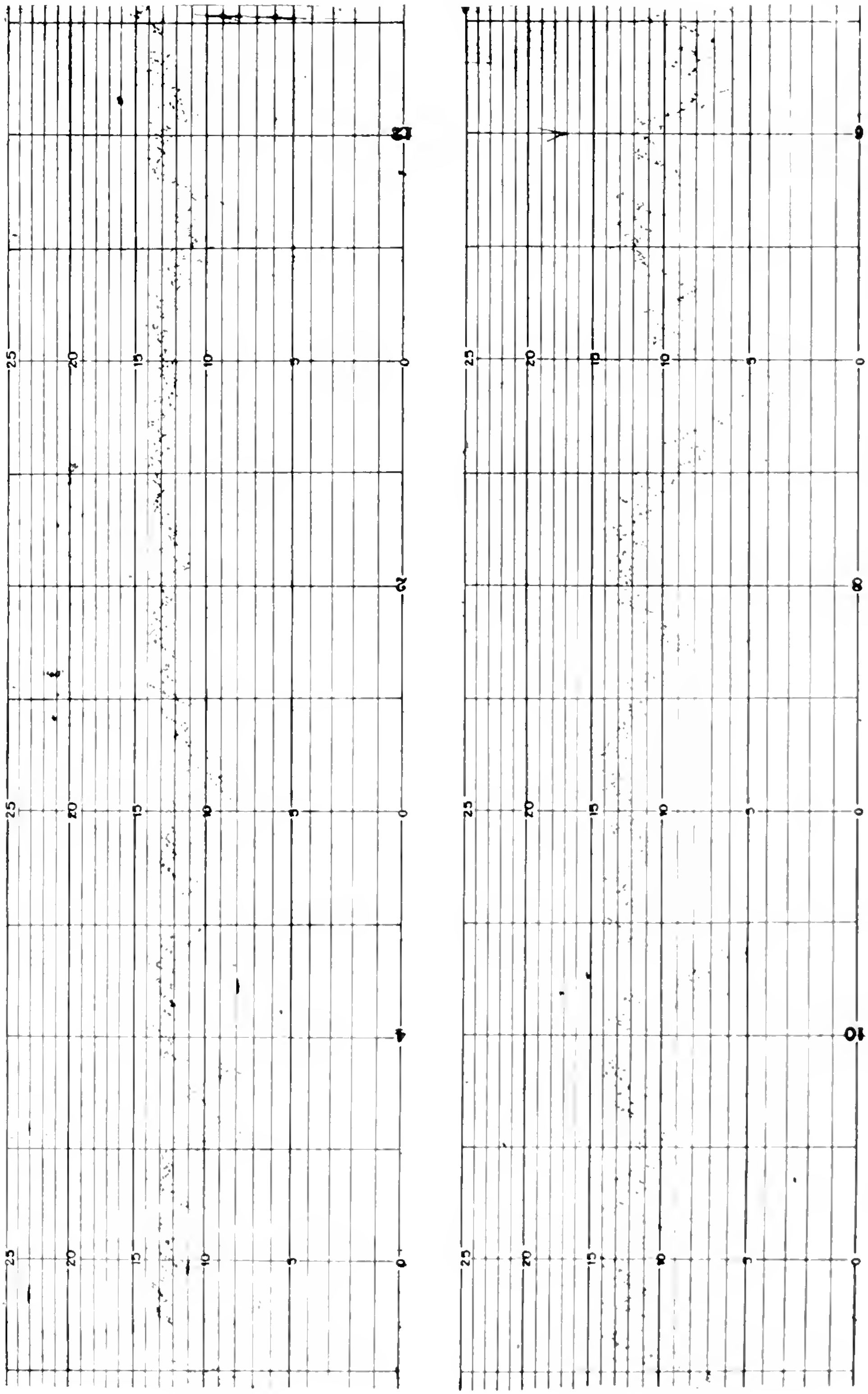

Fig. 16. Two Sample Sections of Record Made by the Curve Drawing Totalizing Tapalog Wattmeter on the C., M. & St. P. Rwy. These show how closely the power-limiting equipment holds a continuous heavy demand within the peak setting of 14,000 kw.

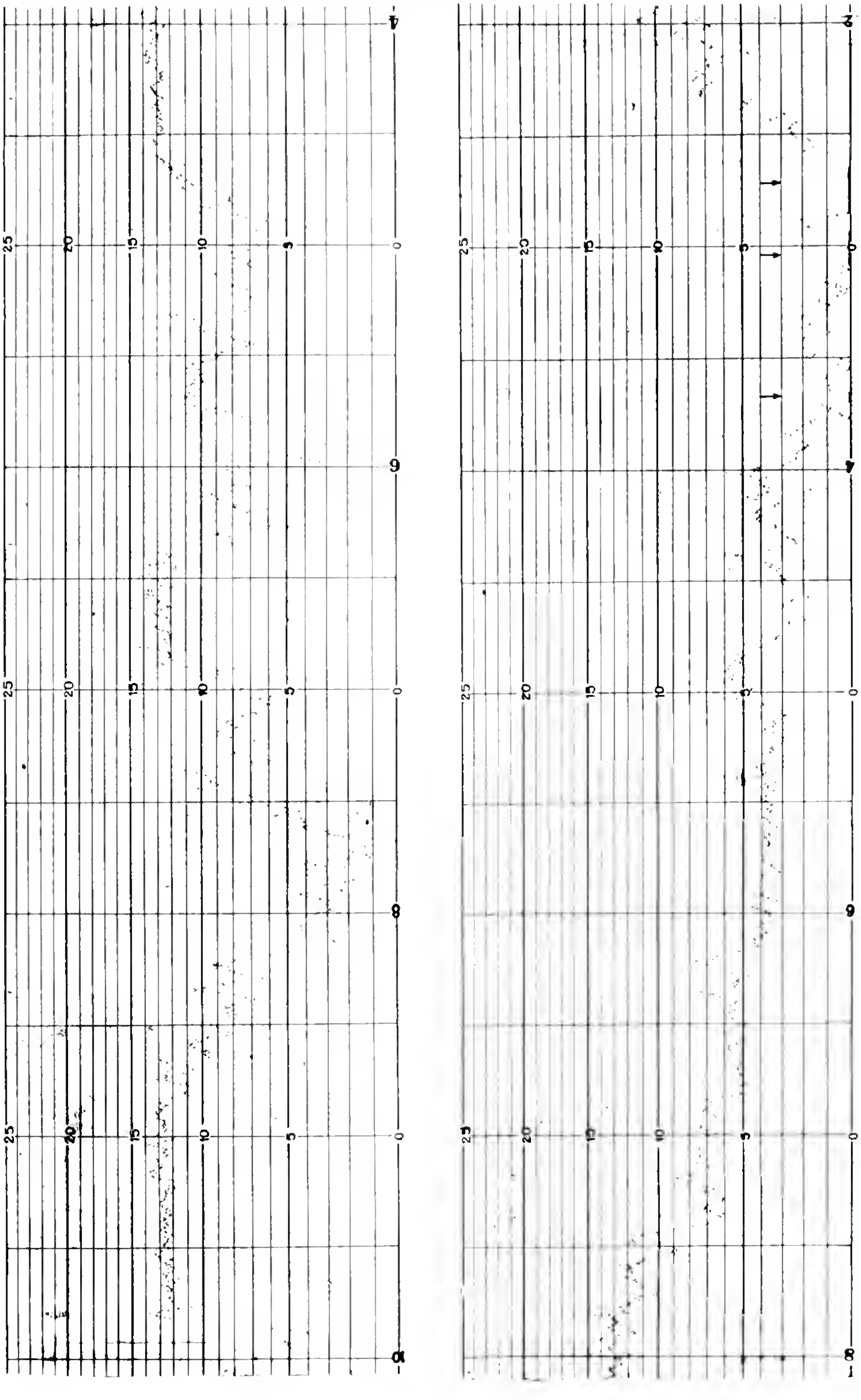

Fig. 17. Sample Records Similar to Those in Fig. 19, except that these show a very variable load. The vertical arrows on the lower record indicate points of regenerated power. The amounts are not recorded as the meter is not capable of giving negative indications

railway operation. The peak limit was set at 14,000 kw. for the Rocky Mountain Division on April 1, 1919, and operation has been very satisfactory on this basis. The average load-factor per month for six months is given in Table IV, or a total average load-factor of 56.8 per cent, which is a unique showing for railway operation and which confirms the wisdom of the railway company in specifying and installing the equipment described in this article.

The railway company pays 0.536 cents per kilowatt-hour for 60 per cent of the peak irrespective of whether this amount is actually used. The load-factor maintained is so near 60 per cent that the increase in cost of power or the cost of power not used is very slight. With increase in the number of trains, the load-factor will be raised and no difficulty should be experienced in holding a load-factor of 60 per cent or better.

Short lengths of the curve-drawing totalizing wattmeter record are shown in Figs. 16 and 17. These records were taken with a peak setting of 14,000 kw. and show how close the peak power consumption is kept to this point. One section shows an input of 14,000 kw. for several hours, varying from this amount to zero reading or reversal of energy, all of the stand-by losses being supplied by power regenerated by the locomotive.

If the power-limiting feature is removed, peaks as great as 7000 to 8000 kw. above the 14,000 kw. limit result.

One of the great indirect benefits obtained is the valuable assistance the indicating equipment gives the train dispatcher in dispatching trains in such a manner as not to give excessive peaks and thereby lowering the voltage due to the power-limiting equipment. By careful train dispatching so that one train is ascending the mountain grade while another train is descending, it is possible to assist the automatic equipment in maintaining a good load-factor very materially and to greatly increase the efficiency of the general operation of the railroad.

Great credit is due Messrs. E. S. Johnson, J. R. Craighead, J. B. Taylor, and E. J. Thiele for valuable suggestions, improvements, and assistance in working out the details of the great number of new and untried features.

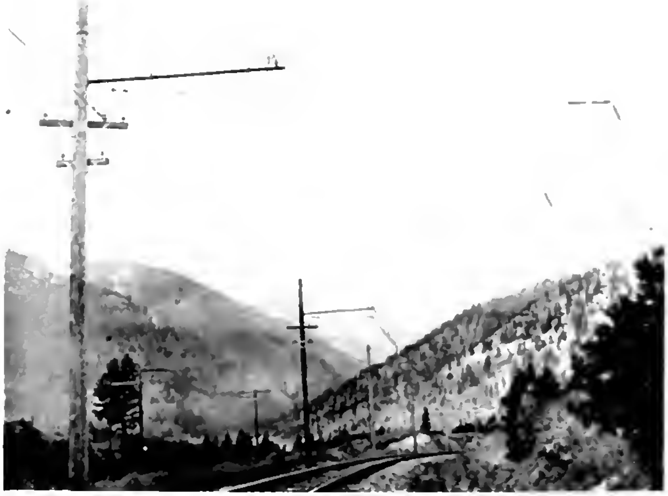

Fig. 18. View taken on the Missoula Division of the C., M & St. P. Rwy The lower cross arms on the poles at the left carry the power-limiting and indicating pilot wires

Electrification of the Hershey Cuban Railway

By F. W. Peters
Railway and Traction Engineering Department, General Electric Company

The unqualified success that has attended the operation of high-voltage direct-current railways in the United States is attracting more and more attention abroad. As reported in another article in this issue, the high-voltage direct-current system very favorably impressed the French Mission recently sent to this country to study railway electrification. The article below describes such an electrification now being put into operation in Cuba.—Editor.

F. W. Peters

At all large Cuban sugar mills, railroads for transporting cane extend in various directions to tap the areas where cane loading stations are located. Two wheeled ox drawn carts are used to gather cane in the fields and haul it to the loading station where it is placed aboard especially constructed cane cars which are later made up into trains and hauled to the mill. The necessity of grinding cane shortly after it is cut, in order to obtain a maximum sugar yield, renders desirable the maintenance of a reliable railway system to supply the mill with a continuous flow of cane, thereby eliminating cane "shortage" shut downs which prove so costly to the sugar operator.

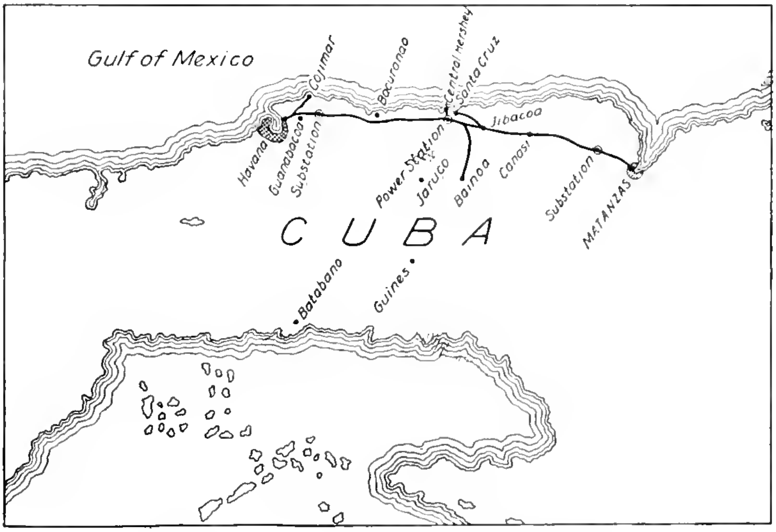

Fig. 1. Map Showing Route of Hershey Cuban Railway

The industry has assumed such proportions that the mills command attention not only for their size, intensive operation, and efficiency, but also for the supplementary industrial activities necessary to the support of the mills during that five-month period of 24-hours per day cane grinding when nothing but a break down or an important holiday is deemed sufficient cause to stop operations.

Hershey Central, a beautifully situated town overlooking the Gulf of Mexico, is located on the north coast of Cuba practically midway between the cities of Havana and Matanzas, some 56 miles apart. The major activity, at this as well as numerous other Centrals on the island, is the manufacture of sugar. This mill is now served by the Hershey Cuban Railway, a steam operated road having approximately 35 miles of single track. The present motive power consists of seven steam locomotives ranging from 20 to 40 tons on drivers. Both coal and oil fired types are in use, which, on account of the very high cost of fuel in Cuba and the inefficient operation of such engines, constitute an expensive item in overall operation and preclude an efficient expansion of traffic such as outlined herein.

In keeping with the broad plans of the management, the road is being electrified, and extensions which will comprise the main line are being completed to Havana on the west, and to Matanzas on the east. Branch lines between Havana and Cojimar, 4½ miles, between the main line and Bainoa, 7½ miles, and between the main line and Santa Cruz, 4½ miles, are completed. These with numerous short spurs and sidings will total 80 miles of electrified single track. The road is built over a private right of way through a rolling country in which the ruling grade is 2½ per cent. The track is standard gauge with 85 lb. per yard running rails rock ballasted over the greater portion.

The service to be maintained upon inauguration of electric operation will consist of cane and sugar transportation besides through and local commodity freight, express service, and multiple unit passenger train service operating on one-hour headway between Havana and Matanzas.

Fig. 2. Transferring Cane From Bullock Carts to Railway Cane Cars

Fig. 3. Sugar Mill at Central Hershey

The 1200-volt direct-current electric railway system was selected by the railroad management after a thorough investigation of various types of electrified roads, as being that which would fulfill to the best advantage the present conditions of electrical operation, as well as provide for efficient expansion incident to anticipated growth. Ten-point catenary type trolley wire construction was chosen, to be suspended largely from bracket arms on creosoted pine poles which carry in addition the steel cored aluminum transmission circuits and the 795,000 cir. mil. aluminum 1200-volt direct-current feeders.

Locomotives

The motive power furnished for operating the foregoing cane and general freight service consists of seven 60-ton four-motor 1200-volt direct-current electric locomotives arranged for multiple unit operation when necessary. They are equipped with swivel trucks, steeple cab type super structure, and are designed to meet American standards throughout. The control provides for connecting the motors in series or series-parallel, and consists of two master controllers (one located at each driving position in the main cab) with resistors, dynamotor blower set, solenoid contactors, and other auxiliaries mounted principally under the end cabs. Power for operating the control equipment is obtained at 600 volts from the dynamotor. A pantograph type trolley is mounted on top of the main cab with provision for the convenient use of pole trolleys, to provide for operation over adjoining electric railways necesitating such types of trolley. Combined straight and automatic air brake equipment is used with two 35-cubic foot displacement per minute air compressors placed in the main cab and operated directly from the 1200-volt trolley wire.

Motor Car Equipments

This class of rolling equipment consists of ten straight passenger cars, three combination passenger and baggage cars, and two combination express and mail cars. The passenger cars seat 50 persons, have a free running speed of approximately 40 miles per hour, and will weigh completely equipped about 29 tons. Four motors per car are provided with automatic electro-pneumatic double-end multiple unit control equipment arranged to connect the motors in series and series parallel. Power for the control circuits and car lighting is obtained from a 32-volt constant potential generator driven by a 1200-volt direct-current motor operating from the trolley circuit. Pantograph type trolley and bases for pole trolleys are mounted on the car roof.

Line Work Car

The line work car mounts at one end a short cab, on top of which is an adjustable insulated platform for use when working on the live trolley. The other end of the car floor carries a hand crane. Four motors similar to those on the passenger cars, but geared for lower speeds, are used with a Type K four-motor control for connecting the motors in series or series-parallel.

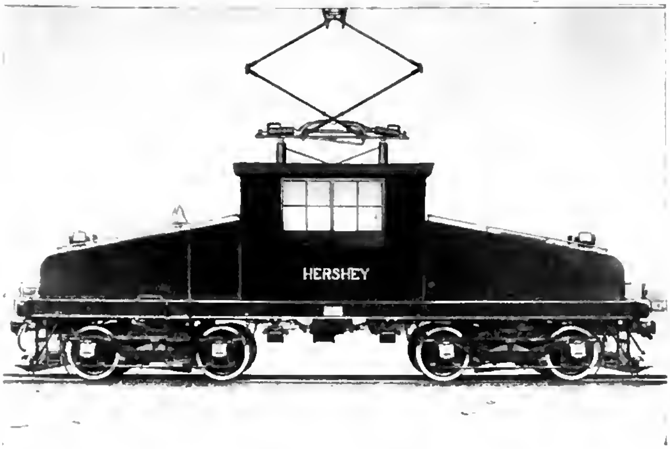

Fig. 4. 60-ton, 1200-volt Direct-current Electric Locomotive

Power Generating and Substation Equipment

The power station and substation equipment selected to operate the railroad and to furnish commercial power to Matanzas and smaller towns along the right of way consist of the following:

GENERATING STATION	Number
2500-kv-a. turbine alternators	3
35-kw. turbine exciter	1
50-kw. motor-generator exciters	1
600-h.p. oil-fired steam boilers	4
3000-kv-a. step-up transformer banks	2
300-kv-a. station auxiliary transformer banks	1
Switchboard	1
Spray pond	1

MAIN RAILWAY SUBSTATION	
1000-kw. 1200-volt d-c. synchronous converter groups	2
1050-kv-a. step-down converter transformer banks	2
Railway switchboard	1

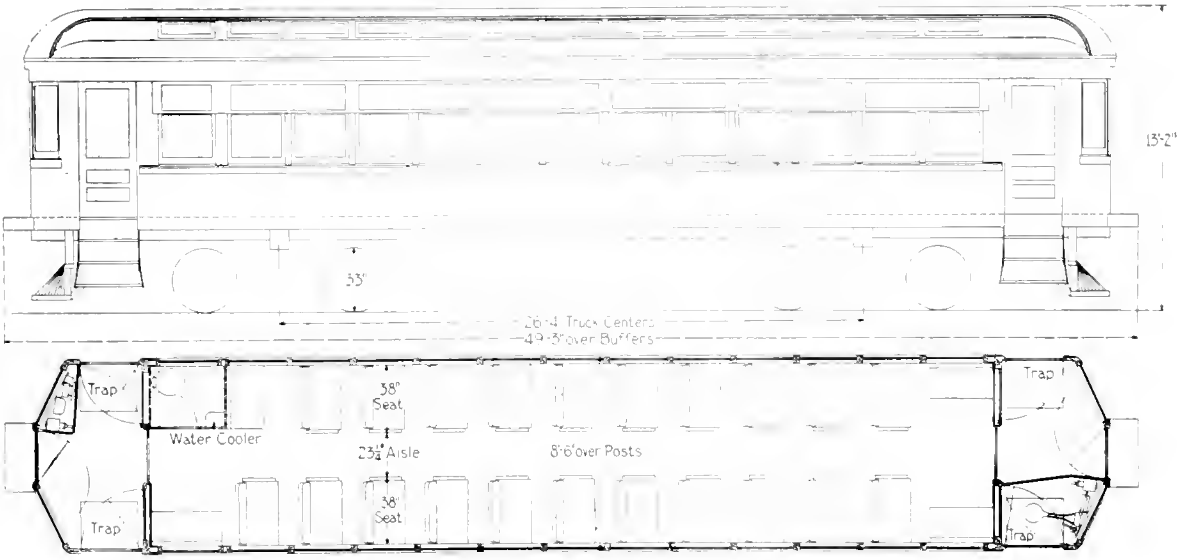

Fig. 5. Passenger Car Seating 50 Persons. Four D-C. Motors

EACH OF TWO OUTLYING AUTOMATIC SUBSTATIONS

1000-kw. 1200-volt d-c. synchronous converter groups	1
1050-kv-a. step-down converter transformer banks	1
500-kw. 600-volt d-c. spare converter	1
350-kv-a. single-phase step-down spare transformer	1
Automatic control equipment	1

The architectural design of the power station as indicated in Fig. 6 is such as to permit of readily building extensions and making additions to apparatus to provide for future enlargement. Care has been taken to obtain the maximum ventilation and light which, with the symmetrical arrangement of equipment, affords a pleasing and efficient working combination.

The steam pressure adopted was 250 lb. at 150 deg. F. superheat, with boiler capacities and arrangement to permit of the most efficient operation. The main generating voltage is 2300 three-phase 60-cycle from which step-up transformers between the main 2300-volt bus and the high-tension bus distribute power at 33,000 volts three-phase to the outlying substations and points of commercial distribution. Power for station auxiliaries and shops is obtained from transformers stepping down from 2800 to 480 volts. This latter voltage, largely used in sugar mill work, was selected to permit a direct tie-in when necessary with the main bus of the sugar mill power house which is close to, but distinct from the new railway station.

The railway synchronous converters located in the main station consist of two groups in parallel, each group comprising two 500-kw. 600-volt machines connected in series for 1200 volts. These receive their power from the main 2300-volt station bus through step-down transformers.

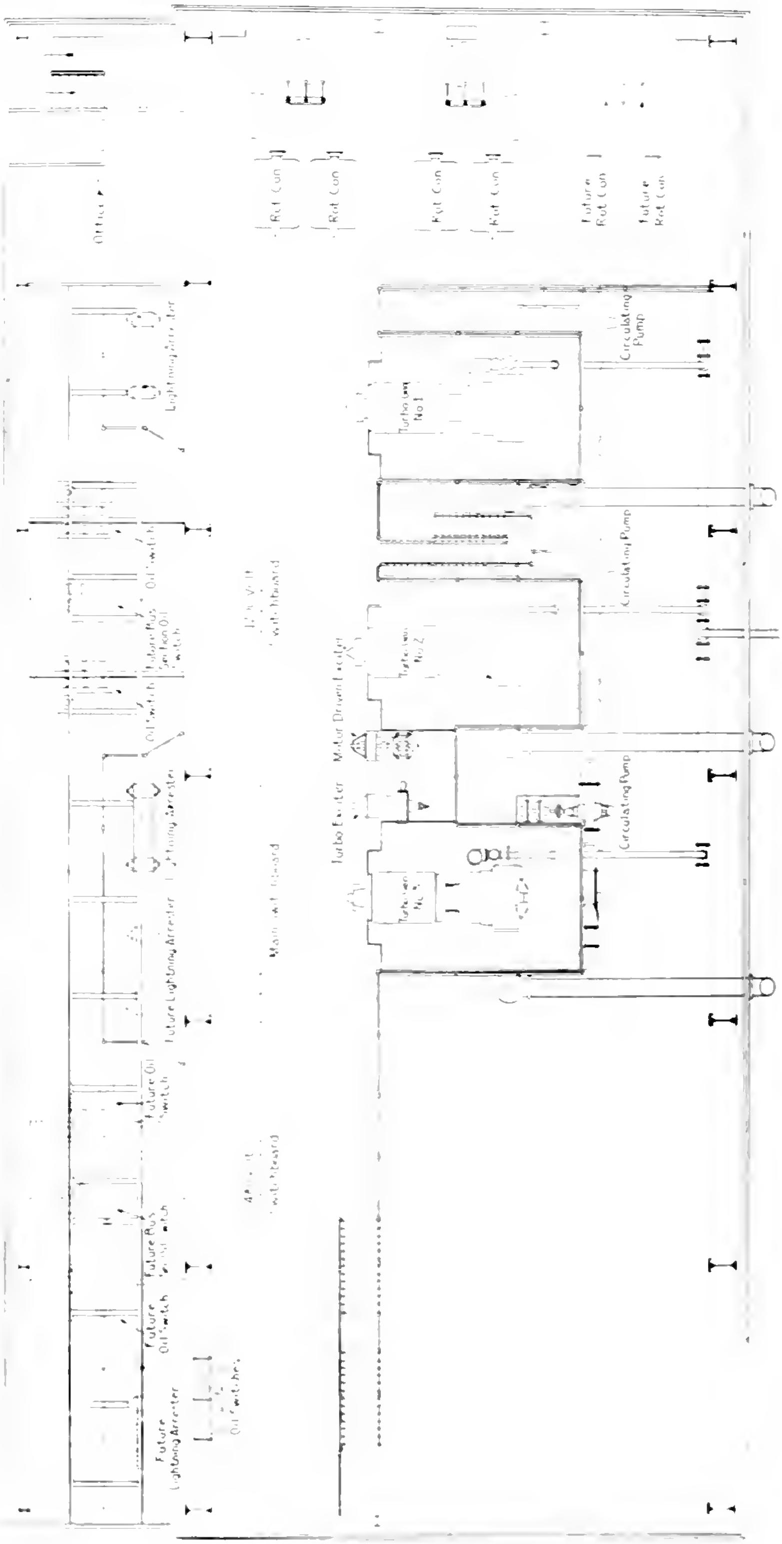

Fig. 6. Plan View of Generating Room and Main Substation

Surface condensers are used with the turbines and have motor-driven circulating pumps receiving cooling water from a nearby spray pond. Air washers, feed water heaters, emergency feed water supply, piping, oiling system and pumps have been chosen throughout with a view to reliability and economy.

Because of the mild climate, the boilers have been located out of doors adjacent to the sugar mill boilers with only a roof over them for protection against the tropical rains. This arrangement affords the most agreeable working conditions for the men, and has the advantage of lowered initial building cost and reduced operating expense since one boiler house organization can serve both the sugar mill and railway boilers.

For oil firing a steam atomizing system is used with exhaust steam surface heaters arranged to heat the oil to the right viscosity for proper atomization. Two 7500-gallon capacity auxiliary fuel oil tanks are located near the boiler room, each of which holds approximately one day's supply based on the estimated load for the near future, while some distance away are the main oil storage tanks having a 500,000-gallon capacity. No attempt was made to utilize bagasse, the refuse from ground cane, as fuel for the railway power station since the quantity produced by the grinding rolls is practically all consumed by the sugar mill boilers.

The stack is constructed of radial brick similar in design to that used for the sugar mill. It is eleven feet inside diameter and reaches 200 feet above the level of the boiler room floor. A lined steel breeching conducts the burned gases from the boilers to the stack.

Provision has been made for conveniently installing coal burning machinery without disturbing the boiler settings or auxiliaries should a readjustment in the relative price of coal and oil necessitate the use of coal for economy.

A spray pond constructed of concrete is located 600 feet distant from the power house and is connected by two 36-inch concrete pipes, one of which connects to the intake and the other to the discharge wells, in the generating room, used for the condenser circulating water. Three motor-driven 4600 g.p.m. high efficiency pumps which force the discharged circulating water through the spray nozzles are located in the pump house at the spray pond.

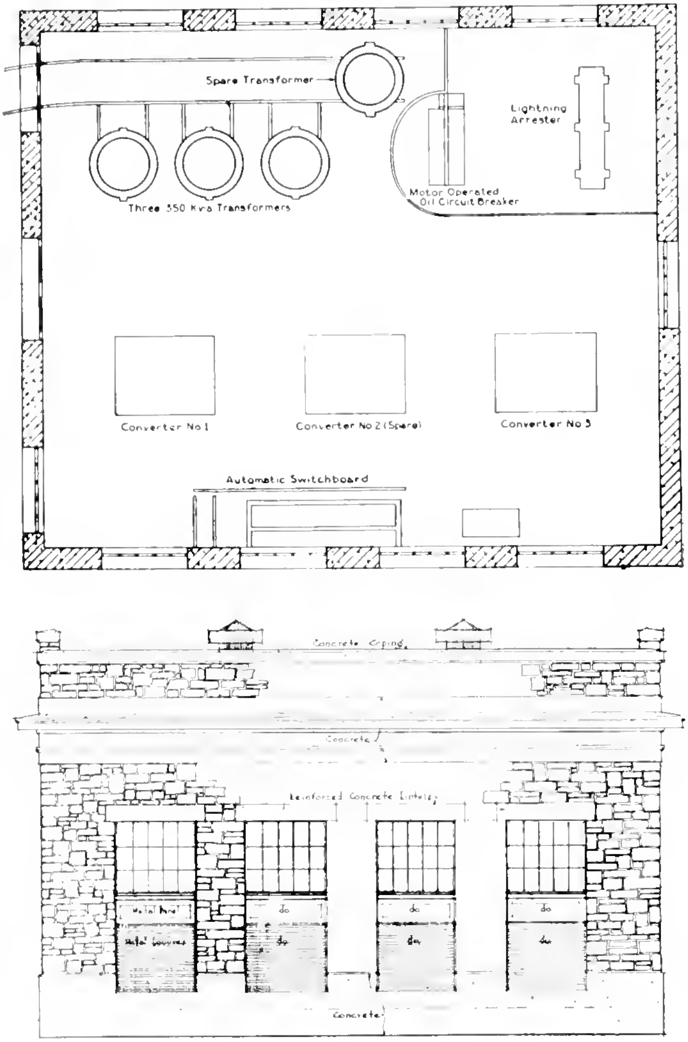

Fig. 7. Plan and Elevation of Substation

Substations

The two outlying automatic substations, one of which is located near Havana and the other near Matanzas, are duplicates and each contains one 1000-kw. group of synchronous converters consisting of two 500-kw. 600-volt machines connected in series. A third 500-kw. 600-volt spare converter is provided with change over switches so that it may be conveniently substituted for either the high or low machine of the group. Three 350-kv-a.

single-phase 33,000-volt high-tension self-cooled transformers having double secondary windings are regularly employed for operating the converters with a fourth transformer supplied as a spare. The switching equipment is completely automatic in operation and is similar to those which during the past few years have proven very successful in many parts of the United States. No regular attendants are required for the operation of the equipment since it starts automatically on a power demand and stops when the demand ceases. During operation the equipment is protected from injury due to excessive overload by the use of flash barriers and load limiting resistors on the direct-current side of the machine. All irregularities emanating from disturbance on the high-tension lines or improper functioning of the equipment are fully protected against, so as to promote reliable operation. Two feeder circuits leave each substation to allow the trolley and line feeder cable to be sectionalized in front of each station.

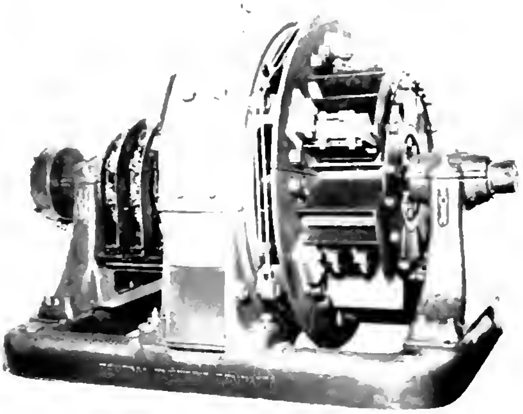

Fig. 8. 500-kw., 600-volt Synchronous Converter Located in Automatic Substation

Transmission

Provision is made for carrying two three-phase transmission circuits on a single line of poles between the power station and Matanzas. These will serve the railway substation on the Matanzas Division as well as certain railway and commercial power applications in the city of Matanzas. On the Havana Division, immediate provision is made for carrying one three-phase transmission circuit to serve the Havana Division railway substation as well as any commercial power adjoining the right of way. Should occasion demand, however, arrangements are such that an additional three-phase circuit can be conveniently added to the existing pole line.

Forty-five foot creosoted poles on 150-foot spacing have been used over practically the entire distance. The pole line carries at the top a $\frac{1}{4}$ inch galvanized steel strand ground wire and either one or two number 1/0 B.&S. steel reinforced aluminum 33,000-volt three-phase transmission circuits mounted on pin type insulators and creosoted wood cross arms.

The 1200-volt direct-current feeder consists of a 795,000 cir. mil. standard aluminum cable carried over practically the entire right of way. It is supported on pin type insulators mounted on creosoted wood cross arms located below the transmission circuits. For approximately four miles each side of the sugar mill, where the steepest grade and heaviest service is encountered, a second 795,000 cir. mil. feeder is used.

A catenary type construction is employed for suspending the 4/0 B.&S. gauge grooved trolley wire. The messenger wire is $\frac{7}{16}$ inch galvanized steel strand carried on pin type insulators and galvanized tie iron bracket arms. On sidings and at special work, however, cross span suspension construction is used to support the messenger wire. Steel terminal 4/0 B.&S. copper strand acetylene gas weld rail bonds are used throughout.

To protect against the rapid deterioration of exposed ferrous metals, so prevalent in tropical countries, all iron parts employed in the transmission system are protected by hot dipped galvanizing or sherardizing. It has also been found that a greatly increased life may be expected from wood poles treated with creosote, which in this case has led to their adoption entirely.

HIGH-VOLTAGE DIRECT-CURRENT RAILWAY INSTALLATIONS IN THE UNITED STATES AND CANADA

Supplement to General Electric Review, April, 1920

Compiled by GENERAL ELECTRIC COMPANY Railway and Traction Engineering Department Schenectady, N. Y. March 1, 1920 W.D.B	PERMANENT WAY				OVERHEAD CONSTRUCTION					POWER			ROLLING STOCK																				
					Trolley or Third Rail		Transmission Line			Generating Stations	Substations		Motor Car Equipment					Pass. Trailers	Locomotives			Control (Pass.)				Heaters	Air Brakes				Date Started High Voltage Operation	Previous System of Operation	Chief Points Connected
	Length of Route	Length of Track (Single Track Basis)	Miles of 600-volt City Operation	Track Gauge S—4 ft. 8½ in. Weight of Rail	Type	Voltage	Voltage	Frequency	Phases	Number, Capacity and Type of Generator Equipment	No. of Subs.	Type, Capacity and Voltage of Apparatus	Number Motor Cars	Weight Eq'p't Tons	Principal Motor Equipment	Free Running Speed	Seating Capacity	Number	Number	Weight Eq'p't	Motor Equipment	Type A=Auto. NA=Non-auto. K=Cylin.	Multiple Unit Operation	Single or Double End Operation	Speed on Half Voltage		Type of Air Brakes	Type of Compressor	Capacity—Ft./Min.	Voltage			
Aroostook Valley Ry. Co., Presque Isle, Maine	32	38	0	S-70	Direct Suspension	1200	11,000	60	3	Power purchased from Maine & N. Brunswick El. Pr. Co.	2	(4) TC-6-200-1200-600/1200 H.R. Transformers G.E.	2 2 1 Ex	28 32 33	(4) G.E. 217-600 Volts (4) G.E. 217-600 Volts (4) G.E. 205-600 Volts	30	50	Fgt.	1	40	(4) G.E 206-600 Volts	M-NA (2) K	Yes . . .	D	Half	1200	St. & St. Auto. G.E.	C.P.-22 C.P.-29	24	600 1200	July, 1910	Steam & New Exten.	Presque Isle, Caribou, Washburn, Sweden
Butte, Anaconda & Pacific Ry., Butte, Mont	30	114	0	S-85	11 Point Catenary Trolley	2400	100,000	60	3	Power purchased from Montana Power Co. (Hydro-Elec.)	2	(7) 1000-kw. Syn. M.G. Sets, 1200/2400 Volts G.E.	0	. . .	. . . .	. .			28 3	80 40	(4) G.E. 229-1200 Volts (2) G.E. 229-1200 Volts	. . . . .	. . . .			2400 Elec. Hot Air	W. St. & Auto.	C.P. 26	100	600	June, 1913	Steam	Butte, Anaconda, Mines & Smelter.
Canadian [illegible] Ry., Montreal, Can.	10	30	0	S-90	Catenary Double Trolley	2400	11,000	60	3	Power purchased from Montreal Lt., Ht. & Pr. Co	1	(2) 1500-kw Syn. M.G. Sets, 1200/2400 Volts-11,000 Volts G.E.	8	80	(4) G.E. 239-1200 Volts	50	70		6	83	(4) G.E. 229-1200 Volts	M NA	Yes	D	Half	2400 Volts Elec. Hot Air	Comb. St. & Auto. G.E.	C.P. 33	100	2400	Sept., 1918	New Steam Terminal	Montreal, through Tunnel to Mt. Royal
Central [illegible] Traction Co., Stock[illegible]	69	71	7	S-75	Third Rail and Catenary	1200	60,000	60	3	Power purchased from Western States Gas & Elec. Co.	3	(1) 300-kw., and (2) 500-kw. Syn. M.G. Sets, 1200 Volts, G.E.	8	38	(4) G.E. 205-1200 Volts	45	46 50	2	3	41 46	(4) G.E. 205-1200 Volts	M NA	Yes	D	Half	1200	West. G.E. Comp.	C.P. 22	24	600	June, 1908	New	Stockton & Sacramento
Charles City [illegible] Ry., Charles City, Iowa	25	30	0	S-70	Direct Suspension	1200	2,300	60	3	Power purchased from Cedar Valley Pr. Co.	1	(2) 300-kw., 1200-volt M.G. Sets, 2300-volt G.E.	4	11 21 28	(3) (2) G.E. 217 (1) (4) G.E. 217	30	34 52	.	1	35	(4) G.E. 205-500 Volts	K R-200	No.	D	Half	1200	St. & Auto. Straight G.E.	C.P.-29 C.P.-30	27 30	1200	July, 1915	Steam	Charles City & Marble Rock
Chicago, [illegible] & St. Paul R. R. ([illegible]ation)	440	591	0	S-90	Catenary Double Trolley	3000	100,000	60	3	Power purchased from Montana Pr. Co. (Hydro-Elec.)	14	(23) 2000-kw. M.G. Sets 9-1500-kw. M.G. Sets, 1500/3000 Volts G.E.	. .	.	. . . . .			. .	30 *12 4 10	282 300 70 275	(8) G.E. 253-1500 Volts (4) G.E. 255-1500 Volts (6) W. 348-750/1500 V. Twin Arm. Quill				.	Oil Fired Steam	W. St. & Auto.	(2) C.P. 31	[illegible]	3000	Dec., 1915	Steam	Harlowton, Montana to Avery Idaho
Chicago, [illegible] & St. Paul R. R. ([illegible]ation)	217	280	0	S-90	Catenary Double Trolley	3000	100,000	60	3	Power purchased from Washington Water Power Co. and Puget Sound Tr., Lt. & Pr. Co.	8	(8) 2000-kw. M.G. Sets, 1500/3000 Volts, G.E. (6) 2000-kw. M.G. Sets, 1500/3000 Volts, West.	0	. . .	. .	. .	.		5	265	(12) G.E. 100-1000/3000 Volts, Gearless				. . .	Oil Fired Steam	W. St. & Auto.	C.P. 34	150	3000	Jan., 1920	Steam	Othello to Seattle and Tacoma Wash
Chicago, [illegible] & St. Paul R. R. ([illegible]inal)	4	7	0	S-90	Catenary Trolley	1500	6,600	60	3	Power purchased from Montana Pr. Co. (Hydro-Elec.)	1	1-300-kw., 1500-volt M.G. Set, 6600-volt G.E.	. . . . . .	. .	. . . .	. .	. .		1	50	(4) G.E. 207-750 Volts		. . . .	. . .			W. St. & Auto.	(2) C.P. 29	27	1500	Feb., 1915	Steam	Great Falls Yards and Terminal Station
Da[illegible]tine Ry., Davenport, [illegible]	30	30	4	S-70	Catenary Trolley	1200	33,000 Y	60	3	Power purchased from Moline-Rock Island Mfg. Co.	2	(4) 300-kw., 1300-volt M.G. Sets, G.E.	6 1 Ex.	32	(4) G.E. 217-600 Volts	39	52	0	0			K	No.	S	Half	.	West D-2-K	W	18	1200	Aug., 1912	New	Davenport, Muscatine
Eas[illegible]ric Co., Beaumont, [illegible]	20	20	4	S-70	Catenary	1200	None			Power purchased from Beaumont & Pt. Arthur Lt. & Pr Co., Sub. in P. H.	2	2-Syn. M.G. Sets, 60-cycle, 2300-volt, 1200-volt, d-c. G.E.	6 1 Ex.	30	(4) G.E. 233-600 Volts	45	46	4	0	. .	. . . . . .	K	No.	S	Half	. . . . .	.	W	25	600	1914	New	Beaumont & Port Arthur
F[illegible] Moines & So. Ry., B[illegible]	120	145	5	S-70	Direct Suspension	1200	22,000 △	25	3	6500-kw. Curtis Turbine 4000-kw Curtis Turbine	6 1 Port	(8) 400-kw., 600-volt Syn. Conv. (2 in Series) (1) 300-kw., 1200-volt Syn. Conv. G.E.	10	42	(4) G.E. 205-600 Volts	45	50	8	7 4	40 60	(4) G.E 206-600 Volts (4) G.E. 251-600 Volts	K	Yes	S	Full	Hot Water	West. St & Auto	C.P. 28	25	600	Sept., 1911	600 Volts	Fort Dodge, Boone Des Moines & Rockwell City
H[illegible]reek Traction Co., [illegible]	14.8	15.2	0	S-70	Direct Suspension	1200	11,000	60	3	Power purchased from Hocking Pr. Co.	1	(4) 200-kw., 600-volt Syn. Con. West	3 1	23.5 35	(4) W-324-600 Volts	42	48	0	0	.	. . . . .	HL	Yes	D	Half	Hot Air	W.-A.M.M.	W D.-2K.	53	1200	May, 1915	600 Volts	Nelsonville & Athens
[illegible]sville Traction Ry. [illegible], Ind.	41	41	Traffic Rights 75	S-75	Direct Suspension	1200	None			(4) 300-kw., 600/1200-volt D-C. Engine Driven Generators	0	Direct Feed	10	34	(4) G.E. 205-600 Volts	53	50	0	0		. . . .	M-NA	Yes	S	Full	Hot Water	Emergency Straight G.E.	C.P. 22	24	600	Oct., 1907	New	Seymour & Sellersburg & Indianapolis & Louisville, via 600 Volts
I[illegible] Cedar Rapids, Iowa	28	28		S-70	Direct Suspension	1200	16,500	60	2	Eng. Drive A-C. 7000-kw., Turbine Units 10,250-kw., 2300-volt, 2-phase	2	(1) 500-kw., 2-unit, 600/1200-volt Syn. M.G. Set (1) 500-kw., 600/1200-volt Syn. Con. G.E.	5	45	(4) G.E. 205-600 Volts	41		5	1	50	(4) G.E. 207-600 Volts	M-K	Yes	D	Full		G.E. Straight Air	C.P. 28	25	600	Operated at 600 Volts	600 Volts	Cedar Rapids, Iowa City & Toledo
Ka[illegible] C[illegible] & St. Joseph Ry.	72	74	9	S-70	Catenary	1200	33,000	25	3	Power purchased from Kansas City Rys. Co.	3	(6) 500-kw., 750-r.p.m., 1200-volt Syn. Con. West	22 5	41	(4) G.E. 225-750 Volts (4) W-327-750 Volts	60	66	0	0		. .	M-A HL-A	Yes	D	Half	Hot Water	Comb. St. & Auto. G.E.	C.P. 29	25	1200	Jan., 1913	New	Kansas City, St. Joseph & Excelsior Springs
Lake E[illegible]thern Ry., Ontario, [illegible]	54	56	1	S-85	Catenary Trolley	1500	26,400	25	3	Power purchased from Hydro-Elec. Pr. Commission of Ont.	3	(3) 500-kw., 1500-volt Syn. Con. (1 Portable) Cand., G.E.	6	40	(4) W-85-h.p., 750 Volts	45	70	3	2	60	(4) W-562-D-5, 750 Volts	West. A-B	Yes	D	Half	1500 Volts	West. Automatic	Dyna Comp.	25	1500	Feb., 1916	New	Galt, Brantford, Simcoe & Pt. Dover
L[illegible]anley Ry., London, Ont	24	30	0	S-70	Catenary	1500	13,200	25	3	Power purchased from Ontario Hydro-Elec Pr. Com.	2	(4) 500-kw., 1500-volt Syn. Con., West.	8	51	(4) G.E. 225-750 Volts	50	56	10	3	63	(4) G.E. 251-750 Volts	M-NA	Yes	D	Half	Hot Water	Comb. St. & Auto. G.E.	C.P. 29	25	1500	Aug., 1915	Steam	London, St. Thomas & Port Stanley
[illegible]tric Ry. Co., Annapolis, M[illegible]	25.3	32.3	0	S-80	Catenary	1200	13,200	25	3	Power purchased from Consol. Gas, Elec. Lt. & Pr. Co.	2	(5) 300-kw. Syn. Con., 1200-volt, d-c., West.	12 1 Ex.	40	(4) W-317-A-4, 600 Volts	45	52	0	1	52	(4) W-562-600 Volts	H-L-P NA	Yes	D	Half	Hot Air	W.-A.M.M	D.-2K.	25,3	1200	Jan., 1914	6600 Volts, 1φ & Steam	Baltimore & Annapolis
Mi[illegible] Co., Kalamazoo-Grand Ra[illegible]gan-Battle Creek	92	95	4	S-80	Third Rail Over-running Catenary	1200	70,000	30	3	Power purchased from Consumers Pr Co., Jackson, Mich.	3	(8) 500-kw., 1200 volt Syn. Con. G.E.	8 2 4	70 65 65	(4) G.E. 239 (2) G.E. 239-1200 Volts (4) G.E. 254-600 Volts	70 50	52	Fgt	4 Exp.	55	(4) G.E 239-1200 Volts	M-NA	Yes	S	Full	Hot Air	Comb. St & Auto. G.E.	C.P. 28	25	60	May, 1915	New	Kalamazoo, Grand Rapids, Allegan & Battle Creek
Mi[illegible] Flint-Bay City	46	46	5	S-80	Third Rail Over-running Direct Suspension	1200	20,000	60	3	Power purchased from Consumers Pr Co., Jackson, Mich.	2	(4) 500-kw., 1200-volt d-c.; 5000-volt a-c. Syn. Motor-Generator Sets G.E.	12	40	(4) W-333-600 Volts	60	55	0	0		. . . .	HL	Yes	S	Full	1200 Volts	West. A.M.M.	Dyna Comp.	25	1200	May, 1914	New & 600 Volts	Flint, Saginaw & Bay City
Michigan Ry. Northwest Div., Grand R[illegible]	45	77	5	S-60 S-70	Direct Suspension	1200	20,000	30	3	Power purchased from Consumers Pr. Co.	1	(2) 500-kw., 1200-volt Syn. Con. G.E.	10	35	(4) W-333-600 Volts	60	55	0	0		. . . . .	M NA	Yes	S	Full	Hot Water	West.	Dyna. Comp.	25	1200	May, 1915	600 Volts	Grand Rapids, Holland & Lake Resorts Macatawa and Saugatuck
Milwaukee Electric Ry. & Lt. Co., Milwaukee Wis.	135	135	47	S-80	Catenary Trolley	1200	13,200 38,000	25	3	Part of an Extensive System	6	(12) 300-kw. } Syn. Con., 600-volt, 2 in Series (5) 500-kw. } G.E.	11 15	43.5 39.5	(4) G.E. 205-600 Volts (4) G.E. 207-600 Volts	45	64	59	0		. . . . .	M NA	Trailers Only	D	Full	Hot Water	West. D.-3 N			600/1200	Mar., 1910	3300 Volts Single-phase	Milwaukee, E. Troy, Burlington & Watertown
Nashville-Gallatin Inter. Ry., Nashville, Tenn.	27	27	3.5	S-70	Direct Suspension	1200	33,000 Y	60	3	Power purchased from Nashville Ry. & Lt. Co.	1	(3) 200-kw., 600-volt Syn. Con., 2 in Series, G.E., 1 spare	4 1 Ex.	38	(4) G.E. 205-600 Volts	40	50	0	0		. . . .	K	No	S	Half	Hot Air	G.E. Straight	C.P. 29	25	1200	Apr., 1915	New	Nashville & Gallatin
Oakland, Antioch & Eastern Ry., San Francisco, Cal.	118	118	4	S-70	Catenary	1200	11,000	60	3	Power purchased from Great Western Pr. Co.	5 1 Port	(6) 750-kw., 1300-volt Syn. M.G. Sets; 11,000-volt, a-c., West. (1) 300-kw., 1200-volt Syn. M.G., G.E.	3 G.E. 15 W.	40	(4) G.E. 205-1200 Volts (4) W-322-600 Volts	55	50	18	2 2 2	49 62 35	(4) W-308-B. 600 Volts (4) W-321-600 Volts (4) G.E. 205-1200 Volts	M-NA W-HL	Yes	D	Full	1200 Volts	West.	Dyna. Comp.	2x25	1200	Sept., 1913	New	Oakland, Antioch, Sacramento & San Francisco
Oregon Electric Ry., Portland, Ore	154	180	25	S-70 S-75	Catenary	1200	60,000	33	3	Power purchased from Portland Ry. & Lt. Co.	6 1 Port 6	(6) 500-kw., 600/1200 Syn. Con. (7) 500-kw., 1200-volt Syn. Con. G.E.	53 8 Ex. 1 W.	45	(4) G.E. 205 (4) G.E. 222-600 Volts (4) W-321-600 Volts	45	62	28	6 4	60 50	(4) G.E. 212-600 volts (4) G.E. 207-600 Volts	M-A	Yes	D	Full	Hot Water 1200 Volts	West. D-3		35	1200	Aug., 1912	600 Volts & New	Portland, Salem, Albany & Eugene
Pacific Electric Ry., Los Angeles, Cal.	57	91.5	1.7	S-70 S-75	Catenary	1200	15,000	50	3	Power purchased from So. Cal. Edison Co.	4 1	(4) 1000-kw., 1200-volt Syn. M.G. Sets; 15,000-volt, a-c. G.E (1) 1000-kw., 1200-volt M.G. Set, A. C. Co.	24 5 44 2	54 44	(4) G.E. 254-600 Volts (4) G.E. 222-600 Volts (4) W-333-600 Volts (4) W-557-600 Volts	60	60	0	10	65	(4) W-308-600 Volts	M-A HL-A	Yes	D	Full	1200	West Automatic	Dyna. Comp.	35	1200	May, 1914	600 Volts	Los Angeles, San Bernardino & Riverside
Piedmont & Northern Lines, Charlotte, N. C.	125	125	10	S-80	Catenary	1500	2,400 13,200 2,000 44,000	60	3	Power purchased from Southern Pr. Co. (Hydro-Elec.)	8 1 Port	(12) 500-kw., 1500-volt, 3 unit M.G. Sets (6) 250-kw. Syn. Con., 2 in Series, for 1500-volt, West.	31 2	42	(4) W-321-750 Volts (2) G.E. 217-750 Volts	45	60	0	6 W 6 G.E.	55 64	(4) W-308-750 Volts (4) G.E. 212-750 Volts	West. HL R-200	Yes	S	Half		West. Variable Release	Dyna. Comp.	25	1500/750	May, 1912	New & Single-phase	Charlotte, Greenville, Spartanburg & Anderson
Pittsburgh, Mars & Butler Ry. Co., Pittsburgh, Pa.	33	33	5	5 ft. 2½ in. 80	Catenary	1200	22,000	25	3	(1) 1500-kw., (2) 750-kw., Turbine Generator Sets, 6600 volts, West.	2	(4) 300-kw., 1200-volt, Syn. Con. G.E.	13	38	(4) G.E. 225-600 Volts	47	48	0	0		. . . .	M-NA	Yes	D	Full	Hot Water	G.E Straight Air	C.P. 28	25	600	Aug., 1913	6600 Volts Single-phase	Pittsburgh & Butler
Pittsburgh, Harmony, Butler & New[illegible]	71	82	4	5 ft. 2½ in. 80	Direct Suspension Double Trolley	1200	13,200	60	3	(2) 1500-kw., Turbine Generators, 13,200 G-E also pur-	4	(6) 400-kw., 1200-volt, 3-unit Syn. M.G. Sets (1) 500-kw., 1200-volt, 3-unit Syn. M.G. Sets;	22 G.E. 7 W.	35 32	(4) G.E. 205-600 Volts (4) W-322-600 Volts	45	60	51 Fgt.	0	.	. . . .	M-A P.C	Yes	S & D	Half Full	Hot Water	G.E. Emer. Straight	C.P. 22 30	24 25	600 600/1200	July, 1908	New	Pittsburgh, Butler, Harmony & Ellwood City, Beaver Falls & New Castle

sas City R Co.												West	5		(4) W-327-750 Volts							M-A HL-A	Yes	D	Half	Hot Water	Comb. St & Auto. G E.	C P. 29	25	1200	Jan., 1913	New	Kansas City St Joseph & Excelsior Springs
K N Ry., Ontario,	54	56	1	S-85	Catenary Trolley	1500	26,400	25	3	Power purchased from Hydro-Elec. Pr. Commission of Ont.	3	(3) 500-kw., 1500-volt Syn Con. (1 Portable) Cand., G.E.	6	40	(4) W-85-h.p., 750 Volts	45	70	3	2	60	(4) W-562-D-5, 750 Volts	West. A-B	Yes	D	Half	1500 Volts	West. Automatic	Dyna. Comp.	25	1500	Feb., 1916	New	Galt, Brantford, Simcoe & Pt Dover
Ry. London, Ont.	24	30	0	S-70	Catenary	1500	13,200	25	3	Power purchased from Ontario Hydro-Ele Pr Com.	2	(4) 500-kw., 1500-volt Syn. Con., West.	8	51	(4) G E. 225-750 Volts	50	56	10	3	63	(4) G E. 251-750 Volts	M-NA	Yes	D	Half	Hot Water	Comb. St. & Auto. G.E.	C P. 29	25	1500	Aug., 1915	Steam	London, St. Thomas & Port Stanley
Ry. Co., Annapolis,	25.3	32.3	0	S-80	Catenary	1200	13,200	25	3	Power purchased from Consol. Gas, Elec. Lt & Pr. Co.	2	(5) 300-kw. Syn. Con., 1200-volt, d-c., West.	12 1 Ex.	40	(4) W-317-A-4, 600 Volts	45	52	0	1	52	(4) W-562-600 Volts	H-L-F NA	Yes	D	Half	Hot Air	W.-A.M M	D.-2K.	25.3	1200	Jan., 1914	6600 Volts, 1ϕ & Steam	Baltimore & Annapolis
Kalamazoo-Grand Battle Creek	92	95	4	S-80	Third Rail Over-running Catenary	1200	70,000	30	3	Power purchased from Consumers Pr Co., Jackson, Mich.	3	(8) 500-kw., 1200-volt Syn. Con. G E.	8 2 4	70 65 65	(4) G.E. 239 (2) G.E. 239-1200 Volts (4) G.E. 254-600 Volts	70 50	52	Fgt.	4 Exp	55	(4) G.E 239-1200 Volts	M-NA	Yes	S	Full	Hot Air	Comb. St & Auto. G E.	C P. 28	25	600	May, 1915	New	Kalamazoo, Grand Rapids, Allegan & Battle Creek
Bay City	46	46	5	S-80	Third Rail Over-running Direct Suspension	1200	20,000	60	3	Power purchased from Consumers Pr Co., Jackson, Mich	2	(4) 500-kw., 1200-volt d-c; 5000-volt a-c. Syn. Motor-Generator Sets G E.	12	40	(4) W-333-600 Volts	60	55	0	0	.	.	HL	Yes	S	Full	1200 Volts	West. A M M.	Dyna Comp	25	1200	May, 1914	New & 600 Volts	Flint, Saginaw & Bay City
west Div., Grand	45	77	5	S-60 S-70	Direct Suspension	1200	20,000	30	3	Power purchased from Consumers Pr. Co.	1	(2) 500-kw., 1200-volt Syn. Con. G.E.	10	35	(4) W-333-600 Volts	60	55	0	0	.	. .	M NA	Yes	S	Full	Hot Water	West.	Dyna Comp.	25	1200	May, 1915	600 Volts	Grand Rapids, Holland & Lake Resorts Macatawa and Saugatuck
& Lt. Co Mil-	135	135	47	S-80	Catenary Trolley	1200	13,200 38,000	25	3	Part of an Extensive System	6	(12) 300 kw. } Syn. Con, 600 volt, 2 in Series (5) 500-kw } G E.	11 15	43.5 39.5	(4) G E. 205-600 Volts (4) G E. 207-600 Volts	45	64	50	0		. .	M NA	Trailers Only	D	Full	Hot Water	West. D.-3 N			600/1200	Mar., 1910	3300 Volts Single-phase	Milwaukee, E. Troy, Burlington & Watertown
Ry., Nashville,	27	27	3.5	S-70	Direct Suspension	1200	33,000 Y	60	3	Power purchased from Nashville Ry & Lt. Co.	1	(3) 200-kw., 600-volt Syn. Con., 2 in Series, G.E., 1 spare	4 1 Ex.	38	(4) G.E. 205-600 Volts	40	50	0	0	.	.	K	No	S	Half	Hot Air	G.E. Straight	C P. 29	25	1200	Apr., 1915	New	Nashville & Gallatin
& Eastern Ry., San	118	118	4	S-70	Catenary	1200	11,000	60	3	Power purchased from Great Western Pr. Co.	5 1 Port	(6) 750-kw., 1300 volt Syn. M G Sets; 11,000-volt, a-c., West. (1) 300-kw., 1200-volt Syn. M G., G.E	3 G E. 15 W.	40	(4) G. E. 205-1200 Volts (4) W-322-600 Volts	55	50	18	2 2 2	49 62 35	(4) W-308-B, 600 Volts (4) W-321-600 Volts (4) G E 205-1200 Volts	M-NA W-HL	Yes	D	Full	1200 Volts	West.	Dyna. Comp.	2x25	1200	Sept., 1913	New	Oakland, Antioch, Sacramento & San Francisco
Portland, Ore	154	180	25	S-70 S-75	Catenary	1200	60,000	33	3	Power purchased from Portland Ry & Lt. Co	6 1 Port 6	(6) 500-kw., 600/1200 Syn. Con. (7) 500-kw., 1200-volt Syn. Con. G E.	53 8 Ex. 1 W.	45	(4) G.E. 205 (4) G.E. 222-600 Volts (4) W-321-600 Volts	45	62	28	6 4	60 50	(4) G.E. 212-600 volts (4) G.E. 207-600 Volts	M-A	Yes	D	Full	Hot Water 1200 Volts	West. D-3		35	1200	Aug., 1912	600 Volts & New	Portland, Salem, Albany & Eugene
ific Angeles, Cal.	57	91.5	1.7	S-70 S-75	Catenary	1200	15,000	50	3	Power purchased from So. Cal. Edison Co.	4 1	(4) 1000-kw., 1200-volt Syn. M.G. Sets; 15,000-volt, a-c. G.E. (1) 1000-kw., 1200-volt M G. Set, A. C. Co.	24 5 44 2	54 44	(4) G E. 254-600 Volts (4) G.E. 222-600 Volts (4) W-333-600 Volts (4) W-557-600 Volts	60	60	0	10	65	(4) W-308-600 Volts	M A HL-A	Yes	D	Full	1200	West Automatic	Dyna. Comp.	35	1200	May, 1914	600 Volts	Los Angeles, San Bernardino & Riverside
iedm N C nes, Charlotte,	125	125	10	S-80	Catenary	1500	2,400 13,200 2,000 44,000	60	3	Power purchased from Southern Pr Co. (Hydro-Elec.)	8 1 Port	(12) 500-kw., 1500-volt, 3-unit M G. Sets (6) 250-kw. Syn. Con., 2 in Series, for 1500-volt, West.	31 2	42	(4) W-321-750 Volts (2) G.E. 217-750 Volts	45	60	0	6 W 6 G E.	55 64	(4) W-308-750 Volts (4) G.E 212-750 Volts	West. HL R-200	Yes	S	Half		West. Variable Release	Dyna. Comp.	25	1500/750	May, 1912	New & Single-phase	Charlotte, Greenville, Spartanburg & Anderson
Pittsburg Pittsbur er Ry Co.,	33	33	5	5 ft. 2½ in. 80	Catenary	1200	22,000	25	3	(1) 150 kw., (2) 750-kw., Turbine Generator Sets, 6600 volts, West.	2	(4) 300-kw., 1200-volt, Syn. Con., G E.	13	38	(4) G E. 225-600 Volts	47	48	0	0		.	M-NA	Yes	D	Full	Hot Water	G E Straight Air	C.P. 28	25	600	Aug., 1913	6600 Volts Single-phase	Pittsburgh & Butler
Pittsburg & New-castle R	71	82	4	5 ft 2½ in. 80	Direct Suspension Double Trolley	1200	13,200	60	3	(2) 1500-kw., Turbine Generators, 1200 G-E also purchase Duquesne Lt. Co.	4	(6) 400-kw., 1200-volt, 3-unit Syn. M G Sets (1) 500-kw., 1200-volt, 3-unit Syn. M G Sets; G.E. (2) 250-kw. Syn. Con., 2 in Series (2) 500-kw., 1200-volt, 3-unit, and (2) 200-kw., 2-unit, 600-volt Syn. M G. Sets, 2 in Series, West. (2) 500-kw., 1200-volt 2-unit M.G. Sets, G.E.	22 G E. 7 W. 2 G.E.	35 32	(4) G.E. 205-600 Volts (4) W-322-600 Volts (4) G.E 225-600 Volts	45	60	51 Fgt.	0		.	M-A P.C	Yes	S & D	Half Full	Hot Water	G E. Emer. Straight	C.P. 22 30 28	21 25	600 600/1200	July, 1908	New	Pittsburgh Butler, Harmony & Ellwood City, Beaver Falls & New Castle
Salt Lake, Garfield & Western Ry.	20	20	1.25	S-60	Direct Suspension	1500	44,000	60	3	Power purchased from Utah Pr & Lt Co.	2	(2) 600-kw., 1500-volt, Ind Motor Gen. Sets, G E. Automatic Control	6	45	(4) G.E. 240-750/1500 V	45	56	18	0	.	.	P C.	Yes	D	Full	Hot Water	Comb St. & Auto G.E.	C.P. 28	35	1500	Aug., 1919	Steam	Salt Lake City & Saltair Beach
Salt Lake & Utah Ry., Salt Lake City, Utah	77	77	1	S-75	Catenary Trolley	1500	44,000	60	3	Power purchased from Utah Pr & Lt. Co.	4	(12) 250-kw Syn. Con., 750-volt, 2 in Series, 1 spare, West.	2 Ex. 14 2	35 44 11¼	(4) W-562-A-5-750 Volts (4) W-334-E-750 Volts (2) W-530-750 Volts	50	62	0	2	50	(4) W-562-A-5-750 Volts	HL-NA R-200	Yes	D	Full	1500 Volts	West. St & Auto.	Dyna. Comp.	37	1500	July, 1914	New	Salt Lake City, Provo & Payson
Shore Line Electric Ry Co., Saybrook, Conn.	56.4	58	10.3	S-70	Catenary and Direct Suspension	1200	11,000	25	3	(2) 1500-kw., Turbine Generator, 11,000-volt, G.E. Saybrook	2	(8) 200-kw., 600-volt Syn. Con., 2 in Series, G E.	14 2 8 W.	30	(4) G.E. 217-600 Volts (4) G.E. 205-600 Volts (4) W-327-600 Volts	43	44	0	0		. . .	M-NA HL-NA	Yes	D	(14) Half (8) Full	1200 Volts	Emer. St & Auto. G E.	C.P. 29-28	25	600/1200	Sept., 1910	New	New Haven & New London
So. Cambria Ry. Co., Johnstown, Pa	27	28	0	S-70	Direct Suspension Double Trolley	1200	None			(2) 300-kw., 600/1200-volt, (2) 500-kw., 600/1200-volt, Engine Driven Gen., G.E.	0	Direct Feed	10 G E.	38	(4) G.E. 205-600 Volts (4) G.E. 217-600 Volts	43	50	0	1	35	(4) G E. 205-600 Volts	M-NA	Yes No.	D	Full	Hot Water	Emer. St. Air G.E.	C P. 22	21	600	1910	New	Johnstown, Ebensburg, South Fork, and Nant-Y-Glo
So. Illinois Ry. & Pr. Co., Harrisburg, Ill.	15	17	0	S-80	Catenary Trolley	1200	33,000	60	3	(2) 1000-kw., 2300-volt Curtis Turbine at Muddy	1	(2) 300-kw. Syn. M.G. Sets, 1200-volt, located in P.H., G.E.	5	40	(4) G.E. 205-600 Volts	41	46	2	0		. . .	M-NA	Yes	D	Half	Hot Water	Comb. St & Auto. G.E.	C.P. 29	25	1200	Sept., 1913	New	Eldorado, Harrisburg, Carriers Mills
Southern Pacific Co., Electric Division, Portland, Ore	146	162	3	S-75 S-90	Catenary	1500	13,200 60,000	60	3	Power purchased from Portland Ry., Lt. & Pr. Co.	5 1 Port	(7) 500-kw., 1500-volt Syn. M.G. Sets, G.E. (4) 500-kw., 750-volt Syn. Con. West., 2 in Series	30 5 Ex. 3 Mail	51	(4) G.E. 205-750 Volts	50	60	11	3	60	W-308-750 Volts	M-A	Yes	D & S	Full	1500 Volts	West.	Dyna. Comp.	35	600/1500	Jan., 1914	Steam & New	Portland, Oswego, McMinnville, Forest Grove, Independence & Corvallis
So. Pacific Railroad (Oakland, Alameda & Berkeley Div.)	118	138	0	S-80	Catenary	1200	13,200	25	3	(2) 5000-kw. Turb. Gen. West. (1) 2500-kw., 60/25-cycle Freq. Ch Set G.E. Pr. also pur. Gt Western Pr. Co.	3	(20) 750-kw., 600-volt Syn. Con., 2 in Series, G.E.	81 10	50½ 30	(4) G.E. 207-600 Volts (4) W-337-600 Volts	40 27	88 116 52	40	0		. . . .	M-A HL	Yes	D	Half		West A.M M	West.	35	1200	Apr., 1911	Steam	Oakland, Alameda & Berkeley
Southwestern Traction & Pr. Co., New Iberia, La.	14	14	0	S-60	Catenary	1200	None			(1) 200-kw., 1200-volt d-c. Gen. Engine Driven, G.E.	0	Direct Feed	3	26	(4) G.E. 217-600 Volts	36.5	46	0	0	.	....	K	No	D	Half		Straight Air G.E.	C.P. 29	25	1200	May, 1912	New	New Iberia & Jeanerette
Texas Electric Ry., Dallas, Texas	158	158	0 5	S-70 S-80	Catenary	1200	66,000	60	3	Purchased from Texas Pr. & Lt. Co.	6 1 Port	(4) 400-kw., 1200-volt Syn. M.G. Sets (6) 400-kw., 600/1200-volt Syn. M.G. Sets, G.E.	22 6 Ex.	41	(4) G.E. 225-600 Volts	65	56	12	2	25	(4) G E. 225-600 Volts	M-NA	No	5-D 23-S	Full	1200 Volts	West. A M N. G E Comp.	C.P. 29	25	600	Oct., 1913	New	Dallas, Waco & Corsicana
Tidewater So. Railroad Co., Stockton, Cal.	33	33	0	S-65	Catenary	1200	16,500	60	3	Power purchased from Sierra & San Francisco Pr. Co.	2	(4) 200-kw., 600-volt Syn. Con., 2 in series, West.	3	30	(4) G.E. 201-600 Volts	43	40	0	1	40	(4) G.E 207-600 Volts	M-A	Yes	D	Half	1200 Volts	West.	Dyna. Comp.	35	600/1200	Nov., 1913	New	Stockton & Modesta
Toronto Suburban Ry., Toronto, Can.	49	56	3	S-70	Catenary	1500	25,000	25	3	Power purchased from Toronto Pr. Co	3	(4) 500-kw., 1500-volt Syn. Con., G.E. (1) 500-kw., 1500-volt Syn. Con., Cand., G E.	6	45	(4) G.E. 240-750 Volts	52	56	0	0	.	....	M NA	Yes	S	Half	Hot Water	Comb. St. & Auto. G.E.	C P. 28	25	750	Nov., 1916	New	Toronto, Georgetown & Guelph
United Rys., Portland, Ore	20	27	0	S-60 S-90	Catenary	1200	60,000	33	3	Power purchased from Portland Lt. & Pr. Co.	1	(2) 500-kw., 600-volt Syn. M.G. Sets in Series, West.	7	40	(4) G.E. 73 and 205 (4) G.E. 205-600 Volts	45	62	3	1	40		M-A	Yes	D	Full	1200 Volts	West. Auto.	West.	35	600/1200	Jan., 1913	600 Volts, D-C.	Portland & Wilkesboro
Utah-Idaho Central Railroad Co.	97	97	0.2	S-70	Catenary	1500	44,000	60	3	Power purchased from Utah Power & Lt. Co.	3	(5) 500-kw., 1500-volt Syn. M.G. Sets, 2300-volt a-c., West. (1) 500-kw., 1500-volt, 3-unit M.G. Set. 2300-volt a-c., West.	19	45	(4) W-334-750 Volts	47	56	6	5 1	50 30	(4) W-562-A, 750 Volts (4) W-334-750 Volts	West. HL-NA	Yes	D	Full	1500 Volts	West. A.M.M.	Dyna. Comp.	36	1500	Apr., 1915	New	Ogden, Logan & Preston
Washington, Baltimore & Annapolis Elec. R. R., Baltimore, Md	61	103	14	S-80	Catenary	1200	33,000	25	3	Power purchased from Potomac Elec. Pr. Co.	4	(15) 300-kw., 600-volt Syn. Con., 2 in Series, G E.	53	40	(4) G.E. 205-600 Volts (4) G.E. 233-600 Volts	45	54	0	3	45	(4) G E. 207-600 Volts	M-A	Yes	D	Half	Hot Air	West. G.E. Comp.	C.P. 29	25	1200	Feb., 1910	6600 Volts, 1ϕ & Steam	Washington, Baltimore & Annapolis
Waterloo, Cedar Falls & Northern, Waterloo, Iowa	60	65		S-72	Catenary	1200	40,000	25	3	(2) 1500-kw., (1) 3000-kw. Turbine Generator	4	(4) 500-kw., 1300-volt, Syn. Con., Allis Chalmers Co.	8 5	47 32	(4) W-333-600 Volts (4) W-317-500 Volts	60	52		5	60	(4) W-308-600 Volts	HL	Yes	S	Full	Hot Water	West. A.M.M.	Dyna. Comp.	38	1200	Sept., 1914	New & 600 Volts	Waterloo & Cedar Rapids
Willamette Valley Southern Ry.	30	32	0	S-60	Catenary	1200	57,100	60	3	Power purchased from Portland Ry. & Light Co.	2	(2) 500-kw., Syn. M.G. Sets, 1200-volt, West.	3	34	(4) G.E. 240-600 Volts	40	58	3	1	50	(4) G.E. 207-600 Volts	M-NA	Yes	D	Full	1200 Volts	West. Auto. Air	Dyna. Comp.	25	1200	Jan., 1914	New	Oregon City, Beaver Creek, Mt. Angel

FOREIGN HIGH-VOLTAGE DIRECT-CURRENT RAILWAYS, GENERAL ELECTRIC

Bethlehem Chile Iron Mines Co., Tofo, Chile	15	24	0	S-100	Catenary	2400	2,300	60	3	(2) 3500-kw., 2300-volt Turbine Generator, General Electric	1	(2) 1000-kw., 3-unit, 2400-volt d-c, Syn. M.G. Sets, 2300-volt a-c., G.E.	0	...	....	..	..	. .	3	120	(4) G.E. 253-1200 Volts	......	.....	..	.. ....	....	West. St. & Auto.	C P. 34	150	2400	1918	New	Tofo Iron Mines & Cruz Grande
Hershey Cuban Ry., Cuba	75	81	0	S-85	Catenary	1200	33,000	60	3	(3) 2000-kw. G.E. Turbines	3	(10) 500-kw., 600/1200 Syn. Conv. G.E.	16	29	(4) G.E. 263-600 Volts	39	50	0	7	60	(4) G.E. 251-600 Volts	P.C.	Yes	D	Half	None	Comb. St. & Auto.	C.P. 29	25	1200	Bldg., 1920	Steam	Havana & Matanzas
Imperial Railways, Japan	20	40	4	42 in.	Catenary	1200	11,000	25	3	(3) 1500-kw., 11,000-volt Gas Eng. Alternators Dick. Kerr.	1	(2) 1000-kw., 3-unit, 1200-volt Syn. M.G. Sets, Siemens	40	40	(4) G.E. 244-600 Volts	45	45	14				M-A	Yes		Full		G.E. Comb. St. & Auto.				1915	Steam	Tokio, Yokohama
South Manchurian Ry., China	25	43	0	S-50 S-80	Catenary	1200	2,300	60	3			(3) 400-kw., 1200-volt Syn. M.G. Sets, G.E.	4	35	(2) G.E. 205-1200 Volts	25			3 10	40 56	(4) G E. 206-600 Volts (4) G.E. 207-600 Volts	M	No	D	Half			C.P.	25	1200	1914	Steam	Fushun, Colliery
Victorian Rys., Melbourne, Australia	150	325	0	85 5 ft., 3 in.	Catenary	1500	20,000	25	3	(6) 10,000-kw. Parsons Turbine	15	Syn. Con., 750 to 3000 kw. each. Total, 81,000 kw. Subject to change	400	50	(4) G.E. 237-750 Volts	52	70	400	0	..	....	M-A	Yes	D	Half		G.E. Comp.	C.P. 29	27	1500	May, 1919	Steam	Melbourne & Suburbs

* To be transferred to Cascade Division for freight service.

Summary of High-voltage Direct-current Railways

By W. D. Bearce

Railway and Traction Engineering Department, General Electric Company

W. D Bearce

The movement toward higher direct-current voltages began with interurban railways in 1907, when the Indianapolis and Louisville Traction Rwy. started operation at 1200 volts. This installation was followed shortly afterward by the Pittsburgh, Harmony, Butler & New Castle Rwy. and many others. In 1913, the Butte, Anaconda & Pacific Rwy. adopted 2400 volts direct current for a 30-mile steam-road electrification; and, after this successful demonstration, 3000 volts direct current was selected for the main line electrification of the Chicago, Milwaukee & St. Paul R. R.

The universal success of the higher direct-current trolley voltages is due in a large part to its logical development from existing well-tried 600-volt equipment. The first 1200-volt car equipment used 600-volt motors, two in series, followed later by straight 1200-volt motors on the Central California Traction lines. From this point it was only a short step to 1200/2400-volt and 1500/3000-volt motors for steam-road electrifications.

Even less difficulty was encountered in building substation equipment for the higher voltages. Synchronous converters are operating at 1500 volts on 25 cycles with the same success as 600-volt machines, while 2400-volt and 3000-volt motor-generator sets are giving unquestioned reliability under severe service conditions.

During the past few years there has been little progress in the construction of interurban railways, due to adverse financial conditions, so that comparatively few new high-voltage direct-current installations have been made. The accompanying table is a revision of a similar tabulation published in the General Electric Review, November, 1916, and contains information on additional equipment and new roads. Notable additions to this table include the Othello-Seattle Tacoma Division of the Chicago, Milwaukee & St. Paul R. R., with 217 miles of road, which has been electrified with 3000-volt direct-current; the Hershey Cuban Railway in Cuba, at 1200 volts; and the Salt Lake, Garfield & Western Railway, at 1500 volts. Below is a summary of high-voltage lines in the United States and Canada grouped according to trolley voltage.

System	Number of Installations	Miles		Rolling Stock	
		Route	Single Track	Cars	Locomotives
1200 volts	32	1847	2082	604	62
1500 volts	9	596	630	134	29
2400 volts	2	40	144	8	37
3000 volts	2	657	871	0	61
Total	45	3140	3727	746	189

Control for 1200 and 1500-volt Car Equipments

By R. S. Beers and C. J. Axtell
Railway Equipment Department, General Electric Company

R. S. Beers

C. J. Axtell

With the advent of the high-speed interurban lines it became necessary to increase the trolley voltage in order to reduce the sub-station and distribution system investment. The higher voltages which have been used are 750, 850 1000, 1200, and 1500. The last two voltages have become standard in America, and foreign countries are rapidly adopting them.

With these higher voltages the control differs only in the addition of "breaks" or contacts, increased insulation, and auxiliary circuit apparatus. The direct control of the motors is accomplished with either a drum controller or a multiple-unit controller, the same as is used in standard 600-volt practice. On small cars and where train operation is not essential, the drum controller has the same advantages that it possesses for 600-volt work. In a large majority of cases, the capacity of the equipments and the necessity of train operation require multiple-unit control.

The latest development in multiple-unit control systems is one in which the individual contactors are closed by cams.* The use of cams is advantageous in that it secures an absolutely definite sequence of closing and opening the contactors, thereby entirely eliminating the electrical interlocks required for this purpose on individually operated contactors. This sequence is accomplished by mounting the cams on a shaft which is actuated by a single air cylinder with two pistons, the air being governed by two magnet valves. In addition to the cam operated contactors, the complete controller contains line breakers, reverser overload and accelerating relays, thus embodying in one piece of apparatus all of the motor control parts except the resistors required to accelerate, series-parallel, and reverse the motors, as well as to rupture the motor circuit under normal and overload conditions.

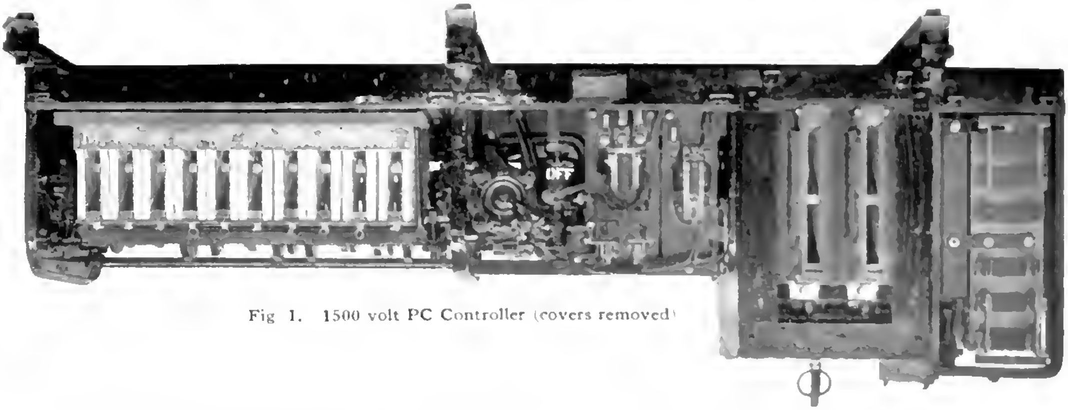

Fig 1. 1500 volt PC Controller (covers removed)

The 1200 and 1500-volt car equipment presents many interesting features on account of the possible variations, due to operation on existing 600-volt lines, in the source of energy for the auxiliary circuits, such as headlights, lights, compressor, and control.

The simplest control is that for operation at one voltage. With the exception that two motors of each pair are permanently connected in series, a 1200-volt equipment is similar to one for 600 volts. Each motor is essentially a 600-volt motor having its windings insulated for 1200 volts.

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* This method of control is commonly known as the "Type PC."

While this is the simplest method of operation, in the majority of cases it is also necessary to operate at some lower voltage, usually 600 volts, to enter cities over existing systems. When operation on the lower voltage is at half speed the main motor circuit is unchanged, though it is necessary to change over the auxiliary circuit connections.

A third motor-circuit combination arises when it is required to operate the equipment at full speed on both the high and low-voltage sections of the system. Under these conditions the simplicity of the other two equipments is lost to a considerable degree, for it becomes necessary to commutate the motors to obtain full speed. When the motors are commutated, the current capacity of the other parts of the circuit must be increased to compensate. This, in detail, means additional length and double cross-section of cables, and the commutation of motor resistors to obtain a smooth acceleration and of the line breakers for capacity, as well as commutating the overload device to obtain the same degree of protection with both voltages. At the same time it is necessary to commutate some of the auxiliaries.

In many cases an analysis of the requirements shows that the simpler equipment works out most advantageously in both city and interurban operation. This is due to the fact that the speed for which the interurban cars are normally geared cannot be economically or safely used in city operation. Thus, the 600/1200-volt equipment operating at half speed on 600 volts automatically accomplishes, without complication, that which some operators have added considerable apparatus to a 600-volt equipment to obtain.

Figs. 4 and 5 show in a simple manner the connections of the two types of equipments. It is self-evident that the equipment for half speed on 600 volts (Fig. 4) is much simpler than that for full speed on both voltages (Fig. 5), also that a further simplification will be effected by omitting the commutating connections of the compressor and motor generator if operation on but one voltage is required.

On 1200 and 1500-volt equipments it is the practice to use a low-potential source for some of the auxiliary circuits. Economy, safety, and reduction in size of apparatus have been the deciding factors in this respect. The auxiliaries to be provided for are: lights, headlights, control, compressor, and sometimes heaters. Power for these auxiliaries has been derived in the following ways:

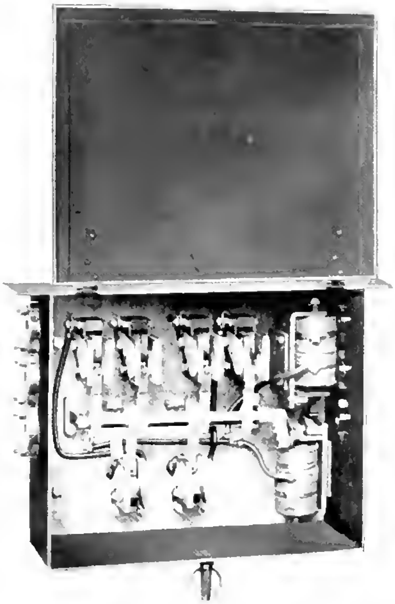


Fig. 2. Commutating Relay for Auxiliary Circuits When Operation is at Half Speed on 600 Volts

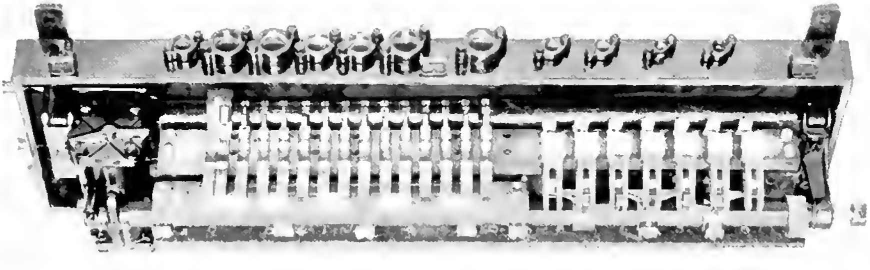


Fig. 3. Commutating Switch for Main and Auxiliary Circuits When Operation is at Full Speed on 600 Volts

Direct from Trolley

Lights, headlight, compressor, and heaters.

"Potentiometer" or Resistance Method

Control.

Storage Battery
    Lights, headlight, and control.
Dynamotor
    Lights, headlight, control, and compressor.
Motor Generator
    Lights, headlight, and control.

Supplying the car lights and headlight with power directly from the trolley requires ten lamps connected in series, thereby causing a loss of one third to one half of the illumination if a single lamp burns out. With a headlight of the ordinary luminous-arc type there is an energy loss of over 4 kw. in the headlight resistor. The fixtures and switches for both the lighting and headlight must necessarily be larger and more expensive than the same devices for lower voltages. Up to the present time the use of a high-power incandescent headlight operated directly from 1200 volts has not been feasible, due to the inability to arrange the filament for both illumination and safety.

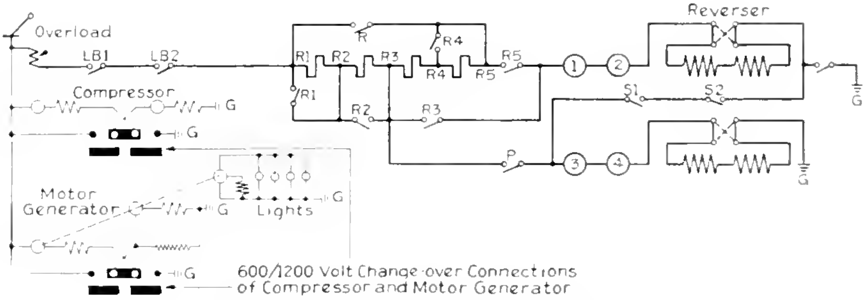


Fig. 4 Circuit Connections for Half Speed Operation on 600 Volts

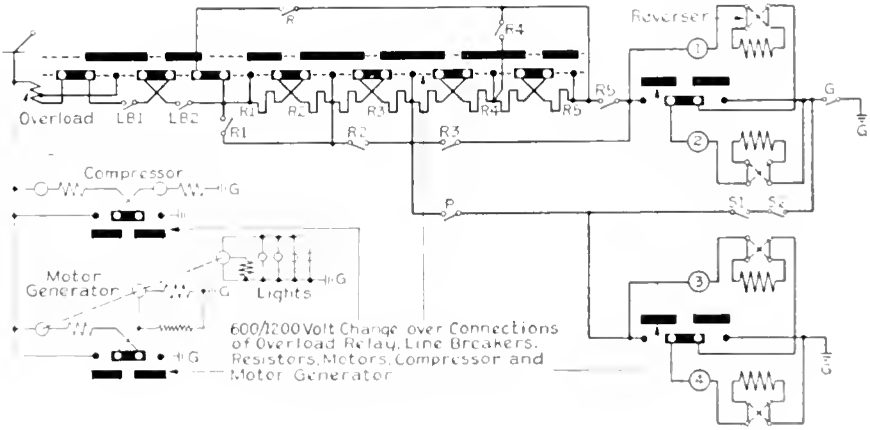


Fig. 5. Circuit Connections for Full Speed Operation on 600 Volts

The compressor and heaters can be operated most advantageously direct from the trolley; any other method means a large increase in rotary transforming apparatus, as the compressor and heaters are a very large percentage of the total auxiliary load. Where it is essential that the heaters or compressors deliver full output on 600 volts, they may have their circuits changed over like the motor circuits.

With the "potentiometer" or resistance method of obtaining a source of power for the control, certain disadvantages are inherent. Among these disadvantages are: a waste of energy in the resistor, a varying voltage of the control circuit due to the varying load, an increased size of the master controller, due to rupturing the high-voltage circuit through the resistor whenever the controller is turned off, and a train line through the coupler at trolley potential. Furthermore, this method does not provide any means of obtaining low-voltage current for the other auxiliaries.

The second method of obtaining a low-voltage source of current which has been used to a limited extent is a storage battery. A small storage battery which will furnish enough power for controlling the pneumatic cam motor controller can be charged in series with the air compressor motor. A 32-volt storage battery has usually been selected in order to keep the number of cells at a minimum. Such a battery will not furnish sufficient energy to light the car, as the energy available from the compressor motor is limited.

A storage battery supplying energy for control, car lights, and headlights must be of considerable size, as during the winter season lighting is required for 10 to 14 hours per day. Aside from the high first cost and heavy weight of these batteries, the serious problem involved is to find some method of charging. This can be accomplished in one of three ways; by connecting the battery in the grounded side of one motor, by putting a separate motor-generator set on the car for charging, or by charging the batteries at the terminal stations. If the first method of charging is used, a very high ampere capacity battery is required in order that the high accelerating current of the motor does not cause rapid deterioration of the plates. The second method involves a considerable complication of apparatus, aside from the motor-generator set, such as relays, etc., to charge the battery properly. The method of charging at the terminal has been employed to a certain extent on Pullman cars, but has not worked out satisfactorily, due to the fact that cars do not arrive at terminals at regular intervals and can not be held over long enough to obtain the proper charge.

Fig. 6a. 1200-volt Receptacle

Fig. 6b. 32-volt Receptacle, Lamp, and Reflector

With a storage battery on the car, some means of automatic regulation for maintaining a constant voltage on the lights and headlights must be provided, as the regulation of the batteries from full charge to discharge is too great for the satisfactory operation of the lamps. Furthermore, a storage battery must be properly maintained by skilled labor; and even then the maintenance for such service will be high compared with other methods of obtaining power.

A dynamotor used as a source of auxiliary power, while operating satisfactorily and providing current for lights, headlights, control, and possibly compressor, has the disadvantage that to be built of an economical size it must divide the trolley voltage in the ratio of about two-to-one. This necessitates operating the lamps in the car connected five in series which does not afford as flexible or as economical an arrangement of lighting as when the lamps can be connected in multiple. Also, to obtain a headlight satisfactory for high-speed operation, a considerable amount of energy is wasted in a headlight resistor. The voltage variation of the dynamotor is practically the same as the voltage variation of the trolley line, since the machine does not provide any means of maintaining uniform illumination of the car with varying trolley voltage.

With pneumatic cam control equipments, the most satisfactory source of power is a small motor-generator, mounted on the car, furnishing power for lights, headlights, and control. The set furnished on such equipments is 1.5 kw. capacity, the motor being designed with two windings and two commutators with provision for connecting these windings in series when operating on 1200 volts and in parallel when operating on 600 volts. A novel design of generator provides inherent regulation to hold a practically constant potential of 32 volts on the generator with any normal variation in trolley potential.

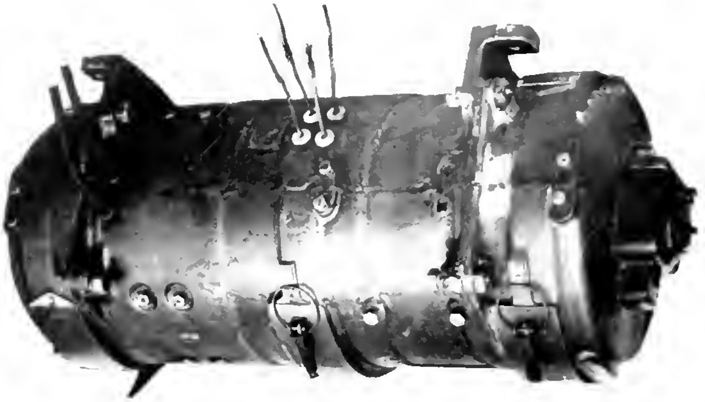
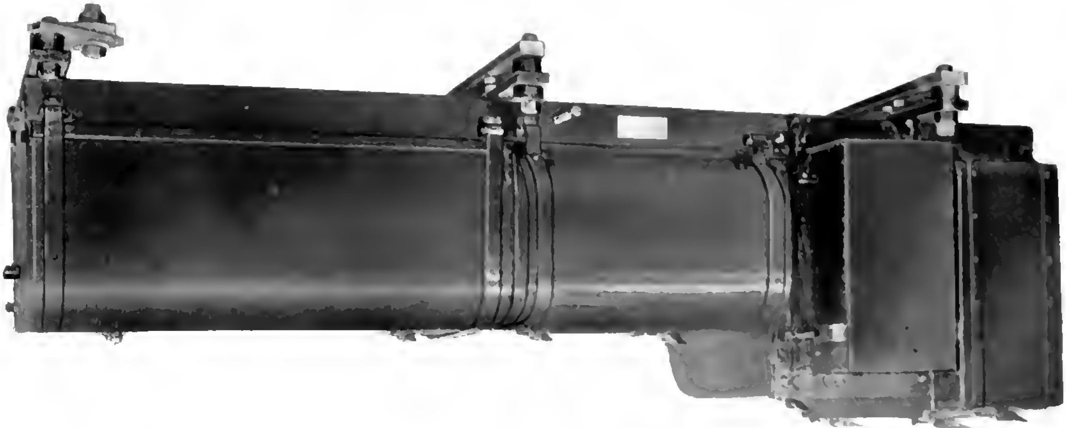


Fig. 7. 1½-kw. Motor-generator, 600 1200-volt Motor, 32-volt Generator

A potential of 32 volts for the auxiliary circuits was selected after a careful study of the various voltages used in steam railway practice. This voltage is sufficiently high so that troubles from loose and dirty contacts, inherent with much lower voltages, are not experienced. It permits the use of a lamp for the interior lighting that has a stronger filament than those for a higher voltage. The 32-volt incandescent headlight has been adopted as the most satisfactory one obtainable, as it provides not only a powerful direct beam but the necessary diffused illumination at the sides of the track. The 32-volt 250-watt incandescent headlight is equal in illumination to a 4-amp. luminous arc headlight at its best and never has the unsteadiness of beam inherent with any arc lamp.

With this lower voltage lighting in the cars all lamps are connected in multiple, so that the burning out of a single lamp does not affect the illumination of any of the other lamps and permits the use of any number and size of lamps desirable for car, vestibule or signs.

The inherent regulation of the motor-generator means a uniform brilliancy of illumination from the lamps and the headlight which is most agreeable to both the passengers and crew. It is obtained without any moving parts other than the motor-generator.*



1500-volt Controller, Cover in Place

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* This lighting equipment was completely described in the article "An Improved System for Lighting Interurban Trolley Cars," by W. J. Walker, GENERAL ELECTRIC REVIEW, Feb., 1918.

The Public Trusteeship of the Boston Elevated Railway

By Edward Dana

General Manager, Boston Elevated Railway Company

Several years ago our city transportation systems called to the public's attention the fact that increasing cost of operation on the one hand and fixed remuneration for service on the other were assuming the character of "the devil and the deep blue sea" and also that the intervening gap within which the companies could remain financially sound was becoming constantly narrower. The engineer responded to the call of distress and designed more efficient equipment to retard the approach of the devil, but the deep blue sea resisted all entreaties to recede until the public was made to realize that the funeral of the traction companies would be its own as well. Various methods have subsequently been used in readjusting the rates of fare. In the following article Mr. Dana first describes the events which led up to the Public Trustee plan employed in operating the Boston Elevated and then appends a brief of the provisions of the Trusteeship.—Editor.

Events Leading Up to the Trusteeship


Edward Dana

Numerous articles have been written in the past two years relative to the appointment of the Public Trustees of the Boston Elevated Railway Company, and consequently it may be interesting to go back for a period of ten years and briefly state a few of the salient facts which were brought forth when the road was privately operated, and which ultimately led to the necessity for placing the road under public operation.

In response to an order adopted in June, 1908, by the Massachusetts Senate, the Railroad Commissioners subsequently reported that: "A careful study and comparison of systems of street railways in Massachusetts and elsewhere show no grounds for serious criticism of the service rendered in this Commonwealth. The street railway companies here are fulfilling their functions quite as well as any similar utility elsewhere." At the same time, early in 1909, one of the officials of the Company showed that the capital invested had increased 58 per cent in five years, whereas the increase of earnings was but 3.4 per cent and that "a study of the foregoing figures shows clearly that under the present system of fare and transfers the company is rendering a greater service than it can afford for the compensation received." Therefore, as early as 1908, although the street railways were satisfactorily performing their duties to the public, it was beginning to be recognized that the capital investment was increasing at a rate all out of proportion to the increase in return to the companies.

Again in November, 1910, the President of the Company, at a hearing before the State authorities, stated that the Company had made large contributions toward transportation facilities; that whereas, when the West End property was taken over by the Elevated, in 1898, there were $26,000,000 invested, in 1910 there were upward of $81,000,000; that the company had undertaken to expend in the following four or five years $31,000,000, making a total investment for 1914 of $112,000,000; that the demands for improved facilities had increased far beyond the increase in revenue; and that the Company was in no position to assume new burdens in the way of subways and tunnels with the uncertainty existing as to the future return. This in effect was a protest against the constant agitation on the part of the public for extensions of the subway and tunnel facilities, on all of which the Company had to pay the entire interest on the cost, as well as to contribute a certain percentage on the cost each year toward an amortization fund.

In the years 1910 to 1914 constant agitation was made for additional facilities until, in February, 1915, the President of the Company before a committee of the Massachusetts Legislature protested that: "The people of Metropolitan Boston in street cars are getting more than they pay for, or as I prefer to put it, they ought to pay more for what they are getting—and the investors are not getting a fair return."

No relief was forthcoming and on May 22, 1916, the Company asked the Governor of Massachusetts to request the Legislature to make provision for the appointment of a commission to report to the next General Court as to whether in its opinion "it is advisable for the State to take any action, either by way of legislation or otherwise, with a view to enabling the Company to obtain a net revenue adequate for its corporate and public purposes; and, if so, what action."

In September, 1916, the Company through counsel submitted an elaborate report as to its financial condition to the Special Commission, and in it said: "The present financial condition of the Elevated Company is due to the following three causes.

(1) The increase in cost of materials and labor has made it impossible to secure the reductions in operating costs which should otherwise have resulted from improved methods and increased efficiency.

(2) The enormous increase in the permanent investment has been at a much greater rate than the growth of the business has warranted.

(3) Owing to the extension of the length of rides in connection with the free transfer system, the revenue has not been increased in proportion to the service rendered."

This statement further said: "Whatever action is recommended by this Commission, it should include some arrangement for a period of years, say until the expiration of the present subway leases, by which the Company may be assured of six per cent dividends so long as it is properly managed and properly performs its functions as a public agent."

The result of the investigations of this Special Commission of 1916 was the passing of an Act by the Legislature providing for an investigation of the Company by the Public Service Commission; and at the same time another commission was appointed by the Legislature to investigate the situation on all the street railways of the State, to look into the situation all over the country, and to report as to what might be accomplished toward relief of the street railway properties.

In appearing before the Street Railway Investigation Commission in 1917, the President of the Company said: "I suggest to your honorable Commission the expediency of recommending to the next Legislature the enactment of legislation to accomplish the result of permitting street railway companies to fix what they believe to be fair, proper and necessary tariffs, subject to corrective supervision."

Early in 1918 the Special Street Railway Investigation Commission reported to the Legislature recommending among other things a service-at-cost act for the street railways, and shortly thereafter the Public Service Commission recommended as a result of its investigation of the Elevated Railway that the Company should be placed under public control under a Board of Trustees of five members.

The Company at this time was in dire straits financially. The country was at war, the cost of material and labor were mounting with rapid bounds, the cost of new subway and tunnel extensions together with the greatly increased capitalization of the property itself were bringing the results predicted; and finally on March 1, 1918, Samuel W. McCall, Governor of Massachusetts, sent a special message to the Legislature stating: "I am convinced that immediate action on this subject is necessary in the interest of the public, as well as those who own and operate the Elevated Railway."

The following month a bill was reported from the Committee on Metropolitan Affairs to the Legislature containing the Trustee plan, and on May 22, 1918, the plan as finally approved was passed under Chapter 159 of the Special Act of 1918. A Board of five Trustees was appointed by the Governor and took office on July 1st following.

It is interesting to note that over nine years elapsed from the time that the officials of the Company first began pointing out the impossibility of increasing capital invested for improved facilities way out of proportion to the increase in revenue obtained, and that, entirely apart from the foregoing brief sketch of salient points leading up to the establishment of Public Trustees, the Company and its affairs were constantly in the public eye. There has been nothing hasty in the action of placing the Boston Elevated Railway under public control. It is merely the careful working out of a situation that had been developing for a number of years previously.

Provisions of the Trusteeship*

1. *Life*

The period of public operation specified in chapter 159 of the special acts of the Massachusetts Legislature of 1918 is ten years from the date when the act took effect, but unless terminated by the State continues indefinitely. (*Secs. 1 and 12.*)

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* This section of the article was prepared by Mr. H. C. Clark for the purpose of outlining the details of the Act, and is here being reprinted from *Aera*, October, 1919.

2. *Renewals*

   Public operation and management shall continue after the expiration of the ten-year period until such time as the Commonwealth shall elect to discontinue it. (*Sec. 12.*)

3. *Forfeiture*

   By appropriate legislation, passed not less than two years before the date fixed for termination, the Commonwealth may terminate public management, either at the expiration of the ten-year period or at any time thereafter. (*Sec. 12.*)

MUNICIPAL PURCHASE

1. *By the City* (in this instance by the Commonwealth or any political subdivision thereof):

   (a) When Purchase Can be Made:

   Under provisions of the act, at any time during the period of public management and operation; under the State's power of eminent domain, at any time. (*Sec. 16.*)

   (b) Terms of Purchase:

   Upon the assumption of the Company's outstanding indebtedness and liabilities and the payment of an amount in cash, equal to the amount paid in cash by its stockholders for its stock then outstanding. (*Sec. 16.*)

   Readjustment of this provision in order to meet conditions which would arise through the purchase, the terms of which are already provided by law previously enacted, of the West End Street Railway Company, now leased by the Boston Elevated Railway Company is provided for, but the principle involved is the same. (*Sec. 16.*)

2. *By License of City* (in this case by the State or any political subdivision thereof):

   No provision for purchase by license.

CONTROL

1. *Corporate Autonomy*

   The Company practically surrenders its corporate autonomy. A Board of Directors is retained, elected by the stockholders, but the President, Treasurer, Clerk and all other officers of the Company are appointed and may be removed by the Public Trustees. The Directors shall "have no control over the management and operation of the street railway system, but its duties shall be confined to maintaining the corporate organization, protecting the interests of the Corporation as far as necessary, and taking such action from time to time as may be deemed expedient in cases, if any, where the Trustees cannot act in their place." (*Sec. 4.*)

   The Trustees shall allow the Board of Directors from each year such sum as may be deemed reasonable to provide for the corporate organization and enable the Board of Directors to perform its duties. (*Sec. 4.*)

2. *Of Service*

   (a) Within Municipality (This Act provides for State control regardless of municipal divisions):

   The control of service lies entirely with the Board of Trustees. The act provides that they "shall determine the character and extent of the service and facilities to be furnished, and in these respects their authority shall be exclusive and shall not be subject to the approval, control or direction of any other State Board or Commission." (*Sec. 2.*)

   (b) Outside of Municipality:

   Powers of Trustees extend over entire system.

3. *Extensions, Betterments and Permanent Improvements*

   (a) Definitions:

   The act contains no definition of Extensions, Betterments or Permanent Improvements.

   (b) Within Municipality (This Act provides for State control regardless of municipal divisions):

   The State's control is complete, except that contracts for the operation or lease of subways, elevated or surface lines, or extensions thereof beyond their present limits, may not be made if they involve the payment of rentals or other compensation by the Company, after the period of management and control by the State, unless consented to by the Company's Board of Directors. However, surface lines may be constructed, or purchased, beyond the limits of existing lines, even should the Board of Directors refuse if, after a public hearing, the Board of Trustees decide that public necessity and convenience requires their construction or operation. This power lapses, when the Commonwealth has passed legislation providing for the termination of public control and operation. *(Sec. 3.)*

(c) Outside of Municipality:

Powers of Trustees extend over entire system.

4. *Capitalization, Finances and Accounts*

(a) Ordinary Expenses:

Control complete. *(Sec. 2.)*

(b) Securities:

The Trustees have authority to make contracts in the name of the Company and to issue stocks, bonds and other evidences of indebtedness in its behalf. *(Sec. 3.)*

In spite of the fact that the Company, by the acceptance of the act, has consented to this power being lodged in the Board of Trustees, the Board of Directors are required by the provisions of the act to take such action as they may be requested to by the Board of Trustees to validate its acts in relation to the issuance of securities. *(Sec. 4.)*

(c) Bookeeping:

Control in hands of Trustees.

(d) Methods and Practices:

Control in hands of Trustees.

5. *Use of Tracks, etc., by Other Companies*

No provisions covering these matters in the act, but as Sec. 2 takes jurisdiction away from the Public Service Commission, that body is now without power to order joint use of track.

6. *Machinery of Control*

(a) Power, Where Lodged:

All control is lodged in a Board of five Trustees, appointed by the Governor, with the advice of his Council. Their term is ten years, the fixed period of public management and control. If this period is extended, their successors may be appointed for a like term, but not for longer than public management and control shall continue. They shall own no stock, or other securities of the Company, or companies leased or operated by it. They receive $5,000 a year, each, paid by the Company. They may be removed for cause by the Governor, with the advice and consent of the Council. Vacancies are filled by the Governor with the consent of the Council.

The Trustees are relieved by the act from the legal inhibition against the employment by the Company of any person at the instigation of public officers, in so far as it might apply to them as public officers. In other respects they are subject to the laws of the State governing public officers, as are the Directors of the Boston Elevated Railway Company. *(Sec. 1.)*

In the manangement and operation of the Company, the Trustees shall be deemed to be acting as agents of the Boston Elevated Railway Company and not of the Commonwealth, and the Company is liable for their acts as if they were in Company employ; but the Trustees shall not be held personally liable. *(Sec. 2.)*

A majority of the Board constitutes a quorum for the transaction of business. *(Sec. 2.)*

(b) Administration:

The affairs of the Company are administered by the Board of Trustees, a majority of whom shall constitute a quorum. *(Sec. 2.)*

(c) Powers and Duties of Administrative Body or Officer. The Board of Trustees shall:

Manage and operate the Company and the properties owned, leased or operated by it. *(Sec. 2.)*

Exercise all the rights and powers of the Company and its directors. *(Sec. 2.)*

Appoint, and remove at its direction, the President, Treasurer, Clerk, and all other officers of the Company. *(Sec. 2.)*

Fix and regulate fares, including the issue, granting and withdrawal of transfers and the imposition of charges therefor. *(Secs. 2, 6, 7, 10.)*

Determine the character and extent of the service and the facilities to be furnished. *(Sec. 2.)*

Receive and disburse the income and funds of the Company. *(Sec. 2.)*

Make contracts in the name of and in behalf of the Company. For limitations, see Control, 4 (b). *(Sec. 3.)*

Issue stocks, bonds and other evidences of indebtedness for the Company. For limitations, see C 4 (b). *(Sec. 3.)*

Collect from the Commonwealth, at stated intervals, sums sufficient to make up deficiencies in the Reserve Fund, caused by the failure of revenue to pay the cost of service. (*Sec. 11.*)

Repay to the Commonwealth, when the condition of the Reserve Fund permits it, moneys received to make up deficiencies. (*Sec. 11.*)

Borrow needed sums in anticipation of payments by the Commonwealth to make up deficiencies in Reserve Fund. (*Sec. 11.*)

Maintain the property of the Company in good operating condition and provide for depreciation, obsolescence and rehabilitation. (*Sec. 13.*)

6. *Arbitration*
   (a) Machinery for:

   No provision is made for arbitration. In the event that the Trustees desire to make extensions to, construct, or purchase surface lines beyond the limits of existing lines and the Board of Directors of the Company refuses consent, on the ground that it entails rentals, or other obligations, upon the Company after the period of public management and control, the Trustees are required to hold a public hearing. After such hearing they may, however, decide that public necessity and convenience requires the construction of the proposed line, under which circumstances they may proceed with its extension, construction or purchase, despite the failure of the Board of Directors to consent. (*Sec. 3.*)

   (b) Powers of Arbitration Boards:
   No arbitration boards provided for.

   (c) Penalties:
   No arbitration provided for.

   (d) Expenses of Arbitration:
   No arbitration provided for.

RETURN

1. *Initial Value*

   No initial value is fixed. The act provides for the payment of rentals interest on all indebtedness, fixed dividends on preferred stock, and dividends on common stock at stipulated rates. The capitalization of the Company at the time of the taking effect of the act was thus recognized. (*Sec. 6.*)

2. *Added Value*

   No provision is made for added value. The Trustees have the power to issue stocks, bonds and other evidences of indebtedness and may fix the rate of return thereon, excepting that the return on common stock is limited by the provisions of Section 6. (See Return, 4, Return on Common Stock.) (*Sec. 3.*)

3. *Deductions from Value*

   None.

4. *Rate of Return*

   On Rented Property—rents stipulated in lease. (*Sec. 6.*)

   On Indebtedness—interest fixed by securities or other evidences of indebtedness. (*Sec. 6.*)

   On preferred stock—fixed dividends. (*Sec. 6.*)

   On special issue of preferred stock authorized by act to provide $2,000,000 for betterments and improvements and $1,000,000 to provide a Reserve Fund—fixed dividends not to exceed seven per cent. (*Sec. 6.*)

   On Common Stock—five per cent for the first two years of the ten-year period of public management and control; five and one-half per cent for the next two years, and six per cent thereafter. (*Sec. 6.*)

5. *Additional Allowances*

   None.

6. *Assurance of Return*

   If, on the last day of June, or the last day of December, in any year, the amount in the Reserve Fund shall be insufficient to make good any deficiency in the cost of service, the Trustees shall notify the Treasurer and the Receiver General of the State of the amount of such deficiency, less any amount remaining in the Reserve Fund, and the State shall thereupon pay over to the Trustees the amount so ascertained, which shall be used for the purpose of paying such deficiency, (*Sec. 11.*)

Pending the payment of this sum by the State, it shall be the duty of the Trustees to borrow such sums as will enable them to meet all deficiencies, including dividend payments. (*Sec. 11.*)

If, on the last day of June, or the last day of December of any year, the Reserve Fund shall exceed the original $1,000,000, the Trustees shall apply the excess, so far as necessary, to the reimbursement of the State for the money advanced to to the Trustees to meet deficiencies. (*Sec. 11.*)

The Treasurer and Receiver General of the State may borrow, if necessary, the money with which to pay the deficiencies ascertained by the Receiver General. (*Sec. 11.*)

The amounts so paid to the Trustees shall be assessed upon the cities and towns in which the Company operates by an addition to the State tax next levied, in proportion to the number of persons in said towns and cities using the service of the Company at the time of the payment, this proportion to be ascertained by the Trustees and certified to the Treasurer and Receiver General. (*Sec. 14.*)

COST OF SERVICE

1. *Definition*

The cost of the service includes:

- Operating expenses,
- Taxes,
- Rentals
- Interest on indebtedness,
- Depreciation,
- Obsolescence,
- Losses in respect to property sold, destroyed or abandoned,
- All other expenditures and charges which, under the laws of the Commonwealth now or hereafter in effect, may be properly chargeable against income or surplus.

Fixed dividends on preferred stock:

- Dividends on par value of common stock, at five per cent, for first two years of period of public control and management; five and one-half per cent for next two years, and six per cent thereafter. (*Sec. 6.*)

2. *Allowances*

(a) Operating:

No allowances are fixed by the Act. Expenditures are made in the judgment of the Trustees.

(b) Maintenance, Repair and Renewal:

No allowances fixed by the Act. Expenditures are made in the judgement of the Trustees.

(c) Depreciation:

The allowance for depreciation is specifically left to the judgement of the Trustees. They are, however, required to provide for obsolescence and "losses in respect to property sold, destroyed or abandoned." (*Sec. 6.*)

The Trustees are further required to maintain the property in "good operating condition and to make such provision for depreciation, obsolescence and rehabilitation, that, upon the expiration of the period of public management and operation, the property shall be in good operating condition." (*Sec. 13.*)

3. *Special Tax and Impost Features*

No special taxes or imposts are provided for, but the Act contains the following declaration: "Nothing herein contained shall be held to affect the right of the Commonwealth or any subdivision thereof to tax the Company or its stockholders in the same manner and to the same extent as if the Company had continued to manage and operate its own property." (*Sec. 2.*)

FARES

1. *Schedule of*

The Trustees were required, within sixty days of the taking effect of the Act, to put into operation rates of fare, which in their opinion were sufficient to pay the cost of the service, and within sixty days thereafter to adopt a schedule of eight different grades of fare, four above and four below the rate first established, and to at all times keep the schedule, so that there shall be four grades above and four below the rate in effect at the time. (*Sec. 7.*)

The Trustees may at any time change the schedule so as to alter the rates, or the method and basis of charges for fares and transfers. (*Sec. 7.*)

2. *How fixed*

The Company was required, before the Act took effect, to provide the sum of $1,000,000, through the sale of its preferred stock, to be used as a Reserve Fund. (*Sec. 5.*) This fund can be used only for making good any deficiencies in cost of service, or for reimbursing the Commonwealth for moneys advanced to meet such deficiencies. (*Sec. 8.*)

Into the fund is paid any surplus remaining after the cost of service is paid, and from it is taken any amount needed to meet deficiencies in the cost of service. (*Sec. 9.*)

If, at the termination of the period of public management and operation, the Reserve Fund shall contain less than the amount contributed thereto by the Company, the State shall pay to the Company the deficiency. If, on the other hand, there is a surplus in the fund, it shall become the property of the State, which shall distribute it among the cities and towns served by the Company, in proportion to the number of people in such cities and towns using the Company's service at the date of the termination of the period of public management and operation. (*Sec. 13.*)

If, on the last day of any September, December, March, or June, the amount in the Reserve Fund shall exceed by thirty per cent the amount originally established and, for the proceeding three months, income shall have exceeded the cost of service, the Trustees are required to put into effect the next lowest rate of fare in the fare schedule; and, if on, the same dates the amount in the fund shall be less than seventy per cent of original sum and, for the preceding three months, income shall have been less than the cost of service, they are required to put in effect the next higher fare. In like manner the fare shall continue to be increased or decreased, as the case may be, on succeeding quarterly dates. In determining the state of the Reserve Fund, money received from the State and paid therein, and for which the State has not been reimbursed, shall first be deducted. (*Sec. 10.*)

TRANSPORTATION OF FREIGHT, EXPRESS, ETC.

No provisions are made for the transportation of freight, express, etc., such matters being under the jurisdiction of the Trustees. (*Sec. 2.*)

SPECIAL PROVISIONS

1. *When Grant Expires*

When the period of public management and operation expires, the Company is given the right to fix its own fares, so as to provide for the cost of service, including a six per cent return upon the par value of its common stock outstanding, and may establish an automatic scale of fares; but the Commonwealth is released from its obligation to make up deficiencies in the cost of service. The Company shall, under such conditions, be subject to such regulation as the Legislature may decide upon, but such regulation shall not be exercised so as to reduce its income below the reasonable cost of the service as defined in the Act. (*Sec. 15.*) But this provision is declared not to be a contract binding upon the Commonwealth. (*Sec. 18.*)

Operating Costs of Various Types of City Cars

By J. C. Thirlwall

Railway and Traction Engineering Department, General Electric Company

The shrinking margin of profit in city traction gave birth to the light-weight, one-man safety car as a means of reducing operating costs. The many illustrations of this type of car have already demonstrated its merits. The question now arises as to what extent it can displace the larger and heavier cars. The author believes that the use of the safety car can be extended to all city surface lines and that, at least for the all-day runs, it will be the more efficient. In substantiation of his claim, he furnishes tabulations of comparative costs.—Editor.

J. C. Thirlwall

THE tremendous success of the light-weight, one-man car under a great variety of operating conditions has led to considerable discussion among operators as to just how far the use of this type of vehicle can be extended upon our urban transportation systems A general consensus of views, at present, seems to be that in cities of less than 100,000 population there are few, if any, routes for which the safety car is not pre-eminently suited; that for larger cities only a limited part of the service can be handled by this size of car; and that all of the heavier lines in the largest cities will have to continue to operate large capacity double-truck two-man cars, singly or in trains. But, while this is perhaps the general opinion of the industry, there are many experienced operators who disagree with the majority and who feel that there are no surface routes in any city that cannot use the safety car for at least the all-day runs, and that the use of this car will afford greater efficiency than any other type. The writer, who has watched and studied the performance of the safety car since its inception, has come to agree with this minority, and some figures are presented herewith bearing on the question as to which type of car is most suitable for extremely heavy traffic in the largest cities.

A number of typical double-truck cars of modern design have been selected; and in order to determine the relative advantages of each type, a study of their operating costs, based on handling similar numbers of passengers at various hours of the day, has been made and the results are presented in tabulated form. It is not the writer's idea that this comparison holds absolutely true for every property, but the purpose of this article is to suggest a line of thought which can be developed by the transportation engineers of any railway whenever new cars are to be purchased.

It is of course obvious that several items of operating cost are dependent upon the weight of the rolling stock used, that the power consumption varies in about direct proportion to the ton-miles operated, and that the maintenance, both of track and of equipment, is largely influenced by the weight factor. We will assume certain costs per ton-mile for these items, which will vary between different cities but which will enable us to make a comparison of the efficiency of these various types of cars. The figures used are based on the average costs of operation of eastern electric railways for August, 1919, as reported in the *Aera* magazine.

Fig 1 Safety Car, Brooklyn Rapid Transit

The power cost for these roads is 5.45 cents per car-mile. As the average weight of cars operated in eastern cities is about 20 tons, the cost per ton-mile is 0.27 cents.

(This is checked by the known fact that, in frequent stop service, energy consumption at the central station is about 200 watt-hours per ton-mile, and power costs in steam plants run from 1.25 to 1.5 cents per kilowatt-hour.)

The average cost of track maintenance is 5.7 cents per car-mile. Of this, probably one half, or 2.8 cents, is directly affected by the weight of the cars used; and we will assume, therefore, 0.14 cents per ton-mile for this item.

The maintenance of equipment costs 3.7 cents per car-mile, and of this we believe 75 per cent or 2.8 cents is governed by car size and weight, or 0.14 cents per ton-mile. For the items of power and maintenance, therefore, we have a total of 0.55 cents per ton-mile.

For crew costs, we have assumed 55 cents per man-hour for the double-truck cars, and 61 cents per hour for the one-man safety cars (these figures being rather under than over present wages).

In frequent stop service in the larger cities, schedule speeds including lay overs do not average over 8.5 m.p.h. A 19-hour

TABLE I

CAPACITY, WEIGHT, ETC., OF TYPICAL CITY CARS

Designation	Car Length Feet	Seating Capacity	Maximum Load	Number Motors	Car Weight Tons	Where Used
A	41	44	100	2	18	New England; Philadelphia
B	41	44	100	4	22	New England; Brooklyn
C	46	54	125	4	25	Chicago
D	46	58	125	2	19	New England; Brooklyn; Chicago
E	49	58	125	4	22	Boston
F	51	58	150	4	22	Cleveland (Longitudinal seats)
F-1	104	118	300	4–0	35	Cleveland train (Longitudinal seats)
G	51	58	150	4	17	Buffalo, Rochester (Longitudinal seats)
H	28	32	65	2	8	Brooklyn; New England
H-1	28	32	75	2	8	(Longitudinal seat Safety Car)

TABLE II

OPERATING COSTS FOR POWER, MAINTENANCE, AND CREW WAGES

Costs	All-day Operation	Rush Hour Only
Power and maintenance per ton-mile	0.55c.	0.55c.
Crew wages per car-hour (two-man cars)	$1.10	$1.10
Crew wages per car-hour (one-man car)	0.61	0.61
Crew wages per train-hour (two cars)	....	1.65
Car-hours per annum	$6950	$1565
Car-miles per annum	59000	13300

ANNUAL COST FOR ABOVE ITEMS, EACH TYPE OF CAR

Type of Car	ALL-DAY OPERATION			RUSH HOUR ONLY		
	Power and Maintenance	Crew	Total	Power and Maintenance	Crew	Total
A	$5825	$7645	$13470	$1315	$1720	$3035
B	7125	7645	14770	1610	1720	3330
C	8100	7645	15745	1830	1720	3550
D	6160	7645	13805	1390	1720	3110
E	7125	7645	14770	1610	1720	3330
F	7125	7645	14770	1610	1720	3330
F-1	....	....	.....	2565	2580	5145
G	5510	7645	13155	1245	1720	2965
H	2590	4240	6830	585	955	1540
H-1	2590	4240	6830	585	955	1540

run, operated 365 days per year at this schedule speed, requires 6950 car-hours or 59,000 car-miles annually. Rush hour extras or trippers, in general, will not operate over 5 hours daily, and for only 313 days per year, so each car so used makes annually 1565 car-hours or 13,300 car-miles.

In cities of 200,000 to 500,000 population, the rush-hour service ordinarily doubles the all-day service; in the largest cities it frequently triples it; in other words, from a half to two thirds of the cars owned are operated only in rush-hour traffic. This fact, of course, is responsible for the introduction and development of cars of large seating and standing capacity, and, in several cities, for the adoption of train service, either of motor car and trailer or of two motor cars with multiple unit control.

Various types of these cars are indicated in Table I. Cars *A* and *B* are the most typical of the older double-truck designs; units seating 41 and capable of carrying about 100 as a maximum load, and weighing from 18 to 22 tons depending upon whether two or four motors are used. Cars *C*, *D*, and *E* are of the more modern, larger capacity, cross-seat types, representing the latest designs used by Chicago, New York, Brooklyn, and Boston. Type *F* is the Witt car used in Cleveland, and *F-1* is the Cleveland motor car and trailer; Car *G* is the lighter weight Witt type used in Buffalo and other cities, but not arranged for train operation. Due to the use of longitudinal seats the maximum capacity of the Witt car is somewhat larger than that of the preceding types. Car *H* is the standard Birney safety car, and *H-1* the same car with longitudinal seats.

The operating costs of each of these types when used in all-day service and when operated as "trippers" only is shown in Table II

There are few lines in even the largest cities that operate on less than three-minute headways outside of rush hours. To make

TABLE III

LENGTH OF ROUND TRIP 8.5 MILES: RUNNING TIME 60 MINUTES

Type Car	NUMBER REQUIRED			Seats per Hour Normal	CAPACITY PER HOUR		COMPARATIVE COSTS PER YEAR		
								Extras	
	Normal	90-second Rush	60-second Rush		90-second Rush	60-second Rush	All-day Cars	90-second Rush	60-second Rush
A	20	40	60	880	4000	6000	$269,400	$60,700	$121,400
H	28	61	92	896	4000	6000	191,000	50,900	98,500
A + H	28	28 + 21	28 + 11	896	4000	6000	191,000	63,700	124,000
B	20	40	60	880	4000	6000	295,400	66,600	133,200
H	28	61	92	896	4000	6000	191,000	50,900	98,500
B + H	28	28 + 21	28 + 41	896	4000	6000	191,000	70,000	136,500
C	20	40	60	1080	5000	7500	314,900	71,000	142,000
H	34	77	115	1090	5000	7500	232,000	66,200	124,500
C + H	34	34 + 22	34 + 42	1090	5000	7500	232,000	78,000	149,000
D	20	40	60	1160	5000	7500	276,100	62,200	124,400
H	36	77	115	1152	5000	7500	246,000	63,100	121,500
D + H	36	36 + 21	36 + 41	1152	5000	7500	246,000	65,500	127,500
E	20	40	60	1160	5000	7500	295,400	66,600	133,200
H	36	77	115	1152	5000	7500	246,000	63,100	121,500
E + H	36	36 + 21	36 + 41	1152	5000	7500	246,500	70,000	136,500
F + F-1	20	*40	*60	1160	6000	9000	295,400	36,300	87,750
H-1	36	80	120	1170	6000	9000	246,000	63,100	124,500
F-1 + H-1	36	36 + 11	36 + 21	1170	6000	9000	246,000	56,600	108,000
G	20	40	60	1160	6000	9000	263,100	59,300	118,600
H-1	36	80	120	1170	6000	9000	246,000	63,100	124,500
G + H-1	36	36 + 22	36 + 12	1170	6000	9000	246,000	65,400	124,200
H-1 all day	30	30	30	960	2250	2250	204,900		
F-1 rush extras		9	18		2700	5400		18,800	97,600

* 20 and 30 two-car trains respectively.

Fig. 2. Two-car Train, Low-wheel, Light-weight Cars, Buffalo and Lake Erie Traction Company

the comparison on very heavy traffic routes, therefore, we will assume two city lines giving three-minute normal service; on one we will reduce this to 90-second headways for the rush hours, and on the other to 60-second with single cars or to two-minute headways with two-car trains. Few, if any, routes can secure anywhere near a seated load for large capacity cars on a three-minute headway, outside of one or two trips in the morning and evening; and there are very few which would not provide seats for all passengers outside of rush hours if the Birney safety cars were used on present headways. But, to make the comparison as severe as possible, let us assume that the Birney cars must at all times furnish equal seating capacity per hour and equivalent maximum capacity per hour or for any fraction of the hour at the peaks. Table III shows how many cars would be required, as compared with each of the larger types, if used exclusively; and also if used for the all-day runs, the larger cars being employed for trippers. The respective cost of operation, based on the figures in Table II, is also shown.

To properly analyze the figures in Table III, we will summarize the operating cost

TABLE IV

INVESTMENT, FIXED CHARGES, AND OPERATING COSTS

Type Car	Total No.		Purchase Cost		Fixed Charges		Operating Cost		Net Annual Saving by Safety Cars	
A	40	60	$500,000	$750,000	$75,000	$112,500	$330,000	$391,000	......	....
H	61	92	366,000	552,000	55,000	82,500	242,000	290,000	$108,000	$131,000
A + H	49	69	431,000	682,000	65,000	102,100	255,000	315,000	85,000	86,000
B	40	60	560,000	840,000	84,000	126,000	362,000	429,000	..	......
H	61	92	366,000	552,000	55,000	82,500	242,000	290,000	149,000	183,000
B + H	49	69	462,000	742,000	69,000	111,000	261,000	328,000	116,000	116,000
C	40	60	600,000	900,000	90,000	135,000	386,000	457,000	....	......
H	77	115	462,000	690,000	69,000	104,000	298,000	357,000	109,000	131,000
C + H	56	76	534,000	834,000	80,000	125,000	310,000	381,000	86,000	86,000
D	40	60	520,000	780,000	78,000	117,000	338,000	400,000		
H	77	115	462,000	690,000	69,000	104,000	309,000	368,000	38,000	45,000
D + H	57	77	489,000	748,000	73,000	112,000	312,000	374,000	31,000	31,000
E	40	60	560,000	840,000	84,000	126,000	362,000	429,000	......	....
H	77	115	462,000	690,000	69,000	104,000	309,000	368,000	68,000	83,000
E + H	57	77	510,000	790,000	76,500	118,500	316,000	382,500	53,500	54,000
F-1	20T	30T	460,000	690,000	69,000	103,500	332,000	383,000	......	.....
H-1	80	120	480,000	720,000	72,000	108,000	329,000	391,000	......	*12,500
H-1 + F-1	47	57	469,000	699,000	70,500	105,000	303,000	354,000	27,500	27,500
G	40	60	520,000	780,000	78,000	117,000	322,000	382,000	......	......
H-1	80	120	480,000	720,000	72,000	108,000	329,000	391,000	1,000	*18,000
H-1 + G	58	78	502,000	761,000	75,000	114,000	311,000	370,000	1,400	1,500
H-1 all day	30	30	180,000	180,000	27,000	27,000	254,000	302,000	....	....
F-1 rush	9	18	207,000	414,000	31,000	62,000				

* Increased cost with Birney safety cars.

figures and add a comparision of the amount of investment and the annual fixed charges (or cost of capital) covering interest, depreciation, taxes, and insurance (which will be about 15 per cent). These data are given in Table IV.

These figures indicate (neglecting for the moment the question of track capacity or saturation) that the Birney safety car can be used under even the most extreme conditions of surface traffic, and that in first cost and in operating cost per passenger handled it will be more efficient than most types of double-truck cars now used and equal to the best of the latter. The only question that can be raised is whether schedule speeds would be seriously interfered with by attempting to operate the small cars on 30-second headways. The writer believes there would be no difficulty on this score. All of his observations and experience have indicated that the reduction in stops made and in the number of passengers handled per stop would enable the Birney car on a 30-second headway to maintain schedules and spacing better than would the larger trains on a two-minute headway, or the large single car on a one-minute interval.

But, if such short headways should produce serious interference in sections where several routes operate over the same track, the combination of large cars or trains for the rush-hour extras with the Birney cars on the all-day runs will be found to afford a smaller initial investment and a lower operating cost than can be secured by the exclusive use of any type of double-truck car; and will give a wider rush-hour spacing than the exclusive use of Birney cars, and a shorter all-day headway than is afforded by the larger types. While this might not be productive of any such increased riding as results when shortening five-minute or longer headways, still it is probable that some increase in traffic could be looked for. This is an additional argument for the selection of the Birney safety type car.

But the most decisive factor is the fact that in every city there will be available, as Birney cars come to be used more and more for the all-day service on various routes, an increasing amount of displaced large capacity rolling stock, which while inefficient for all-day service can be profitably employed in rush hours; and these cars can and will be used for tripper service to supplement the Birney types and to produce the big economics of all-day operation that can be made with a minimum investment in new equipment.

Fig. 3. Peter Witt Car, Schenectady Railway

Motor Busses or Trackless Trolleys

By H. L. Andrews

Railway and Traction Engineering Department, General Electric Company

The trackless trolley, which is a vehicle practically unknown in this country, is making an exceptionally good record for earnings and service abroad. A comparison of its operating cost with that of the motor bus, and a balancing of each against that of the most modern street railway practice, shows that on an equal service basis at an equal fare the motor bus cannot compete with the street car but that the trackless trolley can. Therefore it will not be long before the American street railway operator must seriously consider this trackless conveyance as an adjunct to his own equipment or as a competitor of it. Because the propulsion equipment of this new type of vehicle and the power distribution to it are essentially the same as that of the street car, and the vehicle's qualifications make it preëminently suitable as an auxiliary to a street car system, the author of this article earnestly recommends that the railway operator adopt it and thus in one move secure its benefits and eliminate its competition.—Editor.

H. L. Andrews

With the growing use of gasolene motor busses as feeders to street railway systems and also as competitors to established street railway systems, it seems desirable that some analysis be made of the relative merits of gasolene and electric power for this type of public conveyance and that the operating costs be compared with those of an electric car.

Gasolene motor busses have been given thorough trials by a number of railway companies which have operated them as feeders to their established street railway systems or in connection with their systems to serve a portion of the city not served by existing street car lines.

Experience in the operation of the gasolene propelled bus, so far as it has been developed, has proved:

(1) That they cannot compete in operating costs with an electric street car and cannot maintain an equal service at an equal fare.

(2) That they are an excellent type of vehicle to operate as feeders, or to connect up street railway routes.

(3) That they are unsuitable for dealing satisfactorily with heavy town traffic.

(4) That they are not adequate for dealing with peak loads.

(5) That they have no advantage over the electric car as regards schedule speed.

There is no question but that the gasolene motor bus has come to stay and that its use will increase. Rather than meet it as a competitor, the street railway people should handle and develop this bus as their experience will enable them to make the bus a successful auxiliary to their established business.

While it has been demonstrated by actual application that the gasolene propelled bus cannot compete in operating costs with the street car, it has also been demonstrated that the gasolene bus can be a worthy competitor of the street railway system by providing a higher class of service and charging a correspondingly higher fare.

The operation of the gasolene propelled busses in Baltimore is an excellent example of the failure of this vehicle to compete successfully with the street car on an equal fare basis, but the Fifth Avenue busses of New York City and the Chicago busses are illustrations of successful operation by providing a higher class of service and charging a higher fare. The success of this latter type of installation is best shown by the fact that the operation of gasolene busses in Chicago is to be extended and that gasolene busses are to be installed in Detroit. The City of New York is furnishing service by means of gasolene operated busses to the former patrons of those street

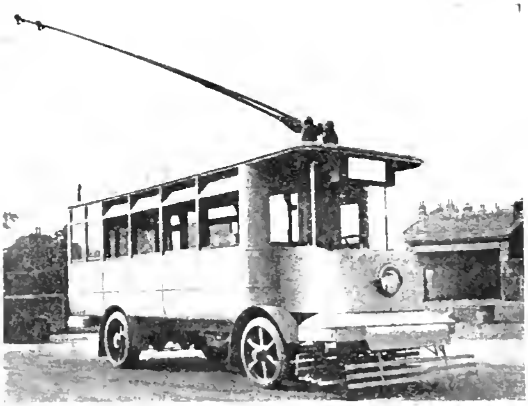


Fig. 1. Typical Trackless Trolley Bus Used in England

car lines which have been discontinued due to their inability to earn operating costs.

The gasolene propelled bus, due to its cost of operation, will undoubtedly never displace the street car; but the bus with very little change from standard automobile construction can be converted into a trackless trolley driven by railway motors supplied with power from two trolley wires. In this converted form the motor bus, or trackless trolley, may prove to be a very worthy competitor of any street railway; and it can compete in operating costs with the Safety car, which is the most efficient means of transporting passengers on steel rails.

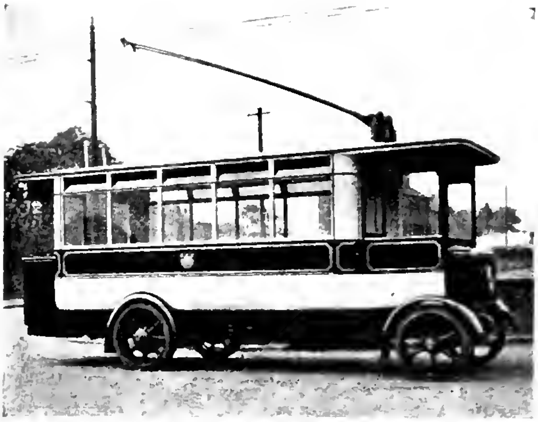


Fig. 2. Trackless Trolley Bus Operation on Tees Side System, England

An analysis of the operating costs of the gasolene bus immediately suggests to the railway operator the reduction of this cost by the application of a railway motor as the power unit. Nearly 50 per cent of the operating cost of the gasolene bus is for power, maintenance, and depreciation. The costs of operation of two gasolene bus lines are approximately as given in Table I.

TABLE I

	CENTS PER BUS MILE	
	A	B
Maintenance of equipment	10.57	6.51
Gasolene and oil	4.84	5.09
Conducting transportation	13.88	15.9
General and miscellaneous	4.3	3.54
Traffic expense	0.04	0.04
Taxes	1.65	1.65
Total	35.28	32.73
Depreciation	3.22	6.59
Total	38.50	39.32

These operating costs are actual figures from typical installations of gasolene busses, and reference to columns *A* or *B* indicates that the cost of maintenance, gasolene, and depreciation is 45 to 50 per cent of the total operating expense. In comparing these three items with the most recent and most efficient street car, the Safety car, we have the results given in Table II.

TABLE II

	GASOLENE BUS		ELECTRIC CAR
	Cents per Bus Mile		Cents per Car Mile
Maintenance of equipment	10.57	6.51	2
Gasolene	4.84	5.09	—
Power			1.5
Depreciation	3.22	6.59	2
Total	18.63	18.19	5.5

These operating costs, which are for the same general type of vehicle as regards seating capacity and service rendered, indicate a reduction of approximately 13 cents per mile in favor of the electric street car.

The operating costs as given in Tables I and II for the gasolene operated bus are based on two-man operation. While there are gasolene propelled buses in service with only one operator, no attempt has been made to operate these busses in congested districts; and the gasolene bus as it is developed today cannot be operated by one man with the same degree of safety and efficiency as a trackless trolley or a Safety car. The successful operation of more than 2000 Safety cars in over 200 cities in the United States has proved that one operator can successfully handle congested traffic, provided the car is equipped with safety features designed to minimize labor and protect passengers. These safety features could be adapted to the trackless trolley, and thus equipped the vehicle could be successfully handled in heavy traffic by one operator with the same degree of safety as a Safety car.

A true comparison of the relative operating costs of the gasolene motor bus, the trackless trolley, and the Safety car, assuming that the gasolene bus can be operated with one man, is best represented by Table III

By giving the motor bus and the trackless trolley the benefit of their comparatively lower capital expenditure, which will vary with the frequency and headway of service, we have the comparison of operating costs

TABLE III

	CENTS PER BUS MILE		CENTS PER CAR MILE
	Gasolene Bus	Trackless Trolley	Safety Car
Maintenance of overhead	.	0.5	0.5
Maintenance of way		.	1.5
Road taxes	0.75	0.75	. .
Maintenance of equipment	8.54	3.0	2.0
Platform expenses	8.0	8.0	8.0
Traffic expenses	0.04	0.04	0.04
Power	4.54	1.8	1.8
General	3.54	3.54	3.54
Depreciation	6.59	2.0	2.0
Total	32.00	19.63	19.38

Fig. 3 Trackless Trolley Bus on Shanghai Tramways, China

as given in Table IV. This comparison indicates that the operating cost of the trackless trolley is approximately 66 per cent of that of the gasolene propelled bus, and is approximately the same as that of the Safety car.

It will be noted that the comparison in Tables III and IV includes a road tax for the gasolene bus and for the trackless trolley. It may not have been the custom to charge the gasolene propelled bus for the use of city streets, but if this bus should come into general use and provide a regular service on a specified schedule, a tax would probably be imposed; and in order to make a true comparison of operating costs this tax has been included.

In comparing the maintenance of the gasolene propelled bus with the trackless trolley, consideration must be given to the cost of maintaining the gasolene engine, clutch, gear box, differential, radiator, magneto, and lighting set as against a railway motor, worm drive with differential, controller, and two trolley poles.

The maintenance costs of railway motors, controllers, and trolley poles are well known figures. The maintenance of the gasolene propelled bus has not been as definitely determined, but all information available indicates that the maintenance figure used in the foregoing tabulations for the gasolene propelled bus is a conservative one.

The body maintenance of the gasolene propelled bus and of the trackless trolley will

TABLE IV

	CENTS PER BUS MILE		CENTS PER CAR MILE
	Gasolene Bus	Trackless Trolley	Safety Car
Operating costs	32.0	19.63	19.38
Capital expenditure	1.85	2.85	3.37
Total	33.85	22.48	22.75

be no more than that of a street car, and the truck maintenance incurred in street railway practice will be almost eliminated. Against this lower body and truck maintenance must be balanced the relative cost of rubber tires and steel wheels. From all data available, the cost per bus-mile or per car-mile for tires and wheel wear is in favor of the steel wheel. The relative figures are given in Table V.

TABLE V

Tire Life in Miles	Cents per Bus Mile	Wheel Life in Miles	Cents per Car Mile
19,000	1.00	45,000	0.24
28,000	1.51		
13,500	1.35		
22,166 ave.	1.28 ave.		

This tabulation indicates that the cost per bus-mile for rubber tires will be approximately five times the cost for steel wheels; or the cost of rubber tires on a gasolene propelled bus or a trackless trolley will be one cent per bus-mile greater than the cost of wheel wear on a Safety car. Taking into consideration the higher cost of rubber tires per bus-mile, and knowing the cost of maintaining a Safety car, it seems conservative to estimate the maintenance of the trackless trolley as 50 per cent greater than that of a Safety car, particularly if the trackless trolley is equipped with a single motor without gears, axle linings, or gear case.

The trackless trolley could be built with approximately the same seating capacity as the Safety car for a weight not to exceed 12,000 lb. or approximately 75 per cent of the weight of the present Safety car. A single-motor drive with necessary control can be supplied which will permit of the adoption of all the safety features now standard for the Safety car. For a trackless trolley the power consumption will be approximately the same as for a Safety car, as the weight will be 75 per cent of that of the Safety car and the frictional resistance of a rubber tired vehicle on a good asphalt, wood block, or smooth brick pavement is very little higher than on steel rails, particularly where there is used a grooved rail laid in paving.

On first thought, it would appear that the gasolene propelled bus has an advantage over the trackless trolley as regards unlimited flexibility. It is true that a gasolene propelled bus can operate on any route and can readily have its route changed without incurring any expenditure for changing overhead construction. There is little question, however, but that with the introduction of the gasolene propelled bus the city authorities would insist on a definite route and a definite time table and while the gasolene propelled bus has unlimited flexibility as regards routing it would be as definitely bound to a specified routing by ordinances or legislation as a trackless trolley would be by reason of the overhead construction. It is questionable, therefore, whether either type of vehicle has any actual advantages as regards flexibility for both vehicles can pass other traffic. With proper overhead construction and proper collectors, the trolley bus can have a range of operation of 15 ft. either side of the trolley wires, which is ample to permit passing other traffic.

These estimates would illustrate that a bus similar to the gasolene propelled bus could enter the urban transportation field and become a worthy competitor of the street railway system, giving equal service for equal fare. This is particularly true where the officials of railway companies have not profited by the experience gained in the application of the Safety car and have not applied its principles to their transportation problems. The trackless trolley having lower operating cost than the gasolene propelled vehicle will be successful where a gasolene bus could not operate.

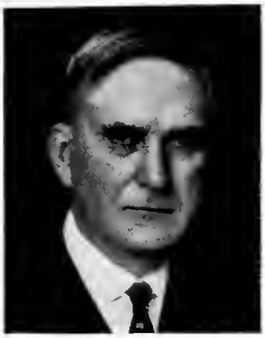
Sooner or later the street railway industry is going to meet the gasolene bus or trackless trolley in competition, and it seems desirable that railway operators study their transportation problems with a view to utilizing the trackless trolley as an auxiliary to their present transportation system rather than to meet it in competition.

Improvements in the Design and Construction of Railway Motors

By E. D. Priest

Engineer, Railway Motor Department, General Electric Company

The modern light-weight railway motor for the same weight as its predecessors is capable of handling, under ordinary conditions, a car about twice as heavy per pound of motor. These improved motors are the result primarily of developmental and research work and secondarily of the fact that there are available today better materials and methods of manufacture than heretofore existed. In the following article Mr. Priest details a number of the more prominent features in the design and construction of the latest General Electric railway motors.—Editor.



E. D. Priest

In the November, 1913, number of the General Electric Review, the writer published a short article entitled: "The Development of the Modern Direct-current Railway Motor." This article was a brief review of the subject. Since its publication there have been many substantial improvements in the design and construction of railway motors; and it is the purpose of this article to supplement the earlier one in a measure and to describe briefly some of these improvements.

A marked advance has been effected in the design of railway motors. This has been accomplished by the use of higher grade materials, refinements in design, increased ventilation, higher armature speeds, increased gear ratio, and reduction in weight made possible by these changes. If it were not for these improvements, the present manufacturing cost of railway motors, to perform a given service, would be much higher.

Heat-treated alloy steel is now used for the armature shafts. The steel in the smaller motor shafts is substantially the same and, for like sizes, is equal to that used in the crank shafts of the "Liberty motors" designed for use in airplanes.

The quality of steel in gears and pinions has been improved and improved methods of heat treatment have been developed. The highest grade materials are now used for railway motor gears and pinions. New ways have been found of tempering cast-steel gears which produce qualities substantially equal to forged gears.

Bearing metals are now of the highest quality obtainable. All babbitt is genuine tin-base babbitt. This is the most expensive babbitt manufactured and long experience has shown it to be the best. The highest grade bronze is used in the linings.

In some instances key stock is heat treated to secure hardness and is ground to size to insure close fits and freedom from wear.

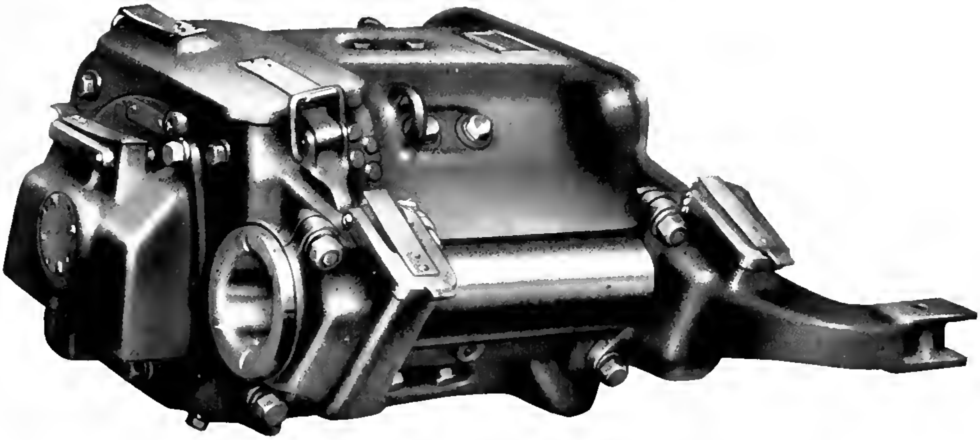


Fig. 1. A Modern Light-weight Railway Motor, showing Axle Side

Heat treated carbon steel bolts are quite generally used in the construction of motors and in some motors heat-treated alloy steel is used

For brush-holders, expensive high-grade bronze castings are used exclusively and carbon brushes are of the highest grade obtainable.

All castings other than bronze are either malleable iron or steel, no cast-iron being employed in the construction of railway motors.

In general, the quality of materials now used is the best, and no inferior substitutes are employed. Operating conditions are so severe that maximum all round economy can be obtained only by the use of the best materials.

Much study and research has been devoted to producing higher grade varnishes employed for insulating purposes, and in the past few years there have been developed greatly superior varnishes which have higher insulating values and slower ageing qualities.

As with materials, so with workmanship; the best workmanship has been found to be the cheapest since reliability in service is of far more importance than first cost. While the rough exterior of a railway motor suggests quite ordinary workmanship, as a matter of fact it is doubtful if any other line of machinery manufactured has closer fits and more accurate workmanship.

Some of the tolerances in armature shaft fits are plus 0.00025 to minus .00000. For frame-head fits in box-frame motors, plus 0.002 to minus .000 are allowed. The fit must be so close as to require that the heads be driven into place. In boring the heads for armature linings and in turning the linings, very close tolerances are required in order to secure the proper pressing fit of the linings in the heads. A tolerance of plus 0.001 to minus 0.000 is used in the bore of solid gears.

The thread fit for frame-head bolts and for screws is made so close that special taps and dies are required to insure tight fitting threads. Throughout the whole construction of the motor, limits in workmanship are very close as it is found that imperfectly fitting parts rapidly loosen and wear in the abnormally hard service to which railway motors are subjected.

Armature shafts in bearings are ground to size and rolled, a process which produces a hard smooth polish having an ideal bearing surface. Equal care is taken to secure a hard smooth surface on the babbitt in the bearing linings.

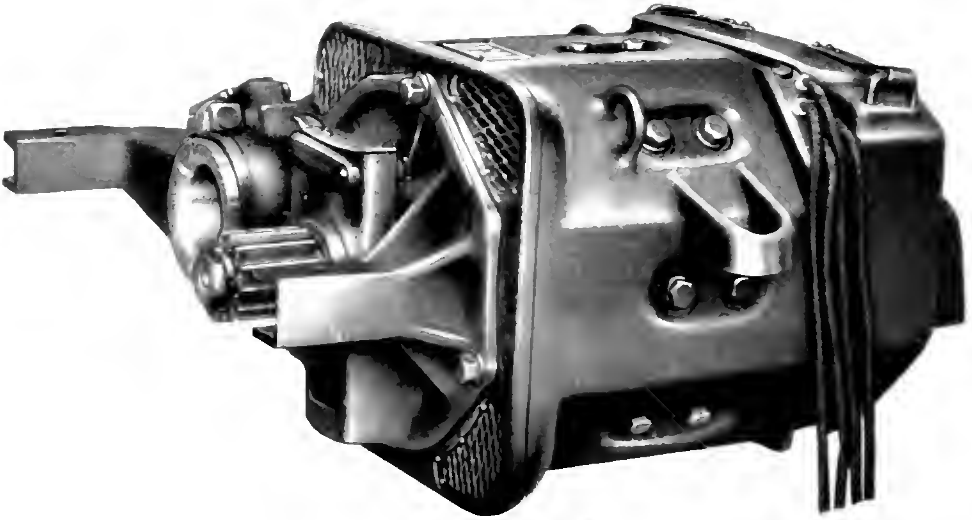
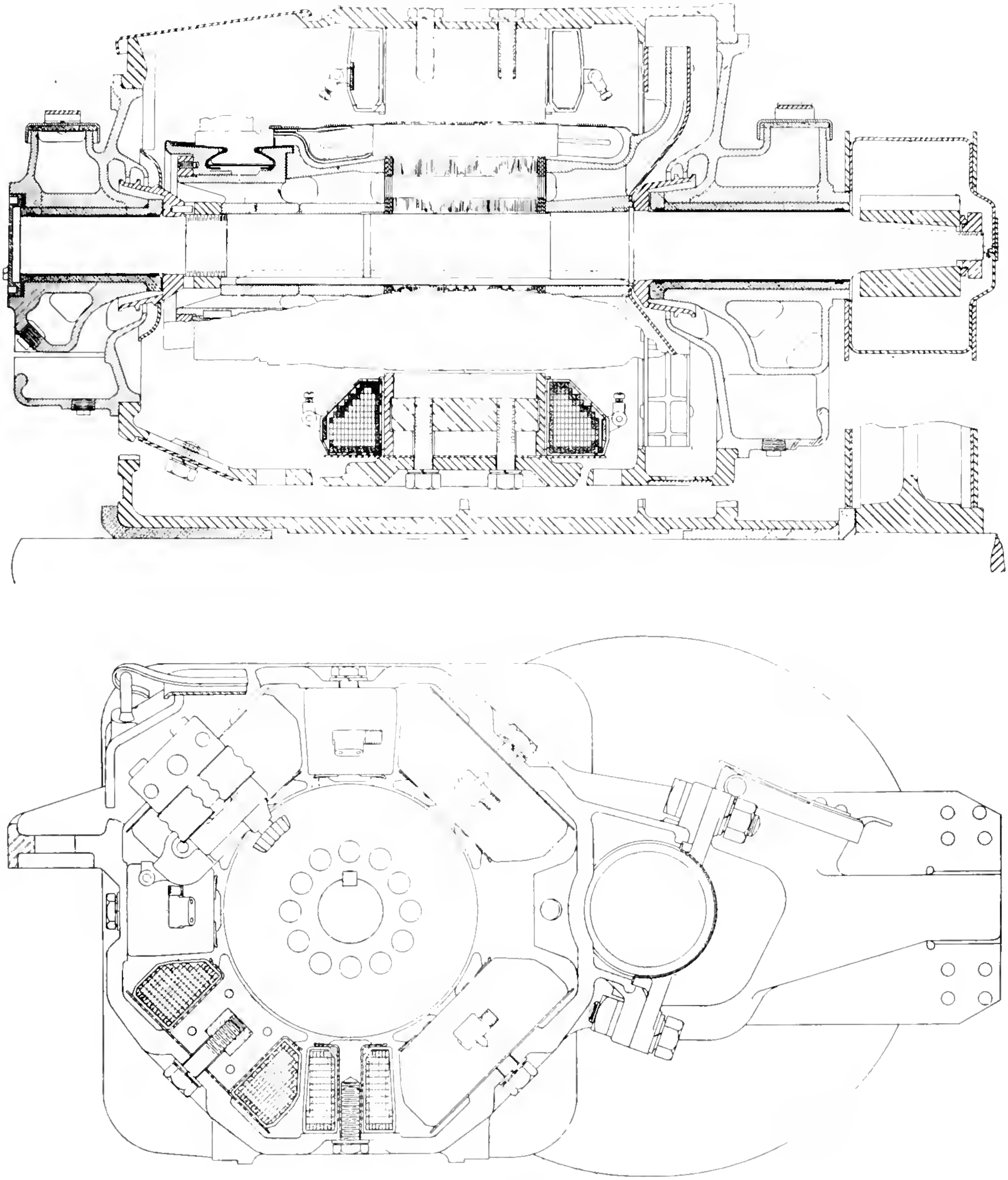


Fig. 2. Suspension Side of the Light-weight Motor Shown in Fig. 1

In order to prevent vibration due to armatures being out of balance, the detail parts of the armatures are balanced separately before being assembled on the shafts, and after assembly the completed core is balanced.

Aside from material and workmanship, substantial improvements have been made in the design of motors. Box-frame motors have come into almost universal use, this construction being greatly superior to the split-frame type in sturdiness and reliability of operation.

The ventilation of motors has been much improved so that multiple ventilated motors have largely increased service capacity. The continuous capacity in some instances is 70 per cent or more of the hourly rating. Ventilating fans have been strengthened so that trouble from breakage has been largely reduced.



Figs. 3 and 4 Sectional Drawings of the Light-weight Railway Motor shown in Figs. 1 and 2

A superior construction of armature bars applicable to large sizes of motors has been developed. This construction permits the use of thin folded crossed bars which make it possible to obtain greater capacity with a given size of armature core without increasing eddy current losses due to heavy copper sections.

A method of connecting bars at the back end of one-turn armatures has been devised which eliminates the use of soft solder that is liable to melt if motors are subjected to excessively heavy overloads which sometimes occur in locomotive service. The improvement consists in using electrically brazed joints in place of soldered joints.

In armature windings of more than one turn per coil, wire of rectangular section has come into more general use. The space factor with rectangular wire is materially higher than with round wire. This results in an increase in capacity of armatures for given core sections.

Taking greater advantage of the possibilities of employing commutating poles, the use of two turns per coil in armature construction has been extended to much larger motors than formerly thought possible, thereby decreasing the weight and cost of the motors.

Sheet steel gear cases have been developed to a higher point of perfection so that they are proving more reliable in service than sheet steel cases of earlier designs.

A much desired improvement has been brought about in the method used to prevent rotation of axle linings in large sizes of motors. The construction consists in the use of a long key set in the bore of the magnet frame for the lining, along the lower edge of the split in the lining. The lining is not materially weakened since it is at the point of separation of the two halves. This construction has been found to hold linings very securely.

Spring gears have been developed, the use of which in heavy work prevents excessive shocks on gear and pinion teeth, resulting from imperfections in the teeth or rough service conditions. When twin gears are used spring gears tend to equalize the work on the two sets of gearing.

Motors have been designed for largely increased potentials and 3000-volt direct-current railway motors have been in most successful operation for a number of years, handling the severest of service.

Higher armature speeds have been made possible by the use of stronger material in the shafts and in the pinions and gears, and by improved shape of gear and pinion teeth which permits the use of a finer pitch gearing, a smaller pitch diameter of pinion, and a smaller number of teeth in the pinion, without a reduction in the strength of the teeth as compared with coarser pitch gearing with inferior shaped teeth.

For many years the standard gear used in street railway service had three pitch $14\frac{1}{2}$ deg. angle teeth. By changing the angle to 20 deg. approximately 25 per cent stronger teeth have been secured, and by lengthening the pinion teeth addendum and shortening the dedendum with a corresponding shortening of the gear teeth addendum and lengthening of the dedendum it is possible to change a three pitch to approximately a $3\frac{1}{2}$ or 4 pitch without sacrificing strength, and with an incidental possibility of increasing the gear ratio. The shortening of the dedendum of pinion teeth and the use of a finer pitch permits a reduction in the number of teeth without a reduction in the thickness of the metal between the base of the teeth and the bore.

An increase in strength of the pinion and shaft has been effected by reducing the depth of the keyway in the pinion so that metal is not cut away at the large end of the bore and by shortening the keyway in the shaft so that it does not extend to the inner end of the pinion but is stopped inside the pinion fit at a point where the shaft is supported by the shrink fit of the pinion.

The maximum armature speed for a given car speed is of course fixed by the gear ratio. Consequently an increase in gear ratio makes it possible to design a lighter and cheaper motor for a given service. Increased armature speed not only reduces the size and cost of motors due to increase in speed, but also makes possible a further reduction because of increased ventilation resulting from increased speed.

The minimum number of teeth in pinions for a given pitch and tooth shape is limited by the diameter of pinion bore. Sufficient metal for ample strength being allowed between the base of the teeth and the bore, it is obvious that the higher the grade of armature shaft stock used the smaller the pinion fit and pinion bore can be made. Therefore the size of a motor is fundamentally affected by the grade of material used in the armature shaft and the grade of material used in the pinion and gear as well as by the pitch and shape of the pinion and gear teeth.

An improvement has been made in the design of pinions of small diameter by making them slightly bell-mouthed at the large end of the bore for a distance of 3/8 to 1/2 inch from the end of the pinion. By relieving the pinion in this way, so that for this distance it has no bearing on the shaft, the metal in the body of the pinion at the large end of the bore is stressed less when the pinion is driven and shrunk on the shaft. Consequently, there is less danger of failure from breakage both in the body of the pinion and in the teeth. Incidentally, this permits of a better design of shaft, since it is possible to use a fillet with a larger radius on the shaft between the pinion fit and the journal bearing.

In the modern light weight motor, used on safety cars, very careful consideration has been given to the design of the motor with particular reference to armature shaft and gearing. The construction of the motor in other particulars is also worked out to secure maximum strength, reliability, effective ventilation, and lightness. This has resulted in the development of motors with continuous ratings equal to that of earlier types of non-ventilated motors of three to four times the weight.

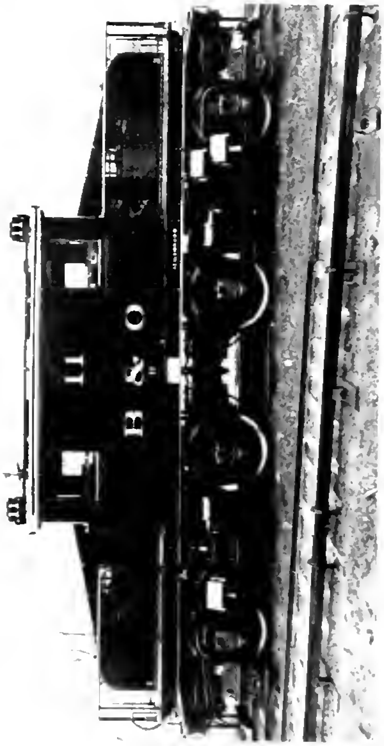
In practical operation these light weight motors do not have increased service capacity in full proportion to their increased continuous rating. This is due to the fact that there is a larger short-time thermal capacity in heavy motors than in light motors, the heat generated being absorbed in the mass of material and slowly dissipated during periods of light load. However, the modern light weight motor is capable under ordinary operating conditions of handling a car about twice as heavy per pound of motor and of doing this with a much lower temperature rise. In fact, the service temperature of a modern safety car motor does not usually exceed 40 deg. rise as compared with older and heavier motors which are ordinarily run at a temperature of 60 to 65 deg. rise.

Street railway motors are now so efficiently ventilated that there is generally no substantial advantage in using heat proof insulation, since the losses are so effectively dissipated that it is questionable whether there is economy in operating at higher temperatures with increased losses and decreased power efficiency. Good ventilation has made it possible to use with economy non-heat-proof insulation which is cheaper in material cost and in application and is also more impervious to moisture.

Some of the railway motor improvements which have been briefly outlined are the most marked and far reaching that have been made during the past half dozen or more years. It would be possible to enumerate other improvements. Only the "high spots" can be touched in a short article and doubtless the writer has not mentioned all of these. Railway motor problems are being given constant study and further improvements will surely be made. However, the prediction of the writer, in the article referred to at the beginning, that "A pound of material will be made to do more and better work" has already been fulfilled in large measure.


Butte, Anaconda & Pacific, 80 ton Locomotive, Three quarter View


Bethlehem Chile, 120-ton Locomotive, Right End, Three quarter View


Baltimore & Ohio, 90 ton Locomotive, Side View


Detroit River Tunnel, 120 ton Locomotive, Right End, Three quarter View

Importance of Simplicity in Locomotive Design

By A. F. Batchelder

Engineer Locomotive Department, General Electric Company

A. F. Batchelder

THAT it is economical and practical to operate many of our trunk line railways electrically is no longer open to question. It has been proven beyond a doubt by actual experience that, under limiting physical conditions where the traffic is dense or is on severe grades, the electric locomotive, in point of reliability and cost of operation, is superior to its steam competitor. The questions which are now assuming increased importance are the method of financing and the design of equipment, rather than the question of the advisability of electrification.

The matter of financing is one for financial interests to consider, but the matter of design of the equipment must be determined by the engineers. On them will rest the responsibility of maintaining high standards of reliability and economy of operation; and for this reason, in connection with the design of electric locomotives, we should emphasize the importance of adopting locomotive designs which are fitted to perform the particular service requirements with the least amount of complication in the construction and the operation of the mechanical as well as the electrical equipment.

The simple design and construction of the locomotives that are in use on the direct-current systems of this country is the fundamental explanation of much of the economic advantage that has been demonstrated by our experience in heavy railway electrification. If a careful analysis is made of the time out of service and the cost of maintenance of the locomotives which are in operation at the Baltimore Tunnel, the Detroit River Tunnel, the New York Grand Central Terminal, the Butte, Anaconda & Pacific Railway, and the electrified zone of the Chicago, Milwaukee & St. Paul Railway, all of which are handling heavy railway equipment, and if these figures are compared with similar figures from other lines which are handling similar traffic, but using locomotives of more complicated design, the advantage of adopting the more simple designs will be shown very definitely.

It is also important to reduce the weight of the locomotive to such a minimum as is consistent with the requirements for traction purposes in order to reduce the tonnage movement and the power requirements to a minimum. This makes it desirable in considering locomotives for freight service to design them with all of their weight on drivers. It is possible with the direct-current motor to build a locomotive which has all the weight of the locomotive on driving wheels and which has a continuous electrical capacity sufficient for any railway service. Experience has shown that, for freight service, locomotives made in this manner give satisfactory operation, the maintenance of both the locomotive and the track being low. Our observations indicate that there is no real necessity of providing idle axles for any of our low-speed locomotives. At the Detroit River Tunnel there are such locomotives weighing from 100 to 120 tons, some of which have been in operation for 10 years. At the Baltimore Tunnel there are locomotives of similar design and weight which have been in operation for the same length of time. The Butte, Anaconda and Pacific has 28 locomotives, weighing 80 tons each, of the same general design which have been in operation for seven years, and some of these have been hauling passenger trains at speeds of 50 miles per hour.

All the locomotives mentioned are of the two-truck articulated type, illustrations of which are shown in Figs. 1, 2, 3 and 4. The freight locomotives of the Butte, Anaconda & Pacific are capable of developing continuously a tractive effort of 25,000 pounds at the rim of the drivers. The total weight of the locomotive is 160,000 pounds, and as a consequence the total continuous tractive effort capacity is 15 per cent of the weight on drivers. It is possible to build freight locomotives of almost any desired capacity to operate trains at speeds as high as 30 miles per hour with a tractive effort of 15 per cent of the weight on drivers, and in some cases as high as 20 per cent, and still maintain a simple and rugged construction throughout.

Modern Devices and Control for Automatic Railway Substations

By Cassius M. Davis

Railway and Traction Engineering Department, General Electric Company

In view of the number of descriptions of automatic substations that have appeared in the technical press, the author in preparing the following article presupposes that the reader has a knowledge of the fundamental scheme of operation employed. Two of the earlier articles appeared in this magazine: "Automatic Railway Substations," October, 1915, page 976, and "Give the Operator a Job," November, 1916, page 1030. The present article deals with the improvements which have been made in the controlling devices and describes in detail the automatic operation of the substation; including the starting up, shutting down, protection, and adjustment of the equipment.—Editor.

Cassius M. Davis

SINCE the introduction of the automatically controlled substation by the General Electric Company several years ago, many stations have been converted from manual to automatic control and many entirely new automatic equipments have been placed in operation. The development of any new device or new scheme of operation necessarily changes rapidly in detail but usually slowly in fundamental principles. The automatic railway substation has been no exception.

It will be the purpose of this article to record the principal improvements and changes which have been found desirable; also to describe, more or less in detail, the scheme of operation and the functions of the various individual devices in an up-to-date installation. It is assumed the reader has a general knowledge of the principle of the automatic substation.

Experience with over fifty operating equipments has shown the fundamental scheme of operation to be rational in its conception and successful in its application. This same experience has shown also the limitations of various types and designs of individual apparatus on the one hand, and the entire suitability of other individual devices on the other.

Without attempting to present in any chronological order the changes and improvements which have been made, we will consider more from the point of view of importance the new equipment which has been designed.

It might be said in passing that it is one thing to design a mechanism which operates only at infrequent intervals, say two or three times a day, and quite another to design a mechanism to do the same work twenty or thirty times a day. This statement applies to practically all the apparatus used in an automatic substation and can be made as a general statement, rather than one applying specifically to the oil switch mechanism, but is particualrly true with reference to mechanisms which are designed to operate high-tension oil circuit-breakers, and which must not contain too many small and delicate parts. Any device which has a number of small and relatively delicate parts which must be kept in close adjustment is bound to have a shorter life and give more interruptions than one composed of a few and relatively rugged parts. So it has been with the apparatus under discussion.

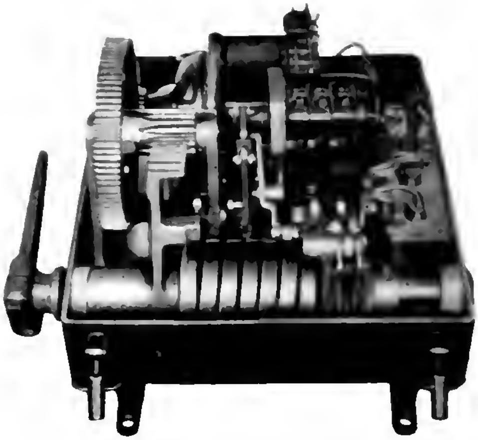


Fig. 1. A-C. Motor Mechanism for Operating Oil Circuit Breakers

The mechanism which now forms part of the standard equipment is illustrated in Fig. 1. It was designed after a most careful and painstaking study of the conditions to be met and was accepted for the service only after having proved its ability to withstand successfully over 100,000 operations. The device which has proved satisfactory under these conditions consists of an operating motor which is of the alternating-current, single-phase type, the motor operating through a mechanism affording a gear reduction and also through a spring to move the circuit-breaker to the circuit-closing position. When the circuit-breaker is moved to its closing position, the circuit of the motor is then interrupted and the circuit-breaker held latched in its closed position. After the circuit-breaker is closed, there is considerable tension exerted by the spring which, thereupon, functions as a source of power to return the motor and its auxiliary mechanism to their initial position, leaving the switch mechanism in such a position that the mechanism is adapted when tripped open to move freely to its open position.

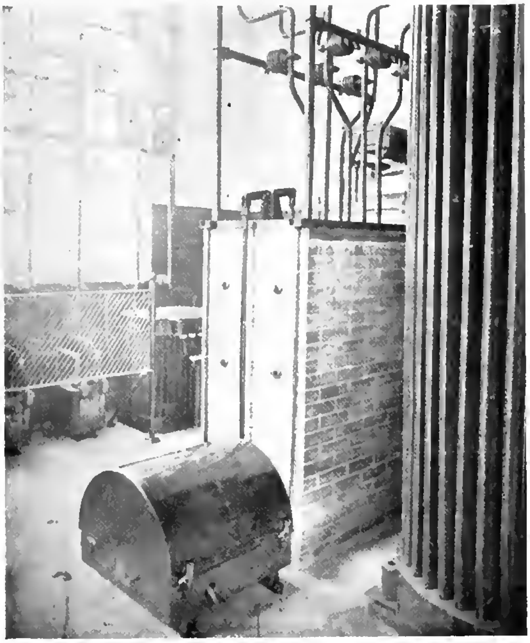


Fig. 2. Motor Mechanism Assembled with 15,000-volt Breaker in Cell

All parts of the mechanism are made with a very large factor of safety. There are practically no small moving parts and such levers and links as are used are made from heavy stock capable of withstanding the forces applied to them. A sheet metal cover encloses the moving parts and the complete device forms a weather-proof unit which is suitable for outdoor work where necessary. Fig. 2 shows one of these mechanisms as connected to a 15,000-volt oil circuit breaker mounted in a cell.

The early installations were of 300- and 500-kw. capacity, hence, at 600 volts, the

Fig. 3. Shunt Type Relay used for Reverse Current and Underload

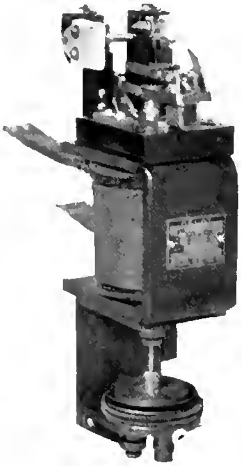


Fig. 4. Shunt Type Relay Used for D-C. Overload Protection

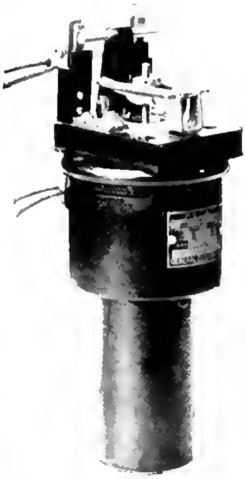


Fig. 5. Time-limit Relay Used to Obtain Delayed Action When Starting and Stopping

50 per cent overload current did not exceed 750 amp. and 1250 amp. respectively. When handling circuits of this capacity it was comparatively easy to build direct-current relays having series coils. However, as soon as larger capacities were encountered it became

evident that more suitable relays should be used. It was possible in some cases to operate relays in multiple but it was recognized that this was only begging the question and it would soon be necessary to devise relays which could be conveniently employed on circuits of any commercial capacity.

In order to meet this condition a line of shunt-type direct-current relays was developed. The coils have a normal current capacity of approximately 100 amp. but receive their current from shunts connected in series with the direct-current load circuit.

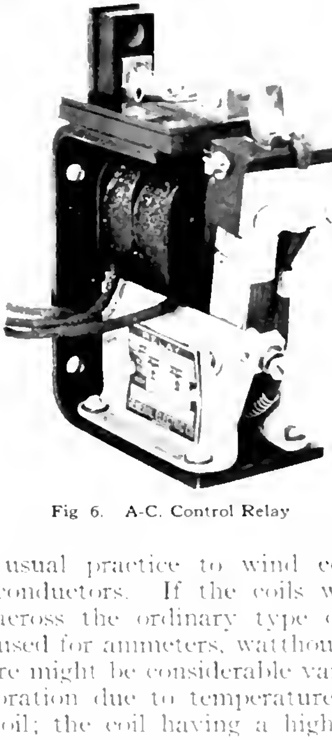


Fig 6. A-C. Control Relay

It is usual practice to wind coils with copper conductors. If the coils were connected across the ordinary type of shunts such as used for ammeters, watthour meters, etc., there might be considerable variation in the calibration due to temperature changes in the coil; the coil having a high positive temperature coefficient and the meter shunt a very small temperature coefficient. The obvious way of taking care of the situation was to use the same conductor material for both the shunt and the coil. This was done and both are now made of copper. The shunt is simply a copper sheet of such dimensions as to carry the current and give the necessary voltage drop for operating the relay.

The use of shunt-type relays made it possible to use the same relay for any capacity circuit by varying the size of the shunt. In the early equipments, the overload relays which controlled the steps of the load limiting resistance were operated from current transformers connected in the leads to the slip rings of the synchronous converter. While such an arrangement permitted the use of the same relay for any capacity circuit it was subject to the disadvantage that any change in field setting necessitated a corresponding change in the relay setting. Consequently, with the advent of the shunt-type relay, it was possible to place the overload control on the direct-current side of the machine, which, of course, is more satisfactory from every point of view.

The standard equipment now includes shunt-type direct-current devices for the reverse-current relay *29*, the underload relay *37*, and the overload relays *23*, *24*, and *25*, in Figs. 3, 4 and 11.

The first time-limit relays which were employed were equipped with small oil dashpots. These frequently gave trouble, due primarily to the fact that the dashpots were so small it was difficult to get the time setting desired, especially on relay *3* which is used to delay the shutting down of the equipment. It was also found that the contacts were not suitable for the service. These relays were therefore entirely redesigned, bellows were substituted on relays *23*, *24*, and *25*, and an entirely new design of dashpot was applied to relay *3*. The contact mechanism of all of them was radically changed and improved.

The latest type of *3* relay is shown in Fig. 5. In this, the oil dashpot has been made much larger and the stroke of the piston longer. This permits the use of a greater volume of oil and reduces the necessity of small clearances. The dashpot is so attached to the body of the relay as to form practically an integral part. The piston is self-aligning and has a long bearing surface. The needle valve for adjusting the time has undergone a radical improvement, making it possible to adjust the setting of the relay with considerable accuracy. Since the cylinder practically forms a part of the body of the relay itself the oil is kept at nearly uniform temperature, due to the heat generated by the coil. While the use of oil is open to the criticism that it changes its viscosity with change in temperature, yet with the type of relay under discussion, this change is reduced to a minimum. A variation in time setting is to be expected between summer and winter but the ordinary daily changes of temperature will have very little effect. Furthermore, since it is not necessary that this relay be an accurate timing device the slight changes in viscosity which take place from day to day are unimportant. That is to say, if a certain relay is set to operate in five minutes it will have no noticeable effect upon the operation of the substation if on a hot day it opens in four minutes and on a cold day in six minutes.

The contacts of the relays *3*, *23*, *24*, *25*, and *30* have received a great deal of attention. After many exhaustive tests both on the alternating-current and direct-current circuits involved it was found that silver to silver contacts behaved the best, both from point of view of wear and burning due to arcs. The contacts are still operated by a toggle mechanism but it has been so changed as to provide a quick make and a quick break feature. With this type of mechanism it is impossible for the contacts to open or close part way, thereby tending to hold an arc. The toggles are so arranged that when the contacts start to move they are forced over center by springs to complete the motion to the end of the travel. All contacts which handle direct-current circuits are provided with small blowout coils to decrease the time of rupturing the arc. The travel of the contacts, however, is sufficient to break the arc even without the blowout coils.

In the early stages of the application of automatic control a need was felt for a simple and ruggedly constructed alternating-current relay which was self-contained on its own base, could be easily mounted in a narrow space on the panel, and would handle currents of somewhat larger capacity than any of the standard relays then available. To meet these requirements an entirely new relay was designed which is shown in Fig. 6. It will be noted this is constructed along the lines of a contactor but is provided with an adjustable stop, thus making it possible to adjust the pick up point over a moderate range. The contacts will easily carry ten amperes alternating-current and momentarily much heavier currents. It is of very rugged construction and easy to keep in adjustment.

The first few installations were designed for converters without commutating poles. To adapt the equipment for the commutating pole type it was necessary only to provide some means for mechanically raising and lowering the brushes. A special motor-operated mechanism was developed for this purpose, using a repulsion-induction type single-phase motor driving the brush mechanism through a gear reduction. Suitable limit and auxiliary switches were incorporated in the device.

Only minor changes have been found necessary in the motor-driven controller. The original controller was built with a vertical cylinder. Later this was changed to a horizontal cylinder and minor mechanical changes made to adapt the parts for this type of construction. For some time a dynamic brake was used to bring the controller to rest. The braking was accomplished by throwing a heavy load on the small exciter connected to the driving motor. This was later changed and a solenoid brake employed. This has the advantage of stopping the controller a little more accurately and also prevents any possibility of overloading the driving motor. The views shown in Figs. 7 and 8 give a clear idea of this mechanism. However, they do not show the cover which shields the entire device from dirt and dust.

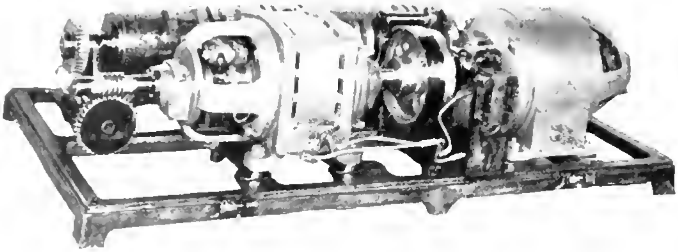


Fig. 7. Motor-driven Controller

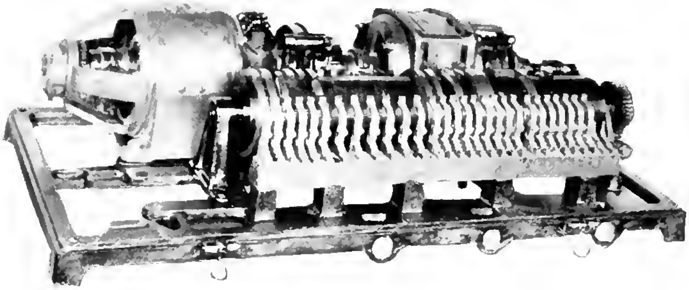


Fig. 8. Motor-driven Controller

An improved type of bearing thermostat has been in use for some time. It consists of a metallic bulb connected to an expansible chamber through the medium of a capillary tube. The bulb, tube and chamber are filled with a liquid which volatilizes at a definite temperature. As the chamber expands, it operates a relay toggle to which the contacts are assembled, Fig. 9.

The bulb is inserted in a hole in the lower half of the bearing, while the relay part is mounted on a bracket conveniently placed on the bearing pedestal. The hole in the bearing is drilled parallel to the shaft and as close to the babbitt surface as mechanically possible. The depth of the hole depends upon the length of the bearing, the bulb being placed as near the center as possible. The bulb is thus located advantageously for registering the highest temperature throughout the bearing length. For very long bearings, two temperature relays are used, one inserted from each end of the bearing.

Fig 9. Bearing-temperature Relay

The relay contacts are normally closed, and open due to excessive temperature. Having once opened they must be reset by the inspector after ascertaining the reason for overheating.

A number of minor modifications have been made here and there to improve the individual devices or the general scheme of operation and protection. For example, the polarized relay *36* has been somewhat changed in design to make it conform in appearance and construction to the reverse-current and underload relays. Also, the speed-limit device *12* has been provided with an additional set of contacts. This device now has a normally closed and a normally open set of contacts. On overspeed, one set closes the circuit to the shunt trip on the line circuit breaker (which is otherwise non-automatic) and the other set opens the control circuit. When the speed-limit device trips, both contactor *18* and the line breaker open, thus doubly insuring that the machine is cleared on the direct-current side.

SCHEME OF OPERATION

In what follows is given a detailed description of the operation of a typical automatic railway synchronous converter substation. The general scheme is almost identical with that used in the first installations.

The motor-driven controller may be considered the "brains" of the outfit, with the contact-making voltmeter and the underload relay acting as the "eyes."

The voltmeter registers the load demand and starts the controller. The controller then fixes the sequence of events and closes or opens the various control devices in the proper order and at the proper time during the starting operations. It serves at once electrically and chronologically to interlock the various breakers, contactors, relays, etc.

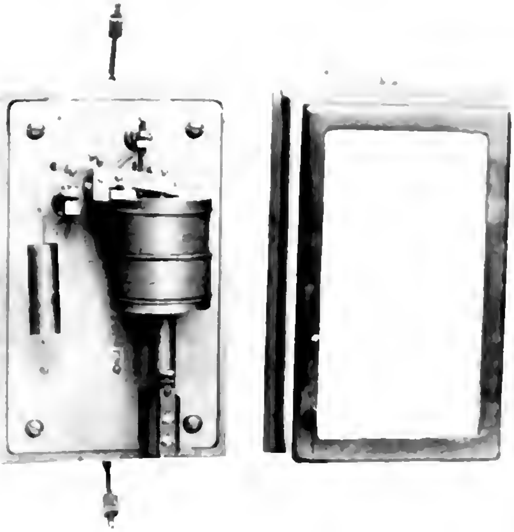


Fig 10. Contact-making Voltmeter

After the machine has been delivering load and the economical demand ceases, the underload relay acts to shut down the station and advance the controller to its initial position ready for the next start.

These remarks, while applying to the control of a synchronous converter, are also

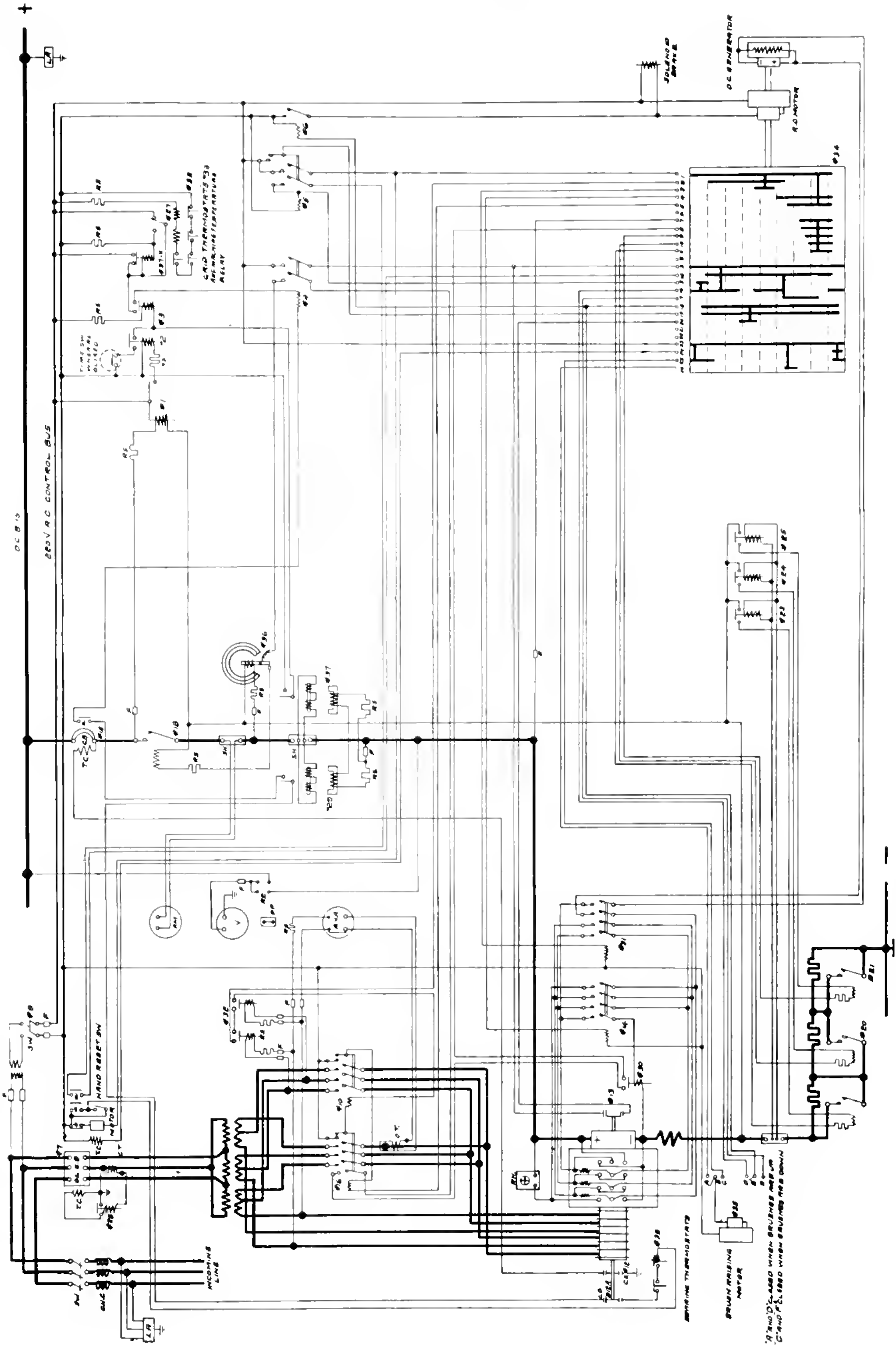


Fig. 11. Typical Wiring Diagram for an Automatic Synchronous Converter Substation

applicable to that of a motor-generator set starting from transformer taps or compensator. The description refers specifically to the wiring diagram shown in Fig. 11.

With the high-tension line energized to its full voltage and the lever switch *8* closed, relay *27* closes its right-hand contact, energizing the coil of *27-X* and closing it. When *27-X* closes, it seals itself in through the circuit completed by its contacts.

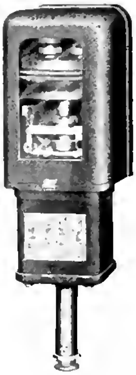


Fig. 12 A-C Inverse Time-limit Overload Relay

Starting Up

A load demand on the equipment is indicated by a reduction in the trolley voltage at the substation. The contact-making voltmeter *1*, Fig. 10, connected between the direct-current bus and ground, utilizes this voltage reduction to start the converter. As long as the trolley voltage is up to normal the contacts remain closed and keep relay *2* energized thereby holding the contacts of the latter open. As soon as the trolley voltage falls to the setting of the voltmeter, the following sequence of operation takes place:

(1) The contacts of the voltmeter *1* open and de-energize relay *2*. The contacts of *2* do not immediately close owing to an adjustable time setting. If the reduced trolley voltage persists continuously, during the time setting of this relay, its contacts close and close relay *3*. A circuit is then established from the upper alternating-current control bus through the contacts of *27-X*, the contacts of *3*, coil of *4*, auxiliary switch on the circuit breaker, contacts of *26*, speed-limit switch, bearing thermostats, and hand reset switch on the oil circuit breaker mechanism back to the lower alternating-current control bus.

(2) Contactor *4* closes, establishing a circuit from the upper control bus through one of its contacts to segment *15* on the controller thence to segment *16*, upper contact of auxiliary switch on brush-raising device, and to the operating coil of contactor *6*, back to the lower control bus.

(3) Contactor *6* closes and starts the motor driving the controller.

(4) Segment *15* on the controller makes contact, closing the circuit to the operating coil of contactor *5*.

(5) Contactor *5* closes, establishing a circuit through one of its contacts to segment *1* on the controller and, simultaneously establishes a circuit from the same contact to the closing circuit of the oil switch motor mechanism.

(6) The oil switch closes, energizing the power transformer and therewith the coils of both relays *32*.

(7) Segment *14* on the controller makes contact, completing a circuit through the auxiliary switch on the oil circuit breaker, one of the contacts of *5* and the operating coil of *5*. This operation thus establishes a holding circuit for contactor *5* as soon as the controller advances beyond segment *15*.

(8) Segment *2* on the controller makes contact, establishing a circuit through the contacts of both relays *32* and the operating coil of contactor *10*.

(9) Starting contactor *10* closes, placing reduced voltage upon the collector rings of the converter from the transformer taps. The converter starts.

(10) If the converter has come up to synchronous speed by the time the first gap in segment *16* is reached, a circuit is established from segment *14* through the contacts of 13 to segment *20* and thence to segment *18* and the operating coil of contactor *6*. This holds contactor *6* closed until the gap in segment *16* is past. If the converter has not come up to speed by the time the gap in segment *16* is reached, the circuit to the operating coil of *6* contactor is broken and the controller comes to rest until synchronous speed on the converter is reached; i.e., until *13* closes.

(11) Segment *3* makes contact, closing the circuit to the operating coil of field contactor *31*.

Fig 13. A-C Low-voltage Relay

(12) Contactor *31* closes and connects the fields of the converter to the 250-volt exciter on the controller, giving proper polarity to the converter. As the converter is brought to the proper polarity, relay *30* closes its contacts.

(13) Segment *3* breaks contact, opening contactor *31*

(14) Segment *4* makes contact, energizing the operating coil of full-field contactor *14*.

(15) Contactor *14* closes and places the field of the converter across its own armature for self-excitation.

(16) Segment *2* breaks contact, opening starting contactor *10*.

(17) Segment *5* makes contact energizing the operating coil of running contactor *16*.

(18) Contactor *16* closes and puts full alternating-current voltage on the collector rings of the converter. At the same time, relay *30* closes due to the establishment of full voltage across the armature of the converter.

(19) Segment *26* makes contact, establishing a circuit through the upper contacts of the limit switch on the brush raising device.

(20) The motor of this device starts lowering the brushes.

(21) If the brushes reach their lowest position and the lower contact of the auxiliary switch on the brush raising device is closed before the controller runs off the second gap in segment *16*, a circuit is established from segment *17* through the lower auxiliary switch of the brush raising device to the operating coil of contactor *6*, thus holding *6* closed and permitting the controller to continue to revolve.

(22) If the controller runs off segment *16* before the brushes are in their lowest position, the operating coil circuit of *6* is opened and the controller stops until the lower auxiliary switch on the brush-raising device closes and completes the circuit from segment *17* described above.

(23) Segment *7* makes contact, giving direct-current potential to segments *8*, *9*, *10*, and *11*.

(24) Segment *26* breaks contact, de-energizing the circuit to the brush-raising device.

(25) Segment *8* makes contact, establishing a circuit through one of the contacts of contactor *4*, the contacts of polarized relay *36*, the contacts of relay *30*, the electrical interlock on contactor *16*, and the operating coil of contactor *18*.

(26) Contactor *18* closes, connecting the converter to the bus through all three sections of the load limiting resistance.

(27) Segment *9* makes contact, establishing a circuit through the operating coil of *21* contactor and the contacts of relay *25*.

(28) Contactor *21* closes, short-circuiting a section of the resistor.

(29) Segment *10* makes contact, establishing a circuit through the operating coil of *20* and the contacts of *24*.

(30) Contactor *20* closes, short-circuiting a section of the resistor.

(31) Segment *11* makes contact, establishing a circuit through the operating coil of *19* and the contacts of *23*.

(32) Contactor *19* closes, short-circuiting the last section of the resistor. The machine is now connected directly to the bus and delivering load. During the last several operations mentioned above, after *18* contactor closed, the contacts of relay *37* close, short-circuiting the contacts of relay *2*. Simultaneously, the voltage of the bus has been brought up to normal and the contacts of *1* again close. This action opens the contacts of *2* but relay *3* still remains energized, due to the by-pass circuit through the contacts of *37*.

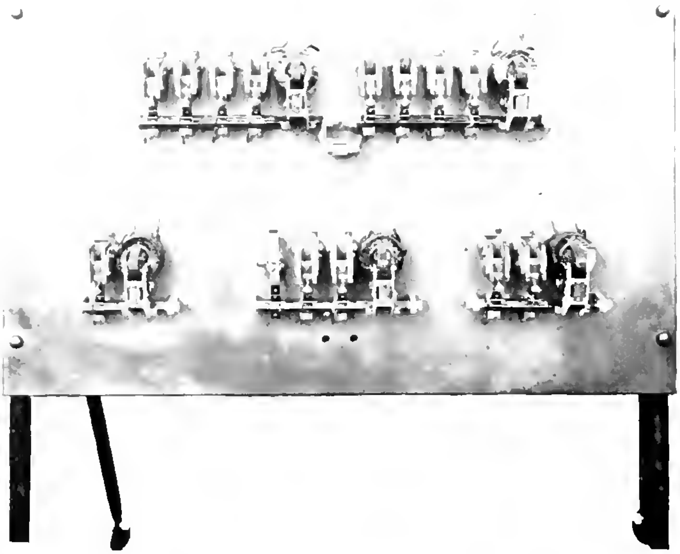


Fig 14 Panel Containing Control and Converter Field Contactors

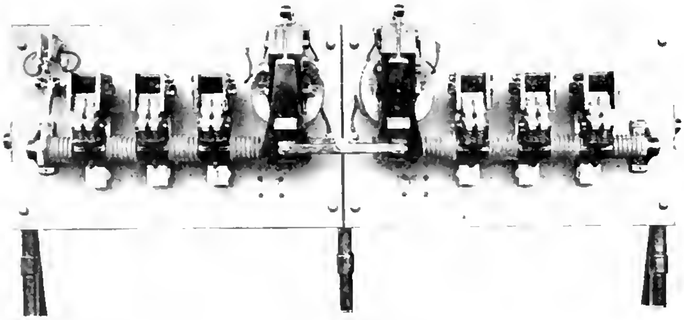


Fig. 15. Typical A-C. Starting and Running Contactors

(33) Segment *17* breaks contact, opening the circuit previously established through the lower contacts of the brush-raising device and the operating coil of contactor *6*.

(34) Contactor *6* opens and the controller comes to rest at the running position.

Shutting Down

(1) When the load demand decreases and reaches the reset value of *37*, the contacts of the latter open and de-energize relay *3*.

(2) If the load does not increase at any time during the time setting of relay *3*, its contact opens and interrupts the coil circuit of contactor *4*. Should the load increase before *3* opens, relay *37* again closes and re-energizes *3*.

(3) After *3* has opened, contactor *4* opens, interrupting two circuits simultaneously; one, the alternating-current supply to the controller segment *13*, and the other, the direct-current circuit including the operating coil of contactor *18*.

(4) The holding circuit for contactor *5* through segment *14* and the auxiliary switch on the oil circuit breaker is broken.

(5) Line contactor *18* and contactor *5* open.

(6) The opening of contactor *5* interrupts the supply to segment *1* on the controller and establishes a circuit through its electrical interlock to segment *19*.

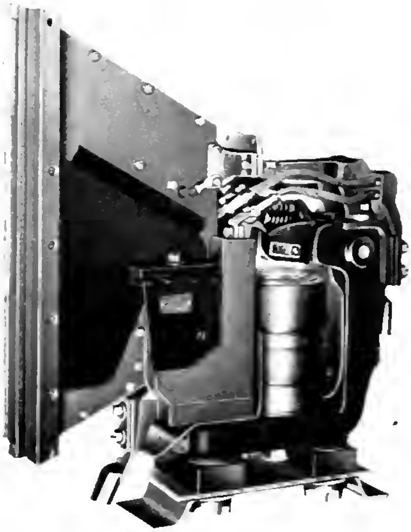


Fig. 16. Typical D-C. Line and Resistor Contactor

(7) Contactors *16* and *14* open, disconnecting the converter from the transformer and discharging its field. The operating coil of contactor *6* is energized through the electrical interlock on contactor *5* and segments *19* and *18*. The controller motor starts, *30* opens and contactors *19*, *20*, and *21* open.

(8) Segment *24* makes contact, energizing the trip circuit of the oil switch mechanism; also segment *25* makes contact through the lower limit switch on the brush-raising device.

(9) The high-tension line is disconnected from the transformer, de-energizing relay *32*, which opens. The brushes are raised from the commutator.

(10) Segments *18* and *19* break contact and controller comes to rest at the off position. In the meantime, the motor of the brush-raising device continues to operate until reaching the end of its travel when the lower limit switch is opened, breaking the supply to the motor.

(11) As the voltage on the converter armature dies down, after contactors *14* and *16* are open, relay *36* opens.

Where individual load-limiting feeder protection is provided, usually only two steps of machine resistance are used, while each feeder is protected by one section of resistance. Thus overload relay *23*, contactor *19* and the corresponding resistor are transferred to one feeder and similar equipment is applied to each of the other feeders. In addition it is customary, in important substations, to provide isolating feeder contactors which entirely disconnect the feeder in case a continued overload is sufficient to heat the feeder resistor above a safe operating temperature.

PROTECTIVE FEATURES

Direct-current Overload

Relays *23*, *24*, and *25* are calibrated at successively higher overloads. They receive their actuating current from a shunt in the machine circuit. The contacts of each relay control a corresponding contactor, *19*, *20*, or *21*. These, when closed, short circuit sections of the load-limiting resistor. When they open on overloads they insert respectively the several sections of the resistor and limit the output of the machine.

Alternating-current Overload

In case of trouble on the alternating-current converter, or in the transformer, protection is afforded by relay *28*, Fig. 12. This is an inverse-time-limit device with a definite minimum setting and is energized by the high-tension current transformer. The current setting is well above the corresponding

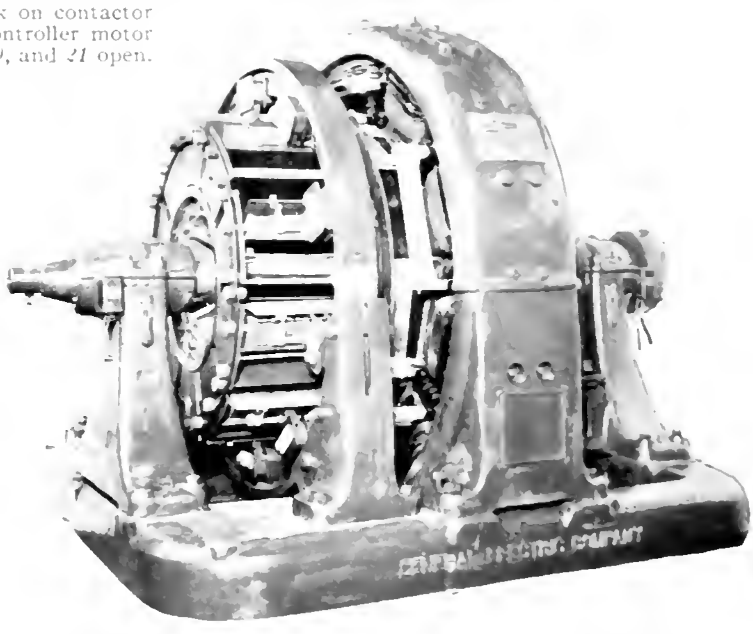


Fig. 17. Synchronous Converter Equipped for Automatic Control

current settings of relays *23*, *24*, and *25*. When relay *28* operates, it trips the oil circuit breaker and with it the hand reset switch. The opening of the hand reset switch interrupts the coil circuit of contactor *4*. Simultaneously an auxiliary contact on the oil circuit breaker breaks the holding circuit of contactor *5*. The machine is thus disconnected first from the high-tension alternating-current side and then from the direct-current and low-tension alternating-current sides.

After the oil circuit breaker has been tripped in the above manner and the hand reset switch opened, the station will not start up again until the hand reset switch is closed by the inspector. Consequently, relay *28* is set very high and is expected to operate only in cases of severe trouble where the attention of an inspector would be necessary in any event.

Low Voltage

Relay *27*, Fig. 13, provides the alternating-current low-voltage protection. When low voltage occurs, the left-hand contacts of *27* are closed which short-circuit the coil of relay *27-X*, opening it and interrupting the supply through the contacts of relay *3* to the coil of contactor *4*. Relay *29*, in a certain sense, performs the function of an alternating-current low-voltage relay whenever the converter is running, since, should the alternating-current voltage fall too much, the converter would invert and supply power from the trolley to the alternating-current system. Relay *29* would then open, interrupt the holding circuit of contactor *4* and shut down the machine.

Overspeed

The speed-limit device, *12*, on overspeed closes the circuit of the shunt trip of the direct-current circuit breaker. When this opens, the auxiliary switch on the circuit breaker interrupts the supply to the coil of contactor *4* and the equipment shuts down. An additional safeguard is also provided by an additional set of contacts on the speed-limit device which, on overspeed, opens the coil circuit of contactor *4* also.

Underspeed

The speed control switch *13* is a centrifugal device, the contacts of which remain open until approximate synchronism is reached.

Sequence

The sequence of events is primarily fixed by the controller. However, in addition to this, there are electrical interlocks on contactors *10* and *16* as well as the holding circuit of contactor *5*, all of which are additional safeguards against incorrect sequence. Furthermore, contactors *10*, *16*, *14*, and *31* are mechanically interlocked.

Polarity

The 250-volt exciting generator direct connected to the motor of the controller fixes the polarity of the converter, but, as an additional precaution, the polarized relay *36* must be energized in the proper direction before allowing the line contactor *18* to close.

Temperature

Should either of the machine bearings overheat, one or the other of the temperature relays *38* will open, de-energizing contactor *4* and shutting down the machine. The relays are hand-reset devices and hence after functioning require the presence of the inspector.

When the load-limiting resistor overheats due to overload peaks, or the machine reaches its maximum heating due to cumulative overloads, one or more of the temperature relays *33* opens. The operation of any one of these relays de-energizes relay *27* which latter then closes the left-hand contact. This action short circuits the coil of relay *27-X* and opens the coil circuit of *4*. The machine then shuts down until the temperature of the resistor or machine lowers to a safe operating value, after which it will again be ready to start on load demand.

Balanced Polyphase Voltage

This protection is provided on the low-tension side of the power transformers by means of the two relays *32* which are connected across different phases. All three phases of the power transformer must be excited to approximately normal voltage; otherwise one or both of the relays *32* will remain open and prevent the starting contactor *10* from closing.

Position of Converter Brushes

Proper position of these brushes is assured by means of the auxiliary switches on the brush-raising device.

Reverse Current

Should the machine start to invert, due either to the lowering or interruption of the alternating-current supply voltage, the reverse current relay *29* will open and de-energize contactor *4* shutting down the machine. The reverse current relay also acts as an

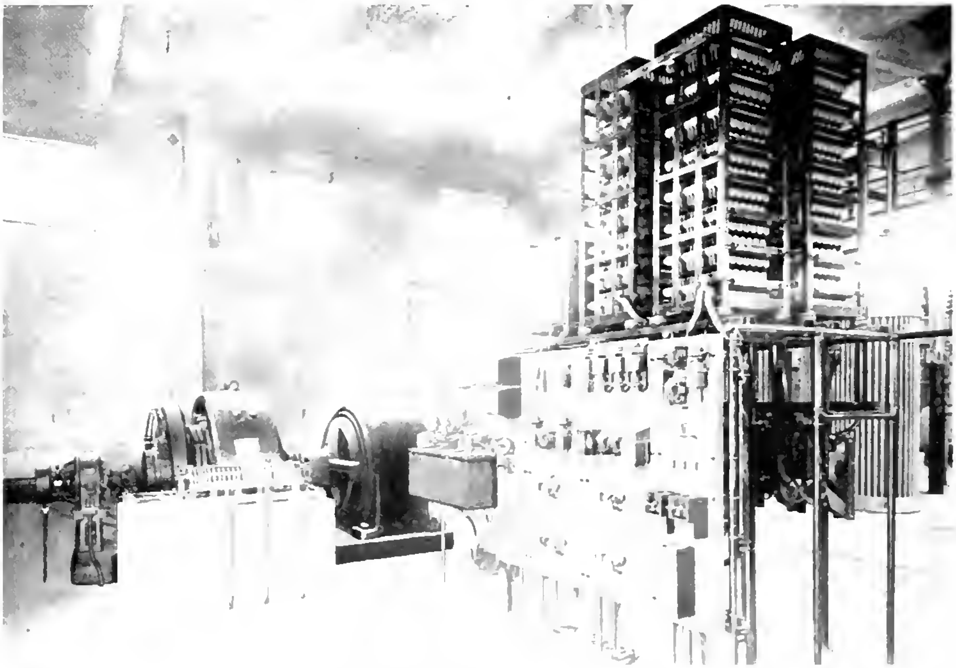


Fig. 18 Automatic Substation of the Salt Lake, Garfield and Western Railway, 600 Kw., 60 Cycle, 1500 Volts

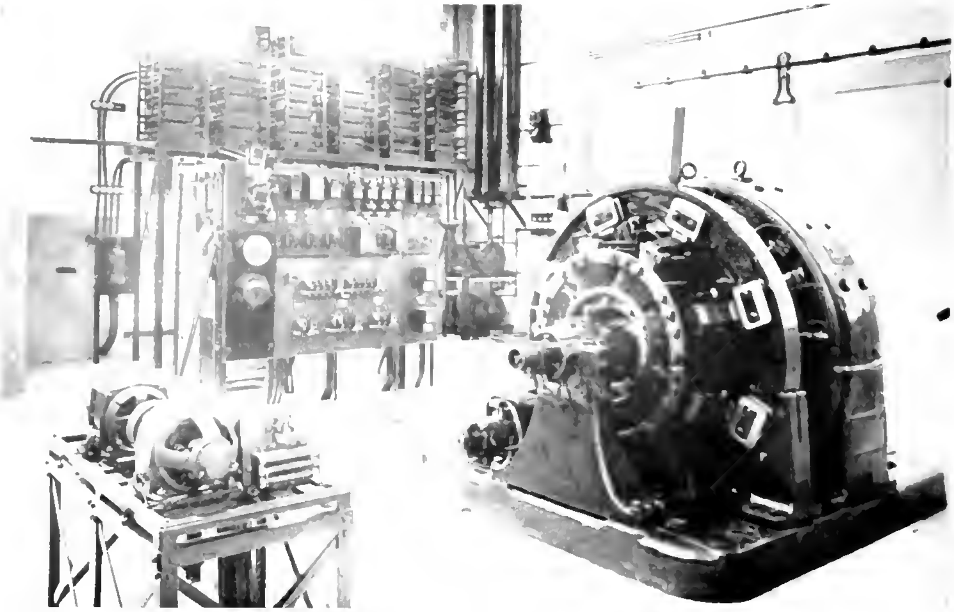


Fig. 19 Automatic Substation of the Pacific Electric Railway, 1000 Kw., 50 Cycle

auxiliary to the overspeed device. It is set to open at the direct-current running-light current of the converter. Consequently upon the loss of alternating-current potential the converter begins to motor, but as soon as it draws an appreciable current from the trolley, and before it can reach a dangerous speed, relay *29* operates disconnecting it from the line.

Interruption of Alternating-current Supply

An interruption of the alternating-current supply may occur at any time during the cycle of operation. Three cases will cover all contingencies.

First, while segment *15* of the controller is in contact. The failure of supply at this point leaves the high-tension oil circuit breaker closed but all other devices (except *1*) are de-energized. When the supply is re-established, and assuming a load demand exists, the sequence of operations at once begins where it left off.

Second, after segment *15* has broken contact and before segment *11* has made contact. The failure of supply leaves the oil circuit breaker closed, but opens all other devices which happen to be closed at the time. When the supply is re-established, contactor *4* closes but contactor *5* cannot close because its holding circuit has been interrupted. Consequently neither the starting contactor *10* nor the running contactor *16* can close. However, a circuit is closed through the auxiliary contact of *5* to segment *19*, thence to segment *18* and the coil of contactor *6*. This action starts the controller and runs it to the "off" position and trips the oil circuit breaker through segment *24*. It is then ready to start the equipment again if there is a load demand.

Third, while the machine is running and delivering load. The failure of supply causes the reverse-current relay to operate de-energizing, through contactor *4*, all other devices. The oil circuit breaker is not tripped. Upon the return of supply the same action takes place as outlined under the second case above.

Field Current

Relay *30* is in series with the converter shunt field; its contacts are in series with the coil of line contactor *18*. Failure of field current at any time thus prevents the attempt to carry load.

Converter Flashover

Converters which are to be used in automatic substations are equipped with flash barriers. These greatly reduce the number of flashovers and materially decrease the damage due to flashing. Practically perfect protection can be obtained by the use of barriers and a high-speed circuit breaker. In addition to barriers, all new 60-cycle converters have high reluctance commutating poles and a protected type of brush-holder. These last features have proven very successful.

ADJUSTMENTS

The foregoing description gives only the bare outline of the various steps by which a converter is started and stopped. During the time the substation is delivering load, it must take care of itself under all conditions. It is not within the scope of this article to go into the many fine points of operation, however, the reader will have already gleaned a general idea of some of the more important characteristics. The description of the protective features brings out many.

One point warrants further mention; namely, the matter of adjustments. An otherwise good equipment may give poor service unless every device is in good working condition and properly adjusted. Unsatisfactory service, for example, may result from the improper adjustment of overload relays *23*, *24*, and *25*. These might be set too high or too low to give the best operating conditions. Another thing; the ohmic values of the load-limiting resistor steps require the careful attention of the engineer in order to best fit in with the current swings during normal and rush traffic. Needless to say, the physical condition of the individual pieces of apparatus requires intelligent and regular inspection.

Herewith are given some of the more important adjustments of which a modern equipment is susceptible. It should be noted that most, if not all, of them are matters of trial after installation. This is necessarily the case since all the operating peculiarities of a given road cannot be anticipated.

The contact-making voltmeter is adjusted to make firm contact with normal voltage on the bus. The contacts should open at a bus voltage such that, after the station cuts in, the machine will deliver an economical load. This value varies according to the service, from 450 volts to 550 volts on a normal 600-volt system.

The primary adjustment on relay *3* is the time element. This varies with conditions but the relay is ordinarily set between three and eight minutes.

The overspeed device *12* is adjusted to function at from 10 to 15 per cent overspeed.

The speed control switch *13* is set to close its contacts at between 95 and 100 per cent speed, with the necessary allowance made in variation of transmission line frequency.

Relays *23*, *24*, and *25* are adjustable both for time and opening value. The current setting of these is usually about 130, 150, and 170 per cent of the full-load current of the machine. Their final setting, however, is entirely dependent upon the load conditions. The time setting is so adjusted that, when all of them have opened on overload, the one controlling the largest section of load limiting resistance should come in first in about five to six seconds, the next one, seven to eight seconds, and the last one, controlling the smallest section of resistance, in nine to ten seconds.

Relay *27* is set just below the minimum point of the high-tension line voltage variation. Ordinarily, if this relay is adjusted to close its left-hand contacts at about 15 per cent reduction in transmission line voltage, it will be satisfactory. In this connection, care is taken to see that the 220-volt alternating-current control bus is as close to normal voltage as possible, changing the taps on the control transformer, if necessary.

Relay *28* is set for about 225 to 250 per cent load with a time setting of from three to four seconds.

Relay *29* should open its contacts when the converter is running light from the direct-current side and with the high-tension oil switch open.

Relays *32* are so adjusted they will not close when the power transformer is energized and one or another of the high-tension disconnecting switches are open. They, of course, should close immediately all three high-tension disconnecting switches are closed.

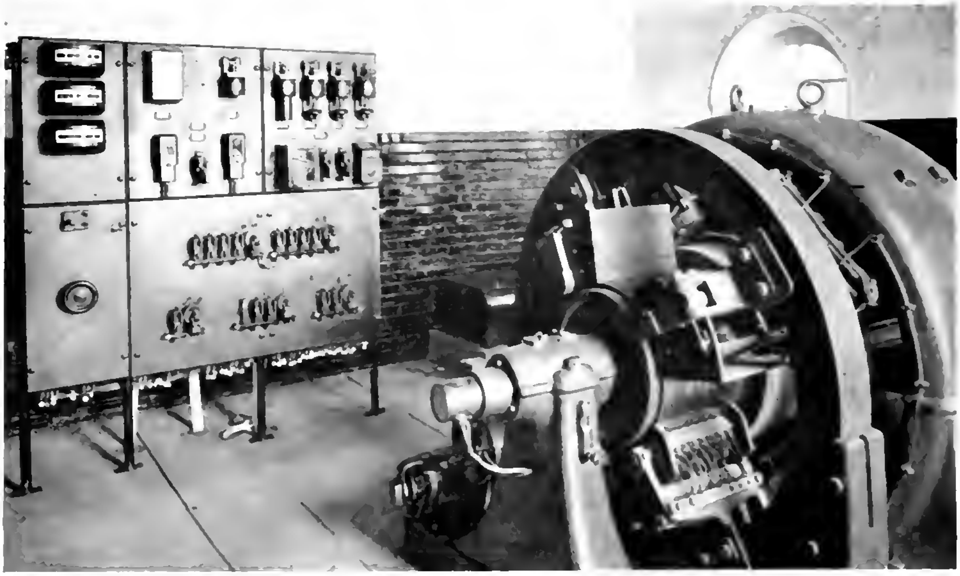


Fig. 20 Automatic Substation of the Conestoga Traction Company, 500 Kw., 25 Cycle

The bearing thermostats have a fixed setting at about 100 deg. C. The thermostats mounted over the load-limiting resistance are adjustable over a wide range and the setting depends entirely upon the method of mounting and distance from the grids. It is usually set by trial, by opening relays *23*, *24*, and *25* and allowing all the current to feed through the load-limiting resistor. This condition is maintained until the resistors reach a temperature well above the boiling point of water and below a dull red heat.

The setting of underload relay *37* is dependent entirely upon service conditions and should be adjusted by trial so the machine will be shut down when delivering an uneconomical load.

N. E. L. A.

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Vol. XXIII, No. 5

May, 1920

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Editorial:

Broadway, Los Angeles, Cal., Lighted by 6.6 amp. Luminous Arc Lamps. This photograph illustrates the effect of intensive White Way lighting

GENERAL ELECTRIC
REVIEW

FROM UNCERTAINTY TO UNPRECEDENTED ACTIVITY

I am delighted to have the opportunity afforded by this issue of GENERAL ELECTRIC REVIEW of expressing to the members of the National Electric Light Association in convention at Pasadena, Cal., the deep appreciation of the General Electric Company for their considerate and patient attitude toward us during the trying period since the closing months of 1918 and throughout the greater part of 1919.

During this period the manufacturer was confronted with stoppage of work and heavy cancellation of orders for apparatus and material, particularly on account of Government contracts, involving accumulations of raw materials serviceable primarily for the completion of such contracts. The sudden cessation of work early in 1919 imposed upon the manufacturer serious problems of redistribution of labor to a more normal condition. Costs of raw materials fluctuated, credits were strained to the limits of safety, and business conditions generally were warped and distorted. It was difficult to deal with these conditions from day to day and impossible to forecast the future with any degree of certainty. It was not a period for initiative and progress; the manufacturer could not venture to provide additional facilities or accumulate stocks of materials; in fact, they "marked time" awaiting a clearer vision of of the immediate future.

It is most astonishing how rapidly industry recovered from the uncertainty. In the early spring of 1919 there were indications of improvement and there arose within four or five months thereafter a demand for electric apparatus and devices that grew to such proportions in the succeeding months of the year that all doubts which existed a few months before were dispelled. This curve of demand continued upwards with such rapidity that the existing facilities were taxed to their maximum, and in the closing months of the year 1919, continuing through January and February of 1920, the electrical industry, and presumably many others, were not in a position to accept additional business assuring reasonably prompt or certain deliveries. Such is the condition today. In less than twelve months there was a complete industrial cycle from uncertainty to unprecendented activity with possibly some misgivings as to the future.

Additional facilities are now being provided as rapidly as possible, regardless of excessive cost of construction and equipment; unfortunately, such facilities are not immediately available and will not be productive for several months. In the meantime every effort is being put forth to stimulate production.

The business of 1919 as it gathered force disclosed rather unusual features. There was less than a normal demand for large generating and distributing apparatus; there was an increasing demand for small apparatus, such as induction motors, especially from industrial plants, stimulated no doubt by the demand for the product of such industrial concerns. Tremendous activity developed for small or fractional horse-power motors and electric ranges and heating devices for domestic and industrial uses. The aggregate rating of such motors contracted for in 1919 from all sources is estimated to exceed a million horse power and the rated capacity of electric heating units in excess of 1,200,000 kilowatts.

Contrary to the general impression there was an increased and well sustained demand for car equipments for electric railways. The electrification of steam roads and terminals did not progress for obvious reasons. Recently, however, there has been a cuickening of thought and action on the part of the management of these properties as the transportation systems are being returned to their original owners and operators.

Throughout the year the central station management likewise had their troubles in their endeavor to meet the demands for power in excess of existing facilities, and to provide, within the accepted limits of sound finance and earning power, funds necessary for improvements and expansion. The future possibilities, however, of the growth of the central station industry are, in my judgment, most hopeful, and the field and scope of operation are expanding and are most promising. It would seem to be a new era of development for the central station industry, and I firmly believe that sound financing will be forthcoming to support the efforts of executives and managers of established public utilities to supply the demand of the public for light and power. Unwise legislation and decisions may retard, but cannot prevent the ultimate development of the central station industry, which is founded on such sound economic principles and conducted in a manner best conserving the interest of the public.

J. R. Lovejoy,
Vice-President, General Electric Company.

ELECTRICITY AT THE PASADENA CONVENTION

In the economic transition that has taken place, electricity emerges the dominant factor in the world's work and as such is confronted with problems and undertakings of a scope and urgency beyond all parallel. The annual convention of the National Electric Light Association to be held at Pasadena, California, May 18 to 22, comes at a time when these considerations are of paramount importance to the future of the industry itself and to the life and activities of the nation at large This convention, representing as it does an invested capital of some $3,000,000,000, will bring into concerted action the great construction forces of the industry to deliberate and devise the physical and practical side of these propositions, and will attract likewise representation on the part of the financial interests who will desire to appraise and compute them as bases of the immense funding requirements that will be needed to consummate.

The tremendous demands that are thrust upon the electrical industry as a result of world-wide depletion of other resources are so immediate and pressing as to give them added proportions. The war and its ravages have served to show how precarious is the supply of natural fuel deposits, such as coal, petroleum and timber, unless carefully conserved Electricity, provided by Nature as her own means of conservation, is now called upon to fulfill this greater destiny and must be made forthwith to meet and perform the many economic needs that await its universal application. Money, men and production are the requisites and above all action, for time is the essence.

Money in enormous quantities will be required to develop water sources during the next ten years and turn them into hydro-electric energy which will become instantly active in the production of foodstuffs which the world craves, and in turning raw materials into finished products. The orderly financing of this new electrical era in a way that will not be inimical to the security of capital honestly invested in other processes over which electricity has taken economic precedence, is of vital interest to the bankers of America The Pasadena Convention is a timely occasion for acquiring first-hand information.

Power generating companies are being called upon from the Atlantic to the Pacific to increase the output of their product against the advancing price of coal, oil and other portable fuel. The railway lines which cobweb the continent and perform the gigantic work of transportation are probably the greatest consumers of the oil and coal in Earth's storehouse. It is apparent that the electrical industry is faced with undertaking the electrification of some of the steam railroads and the increasing of their facilities for generating and carrying this new and ponderous load. Upon the manufacturers devolve the necessity of turning out electrical machinery and apparatus which will facilitate steam and hydro-electric generation and conserve the current required for railroads, factories, lighting and domestic uses.

To make every home in America an electrical one and to see that appliances designed to do the work of coal and oil are of the highest type and perfectly installed will be important matters for jobbers, dealers and contractors but all of these themes must be in attune with the one vibrant chord, Service. Service with profit; Service that will make electricity superlative; Service first, last and always, the Service that serves

R H Ballard
President, N E L. A

PROPOSED CHANGES IN CONDUCTING N.E.L.A.

For some years past the Annual Convention of the National Electric Light Association has seemed to many to have lost interest, because of its thousands of delegates, its numerous meetings, and the extensive and elaborate programs that were attempted to be carried out. In other words, the conventions have seemed unwieldly, and to some extent uninteresting, because of their size and extent.

Also, during the past, it has seemed to many of us in the manufacturing end that the representatives of the manufacturing interests were not given quite that representation in the organization, or that interest in its deliberations, to which they were entitled—this, notwithstanding it has been quite generally recognized that the manufacturing and the operating interests were distinctly in partnership in promoting the business as a whole. The manufacturing interests, with their great research laboratories, have done much to advance the state of the art, perfect machinery, bring out new devices, etc., in thus indirectly promoting the more extensive use of electric current in every branch of our national life.

It goes without saying that the manufacturing interests need the operating interests as an outlet for their product—but to the same extent the operating interests need the manufacturing interests in order to furnish the machinery, devices, new appliances, etc., that are necessary to a proper expansion of the business as a whole. In other words, there is a distinct partnership between the two interests, each needing the other, each vitally and equally interested in the welfare of the other in extending the business in every direction.

Fortunately, our president, Mr. R. H. Ballard, has not only recognized this situation, but has been able to give the interests of the Association his undivided attention during the year of his presidency, and he has sought to correct matters in the following manner:

First:—In the matter of decentralization of the national organization, and the building up of the local associations.

Second:—In adding representatives of the manufacturing interests to at least one of the important committees.

This decentralization of the National and the building up of the Local Associations will, it seems to me, greatly extend the influence of the Association as a whole. It will revive the waning interest of many important men connected with the business, and will bring into the local associations a large number of new men who would not have taken any great interest in the national association. Further, the more frequent meetings of the local associations will help to keep alive the interest of a larger number of important men, and in every way extend the Association's influence.

Representation of the manufacturing interests also seems a step in the right direction and will, in the minds of many, still further extend the influence of the association.

Both steps seem to me very necessary and promising for the future influence of the National Association. It is hoped and expected that the meeting of the National Association at Pasadena in May will ratify and approve both of these measures, thus bringing about a much desired and much needed reform.

THOMAS ADDISON.
Mgr. Pacific Coast District,
General Electric Company

An Alternative for Outdoor Generators

By Henry G. Reist

Engineer, Alternating-current Engineering Department, General Electric Company

In an article on Outdoor Generators, by Mr. H. W. Buck, in our March, 1920, issue, credit was given to Mr. H. G. Reist for having first proposed the construction described therein. Mr. Reist recognizes that, while there are a great many advantages in such construction from an economical standpoint, there are also some disadvantages and these are pointed out in the present article. The principal difficulty is to construct the generator so that windings will be kept dry, and at the same time be properly ventilated. Condensation on the coils under certain atmospheric conditions is also a common occurrence and steps must be taken to prevent it. In cold weather lubricating oils become sluggish and are liable to cause trouble unless the bearings are carefully watched. To overcome these difficulties Mr. Reist suggests as an alternative that standard generators be used and housed under inexpensive semi-portable shelters.—Editor.

Many engineers have in the last few years called attention to the necessity of developing all available water-powers for generating electric current to conserve our fuel supply. While such developments are desirable at this time, it is becoming increasingly difficult to make them, due to the scarcity of materials and capital and to the shortage and high cost of labor.

Dr. Steinmetz has repeatedly proposed small power plants at intervals along streams, to minimize the hydraulic development. No doubt in many places, particularly in rolling land, great saving may be made by utilizing small dams of relatively low head, rather than by building more massive dams which give a larger amount of power at one place. This would probably be the case in a farming country, where with high dams much valuable land would have to be flooded.

With the development of automatic stations the gathering of power from distributed power houses is much more economical than was the case when attendants had to be provided at each installation. Such distributed power installations can utilize either synchronous or induction generators. The induction generator was proposed on account of its simplicity of operation, but with this type of generator magnetizing current has to be supplied from another source, which is not always convenient.

Methods of operating synchronous plants without attendants have been worked out and applied with entire satisfaction; therefore it is probable that synchronous generators will generally be used for small plants as well as for large ones.

One of the methods of saving expense in the construction of power plant installations is in the omission of the power-house, utilizing outdoor generators in the same manner as transformers and switches are used in outdoor sub-stations. There is no doubt that we have spent too much money for houses to roof over waterwheel-driven generators. We should, however, not deceive ourselves and assume that power stations are built wholly to protect the generators. They also generally contain transformers, switchboards, busbars, switches, exciters, repair shops, offices and other conveniences. Since we have learned to put many of these things out of doors, especially transformers and high potential switches and busbars, which take a good deal of room, no doubt power-houses can be built very much smaller along the lines of present construction. These buildings will still need to have considerable height to give head-room for erecting and dismantling the generating unit, and for the traveling crane. The walls must also be heavy to carry the load put on the crane.

Outdoor generators have been proposed frequently, and I believe a few machines have been installed in this way. An article on the subject by Mr. H. W. Buck was published in the General Electric Review of March 1920, in which the advantage of such construction is clearly pointed out. That both sides may be presented I wish to call attention to a few of the difficulties encountered in such construction. We have always assumed and believed it to be desirable to keep the windings of electric machines dry. It is difficult to maintain this condition and get proper ventilation in a generator exposed to the weather, without special construction and additional expense. If the generator is allowed to become cold when not in use there is likely to be condensation of moisture on coils under certain atmospheric conditions. To prevent this, many pieces of electric apparatus are provided with special heaters of some sort to keep the machine warm when it is idle.

In case machines are exposed in very cold weather there is danger of difficulty from the oil becoming too thick. This danger would apply especially to self-oiling thrust bearings placed at the top of the machines, since these might heat at starting before the oil became sufficiently thin to circulate freely.

Automatic stations, which operate without an attendant, should be inspected from time to time by a patrol. In case of very cold or disagreeable weather it is probable that such inspection would be superficial.

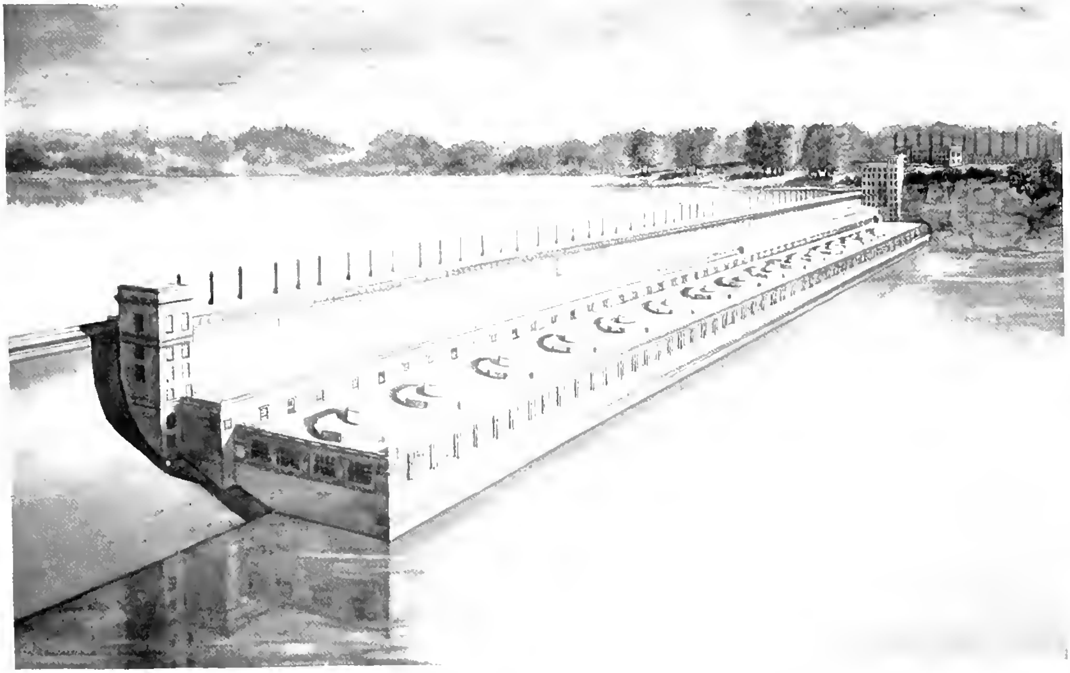
On synchronous machines placed out of doors the installation of exciter units presents difficulties. In small machines exciters are frequently belted and on larger machines they are either direct connected or driven by motors. Whatever arrangement is used considerable inconvenience will be caused by lack of a protecting roof. In some installations these parts, together with the governing mechanism, can be placed in chambers in the masonry below the generator floor; but in other cases, due to danger from high water, this could not be done, and with small low head machines such masonry construction would add considerably to the expense.

I would suggest that instead of building special weather-proof out-of-door generators, standard generators be used and that simple inexpensive semi-portable shelters be erected over them. In the case of several machines in one installation it will be desirable to have a low house extending over the line of machines, with a gantry crane bridging the house—the house, or at least its roof, to be made in sections which can be moved on a track parallel with the line of generators to telescope with the roof over the adjacent generator, or a unit roof over each generator may be lifted bodily from its place by means of a crane. The crane can, to advantage, be enclosed, as suggested by Mr. Buck in his article referred to. There would be sufficient heat generated to keep such a power-house comfortable, and by suitably arranging the ventilators, warm air could be passed over any generator that was not in use, thus overcoming the difficulties which might be experienced with the generators out of doors.

The simple house suggested would provide a shelter for the exciters, waterwheel governors, and the patrol on his visits, and would seem to offer all the advantages of a more expensive power-house.

It is probable that a protecting house, as described, could be constructed for little more than the extra cost of a generator exposed to the weather.

I have tried to show how a considerable amount of the ordinary investment in hydraulic power-house could be saved without losing any operating advantages. We would save money which is sometimes lavishly put into monumental power-houses.



The Outdoor Generating Station, for which an alternative is proposed

Intensive Street Lighting

By W. D'Arcy Ryan

Director, Illuminating Engineering Laboratory, General Electric Company

In 1905 the first ornamental street lighting system was installed on Broadway, Los Angeles. This was the cluster ball globe standard and has been generally copied throughout the country. In 1911 the first real "White Way" was lighted in New Haven, Conn. A single-light ornamental luminous arc standard was used. Similar systems have been installed in many cities. Now comes a new epoch in street lighting, the "Intensive White Way," which has had its inauguration on the Pacific Coast and is rapidly spreading eastward. The author points out the architectural, engineering, commercial, and protective advantages of such a system and gives cost data on the various installations that have been made.—Editor.

Intensive street lighting, which had its inception on the Pacific Coast during the war, is here to stay; and this latest development in street lighting is rapidly moving from the Pacific to the Atlantic.

The first installation was made in San Francisco on Market Street in 1916 and is known as the "Path of Gold." Notwithstanding that the cost of such an installation was far in excess of anything heretofore used, the results were so successful from every point of view that one year later the system was extended to include the entire business triangle; so at the present time San Francisco's main business district is intensively lighted.

A similar system, designed for Main Street, Salt Lake, was also put into operation about the same time. In January of this year the fourth installation of magnitude, viz., Broadway, Los Angeles, known as the Radiant Way, was illuminated with an intensive system; and for the first time two designs of standards were used in order to break the monotony of continuous repeat. This new note in street lighting æsthetics is worthy of careful study.

The so-called intensive lighting fundamentally differs from the ordinary white-way lighting in the following respects: Greatly increased illumination; relatively high lamp standards; initial installation costs ranging from $4.00 to $8.00 per front foot in place of approximately $1.00 to $2.00; and maintenance costs proportionately higher.

In a sense, intensive white-way lighting might be regarded as general floodlighting; advantage being taken of the natural decorative feature of the unit itself as contrasted with ordinary floodlighting where the light is concealed in a uni-directional floodlight housing.

Intensive street lighting is in a class by itself and the expense of installation and operation is borne, for the greater part, by the merchants and property owners. The especially prominent features of this type of street lighting are as follows:

(1) The cosmopolitan atmosphere and dignified æsthetic effects of the standards by day as well as by night.

(2) The minimized window reflections on account of the height of the lamps.

(3) The intensity of the illumination and the uniformity of distribution on the street and building facades, with emphasis on the corners in both the light and the design of the standards.

(4) The readiness with which features of people in the street can be distinguished, particularly in automobiles with the tops up, which demonstrates the undercutting effect of the light.

(5) The brilliancy and sparkle and good simultaneous contrast of the luminous-arc units with the window and sign lighting.

(6) The illumination of the building facades and sharpness of the cornice lines against the sky.

(7) The increased intensity as compared with the lighting of intersecting streets, clearly marking the main thoroughfare.

(8) The golden tone of the glassware which gave San Francisco's Market Street the name of the "Path of Gold."

This glassware is used only on the Pacific Coast and is merely a suggestion of the Golden West. It is intended for the daylight effect, as this tone of glassware is less insistent. However, it is slightly detrimental at night as it naturally tones down the whiteness of the light and reduces the simultaneous contrast In other words, it is a sacrifice made for the day appearance and is not generally recommended.

Notwithstanding the relatively high initial cost, the 6.6-ampere luminous arc lamp has been generally selected for these intensive systems because of its white light, sparkle, and operating economy. It imparts to the street life impossible to obtain in anything like the same degree with a still light and, as previously stated, has the advantage of simultaneous contrast with other lights.

On the other hand, we may look for a wonderful development in Mazda Intensive Lighting. The latest example in this line is embodied in the new system now being installed in Saratoga Springs, N. Y. The glassware used is entirely unique and very graceful in design. One of the principal advantages is the duo-intensity control without the use of additional series wires from the point of distribution, making it possible, for example, to reduce the lighting from 1000 to

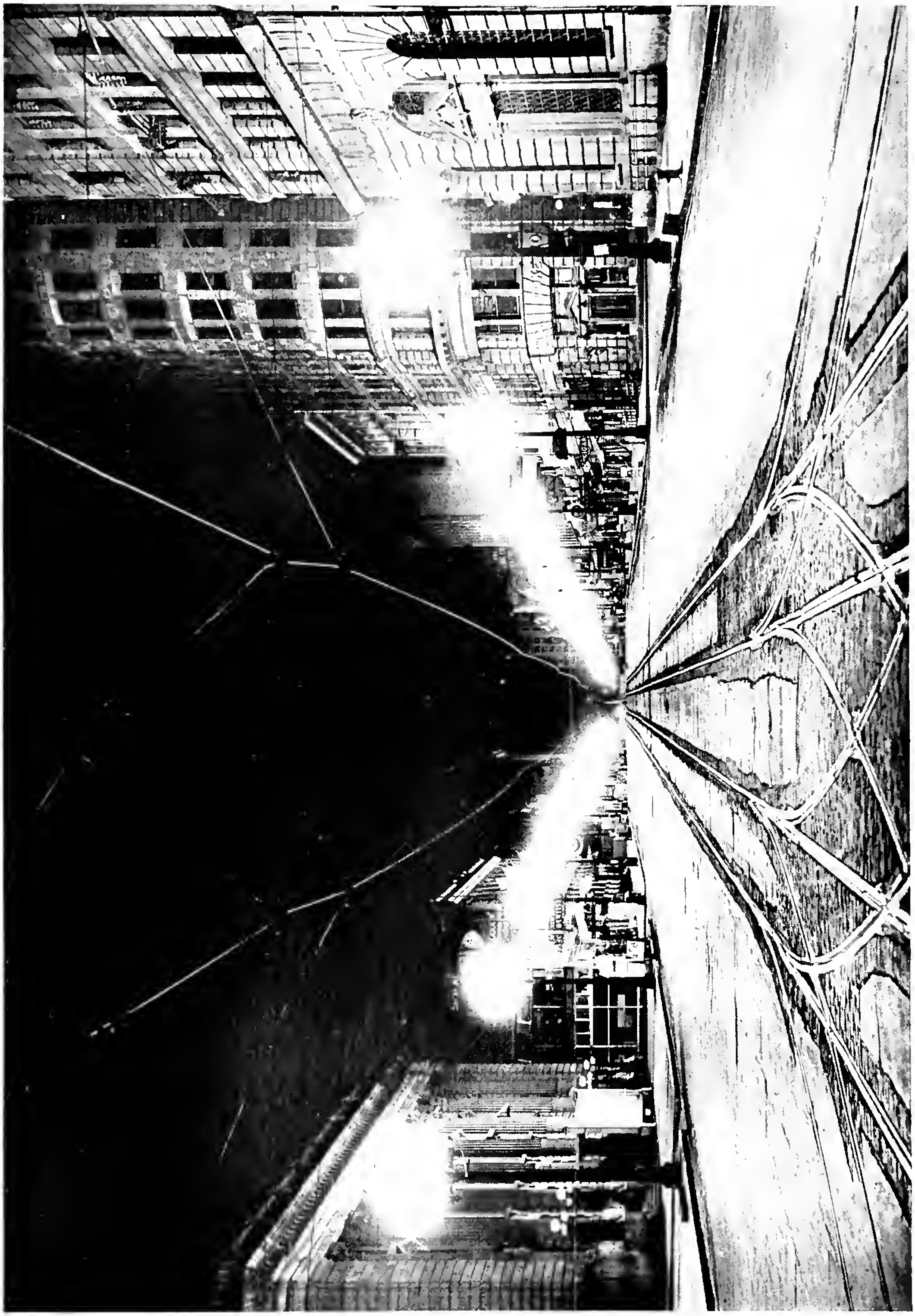


Fig. 1. Main Street, Looking North, Salt Lake City, Utah, Intensively Lighted by 6.6-amp. Ornamental Luminous Arc Lamps

250 candle-power at midnight or other predetermined time. This system will be carefully watched and if it proves as successful as anticipated, it is bound to become a very important factor in street lighting, particularly as it furnishes an intensive system during the early evening and a moderate amount of light throughout the balance of the night, with all lamps burning. This method has many advantages over the present systems of turning out more or less of the lights completely.

There are a number of other points which might be mentioned in connection with Intensive Lighting, but they will not be enumerated, except to say that systems of this kind are not only a benefit to the merchants and property owners in stabilizing real estate values and increasing window shopping, but they are of material assistance to the police and fire departments, a benefit to the general public, and are of considerable advertising value to the city.

The following statistics (by A. F. Dickerson) on some of the recent intensive White Ways which have been installed in accordance with plans issued by the Laboratory are given, together with photographs of the actual installations. It should be borne in mind that these figures represent the costs at the time of installation. In many cases operating costs have increased above those enumerated.

Main Street: Salt Lake City

This system consists of 70 standards, each carrying three 6.6-amp. General Electric ornamental luminous arc lamps. The standard envelopes the trolley pole; spacings are about 100 ft. and the overall height 29 ft. The system was first lighted September 30, 1916.

Total cost	$28,220.40
City's share	2,685.91
Property owners' share	25,534.39
Taxable property, linear feet	6,372.00
Total cost per foot	4.43
Property owners' cost per foot	4.01
City's cost per foot	0.42
Operating cost for three years	29,334,65
Property owners' share for three years	25,174.04
City's share for three years	4,160.61
Operating cost per foot for three years	4.61
Property owners' share for three years	3.95
City's share for three years	0.654
Operating cost per foot front per year	1.54
Property owners' share	1.32
City's share	0.22

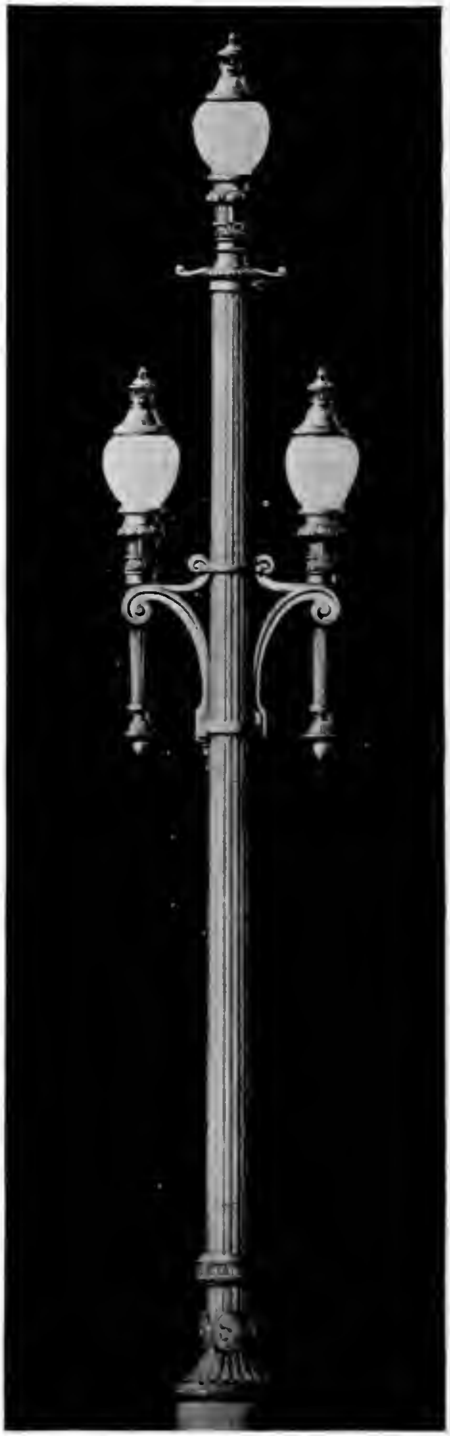


Fig. 2. Lighting Standard, State Street and Broadway, Salt Lake City, Utah, 6.6-amp Luminous Arc Lamps

The installation on Main Street, Salt Lake City, was made by the Utah Light & Power Co., and was paid for as above recorded. The system was put in under the State Street Lighting Improvement Act, so that all frontage on the street was assessed yearly for its maintenance.

State Street and Broadway: Salt Lake City

The new street lighting on State Street and Broadway will be virtually an extension of the Main Street system. There will be 504 General Electric 6.6-amp. ornamental luminous arc lamps used. The standard will envelope the present trolley pole and carry two lamps below the trolley wire and one above. The total cost of this new installation will be approximately $140,000. The Utah Power and Light Company will pay for the substation equipment and the feeders to the street circuits. With the exception of a small amount contributed by the city, the remainder of the installation expense and the yearly maintenance will be borne by the property owners.

Market Street: San Francisco

This system extends from the Ferry to Seventh Street. There are 137 standards each carrying three General Electric 6.6-amp. ornamental luminous arc lamps equipped with eight-panel globes. The standards are spaced approximately 110 ft. apart and opposite, and are 32 ft. overall in height. The total installation cost approximately $100,000 and was paid for by the Pacific Gas & Electric Co which owns the entire system, with the exception of the trolley pole part of the standard which is the property of the United Railroads. The P. G. & E. Co. entered into a three-year contract with the Downtown Business Men's Association and a yearly contract with the city of San Francisco. The total operating cost per year is $34,753.48. Of this amount the city pays $13,251.33, which is the maintenance of the center all-night lamp. The Downtown Association and the United Railroads pay $14,926.15 and $6,576 respectively for the two lamps on each standard which are extinguished at midnight. The amount paid by the United Railroads is in accordance with their original franchise agreement. The money is obtained by the Downtown Association from voluntary subscriptions. To take care of those who will not contribute, they are asking $2.00 per front foot from both property owner and tenant. On this basis, although they were only collecting for three years, they were able to obtain enough money to operate the lights for five years. The cost of the all-night lamp is $96.725 per year, and the midnight lamp $78.475 per year. The system was first lighted October 4, 1916.

Triangle Lighting: San Francisco

The Triangle District includes all the streets bounded by Market, Powell, Sutter, and Kearny. The installation cost approximately $85,000 and is the property of the Pacific Gas & Electric Company. Two General Electric ornamental luminous arc lamps similar to those on Market Street are used on each standard. The arrangement of standards is staggered, with approximately one standard to each 55 ft. of street. The height of the standard is 25 ft. One hundred and ten lamps, costing $116.80 per year, or a total of $12,848, are burned all night and are paid for by the city. One hundred and sixty-eight lamps, costing $102.20 per year, or a total of $17,169.60, burn until midnight and are paid for by the Downtown Association under a five-year contract. All the trolley poles in this district have been removed; the trolley wires having been fastened to the building facades. The Downtown Association are collecting $1.25 per front foot from both the property owner and the tenant and have sufficient funds to carry them beyond the five-year contract. The system was first lighted about January 1, 1919.

Broadway: Los Angeles

There are 134 two-light ornamental 6.6-amp. luminous arc standards in this installation. Sixty-seven lamps burn all night and two hundred and one are extinguished at midnight. The standards are spaced on an average of 106 ft. apart and opposite and are 27 ft. high. This system was installed under the State's "Street Lighting Improvement Act" and is being paid for by assessing the property owners, some of whom are paying the installation assessment on a ten-year bond plan. The total installation was approximately $85,000, or about $6.50 per front foot. The annual operating cost is $13,700, or about $1.00 per front foot. The Bureau of Electricity of the city of Los Angeles is supplying the power and maintaining the system. The average rate per lamp is $50 per year. The system was first lighted January 17, 1920.

New Orleans

In New Orleans the electric company has entered into a ten-year contract with the

Fig. 3. Market Street, Looking Toward Ferry Building, San Francisco, Cal., Intensively Lighted by 6.6 amp. Ornamental Luminous Arc Lamps

Fig. 4 Market Street, Looking Toward Twin Peaks, San Francisco, Cal, Intensively Lighted by 6.6 amp Ornamental Luminous Arc Lamps

Fig. 5. Carnival on Market Street, San Francisco, Cal., Inaugurating "Path of Gold" Lighting

Fig. 6. Grant Avenue, Looking South, San Francisco, Cal. Intensively Lighted by [illegible] Ornamental Luminous Arc Lamps

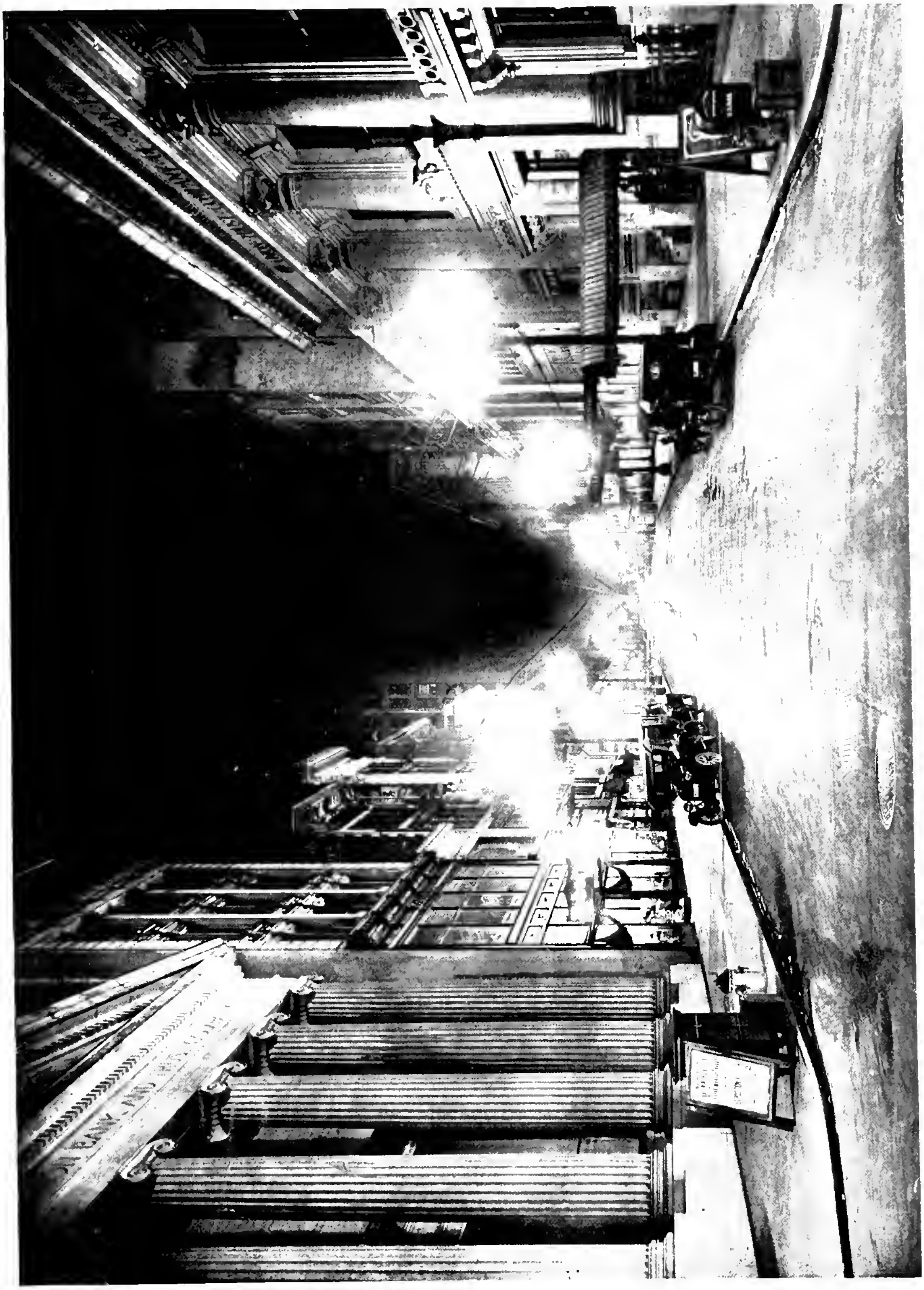


Fig. 7. Grant Avenue, Looking North, San Francisco, Cal., Intensively Lighted by 6.6-amp Ornamental Luminous Arc Lamps

Fig. 8. Day View of Broadway, Los Angeles, Cal., showing 6.6-amp. Ornamental Luminous Arc Lamps. The lamp units on the trolley suspensions were used for temporary lighting during the installation of the arc lamps. A night view is shown in the Frontispiece

Fig. 9. State Street, Looking South, Chicago, Ill., Intensively Lighted by Novalux Stippled Glass Globes Containing 1000-watt Multiple Mazda C Lamps

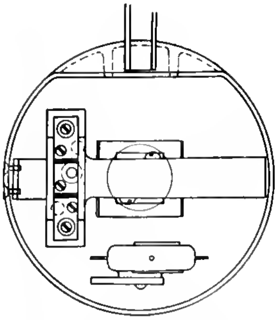


Fig. 10d. Plan Through Casing of Fig. 10c

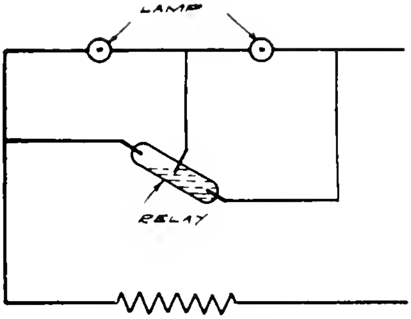


Fig. 10e. Wiring Diagram Duoflux Unit

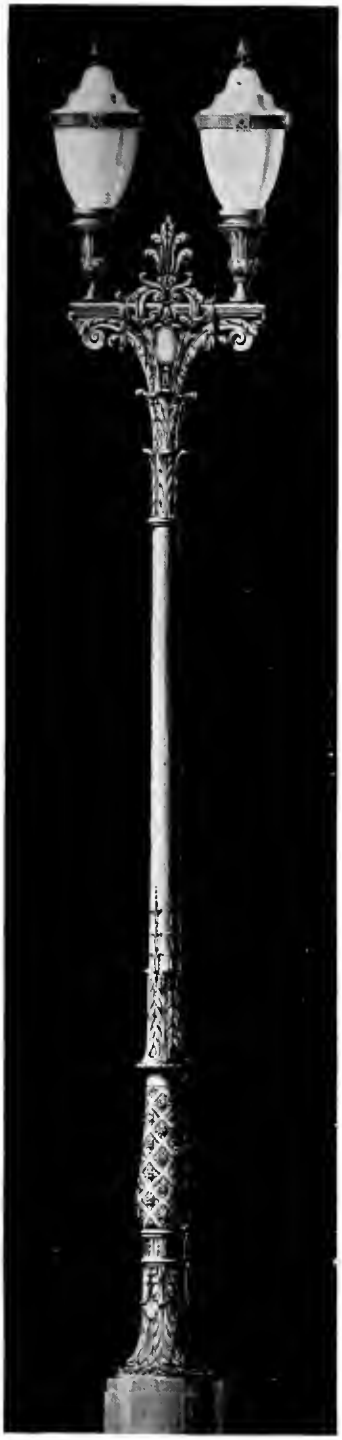


Fig. 10a. Duoflux Lighting Standard Installed on Broadway, Saratoga

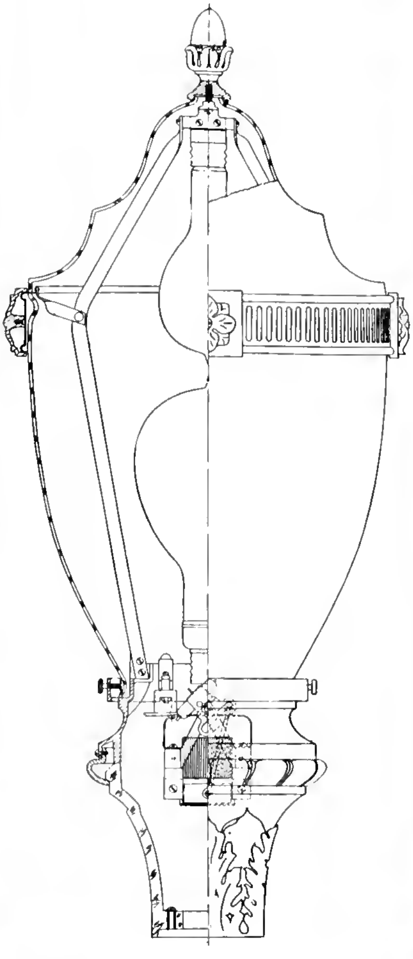


Fig. 10c. Sectional Drawing Duoflux Lighting Unit

Fig. 10b. Novalux Lighting Standard Installed in Congress Park, Saratoga

Fig. 11. Sketch showing Lighting Effect on Randolph Street, Chicago, Ill., by Ornamental Luminous Arc Lamps

city for new street lighting; the city to own the system at the expiration of the contract. During the past few years over a half million dollars has been spent under this agreement, which includes over 1400 standards of boulevard incandescent lighting, 450 two-light incandescent standards on the crosstown business streets, and 3300 pendent luminous arc lamps. The maintenance of all these lights is being paid for by the city. Plans were completed for a very elaborate installation of luminous arc lamps, five to the standard, for Canal Street, but the installation was held up by the war.

Broadway: Saratoga Springs

Construction is now under way and the system should be lighted June 1, 1920. Nearly a mile of street will be lighted by 69 standards. Each standard has two General Electric Duoflux units and each unit contains one 1000-c-p. and one 250-c-p. series Mazda lamp. The Duoflux is an innovation that will soon be widely advertised. Besides being of a new and exceptionally pleasing design, this fixture possesses a distinctive utilitarian feature. The large lamp in each globe is extinguished at midnight and the smaller one is lighted. This arrangement will permit the use of reduced illumination after midnight, without a duplication of lighting circuits. The Saratoga installation will cost about $32,000 and will be installed and owned by the Adirondack Electric Power Corporation. The city will pay the entire maintenance cost of $10,350 yearly.

Randolph Street: Chicago

Proposed plans have been submitted and approved for the lighting of Randolph Street, Chicago. The present trolley poles will be utilized as cores for ornamental enveloping casings. Each standard will carry two General Electric 6.6-amp. luminous arc lamps. It is proposed to extend this system eventually throughout the Loop District.

South State Street: Chicago

A system has recently been installed consisting of General Electric Novalux fixtures on trolley pole brackets with 1000-watt Mazda lamps. Considering the relatively small installation expense, this system has been very successful.

Fig. 12. Main Street, Salt Lake City, Utah, Intensively Lighted by Ornamental Luminous Arc Lamps

Fundamental Principles of Polarity, Phase Rotation, and Voltage Diagrams of Transformers

By A. Boyajian

Transformer Engineering Department, General Electric Company

Perplexing problems frequently arise in determining transformer polarity, phase rotation, and angular displacement, when two or more units are to be arranged for parallel operation. The following article has been prepared to clear up these difficulties and uncertainties. The author explains the fundamental principles first as applied to single-phase circuits and then to three-phase circuits. He discusses their bearing on parallel operation and solves three problems of a practical nature.—Editor.

Polarity and phase rotation are of importance primarily on account of their bearing on parallel operation of transformers. It is desirable, therefore, to treat the subject in such a way as to make their application to parallel operation readily intelligible.

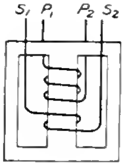


Fig. 1

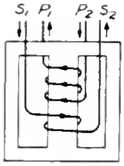


Fig. 2a

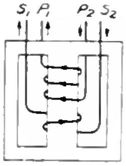


Fig. 2b

SINGLE-PHASE CIRCUITS

Fig. 1 represents a simple single-phase transformer. It is of interest to consider the relative directions of windings, currents, and voltages.

Direction of Winding

It will be observed that coil S_1S_2 is wound in the same direction as P_1P_2 (with respect to the core), assuming that the first starts from S_1 and the second P_1. On the other hand, S_1S_2 is wound in the opposite direction to P_2P_1 if we assume that the first starts from S_1 and the second from P_2. We conclude, then, that whether two coils are to be considered as wound in the same direction or in opposite directions depends on which terminals are considered as the "start" and which the "finish." In some simple forms and combinations of coils, for instance cylindrical high and low-voltage coils, high and low-voltage leads at the same end of the core leg might naturally be taken to correspond to each other; but in more complicated designs, such as interleaved disc windings, no such "natural" guide would be reliable. It is good practice, therefore, in comparing directions of windings, to assume the winding as starting with the first named terminal and ending with the second. Thus, in Fig. 1:

Coils S_1S_2 and P_1P_2 are wound in the same direction.

Coils S_1S_2 and P_2P_1 are wound in opposite directions.

Direction of Currents

In a transformer, the load current in the secondary flows in such a direction as to neutralize the magnetomotive force of the load current in the primary; and, it is ordinarily said, therefore, that primary and secondary currents are opposed to each other. It would be more accurate to say that primary and secondary ampere-turns are opposed to each other. Then, if the directions of the windings are the same, the currents in the high and low-voltage terminal leads are opposed; but, if the directions of the windings are opposed, then the currents are in the same directions, Figs. 2a and 2b.

In the parallel operation of transformers, it is only the voltage vector relations that have a direct bearing, and the current vector relations need not be considered. Of course one can always be derived from the other, but their simultaneous consideration leads to confusion. Hence, it is advisable to neglect currents when discussing polarity and phase rotation.

Direction of Voltages

In speaking of voltages, it at once becomes necessary to specify whether impressed or induced voltages are considered. The confusion of the direction of mpressed and induced voltages probably causes more misunderstanding than any other factor, and hence, it is essential for clarity to use only one throughout a discussion. It would be undesirable to consider the impressed voltage in the primary and induced voltage in the secondry, since it is not always certain which is primary and which secondary and, furthermore, polarity and phase rotation are independent of which winding is primary and which secondary. It is the simplest, clearest, and most logical procedure, therefore, to consider only the induced voltage relations.

Since the primary and secondary induced voltages are induced by the same flux, they must be in the same direction in each turn, Figs. 3a and 3b. However, whether they will appear in the same or opposite directions as viewed from the terminals depends on the relative directions of the windings. Thus, in Fig. 3a, voltages H_1H_2 and X_1X_2 have the same direction, and in Fig. 3b, voltages H_1H_2 and X_2X_1 have opposite directions. If we take the order of lettering to indicate also the direction of voltage, as was assumed above for the direction of winding, then, in Fig. 3a,

Voltages H_1H_2 and X_1X_2 are in the same direction.

Voltages H_1H_2 and X_2X_1 are in opposite directions.

In Fig. 3b,

Voltages H_1H_2 and X_2X_1 are in opposite directions.

Voltages H_1H_2 and X_1X_2 are in the same direction.

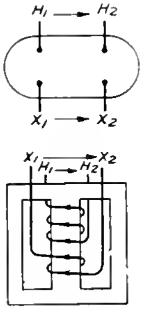


Fig. 3a

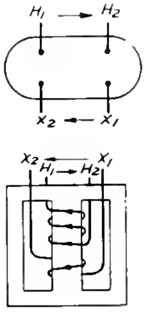


Fig. 3b

Polarity

Since the relative direction of induced voltages, as appearing at the terminals of the windings, is dependent on the order in which these terminals are taken, therefore, in order that "polarity" may have any meaning, it must be referred to a perfectly definite order in which the terminals shall be taken. By common usage, polarity refers to the voltage vector relations of transformer leads as brought outside the case, and both high-voltage and low-voltage leads being taken in the same order (from left to right or right to left) facing the same side of the transformer in both cases. Thus, referring to the tank sketch in Fig. 3a, polarity is the relative direction of induced voltage from H_1 to H_2 as compared with that from X_1 to X_2, both being in the same order (from left to right) with respect to the tank.

Additive and Subtractive Polarity

When the induced voltages of the high and low-voltage sides are in opposite directions, as in tank sketch Fig. 3b, the polarity is said to be *additive;* and when the induced voltages are in the same direction (Fig. 3a), the polarity is said to be *subtractive.*

The reason for this nomenclature will be evident from the following: Referring to the tank sketch Fig. 3a, if we connect a high-voltage lead to the adjacent low-voltage lead, for instance H_2 to X_2 and excite the transformer on either side, the voltage across the other leads H_1 to X_1 will be the difference of the voltages of the two sides. Following the voltage from X_1 through X_2 to H_2 and then to H_1 it is evident that the voltage H_2 to H_1 will oppose the voltage X_1 to X_2. Hence the polarity is *subtractive.*

Referring again to the tank sketch Fig. 3b, which shows primary and secondary induced voltages in opposite directions, if we connect an H lead to the adjacent X lead, for instance, H_1 to X_2, and excite the transformer, the voltage across the other leads, i.e., H_2 to X_1, will be the sum of the primary and secondary voltages, for reasons explained in the previous paragraph. Hence the polarity is *additive.*

Testing of Polarity

The foregoing definition of polarity leads to two general methods for testing the polarity of transformers. First: With primary and secondary in series, one primary lead being connected to the adjacent secondary lead, the transformer is excited from an alternating-current source on either side; and the voltages across the high-voltage winding and also between the free primary and secondary terminals are measured. If the latter voltage is found to be less than that across the high-voltage winding, the polarity is subtractive; if more, it is additive.

Second: With or without primary and secondary in series, the transformer is excited from a direct current source on either side and a direct-current voltmeter is connected to the excited side so that a positive deflection is obtained. The voltmeter leads are then transferred directly to the adjacent terminals of the other winding without crossing. The direct-current excitation is then broken and the inductive kick in the voltmeter observed. If the needle swings in the same direction as before the polarity is additive, otherwise subtractive.

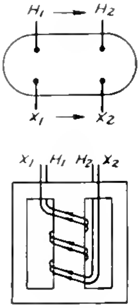


Fig. 4a

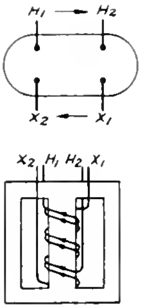


Fig. 4b

In testing for polarity a fraction of the rated voltage is sufficient.

Marking of Leads

It would be desirable that lead designations be indicative of polarity also. This is provided for by the A.I.E.E. Standardization Rules in accordance to which high-voltage leads brought out of a case are to be marked H_1, H_2, etc., and low-voltage leads X_1, X_2, etc., the order being such that "when H_1 and X_1 are connected together and voltage applied to the transformer, the voltage between the highest numbered H lead and the highest numbered X lead shall be less than the voltage of the full high-voltage winding. When leads are marked in accordance with the above rules, the polarity of a transformer is:

Subtractive when H_1 and X_1 are adjacent.

Additive when H_1 is diagonally located with respect to X_1.

To simplify the work of connecting transformers in parallel, it is recommended that the H_1 lead shall be brought out on the right-hand side of the case, facing the high-voltage side of the case.

"Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together, provided their ratio, voltages, resistances, and reactances are such as to permit parallel operation."

The rule can also be stated in this way: If H_1H_2 represents the direction of induced voltage in the high voltage at a given instant, then X_1X_2 must be the direction of the induced voltage in the low-voltage winding Applying this rule to Figs. 3a, 3b, 4a, and 4b, we find that they are correctly lettered and that the polarities are also correct as marked.

Relation of Polarity to Potential Stresses

The polarity of a transformer conveys no information as to the arrangement of the windings or of the internal leads or of the internal potential stresses. Consider Figs. 4a and 4b: H_1H_2 and X_1X_2 are two cylindrical coils. The coils of Fig. 4a are identical with those of Fig. 4b and similarly mounted, except that the positions of the X leads are interchanged and therefore their polarities are reversed. And yet, primary and secondary are wound in the same direction in both cases, and the potential stresses are alike. *Polarity, therefore, cannot be taken as indicative of a higher or lower arrangement of potential stresses within a transformer.*

Standardization of Polarity

Most low-voltage distribution transformers in use today have additive polarity, while of power transformers some have additive and others have subtractive polarity. This situation has probably been very confusing to the operating companies when attempting to connect in multiple, or in bank, single-phase transformers produced by the various manufacturing companies. Appreciating the condition, this matter was considered some time ago by the General Conference Committee on Technical Subjects, which committee consisted of representatives from the A.I.E.E., N.E.L.A. and E.P.C., which definitely recommended that a uniform polarity be standardized and that this be *subtractive* polarity. The reason given for this recommendation is that although polarity has no bearing on internal voltage stresses, yet subtractive polarity has a small advantage over additive polarity in the matter of the voltage stresses between *external* leads as has been explained. That is, if two adjacent high and low-voltage leads should accidentally come in contact, the voltage across the other leads would be the sum of high and low voltages for additive polarity, and their difference for subtractive polarity. Furthermore, under operating conditions with leads insulated from each other, the potential stress between adjacent high and low-voltage leads is one half the *sum* of the high and low voltages for additive polarity, and one half their *difference* for subtractive polarity. This advantage of subtractive polarity, although entirely negligible ordinarily, may become appreciable for transformers of which both primaries and secondaries have very high voltages.

Three-phase Connections

In single-phase transformers primary and secondary voltages are either in phase or in opposition and this is completely specified by the polarity or the lettering of the leads. In polyphase units or banks, however, these vector relations, being more complicated, are represented by voltage diagrams because the mere lettering of the leads does not indicate the polarity or these vector relations. Furthermore, polarity alone is inadequate to represent vector relations in polyphase connections; the subject can be more readily handled by voltage diagrams.

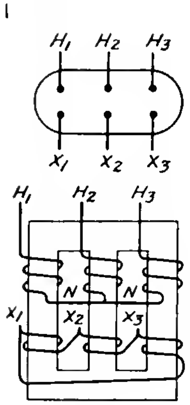


Fig. 5a

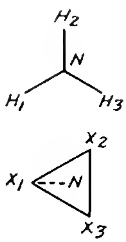


Fig 5b

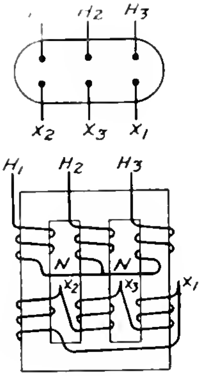


Fig 6a

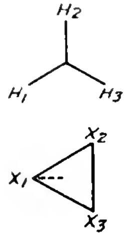


Fig. 6b

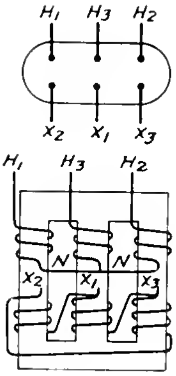


Fig. 6c

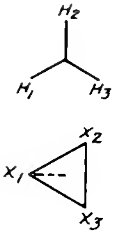


Fig. 6d

How to Construct Voltage Diagrams

The method of constructing the voltage diagram for a given design may best be explained by an example. Fig. 5 represents a Y-delta connected three-phase unit. Draw $H_1H_2H_3$ (Fig. 5b) representing the induced voltages of the Y-connected winding. The voltage diagram of the delta-connected winding can now be drawn. Coils X_1X_2 and H_1N (Fig. 5a), being wound in the same direction, their induced voltages must also be in the same direction. Therefore, we draw X_1X_2 (Fig. 5b) parallel to and in the same direction as H_1N. On the middle leg (Fig. 5a), coil X_2X_3 is wound in the same direction as H_2N, and, therefore, their respective voltages are drawn parallel and in the same direction (Fig. 5b). Similarly for the third phase, and the diagram is complete.

If the delta were improperly formed in Fig. 5a, the delta in Fig. 5b would not close, showing that there would be an unbalanced voltage short circuited through the delta.

The chief three-phase connections that are commonly used are: delta-delta, Y-Y, and delta-Y (or Y-delta).

Y-delta Connection

The method of constructing the voltage diagram of Y-delta connected coils has already been described. It is evident on inspection of Figs. 5a and 5b that that connection has subtractive polarity, 30-deg. angular displacement, and standard phase rotation. Figs. 6a, 6b, 6c, and 6d have additive polarity, 30 deg. angular displacement, and standard phase rotation.

The voltage diagrams of Figs. 5a, 5b, 6a, 6b, 6c and 6d are identical, but the lettering of the leads is different due to the different internal arrangements. The different lettering of the leads is thus equivalent to interchanging the leads since similarly lettered leads are to be connected together for multiple operation. It thus becomes evident that by interchanging leads identical voltage diagrams are obtained on Y-delta transformers that have different internal arrangements, which was not possible with delta-delta or Y-Y transformers. This may be further explained as follows:

Construct a voltage diagram as previously explained for the connection shown in Fig. 7a which will be like Fig. 7b. Interchange two leads on the high side (H_3 with H_2) and two leads on the low side (X_1 with X_2) as shown in Fig. 7c. Constructing the voltage diagram for this new arrangement, the diagram of Fig. 7d is obtained, which is identical in form and lettering with those of Figs. 5b, 6b and 6d. We conclude then that all Y-delta or delta-Y connections can be reduced to the same diagram by properly selecting the order of the leads. This, as before mentioned, is not possible with delta-delta or Y-Y connections.

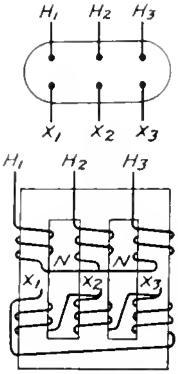


Fig. 7a

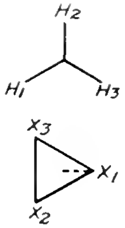


Fig. 7b

Delta-delta Connection

If we try all possible delta combinations in high and low-voltage coils, we find that there are only two diagrams that are operative at all. These are shown in Figs. 8 and 9. It is not intended to convey the idea that the coil windings and combinations shown in these illustrations are the only ones that will give the indicated voltage diagrams. It is meant that these voltage diagrams are the only delta-delta diagrams which are possible or operative at all.

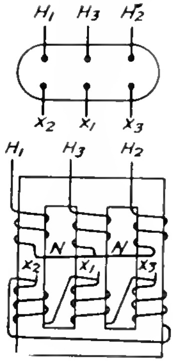


Fig. 7c

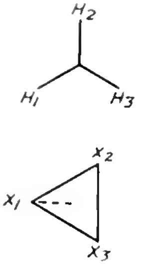


Fig. 7d

Polarity

Considering the polarity of these diagrams, we see that that of Fig. 8 is subtractive and that of Fig. 9 is additive. Polarity, however, does not necessarily sufficiently specify the phase relation between the high and low voltages since they are not single straight lines but polygons, and the angles may not necessarily be only 0 or 180 deg. but also some intermediate value. The phase relation is called "angular displacement" and is defined by the A.I.E.E. Standardization Rules as the angle between the lines H_1N (N being the neutral point of the diagram) and X_1N. The location of the H_1 lead is defined as above for single-phase units, that is, the right-hand side of the observer facing the high-voltage side. The location of the X_1 lead is fixed so as to make the diagram fall under one of the Standardized Groups to be described later. We see that the angular displacement of Fig. 8b is zero, and that of Fig. 9b is 180 deg.

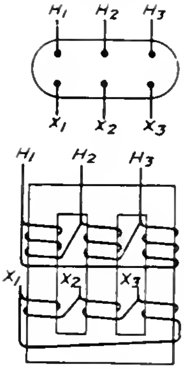


Fig 8a

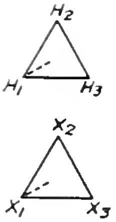


Fig. 8b

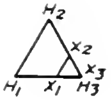


Fig. 8c

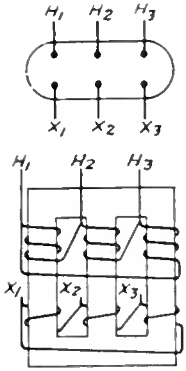


Fig. 9a

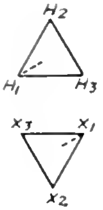


Fig. 9b

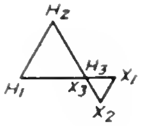


Fig. 9c

Phase Rotation

In order that the relative phase rotation of high and low voltages may have any significance at all, it must refer to a perfectly definite order in which the leads are to be considered. Thus, in Fig. 8b, phase rotation is clockwise in the order $H_1H_2H_3$, but counter-clockwise in the order $H_2H_1H_3$. The phase rotations of $H_1H_2H_3$ and $X_1X_2X_3$ are the same; those of $H_1H_2H_3$ and $X_3X_2X_1$ are opposed. In view of the necessity of specifying the order of leads, the Standardization Rules referred to above provide that the leads shall be marked in such a way that phase rotation of high and low voltages in the lead order $H_1H_2H_3$ and $X_1X_2X_3$ shall be the same. That is, if a three-phase motor were transferred from the high-voltage circuit to the low-voltage circuit, transferring its terminals from H_1 to X_1, from H_2 to X_2, and from H_3 to X_3, its direction of rotation will be the same. Considering Fig. 8b, $H_1H_2H_3$ and $X_1X_2X_3$ have the same rotation and, therefore, correct phase rotation. Considering Fig. 9b, phase rotations $H_1H_2H_3$ and $X_1X_2X_3$ are the same, and therefore, also correct. It will be interesting to note that while Figs. 8b and 9b have opposite polarities and different angular displacements, yet they have the same phase rotation.

It is evident that a voltage diagram indicates only the *relative* phase rotation of primary and secondary, and gives no information as to the *actual* phase rotation on either side, this being determined by the supply circuit. Clockwise or counter-clockwise lettering of the primary voltage diagram, also its location on the paper (pointing one way or another), are of course entirely arbitrary. It is evident also that this *relative* phase rotation of the two sides refers to a definite sequence of leads.

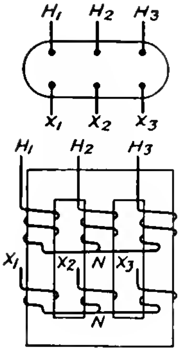


Fig. 10a

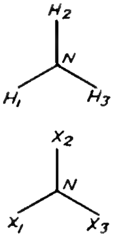


Fig. 10b

It will be seen that changing the lettering or interchanging the leads (leaving coil connections unchanged) cannot alter the voltage diagrams of Figs. 8 and 9. That is, the transformer in Fig. 8a cannot be made to give the diagram of Fig. 9b by manipulating its external leads. The only way to effect such a change would be to change the internal connections of the coils.

With delta-delta connected transformers the lettering of the leads is the same regardless of the angular displacement, as seen from Figs. 8a and 9a.

Y-Y Connection

The method of constructing the voltage diagrams of Y-Y connected transformers is the same as that described in the foregoing. Two connections are possible as shown by Figs. 10b and 11b. The first has subtractive polarity, zero phase displacement, and standard phase rotation. The second has additive polarity, 180-deg. angular displacement, and standard phase rotation. It will also be evident that no manipulation with the external leads will change the diagrams, although it may change the order of lettering of the voltage diagrams.

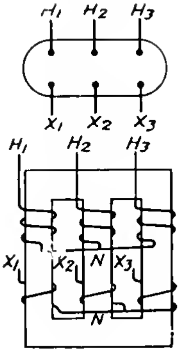


Fig. 11a

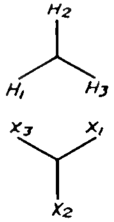


Fig. 11b

With Y-Y connected transformers, the lettering of the leads is the same regardless of the angular displacement, as seen from Figs. 10a and 11a.

To Obtain Voltage Diagrams by Test

We have described the method of constructing a voltage diagram when the design is given. If the design is unknown, coils and connections inaccessible, and no vector diagrams furnished, these can be obtained by test. Polarity and phase rotation tests are valuable checks when the diagram is given (or assumed), but are not necessarily sufficient to enable one to draw it. Voltage diagrams can be determined by the following method, neglecting the polarity and phase rotation tests if desired: Connect one of the high-voltage leads to one of the low-voltage leads, excite the transformer at a voltage safe for the low-voltage circuit, measure the voltages between all the other high and low-voltage leads, and plot them to scale. For instance, referring to Fig. 8a, if we should connect H_3 to X_3 and make these measurements, we would obtain a diagram like that of Fig. 8c; or referring to Fig. 9a, if we connect H_3 to X_3 we would obtain a diagram like Fig. 9c.

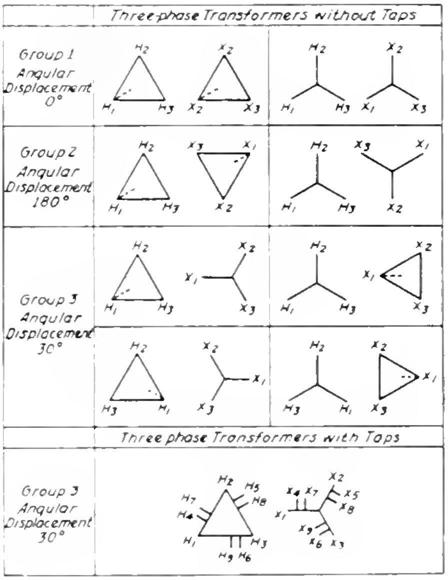


Fig 12a

If we should apply this test to a Y-Y connected unit of the same polarity (Figs. 10a and 11a), we would obtain the same diagrams as in Figs. 8c and 9c respectively. That is, it would not be possible to determine by such tests whether the internal connection is delta-delta or Y-Y. However, so far as parallel operation is concerned, the distinction is unnecessary.

The test will indicate the angular displacement between high and low-voltage circuits, but cannot distinguish between connections that belong to the same group, that is, connections which will successfully parallel with each other.

It will be evident that obtaining voltage diagrams by such measurements becomes difficult when the low voltages are very small compared with the high voltages.

PARALLEL OPERATION

In order that two transformers of similar voltage rating may safely be connected in multiple, their polarity, phase rotation, and angular displacement must be the same. Delta-delta and Y-Y transformers have correct angular displacement when their polarity and phase rotation are correct. This, however, is not necessarily true for delta-Y (or Y-delta) transformers. In this case, however, these can be adjusted by the proper selection of the sequence of leads.

If the voltage diagrams of the transformers which are to operate in parallel are available, it is then only necessary that these diagrams coincide and corresponding terminals be connected together. *It is entirely unnecessary then to raise questions of polarity and phase rotation, because when the voltage diagrams coincide, leads which are to be connected together will have the same potential*, this being the basic requirement for multipling; whereas, polarity, phase rotation, etc., are merely means to arrive at this condition. When voltage diagrams coincide, polarities and phase rotations must necessarily agree, although the converse of this is not necessarily true.

For the purpose of simplifying the connecting of transformers in parallel and avoiding the necessity of testing for polarity, phase rotation, etc., the A.I.E.E. and N.E.L.A. have standardized the marking of transformer leads (covered in A.I.E.E. Rules, Sections 600-617) as has been explained in this article. Transformers that are marked in this manner can be operated in multiple by simply connecting similarly lettered leads together. This, of course, is contingent on the transformers having proper characteristics, i.e., ratio, impedance, angular displacement, etc.

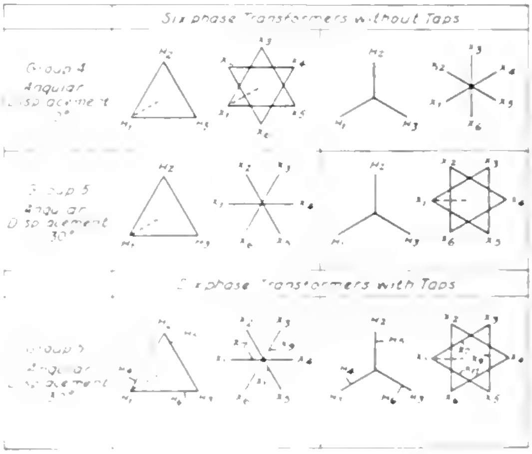


Fig 12b

Three-phase transformers are divided into three groups based on their angular displacements as shown in Fig. 12a.

Four of the usual three-phase to six-phase diagrams are shown as Groups IV and V in Fig. 12b Their construction involves nothing more complicated than the method indicated for three-phase to three-phase connections.

To operate in multiple, transformers must belong to the same group. No interchange of external leads can change one group into another. Thus, two delta-delta transformers, one of Group I and the other of Group II, cannot be operated in multiple. If the high-voltage diagrams be superposed, the low-voltage diagrams will not coincide. All Y-delta or delta-Y transformers, however, can be reduced to the same diagram, and, therefore, they are classed in only one group.

Practical Problems

Polarity, phase rotation, etc., are of interest primarily on account of their bearing on the parallel operation of transformers. The operator wishes to know these facts about his apparatus before connecting in multiple, as otherwise a wrong connection subjects the apparatus to short circuit. Some of the problems that come up in practice will be discussed.

(1) Transformers lettered in accordance with the A.I.E.E. rules, i.e., high-voltage leads marked H_1, H_2, *etc., and low-voltage leads marked* X_1 X_2, *etc.*

Single-phase transformers which are so marked and have like ratios and impedances may be connected together in the order of lettering regardless of any question of polarity since the method of lettering takes care of polarity.

Three-phase units also may be connected together in the order of lettering, *provided, however, that the units belong to the same group, i.e., have the same angular displacement.* Otherwise they cannot be operated in multiple at all. Angular displacement cannot be altered by manipulating the external leads without changing the internal connections. The same applies to the parallel operation of six-phase transformers.

The connections of six-phase transformers to synchronous converters is simplified by a correct understanding of the manner in which the windings of the latter are tapped and brought to the slip rings, and the system of numbering used Fig. 13 shows how the winding is tapped and brought to slip rings. The slip rings are numbered *1*, *2*, *3*, etc., beginning from the bearing and proceeding towards the armature. The diagram also shows the actual direction of the physical rotation of the armature which is counterclockwise looking from the slip-ring end of the machine. The actual electrical phase-rotation is clockwise, i.e., in the order *1*, *2*, *3*, etc. Evidently, the transformer must be so connected to the converter that neither the rotation of the latter is reversed nor any one phase is short-circuited. As explained previously, when the phase rotation on the high-voltage side of the transformer is in the order, H_1, H_2, H_3, the phase rotation on the low voltage side is in the order X_1, X_2, X_3, etc. Therefore, if the high-voltage supply phases are correctly connected to the high voltage of the transformer, the transformer and converter will operate properly when X_1 of the transformer is connected to ring *1* of the converter, X_2 of the transformer to ring *2* of the converter, etc. Although this is the standard connection, there are eleven others or altogether twelve operative connections which may be used if for any reason they are found more convenient. Of these twelve operative connections, six correspond to one-phase rotation on the primary, and the other six to the opposite phase rotation on the primary. Thus, six of the possible con-

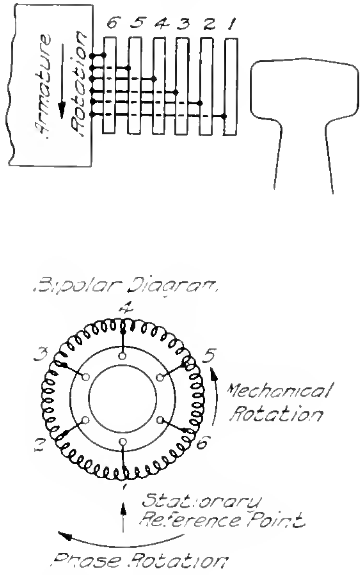


Fig. 13

nections for one phase-rotation are as follows:

Connect X_1 to Ring *1* or *2* or *3* or *4* or *5* or *6*.
Connect X_2 to Ring *2* or *3* or *4* or *5* or *6* or *1*.
Connect X_3 to Ring *3* or *4* or *5* or *6* or *1* or *2*.
Connect X_4 to Ring *4* or *5* or *6* or *1* or *2* or *3*.
Connect X_5 to Ring *5* or *6* or *1* or *2* or *3* or *4*.
Connect X_6 to Ring *6* or *1* or *2* or *3* or *4* or *5*.

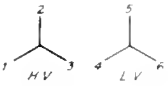


Fig 14a

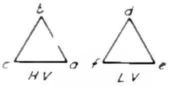


Fig 14b

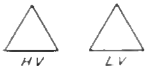


Fig 15a

Fig 15b

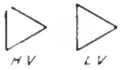


Fig. 15c

Each vertical row constitutes one operative set. Connections must not be made partially from one vertical row and partially from another. If on connecting to the supply, converter rotates in the wrong direction, it can be corrected by reversing one phase on the high-voltage side.

It will be observed that when transformers are lettered in accordance with the A.I.E.E. rules, and also their angular displacement given, a vector voltage diagram is not necessary to be able to connect them properly although it usually is given by some manufacturers as an added safeguard.

(2) Transformers not lettered in accordance with the A.I.E.E. rules, but their voltage diagrams available.

When voltage diagrams are available no questions of polarity or phase rotation need be asked. It is necessary and sufficient to determine whether the diagrams of the two units (or banks) will coincide; i.e., whether they have the same angular displacement between the primary and secondary. For instance, a transformer of which the voltage diagram is shown in Fig. 14a can be paralleled with one whose diagram is as shown in Fig. 14b. Superposing the two diagrams, both high and low-voltage lead potentials coincide; thus *1* with *c*, *2* with *b*, *3* with *a*, *4* with *f*, *5* with *d*, and *6* with *e*. There can be no difficulty about telling which leads are to be connected together. The fact that the voltage lines of the two diagrams do not coincide, one being a Y diagram and the other a delta diagram, is of no consequence, since the points which are to be connected together coincide and must therefore have the same potential.

Confusion is sometimes experienced when voltage diagrams are shown in different positions, as for example, in Figs. 15a, 15b, and 15c, where identically the same voltage diagram is shown in three different positions. What a voltage diagram indicates is not the actual potential of the terminals, but the voltage vector relation between the two windings. This relation is identical in the above three figures. This can be seen still better if we rotate the high and low-voltage diagrams of Fig. 15b through either 60 or 180 deg., when it becomes identical with 15a. The same refers to 15c which would have to be rotated counter-clockwise 90 deg. or clockwise 30 deg. to coincide with 15a.

In rotating a diagram, care must be taken not to alter the relative position of the primary and secondary voltage diagrams with respect to each other. This being done, the rotation of a diagram through any angle is permissible. It will also be seen that diagrams which are alike can be superposed and made to coincide in three different positions. For instance, Fig. 14b can be superposed on Fig. 14a, making *1* coincide with *c*, *b*, or *a*. There are

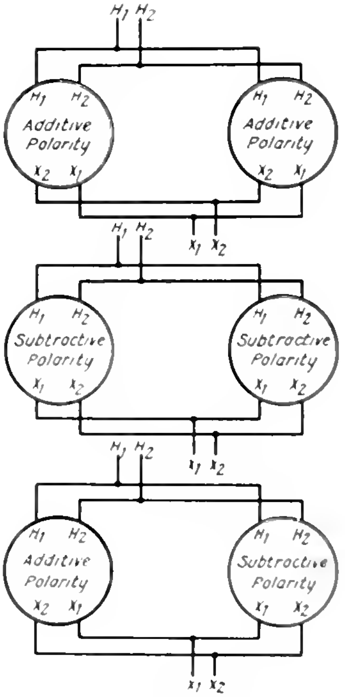
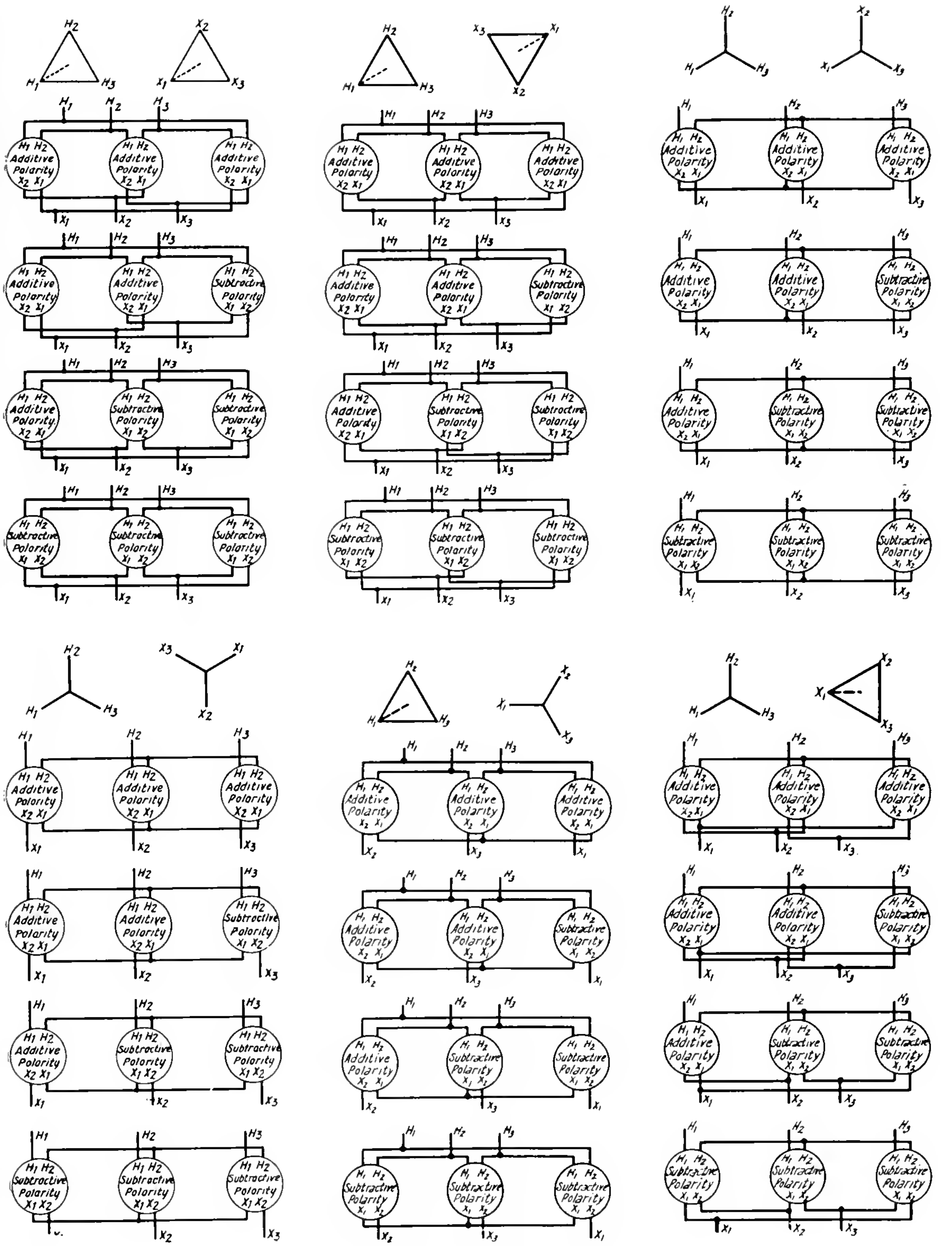


Fig 16 Quarter-phase Connections



Figs. 17 to 22 Three phase Connections

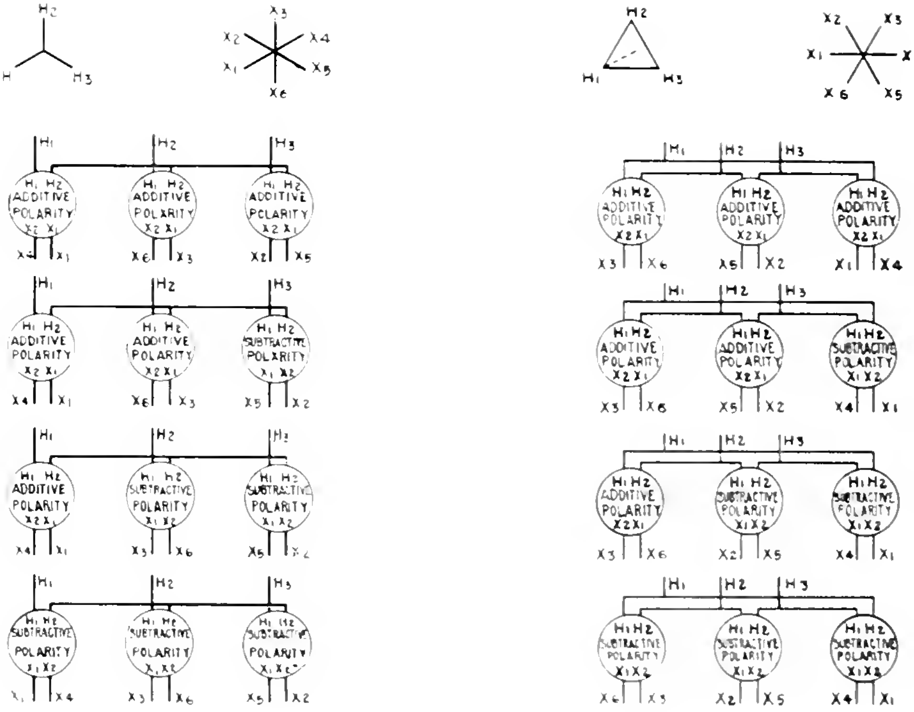
thus three ways of connecting three-phase units for multiple operation.

(3) *One or both units not lettered in accordance with the A.I.E.E. rules and no voltage diagram available.*

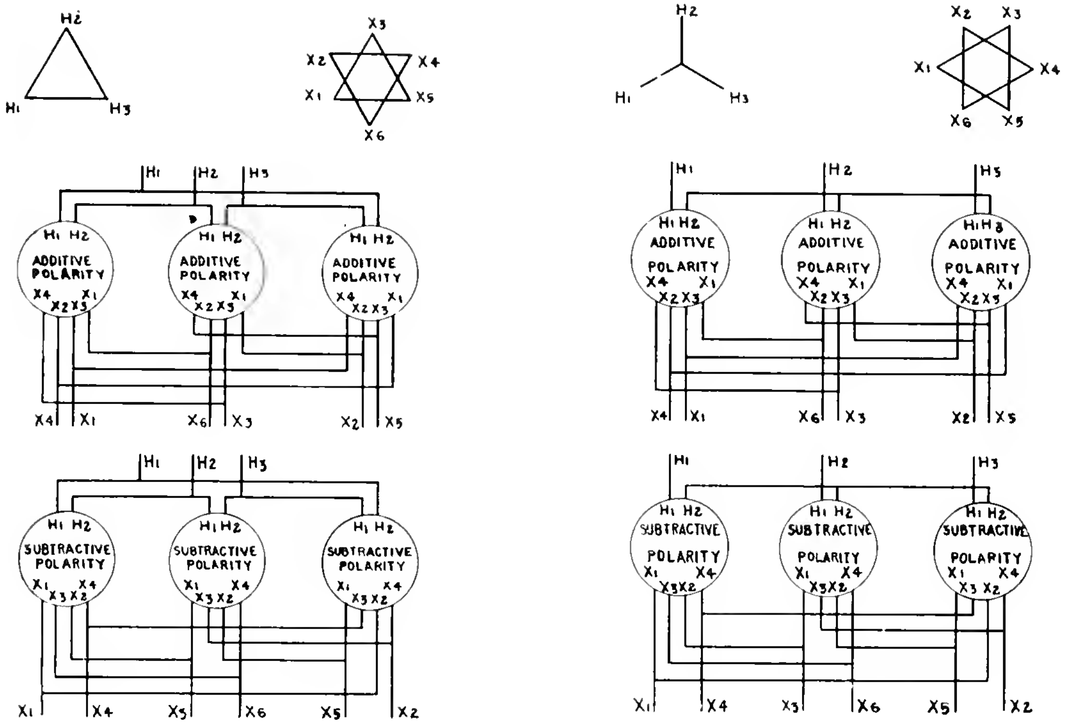
With single-phase units the procedure may be either to test their polarity prior to connecting them in multiple, or they may be multipled for a trial through a fuse or voltmeter and when the connection is found to be O.K. the fuse or voltmeter may be short circuited. In important cases both precautions may be taken.

In multipling two three-phase units for trial at least two of the three phases should be fused, and preferably three. The fuse should be connected between the leads which are to be connected together, preferably on the low-voltage side, and the excitation applied to the transformers should be small. Preliminary tests for voltage diagrams, as has been explained, would be very desirable; however, trial multiple operation through fuses is frequently found very simple. A better scheme is to substitute a voltmeter for the fuse. For instance, having multipled the high-voltage leads, connect a pair of low voltage leads together (fused or unfused); the second pair of low-voltage leads should now be connected together through a voltmeter. If the voltmeter indicates no voltage, it may be short circuited, taken out and used to test the third phase. It will be appreciated that the voltmeter must be capable of withstanding twice the line voltage on the leads to which it is being connected, since, if the polarity is wrong the phase voltages will add in the voltmeter and give a large deflection instead of neutralizing each other and giving a zero deflection as would happen if the connection were correct.

If the two units which are being tested are in Y-delta or delta-Y connection, and having first connected the high-voltage sides in parallel, it is found that no combination of the secondary leads is operative, one phase on the high voltage of one of the units should be reversed, and then an operative combination of the low voltage leads can be found. This is a characteristic of the Y-delta and delta-Y connections and sometimes shows itself in a puzzling manner. For instance, in connecting



Figs. 23 and 24. Three-phase to Six-phase Connections two identical Y-delta units in multiple, if one phase of one unit is reversed on the primary side, the secondaries cannot be multipled regardless of any reversals that may be attempted on the secondary sides. If two phases are reversed on the primary, then an operative combination of phases can be found on the secondary sides. Delta-delta and Y-Y connected transformers differ from the Y-delta or delta-Y transformers in that: (a) a reversed phase on the primary of the former can be made good by a reversed phase in the secondary, and (b) with a given connection of primaries in multiple, if an operative combination of secondary leads cannot be found, no other combination of primary leads will make parallel operation possible for them.



Figs. 25 and 26 Three-phase to Six-phase Connections

Figs. 16 to 26 show the connection of single-phase units of different polarities in various single and polyphase banks.

Relative Merits of Connections Employed in High-Voltage Generating Stations

By Ernest Pragst

Power and Mining Engineering Department, General Electric Company

In planning a system of connections for a central station consideration must be given to the factors of personal safety and protection to transformers and generators; also a degree of flexibility comparable with the importance of the station should be provided, so that facilities will be available for operating the station economically at all times whether at full load or fractional load. The author presents and discusses eight different systems of station connections, ranging from the simplest to the most elaborate.—Editor.

In the evolution of the modern high-voltage generating station a number of commonly accepted arrangements of interconnection between the generators, transformers and lines have come into use, each having its advantages, disadvantages and particular field of application. In this article the writer proposes to set forth a number of these basic or fundamental systems of connections (limiting himself solely to their application to generating stations, where power is stepped up in potential and transmitted over high-tension transmission lines), analyze them, and attempt to determine their particular field of application.

Any system of switching, along with power transformers, transmission lines, etc., is selected with one primary object in view; namely, to transport the electrical energy available at the generator terminals to one or a number of sources of load. With a natural realization of this object, it is at once recognized that the system of connections contemplated for a generating station is influenced not only by the selection of the prime movers with their corresponding generators, but also to an equal if not greater extent by the character of load, its geographical location in relation to the generating station, and, in the case of existing systems, the relation of the generating station under consideration to the existing system.

A detailed study of the interconnection of apparatus within the station, with an ever watchful eye on the influence of these connections on those external to the station, will show that any successful arrangement should fulfill the following conditions:

(a) It should not afford an undue risk to the operating force, particularly when conducting switching operations as a result of such abnormal conditions as electrical failures of lines and apparatus.

(b) It should permit of the economic operation of apparatus.

(c) It should be simple in principle, electrically.

(d) It should lend itself to simple and rugged mechanical arrangement and construction.

(e) It should have a reasonable degree of flexibility.

(f) It should assure a degree of continuity of service commensurate with the class of load served.

It might be well to elaborate on condition (b). Here it is meant that the connections should be such as to permit the operation of apparatus at a load as near as possible to that corresponding to maximum efficiency or full load, as desired. To do this, it is usually necessary to arrange to operate all apparatus in parallel. In the generating station this is provided for by paralleling all apparatus on a low tension or high tension bus or both. It is also customary to operate all plants in a given location interconnected or in parallel. This permits of the necessity of carrying but a minimum amount of spare generating capacity, makes possible the operation of a system at maximum efficiency, and automatically takes advantage of any diversity in load that might exist on the system. Also should the failure of any one piece of generating apparatus occur, if the system is large in proportion to the capacity of the lost generator, system operation in all probability will not be affected, as the load suddenly lost by the generator which has failed is distributed among all units remaining in service.

Having determined in a general way the factors influencing any system of station connections and the conditions these connections should fulfill, let us next consider the means of making and changing these connections to accomplish the desired results. We have at our disposal:

(a) Simple disconnecting switches, whose application is limited solely to the isolation of apparatus. They are not applicable for disrupting the flow of current.

(b) Multi-pole (usually triple-pole) air-break disconnecting switches. These are usually manually operated, are used for the isolation of apparatus, and can be employed for disrupting small amounts of current such as the charging current to short lengths of high-tension line, the exciting current of transformers of medium capacities, and light loads. One of their chief fields of application in the type of generating station under consideration is for use in the high-tension circuits in place of the simple single-pole disconnecting switches as a result of the increased facility and speed with which switching operations can be performed when they are employed.

(c) Air-break circuit breakers (automatic and non-automatic). The application of these is limited almost exclusively to low-voltage (usually under 600 volts) high-current circuits.

(d) Oil circuit-breakers (automatic and non-automatic). These are used in all circuits where currents of large magnitude must be broken, where quick switching operations must be conducted, or in circuits which, if opened or closed by other forms of switches, might present an undue hazard to the operators.

Hand-operated knife switches, fuses, special combinations of fuses and switches and the like, have been omitted from the foregoing tabulation, because their application in a modern generating station is extremely limited.

As a rule more than 95 per cent of service interruptions are the result of insulation failures external to the generating station; hence the control of the outgoing lines from the station should be such as to permit of carrying on switching operations with rapidity. Although failures of this class are extremely numerous, annoying and costly to the power consumer, the value of the apparatus lost in this manner represents a small item when compared to that lost as a result of apparatus failure in the generating station. Even though failures within the generating station are relatively rare, when they do occur their results are often far reaching both in interruption to service and expense of replacement. Therefore, whereas the method of controlling outgoing lines should be designed with a view to quick switching operation, the control of the circuits within the station should be designed with particular reference to the prevention or localization of possible failures of apparatus.

When considering the switching arrangement of a generating station as a part of a system or of the individual pieces of apparatus in their relation to the station as a whole, one must appraise the relative importance of the part under consideration in its relation to the whole. For example, should the station represent but a small and unimportant part of a large system, a station which can be dispensed with for a short time without materially affecting service, then we are naturally justified in employing an inexpensive switching scheme. If a generator in a station can be spared, one oil circuit breaker for its control is sufficient; and the same holds in the case of transformer control, busses, etc.

Having now a clear vision of the objects we wish to accomplish and a knowledge of the limitations of the apparatus at our command, let us investigate some of the more commonly used station connections.

Fig. 1. shows one of the simplest forms of station connections and represents, perhaps, a minimum expenditure for switching material. Here each generator is rigidly connected to and used as a unit with its corresponding transformer bank. The station auxiliaries are fed from an auxiliary bus, which in turn can be served from any one or all generators through the circuit breakers *a*. The chief criticism of this arrangement is its lack of flexibility. Each generator must be used as a unit with its corresponding transformer bank. Failure of either or of the conductors

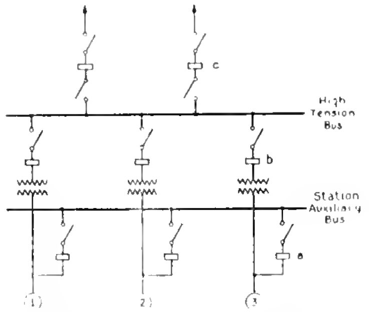


Fig. 1. Simple Station Connections Employing Generators and Transformers Rigidly Connected as Units

between them will result in the shut-down of both. Also, as in the case of most single bus arrangements, a failure of the high tension bus will result in a complete shut-down of the plant until such time as repairs can be made. As long as no trouble occurs within the station, normal switching operations may be conducted without inconvenience or hazard; the generators and transformers being placed in and removed from service by means of the oil circuit breakers *b*, and the lines controlled through the oil circuit breakers *c*. This arrangement finds its particular application in the case of small stations supplying loads where continuity of service is not of primary importance and where the cost of the installation must be held to a minimum at a sacrifice in flexibility and assurance of service continuity

Fig. 2 represents, no doubt, the most commonly used system of connections. Here all generators and transformers are connected to a common low tension bus, while the high tension side of the transformers and outgoing lines are connected to a common high tension bus. The capacities of generators, transformers and lines need not bear any definite relation to each other as in the case of Fig. 1. For switching under normal conditions and the protection of apparatus in case of failure, this arrangement will meet every requirement; that is, for failure within a generator, circuit breaker *a* may be opened, and in case of trouble within a transformer bank, the bank can be isolated through the opening of circuit breakers *b* and *c*. The criticism of this arrangement is its inflexibility. A failure of any generator circuit breaker results in the forced withdrawal of the corresponding generator from service; and similarly with the transformers, should a failure of oil circuit breakers *b* or *c* occur; and with the lines in case of failure of oil circuit breakers *d*. Should a failure of either bus occur, a complete shut-down of the station will naturally result. This is often partially guarded against by the introduction of sectionalizing disconnecting switches in the busses. Because of the expense of high potential oil circuit breakers, it is often customary to substitute for oil circuit breaker *c* and its corresponding disconnecting switches a triple pole air break disconnecting switch, with the result that operating flexibility and assurance of service continuity are lessened. Though open to these criticisms, the arrangement of Fig. 2 is well adapted to the requirements of small and medium sized installations, as the protection to apparatus is good and the personal hazard to operators is small, also, as the probability of failure of properly selected oil circuit breakers and well constructed bus structures is very small, continuity of service is quite well assured.

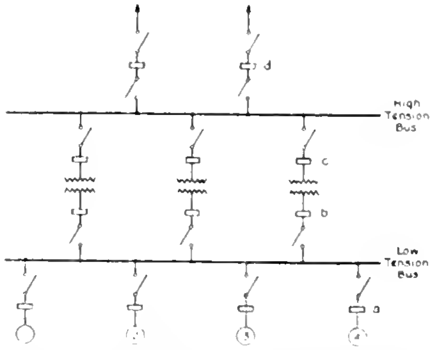


Fig. 2. A Commonly Used Arrangement Employing Single High and Low Tension Busses

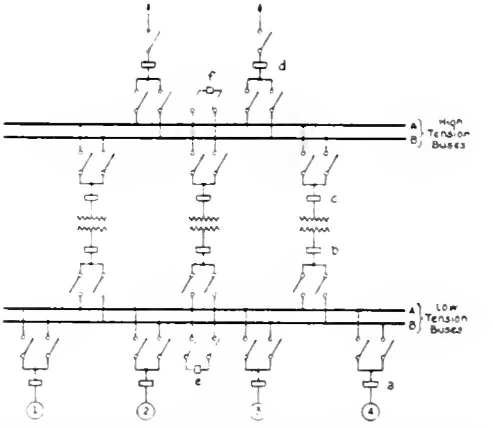


Fig 3. An Elaboration of Fig. 2. Using Low and High Tension Busses with a Single Oil Circuit Breaker and Selector Disconnecting Switches in Each Circuit

Fig. 3 shows a diagram of connections which is an elaboration of Fig. 2, double high and low tension busses being employed. Approximately twice the amount of bus material and number of disconnecting switches are required as for the arrangement of Fig. 2. This arrangement will practically eliminate the possibility of a prolonged shut-down as the result of a bus failure. It also permits of maintaining service when working on either bus. However, it will not eliminate the necessity of withdrawing apparatus from service in case of trouble with its corresponding circuit breaker The arrangement has one marked advantage over those of Figs. 1 and 2; namely, should a feeder trip out it is possible first to test it out, thus avoiding the risk of again tripping it out or causing surges on other feeders by placing it back in service when it is still short circuited or grounded. For example, suppose generators Nos. 1, 2 and 3 are in operation with transformer banks Nos. 1 and 2 and connected to low and high tension busses *A*, with generator No. 4, transformer bank No. 3 and busses *B* in reserve. If one of the feeders trips out from some unknown cause it will be an easy matter to test it out with generator No. 4 and transformer bank No. 3 operating through busses *B*. Bus tie circuit breakers *e* and *f* are often included to facilitate this class of switching operation. Should the tested line prove good, it could at once be placed in service by closing either circuit breakers *c* or *f*, or both. With circuit breakers *e* and *f* closed and, of course, the *A* and *B* busses in synchronism and at the same potential, the transfer of a circuit carrying power from one to the other bus can be effected without danger or interruption to service by means of the disconnecting switches.

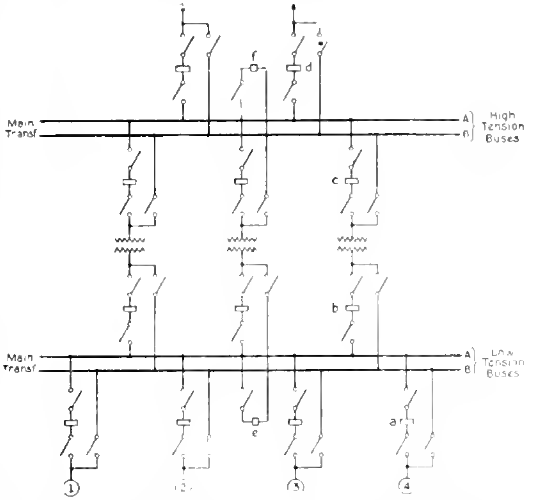


Fig. 4. Another Elaboration of Fig. 2, Using Single Main High and Low Tension Busses with Transfer Busses for Utilizing a Reserve Circuit Breaker in Each of the High and Low Tension Circuits

Fig. 4 is a further elaboration of the connections of Fig. 2. The arrangement of Fig. 3 provides for the failure of a bus, but makes no improvement in the operating limitations of the oil circuit breakers over the arrangement of Fig. 2, while Fig. 4 provides for the withdrawal from service of any oil circuit breaker without interrupting the operation of the corresponding apparatus, but makes no provision against bus failure. The amount of switching equipment required for the scheme, Fig. 4, is almost identical with that of Fig. 3, and the two systems of connections are an improvement over that of Fig. 2, Fig. 3 providing against a possible bus failure and Fig. 4 against a failure of circuit breakers only. Under normal operation all apparatus will operate from the main or *A* busses. Should it be desired to withdraw from service a circuit breaker, it can be done without interruption by connecting the corresponding piece of apparatus by means of its disconnecting switches to the transfer or *B* bus and connecting the two busses *A* and *B* together through the bus tie switch *e* or *f*, as the case may be, after which the circuit breaker in question can be withdrawn from service.

Fig. 5 is included primarily to illustrate a method of high tension connection which has been very commonly used in past years for high tension stations. The low tension arrangement may be as shown or similar to that of Figs. 3 or 4 without materially affecting the high tension system. Here transformer banks are operated as a unit with the lines. As shown, three high tension oil circuit breakers *c*, *d* and *e* are employed for each group of transformer and line. Because of the expense of these high potential circuit breakers, triple-pole air-break disconnecting switches are often substituted. When this substitution is made, circuit breakers *c* or *d* or both are those usually replaced. In the case of line failure, it is customary to trip the line along with its corresponding transformer bank by means

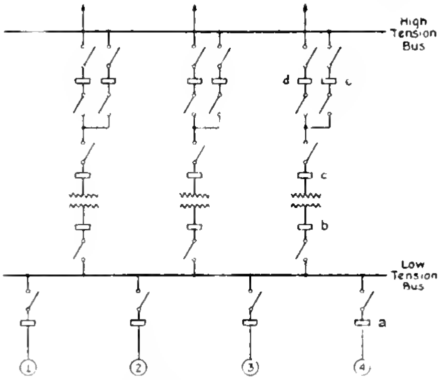


Fig. 5. A Wiring Arrangement Based Upon Operating a Transformer Bank as a Unit with a Line

of the low tension circuit breaker *b*. The chief advantage of this arrangement lies in the fact that when operating in this manner the magnitude of the surges resulting from switching operations on the high tension system is reduced to a minimum. On the other hand the arrangement presents numerous disadvantages. It does not usually lend itself well to connection in a network; and is uneconomical in those cases where the generating station supplies widely separated loads, as in this case the transformers in all probability must be of different capacities to meet the load requirements, which is an undesirable feature from a construction and maintenance point of view. Also, when tripping transformers with their transmission lines, there is a marked increase in potential drop over the remaining circuits as compared with the case where all transformer capacity continues in operation supplying power to the lines remaining in service. The significance of this potential drop will readily be appreciated particularly in the case of low power factor loads, when it is recalled that the reactance of a transformer bank is very often the equivalent of that of the line, while the combined reactance of both the generating station and substation transformers might be twice that of the line. With the present state of the art of designing and building high potential apparatus, when it is possible to be reasonably assured that the apparatus if properly applied will withstand all of the usual abnormal stresses experienced in practical operation, it is doubtful whether the advantages gained by reducing the surges incident to switching by resorting to low tension switching are sufficient to outweigh the limitations of this method of connection and operation in most cases. The arrangement finds its particular application in those cases where power is generated at one station and transmitted over a number of lines to a single substation. In such cases it affords an effective and economical arrangement.

Fig. 6 represents a rather novel scheme which contemplates the operation of a generator and transformer bank as a unit during normal conditions and practically eliminates all of the usual low tension circuit breakers. It is particularly interesting in that all normal switching operations are to be performed on the high tension side of the station. Although almost all oil circuit breakers have been omitted from the low tension circuits, provision has been made to operate any generator with any transformer bank in case of trouble. A careful study of this arrangement will reveal the fact that when it is necessary to do any low tension switching, involving the use of disconnects *a*, *b*, *c* and *d*, great care must be exercised, necessitating perhaps the withdrawal of apparatus from service to avoid a possible severe accident should a mistake be made in switching. Besides the chance of accident to the operating force and bus structure when doing low tension switching, the time required to make the change-over, and the fact that considerable capacity must be withdrawn from service during such time, makes it appear that this particular arrangement has but limited application except in those stations where there are installed a large number of units and sufficient spare capacity to make the necessity of operating a generator with other than its corresponding bank of transformers an unusual procedure.

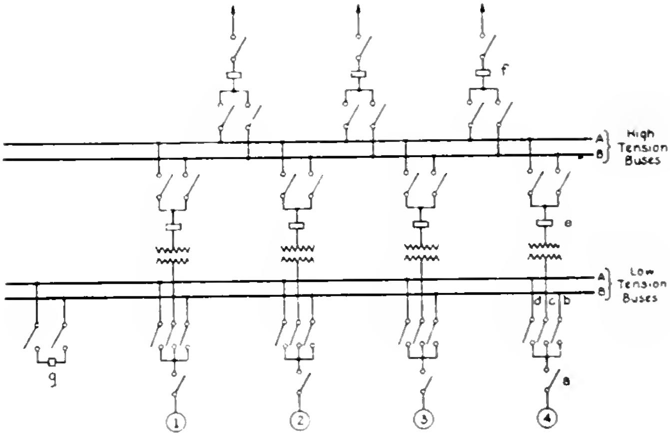


Fig. 6. An Arrangement Omitting Low Tension Circuit Breakers Throughout

Fig. 7 shows an arrangement with a complete duplication of switching equipment and busses. Such an arrangement will fulfill all the technical requirements of a well designed switching scheme for the majority of cases. As a matter of fact, the strongest criticism that can be advanced against such an arrangement is the expense involved; and for this reason such an arrangement can be adopted only in large capacity stations where continuity of service is of primary importance and where its assurance will justify the expense.

Fig. 7 is made up on the basis of using on the low tension side a main and auxiliary bus. The main bus has been segregated by means of bus sectionalizing circuit breakers *j*. Current limiting reactors *k* are also shown, as they are invariably required in the case of large capacity stations, and are usually placed as shown in such a bus arrangement as this. Only a simple single auxiliary bus is used without sectionalizing switches or reactors on the theory that it will never be necessary to withdraw from service more than one main bus section at a time. With such a bus arrangement all normal switching operations, and those of an abnormal nature as well, can be performed by the station operator from the main control board with a minimum loss of time. The arrangement also lends itself very nicely to a station feeding power at several potentials, in which case all generators and low tension sides of transformers can be paralleled on the common low tension bus as shown, utilizing the necessary number of independent high tension bus structures. To reduce the cost of the switching equipment, a common and well worth considering alternative to the high tension arrangement as shown is sometimes employed, namely, the use of a single oil circuit breaker and selective disconnects as shown in Fig. 3. To facilitate switching operations in this case, the selective disconnects often take the form of triple-pole manually operated air-break disconnecting switches, particularly in the case of stations operating at the higher potentials.

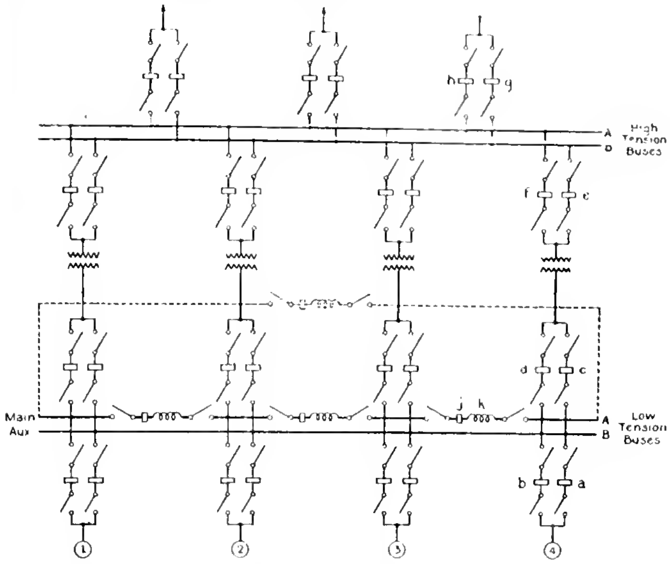


Fig. 7. An Elaborate Arrangement Employing Double Busses and Double Selector Oil Circuit Breakers in Both the High and Low Tension Circuits

Fig. 8 is another very common arrangement, used in large stations stepping up all power to one potential. The scheme contemplates operating each generator as a unit with a transformer bank, and paralleling all generators on a common low tension transfer bus. Where it is necessary, as with large capacity stations, to install current limiting reactors, they are usually placed as shown *f*. This arrangement is less expensive than that of Fig. 7, but does not give the same assurance of continuity of service in the case of a circuit breaker failure, although should the failure of circuit breaker *a*, *b* or *c* occur, it could be cut out of service by means of a jumper placed around it and further switching operations carried out with the remaining two breakers with but slight inconvenience.

In addition to the arrangements shown, there are an almost unlimited number of others, but on analysis they prove to be as a rule nothing more than an elaboration or a slight modification of those considered here. It is not possible to give any set rules governing the selection of a switching scheme; each case should be decided separately after a careful analysis of the various factors involved

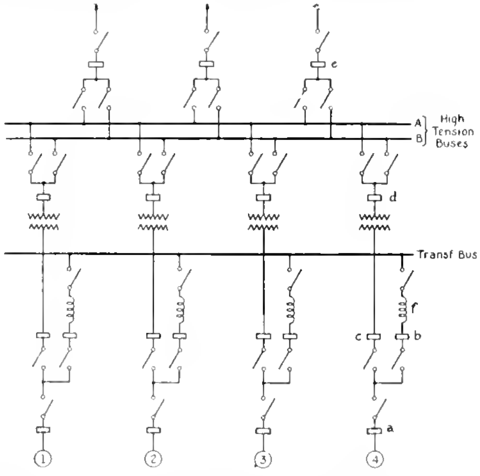


Fig 8. A Popular Arrangement Using the Generators as Units with Corresponding Transformer Banks and Paralleling on Double High Tension Busses Through Single Oil Circuit Breakers and Selector Disconnecting Switches

60-cycle Converting Apparatus

By J. L. Burnham

Engineer, Direct-current Engineering Department, General Electric Company

The popularity of the synchronous converter is attested to by the fact that 2½ kilowatts of this type of apparatus are built for every kilowatt of motor-generator. The 60-cycle converter for voltages up to 300 has proved very successful, but for voltages of 500 and 600 it has been very susceptible to flashing at the commutator when subjected to short circuits or quick changes in load. Because of this trouble the whole phenomenon of flashing was thoroughly studied, and as a result several devices have been developed which, when employed together, effectively prevent flashing even on complete short circuit. This freedom from flashing is secured through the use of high reluctance commutating poles, a special form of brush rigging, screened flash barriers, and the high speed circuit breaker. Another disadvantage of the synchronous converter is the inflexible ratio between alternating-current and direct-current voltage. Direct-current voltage regulation is therefore usually effected from the alternating-current end by means of the synchronous booster. In conclusion the author makes a comparison between the synchronous converter and the motor-generator on the bases of efficiency, reliability, flexibility, costs and floor space.—Editor.

The great increase in use of 60-cycle generators and extension of 60-cycle transmission systems in recent years has resulted in a corresponding demand for 60-cycle converting apparatus to supply direct current. This demand has not been difficult to meet successfully with motor-generator sets or with converters delivering up to 300 volts direct current, but has emphasized the difficulties with synchronous converters for 600 volts and over.

The inherent sensitiveness to flashing of 60-cycle railway converters has always been more or less annoying to operating companies. Changes in conditions of operation, such as lengthening of feeders, have given some relief but still there is a need for more stable characteristics.

By the use of commutating poles it was possible to increase the output per pole thereby giving higher angular speeds. At about the same time designs with greater spacing or pitch of brushes and poles were made to increase the flashing distance and reduce the voltage on the commutator adjacent to the brushes. Bridges were improved to give greater stability and many minor improvements added, but only recently has the most promising development been accomplished.

Several years ago a special study of the causes of flashing and remedies was undertaken and has reached a stage where, with certain equipment now developed, the 60-cycle railway converter may be made immune from flashing at the commutator as a result of direct current short circuits.

In a paper entitled "Protection from Flashing for Direct Current Apparatus," presented at the A.I.E.E. convention in June, 1918, experimental results were given showing that protection by high speed circuit breaker and flash barriers would give complete protection against flashing. Since that time further improvements in both the converters and the new type of high speed breaker have been made to give still greater margins of safety. Changes in the 60-cycle railway converters are principally in the form of commutating pole and its windings and in the brush rigging.

Commutating Poles

The commutating pole construction which is now applied to our line of standard 60-cycle railway converters makes use of non-magnetic material in the place of steel for a large portion of the pole next to the magnet frame. The resulting increase in reluctance of the commutating pole magnetic circuit requires much higher excitation and thus an increased number of turns in the winding to give the same flux density necessary for commutation.

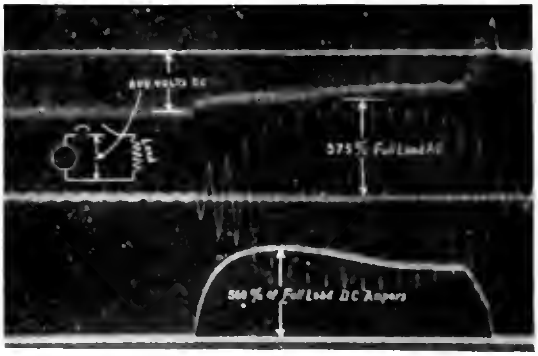


Fig. 1 Oscillogram Showing Values of Alternating and Direct Current in 1000-kw., 500 volt, 60-cycle Transformer When Subjected to Six Times Full Load and Tripped with Ordinary Type of Breaker

The principal advantages are:

1. The excitation may be increased to a value in excess of the direct current armature reaction.

2. Reduction of the effect of saturation.
3. The commutating field responds more quickly to changes in load.

1. When a converter is suddenly loaded the direct current increases more rapidly proportionately than the alternating current for a short period and then the reciprocal relation is established on the reverse swing of pulsation, etc. Thus the balance between the alternating and direct current reaction is different than for steady loads. The oscillogram of Fig. 1 is a record of the relations of direct and alternating current when about six times full load is thrown on and tripped off a 1000-kw., 60-cycle, 600-volt converter with a breaker of ordinary speed.

Fig. 1a is calculated from the value of current in Fig. 1 and shows excitation of the commutating pole resulting from current in the field winding and armature reaction combined. The straight lines show the required excitation to give best commutation for all-steel poles and for high reluctance poles. The sequence of relations after application of the load is given by the arrows. It will be seen that the maximum percentage departure from best excitation is nearly four times greater with the all-steel poles than with high reluctance poles. A severe short circuit might give three or four times greater load which would reverse the all-steel poles, but would only weaken the high reluctance poles as the field winding excitation of the latter is stronger than the armature reaction.

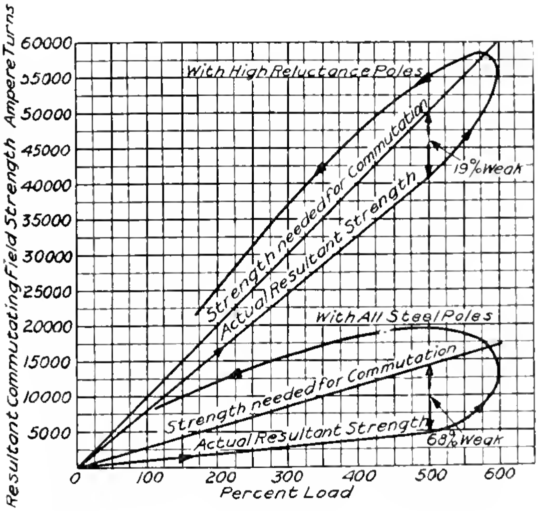


Fig. 1-a. Curves Plotted from Oscillogram in Fig. 1, showing Effect on Excitation of Commutating Poles

2. As the greater part of the excitation is used to overcome the reluctance of non-magnetic material, the effect of saturation is lessened, and thus more nearly can the commutating field strength be maintained proportional to load during the heavy overload when it is most needed. For the same reason the effect of hysteresis is reduced.

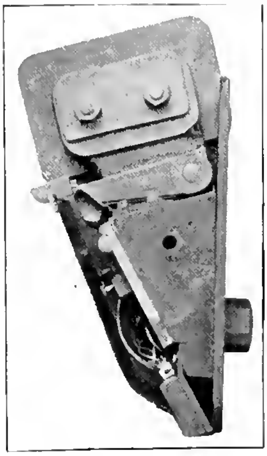


Fig. 2. Radial Brush-holder Unit with Outer End Insulation Removed

3. The greater speed in establishing the required field with the greater magnetizing force is self-evident.

Brush Rigging

The most vulnerable points of brush rigging are at the outer end of the commutator and the leaving side of the brushes. It is therefore desirable to avoid overhanging parts in the direction of rotation, or outward from the end of the commutator. This is particularly so with 600-volt, 60-cycle converters, which inherently have a short space between adjacent sets of brushes of opposite polarity. The new rigging recently applied to railway machines, which is designated as radial unit type, accomplishes the desired end by having

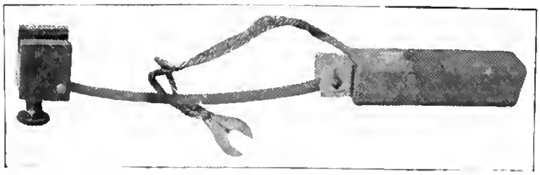
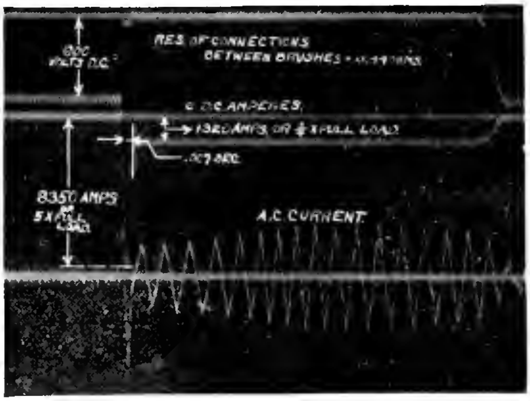
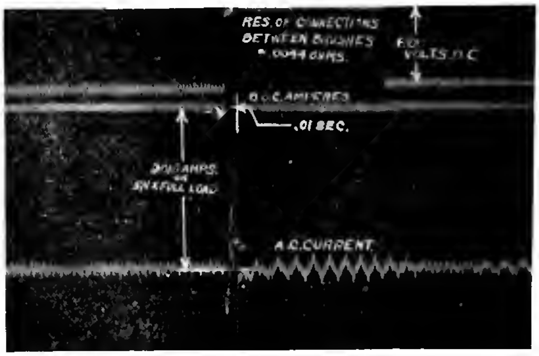


Fig. 3. Spring and Pressure Adjusting Slide for Radial Brush-holder, Shown in Fig. 2

no overhanging parts for springs or supports (Fig. 2). The spring is made of a slightly bowed strip of steel placed radially over the brush and having radial adjustment for pressure (Fig. 3). The attachment for supporting the set of brushes is at a radial point near the inner end of the commutator where an arc from flashing has the minimum tendency to form. This type of rigging has the further advantage of simplicity when it is desired to adapt fire-proof insulation which gives still further protection to the rigging from burning by reducing the exposed metallic surfaces on which the arc might play and produce more conducting gas.





Figs 4 and 5. Oscillograms Showing Conditions During Short Circuit with Only High Speed Circuit Breaker, Switch, and Slower Breaker in Circuit In Fig. 4 high speed circuit breaker shunts a resistance, and in Fig. 5 the breaker is connected directly in series

Flash Barriers

As a further protection for extreme conditions, flash barriers of a special form have been developed. It was early recognized that the arc could not be confined, if we could not dispose of the large volume of gas generated at considerable pressure. A barrier consisting of a box fitting closely to the commutator around each set of brush-holders is worse than no protection at all, as it confines the gases, making them highly conducting, and the resulting concentration of energy is very destructive. The problem of disposing of the hot gases has been successfully solved by the use of metal screens inside of the box structure. Next to the commutator a scoop-shaped member of the box is arranged to deflect the gases from the commutator into the screen and thus cool and condense them. Barriers of this type are successful when kept clean and properly fitted with a small clearance between them and commutator. However, the closing in of the brush rigging, rendering it less accessible for inspection and adjustment, is undesirable. Further study is now being made to overcome this feature.

High Speed Circuit Breaker

In parallel with the study of the converter, a search for improvements in external protection was carried on. A higher speed breaker first presented itself as offering the greatest possibility. It was realized that such a breaker would have to be radically different from those available in that it must be many times faster. It was anticipated that the circuit should be opened in less than 1/120 of a second. The objective was therefore placed at about 0.006 second, which is within a half cycle, or the time in which a commutator bar passes from one brush to the next

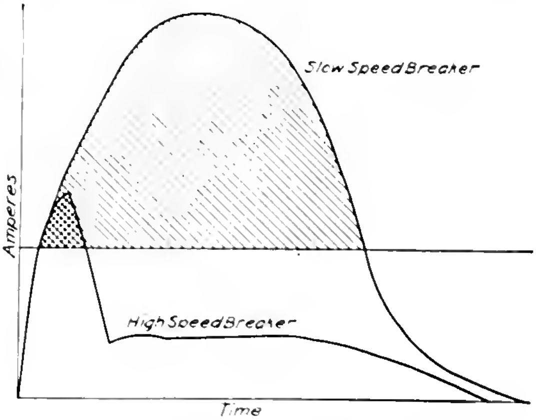


Fig 6. Curves Showing Relative Effects Tending to Produce Flashing, with High Speed Circuit Breaker and with Usual Type of Breaker

brush of opposite polarity. In this time it was anticipated that the arc would not be carried completely across and the energy absorbed would not be sufficient to cause serious pulsation.

Figs. 4 and 5 are records of direct current and voltage and alternating current during short circuit, with the high speed breaker, switch, and slower breaker only in circuit. In Fig. 4 the high speed breaker is connected across a resistance that reduces the current to 80 per cent load in 0.007 seconds from the beginning of the short circuit. It will be noticed that this load is steady until the slower breaker opens and that the d-c. voltage then returns to a steady normal, indicating no pulsation or flashing. Fig. 5 is the same except that there is no resistance across the high speed breaker which opens the circuit completely in 0.01 sec. from the beginning of the short circuit. Both records show that the flashing load (about 5 times full load) was on for a small fraction of the total time, being barely reached in Fig. 4. With a standard breaker the load would have reached about 25 times full load for a much greater time. A comparison of the relative effects which tend to produce flashing with the high speed and usual speed circuit breakers is shown in Fig. 6. The relation of areas indicating relative causes for flashing is very striking.

Without further details of the development it may be said that two types of breakers have been made to give the desired speed, and the simpler one of these is now available. A number of tests for all values of short circuit up to the maximum that could be obtained with only the necessary connections for switches and circuit breaker have been made with the improved design of converter and high speed breaker with absolute freedom from flashover. It may therefore be said that the problem of preventing flashing of 60-cycle 600-volt converters from direct current short circuit has been solved, and the necessary equipment is now available for the first time.

Voltage Control and Commutation Regulating Devices

The voltages at the collector and at the commutator of the simple converter have an approximately fixed ratio. To regulate the direct current voltage it is therefore necessary to have some means for regulating the a-c. voltage. A special arrangement of poles in the split pole type produces a change in ratio within the machine, but few of these machines are now being built on account of complication with the application of commutating poles. The a-c. voltage is now regulated mostly by means of the synchronous booster except for the smaller ranges (under 10 per cent) or where accurate adjustments are not needed. About 10 per cent regulation is possible by field control of the converter, with proper proportions of field and armature windings. With 15 per cent to 20 per cent reactance the power factor at full load need not be less than 95 per cent nor the corresponding wattless current materially exceeded at other loads.

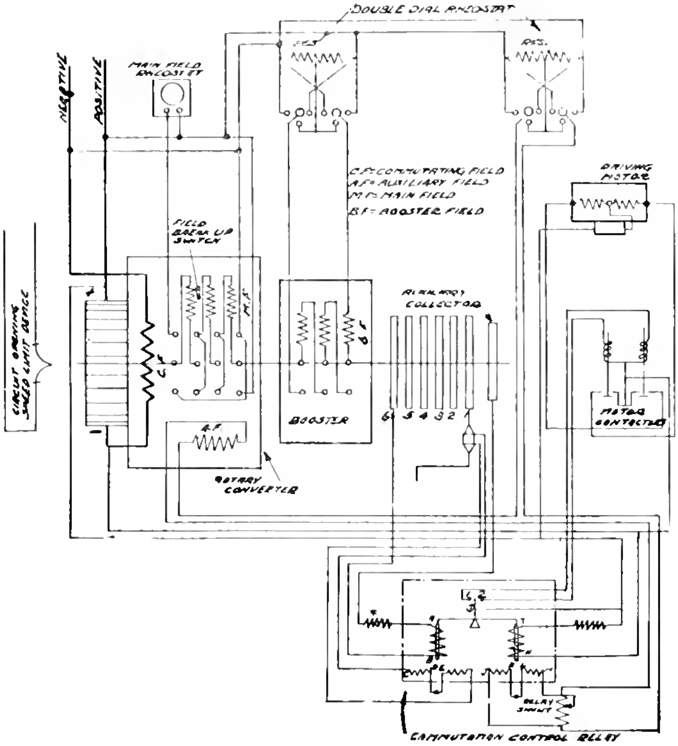


Fig. 7. Connections of Synchronous Condenser Employing Synchronous Booster for Regulation of Voltage. Commutation is automatically controlled by two-element contact-making relay

The usual arrangement is to drive the synchronous booster from the converter, in which case it has the same number of poles as the converter. In a few instances with large machines it has been advantageous to drive the booster with a separate motor of the same number of poles, thus making a much smaller high speed booster and eliminating control equipment for commutation.

When the booster is driven by the converter to raise the a-c. voltage to be applied to the converter armature, it acts as a series generator requiring additional motor current through the converter armature to drive it. Conversely, when the booster serves to lower the a-c. voltage it acts as a motor and drives the converter armature as a generator. These additional motor and generator currents in the armature give reactions on the commutating pole which would seriously affect the commutation if proper correction were not applied. Several schemes for cancelling these reactions are in use. Two of them are:

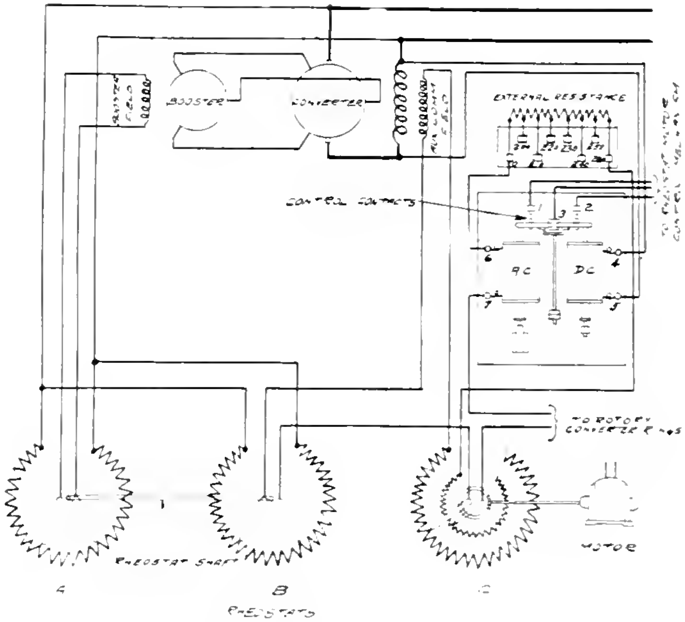


Fig. 8 Another Method of Maintaining Satisfactory Commutation When Employing Synchronous Booster. This method employs rheostats in the booster field and in the auxiliary commutating field

(1) Since the additional current in the rotary armature is proportional to the kilowatts that the booster is carrying, that is, the product of volts and amperes, a two-element balanced contact-making device responsive to kilowatts in the booster was devised. The wattmeter element contains two coils, one carrying current from a series transformer in the main load circuit and the other receiving the voltage of the booster across the corresponding phase. Balanced against this element is another element carrying commutating field current in one coil and constant source of excitation in the other. When properly adjusted the correct balance between kilowatts on the booster and auxiliay commutating field current is obtained by the operation of a motor-driven rheostat in the commutating field circuit controlled by the contact-making mechanism. Connections are shown in Fig. 7.

(2) Rheostats in the booster field and auxiliary commutating field circuits are mechanically connected so that they keep the two excitations proportional. This gives the voltage element of kilowatts. The current element of kilowatts is obtained by another rheostat in series with the auxiliary commutating field which is driven from a contact-making relay balanced against load amperes. Connections are given in Fig. 8.

Comparison of Motor-generators and Synchronous Converters

The great amount of work that has been done to meet operating requirements with converters, instead of motor-generators, must be backed by good reasons other than simplicity. The following comparison on efficiency, reliability and flexibility, cost and floor space, therefore seemed desirable to assist in arriving at a choice of apparatus for a given service.

Efficiency

As there are many combinations of a-c. and d-c. voltages between which conversion is desired there are also different efficiencies of conversion for a given size of machine. Curves were plotted showing the amount by which the efficiency of the converter with its necessary transformers exceeds that of the motor-generator without transformers for different a-c. voltages up to 13,200, the assumed limit for motor voltage. Converter curves included those with synchronous boosters to give 20 per cent voltage adjustment for lighting service, the range in d-c. voltage being 240/300. The curves for the various conditions were all combined and lie within the areas.

At 240 volts, or 10 per cent buck, the converter efficiency may be about 1 per cent less than given by the lower edge of the efficiency area (Fig. 10). For a-c. voltages exceeding 13,200, which requires a transformer for the motor-generator, the difference in efficiency will be about 2 per cent greater than shown. The comparison of 600-volt railway machines does not include so many variations, in that the converter only without a booster is considered (Fig. 9).

Methods as defined by the A.I.E.E. rules were used in the determination of these curves.

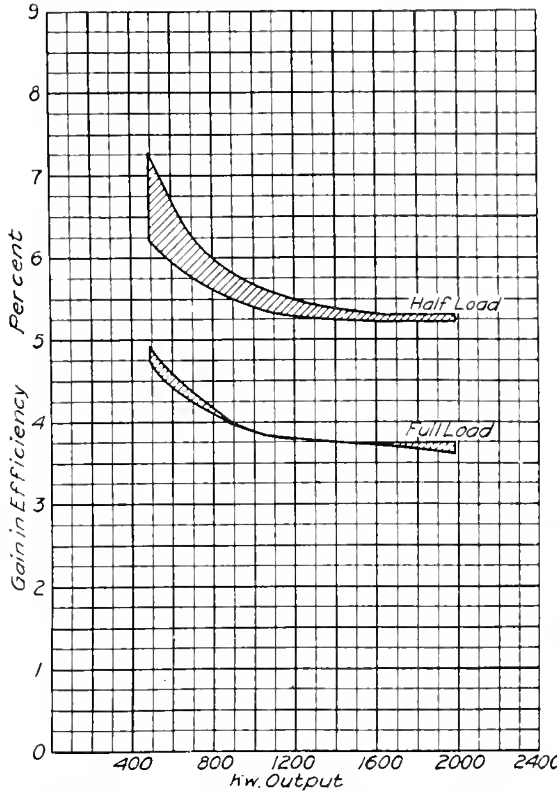


Fig. 9. Gain in Efficiency of Synchronous Converter with Transformers over Motor-generator Set for 600-volt Direct-current Operation. Gain in efficiency varies over shaded area for alternating-current line voltage from 2300 to 13,200

Attention is directed to the fact that indeterminate losses omitted in the efficiency calculation of the booster converter would be greater than those of a motor-generator, so that the actual gain given for the booster converter would be somewhat less than shown.

There will also be a small extra loss in the heavy conductors from a converter to the low voltage secondary of its transformer as compared to the usual higher voltage connections of the motor

The greater the d-c. voltage range the less efficient will the converter become and at more than 25 per cent range will lose much of its advantages.

Reliability and Flexibility

A simple converter has the same windings as a generator, but requires a large collector. The collector probably involves less risk to interruption of service than the motor of a motor-generator set. When a booster is added to the converter it involves the same risks as the motor of a motor-generator set, and the converter outfit then has the added risk of a large collector. Rather sharp distinctions must be drawn to show the advantage of either. The converter will require more attention to its large collector than is necessary with the small collector of a motor, but if this is given reliability is not affected.

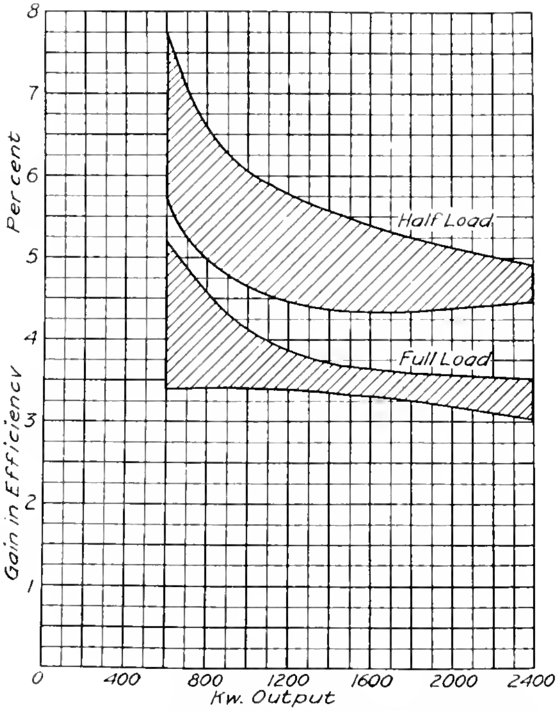


Fig. 10. Gain in Efficiency of Synchronous Booster Converter with Transformers Over Motor-generator Set. For 240/300-volt direct-current operation. Gain in efficiency varies over shaded area for alternating-current line voltage from 2300 to 13,200 with and without boosters. Figures at 270 volts

The direct connection of the armature winding of the converter to both the a-c. and d-c. systems is generally not as desirable as to keep the systems separate, as with a motor-generator. The ability of the motor-generator to control power factor and d-c. voltage independently is sometimes an important feature.

In general, voltage delivered by a motor-generator is subject to less sources of variation than that from a converter. With steady frequency the a-c. voltage fluctuations and line drop do not affect the d-c. generator voltage.

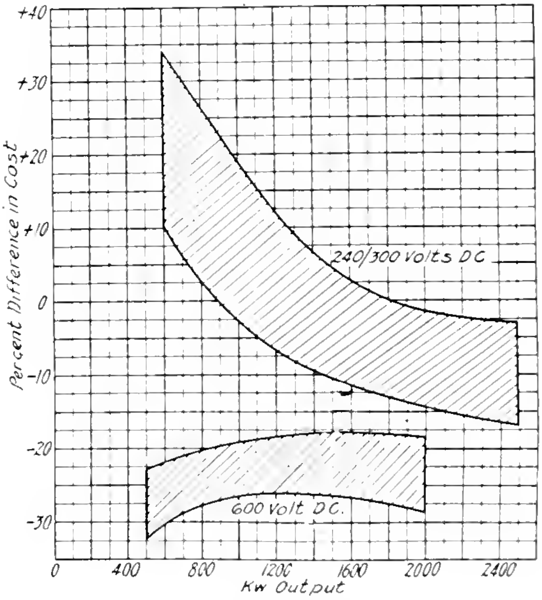


Fig. 11. Per Cent Difference of Cost of Synchronous Converter with Transformers Compared with Motor-generator Set (100 per cent). Cost difference varies over shaded area for alternating-current line voltage from 2300 to 13,200

Cost

The comparison of costs for both railway and lighting machines (Fig. 11) is based on the same combinations of apparatus as were considered under Efficiency. For higher voltages than 13,200, the cost of transformers would be added to the motor-generators. As the range in transformer costs is rather wide, depending on efficiency, method of cooling, and voltage, no attempt has been made to give the additional percentage.

Floor Space

Fig. 12 is for a-c. voltages up to 13,200. At higher voltages the floor space for motor-generators with transformers would be about 15 per cent greater.

Conclusions

From the foregoing data the saving of power by using the synchronous converter is quite evident and especially attractive when the a-c. line voltage is over 13,200. The cost and floor space are generally in favor of the converter below 13,200 volts, and decidedly so at higher voltages. Unless the service is very exacting or special, requiring wide range of voltage control or high d-c. voltage, the choice would favor the converter. This is proved by the proportions of this apparatus built in the past five years, which is about 2½ kilowatts of converters for each kilowatt of motor-generators.

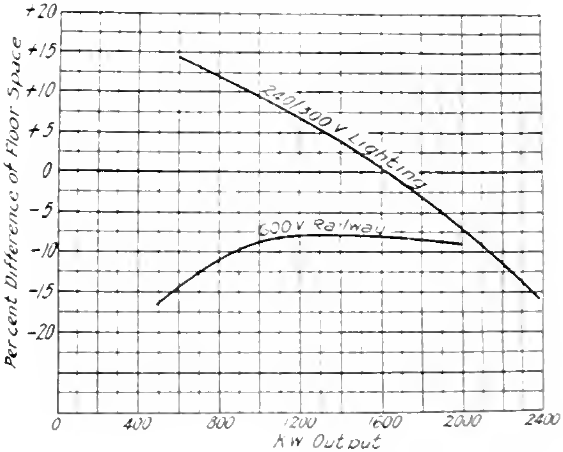


Fig. 12. Per Cent Difference of Floor Space of Synchronous Converter with Transformers Compared with Motor-generator Set (100 per cent)

Design of a Superpower Station

Steam Turbine Generating Station of 245,000-kw., 300,000-kv-a. Capacity, 66,000-volt Distribution

By H. Goodwin, Jr.
Power and Mining Engineering Department, General Electric Company

MECHANICAL DESCRIPTION AND STATION DESIGN

By A. R. Smith
Construction Engineering Department, General Electric Company

The proven economy of large capacity generating units operating at high steam pressure, and the even greater economies to be obtained when a number of these are located in one station, are leading to the development of power in large blocks. Under these conditions the old systems of cable distribution are inadequate and the introduction of high voltage cables of large kilowatt capacity is necessitated, introducing further problems. In this article the authors deal with the design of a station to meet all these conditions. This has been done by keeping unit design and flexibility as prominent conditions. Therefore, while the design was made for a particular location, it should be very widely applicable where economy calls for large generating stations.—Editor.

The general tendency towards the consolidation of existing power plants and transmission systems and the probability of the construction of superpower lines will undoubtedly result in the erection of large generating stations which can be operated at practically full load throughout the year. Whether such plants be located near coal mines where fuel is reasonably cheap or in localities where the transportation cost of fuel is considerable, the fact that the load factor is high will justify the construction of a most economical plant.

Aside from the economy of fuel based entirely on its present value per ton, consideration must be given to its extravagant use and the possible value many years hence. Another fact that is often lost sight of is that the more coal consumed per kilowatt-hour the greater must be the capacity of boilers, stokers and coal and ash handling facilities; and the greater the steam consumption the larger the piping, condensers and water tunnels. In brief, the cost of much of the apparatus that is necessary only for economic reasons may be largely offset by the reduction in cost of the essential apparatus because of the reduced demands on it.

The design herein described was developed for a particular condition where some of the fundamental considerations were: high fuel cost, moderately good load factor, extreme river floods, and high voltage underground distribution. This design is of recent origin and has therefore not been fully developed; consequently some of the apparatus shown, particularly the boilers, economizers and pre-heaters, are proposed designs.

The more unusual features of the design are:

- High steam pressure, 350 lbs.
- High superheat, 350 deg. F.
- Independent power supply for station aux.
- Air pre-heaters for stokers.
- All electrically driven auxiliaries.
- Minimum overhead coal storage.
- Simplicity of boiler room building.
- Outdoor switch gear for 66,000-volt distribution.
- Means of cleaning circulating water tunnels and possible utilization of circulating pumps in case of flood.

The ratings of the principal pieces of apparatus are:

Seven main generators of 35,000-kw., 0.8-p-f., 43,750 kv-a. capacity at 13,200 volts 3 phase, driven by steam turbines.

Seven 45,000-kv-a. transformer banks for stepping from generator voltage to 66,000 volts, each bank composed of three 15,000-kv-a. single phase units. One generator and one transformer bank are designated as reserve capacity.

Ten underground and two overhead feeders, all at 66,000 volts. The underground feeders will each be composed of three single conductor underground lead-covered cables and will have an individual capacity of 45,000 kv-a. The overhead feeder capacity is approximately 10,000 kv-a. each.

Coal Handling Equipment

Coal handling equipment has been designed with the idea that the bulk of the coal will be unloaded from barges by means of traveling crane towers at the dock and transported

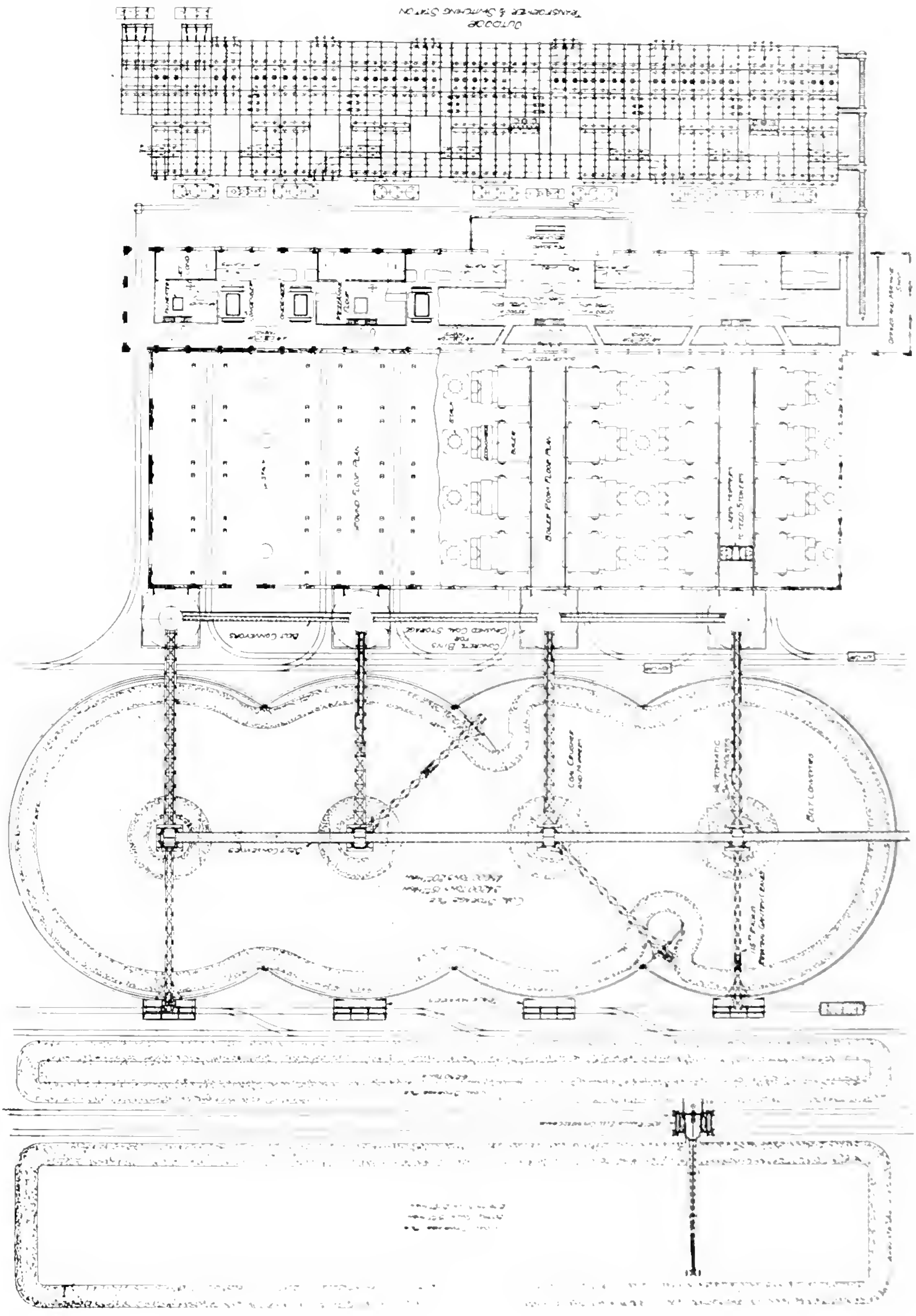


Fig. 1. Plan of Complete Station

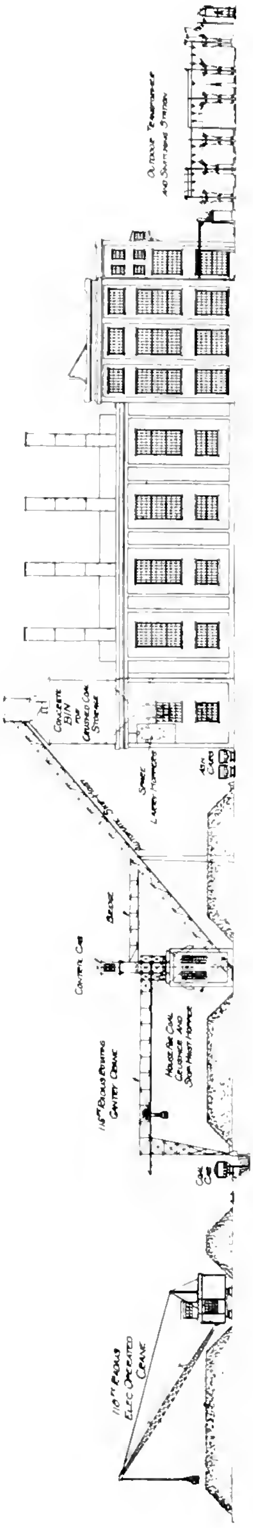


Fig. 1. Elevation

by two belt conveyors directly to the four receiving hoppers and crushers. Fig. 1 shows the construction quite clearly. The duplicate belt conveyors provide a large coal handling capacity when needed, but at the same time the system is not dependent upon a single conveyor. It should be noted that there are no travelling trippers, as all belts are dead ended. From the receiving hopper the coal is delivered directly to the outside storage or through a crusher and skip hoist to the overhead outside bins. These overhead bins are connected by an emergency belt conveyor so that in case of failure of a skip hoist, a crusher or any part of a receiving hopper tower, the crushed coal can be transported from the adjacent overhead bin.

The intention is that one operator located in a control cab above each receiving hopper will operate the revolving gantry crane, the crusher, the skip hoist, etc. Another operator will be located on each electrically operated larry to transport and weigh the coal from the overhead bins to each boiler. The emergency coal storage handled by the locomotive travelling crane will be operated only when the excess coal is being stored or reclaimed.

It is proposed that there be one spare larry which can be readily run into any one of the four firing aisles to replace any defective larry. It will be observed that the revolving gantry crane reclaims the coal from the circular storage without moving the bridge; thus, this method is very rapid when reclaiming coal, although in distributing the coal the bridge will have to be moved slightly from time to time, but to minimize this movement outside shoots are shown on the four sides of each receiving hopper tower. The revolving gantry cranes overlap so that coal can be transferred from one pile to another and, furthermore, the design shown can be partially built and extended from time to time without interfering with operation or without changing existing structures.

Ash Handling Equipment

It is proposed to dispense with all kinds of ash conveyors, which are at best troublesome. The ash hopper under each boiler will be of such capacity as to contain 12 or 24 hour storage so that ashes need be removed only once or twice during the day. The ash hoppers will empty directly into standard railroad cars which will be hauled by a storage battery locomotive.

Boilers

The boilers (shown in Figs. 2 and 3) will have a rating of some 1600 h.p. or 16,000 sq. ft. of heating surface. The exact rating, of course, will depend a great deal on the type of stoker selected, the type of boiler proposed, etc. The proposed separation of the two banks of tubes with the superheater in between is suggested for two reasons: First, to permit using a two-pass boiler and keep the economizers on the main floor, which means a greater number of tubes in height; second, to get a high amount of superheat without an excessive amount of superheat surface. The baffling of this boiler is simple. All of the heating surface should be effective, as there are no idle pockets, and the draft loss, because of the two passes instead of three, will probably be less in spite of the fact that the boilers may be several rows of tubes higher than the usual standard.

Four boilers per turbine are shown, but as there will be one spare turbine, there will naturally be four spare boilers, and some steam may have to be transmitted through the interconnecting steam header depending on which boilers are idle.

Stokers

The "extra long" underfeed stoker has been shown, as the grate area must be commensurate with the increased heating surface resulting from a very high boiler. In this case the demand for economy was prompted more by the high price of fuel than by the high load factor. Where the load is uniform the stokers must have a greater relative combustion area.

Blowers and Fans

With the use of economizers and preheaters induced draft fans will be necessary because of the increased draft loss and the low temperature of gas entering the stacks. These fans might be of the ordinary plate type, or possibly of the multi-vane type, because the temperature is low and the pressure comparatively high. In other words, with the introduction of preheaters in addition to economizers a more desirable fan

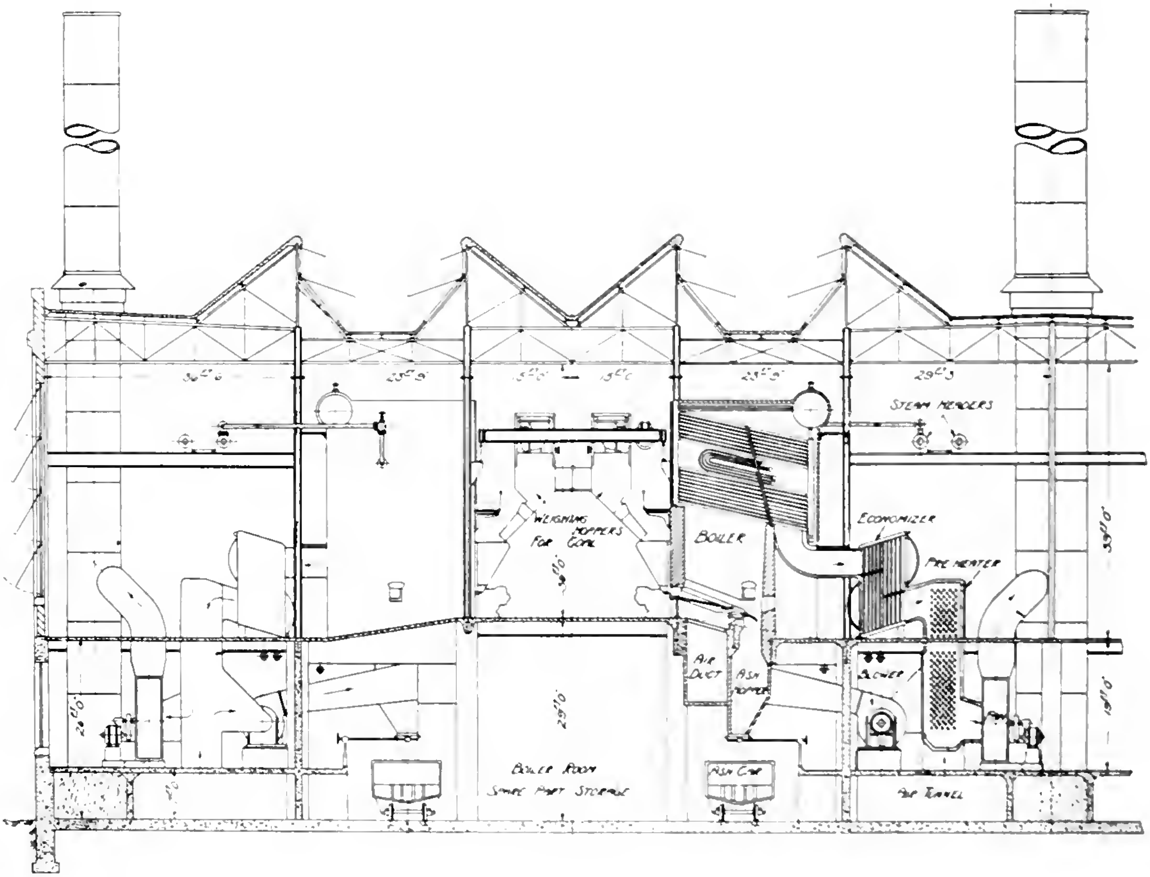


Fig. 2 Section of Boiler House

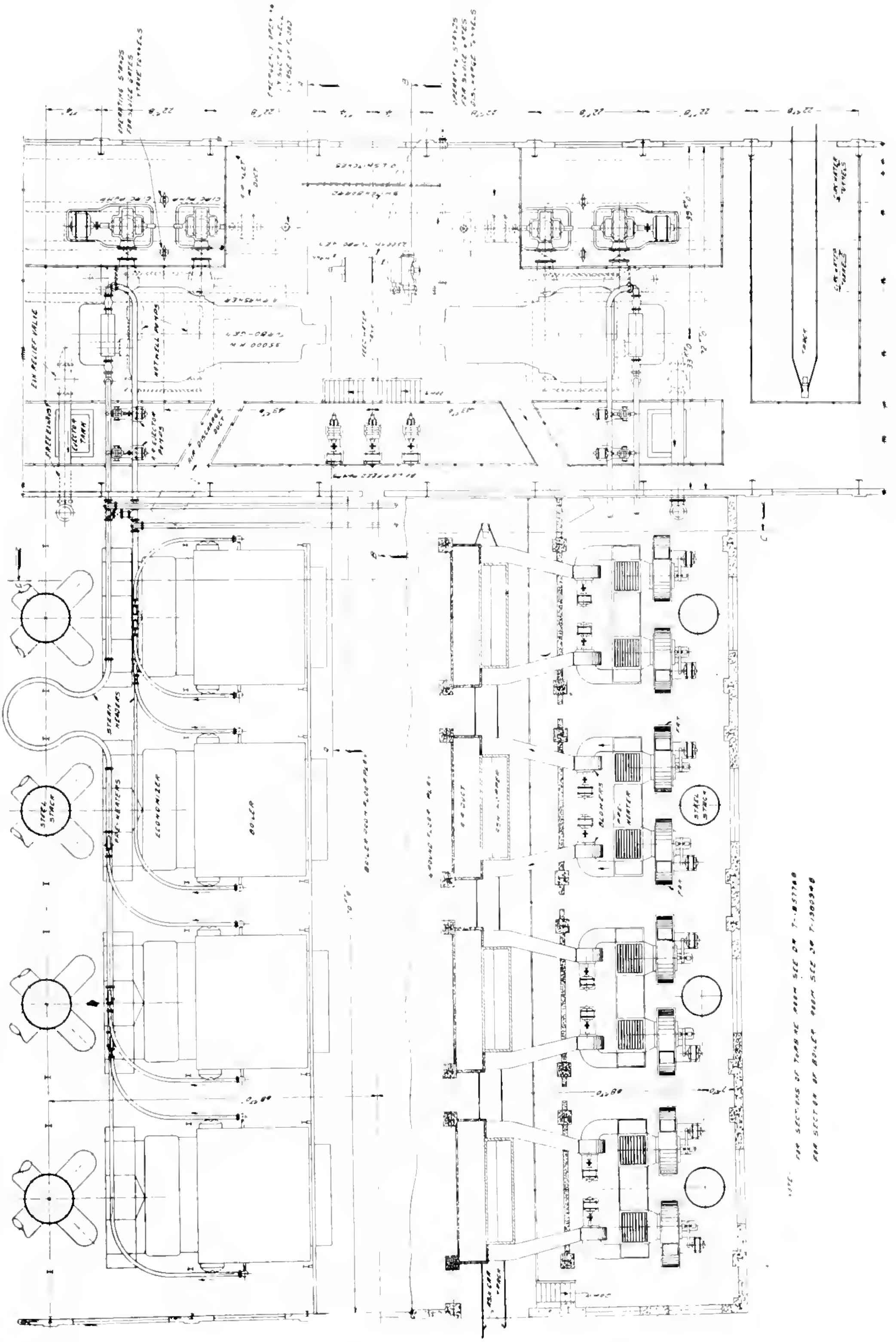


Fig. 3. Sectional Plan Showing Two Main Units and Their Complementary Boilers and Auxiliary Turbine

requirement for induced draft purposes is obtained than would be the case if the preheater or the economizer were omitted. However, the induction type of stack employing high pressure blowers may be substituted.

Both the induced draft fans and the stoker blowers are in duplicate for each boiler, although each would be of only half the maximum capacity required per boiler; thus, in event of failure of any fan or motor the boiler would be operated at a reasonably high rate with a possible slight reduction in the fan and blower efficiencies.

Economizers

Wrought tube economizers of the same construction as the boilers, that is, with headers inclined with relation to the tubes, are proposed. The economizers will be practically the same width as the boilers; thus, there will be no change in the sectional area of the flue connecting between the boiler and the economizers. The economizers will be cleaned with steam soot blowers instead of scrapers, and it is anticipated that there will be no moist soot deposit because the water entering the economizers will first be heated to 150 deg. or 160 deg. with exhaust steam, thus bringing the temperature well above the dew point of the gases.

Special attention is called to the natural thermo-siphon flow of water in both the vertical tubes and the headers, and the counter-current flow of the gases and the water in the economizers; also, to the convenience of piping the feed water from the headers in the basement through the economizers to the boiler drums.

To avoid internal corrosion of the wrought steel economizer tubes it is proposed to eliminate as completely as possible all air from the feed water either in the condenser or between that and the economizers.

Preheaters

The air from each turbo-generator is discharged into a duct leading from the generator room to the end of the boiler house. This is shown clearly in Fig. 3. The tunnel is shown in section in Fig. 2. The far end of this duct, being open to the atmosphere, gives a free discharge for the generators in case no blowers are in operation, and any air required for the boilers over and above that supplied by the generator will be taken in at this end. From this main duct the air passes through the heating tubes in each preheater, the preheater being divided into two units per boiler to make a more practical design. With this arrangement the boilers nearest to the turbine room will burn the heated air discharged from the generators, whereas the boilers at the far end will burn the air from outside.

Preheaters have not been in general use in stationary plants, although they have been applied for many years on board ships. It is believed, however, that they are perfectly practicable, and if the cost of coal is at all high, as in the case under consideration, they can undoubtedly be made to show a good return on the investment.

Piping

On account of the high pressure and high superheat involved, it is proposed to simplify the steam piping as much as possible so as to make the entire piping system more flexible and to reduce the serious consequences of a ruptured pipe or fitting. There are no steam headers in the general sense of the word, but there is an auxiliary header or, better named, a transfer header for equalizing pressures and transferring steam between boiler rooms. The omission of all steam-driven auxiliaries except the house or auxiliary turbines, of which there is one for every two main units, greatly simplifies the steam piping and materially reduces the cost of the plant.

The boiler feed piping would resemble in design the steam piping, inasmuch as there is a group of boiler feed pumps for each boiler room. This piping, therefore, can be segregated in a most advantageous manner and the sizes of the pipes kept very small.

Circulating Water Tunnels

Fig. 4 shows a cross section of the turbine room and below this the circulating water tunnels. The elevation and design of water tunnels depend upon the water level of the river, conditions and kind of soil on which the building rests, etc., and therefore would probably be modified for each locality. On account of the large size of these tunnels it appeared best to divide them into two parts. With two intake and two discharge tunnels they should by all means be arranged so that either one can be taken out of service for cleaning or for repairs. This statement applies most forcibly to the intake tunnels, which invariably fill up with sand or silt. Sluice gates have therefore been shown connecting between the intake tunnels and a center chamber formed by the two tunnels. There is one center chamber for each main

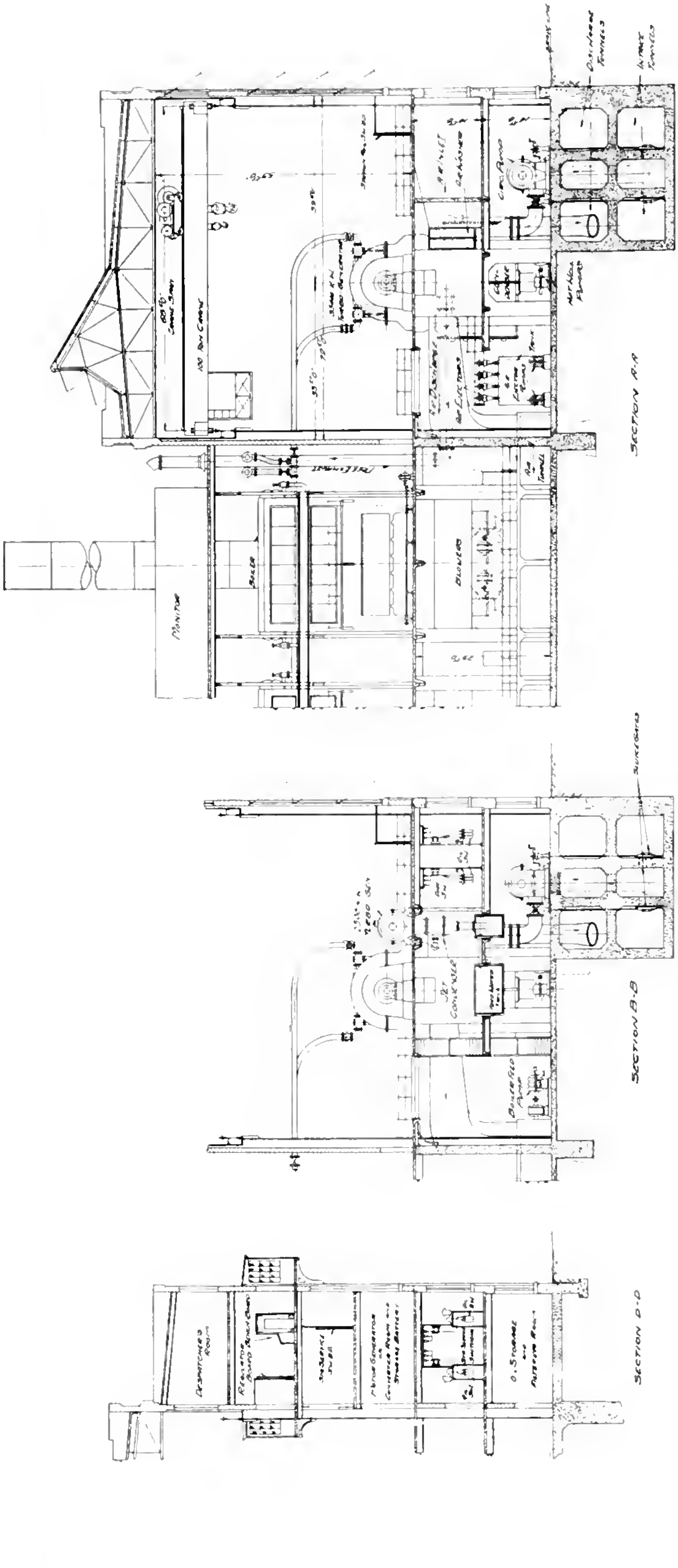


Fig. 4. Sections of Turbine Room and Operating Galleries

turbo-generator; thus, any one or all of the circulating pumps can get suction from either tunnel. In the event of a flood with the water entering the power station basement any one or all of the circulating pumps could pump this drainage by simply closing the sluice gates on both sides of any or all of these center chambers.

The discharge tunnels are connected together to reduce the head loss, but if found advisable these two tunnels might be provided with isolating sluice gates.

House Turbines

The very high steam temperature involved with 320-deg. F. superheat at 325-lb. gauge at the turbines practically precludes the use of any small steam-driven auxiliaries, such as boiler feed pumps, etc. Since the water in the boilers would be evaporated to a dangerous level in a very few minutes, were the boiler feed shut off, it is evidently necessary that a most reliable source of power be provided for the supply of boiler-feed water. The installation of low pressure boilers to operate the boiler feed pumps only might be considered, but this would have the disadvantage of defeating the unit-design of the plant, and unless this auxiliary supply were made of practically double capacity it would not give the necessary reliability. Further, the necessity for the use of some steam for the heating of the feed water would make a most complicated arrangement were the auxiliaries to be operated from a separate set of boilers and their exhaust used for heating the main feed water. Power for driving the feed pumps is not considered sufficiently reliable when supplied from the main busses.

In order to provide for a very reliable supply of power to drive all essential station auxiliaries electrically and thus obviate the necessity of employing many small turbines adapted to high pressure high superheat steam, it is proposed to use one 2500-kw. auxiliary or house turbine for each pair of main turbines. Such a unit can be admirably adapted to the steam conditions contemplated and will have sufficient capacity to supply all such auxiliaries as boiler feed pumps, stoker blowers, stoker drive, induced draft fans, and condenser auxiliaries.

Each house turbine will be provided with a low jet condenser which will normally produce about fifteen inches of vacuum. The circulating water for this condenser is the condensate from the main units. It is proposed to make this condenser design such that the discharge water would have a temperature as close as possible to the temperature corresponding to the vacuum. Of course, any vacuum desired can be maintained, but where there are economizers in the station it is most economical to heat the feed water up to 150 deg. F. or 170 deg. F. by reducing to a minimum the steam consumption of the house turbine.

The auxiliary power and therefore the load on the house turbo-generator will not be proportional to the load on the main units; consequently, with a fluctuating quantity of circulating water the vacuum will tend to vary through quite a wide range. It is therefore intended that the house alternator be paralleled with the main bus so that a portion of the auxiliary load can be shifted automatically or manually from the house alternator to the main alternators to maintain a constant vacuum under all conditions. This electrical interconnection would be so made that a drop in potential or a lowering of the frequency, due to disturbances on the main system, would automatically disconnect the two and keep the auxiliaries connected to the house alternators.

In order to provide for a constant flow of water through the condenser of the house turbine, some of the water may be recirculated. In other words, if a condenser is designed for a quantity of water equivalent to $^3/_4$ load on two main units and only one main unit is in operation, the circulating pump for the house turbine condenser would recirculate half of the water. This condenser obviously serves as a feed water heater. The tank shown just in front of the condenser (Fig. 4), is a storage or surge tank for the boiler feed supply. This performs an important function because it is impossible to feed the boilers at the same rate as the condensate is being returned from the main condensers. This surge tank therefore equalizes the discrepancy and prevents overflowing of hot distilled water and the use of excessive cold, raw, or treated water. There is not space here to dwell upon all of the merits of a house turbine condenser.

Main Condensers

There is little to be said in connection with the main condensers because they are of ordinary standard design, each being supplied with two circulating pumps, two hot well pumps, and two air pumps. The hot well pumps are each of full capacity. The others are of half the maximum capacity. It is expected that with a reasonably tight condenser system only one air pump will have to be operated at a time and in case of very cold water one circulating pump will be sufficient. It should be borne in mind that one circulating pump may give 60 per cent to 70 per cent of the capacity of two pumps due to the reduction in condenser and pipe friction resulting from the reduced flow of water.

The condensers will be mounted on springs to take care of expansion and to avoid introduction of an expensive and undesirable expansion joint between the turbine and the condenser.

Auxiliary Power Supply

All of the power supply for the more or less non-essential auxiliaries, such as cranes, coal larries, conveyors, lighting, miscellaneous pumps, etc., will be from transformers connected to the main bus and supplied through a switchboard located in the first gallery. All of the essential auxiliaries, such as condenser pumps, feed pumps, blowers, etc., will be controlled from switchboards located on the main turbine room floor at each auxiliary turbine. The operator at the switchboard will have immediate control of all of the turbine room auxiliaries within his vision and the control of the supply of power to all of the boiler room auxiliaries supplying that particular section of the turbine room; thus, there will be four switchboard operators on the turbine room floor in addition to the main switchboard operators in the galleries.

Electrical Design

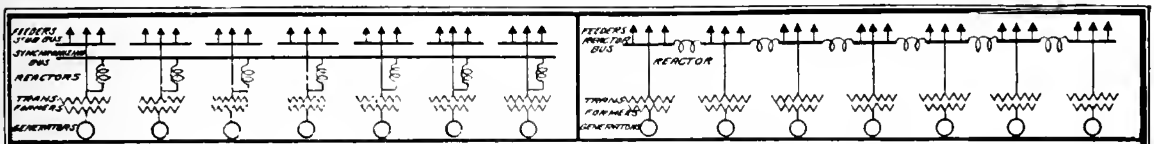
The first consideration in the electrical design is the determination of the fundamental connections between the generators, busses and feeders, that is, the "backbone" of the system under normal conditions. This is influenced by many conditions, chief of which in a large station is the concentration of power which it is considered advisable to allow at short circuit. If this limit is very high the rupturing capacity of switches available must be considered, and in any case the value of simplicity of arrangement must be balanced against the greater cost of switches to handle heavier short circuits. On the other hand, if the use of the largest switches available is not considered, the value of protective apparatus to reduce short circuit intensities must be balanced against the reduction in cost of switches.

In this particular case one of the specified conditions was distribution by means of 66,000-volt underground single conductor cables. It was decided that the concentration of energy in a short circuit on these cables should be limited to 500,000 kv-a. on account of the possible resulting damage to adjacent cables. Comparing this with the rupturing capacity of available 66,000-volt oil switches showed that a switch having a rupturing capacity of 583,000 kv-a. would best suit the service.

At this point it should be noted that the capacity of a generator is practically equal to the capacity of a transformer bank and that one feeder working at full capacity would distribute the entire load of a generator and transformer bank.

Use of Reactors

Preliminary calculations proved the necessity of sectionalizing the station bus by reactors in order to approach the 500,000-kv-a. limit which had been set. Both low tension and high tension busses were considered, but the use of a low tension bus was not only found unnecessary but it made the problem much more difficult. The reactance of the transformers added directly to the generators before either were connected to the bus would assist in reducing the short circuit intensities very considerably. Many arrangements of busses and reactors can be considered, but if sufficiently simple for practical operation all are reduced fundamentally to the two forms shown in Fig. 5. The objection may be raised that a ring bus is not shown. Obviously a ring bus would not change the



GENERATORS: 43,750 KVA, .8 P.F. 35,000 KW
TRANSFORMERS. 45,000 KVA
REACTORS: 45,000 KVA

REACTANCE			INSTANTANEOUS SHORT-CIRCUIT ON A FEEDER
TRANSFORMERS	GENERATORS	REACTORS	
8%	28.5%	10%	367,000 KVA
		5%	487,000 KVA
	18.0%	10%	441,000 KVA
		7.5%	494,000 KVA
		5%	598,000 KVA
	15%	10%	472,000 KVA
		9%	435,000 KVA
		8%	523,000 KVA
	12.3%	11%	485,000 KVA
		10%	505,000 KVA

REACTANCE			INSTANTANEOUS SHORT-CIRCUIT ON A FEEDER
TRANSFORMERS	GENERATORS	REACTORS	
8%	28.5%	10%	450,000 KVA
		5%	604,000 KVA
	18.0%	13%	497,000 KVA
		12%	513,000 KVA
		10%	552,000 KVA
	15%	16%	490,000 KVA
		15%	504,000 KVA
		10%	621,000 KVA
	12.3%	19%	493,000 KVA
		18%	504,000 KVA
		10%	640,000 KVA

Fig. 5. Comparison of Different Methods of Using Reactors

diagram shown at the left. Consider a short circuit on a feeder supplied from the central section of the bus in the diagram at the right. It is evident that one generator supplies current directly to this and that the three generators on each side contribute equally. Therefore no connection, either directly or with reactors between the two ends of the bus, would change the short circuit intensity in this case. But such a connection would, however, make each feeder in turn a "center" feeder, whereas in the diagram shown the short circuit intensities on the end feeders would be considerably smaller than on the center. Thus if a center feeder is considered in the calculations the results will be good whether the bus is made in a ring or not, and the connection in a ring can later be decided from the point of view of flexibility. The above is true for an odd number of machines; were there an even number of machines the short circuit intensity would be increased slightly by forming the bus in a ring.

The tables given in the lower half of Fig. 5 show all of the different conditions assumed. The transformers in any case would have a reactance of 8 per cent and it would not appear to be advisable to consider increasing this value. The generators would have a minimum reactance of 12.3 per cent, and under certain peculiar conditions this might be increased to 28.5 per cent. Therefore, the calculations were carried through for various values of generator reactance. Inspection of the table shows the minimum size reactor which could be used in connection with any generator reactance in order to limit the short circuit intensity to approximately 500,000 kv-a. This reveals the fact that the synchronizing bus shown on the left side of the figure is necessary in order to limit the reactors to a reasonable size. The reactors should be rated to carry the total output of a generator.

Detail Arrangement of Busses and Switches

Having decided on the fundamentals of the electrical system, the other features can now be considered. These include arrangement of switches to give the necessary flexibility and reliability; the location of transformers, reactors, switch gear and high tension busses indoors or outdoors; arrangement or location of main benchboard for visibility of turbine room and outdoor switch gear; provision for station auxiliary power.

All of these subjects have to be considered in turn and their effect on each other considered in order to arrive at the final conclusion. Their relation to the mechanical section of the station is also involved. It was desired to keep a unit arrangement right through the station, and this meant that the switch gear for each generator and its group of feeders should not occupy more length than would be required for the corresponding mechanical equipment of generator and boilers. Fortunately these all work together very well and allow enough space on each generator stub-bus for the feeders required.

Main Bus Arrangement

The calculations considered above showed the use of reactors to be necessary, and also the fundamental arrangement which should be used. Fig. 6 shows the final complete solution. The neutral point of each generator will be grounded directly and positively. Since there is no low tension bus, grounding of all generators cannot cause circulating harmonic currents between the generators. The main leads of each generator are connected directly to the corresponding transformer bank and through a main oil switch to a stub-bus.

The transformer connection is delta on the low tension side and Y grounded on the high tension side. It is particularly necessary that the ground resistance be made very low so that in case of short circuit on one of the single conductor cables the neutral may not be distorted, thus placing an increased voltage stress on all of the cables of the other phases.

From each generator stub-bus three connections are made; one through the reactor to the synchronizing bus and the other two to double feeder stub-busses. The three selector switches connecting to the busses are non-automatic. The main switch is arranged for automatic opening in case of internal failure in the generator or transformer. This is accomplished by the use of relays differentially connected around the generator and around the transformer bank. Oil switches are shown for breaking the synchronizing bus at two points so that a section may be readily cleared for cleaning, extension or repairs. The stub-busses are also arranged to be connected together so that at times of light load a small number of generators may carry the load of the whole station without feeding through the reactors. Referring to Fig. 6: connection between the stub-busses in the lower line is provided for by oil switches, and in the upper line by horn-type air-break switches. The oil switches would be operated

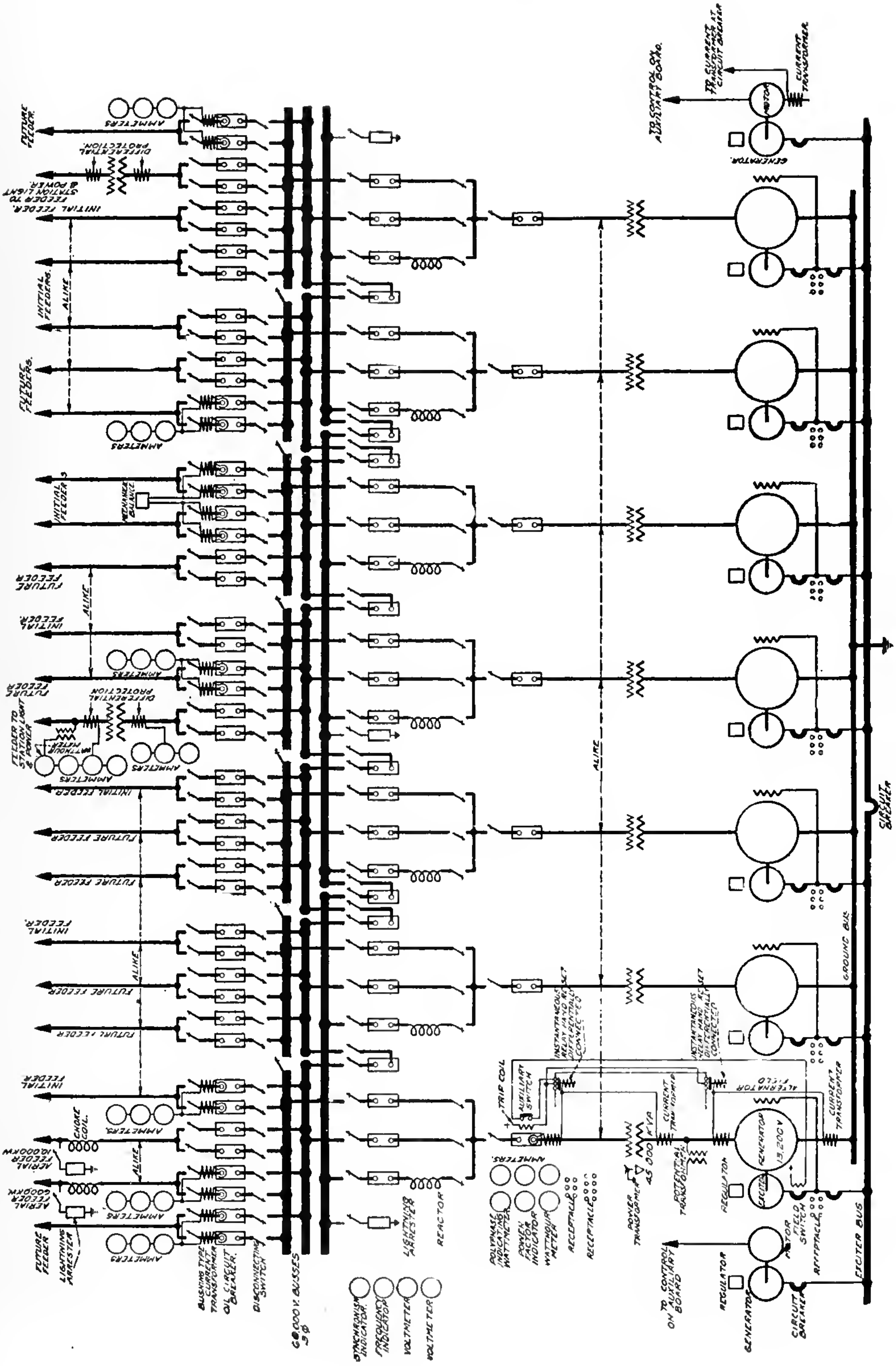


Fig. 6. Main Single Line Wiring Diagram

from the main bench board and the air break switches locally by hand through permanent levers.

Each feeder is equipped with two oil switches to select either one of the two stub-busses. Each would be equipped with induction type overload or other suitable type of relay, depending on the detail connection and interconnection of the distribution system.

It is thus seen that a very complete and flexible arrangement is provided. Normally, the generators are operated in parallel through the reactors and synchronizing bus, but it is possible by proper interconnection of the feeder stub-busses to transfer loads from one generator to another in almost any manner desired.

Excitation

Each generator will have a direct-connected exciter controlled by a TA automatic regulator. With this method no main field rheostat is necessary. The exciter will be provided with a field rheostat. For emergency excitation two motor-generator sets are proposed, supplying a sectionalized bus. These spare exciters will also be provided with automatic regulators. The motors driving the exciters will be supplied from the main station power board but will be controlled from the main auxiliary board opposite the bench board. Indicating lamps on the power board will show the position of the switches so that there may be no danger of the operator of the station power board pulling disconnecting switches or otherwise interrupting service to a motor-generator exciter set while in operation.

Bench Board

For the control of the apparatus shown in Fig. 6, the bench board shown in Fig. 7 is

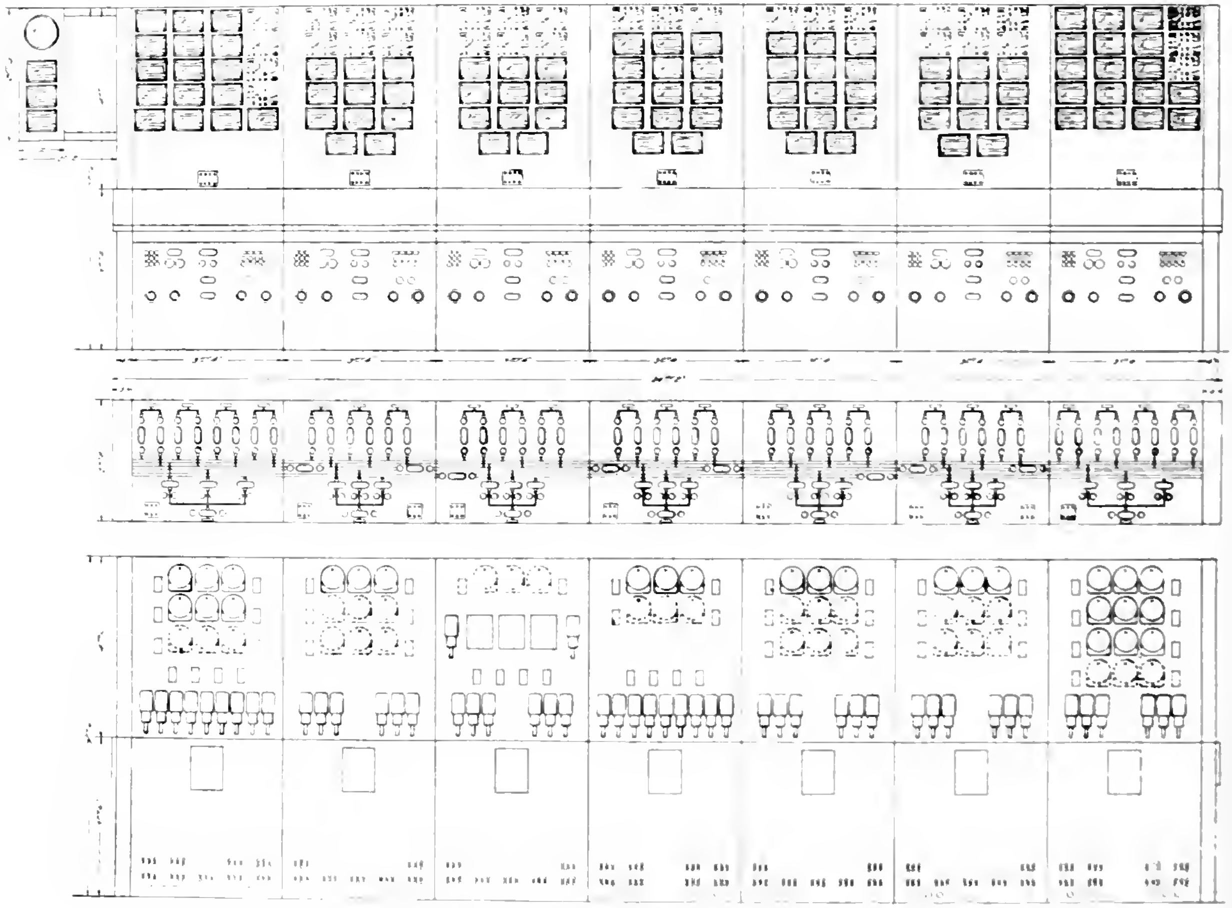


Fig. 7 Main Bench Board for Control of Main Generators, Transformers and Feeders Above: Front View Center: Plan of Bench Showing Mimic Bus Below: Back View

proposed. This shows the front view, the plan of the bench with the mimic busses, and the rear view. Opposite to this would be placed a vertical auxiliary board on which would be mounted the automatic regulators and field control switches.

Auxiliary Power Supply

As previously outlined, it was determined that turbines for auxiliary power would be necessary and that these should be connected with the main busses through a central auxiliary switchboard and transformers. A detailed study showed that one auxiliary turbine could best be used in connection with two main turbines and that these auxiliary units should be rated at 2500 kw., 0.7 p-f., 3570 kv-a.

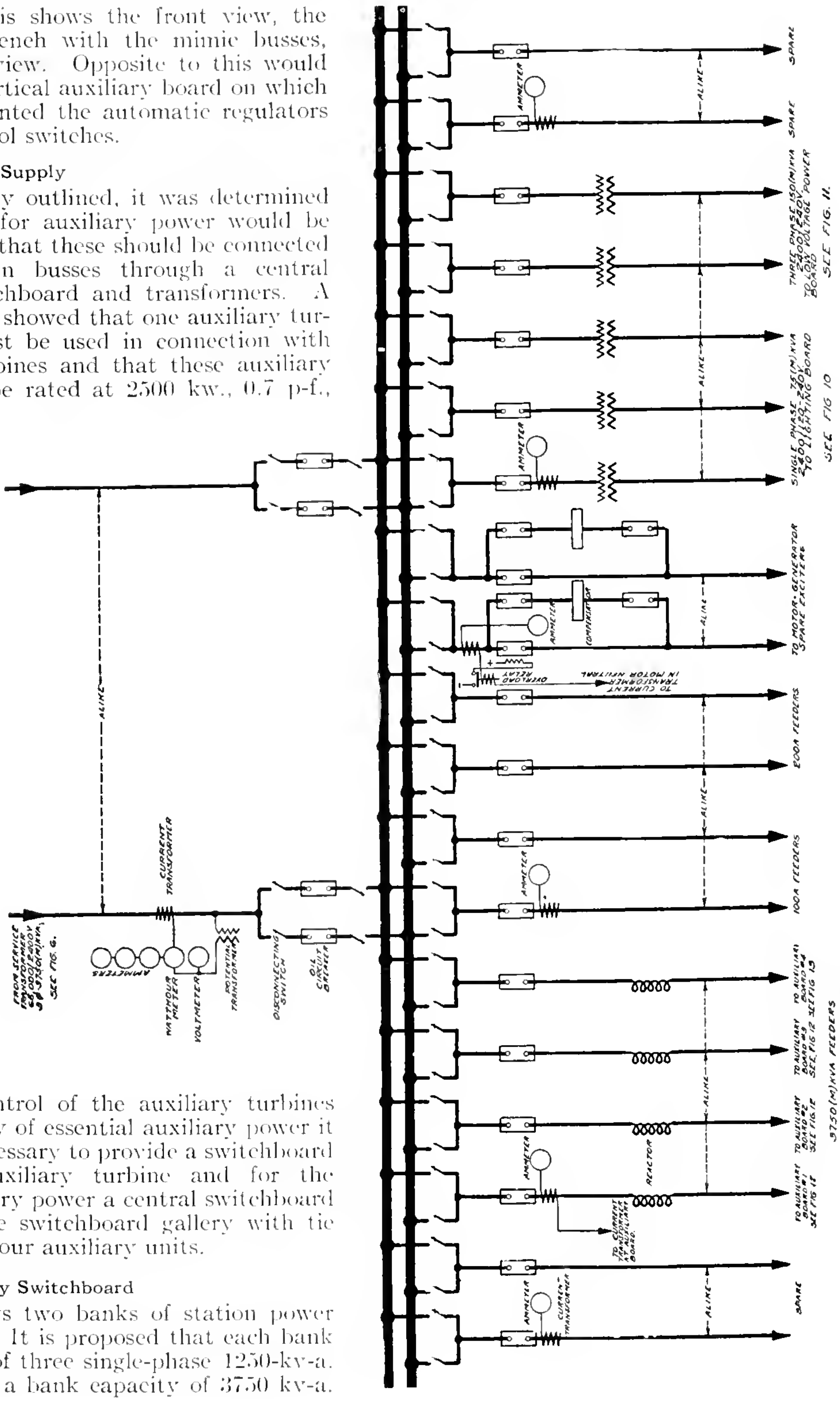


Fig. 8. Single Line Wiring Diagram of Central Auxiliary Power Switchboard

For the control of the auxiliary turbines and the supply of essential auxiliary power it was found necessary to provide a switchboard near each auxiliary turbine and for the general auxiliary power a central switchboard located on the switchboard gallery with tie cables to the four auxiliary units.

Central Auxiliary Switchboard

Fig. 6 shows two banks of station power transformers. It is proposed that each bank be composed of three single-phase 1250-kv-a. units, making a bank capacity of 3750 kv-a.

connected delta-delta. These transformers would be located out of doors. The high tension switches would be controlled from the main bench board and the low tension switches from the auxiliary power board.

Fig. 8 shows a single line diagram for the central auxiliary power board. The reactance of the auxiliary transformers must be considered in connection with the reactance of the main units in order to limit the concentration of energy on the station power bus to a value which can be handled by reasonably small switches. Reactors are required in each of the four feeders connecting to the turbine auxiliary switchboards to limit the short circuit intensity and permit the use of small rupturing capacity switches. It is proposed that these tie feeders to the turbine auxiliary boards be protected by differential relays connected to current transformers at each end of each line. In case of trouble on a cable it will be automatically disconnected and will allow the auxiliary turbine to continue supplying the essential auxiliaries without interruption. Reverse energy protection at the turbine auxiliary boards is also provided so that in case of a severe drop in voltage or frequency on the main system, the auxiliary turbines will be automatically disconnected and allowed to run independently, carrying the essential auxiliaries.

Other feeders are shown for the supply of the pumps for the transformer cooling water, coal handling apparatus, spare exciters, station lighting and low voltage power. The central auxiliary board would be a vertical board with mimic busses and electrically operated remote control oil switches, as shown in Fig. 9.

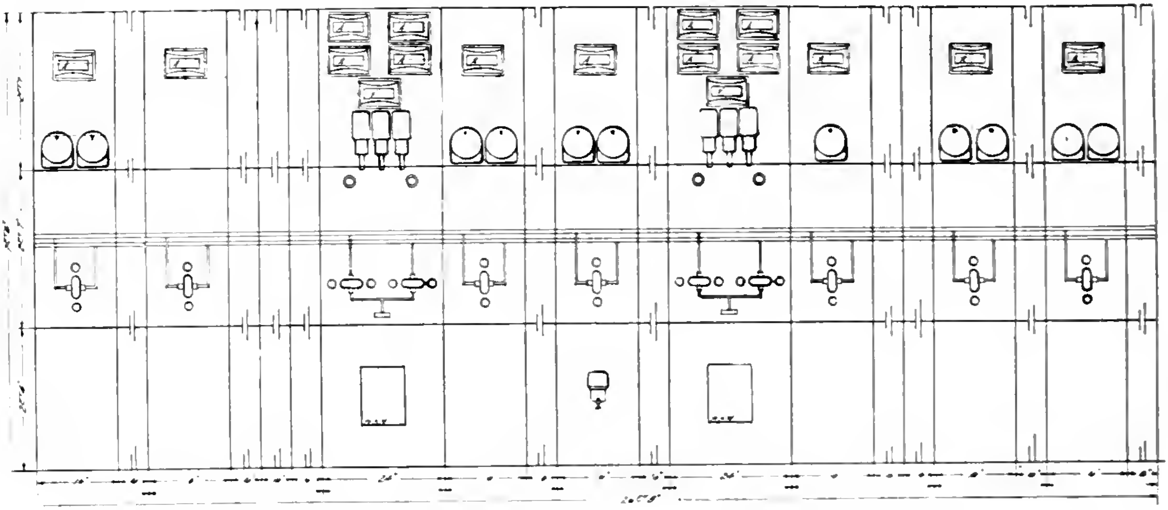


Fig. 9 Front View of Central Auxiliary Vertical Control Board

Station Lighting and Low-voltage Power Supply

Fig. 10 shows a single line wiring diagram of the lighting system proposed. Three 75-kw. single-phase transformers controlled independently and connected for 3-wire, 115 230 volts would form the supply. It is proposed that all lighting feeders be 3-wire, 115 230 volts, and be arranged in three groups which will normally operate on different transformers, but which in case of failure of a transformer can be manually thrown to one of the other transformers. Fig. 10 also shows a connection from the 125-volt d-c. board, which will control the storage battery for circuit breaker control, so that in case of failure of service on the a-c. lighting system certain emergency lights will be automatically connected to the battery.

Fig. 11 is a single line diagram of the low voltage power board, supplied by two 150-kv-a. transformer banks and operating at 240 volts, 3-phase. This board is arranged for miscellaneous power supply, such as the machine shop, turbine room cranes, house supply pumps, etc.; also for the supply of motor-generator sets for charging the storage battery and a spare motor-generator exciter set for the auxiliary turbines.

Fig. 11 also shows the storage battery proposed and the control circuits for operating the oil switches.

Turbine Auxiliary Boards

Fig. 12 gives a single line diagram of boards proposed for Nos. 1, 2 and 3 auxiliary turbines, each of which will operate in connection with two main units. Fig. 13 is a single line diagram for board for No. 4 auxiliary turbine, which will operate in connection with a single main unit. Each auxiliary generator is to be protected differentially just like the main generators. The tie tothe central auxiliary power board has been previously discussed.

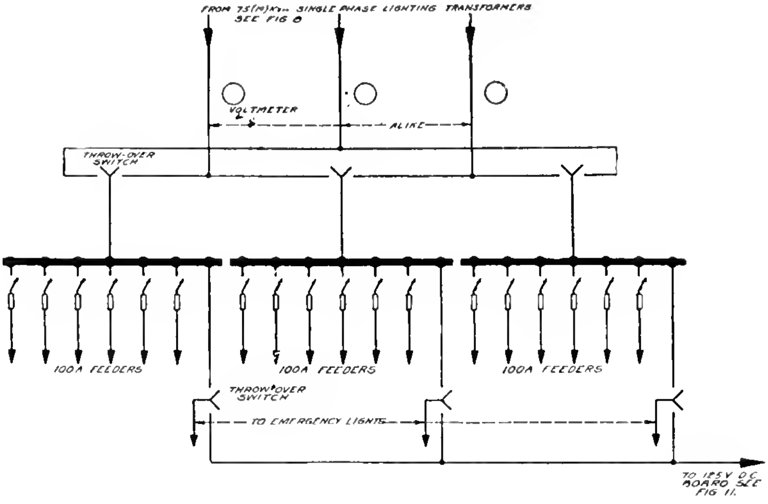


Fig 10. Single Line Wiring Diagram of Station Lighting System

Two circuits are provided for the blowers and fans for each set of four boilers. As each boiler has two blowers and two fans, one of each would be connected to each circuit. This should insure the operation of at least half of them, which would allow the boilers to operate at a high percentage of their rating at all times.

Since stoker motors are of small size, it is proposed to install two transformer banks, each consisting of three 37.5-kv-a. single-phase transformers to supply them. A double circuit arrangement quite similar to that proposed for the blowers and fans is suggested with a double-throw switch at each stoker motor.

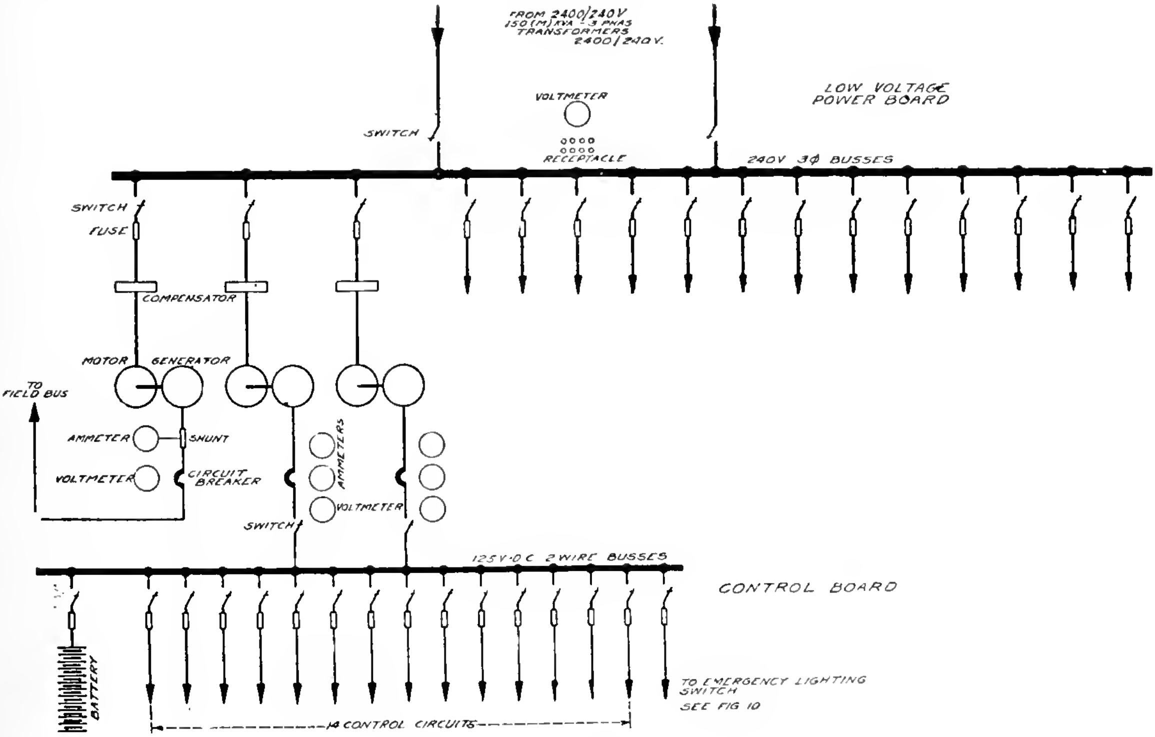


Fig. 11. Single Line Wiring Diagram of Low Voltage Power Board and Direct Current Control Board

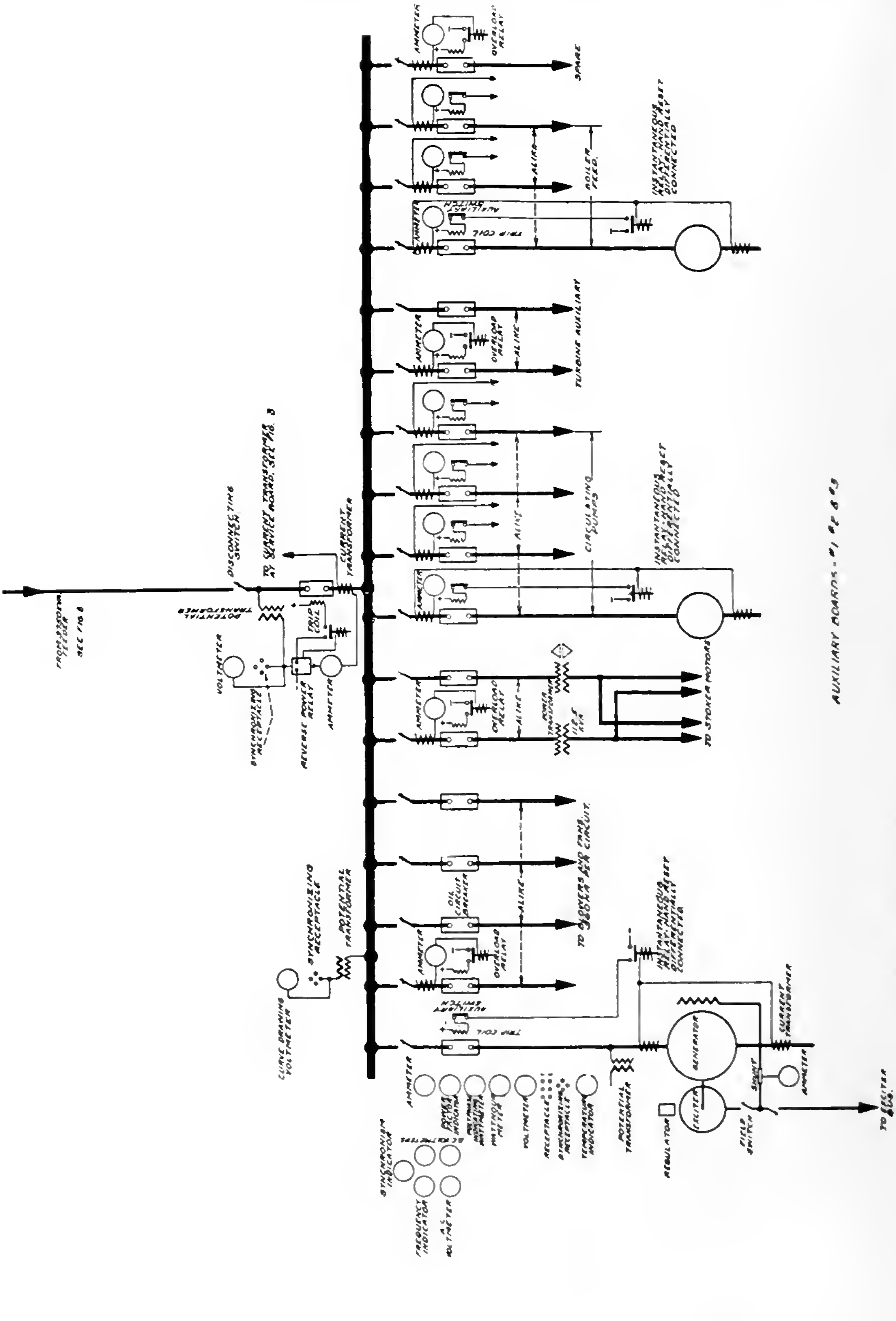


Fig. 12. Single Line Wiring Diagram of Switchboard for Auxiliary Turbo-generators Nos. 1, 2 and 3

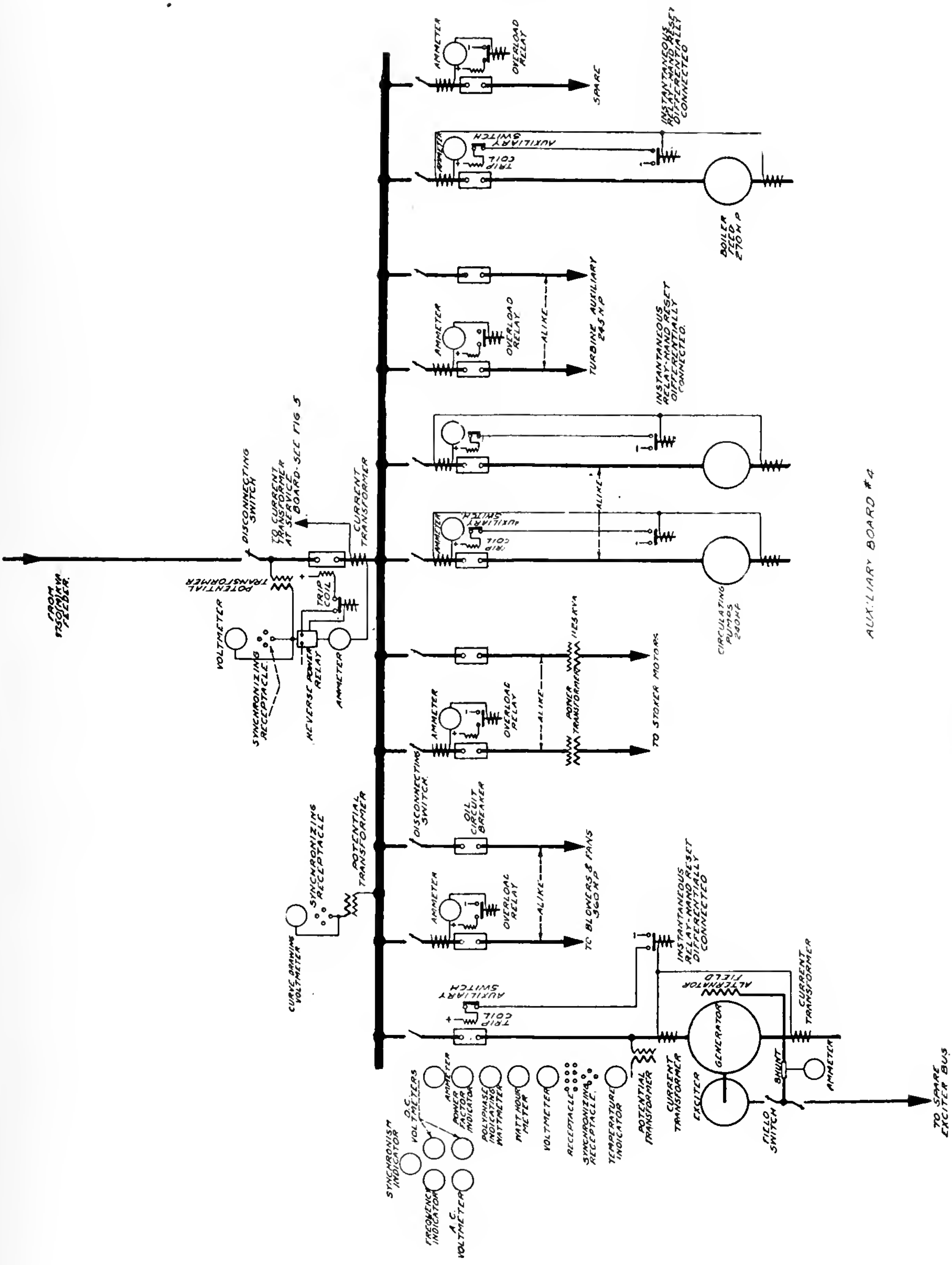


Fig. 13. Single Line Wiring Diagram of Switchboard for Auxiliary Turbo-generator No. 4

It is proposed that the circulating pumps be driven by 2300-volt motors with the neutral brought out for differential protection and that this protection be provided from the oil switch on the switchboard to the neutral in the motor, thus also including the cable supplying the motor. This system will insure the operation of the circulating pump motors under all conditions of voltage and frequency fluctuation. For the various other auxiliaries for the turbines, two circuits are proposed with overload protection, the individual auxiliaries to be provided with no overload protection. For the smallest auxiliaries a lower voltage will probably be necessary and it is suggested that adjacent to these auxiliaries for each turbine a bank of transformers be installed for stepping down to 240 volts.

It is proposed that boiler feed pump motors be made for 2300 volts and protected differentially, including their cables, in a manner exactly similar to that employed for the circulating pumps, so that as long as there is any power, either from the main bus or from the auxiliary turbine, it will be possible to maintain feed to the boilers.

Boiler Room Auxiliaries

It is to be noted in the proposals above that complete alternating current drive has been provided for the boiler room. Some of the most recent installations have adopted this method.

Elimination of apparatus for conversion from a-c. to d-c. should increase the reliability. For the blowers and fans, brush-

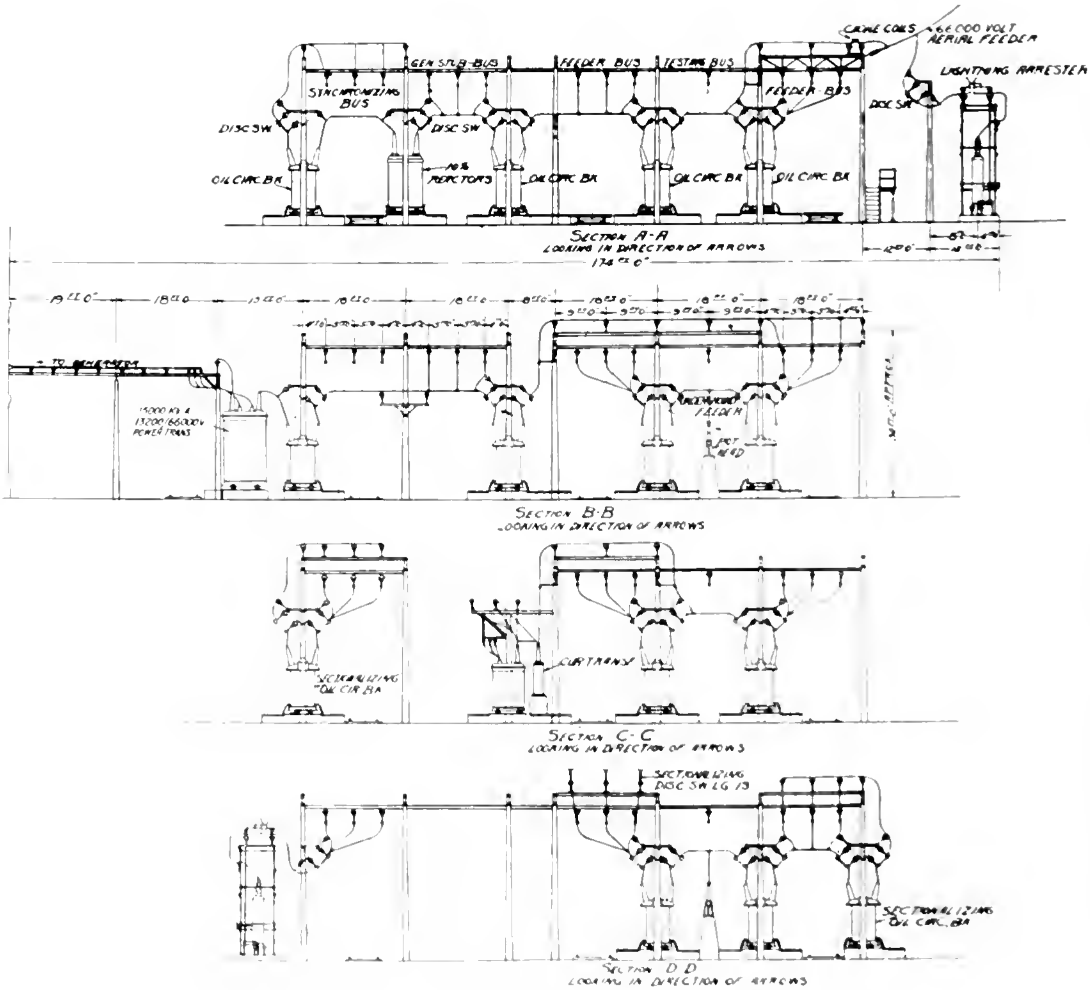


Fig. 14 Various Sections of 66,000-volt Outdoor Switch Gear

shifting motors are suggested. For the stokers, four-speed multi-speed motors are suggested, and if a stoker with mechanical arrangements for two speeds is used, six speeds of the stoker may actually be obtained.

If it were decided that direct current for the stoker motors is necessary, it is suggested that two synchronous converters be installed in connection with the main power board, and that duplicate feeders be run to each of the auxiliary boards for supplying the stokers at 230 volts. If direct current is necessary for all of the boiler room auxiliaries, a synchronous converter could be installed in connection with each auxiliary turbine and one spare converter in connection with the main power board and connected to the others by emergency feeders. This system would also supply 230 volts at the motors

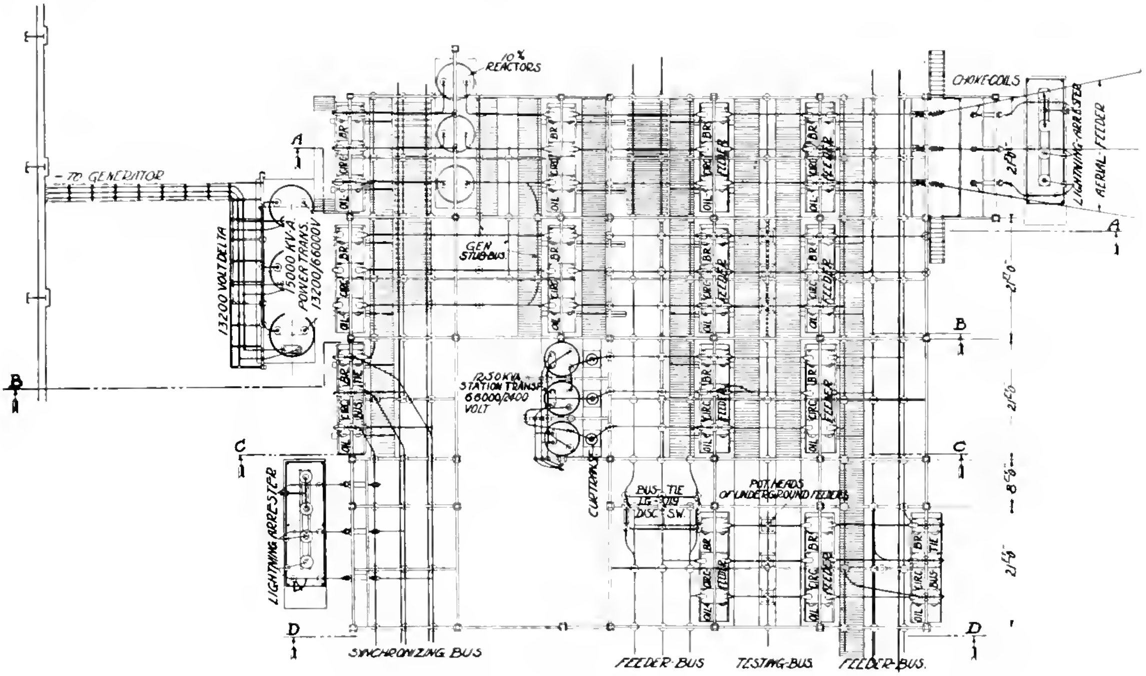


Fig. 15. Plan of Unit Section of 66,000-volt Outdoor Switch Gear

Arrangement of Electrical Apparatus

Fig. 1 is a general layout of the whole station, showing the main generators, and alongside of each pair the auxiliary turbine generator. It shows the extension to center of the building to provide operating galleries for the benchboard, main auxiliary board, etc. The general arrangement of the busses and switching apparatus outside is also shown.

Fig. 3 shows the main and auxiliary units in greater detail, and also shows the location of the auxiliary board adjacent to the auxiliary unit. These points are again shown in Fig. 4, which is a section of the turbine room. This figure also shows a section of the galleries. At the top there is a space reserved for a load despatcher's room. Below this are the main bench board, station service board, switches, transformers, etc.

Figs. 14 and 15 show the outdoor station in greater detail. Fig. 15 shows the section corresponding to one generator and the characteristic arrangement for an overhead feeder, an underground feeder, station service transformers, and tie to the next section of each bus. Fig. 14 shows sections through the outdoor structures at these various points.

Reactors

The reactors to be used are of particular interest on account of the high voltage and use out of doors. For these reasons an oil-cooled type of reactor is recommended. This consists practically of a set of transformer coils of the proper number of turns and current capacity, arranged and held just as they would be in a transformer, except that the iron core is omitted. Such units would be water-cooled like transformers, but the quantity of water required would be comparatively small.

Test Bus

The high voltage of the cables proposed necessitates particular arrangements for testing them on installation and after repairs. Also, it is considered that it would be better practice to test any cable before it is put back in service, after the switch controlling it has opened automatically. This means that arrangements must be made for making quick tests. To accomplish this a testing set is to be placed in one of the galleries and from this a connection made to the test bus outdoors, shown in Fig. 15. Disconnecting switches are located at convenient points along this test bus so that flexible cables can be carried easily from one of them to the cable to be tested. This arrangement, considered in connection with the fact that the operator can view the whole switch yard, should make testing of cables and restoration of service most expeditious.

Outdoor Structures

The outdoor structure has been planned with a view to greatest convenience of operation, low maintenance cost and low first cost. Figs. 14 and 15 show the structure in sectional plan. It is proposed to use concrete poles with structural steel members connecting them at the top. This design results in a very rigid structure from which the wiring is supported at frequent intervals. The breaking of an insulator will not result in dropping a bus or a connection and such insulator can be replaced with the greatest facility. The few structural steel members will not require frequent painting. To provide for reaching the disconnecting switches easily a plank walk raised slightly above the ground is proposed. This will make it possible to reach all of the disconnecting switches with a standard insulated switch hook, and it can easily be kept free from snow and ice in the winter.

Railroad tracks are run through the various aisles to facilitate the removal of transformers and switches. In this connection it is to be noted that the switches are also to be provided with trucks similar to transformer trucks, so that a whole switch may easily be slid out from its position and taken to the repair shop in the station. To facilitate inspection of switches it is planned to have a truck equipped with an oil tank, a blower and a pump so that any switch requiring inspection may be quickly emptied and the oil fumes blown out of the tanks.

Conclusion

While it is stated in the introduction that this station was designed to meet certain specified conditions, it is felt that the design described is such as to be very generally applicable. This is important for local conditions, as any plant may change slightly from time to time, and the more flexible and generally adaptable the arrangement the better able it will be to meet any slight change in conditions. This same point also has the advantage, when combined with unit arrangement as in this case, of making the design applicable to other changes in details such as higher transmission voltage, and in general, for the conditions of almost any other location requiring such a large station.

Some Corona Loss Tests

By W. W. Lewis

Power and Mining Engineering Department, General Electric Company

This article records the results of corona loss tests on a 150-mile transmission line at potentials up to about 200,000 volts. Comparison is also made between measured and calculated losses. Such tests establish confidence in our formulas for calculating these losses and are especially apropos at this time in view of the current discussion of operating voltages in the neighborhood of 220,000 volts. The extremely high losses found in some of the tests are evidence of the economic importance of such tests.—Editor.

The theory of corona formation and formulas for its calculation on transmission lines have been fully and carefully worked out by Peek.* It is interesting, occasionally, to measure these losses on an operating system and to compare the measurements with the calculated losses.

Many existing systems, especially among the earlier installations, have considerable corona loss at the operating voltage. It is now generally recognized that this loss costs money, and the later installations are usually designed to operate above the corona voltage.

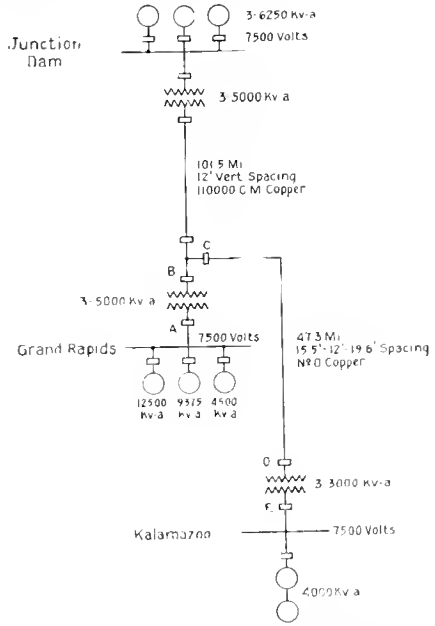


Fig. 1. One-line Diagram of Consumers Power Co. Transmission Line Used in the Tests

Some corona loss tests were recently made on the 30-cycle 140,000-volt system of the Consumers Power Co., in western Michigan. It is believed that these tests were carried to a higher voltage than has been heretofore attained on an actual transmission system, and in view of the present discussion of 220 kv. or thereabouts as the possible next step above the present voltage limits, these tests should be of interest, as they were carried up somewhere in the neighborhood of that voltage.

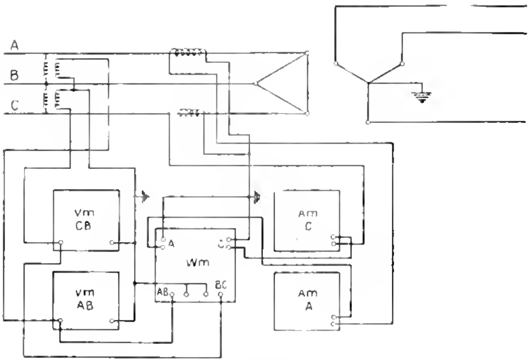


Fig. 2. Connection Diagram of Instruments Employed in the Tests

The transmission line on which the tests were made extends from Junction Dam to Grand Rapids and Kalamazoo, Michigan, in a direction almost due south, a total distance of approximately 150 miles (Fig. 1). The portion from Junction Dam to Grand Rapids consists of three conductors, each of seven strands medium hard drawn copper, total cross-section 110,000 cir. mil. The conductors are spaced practically in a vertical plane 12 feet apart. The distance is 101.5 miles. This line has been in service about two years. The portion from Grand Rapids to Kalamazoo is older and operated for a number of years at 70,000 volts. It consists of 47.3 miles of No. 0 copper arranged mainly in a triangle with sides, respectively, 15.5, 12, and 19.6 feet. The line throughout is insulated with 10 disks in suspension and 12 on strain. The tower spacing is about 530 feet. The height of the lowest conductor in the vertical arrangement is about 40 feet at the tower and about

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* Trans. A.I.E.E., 1911, 1912, 1913.

26 feet at the middle of the span. The average elevation of the line is about 750 feet above sea level.

Switches marked *A* and *E*, Fig. 1, were open throughout the tests, thus separating the transmission line from the Grand Rapids and Kalamazoo busses. Switches *B*, *C*, and

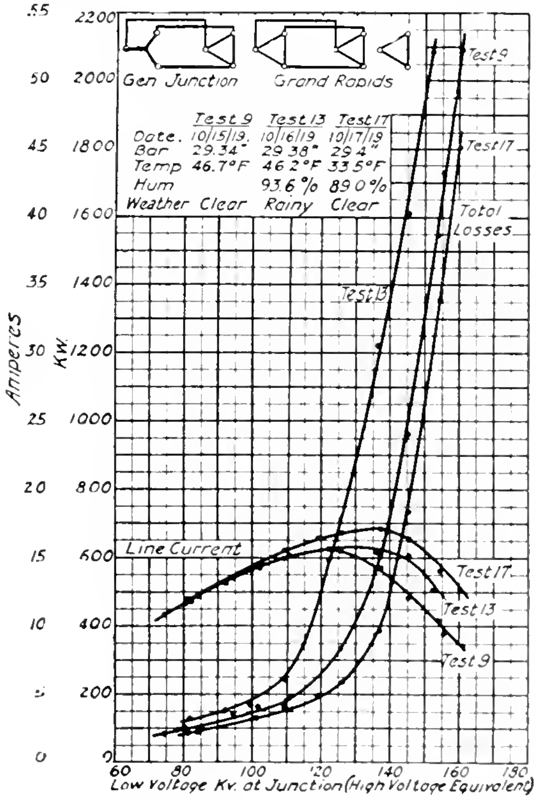


Fig. 3. Corona Loss, Line from Junction Dam to Grand Rapids. Transformers on at Grand Rapids

Junction Dam transformer ratio 135,000:7500.
Grand Rapids transformer ratio (Tests 9 and 13) 125,000: 7500.
Grand Rapids transformer ratio (Test 17) 140,000:7500.

TABLE I

TEST 9			TEST 13			TEST 17		
H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp	Kw.	H.V. Kv.	H.V. Amp.	Kw.
74.6	10.8	84	82.0	11.8	125	81.6	11.8	87
80.7	11.7	101	92.4	13.2	151	84.3	12.2	87
94.6	13.5	142	99.8	14.7	168	101.3	14.6	131
102.0	14.3	162	109.6	15.0	247	109.6	15.6	166
111.0	15.2	188	122.3	15.7	594	119.2	16.5	192
126.0	15.5	336	136.5	15.4	1225	126.0	16.8	235
137.5	14.3	605	145.3	15.2	1610	137.2	17.1	384
145.4	12.1	964	152.6	12.7	2082	145.3	16.4	736
154.0	10.4	1548				154.8	14.1	1358
155.8	9.4	1730				160.2	12.7	1806
161.1	8.7	2090						

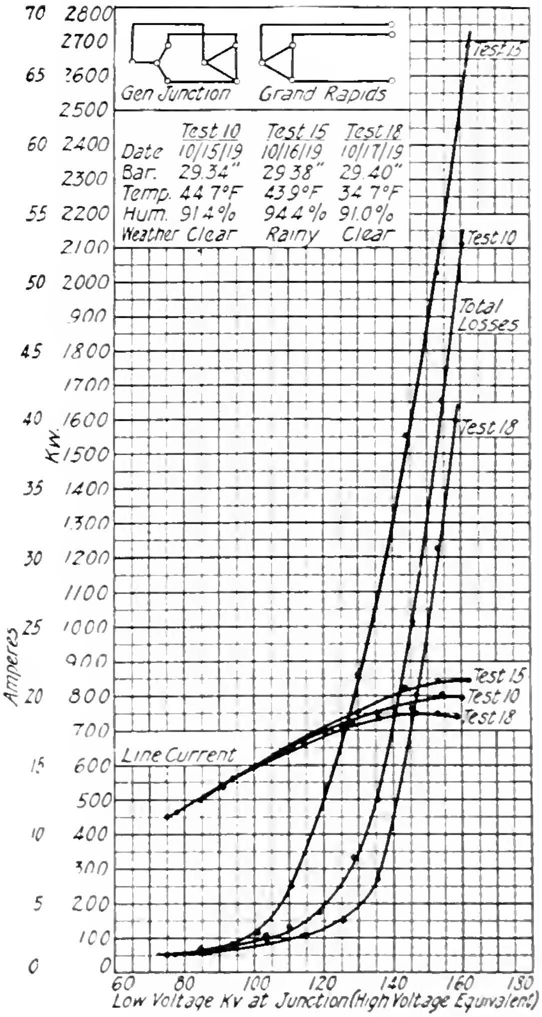


Fig. 4. Corona Loss, Line from Junction Dam to Grand Rapids. No transformers at Grand Rapids

Junction Dam transformer ratio 135,000:7500.

TABLE II

TEST 10			TEST 15			TEST 18		
H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp	Kw	H.V. Kv.	H.V. Amp.	Kw.
75.3	11.3	51	84.6	12.6	66	77.8	11.6	53
94.0	11.1	84	94.0	14.1	87	91.1	13.4	70
103.0	15.2	102	101.0	15.0	114	103.9	15.2	88
110.0	16.1	134	110.4	16.3	250	114.1	16.5	105
118.8	17.3	175	120.2	17.5	538	125.6	17.7	157
128.5	18.2	336	129.8	18.8	866	136.0	18.6	270
135.7	18.8	500	143.8	20.7	1558	146.9	18.9	805
145.8	19.0	1017	153.0	21.2	2030	153.0	18.8	1230
154.6	20.1	1655	162.1	21.2	2690	158.4	18.5	1600
160.2	19.8	2112						

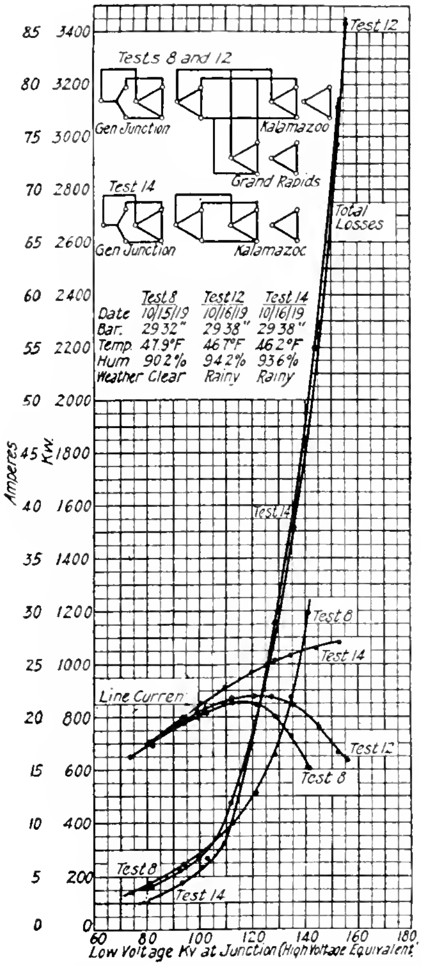


Fig. 5. Corona Loss, Line from Junction Dam to Kalamazoo Tests 8 and 12; transformers on at Grand Rapids and Kalamazoo. Test 14; transformers on at Kalamazoo, off at Grand Rapids

Junction Dam transformer ratio 135,000:7500.
Grand Rapids transformer ratio 125,000:7500.
Kalamazoo transformer ratio (Test 8) 120,000:7500.
Kalamazoo transformer ratio (Tests 12 and 14) 130,000:7500.

TABLE III

TEST 8			TEST 12			TEST 14		
H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp.	Kw.
73.8	16.2	139	81.8	17.6	164	80.0	17.4	115
81.6	17.7	171	92.4	19.4	227	93.3	20.1	177
94.0	19.5	245	99.6	20.6	267	100.8	21.4	233
103.0	20.4	270	112.0	21.8	477	109.4	22.8	329
112.6	21.4	400	120.6	22.0	796	119.5	24.3	705
121.9	21.2	512	127.1	21.9	1058	128.9	25.4	1160
128.9	20.1	658	135.4	21.2	1516	134.6	25.8	1495
135.0	18.2	874	145.2	19.1	2280	144.2	26.5	2200
141.5	15.2	1195	152.6	16.7	2970	153.0	27.0	3110
			156.0	15.9	3430			

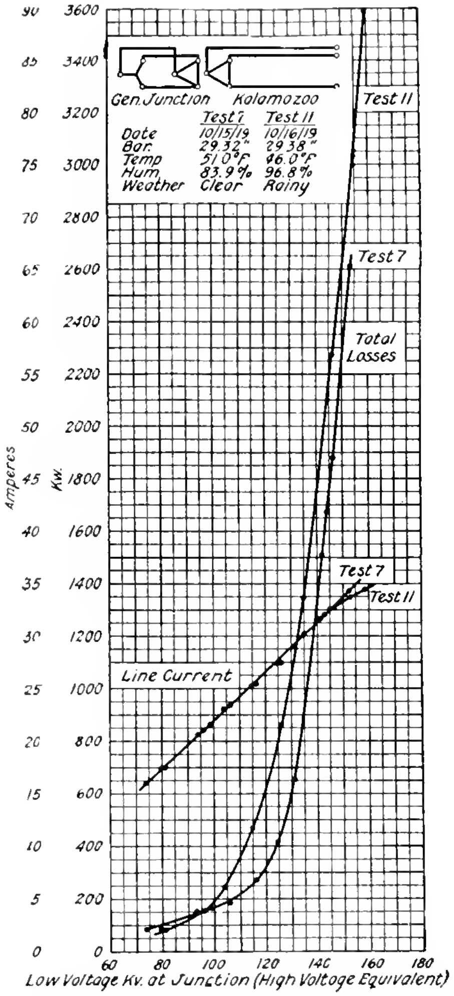


Fig. 6. Corona Loss, Line from Junction Dam to Kalamazoo. No transformers at Grand Rapids or Kalamazoo

Junction Dam transformer ratio 135,000:7500.

TABLE IV

TEST 7			TEST 11		
H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp.	Kw.
73.4	16.0	85	80.2	17.5	86
79.2	17.4	89	95.6	21.1	157
93.1	20.7	155	103.6	23.1	248
98.5	21.6	168	114.8	25.3	470
105.8	23.5	189	125.6	27.5	863
116.0	25.4	274	134.6	30.3	1345
124.2	27.4	418	145.0	32.6	2275
131.0	29.1	656	152.6	33.8	3030
141.1	31.7	1510	158.0	34.6	3590
142.7	32.1	1672			
146.0	32.7	1880			
152.1	34.3	2615			

D were open on occasion. The loss readings were all taken at Junction Dam. Fig. 2 shows the manner in which the instruments were connected.

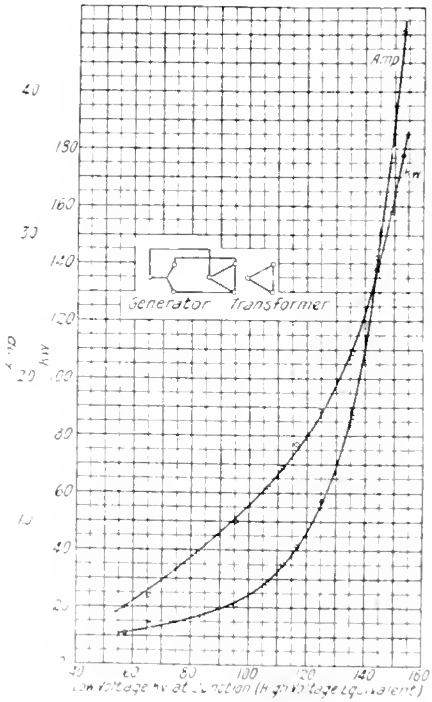
Two series of tests were run:

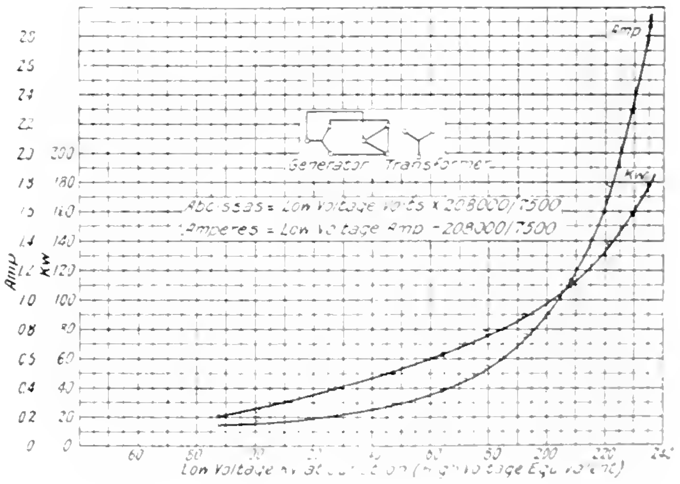
(a) With the step-up and step-down transformers connected delta-delta, which is their normal method of operation; and

(b) With the step-up and step-down transformers connected delta low-tension and Y high-tension, thus allowing the line voltage to be increased 73 per cent with the same low-tension voltage applied.

The transformers at Junction Dam and Grand Rapids are duplicates, each bank consisting of three 5000-kv-a. 30-cycle units. The transformer bank at Kalamazoo consists of three 3000-kv-a. units. The low-tension voltage of all banks is 7500; the high-tension 140,000 with taps for 135,000 130,000 125,000 120,000. In all tests under (**a**) the step-up transformers were connected 135,000 volts delta; and in all tests under (**b**) the step-up transformers were connected 120,000 208,000 Y, thus giving 208,000 volts by ratio with 7500 volts applied on the low side.

The results of the test are shown in the accompanying tables and illustrations. The tables in general give the high-voltage kilovolts (i.e., low-voltage kilovolts times ratio), the high-voltage amperes (i.e., low-voltage amperes divided by ratio), and the measured kilowatts loss. In Table VI the high-voltage kilovolts at Grand Rapids by ratio is also given.





Figs. 7-a and 7 b Excitation Curves of Transformer Bank at Junction Dam Three transformers, 30 cycle, 5000-kv-a 140,000-7500 volts

Transformer ratio, delta connection 135,000/7500
Transformer ratio, Y-connection 120,000/208,000Y/7500

TABLE V

TEST 6

L.V. Volts	H.V. Kv. Delta Conn.	H.V. Kv. Y-conn.	L.V. Amp	H.V. Amp. Delta Conn	H.V. Amp Y-conn	Kw	L.V. Volts	H.V. Kv. Delta Conn.	H.V. Kv. Y-conn	L.V. Amp.	H.V. Amp Delta Conn	H.V. Amp. Y-conn.	Kw.
3165	57.0	87.8	4.0	0.22	0.14	20	6470	116.5	179.4	14.8	0.82	0.53	77
3640	65.5	101.0	5.0	0.28	0.18	24	6950	125.0	192.7	20.6	1.15	0.74	89
4600	82.8	127.5	6.0	0.33	0.22	39	7520	135.4	208.4	31.3	1.74	1.13	109
5310	95.6	147.3	7.5	0.42	0.27	50	8000	144.0	221.8	49.4	2.74	1.78	138
5920	106.6	164.2	10.3	0.57	0.37	62	8280	149.0	229.8	63.5	3.53	2.29	158
6200	111.6	172.0	12.6	0.70	0.45	69	8480	152.6	235.2	79.7	4.43	2.87	178

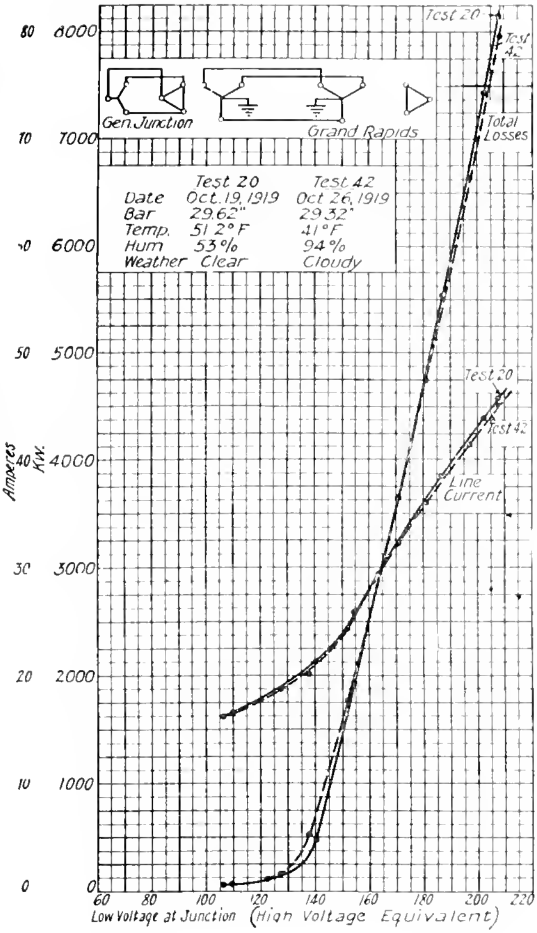


Fig. 8. Corona Loss, Line from Junction Dam to Grand Rapids. Transformers on at Grand Rapids

Junction Dam transformer ratio 120,000/208,00Y:7500.

Grand Rapids transformer ratio (Test 20) 140,000/242,500Y: 7500.

Grand Rapids transformer ratio (Test 42) 125,000/216,500Y: 7500.

TABLE VI

TEST 20				TEST 42			
H.V. Kv.	H.V. Amp.	Kw.	Kv. at G. R.	H.V. Kv.	H.V. Amp.	Kw.	Kv. at G. R
106.5	16.3	72	116.4	109.5	16.6	72	109.1
122.6	19.0	120	133.2	127.4	18.8	168	129.9
140.4	21.3	480	152.6	138.0	20.2	528	138.5
154.8	25.9	1945	166.9	152.0	24.5	1775	159.4
163.6	29.4	2930	177.2	170.9	32.3	3650	178.4
187.0	38.6	5545	201.8	181.0	36.1	4750	188.7
202.5	44.0	7440	219.2	197.0	41.5	6645	206.0
208.0	45.9	8160	224.3	208.2	45.1	7970	218.2

Figs. 3 to 6, inclusive, allow a comparison to be made between the losses on a clear and a rainy day and on two clear days with different temperatures. The marked effect of the exciting current of the step-down transformers in modifying the line current is apparent from these curves.

Fig. 7 shows the excitation of the step-up transformers at Junction Dam, Fig. 7-a

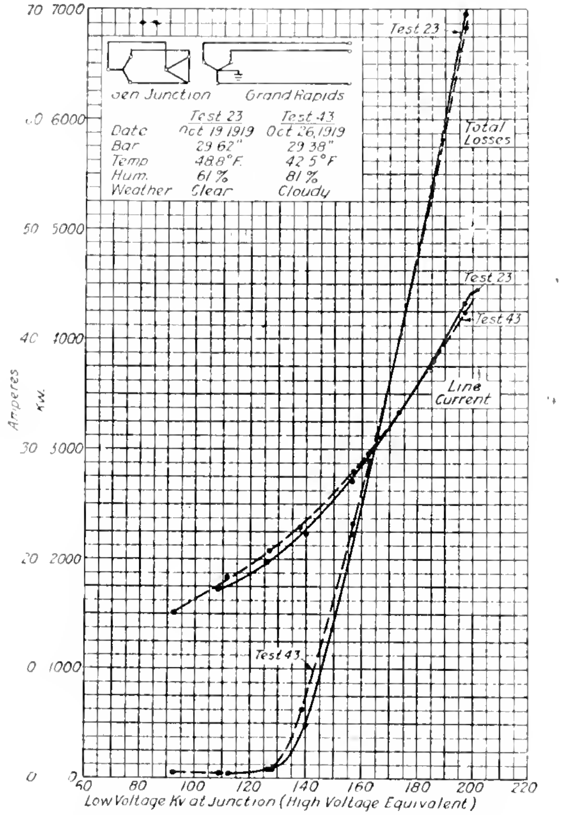


Fig. 9. Corona Loss, Line from Junction Dam to Grand Rapids. No transformers at Grand Rapids

Junction Dam transformer ratio 120,000/208,000Y:7500.

TABLE VII

TEST 23			TEST 43		
H.V. Kv.	H.V. Amp.	Kw.	H.V. Kv.	H.V. Amp.	Kw.
109.0	17.2	48	93.0	15.1	48
126.2	19.8	72	112.0	18.3	48
140.4	22.2	480	127.6	20.8	72
157.6	27.1	2230	139.2	22.8	648
174.2	33.3	4030	157.5	27.8	2330
186.1	37.8	5380	163.6	29.6	2880
198.4	43.2	6960	185.5	37.2	5305
			198.5	42.4	6840

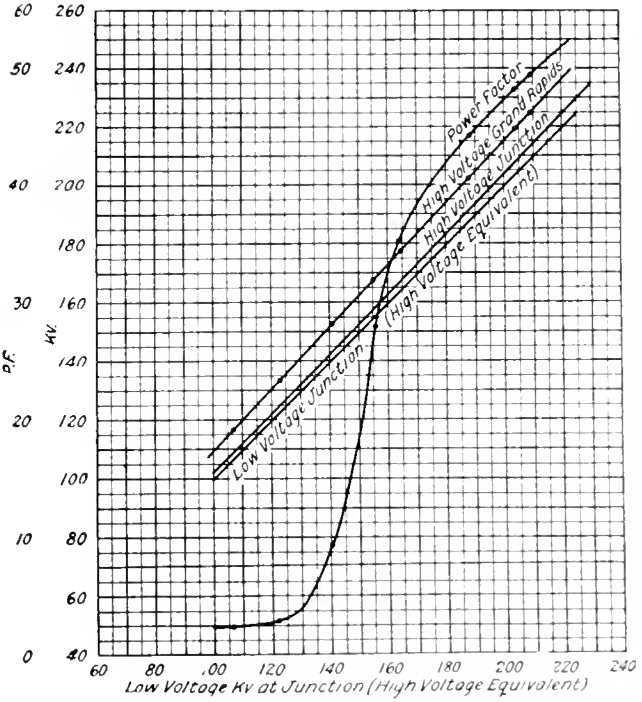


Fig. 10. Comparison of Potentials at Junction Dam and Grand Rapids, Test 20

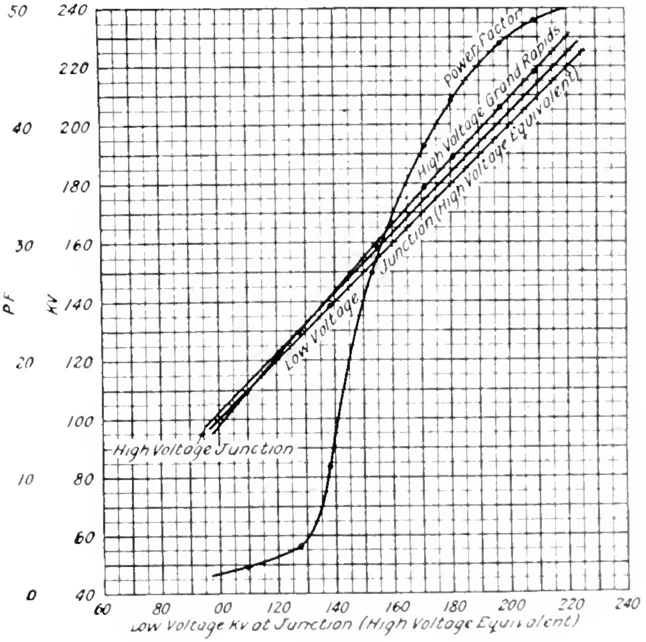


Fig. 11. Comparison of Potentials at Junction Dam and Grand Rapids, Test 42

plotted on the basis of delta high-tension, and Fig. 7-b on the basis of Y high-tension.

Figs. 8 and 9 show the losses with the Y-connection. It will be noted that the readings were taken up to about 208 kv. by ratio. These curves have been plotted with the readings as taken, without correction for instrument transformer ratio or phase angle, for the reason that station instrument transformers were used and the corrections were not available. The readings of Figs. 3 to 6, inclusive, were taken with calibrated instrument transformers and have been corrected for ratio and phase angle. The corrections in any event are small and at the higher values are negligible.

Fig. 10 shows for Test 20 the high-tension voltage at Junction Dam as calculated by means of the line current and the known resistance and reactance of the transformers, also the high-tension voltage at Grand Rapids by measurement and transformer ratio, also the power-factor of the corona readings. Fig. 11 shows similar data for Test 42.

A comparison will be made of the tested and calculated losses for Test 42 (Fig. 8). In order to do this the true line current is determined as shown in Table VIII, with the assistance of Figs. 8 and 11. The true high-tension voltage is calculated as just explained, giving the results shown in Column 10, Table VIII. The high-tension voltage at Grand Rapids is found from Fig. 11.

The corona loss is calculated for Test 42 in the usual way as follows:

Given:	Length	101.5 miles
	Spacing	12 ft. vertical
	Conductor	110,000 cir. mil.
	Barometer	29.32 in.
	Temp.	11 deg. F.

$s = 182$ in.
$r = 0.190$ in.
$g_o = 53.8$ kv. in. effective
$m_o = 0.85$ (assumed).

$$\delta = \frac{17.92b}{459+t} = \frac{17.92 \times 29.32}{459+11} = 1.052$$

$$e_o = 2.303 g_o\, m_o\, \delta\, r\, log_{10} \frac{s}{r} \text{ eff. kv. to neut.}$$

$$= 2.303 \times 53.8 \times 0.85 \times 1.052 \times 0.19 \times log_{10} \frac{182}{0.19}$$

$$= 21.09 \times log\, 958$$

$$= 21.09 \times 2.98137 = 62.85 \text{ kv. to neutral.}$$

$62.85 \times 1.732 = 108.9$ kv. between conductors.

TABLE VIII

DETERMINATION OF HIGH-VOLTAGE POTENTIALS

Conditions of Test 42

1 L.V. Volts Junction H.V. Equiv. Kv.	2 L.V. Cur. Junction H.V. Equiv. Amp.	3 P-F.	4 θ	5 Sin θ	6 $i+ji_1$	7 Trans. Exc. Cur. Assumed 90 deg. Lag.	8 Line Current Col .6+Col. 7	9 Line Cur. Amp.	10 H.V. Volts Junction Calc.	11 H.V. Volts Grand Rapids L.V.× Ratio	12 Avg. H.V. Junction and Grand Rapids
100	15.3	0.018	89° 0′	0.99985	0.268+15.29j	0.12	0.27+15.41j	15.42	102.0	97.8	99.9
110	16.4	0.023	88°41′	0.99974	0.377+16.39j	0.15	0.38+16.54j	16.54	112.0	109.8	110.9
120	17.6	0.032	88°10′	0.99949	0.554+17.59j	0.20	0.55+17.79j	17.80	122.1	121.1	121.6
130	19.0	0.046	87°22′	0.99894	0.874+18.98j	0.24	0.87+19.22j	19.24	132.5	132.5	132.5
140	20.8	0.135	82°14′	0.99083	2.81 +20.6 j	0.25	2.81+20.85j	21.02	142.5	143.9	143.2
150	23.5	0.250	75°31′	0.96822	5.88 +22.8 j	0.26	5.88+23.06j	23.8	152.7	155.1	153.9
160	27.7	0.325	71° 2′	0.94571	9.00 +26.18j	0.26	9.00+26.44j	27.95	163.2	166.2	164.7
170	31.7	0.378	67°47′	0.92576	11.99 +29.32j	0.30	11.99+29.62j	32.00	173.5	177.3	175.4
180	35.4	0.420	65°10′	0.90753	14.86 +32.12j	0.40	14.86+32.52j	35.76	183.8	188.1	186.0
190	38.9	0.453	63° 6′	0.89180	17.60 +34.68j	0.60	17.60+35.28j	39.40	194.1	199.0	196.6
200	42.3	0.476	61°35′	0.87951	20.12 +37.20j	0.80	20.12+38.00j	43.00	204.1	200.5	206.8
210	45.7	0.492	60°32′	0.87064	22.50 +39.80j	1.25	22.50+41.05j	46.80	214.8	220.0	217.4
220	48.9	0.500	60° 0′	0.86603	24.45 +42.38j	1.75	24.45+44.13j	50.50	225.0	229.8	227.4

TABLE IX

CALCULATED CORONA LOSS. TRANSFORMERS AT GRAND RAPIDS

Conditions of Test 42

E Line Voltage Kv.	e Voltage to Neutral Kv.	$e-62.85$	$(e-62.85)^2$	$1.998\times(e-62.85)^2$	Kw. Loss
110	63.5	0.65	0.422	0.884	1
120	69.3	6.45	41.6	83.2	83
130	75.05	12.20	148.8	297.2	297
140	80.8	17.75	314.0	627.7	628
150	86.6	23.75	564.0	1127.0	1127
160	92.4	29.55	872.0	1742.0	1742
170	98.2	35.35	1249.0	2497	2497
180	103.9	41.05	1682.0	3360	3360
190	109.7	46.85	2195.0	4388	4388
200	115.5	52.65	2772.0	5540	5540
210	121.3	58.45	3418.0	6830	6830
220	127.0	64.15	4110.0	8220	8220

$p=a(f+25)\ (e-e_o)^2\times10^{-5}$ kw. per mile single conductor.

$$a=\frac{388}{\delta}\sqrt{\frac{r}{s}}=\frac{388}{1.052}\sqrt{\frac{0.19}{182}}=368.8\sqrt{.001044}$$

$$=368.8\times.03233=11.93.$$

$p=11.93\ (30+25)\ (e-62.85)^2\times10^{-5}$ kw. per mile per conductor

$=656\ (e-62.85)^2\times10^{-5}$ kw. per mile per conductor

$=1968\ (e-62.85)^2\times10^{-5}$ kw. per mile per three conductors

$=1.998\ (e-62.85)^2$ kw. 3 cond. 101.5 mi.

$e_v=2.303\ g_v m_v r\ log_{10}\frac{s}{r}$ eff. kv. to neut.

$$g_v=g_o\,\delta\left(1+\frac{0.189}{\sqrt{\delta r}}\right)\text{kv., in. effective}$$

$$=53.8\times1.052\left(1+\frac{0.189}{\sqrt{1.052\times0.19}}\right)$$

$$=56.6\left(1+\frac{0.189}{\sqrt{0.2}}\right)=80.5$$

$m_v=0.82$ assumed

$e_v=2.303\times80.5\times0.82\times0.19\times2.98137$

$=86.2$ kv. to neutral

$86.2\times1.732=149.3$ kv. between cond.

The results of this calculation are set forth in Table IX.

In Table X is found the net corona loss; i.e., the measured loss minus the transformer losses and I^2R line loss, also the calculated corona loss for the average of the high-voltage potentials at the two ends of the line. This is about as near as we can come to the correct calculated value without resorting to a great deal of refinement, perhaps more than is warranted under the circumstances.

In Fig. 12 the net corona loss curve and the calculated curve are compared. It will be noted that there is a very fair agreement between these two curves. In general, it will be found that the measured curves show a more abrupt bend in the lower part of the curve and are straighter in the upper part than are the calculated curves.

An interesting feature of the tests is the fact that the charging current and the rise in voltage along the line measure considerably greater than shown by calculation. For example, in Test 42 at 200 kv. high voltage (i.e., low voltage multiplied by ratio), the charging current proper for the 101.5-mile line from Junction Dam to Grand Rapids tests about 39 amp. while calculation gives about 29.6 amp. For the same test at 180 kv. high voltage the rise in voltage along the line from Junction Dam to Grand Rapids tests 4300 volts and calculates only about 600 volts.

These discrepancies may be reconciled by assuming that the corona has the effect of increasing the size of conductor thereby increasing the capacitance and decreasing the inductance. For instance, if the radius of the conductor is assumed to be increased from 0.19 in. (the true radius) to 1.01 in., then the capacitance will be increased from 1.322×10^{-6} to 1.75×10^{-6} farads and the inductance will be decreased from 219×10^{-3} to 177.8×10^{-3} henrys for the 101.5-mile line. The charging current will then calculate 39 amp. and the rise in voltage 3200 volts for the conditions mentioned in the preceding paragraph. That such an effect takes place seems reasonable, when it is considered that corona is caused by the air surrounding the conductor breaking down and becoming conducting.

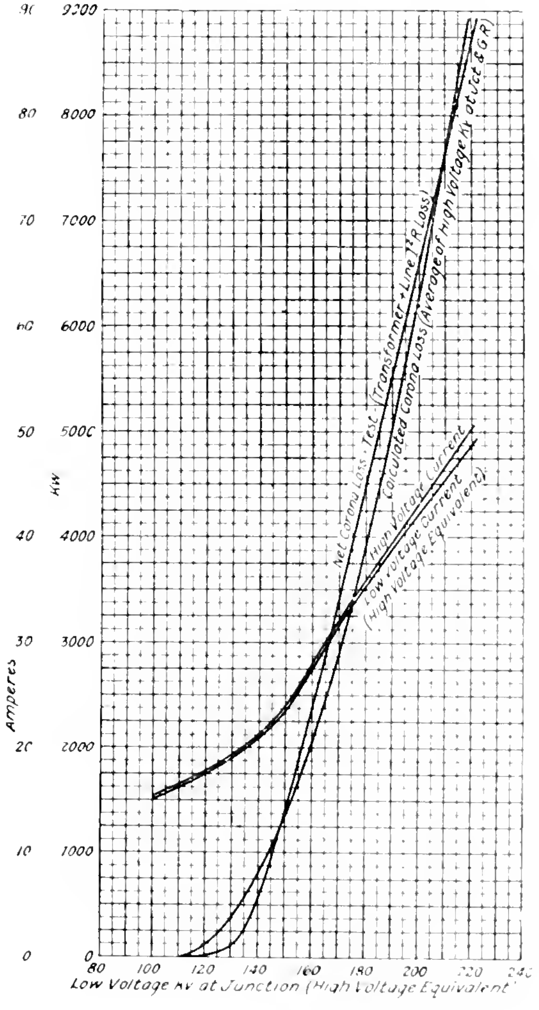


TABLE X

Conditions of Test 42

1	2	3	4	5
Kv.	Total Loss From Test Kw.	Trans. Loss Junction Kw.	Trans. Loss Grand Rapids Kw.	I^2R Line Loss Kw.
100	60	25	24	12
110	75	30	29	13
120	110	34	35	16
130	190	40	41	18
140	675	46	48	22
150	1525	52	55	28
160	2500	58	63	38
170	3560	66	72	50
180	4680	75	82	63
190	5900	86	97	76
200	7000	98	113	91
210	8130	113	133	108
220	9250	133	160	125

1	6	7	8	9
Kv.	Total Trans. and Line Loss	Net Corona Loss Col. 2 — Col. 6 Kw.	Calc. Corona Loss Kw.	Calc. Corona Loss with Avg. of H.V. Potentials at Both Ends of Line Kw.
100	61	0	0	0
110	72	3	1	1
120	85	25	83	110
130	99	91	297	375
140	116	559	628	780
150	135	1390	1127	1350
160	159	2341	1742	2060
170	188	3372	2497	2900
180	220	4460	3360	3925
190	259	5641	4388	5100
200	302	6698	5540	6375
210	354	7776	6830	7825
220	418	8832	8220	9300

Fig. 12 Curves of Comparison of Measured and Calculated Corona Loss

The Alternating-current Network Protector

By H. C. Stewart

Transformer Engineering Department, General Electric Company

Distribution of alternating current from a network fed by a few large transformers offers decided advantages in improved continuity of service, reduced losses, better regulation, etc., over the common system of distribution where a great number of small transformers are used, each feeding a comparatively short independent secondary circuit. One factor, however, has prevented the general adoption of alternating current networks, namely, there is a chance that an internal failure in one transformer may impose an overload, besides the short circuit current, on the adjacent transformer, thereby blowing the primary fuse. This action will progress from transformer to transformer until the entire system is disconnected. The device described in this article has been developed to overcome this difficulty. It has been in use for a number of years on the large network systems in New York City and its operation has proved entirely satisfactory.—Editor.

The advantages of ring and network distribution in connection with direct current systems are well known. The same important advantages, namely, continuity of service and decreased cost of the distribution system for given regulation and loss, can be realized in alternating current network systems supplied by transformers, if the transformers are equipped with the a-c. network protector.

Contrasting the usual a-c. distribution system with the a-c. network, the former has a great number of small transformers, each feeding a comparatively short independent secondary circuit, while in the network a much smaller number of transformers of larger individual capacity supply an interconnected secondary system covering a large area. Because of the diversity of service in this large area it is usually possible to considerably reduce the total installed transformer kv-a. The reduction in cost due to the smaller kv-a. and the lower cost per kv-a. of the larger transformers will about cover the cost of additional equipment required in the network to make the system workable. The advantages resulting from network operation—improved continuity of service, lower losses, better regulation, etc.—are thus clear gain. Temporary overloads or short circuits which would interrupt service on a local independent circuit will not often affect the network, as there is sufficient capacity to carry the overload and generally to burn off any short circuit which takes limited energy.

One deficiency only has prevented the wide use of the a-c. networks. Regardless of how the transformers may be fused there is always the possibility of an internal failure in one transformer throwing an overload, in addition to the short circuit current, on the adjacent transformer, whose primary fuses may blow. This action will continue progressively until the entire system is disconnected from the feeders by blown fuses. The development of a satisfactory static device which would eliminate this difficulty renders the a-c. network practical. The General Electric Company has developed such a protective device under patents granted to Messrs. Sprong and McCoy.

Description and Theory of Operation

The protector is a transformer device with three sets of windings connected as shown in Fig. 1. Two of these windings magnetically oppose each other and the third is arranged so that its magnetic action is neutralized by the division of current, so that when operation is normal there is practically no magnetization of the protector core.

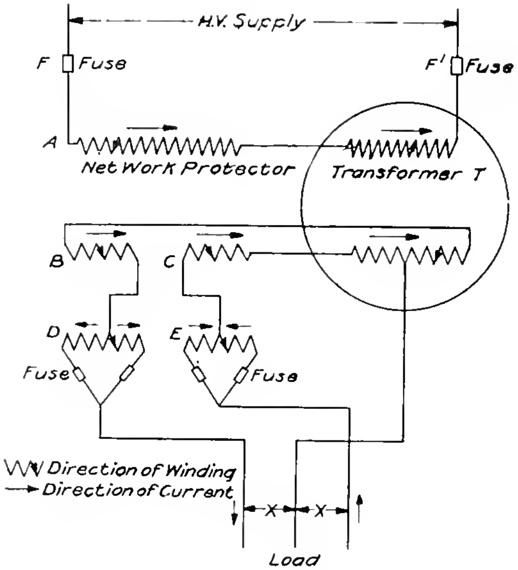


Fig. 1. Connections of Network Protector

One winding A is in series with one of the high tension lines supplying step-down transformer T. The second winding of two parts, B and C, is connected in series with the low tension lines feeding to the network (the neutral of the low tension winding of the transformer *T*, if used, is brought directly to the neutral of the network). The ratio of turns between the two windings *A* and *B-C* is such, and the coils are so wound and connected, that the core is not magnetized.

Fig. 2. 50 kv-a. Subway Transformer Fitted with Network Protector

However, the low tension current passing through windings *B* and *C* passes into the middle point of the parts *D* and *E* of the third winding. It will be noticed that the current divides in passing through these windings so that the magnetic action of these windings is also neutralized. The ends of windings *D* and *E* are connected by fuses to the low tension network. There is no e.m.f. developed in the windings *D* and *E*, since there is no magnetism in the core under normal operating conditions; consequently there will be no flow of current through the local circuits represented by the windings *D* and *E* and the two fuses connecting the ends of these windings to the network.

Now, should a fault develop in transformer *T* it will draw a very heavy current from the line through fuses *FF′* and protector winding *A*. At the same time a heavy current will be fed back into the transformer from the network through the windings *B* and *C* of the protector. This current is reversed to normal operation so that there is no longer magnetic opposition between windings *A* and *B-C*. The protector core is immediately magnetized and a heavy current flows in the local circuits of the third winding *D* and *E* through the fuses. Even though the high voltage fuses *FF′* are blown, this heavy current through the low voltage fuses continues because of the transformer action between the windings *B-C* and *D-E*. In a very short time interval the circulating current through the fuses blows them and disconnects the transformer *T* from the low tension network. The action of blowing the low tension fuses as described in this paragraph takes place instantaneously and seemingly simultaneously with the blowing of the primary fuses *FF′*.

The windings of the protector are of very low resistance and consequently the effect on the regulation of the circuit is negligible.

Construction and Application

A protector is required for each transformer in the network, so that it is desirable to make the protector a part of the step-down transformer.

In order to isolate the protector from the oil in the main transformer and thus eliminate damage which might result from explosion of fuses over oil, it is placed in a separate box on top of and forming a part of the transformer cover. The top of the protector case is securely closed by a clamped cover which has a glass window for inspection of the fuses.

The device has been commercially developed for 50 and 100-kv-a. 60-cycle subway transformers for standard voltages, and is made an integral part of the transformer. Fig. 2 shows a 50-kv-a. subway transformer equipped with the network protector.

Alternating current network systems have not been extensively used in the past, but the present trend of engineering opinion indicates that they are being viewed more favorably, even if expensive oil switches and relays are required. The a-c. network protector successfully meets all requirements and should encourage the general use of a-c. networks. The Brooklyn Edison Company and the United Electric Light Company of New York City have had a-c. networks, using this device, in successful operation for a number of years, and the performance of the network protector on these systems has proved that it functions entirely satisfactorily.

Alternating-current Lightning Arresters

By V. E. Goodwin

Lightning Arrester Engineering Department, General Electric Company

For a number of years the standard form of lightning arrester has been the electrolytic cell. This cell has a high discharge rate and high electrostatic capacity and is ideal for large power stations where attendants are on hand to look after the charging, etc., that is required. A more recent form of lightning protector is the oxide film arrester. The electrostatic capacity of this cell is lower than that of the aluminum cell and from laboratory data the latter would appear to possess better qualities for protection, but in actual service the relative merits are more nearly equal. The oxide film arrester requires no attention and hence is more suitable for isolated installations. Neither of these arresters offer protection against high frequency surges, and therefore it has been necessary to develop a device known as the high frequency absorber, which consists of a static condenser connected in series with a resistance. High frequency absorbers are installed as auxiliaries to the lightning arresters and are recommended for installation on busbars on the important stations of a system.—Editor.

The purpose of this paper is to discuss recent developments in the art of protecting moderate and high voltage electric stations against lightning and other high voltage phenomena.

Abnormal voltages which are dangerous to electrical apparatus are of two general classes: First, those which exceed the test voltage of the apparatus. These may be either high or low frequency disturbances or single impulses. Second, those of high frequency and low voltage which by virtue of their rapid changes of potential, may build up to dangerous values in inductive apparatus.

For the first class of these disturbances it is necessary to have an arrester which operates instantly upon any abnormal rise in voltage and which has sufficient discharge rate, or conductance, to dissipate the energy of the disturbance at a rate which is faster than it is generated and delivered at that point in the circuit. This question of discharge rate is one which is often overlooked in selecting arresters for a particular service. Many people assume, when they see an arrester spark over frequently, that the arrester is doing a lot of good work. Possibly it is, but sensitiveness is only one requisite, which by itself is of no merit since without discharge rate the excess voltage would not be relieved.

For the past twelve years the aluminum, or so-called electrolytic lightning arrester has been the standard form of protector for large

Fig. 1. Aluminum Cell Lightning Arrester for Indoor Service, 3000-5000 Volts

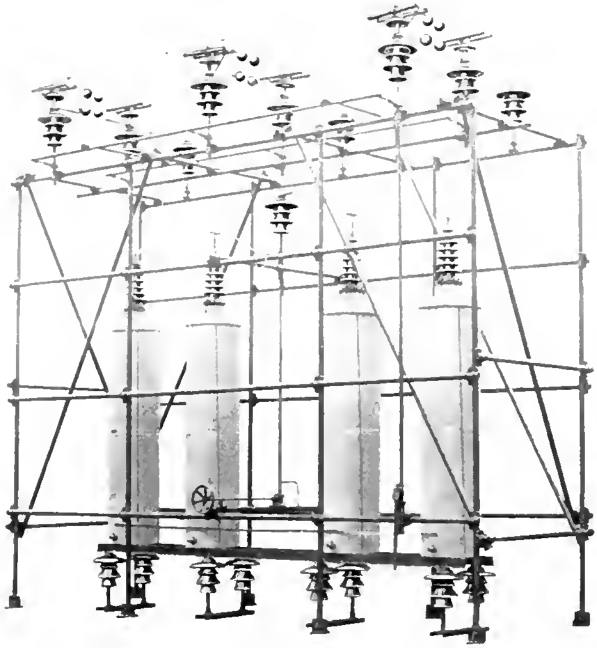


Fig. 2. Aluminum Cell Lightning Arrester for Outdoor Service, 50,000-73,000 Volts

stations. This type of arrester, due to its film or valve action, combined with its high electrostatic capacity per cell, has characteristics which are ideal for this service. This film or valve action of the cells limits the passage of energy current at normal voltage to a small value. If the voltage tends to rise to abnormal values, the current increases rapidly; thus the cells act as a barrier to normal voltage but as a virtual short circuit to the abnormal part of any excess voltage disturbance. By this action the aluminum cell tends to automatically keep the voltage below a predetermined critical voltage at which the apparatus can be safely operated.

The high electrostatic capacity of the aluminum cell is a highly desirable characteristic of a lightning arrester as it provides a ready means for absorbing the energy of any high frequency or steep wave front disturbance, and it also tends to modify the wave form of impulsive voltage disturbances so as to render them less harmful to the system.

A more recent development in this field of protection is the oxide film arrester, previously described in the technical press, (A. I. E. E., June 1918, and G. E. REVIEW). This arrester has many of the characteristics of the aluminum type; namely, the cellular construction, the film or valve action, and the high electrostatic capacity.

While possessing these similar features the two types differ materially in details as well as in operation. The cells of the aluminum arrester consist of aluminum cones or trays, partially filled with electrolyte which forms a film of aluminum oxide on the active surface of the aluminum when current is passed through the cells. These cells are immersed in a tank of oil for cooling and insulating purposes.

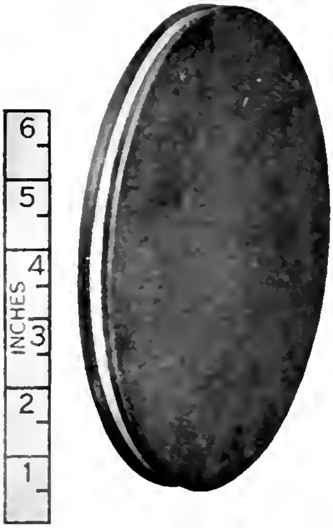


Fig 3. An Element of the Oxide Film Arrester

The cells of the oxide film arrester are self-contained and consist of two metal electrodes securely clamped to a porcelain spacer. The

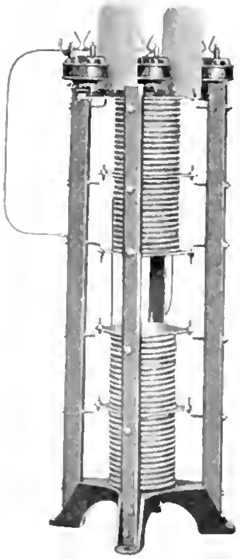


Fig 4 Oxide Film Lightning Arrester for Indoor Service, 5000 7500 Volts

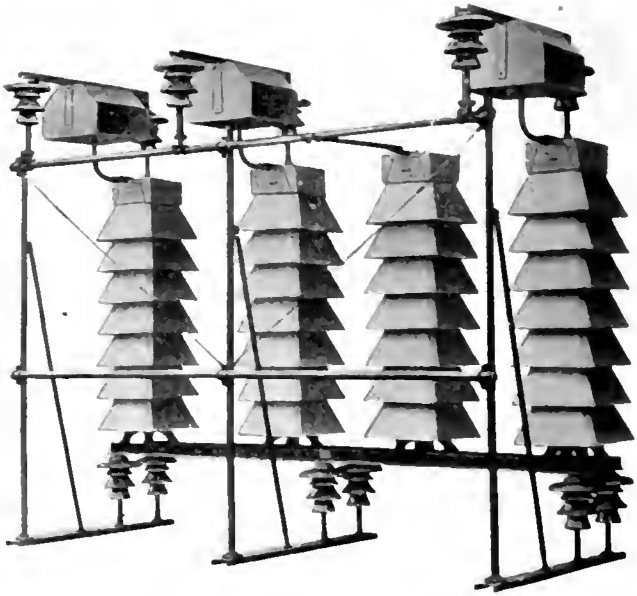


Fig 5 Oxide Film Lightning Arrester for Outdoor Service, 50,000-73,000 Volts

inside surface in the metal electrodes are coated with thin insulating films. Between these two films is the active material consisting of a special grade of lead peroxide. (See Fig. 3.)

The relative film action of the two types is theoretically dependent on the thickness of the films and the quality of the active materials used in the cells. In practice, the critical film voltage in the aluminum cell is somewhat more sharply defined than in the oxide film cell, but it is more variable due to the dissolution of the aluminum film.

As regards the values of electrostatic capacity it is worthy of note that in the present designs the capacity of the aluminum cell is greater than that of the oxide film cell. While this is a question of relative plate areas and thickness of the film, it is doubtful if the capacity of the oxide film cell can ever be made as great as that of the present aluminum cell.

Fig. 6. Interchangeable Insulators for Use With Lightning Arresters Located Out-of-doors

In comparing the two arresters from a protective standpoint, we have two sources of data; namely, laboratory tests and actual service experience. The data from each of these sources seem to indicate that both of these types are superior to any other scheme of protection yet devised. In laboratory tests the aluminum arrester shows up better apparently on account of its higher electrostatic capacity. After four years of experience with the oxide film arrester in actual service at from 2300 to 73,000 volts, there does not seem to be as great a difference in protective qualities as would be indicated in the laboratory tests.

Looking at the problem from a practical standpoint it would seem that the two arresters would fill a somewhat similar field. The oxide film type is better suited to the smaller stations where there are few or no skilled operators in attendance, while the aluminum type will be installed at the larger and more important stations where skilled attendants can look after the charging of the films and give the daily attention necessary with this type. Actual operating experience is the real criterion in determining the value of any lightning protective device; hence the actual defines of these fields of application will have to be determined from more extensive experience by operating engineers.

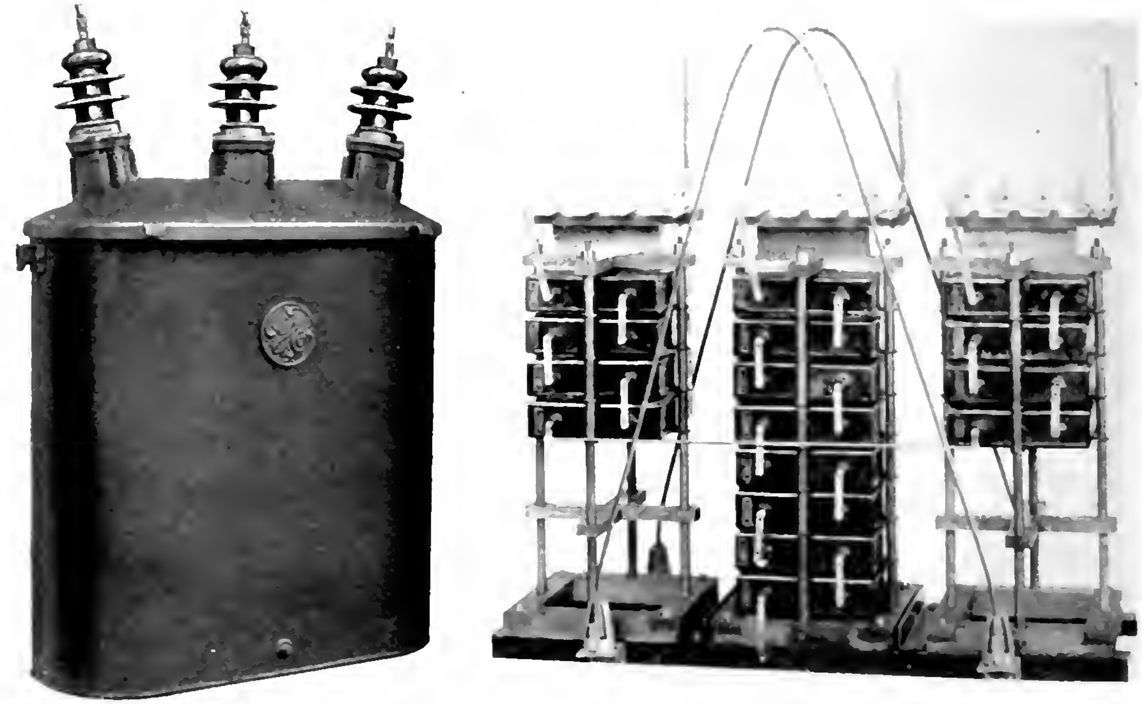
A design feature of particular interest in these two types of arresters is the use of a new line of interchangeable insulators for outdoor service. (Fig. 6.) There are five sizes of insulators used for ratings 7500 to 73,000 volts. The caps and pins have similar drillings and are accurately jigged so that all insulators in a class are identical and all classes are interchangeable. This arrangement is particularly advantageous for use on apparatus which is to be operated at various altitudes or in other places where extra insulation is desired, as it is simply necessary to select insulators having the desired factor of safety and substitute them in the standard design without any change in fittings.

Both the aluminum and oxide film types for a-c. service are equipped with series sphere gaps to prevent rapid deterioration. This arrangement limits their operation to disturbances having voltages sufficient to discharge these sphere gaps. These include all high and low frequency disturbances of voltages in excess of the spark potential of the gaps. The sphere gaps introduce the shortest known spark lag; consequently the arresters thus equipped are best suited to handle steep front impulses which are so dangerous to the insulation on induction windings of apparatus.

For the second class of dangerous disturbances mentioned above, namely, high frequency low voltage, it is necessary to use some form of protection which does not depend entirely on the principle of over.

voltage for its operation and which consequently does not have a series gap. Its function should therefore be to separate and absorb the energy producing the high frequency disturbance.

The high frequency absorber illustrated in Figs. 7 and 8 has been developed to meet this condition. The device consists of a static condenser with a series resistance. The condenser acts as an automatic relief valve for high frequencies and the resistance as a means of absorbing the energy which is tending to produce these oscillations. They are so designed as to pass only small leakage current at normal frequency. If the frequency should increase from some extraneous source, such as an arcing ground, the current through the device would tend to increase nearly in proportion to the frequency if the energy supplying this condition were not limited. This, fortunately, is the case, as the high frequency energy is limited in value. Hence as the current through the condenser and series resistance increases, the resistance absorbs the energy and dampens the oscillations, thus rendering them less dangerous to the system.



Figs. 7 and 8. High Frequency Absorber, 15,000-25,000 Volts

The action of the high frequency absorber as described above can be better understood from a study of the following calculations of an actual design.

The impedance of a condenser with a series resistance is

$$Z=R^2+\left(\frac{1}{2\pi fC}\right)^2$$

R 100 C .01 microfarads $f=60$ cycles.

Then Z at normal frequency $=265{,}000$ ohms. At 13,200 volts the current at 60 cycles would be .05 amperes and the energy absorbed by the series resistance would be $.05^2\times100=.25$ watts per second.

For comparison, let us assume that the frequency be suddenly increased to 100,000 cycles, the other factors remaining constant.

Then $Z=188$ ohms.

At 13,200 volts the current at 100,000 cycles would be 70.3 amperes and the energy absorbed would be $70.3^2\times100=494{,}000$ watts per second.

The high frequency absorbers are installed as auxiliaries to aluminum and oxide film arresters and are usually recommended for installation on the busbars of the more important stations of the system. The high frequency absorber illustrated in Fig. 7 has been developed for service on voltage from 7500 to 25,000.

These high frequency low voltage disturbances are most serious on moderate voltage systems, particularly those where the voltage is stepped down from high voltage transmission circuits. On the higher voltage transmission circuits the long lines seem to act as absorbers and to dampen out these disturbances.

Metallic Resistor Electric Furnaces for Heat Treating Operations

By E. F. Collins

Engineer, Industrial Heating Department, General Electric Company

The advantages of the electric furnace for heat treating are well known. Uniform heat distribution and automatic temperature control are the most important factors. The furnaces described in this article differ radically from the ordinary laboratory furnaces both in construction and in operating characteristics. The heating element consists of bare metallic ribbon uniformly distributed over the interior of the furnace. The ribbons are exceptionally heavy and, being unmuffled, radiate the heat direct; the resistor therefore remains at a lower temperature, produces quicker heating, and is much more sensitive to temperature regulation than the muffled or screened furnace. The sensitive automatic heat control and high rate of heat delivery to the charge insure high termal efficiency. The illustrations show several different types of these furnaces of both the vertical and horizontal form.—Editor.

There exists today a growing demand for heat-treating equipment of large capacity. A considerable demand comes from manufacturers of automobile parts, such as gears, crankshafts, bearings, axles, etc., which are produced in large quantities, and all of which require heat treatment. Many tons of steel are heat-treated each day; therefore the demand for furnaces of large productive capacity and high efficiency.

Electric furnaces have long been recognized as ideal for this purpose, but until the last few years they have not been available in such size and of such rugged design that they could be considered for carrying unassisted the regular production load.

In a paper on "Electric Heating of Steel," presented at the American Steel Treaters' Society meeting at Chicago last September, I described some vertical electric furnaces which were used for a year or more preceding the armistice for heat-treating gun forgings. In this paper the method of control, and the general characteristics and advantages of this type of furnace were discussed.

It is therefore unnecessary to again describe the furnaces in detail; but since it is the purpose of this paper to recount some things which have been accomplished, to give some results of operation and describe the application of the furnace in several forms to the problems of heat treating, it is desirable to again mention some of the salient features of the furnace.

This type of metallic resistor furnace entered the industrial field in 1917 and 1918, and its use has been attended with unusual success in regular manufacturing production. It was first tested under the rigorous conditions attending gun-making in war time, and the results produced were phenomenal.

A basic idea incorporated in the design is the location of the resistor ribbon, unmuffled, in the open heating chamber so that it can directly radiate the heat generated within it.

These ribbons are very rugged mechanically; they are sometimes as much as two inches wide by one eighth inch thick and are formed into loops. They are supported on refactory insulating members projecting from the walls of the heating chamber, the body portion of the support being imbedded in the wall.

The resistor is thus free to deliver its heat by radiation to the charge without the necessity of first forcing the heat through the walls of a muffle, as has been the practice in most metal resistance furnaces heretofore constructed.

In order to force heat through a muffle at high rate and secure rapid heating of the charge, a high temperature gradient, and therefore high resistor temperature are necessary. Hence the unmuffled furnace has inherently a lower temperature resistor, produces quicker heating, and is much less sluggish in point of temperature regulation than the muffled or screened furnace doing the same work. The unmuffled furnace uses direct and reflected radiant heat.

The outstanding features of this furnace are more rugged resistors (absorbing more power yet resulting in a low temperature long-lived resistor), splendid heat distribution and control, and high thermal efficiency due in part to sensitive automatic heat control and high rate of delivery to the charge. A large resistance furnace is more rugged in design and is infinitely more dependable in operation than the small laboratory furnace that has heretofore existed. This fact has been well established from the results of operation in regular production.

Another feature is that heavily heat-insulated walls with at least 9 in. of heat insulation outside a 4-in. refractory lining

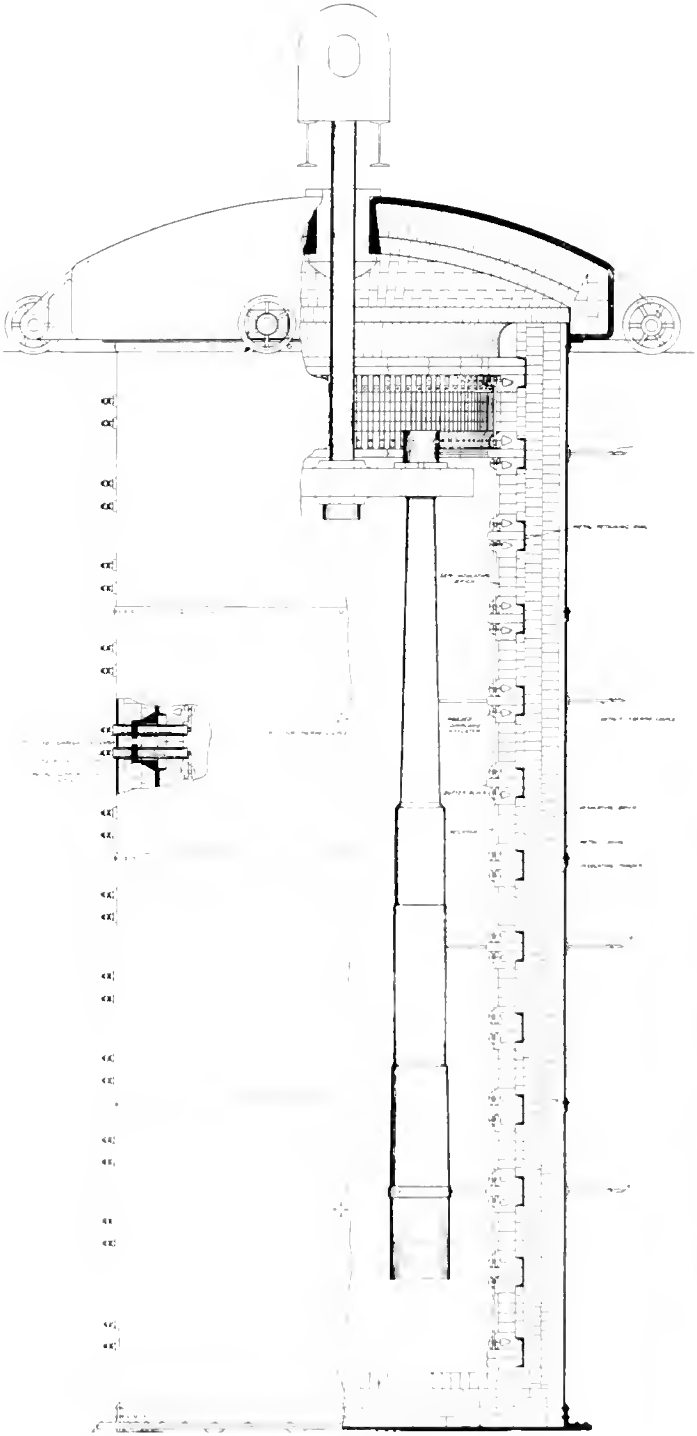


Fig. 1. Cross Section of Cylindrical Vertical Furnace for Heat Treating Gun Forgings

Fig. 2. Section of Resistor Ribbon for Heat Treating Furnace

Fig. 3. Detail of Metallic Resistor and Support for Vertical Furnace

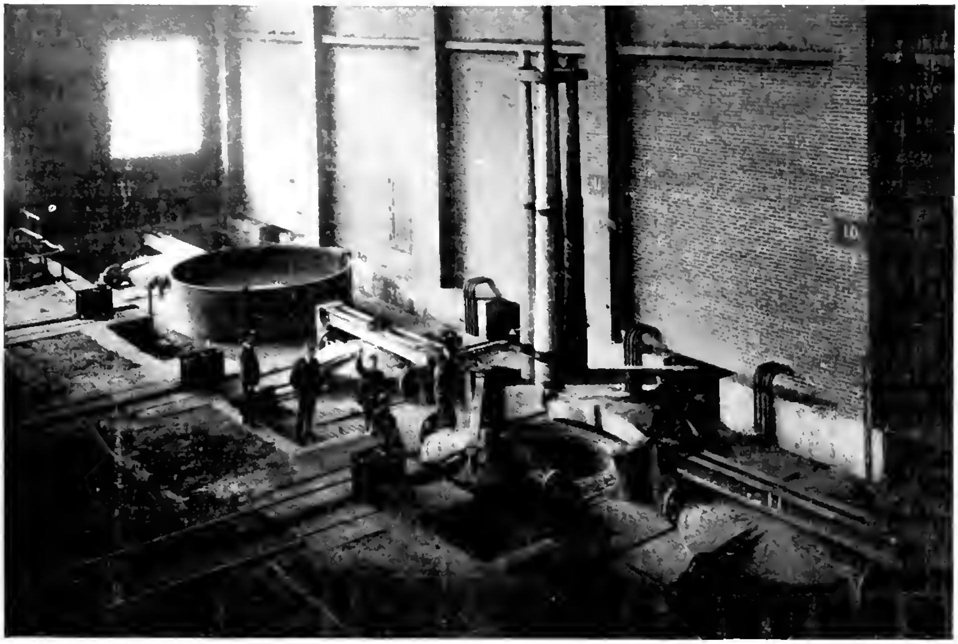


Fig. 5. War-time Plant for Heat Treating Guns

may be used, and gas or air tightness throughout may be maintained by the use of an outer casing. This contributes to thermal efficiency and an operating chamber from which air may be excluded, or in which a gas may be held.

Fig. 4. Showing Interior of Furnace of Fig. 1 and Method of Supporting Metallic Resistor

Fig. 1 shows a cross section of a cylindrical vertical furnace of the metallic resistor type used for the heat treatment of gun forgings. Fig. 4 shows an interior view, and Figs. 2 and 3 show the details of construction. Note the thick walls of heat insulating material, the heavy resistor ribbon and the outlet stud extending through the wall, to which the line connections are made. Note also the welds at the ribbon splice and at the terminal studs.

Fig. 5 shows a typical war-time plant used for heat treating gun forgings. It consists of four furnaces and quench tank. Fig. 6 shows the elevation section of a plant consisting of two furnaces and quench tank. This plant is now being installed in Spain.

All these furnaces have automatic temperature control, a typical control board being shown in Fig. 7. The instruments which control as well as record the temperature are shown on the sub-bases of the panels. A temperature control chart or record is shown in Fig. 8.

A very complete set of tests were run on an installation of these vertical furnaces, the results of which may be summarized as follows:

Heating to 1450 deg. F. Furnaces hot when charged. Furnaces 6 ft. diameter by 24 ft. high, voltage 440, 60 cycles, capacity 400 kw.

Charge	Total Weight Including Holding Fixtures	Energy in Kw-hrs.
12 3-in. gun tubes	21,900 lbs.	1874
7 4-in. gun tubes	22,300 lbs.	1880
3 4-in. jackets	21,700 lbs.	2088
Total	65,900 lbs.	5842

Average lbs. per kw-hr. . . . . $\frac{65{,}900}{5842} = 11.25$

Kw-hr. per ton . . . . $\frac{2000}{11.25} = 173$

Energy cost per ton at \$0.0085 per kw-hr. = \$1.52

This shows what may be done with the electric furnace in moderate scale operations. The time required to heat these charges was $5\frac{1}{2}$ to 6 hours, and the maximum diameter of forgings was $16\frac{1}{2}$ inches. The furnaces were 24 ft. high by 6 ft. diameter inside dimensions, and were exactly like those shown in Fig. 5; the connected load being 400 kw. each. The ultimate or minimum radiation from test was found to be 70 kw. The predicted radiation from design was 75 kw., a satisfactorily close agreement.

The actual operating results for the four furnaces for the month of October, 1918, just before the armistice, when production was at the maximum rate, including both hardening at 1450 deg. F. and drawing at 1150 deg. F., was \$2.76 per ton based on the power rate of \$0.0085 per kw-hr.

The specifications for drawing did not allow the charge to enter a furnace at full drawing temperature. It was therefore necessary to cool the furnace somewhat, and then raise the temperature of furnace as well as charge. It was also required that the charge be held at the drawing temperature for several hours. This of course did not allow of the highest efficiency in pounds of metal heated per kw-hr.

If work at 250 deg. F., to be drawn at 1100 deg. F. enters a furnace at 1100 deg. F. a yield of approximately 24 lbs. per kw-hr. would be realized. This would give:

$\frac{2000}{24} = 84$ kw-hr. per ton for drawing to 1100 deg. F.

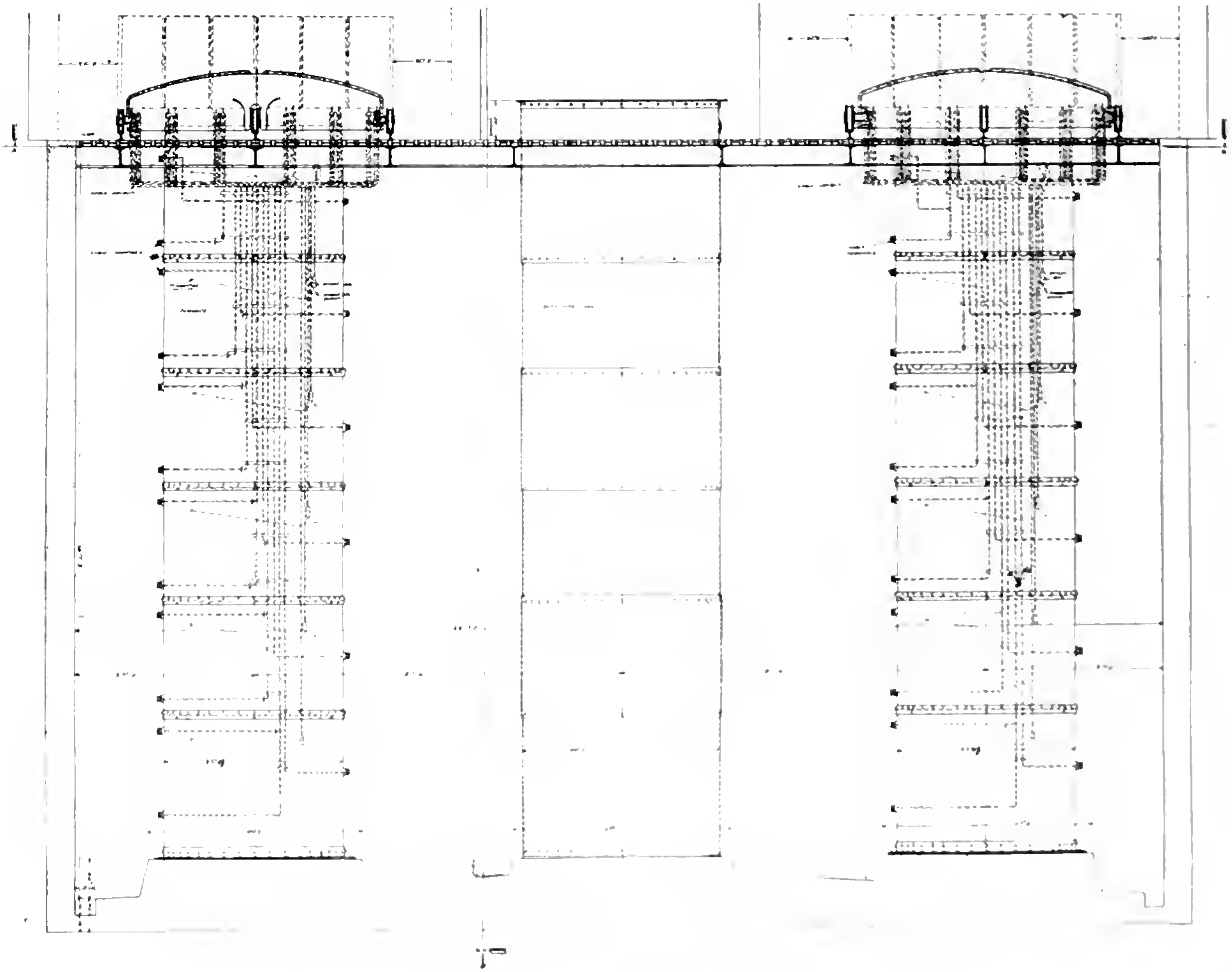


Fig. 6 Sectional Elevation of Two Heat Treating Furnaces and Quenching Tank

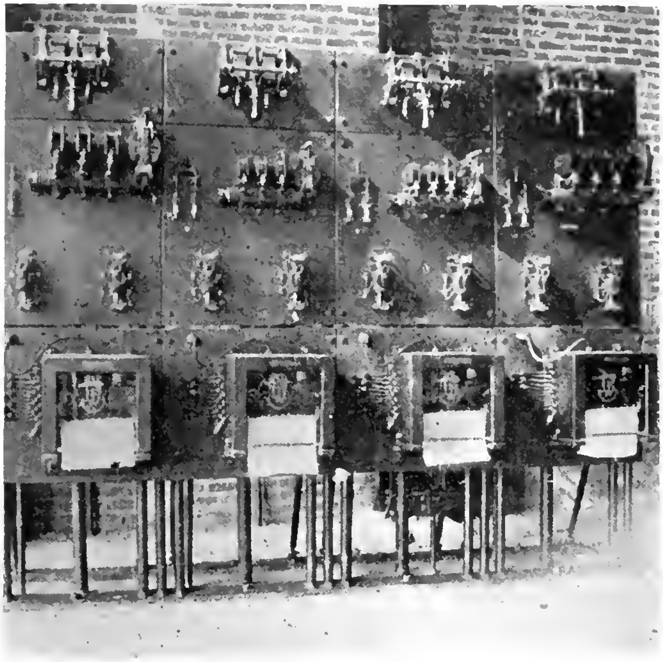


Fig. 7. Control Board for Automatic Temperature Control

Therefore the overall operation would require: To harden, 178 kw-hr. per ton for heating to 1450 deg. F. To draw, 84 kw-hr. per ton for heating to 1100 deg. F., making a total of 262 kw-hr. per ton.

The cost at $0.0085 per kw-hr. will be $2.23 per ton. The cost of $2.76 per ton actually achieved during the month of October, 1918, indicates that the furnaces were handled exceptionally well. They were of course operated continuously without shutdown of any kind, and some preheating was done by putting cold charges in the cooling pits.

These furnaces were in fact the first to be built, and they were therefore very conservatively designed. They could have been rated 600 kw. instead of 400 kw., which would have increased the output and efficiency and also shortened the time of heating, since the radiation loss would be the same in either case, and radiation is the only loss which occurs with this type of furnace. Strictly speaking, this loss is not radiation, but part radiation and part convection. We speak of it as "radiation" for convenience.

They are made air tight, and there is therefore no air passing through the heating chamber, carrying away heat as it escapes. This accounts for the fact that there is practically no scale on the charge, as well as for the ease with which the furnaces can be controlled, because in the absence of air currents there is no tendency for the heat to rise toward the top of the furnace. Heated air will rise, but heat rays will pass from resistor to charge by direct radiation, and any heat distribution may be maintained indefinitely. This of course is in accordance with well known physical laws for radiant heat, but it is interesting to know that they can be applied with great exactness in practice.

Twenty-two of these furnaces for hardening and drawing, with a total rated capacity of 7000 kw., were built during the war period

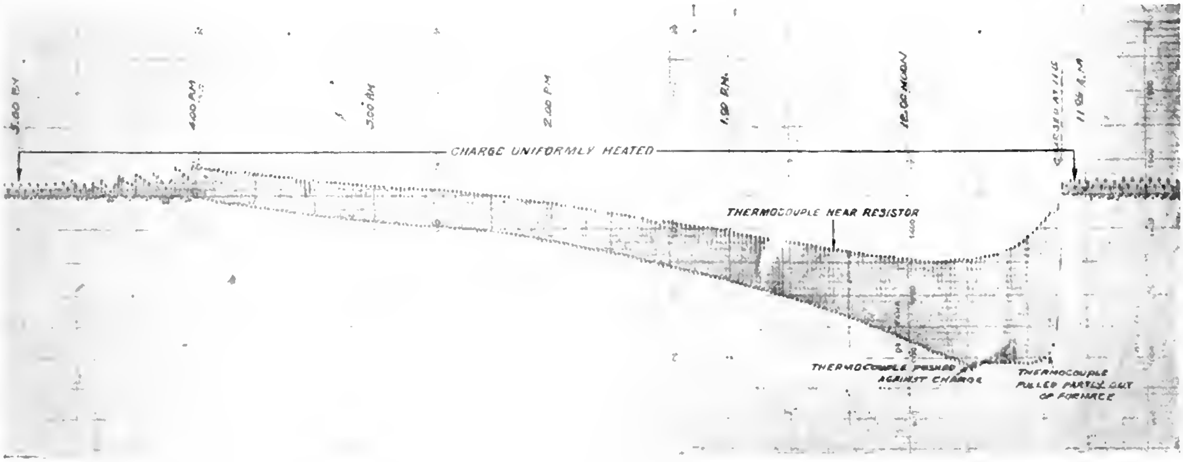


Fig. 8. Temperature Chart of Electric Heat Treating Furnace Fitted with Automatic Temperature Control

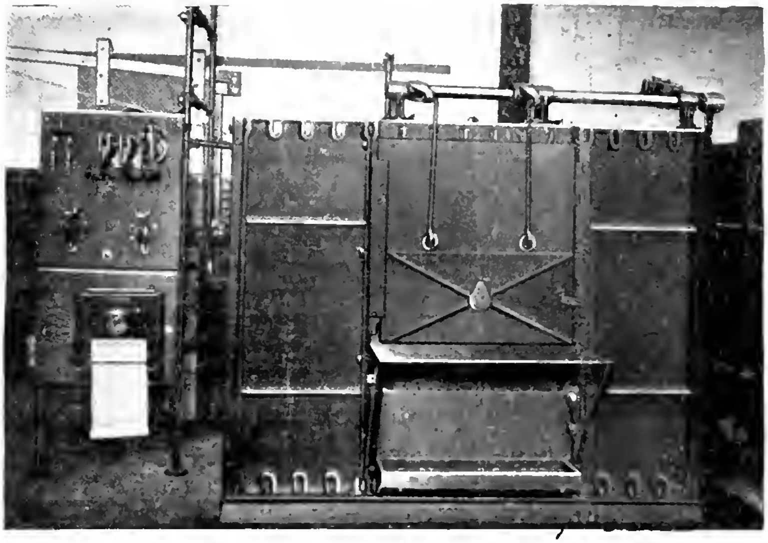


Fig. 9 Box Type Electric Furnace and Control Panel Used for Hardening Punches, Dies and Cutters

for the manufacture of both field and naval guns, the largest being 8 ft. diameter by 35 ft. high, with connected load of 700 kw. Those shown in Fig. 6 are now under construction and are about the same size. There is at present also under construction a furnace 10 ft. 6 in diameter by 105 ft. high with a connected load of 2850 kw., in which forgings weighing 320,000 lb. may be readily heat treated.

The horizontal furnace is better suited to much industrial heat treating, the use of vertical furnaces being restricted to cases where relatively large or long objects are to be treated. The same principles of heating hold whether the furnace be vertical or horizontal, since the metallic type of resistor windings may be applied to any type of furnace chamber. There are in operation, or in process of installation, a large number of furnaces in various forms in which this type of heating element is used.

Fig. 9 shows a box type furnace with its control panel used for hardening punches, dies, and cutters. Fig. 10 shows a small car bottom furnace used to anneal steel castings. This is a very convenient form for annealing. Several of this type are under construction, one of the largest which is to be installed in France for annealing tool steel bars being 17 ft. long by 8 ft. wide and rated 300 kw.

Fig. 11 shows two rotary annular ring furnaces for treating gears and similar parts. The hearth of this furnace revolves about the vertical axis, and is suspended on ball bearings and driven by a motor through a worm gear. Control is by push button or foot switch, by means of which the table may be advanced as desired. The mean diameter of the hearth is about 5 ft., making it equal to a tunnel furnace 15 ft. long. The motor drive, doors, counter weights and foot operated mechanism are clearly shown.

Fig 10 Car Bottom Furnace for Annealing Steel Castings

Fig. 11. Rotary Annular Ring Furnaces for Treating Gears and Similar Parts

This promises to be a very popular furnace for small parts, such as gears, taps, drills, etc. It has a connected load of 60 kw., balanced three-phase automatic temperature control, and is capable of turning out about 300 lb. of steel per hour at 1500 deg. F. quenching temperature.

Fig. 12 is an interior view of two box furnaces under construction showing the resistor windings supported on the wall. These box furnaces are used for carburizing.

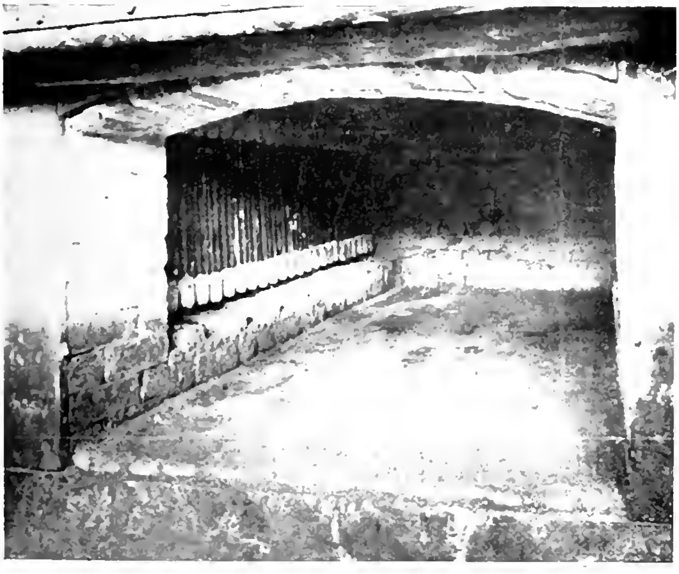


Fig. 12. Interior View of Box Furnace Used for Carbonizing

Another type of vertical furnace for hardening spindles consists of a hearth which revolves on its vertical axis, upon which is mounted a frame of non-oxidizing metal for holding the spindles in a vertical position, there being space for about 40 spindles. The spindles are put in and taken out through two holes in the cover. A small movable cover operated by a conveniently placed handle covers both holes and may be pushed aside to put in or remove the spindles; but only one hole can be uncovered at a time.

Fig. 13 shows a large furnace with flat hearth 12 ft. in diameter which has been in use for several years for tempering leaf springs for automobiles. This furnace operates at 950 deg. F., turning out

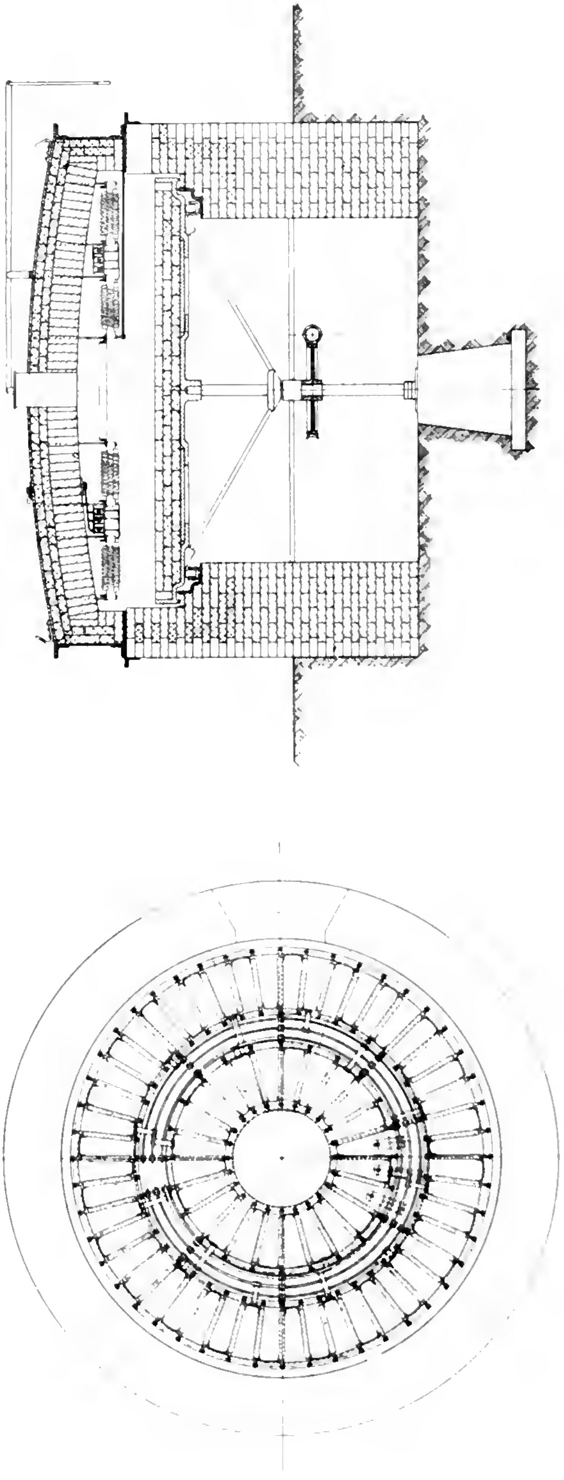


Fig. 13 Large Furnace with Flat Hearth for Tempering Automobile Leaf Springs

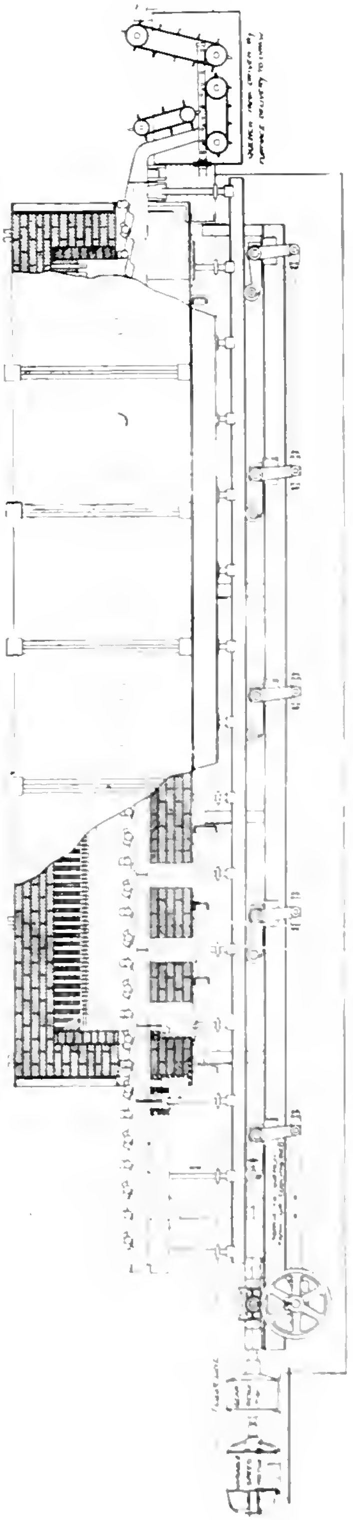


Fig. 14 Conveyor Furnace with Automatic Quench for Large Production of Such Parts as Automobile Cranks and Axles

about 2000 lb. of springs per hour. The connected load is 85 kw. three-phase, all the heaters being mounted in the arch.

Since this furnace operates at a relatively low temperature, 950 deg. F., it is equipped with so-called low temperature heaters, which consist of a number of ribbon wound units mounted on cast-iron frames, in general similar to Fig. 16. This furnace is doing excellent work and in large quantity, turning out about one ton per hour, as stated above. There appears to be great promise in the application of air drawing ovens for heat-treated parts.

Figs. 14 and 15 show a conveyor furnace with automatic quench for a large production of relatively heavy parts, such as cranks and axles. Note that there are heaters in the arch as well as on the side walls. These conveyors are shown as examples of standard fuel furnace equipment which may be employed with electrically heated furnaces. Such furnaces are usually designed special, and they can be built for almost any tonnage desired.

In regard to temperature distribution and control, it may be said that in the cylindrical furnaces this distribution is perfect, as the entire inner surface is covered by the resistors, all of the same size, and all carrying the same current. This condition is very closely approached in a hearth furnace by locating resistors in the arch as well as in the side walls, and by a proper arrangement of arch and reflecting walls, as shown in some of the illustrations.

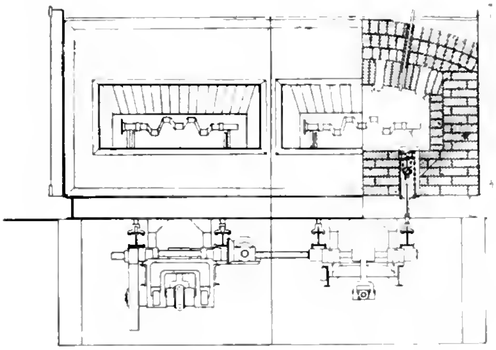


Fig. 15. End Elevation of Furnace of Fig. 14

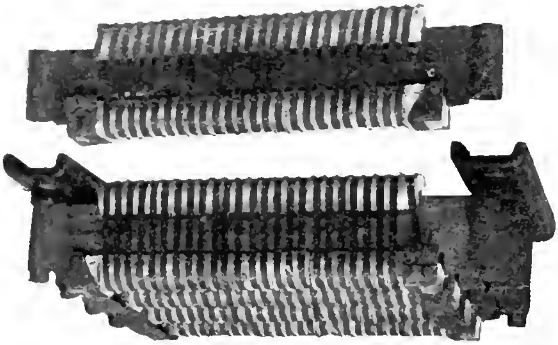


Fig. 16. Low Temperature Heating Units for Furnace Shown in Fig. 13

Automatic temperature control saves time as well as power, and gives a constant temperature; in fact, it is considered essential to successful operation and is always furnished.

Maintenance so far as resistors and refractories are concerned, is very low, since, due to automatic control, they never become over heated and there is no wear or abrasion on refractories except on the hearth.

The resistors are designed to convert a certain number of watts per square inch into heat, which may be calculated with exactness, and so long as safe working limits of temperature and rate of radiation and absorption are not exceeded, the resistors are absolutely dependable and practically permanent.

In conclusion, it should be said that we are indebted to the manufacturers of ordnance, who first demonstrated the success of this type of furnace. Their optimism lead to the installation of electric furnaces, which gave us an opportunity to prove that our claims were correct; and there was inaugurated, to undergo the stress of war demands, a type of furnace for heat treating steel which will be found equally important in time of peace to help the manufacturer win many of his industrial battles.

A New Type of Arc-welding Generator

By S. R. Bergman

Consulting Engineer, General Electric Company

A suitable arc is essential to successful arc welding. The production of this stable characteristic requires some means of regulation. Where each welder is furnished with an individual generator, the necessary regulation is best effected through special inherent regulation in the generator itself. The machine which has been developed to embody this characteristic of constant-energy output is completely described in the following article.—Editor.

A large amount of work has been done to produce direct-current machines having inherent regulation; i.e., having certain characteristics obtained by properties of the windings without the use of any external regulators.

The simplest and most successful machines having inherent regulation are the compound-wound direct-current generators and motors. The compounding may either be accumulative (boosting) or differential (bucking). Accumulative compounding is used to maintain a constant potential in shunt-excited generators. It is also applied to motors in order to give characteristics lying between those of the shunt and the series motor. Differential compounding in generators produces unstable conditions except when the generator is separately excited. This latter condition exists, for example, in a form of generator which is often used for charging storage batteries at an approximately constant rate. In motors, differential compounding is not used since an increase of the load causes an increase of the speed, a condition which is unstable.

The compound winding owes its success to the fact that it can be applied to direct-current machines without any structural changes whatever.

There are, however, a great many problems in direct-current engineering that require motors and generators having inherent characteristics which compound windings cannot give. While a large number of attempts have been made in the past both here and abroad to produce machines of such inherent regulation, none of these attempts have met with any appreciable success. One reason for this failure lies in the difficulties arising from commutation. The greatest forward step in the design of direct-current machines was the introduction of commutating poles, which so far represents the most powerful method of obtaining perfect commutation. It may therefore be expected that, no matter how we otherwise construct direct-current machines, the solution must include proper means for the application of commutating poles.

Some years ago the writer developed a new type of direct-current generator having inherent regulation which type may be called "A Direct-current Machine with Dual Magnetic Circuits." This design supplies means for obtaining a great variety of characteristics and in this article the electro-magnetic properties of an inherently regulated arc-welding generator will be discussed. This recently standardized type of generator possesses the characteristics shown in Fig. 1. Experience

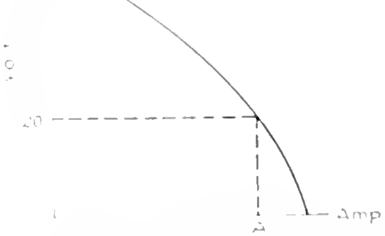


Fig. 1. The Desirable Type of Voltage-current Characteristic for a Single-operator Arc-welding Generator

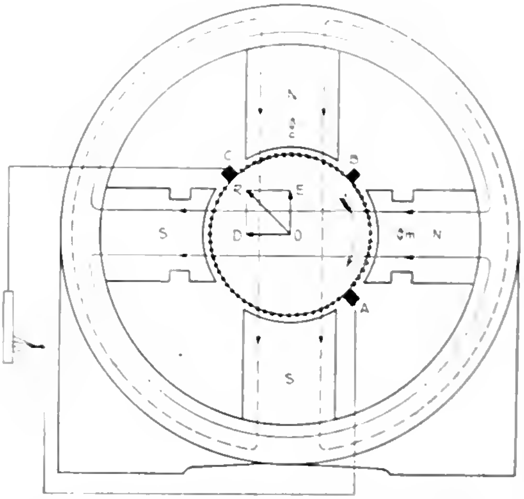


Fig. 2. Elementary Diagram of the Constant-energy Arc-welding Generator, Showing the Paths of the Magnetic Circuits and the Position of the Brushes

has demonstrated that these are the characteristics desirable in the single-operator type of arc-welding generator.

In Fig. 1 the open-circuit potential is 60 volts and the arc voltage is 20. The arc-current is designated as *A* amperes; and the generator is laid out in such a manner that this current can be set or adjusted to different values depending on the work to be done. From one generator the following arc-currents may be obtained at 20 volts: 200, 175, 150, 125, 100 and 75 amperes, the adjustment being made possible by a system of taps as will be explained later.

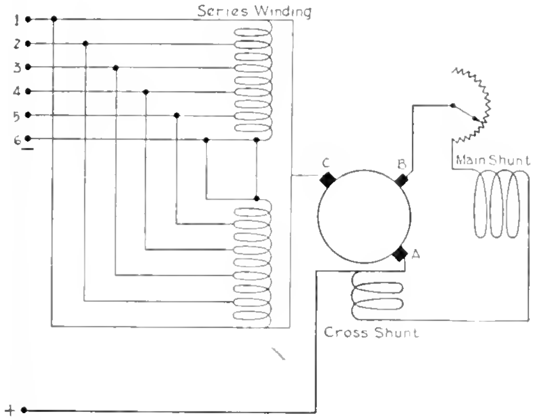


Fig. 3. Simplified Diagram of the Generator, showing the Main and Cross Shunt Windings and the Tapped Series Field Winding by which the Voltage-current Characteristic is Varied in Accordance with Fig. 4

In Fig. 2 is shown a four-pole field structure and an armature wound for two poles. In general the armature should be wound for half the number of poles contained in the field. In standard designs of direct-current machines adjacent poles have opposite polarity, but in this machine the poles are paired in groups of the same polarity. Thus there is a group of two north poles followed by a group of two south poles, etc.

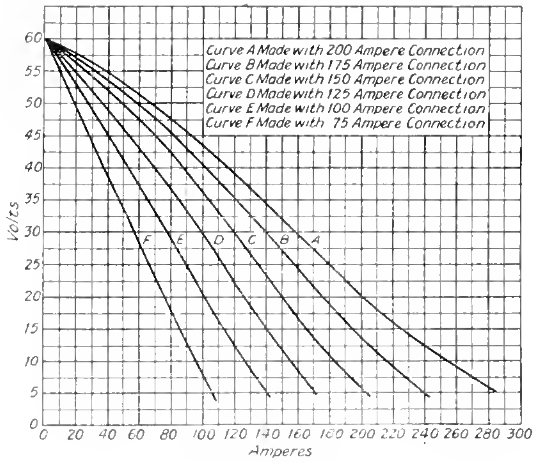


Fig. 4. Voltage-current Characteristics with Various Tap Connections of the Series Field Shown in Fig. 3

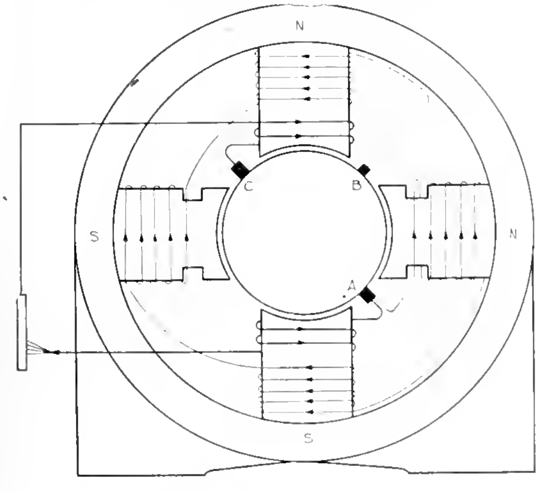


Fig. 5. A Development of the Diagram in Fig. 2, showing the Addition of the Field Windings

In order to establish a working theory, assume that the flux distribution is such as shown in Fig. 2. There exist two fluxes ϕ_m and ϕ_c at right angles; i.e., these two fluxes are displaced ninety electrical degrees in space. The flux ϕ_m will be designated the main flux and the flux ϕ_c the cross flux. If the excitation of the main poles is varied and

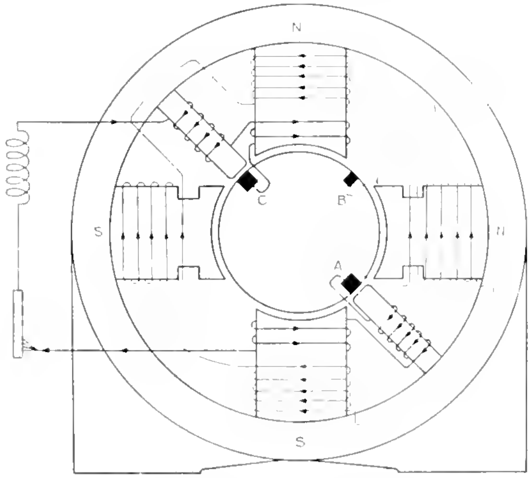


Fig. 6. A Further Development of the Diagrams in Figs. 2 and 5, showing the Addition of Commutating Poles and the Use of an External Reactance

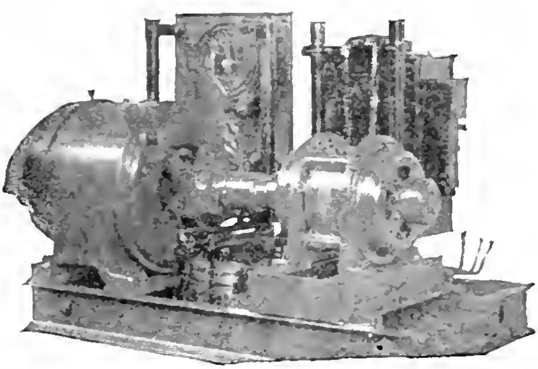


Fig. 7. Rear View of Constant-energy Arc-welding Motor-generator Set Complete with Starting and Control Equipment

at the same time the excitation of the cross poles is kept constant, we obtain a change in the main flux, but the cross flux remains constant; vice versa, if the excitation of the cross poles is changed and the excitation of the main poles held constant, then the cross flux is varied and the main flux remains constant. The reason for this independent action of the two fluxes lies in the fact that the poles are symmetrically located and thus one pair of poles belonging to one magnetic circuit lies at points of equal magnetic potential with reference to the other magnetic circuit. Exactly the same reasoning may be applied to the structure of a standard commutating pole machine having the same number of commutating poles as main poles. In the commutating pole machine we can distinguish two independent magnetic fluxes; viz., the main exciting flux and the commutating flux. These two fluxes are absolutely independent of each other provided that no saturation exists in those parts of the magnetic structure common to both fluxes; viz., the field yoke and the armature core.

The load current of the armature is taken from the two brushes A and C, Fig. 2, placed in neutrals located between poles of opposite polarity. As soon as the armature is loaded an armature reaction is built up which reaction may be resolved into two components at right angles; viz., OD acting in the direction of the main poles and OE in the direction of the cross poles. The component OD supports the main flux and the component OE opposes the cross flux. The main magnetic circuit is so designed that magnetic saturation exists and the component OD, therefore, cannot force any more flux through this circuit Hence, the main flux remains constant independent of the load. The cross magnetic circuit, however, is not saturated; hence, the component OE blows out the cross flux which thus decreases as the load increases. If a third brush B is placed in the neutral between poles of the same polarity it is obvious that the voltage AB remains constant since the conductors on the arc AB are cutting a constant flux at a constant speed. Advantage is taken of this fact to supply the excitation of the generator from these two points which possess a constant difference of potential and thus secure an inherently stable machine at all loads. The diagram of connections for this shunt excitation is shown in Fig. 5.

Referring again to Fig. 2 it may be observed that the voltage BC decreases as the load increases, since the conductors over the arc BC cut at constant speed a flux which decreases as the load increases. Fig. 2 shows that the main flux and the cross flux are entering the armature between the brushes A and C from the same direction. Hence, the electromotive force is induced in the same direction along the arc AB as along

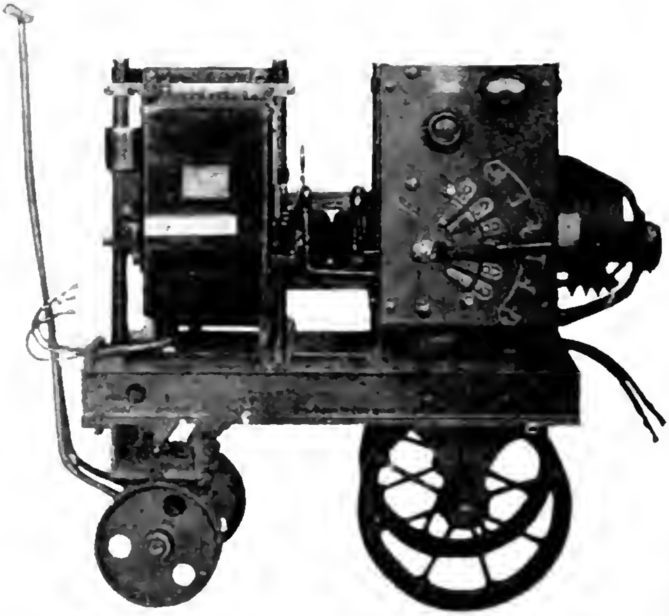


Fig. 8 Front View of the Welding Outfit Shown in Fig. 7 as Mounted on a Truck for Portable Use

the arc *BC*. Therefore voltage $AC = AB + BC$ volts.

Since the voltage *AB* is constant and *BC* decreases with the load, the line voltage *AC* must decrease with the load. The generator is designed to give 60 volts at no load:

$$AB = BC = 30 \text{ volts}$$

hence

$$AC = AB + BC = 60 \text{ volts.}$$

At a certain load the armature reaction is just strong enough to counterbalance the cross excitation; i.e., the cross flux disappears. Then neglecting the small ohmic drop $AC = AB = 30$ volts. As the load increases over this value the cross flux reverses and the voltage *BC* becomes negative. At a certain current, 200 amp., $AC = AB + BC = 30 - 10 = 20$ which is the arc voltage.

If desirable to weld with a smaller current, a series winding is placed on the cross poles having such a polarity as to support the armature reaction, which means that this series field opposes the cross shunt. This series winding is shown in Fig. 5 and is sufficiently strong to limit the arc current to 75 amp. By aid of taps brought out from the series field, the number of active turns may be varied in accordance with the diagram shown in Fig. 3 and any of the following arc currents can be obtained: 200, 175, 150, 125, 100 and 75 amp.

In Fig. 4 are shown the characteristic performance curves of this generator. Each curve corresponds to a series field tap (Fig 3) viz.,

200 amp. corresponds to tap *1*
175 amp. corresponds to tap *2*
150 amp. corresponds to tap *3*, etc.

In order to obtain perfect commutation, commutating poles are added at the points *A* and *C*, Fig. 6, from which the load current is taken. At the point *B* there is no need of any commutating pole since from this brush only a very small current, the exciting current, is flowing from the commutator. Observation has proved that by aid of these commutating poles perfect commutation exists even at the highest loads. In Fig. 6 is also shown a reactance in series with the load. Experience has shown that it is easier to hold a steady arc if a reactance is used since this steadies the current. However, expert arc-welders can weld without the use of this reactance but it is a part of the standard outfit since it has been found desirable for general applications.

The full-load speed of the generator is 1750 r.p.m., this speed having been selected in order to make it convenient to couple this generator to a four-pole 60-cycle induction motor. The horse power of the motor is sufficient to drive the generator at the maximum output. In Fig. 7 the generator is shown direct driven by a standard three-phase induction motor, complete with all controlling equipment. Fig. 8 shows the arc-welding outfit arranged for portable use.

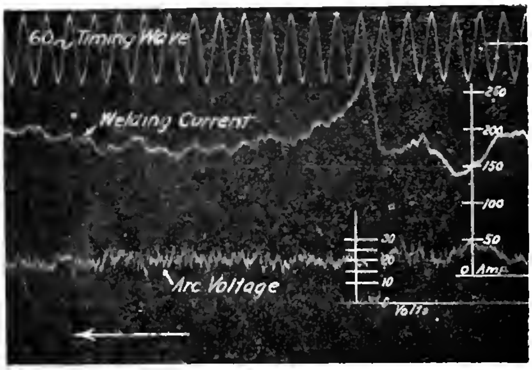


Fig. 9. Oscillogram of Arc Voltage and Welding Current of a Constant-energy Generator showing That the Interaction of the Voltage and Current is Instantaneous

This general arrangement enables the manufacturer to produce one single type of arc-welding generator which may be stocked like any other standard product. With a standard induction motor or a standard direct-current motor it will form an arc-welding set, or it may be belt driven, which from a manufacturing standpoint gives the least possible complications.

The generator has the appearance of an ordinary four-pole machine with two commutating poles. Its manufacture therefore offers no new problems, standard methods being employed throughout.

A thorough and extended investigation shows that a perfect weld can be produced by aid of this machine. One reason for this fact lies in the instantaneous action of the voltage and currents which may be seen from the oscillograph record in Fig. 9. It should be borne in mind that the regulation of this generator is mainly produced by the armature itself. Since the armature is the seat of the induced voltage, it is obvious that if the armature itself is the seat of the regulating power this action is as intimate as can be obtained. Experiments have also shown that it is easy enough to produce a machine which for a steady load gives proper regulation (Fig. 1), but when used for arc-welding absolutely fails due to slow regulation. Such machines will not hold the arc properly and the welds produced are unsatisfactory.

Another advantage of this generator lies in the small amount of power necessary for welding. This may be realized from the fact that a 7½-h.p. motor is sufficiently large to take care of the highest arc output which is 4 kw. It is also of interest to note that when operating from an alternating-current system the power-factor is high, corresponding to the power-factor of the induction motor used to drive the generator.

A New Type of Gathering Locomotive

By John Liston

Publication Bureau, General Electric Company

The output per man in the coal mines of the United States is greater than that of any other country. This result is largely, if not wholly, due to the fact that more machinery is used in the mines of the United States than in those of other countries. The gathering locomotive is one of the most important factors in securing a high per capita output, and its development and refinement has been the subject of continuous study by both mining engineers and electrical manufacturers The particular type covered by this article embodies the latest developments which practical experience has shown to be most desirable for the attainment of a positive and simple system of control which, at the same time, makes it possible to secure maximum operating economy.—Editor.

The electric gathering locomotive has become such a valuable factor in the economical quantity production which modern industrial conditions have rendered imperative in coal mining, that changes in its design and construction tending toward improved control and operating characteristics, reduced maintenance costs, and increased length of service are of great practical importance to both coal mine operators and their engineers.

The new type of gathering locomotive shown in Fig. 1 combines in a single two-motor unit five new features, all of which have successfully withstood such severe and long continued tests in practical coal mine service as to demonstrate fully their general utility.

Electric Braking

By means of a new type of controller (Fig.2) positive and graduated electric braking is secured. Heretofore, in gathering work, there has been a great deal more effort expended in operating the brakes than with the heavy haulage locomotives. The haulage locomotive, as a rule, starts from the same given point and ends at the tipple or shaft bottom a considerable distance away. En-route there are few, if any, stops and the motorman is therefore seldom required to operate brakes on the way. In gathering work the locomotive ordinarily starts and stops many times on account of the switches to be thrown at the room necks, and couplings having to be made to each individual car; therefore, while the gathering locomotive is lighter than the main haulage locomotive, the sum total of braking effort expended by the motorman is considerably greater.

The new controller was designed with the view of relieving the motorman of a large part of this braking and operates so that the locomotive is stopped by its own momentum. This is accomplished by providing on the controller reverse cylinder a set of connections that turn the motors into self-excited generators and the energy developed by them is absorbed in the main resistors. The amount of this energy, and consequently the degree of braking effort, is governed by the main cylinder of the controller. The more resistance cut out of circuit, the more quickly will the stop be made.

The reverse cylinder of the controller is provided with four points, two for each direction of motion. For the first of these points the motors are connected in the regular motoring position. When it is desired to stop, the main cylinder is thrown off in the usual way, and the reverse cylinder is thrown to the second, or braking point. The main cylinder is then turned on again and the motors (or generators, as they are now) begin to retard the locomotive.

The degree of braking is under the motorman's control at all times, for if he finds that he is stopping too quickly, he merely has to throw off the main cylinder and permit the locomotive to coast.

In numerous tests it was demonstrated that, with the trolley disconnected, the residual magnetism of the motors, when acting as generators, was sufficient to insure the maximum braking effect with no appreciable difference in the time element involved as compared with the results obtained with the trolley connected. This is an important factor in estimating the all-around serviceability of electric braking for gathering work.

On a level track the motorman can bring his train to a dead stop without using the ordinary hand brake at all. He can also bring it to a stop on a grade, but since there is no energy developed when the wheels have stopped turning, the locomotive will start and continue to roll, stop and start again unless the hand brakes are set. A runaway is, however, impossible so long as the train weight and grade are within the braking capacity of the locomotive.

With electric braking, the hand brakes, therefore, need to be used very little, and as a result there is very great reduction in the wear of brake shoes and wheel treads as compared with hand braking. Further, with electric braking, since the braking effect is zero as soon as the wheels have stopped rotating, there is practically no skidding of the wheels, and consequently there will be very few, if any, flat spots developed from this cause.

There is another incidental benefit with this type of controller. With the ordinary controller, careless or indifferent motormen do not always use the hand brakes when they want to stop. In many mines it is a rather too frequent practice for the motorman to save effort by reversing the motors when he wants to stop. Stopping in this way, the motors sustain a heavy rush of current and the gearing and other parts of the mechanical equipment receive very severe shocks, all of which tends to shorten the life of the various parts, and runs up the maintenance costs.

The controller is different in another way from the ordinary mine locomotive controller. Most controllers at present are arranged so that the locomotive will start either with the motors in series or with the motors in parallel. Here again the indifferent motorman will not use the series position when running slow. Instead he will leave the reverse cylinder in the parallel position and get slow speed by running on a resistance point. This increases maintenance costs of resistors and, while on slow speed, consumes twice as much current as if the motors were in series.

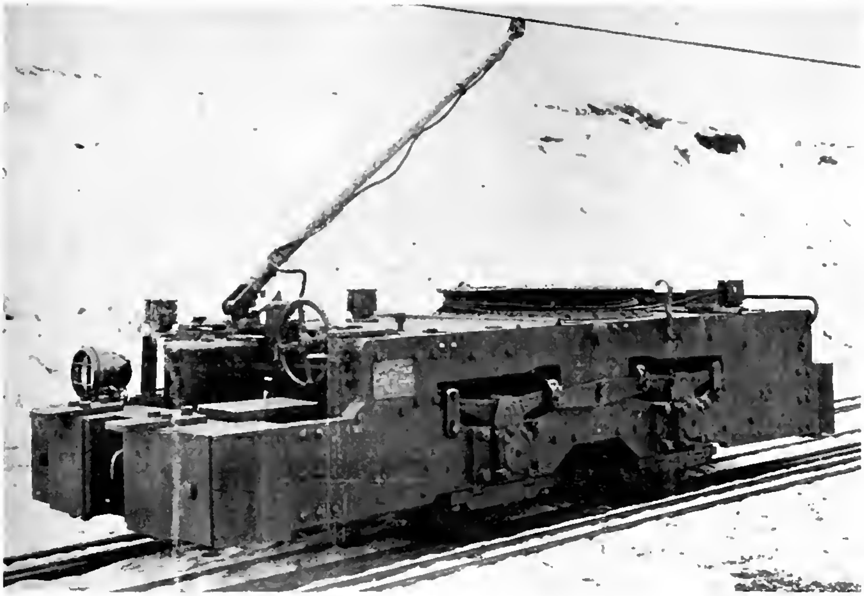


Fig. 1. Eight-ton Gathering Locomotive Equipped with Electric Braking Controller

This question of additional current consumption may not in many cases represent a serious economic loss, but when a number of gathering locomotives are used the total amount of energy wasted in this way in a year of service is always a matter of serious consideration to the mine engineer who is desirous of maintaining a high overall efficiency for the electric system of the mine.

The electric braking controller is a positive insurance against this particular form of waste as it is of the series-parallel type

(Fig. 3) similar to that used on the ordinary street car and the first point of the controller is always series-motors. Therefore the motorman cannot get to parallel until he has gone through all the series points.

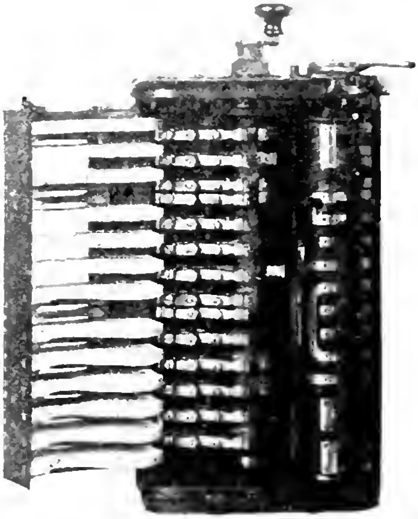


Fig. 2 Electric Braking Controller for Gathering Locomotive

In Fig. 4, the controller is shown with the arc chutes in normal operating position and it will be noted that the apertures are greatly restricted as compared with ordinary controller construction. This arrangement was adopted after exhaustive tests had demonstrated that by this means the arc could be extinguished in about one third of the time required with the more open form of arc chute.

This detail insures longer life for the contacts as for all practical purposes their length of service is inversely proportional to the time of duration of the arc.

Outside Frame

The outside frame construction adopted for the new locomotive (Fig. 5) is very substantial. The side frames are cut from solid rolled steel plates; the end frames are built up with structural steel channels, rolled slabs, and wood bumpers protected by heavy face plates.

The outside frame in this case differs from the usual machine of this type, in that the clearance between the rail head and lower edge of side frame is very high. Ordinarily an outside frame machine would clear the rail head at this point by three or four inches. When the locomotive derailed, the frame would settle down to about the level of the rails and cover up all access to the wheels. With this new construction, the high clearance of the frame permits access to the lower part of the wheel so that blocking or other re-railing devices may be put into position, and the locomotive gotten back on the track practically as quickly as if the wheels were outside of the frame.

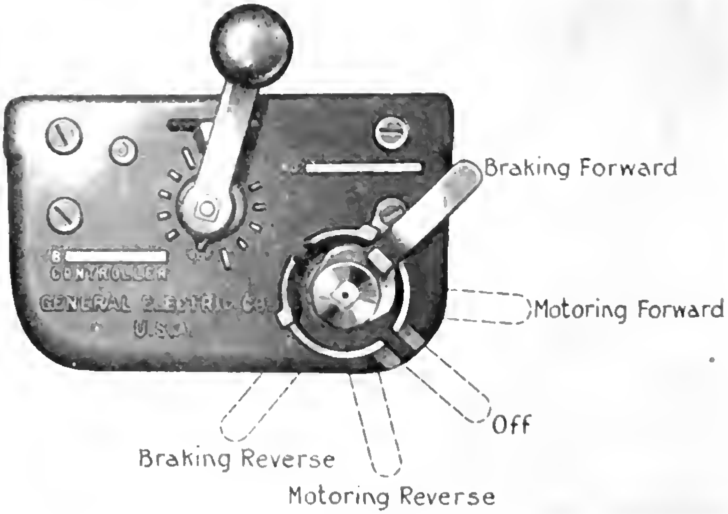


Fig. 3 Top of Electric Braking Controller Showing Control Levers

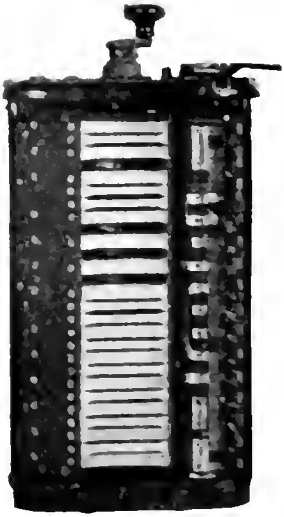


Fig. 4 Arrangement of Restricted Arc Chutes on Electric Braking Controller

There are, of course, some mines where side clearance will not permit the extra width of the outside frame type machine, but as a rule the main objection to this type of construction has been the difficulty of getting it back on the track in cases of derailment. The high clearance feature should remove this objection.

On the other hand, the outside frame construction permits the use of a better journal box, in that it is entirely enclosed at one end, and the back end can be fitted with a dust guard. With an inside frame both ends of the box must be open and boxes must also be made in two halves, which is not as good construction either theoretically or practically. With the outside frame the greater space between the side frames allows more room for the equipment and permits the use of a liberal amount of space for the motorman's cab.

Leaf Type Springs

Heretofore, practically all two-motor locomotives have been equipped with the round wire coil type of journal spring, whereas the heavier three-motor locomotives were provided with leaf type springs to insure smoother running and better distribution of the weight on the drivers on rough and uneven tracks.

As the result of operating experience gained with the three-motor units, the new locomotive was provided with semi-elliptic leaf type springs (Fig. 6) having an equalizing bar between the two journal springs on each side.

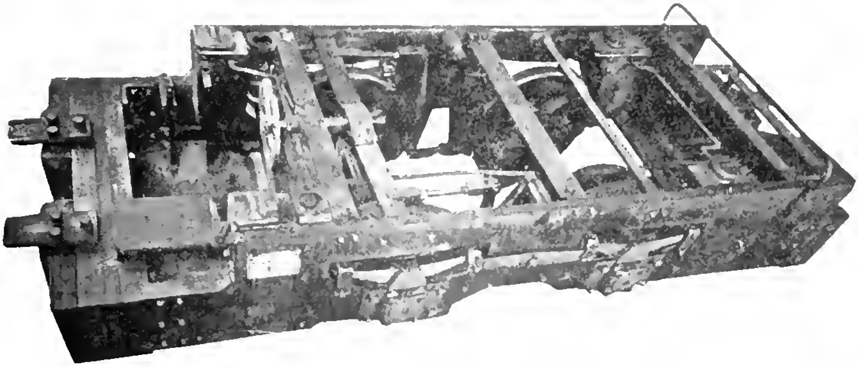


Fig. 5. Outside Frame Construction showing Liberal Space Available for Equipment and Motorman

Due to limited space in the overall dimensions of mine locomotives, the leaf springs can be designed with much greater margin, approaching the elastic limits of material used, than is the case with helical spring design and, therefore, they are mechanically stronger and less liable to breakage.

By using leaf springs and equalizers, the two-motor four-wheel locomotives will accommodate themselves to inequalities in track levels, for the reason that any change in wheel load is transmitted through the equalizing levers to the other wheels, thereby practically equalizing the weight on the drivers. Incidentally, the equalizing lever greatly increases the range of spring action and the tendency toward derailment is thereby minimized.

Fig. 6. Journal Leaf Springs with Equalizer Bar

Finally, the improved riding qualities of the locomotive tend to reduce the wear and tear on the track and roadbed.

Improved Cable Reel

This cable reel is an improved form of the vertical axis motor driven type which has been used successfully for a number of years. No change has been made in the ball bearing motor, but the bearing mechanism of the reel itself has been modified to secure greater stability and better wearing qualities.

Instead of a large diameter of bearing made up of a large number of small balls, the reel now rotates on a heavy duty type combination thrust and step ball bearing (Fig. 7) mounted at the center of the reel disk. The double reduction train of gears is made up entirely of forged steel gears and pinions, heat treated.

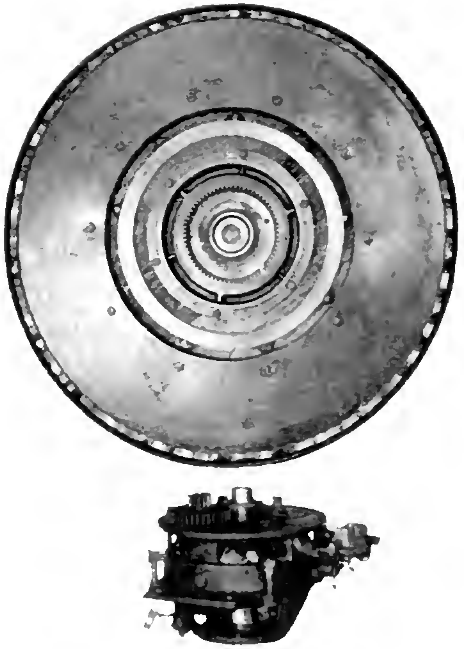


Fig. 7. Under Side of Cable Reel showing Motor-driven Gear Train

Demountable Tires

The construction of these tires (Fig. 8) is very simple and consists merely of two wedge-shaped steel rings drawn together at suitable intervals by bolts. In drawing these rings into position the tire is forced to take its proper alignment with respect to the wheel hub and gauge line, and the wedging action of the rings locks it securely in place.

It will be appreciated that the renewal of this tire is a very much shorter job than in the case of the ordinary shrunk on tire. Socket wrenches are the only tools required, and the change can be made in the locomotive barn. With outside frame locomotives it is only necessary to drop the axles, and with inside frame locomotives the change can be made without taking the axle out of the frame.

The advantages of these demountable tires will be fully appreciated by anyone who has had to replace a shrunk on tire, as the complete replacement of the new tire can be effected by two men in about fifteen minutes for each wheel.

With the co-operation of Mr. W. A. Chandler, Electrical Engineer of the H. C. Frick Coke Company, a 6-ton gathering locomotive with an experimental braking equipment of the type here described was placed in service at the company's coal mines near Uniontown, Pennsylvania, and has been in successful operation for the past two years, during which time the necessary refinements were worked out under actual service conditions.

A 20-ton main haulage locomotive with similar braking control has been handling loaded trains on a 4000-ft. line with four to five per cent grades for about one year. It is, therefore, evident that the principles embodied in the new gathering locomotive have fully demonstrated their value in actual service.

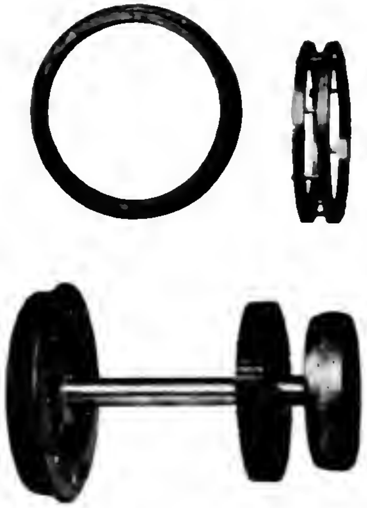


Fig. 8. Demountable Tires Assembled and Disassembled

The new locomotive was designed by the engineers of the General Electric Company.

Self-interest Will Solve the Problems Confronting Electrical Development

Arranged for General Electric Review from an address before Schenectady Section A.I.E.E.

by A. Emory Wishon

Assistant General Manager San Joaquin Light and Power Corporation,
Pacific Coast Manager N.E.L.A.

In many respects the central stations of the country are in the same position as the railroads; their rate of income is regulated by commissions and the enormous increase in the cost of labor and materials has reduced the return on the investment to a point where frequently it is difficult or impossible to attract additional capital for new development that is urgently needed. The solution of the difficulty lies in making a clean breast of the situation to the public, and showing each community just what it is losing from the inability of the central station to supply increased service. The central station that is fair and square in its dealings has nothing to fear from taking the public into its confidence; and by convincing the individual of the fact that whatever hinders the development of the central station will also keep money out of his pocket the greatest obstacle facing the electrical industry will have been surmounted.—Editor.

A. EMORY WISHON

The value to a public utility of preaching the doctrine of Self-interest can be deduced from the case of the railroads. A few years ago we heard from time to time that the railroads were in need of more revenue in order to pay a fair return on the capital invested and in this way to attract new capital for the purpose of increasing and replacing rolling stock and improving transportation facilities generally. We gave the matter no thought; in fact, we were not inclined to believe that there was a real need for additional revenue. We preferred to believe that the railroads were receiving ample return for their services and straightway forgot the matter. Later on, when the war broke out and our business was hurt because we could not get shipments through, when there was an embargo on freight in all parts of the country, and we could not even get coal to run our factories because of the inability of the railroads to haul it, we began to take a personal interest in the railroad situation; and lately we have actually become sympathetic with the arguments of the railroad managements for revised legislation to enable them to earn a fair rate of return. The average business man has lost a great deal through the inability of the railroads to provide prompt and adequate freight service, and today he realizes that his prosperity and that of his community is dependent on the success of the carriers. He is now an advocate of a sufficient increase in freight and passenger rates, although he knows that he and his fellow citizens are the ones who will have to pay this increase. *Self-interest of the individual is reflected from every angle in the recent national legislation that has been enacted for the benefit of the railroads.*

The electrical industry today is equally as important to the public as are the railroads, and the problems of the central station—the source of electric energy—are very similar to the problems of the railroads. In each case their rates of return are regulated by commissions. Sufficient rates to return the authorized amount of earning on the investment will enable the power company to finance and do more development work; lack of return will restrict its expansion and accordingly the expansion of every line of business connected with the electrical industry.

The following statements are axiomatic:

(1) Central station development is the barometer that indicates the degree of

prosperity in the entire electrical industry, because the central station is the source of electric energy that is required by all the common electric appliances, such as railway and power motors, arc and incandescent lamps, electric furnaces, flatirons and other heating devices in the household, etc.

(2) If the electrical industry is to thrive the central station must develop to its fullest capacity. Central station expansion requires financing, and to attract the necessary capital a protected investment and a fair return are necessary.

(3) A fair return is possible only through unbiased and fearless legislation.

(4) Legislation should, and usually does, represent the opinion of the voter.

An analysis of these statements leads to the conclusion that the greatest problem that faces the electrical industry today is to make the public understand what electricity is doing for the nation. This is a big undertaking, but it is not so difficult as it appears at first sight.

It is possible to create real personal and active interest in the progress of electrical development in any community by impressing on the mind of the individual what the world would be today without electric energy, what it would mean to be without electric light or power, without our trolley cars, telephones and telegraphs, without the many comforts and conveniences provided by electricity in the home, and without possibilties. The electrical industry is that wonderful activity which makes possible the world of today, on which depends every line of business for efficient and speedy production, and on which will be based the standards of living of the future.

However, these advantages conferred by electricity are now largely taken as a matter of fact by the public, and the public will not be interested and will not understand the problems that confront the electrical industry until it is shown that these problems are also the problems of the individual, because he cannot do without the many things that electricity is doing for him every day. It is necessary to show every man separately what stagnation in the electrical industry will cost him in dollars and cents, or more correctly, what he stands to gain by exerting his efforts and influence to the end that electrical development may progress to the fullest possible degree.

It is a relatively simple matter to show that any form of legislation, national or state, that delays electrical development delays the development and prosperity of the state and of the nation, and any thinking man by means of a few figures can show where any particular business loses in dollars and cents when hydroelectric development ceases. Prove your case to the individual by proving that the individual's pocketbook is hurt when your business is hurt and you will have a champion who will see that your business will prosper.

When electrical development ceases the prosperity of the dealer, contractor, jobber and manufacturer ceases, and when electrical development is encouraged their business is furthered.

We will consider conditions that exist in the West. Those who have studied the industrial problems of the West know that this section of the country will not develop ahead of its hydroelectric development. Large tracts of western territory are arid lands and depend upon hydroelectric power for irrigation if agriculture is to be further extended. If factories are to be built in the West cheap power must be obtainable.

This western country is yet a long way from electric saturation and will be for many years to come. The engineers and commercial men of the central station companies have plotted their anticipated load curves for several years into the future, basing their estimates upon past experience. By superimposing these projected load curves a composite curve is obtained which shows what increase in generating capacity can be expected for this territory during the next decade, if proper encouragement is given to electrical development. The electrical investment to date is known and also the total kilowatt capacity of equipment, and from these figures the unit cost per kilowatt installed is determined. We are thus enabled to determine for any year in the future the money that will be spent for electrical development in the West

Curves for the entire Pacific Coast will be presented at the National Electric Light Association's Convention at Pasadena in May. These curves will show that within the next eight years approximately $500,000,000 of new capital will be expended in electrical development in this section. From the standard classification of accounting established by the California Regulating Commission for public utilities it is an easy matter to determine the proportionate amounts that will be invested in generators, dams, transformers, copper, etc., during this period if normal conditions continue. These data are all available and it only remains to put them together in graphic form to prove to the individual and to the different interests what this tremendous electrical development in the West will mean to each one in dollars and cents.

To show how this applies to an individual we will take the case of the manufacturer's representative. He is shown by definite graphic proof that if conditions are encouraging a certain load can be added to the Pacific Coast central station systems in the next year. We know the cost of construction per kilowatt of capacity and quickly figure out for the manufacturer's representative just how many millions of dollars will be required for added generating equipment, dams, feeders, etc., to take care of this extra load. Our segregated investment chart shows, for instance, that eight per cent of the money required for this addition to plant will go into transformers. If the manufacturer's representative is wide awake and on to his job he will know at once what part of this transformer business should be his. He will know what his net profits are to be in the sale of those transformers, and he can figure in dollars and cents just what it means to him to have this development go through.

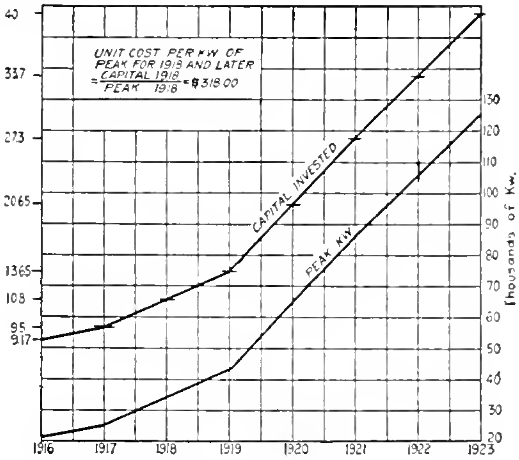


Fig. 1. Curve Showing Estimated Peak Loads of the San Joaquin Light and Power Corporation

This is a direct appeal to the man through his pocketbook, and he will be interested to the extent that he will use his best influence to see that conditions are favorable for the development.

He does not stop there, however. He wishes to convey to the manufacturer the impression that he is on the job, and accordingly communicates the glad message of Self-interest to the sales manager, who will straightway become interested in furthering electrical development on the Pacific Coast.

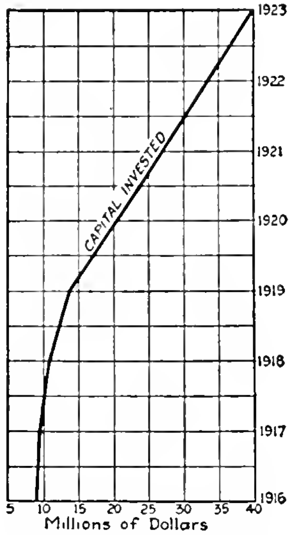


Fig. 1a. Total Capital Invested, Exclusive of Real Estate, Supplies on Hand, etc., San Joaquin System

The manufacturer in turn spreads the message to the steel mill, to the copper mill operator, and to the railroad that will transport the equipment, emphasizing the importance to each one of encouraging electrical development on the Pacific Coast.

That you may judge of the effectiveness of Self-interest in promoting favorable conditions for electrical development, three curves are shown that have been compiled by the San Joaquin Light & Power Corporation. Not forgetting the five hundred million dollars we have said will be required for electrical development in the West during the next eight years, we will, however, confine ourselves to the lesser requirements of the San Joaquin Company, which are typical. This company is at present working night and day on a new 30,000-kw. hydroelectric plant that will be in operation by September. Also, five engineering crews are completing the survey of a hydroelectric development that will have an ultimate capacity of 160,000 kw. Conditions are the same the West over; the public is clambering for electric service and the power companies are making every effort to serve.

Fig. 1 shows that during the next four years the San Joaquin Company will require $26,000,000 for hydroelectric development. This statement is of monetary interest to a great variety of businesses and individuals. The Eastern bond house is interested in this expenditure by the amount it means in commissions on the underwriting and sale of bonds; the electrical jobber is interested to the extent that he will profit from the sale of electrical supplies, not only supplies required for the development but those which will be needed by the new industries which will make the development necessary. The electrical manufacturer is interested in this hydroelectric development in the West because of the profits he will derive from the manufacture of apparatus; and viewed from another angle, the various local industries are interested to the extent to which they depend upon electric power for operation and expansion.

Fig. 2 is a diagram that immediately excites Self-interest. The item that will first command your attention is the item that affects your business; it is invariably so with every man, and it is this fact which proves that the theory of interesting through Self-interest is sound.

Fig. 3 is a segregation by percentage of home building costs. From over 2000 applications for power service made to the San Joaquin Light & Power Company 1200 were applications for agricultural service. Six hundred of these were for the development of new lands requiring homes, barns, fences, and all sorts of farm equipment. Figures that have been compiled show that for every home in the country there are two homes in town. Therefore, when electric service is rendered on these farm applications and the 600 new farm homes are built there will also be 1200 town homes constructed, or in all 1800 additional homes will have been built due directly to electrical development. This represents a building construction program involving $10,242,000, and from our segregation diagram it is possible for the lumberman, the brick manufacturer, the lumber mill, the electrical jobber, and all the several trades involved to figure just what percentage of this business is his. With 15½ per cent of this investment in new buildings going to carpenter work it is only necessary to point out the figures to the carpenter to completely win him to this hydroelectric development which make possible this home building program.

The results of efforts in the West in spreading the doctrine of Self-interest demonstrate beyond question that the solution of the greatest problem that faces the electrical industry today will be an accomplished thing if every man in the ranks makes it his aim and duty to impress upon the public what the development of the electrical industry means to the individual in dollars and cents. When a realization of the simple facts sinks home the public will see to it that nothing interferes to delay electrical development, that fair and adequate legislation is enacted and supported to the end that the return on the investment will be sufficient to attract the necessary capital.

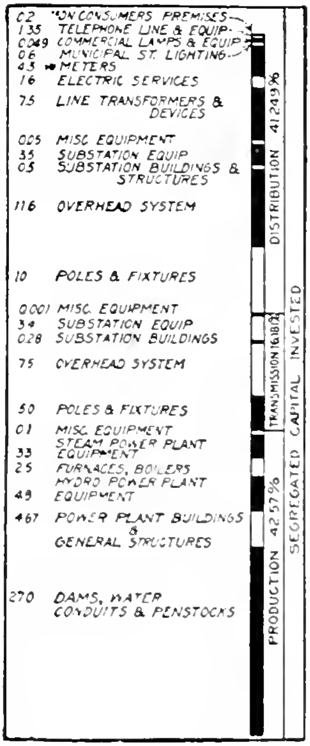


Fig 2 Chart Showing Segregation of Capital Investment of San Joaquin System. The item which first attracts your attention is the one that affects your business, which proves the soundness of the doctrine of Self-interest

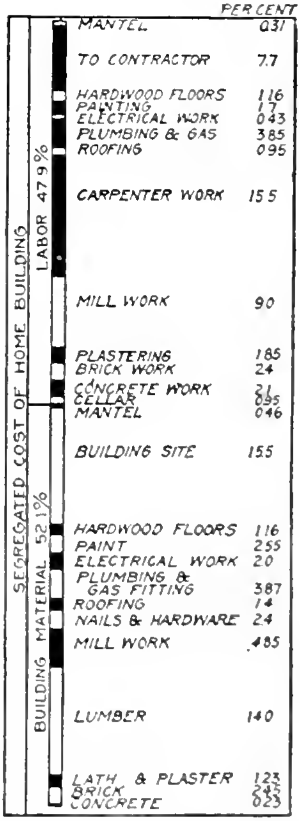


Fig 3. Segregation of Home-building Costs on Pacific Coast. This is a Self interest chart which may be used with unfailing success to enlist the co-operation of every business in the community

The *Mariner:* The First Electrically Operated Trawler

By John Liston

Publication Bureau, General Electric Company

In previous articles in the Review we have described the electric propulsion equipments of the U. S. collier *Jupiter* and the battleship *New Mexico*. With such large vessels the question of economy is of prime consideration, but for vessels smaller than, say 1000 tons displacement, it is doubtful whether this factor alone would warrant the additional expense necessary for electric generators, motors and control equipment. For such vessels it is the flexibility afforded by electric propulsion that strongly appeals to the marine engineer. The electrically propelled vessel described in this article is of only 500 tons displacement.—Editor.

The adoption of electric propulsion for the beam trawler *Mariner* (Fig. 1) was the logical result of the efficient and economical operation secured with this system in numerous craft of various kinds, both in Europe and America during the past twelve years.

In designing the equipment for the *Mariner*, the inherent flexibility of the electrical method of power application made it possible to obtain high economy in fuel consumption, especially under cruising conditions, sustained uniform rate of rotation for the engines, positive control of the propeller speed at all times, a high factor of safety by means of three separate control station, practically instantaneous reversal of the propeller, and the use of electric motors for driving auxiliaries such as pumps, compressors, hoists and ventilating blowers.

The craft is of wooden construction, and is rated at 500 tons with dimensions as follows: length, over all, 150 ft.; beam, 24 ft.

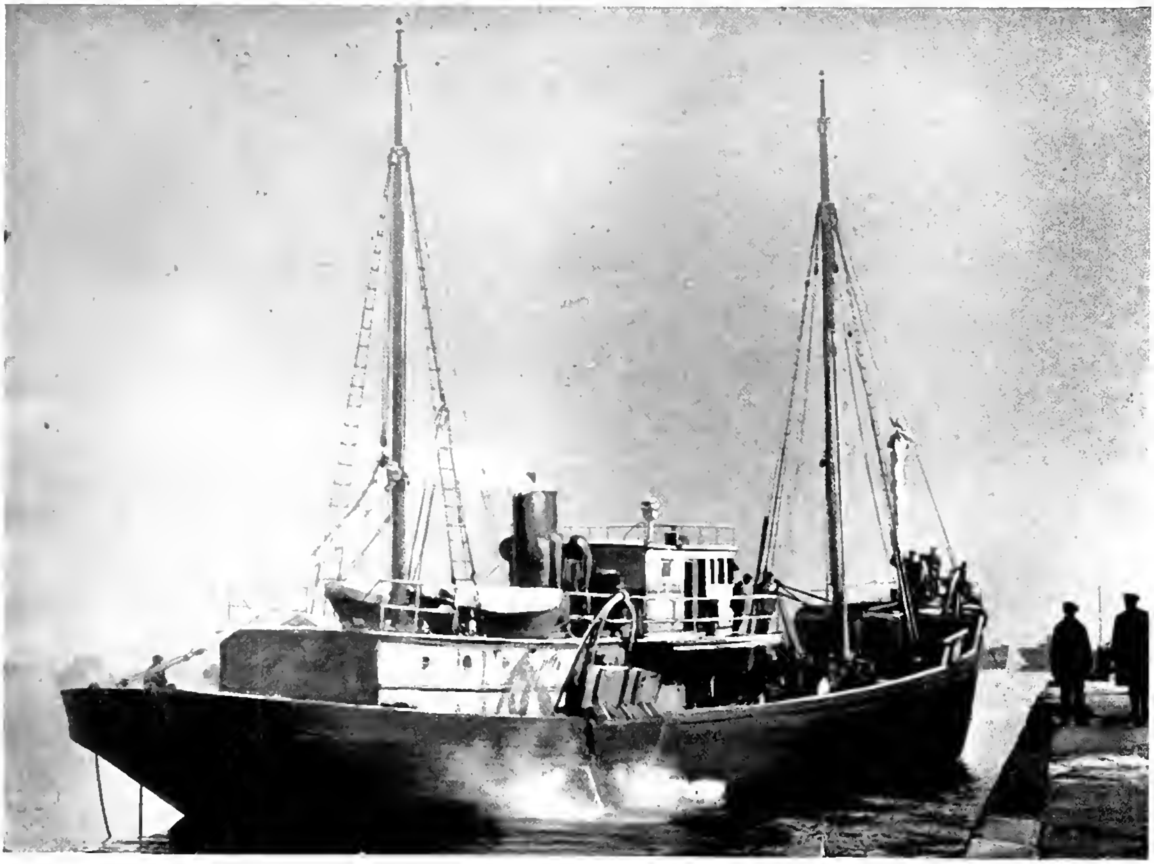


Fig. 1. The Beam Trawler *Mariner*

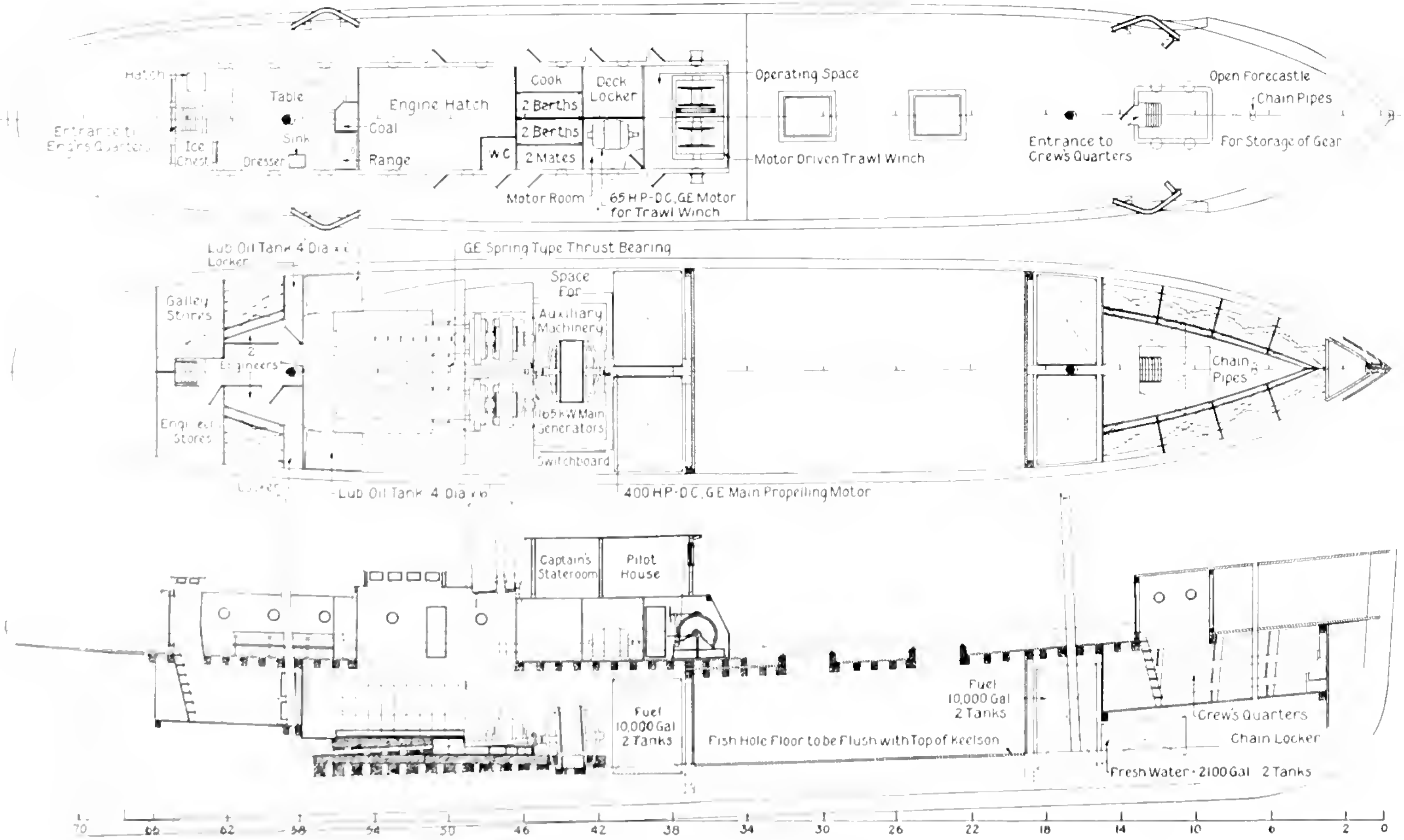


Fig. 2. Arrangement of Propelling Machinery

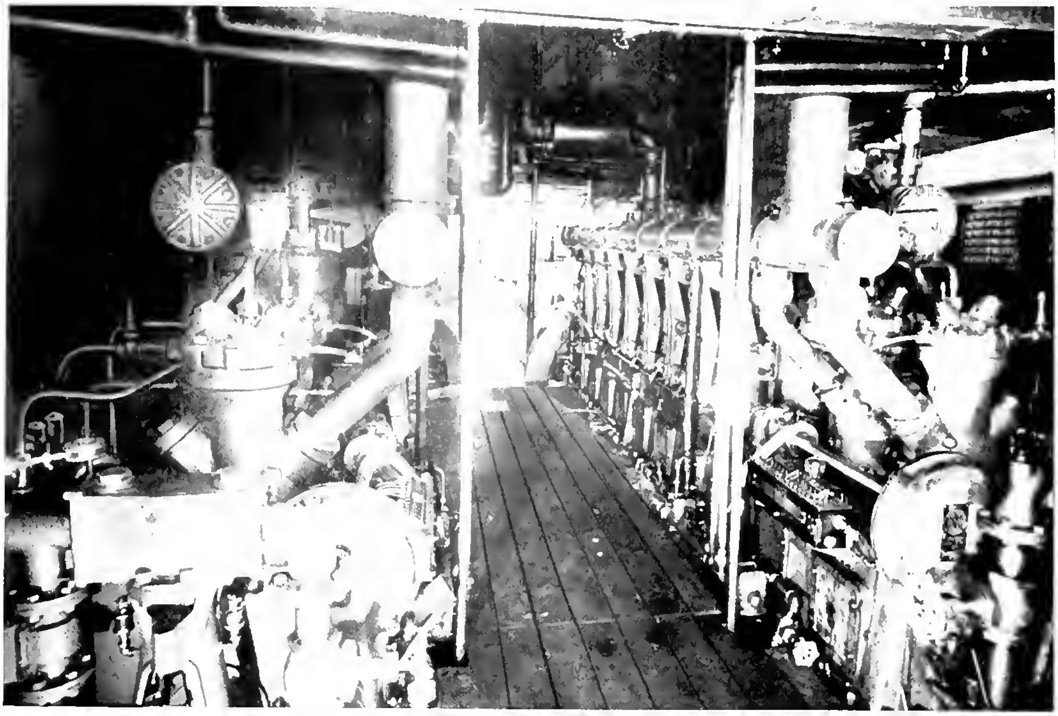


Fig. 3 Engine Room (looking forward), showing Arrangement of Diesel Engines Driving the Main Generators

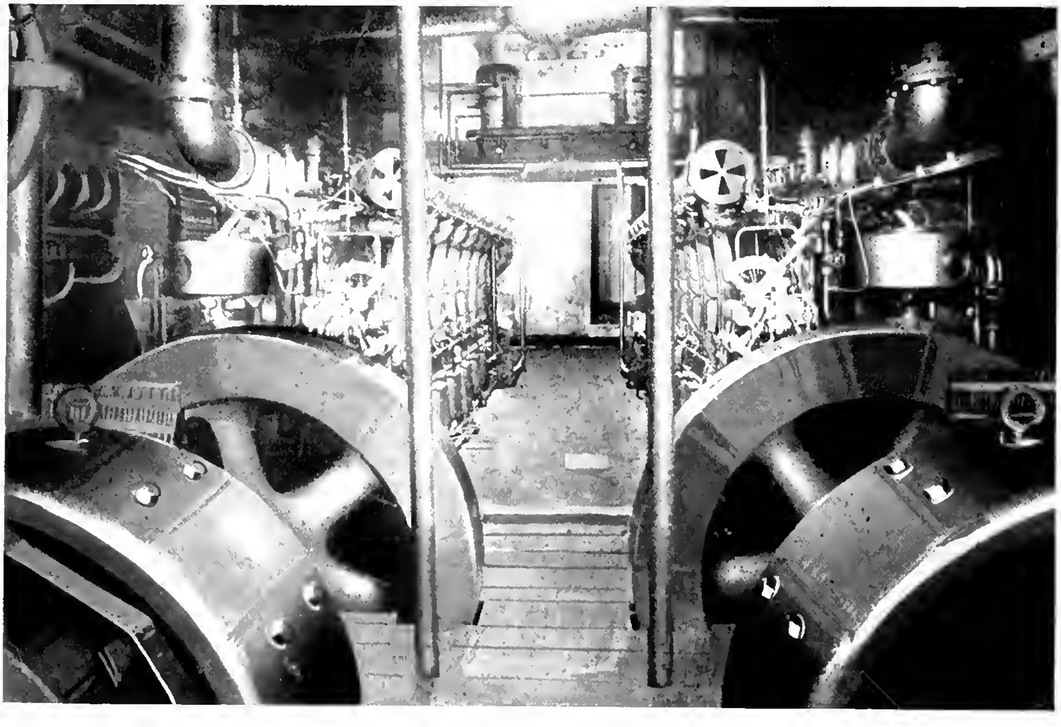


Fig. 4 Engine Room (looking aft), showing Main Generators with the Engine Flywheels Carried on the Generator Shaft Bearings

3 in.; mean draught, 11 ft. 9 in. Her cruising radius at 10 knots is 6000 miles and, at three-quarter speed, 9000 miles.

The propelling equipment (Fig. 2) comprises two eight-cylinder, four-cycle, 350 r.p.m. Diesel engines (Fig. 3), each direct-connected (Fig. 4) to a 165-kw., 125-volt, direct-current generator. The two self-excited generators are normally connected in series and supply current to a 400-h.p. 250-volt, 200-r.p.m. motor (Fig. 5), which is direct-coupled to the propeller shaft.

Two control stations are located in the engine room—one provided with remote control, and one arranged for emergency manual operation; and a remote-control outfit is also located in the pilot house.

Both the generators and the motor are designed specifically for sea duty, and are provided with non-corrodible fittings and heat-resisting insulation throughout. The bearings are a combination of waste-packed and oil-ring type, with special provision against the leakage of oil along the shafts, when the machines are out of their normal positions, due to the rolling and pitching of the ship. Finally, armatures and fields are waterproofed, and the machines are so designed as to prevent flashing in the presence of moisture, due to either atmospheric conditions or flooding of the engine room in rough seas.

In order to insure ample mechanical strength for the electrical machinery, steel castings were used for all rotating parts which would be subjected to unusual strains, or to shocks incident to operation during stormy weather.

The 400-h.p. propeller motor is located forward of the generating sets (see Fig. 2) and has a normal full-load speed range of from 160 to 200 r.p.m. It is a compound-wound machine and, when taking current from both generators, it operates at 250 volts; but, for slow cruising, one engine can be shut down and the motor then receives current at 125 volts. Under these conditions it has a speed range of from 70 to 160 r.p.m.

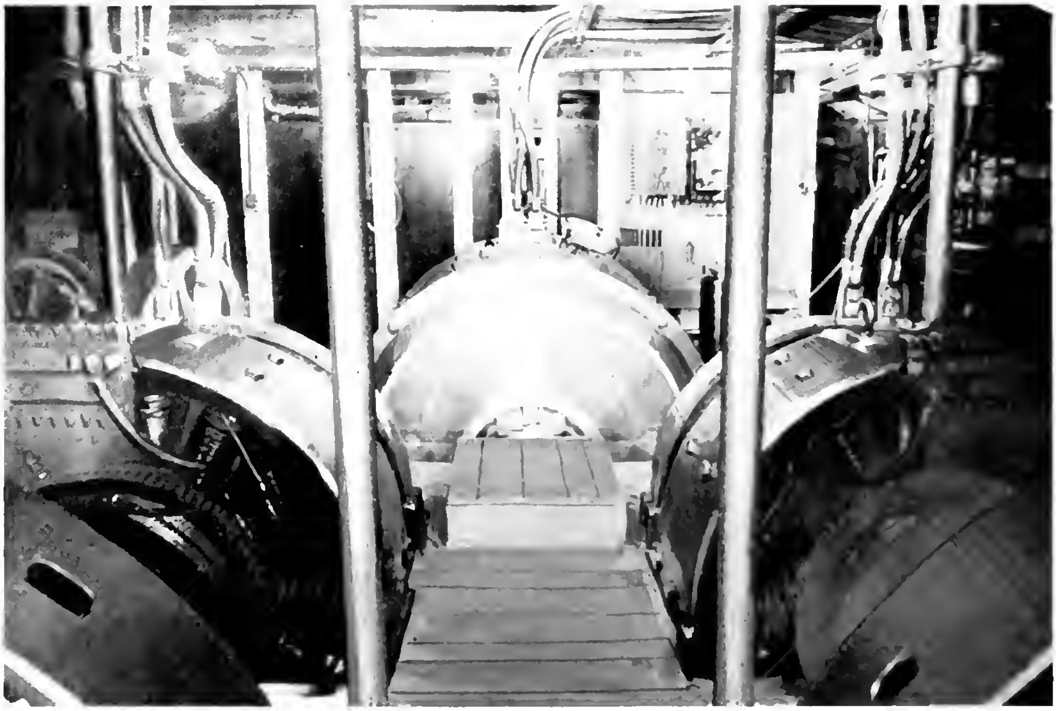


Fig. 5. Forward End of Engine Room (looking forward), showing Main Generators and Propellor Motor with Master Controller at Right

The propeller is 91 in. in diameter by 68 in. pitch and, at full-load rotation of 200 r.p.m., gives a speed of between 7 and $10\frac{1}{2}$ knots, depending upon weather conditions. When hauling the net the full horse power of the motor is developed at a propeller speed of 160 r.p.m.

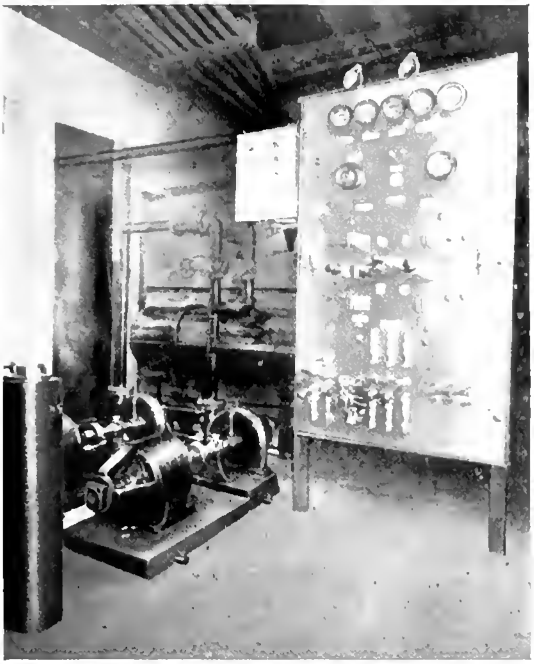


Fig. 6. Main Control Panel in Engine Room and at Left Motor-driven Bilge and Water-supply Centrifugal Pumps

Engine-room control of all electrical circuits is secured by means of a main panel board (Fig. 6), on which are mounted the engine-room meters, generator field switches and rheostats, switches and fuses for the propelling and auxiliary motors, and an overload relay for the main hoist motor. The meters are mounted at the top of the panel and are special instruments designed for shipboard work being equipped with moisture-proof, non-corrodible parts. The d'als are black with white markings, with radium paint on the needles and dial markings. A duplicate set of these instrumenst is installed in the pilot house.

The starting rheostat resistance consists of five boxes of grids (Fig. 7), which are mounted on the starboard side of the engine room. Just forward of these grids, the control contactors (Figs. 8 and 9) are located. This group consists of the necessary current-carrying contactors for starting, stopping and reversing the motor, an overload relay and motor-shunt field discharge resistance, and is normally operated by means of one of two master controllers—one located in the engine room and the other in the pilot house.

During operation from either of these master controllers, the contactors are closed

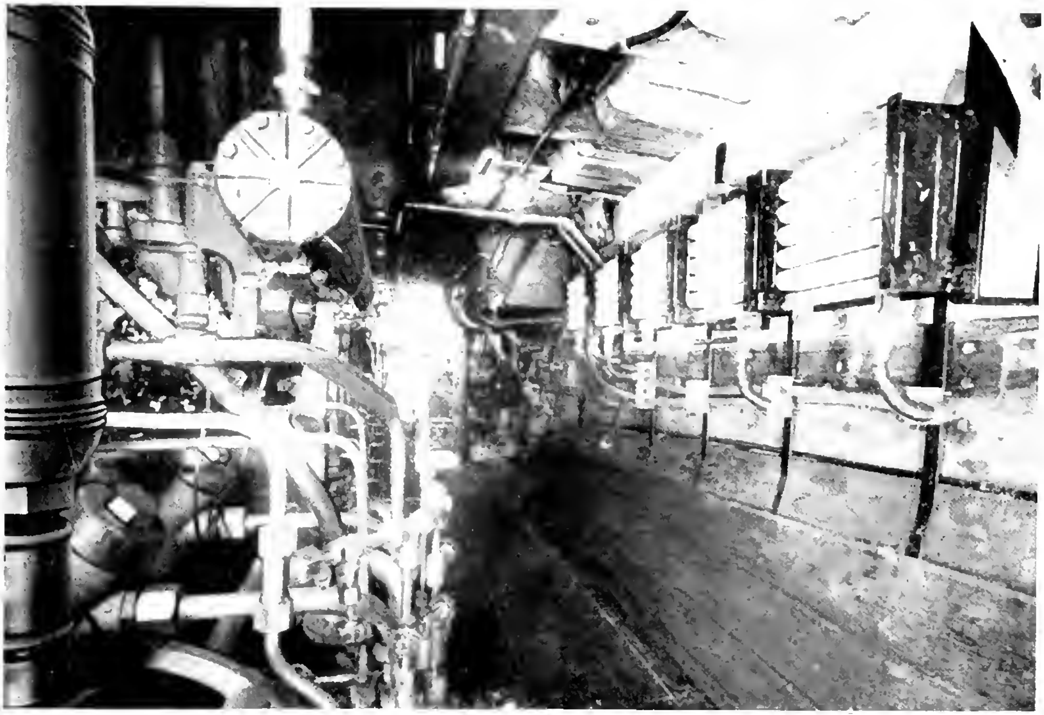


Fig. 7. Engine Room (looking forward, starboard side), showing Bank of Resistance and Amount of Working Space at the Side of the Engine

magnetically; but, if for any reason they cannot be operated magnetically, handles attached to cam shafts are provided which may be operated manually to close the contactors in the desired sequence. The overload relay, in case of overload, opens the circuit through the reversing contactor coils,

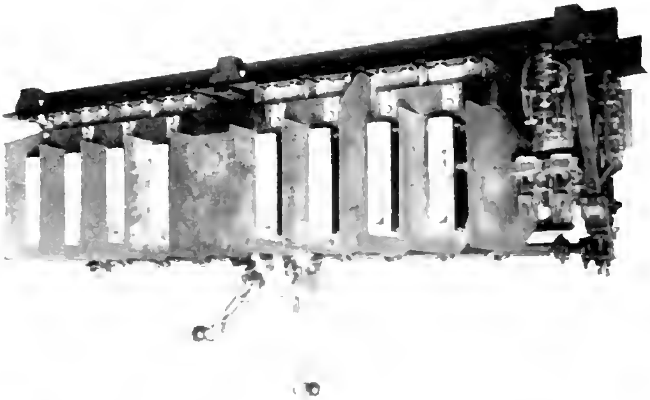


Fig. 8. Arrangement of Main Control Contactors (front view), showing Arc Chutes and Flush Barriers

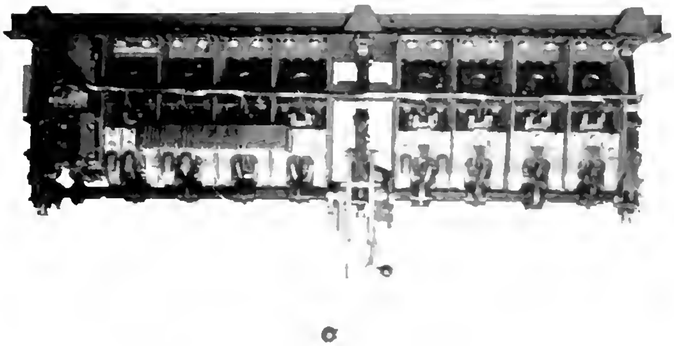


Fig. 9. Main Control Contactors (back view), showing Interlocking Levers for Hand Control

causing them to open the line circuit. The handles for manual operation are so interlocked that the reversing handle must be operated before the accelerating handle; and, therefore, the accelerating handle must be turned off before the reversing handle can be moved. This arrangement insures absolute safety for the control system of the ship, even in the very improbable event of failure of, or injury to, the two remote control equipments.

One of the important advantages of electric propulsion is that of remote control, which permits the actual maneuvering of the ship, to be accomplished directly in the pilot house, if desired, without the necessity for signals to the engine room. At sea, this remote control system is normally only a convenience, as compared with the ordinary combination pilot house and engine-room control; but, in entering and leaving slips in congested harbors, in narrow and swift current waterways, and for quick reversal or change of speed in emergencies, its great practical value is obvious.


Fig. 10. Type of Master Controller Used in Pilot House and Engine Room

The type of master controller installed on the *Mariner* (Figs. 10 and 11) consists of a cast-iron frame, with a sheet-metal cover, in which are mounted a main control cylinder and a reversing cylinder. The construction of the frame and cover is such as to make the controller practically watertight, the cover clamping against felt in a groove in the frame. The control wiring is taken out of the controller at the bottom through the base.

There are two handles on the controller—one main and one reversing. The main handle rotates the main cylinder, which gives 17 operating positions, one off-position and one overload relay reset position. The reversing handle rotates the reversing cylinder and has three positions: ahead, off and astern.

These two handles are so interlocked that the main handle cannot be moved beyond the overload relay reset position unless the reversing handle is in either the head or astern position, and so that the reversing handle cannot be moved unless the main handle is in either the off or reset position.

The rapidity with which the motor-driven propeller can be reversed was demonstrated during the first trial trip when, with the propeller rotating at from 193 to 196 r.p.m., it was reversed from full speed ahead to full speed astern in thirteen seconds; the actual reversal of current in the motor being accomplished in two seconds.

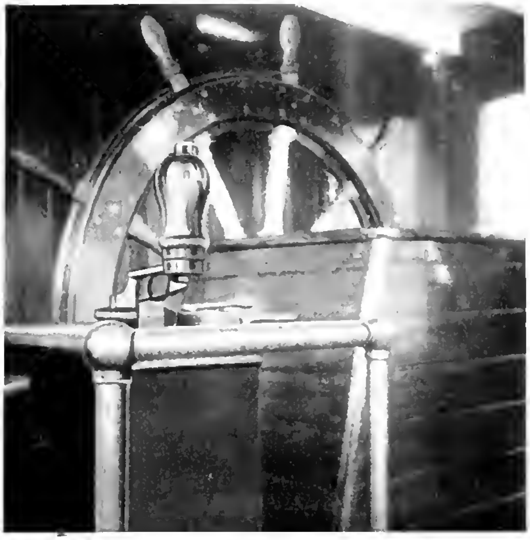


Fig. 11. Arrangement of Wheel and Master Controller in Pilot House

Pilot-house control was used throughout the test run, operating either one or both generators with equal facility. The following extracts from the report of the trial trip may be of interest:

"On Wednesday morning, December 3, 1919, started from New London at 8:45 a.m. and followed a course out around Fisher Island, easterly between Point Judith and Block Island, through Vineyard Sound and around Pollock Rip Lightship; then northerly to Highland Light at the end of Cape Cod; and from there straight away for Gloucester, which we reached at 5:45 a.m. on December 4, 21 hours after leaving New London over a course, estimated by the skipper of approximately 200 nautical miles."

"The best speed attained by the boat during the trip was in the easterly part of Vineyard Sound where, with a favorable tide, it reached approximately $11\frac{1}{2}$ knots. After turning north along Cape Cod there was a head wind with quite a rough sea, so that the speed of the boat was considerably reduced."

"The *Mariner* ran very steadily and the absence of vibration was very noticeable."

"No criticism could be made on the electrical design of either the generators or motor, as the machines operated over the entire range of load without sparking or distress."

Fig. 12. Spring Thrust Bearing for Propellor Shaft

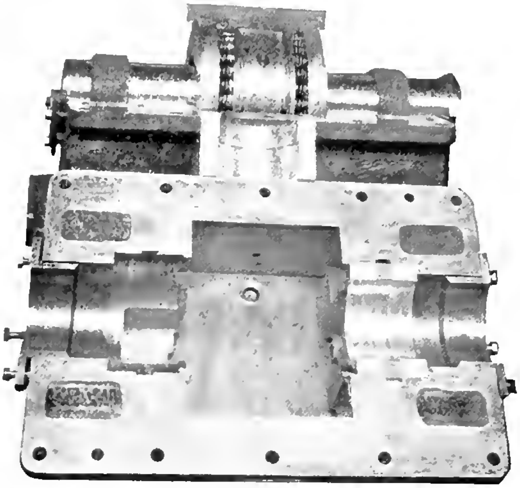


Fig. 13. Upper Housing Removed from Spring Thrust Bearing

Instead of the usual rigid multi-collar type of thrust bearing, a self-oiling spring thrust bearing (Figs. 12 and 13) of the single-collar, self-aligning type is used, located aft of the driving motor and sustaining a thrust of 7500 lb. with the propeller revolving at 200 r.p.m.

In addition to operating the propelling equipment, electrical energy is used for lighting and all auxiliary power purposes and, when the main engines are shut down, current is supplied by means of an independent 15-kw., 125-volt, oil-engine-driven generator (Fig. 15) installed in the forward end of the main engine room on the port side.

The emergency air-compressor outfit is driven by a direct-geared motor (Fig. 14), and is provided as an insurance against the improbable loss of starting air for the engines. Under these conditions it will be utilized to fill the air-starting bottles, as the auxiliary generating set can be started by hand.

The bilge and water-supply pumps are small centrifugal units (Fig. 6), each driven by a direct-coupled motor, and near the main generators and propeller motor a small motor-driven ventilating set is utilized to prevent excessively high temperature in the engine room.

The fishing operations are carried on by means of a 65-h.p., motor-driven, main double-drum hoist, installed on the main deck forward of the engine room, which handles the haulage cables and ropes of the net as they pass through the hoist brackets fore and aft (Figs. 15 and 16) on either side. The unloading of the fish at the dock is accomplished by means of a 5-h.p. motor-driven whip hoist located near the forward mast.

The *Mariner* is now regularly engaged in commercial fishing. She was built by Arthur D. Story, of Essex, Mass., for F. L. Davis, of Gloucester, Mass.; the engines were built and installed by the New London Ship and Engine Company, of Groton, Conn., and the complete electrical-propelling equipment was supplied by the General Electric Company, of Schenectady, N. Y.

Fig. 14. Motor-driven Air Compressor

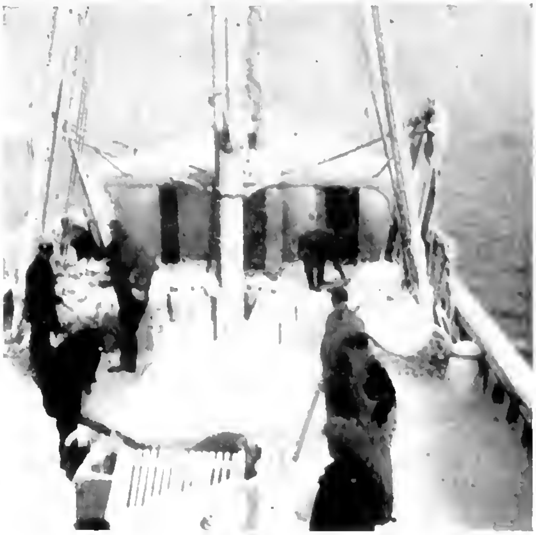


Fig. 15. Main Deck, showing Forward Net Drawing Tackle

Fig. 16. Handling Haul of Fish with Motor-operated Hoist

The Electrically Propelled Trawler *Mariner*

QUESTION AND ANSWER SECTION

The purpose of this department of the REVIEW is two-fold.

First, it enables all subscribers to avail themselves of the consulting service of a highly specialized corps of engineering experts, or of such other authority as the problem may require. This service provides for answers by mail with as little delay as possible of such questions as come within the scope of the REVIEW.

Second, it publishes for the benefit of all REVIEW readers questions and answers of general interest and of educational value. When the original question deals with only one phase of an interesting subject, the editor may feel warranted in discussing allied questions so as to provide a more complete treatment of the whole subject.

To avoid the possibility of an incorrect or incomplete answer, the querist should be particularly careful to include sufficient data to permit of an intelligent understanding of the situation. Address letters of inquiry to the Editor, Question and Answer Section, General Electric Review, Schenectady, New York.

TRANSFORMERS: OPEN-DELTA CONNECTIONS

(128) Where several substations are to be tapped to the same three-phase line would it not be feasible to use the open-delta transformer connection in each substation?

If the open-delta connections are arranged so that the open phase is different from station to station, the system as a whole operates as a closed delta with a rather long connection between transformers. Although this does not give as good an operating condition as does a closed delta in each substation, still it is one that has been successfully used in many installations. The objection to this connection is that the line currents between substations will not be balanced and the substations will carry only 86.6 per cent of their rated capacity.

E.C.S.

INDUCTION MOTOR: ROTOR DELTA OR Y

(693) Why are the rotor windings of slip-ring induction motors usually Y connected?

The Y connection is employed because it produces a secondary voltage 73 per cent higher than that which would result from using the delta connection. In medium size motors relatively high voltage and low current are desirable in the rotor, which are usually bar wound, because these factors permit the use of low-current capacity or small size control apparatus.

For large size motors, however, the delta connection of the rotor is used as commonly as is the Y connection. This condition arises from the fact that a Y connection for some large rotors would produce too high a voltage, one that would lower the factor of safety of the rotor insulation and might be dangerous to handle without specially designed control apparatus. The adoption of the delta connection for such rotors reduces the secondary-circuit voltage in the ratio of 173 to 100 and yet, at the same time, does not increase the current to such a value as could not easily be handled by standard control apparatus.

A.E.A.

ARRESTER: LOCATION OF FUSES

(659) Should a telephone or signal lightning arrester be installed with its fuse end connected to the line or to the device to be protected?

The position of the fuses depends upon the service conditions of the particular system under consideration. Fuses are used to guard against three different conditions:

(1) To clear the instruments in case the signal circuit becomes crossed with higher voltage power or lighting circuits.

(2) To clear the signal circuit in case a lightning arrester fails by grounding.

(3) To protect the signal or telephone instruments in case of abnormal currents.

In order to meet the first two conditions, the fuses should be on the line side of the lightning arrester. In the case of the third condition, the fuses could be on either the line or the instrument side of the lightning arrester.

The objection to putting the fuse on the line side is obvious, in that fuses must necessarily be of very small wire and would frequently be blown by the lightning discharges which they would have to carry. It is therefore sometimes advisable to connect the fuses on the instrument side of the arrester, but this should not be done if there is any possibility of the signal circuit ever becoming crossed with higher voltage power circuits, or if the arrester itself is unreliable or subject to frequent grounds.

V E.G

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JUNE, 1920

The Largest Hammer Head Crane in the World, Located at League Island Navy Yard, Philadelphia, Lifting a Load of 1,010,000 Lb. From left to right the loads are, respectively: Switching Locomotive, 78,000 Lb.; Two Loads of Steel Shapes, 416,000 Lb. each; Locomotive, 100,000 Lb. Total horse power of motors, 530

(See article, page 550)


"NORMA"
NORMA

GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

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Airplane, Equipped with General Electric Supercharger, in Flight Over McCook Aviation Field, Dayton, Ohio. See pages 468, 474, and 476

RELATIVITY

Science, as such, is distinguished from other branches of human knowledge by its dependence upon the use of the measuring stick, balance, and pendulum. Dynamics was born as a branch of science when Galileo used an hour-glass and a yardstick to determine the laws of falling bodies. Alchemy became chemistry when Lavoisier weighed the oxygen in mercuric oxide, and so we can continue with illustrations throughout the whole history of science. All our so-called "laws" of physics and chemistry are generalizations of the quantitative results of innumerable experiments. Progress in science has been achieved by continued *refinement* of our methods of measurements, and the approximate results of yesterday are corrected by the more accurate data of today. Under these conditions, the "laws" of yesterday may be found to be inadequate to account for the new facts, and it may be necessary to go so far as to revise views which have hitherto been held as to the nature of the phenomena under consideration. As Prof. Lotka has expressed it in a recent article on Relativity[*]: "If a new observation cannot by any manner of means be made to fit into our conception of the world, we may be forced to change that conception."

The Theory of Relativity, of which Dr. Tolman's paper in this issue is a splendidly logical statement, is fundamentally an attempt to reconcile with our ordinary notions of dynamics as represented by Newton's laws of motion, certain *experimental* facts which had previously escaped observation because of the degree of accuracy required in their determination.

As long as our experience dealt with velocities small compared with that of light, these laws were found to be apparently quite adequate to correlate the observed results. But, when we came to apply our ordinary Newtonian laws to correlate the energy of the extremely high velocity electrons emitted by radioactive bodies with their mass and velocity, we found these laws inadequate to account for the experimental observation that the *mass* of the electron *increases with its velocity*, so that it becomes infinitely great for velocities approaching that of light.

Similarly in all our notions of energy, we tacitly conceived as the vehicle of this energy, moving bodies whether of atomic or ordinary dimensions. But the phenomena of radio-activity have shown us the existence of stores of energy in the atom itself which are apparently not kinetic in origin. Similarly Michelson and Morley's experiment on the effect of the earth's motion on the velocity of a light beam led either to the hypothesis of Fitzgerald and Lorentz that a moving body contracts or else to the conclusion that our units of space and time are different for moving bodies than for bodies at rest.

The development of the consequences of these *facts* by Einstein has led to a theory of relativity which is extremely general in its significance. As Dr. Tolman shows, Einstein's theory is an extension of the simpler theory of the relativity of uniform motion. This simpler theory is an attempt to express our laws of motion in such a general manner as to be independent of the particular co-ordinates with respect to which we ordinarily define motion and the attempt succeeds as far as systems in uniform relative motion are concerned in space. An extension of this view to systems having any type of relative motion has led Einstein to a very generalized theory in which gravitation itself appears merely as a consequence of our usual limited notions of time and space. That is, in the proper system of co-ordinates, gravitational effects disappear. This is the combined significance of the condition for invariancy and the equivalent hypothesis presented in the latter part of Dr. Tolman's paper.

Such speculations will, of course, be regarded by some as bordering on the metaphysical. Nevertheless they are the logical development of certain experimental facts which our present refined methods of observation have discovered. Probably the contemporaries of Copernicus felt just as mystified about his theory of the universe as most of us feel at present about Einstein's theory of Relativity. Every new conception of the universe has always had to contend with a conservatism and inertia inherent in most intellectual beings which tends to prevent the rapid absorption of any new idea. Pragmatically this is probably as it should be; for we value new ideas only as they become useful in explaining observed facts, and prophesying new ones. Judged on this basis alone, the Theory of Relativity represents an extension of our ideas of the universe into a region which may be even more incomprehensible than is the ordinary notion of "infinity" as a mathematical expression; but so are the facts for which it attempts so successfully to account.

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[*] Alfred J. Lotka, "A New Conception of the Universe, Einstein's Theory of Relativity, with Illustrative Examples." *Harper's Magazine*, March, 1920, p. 477. This is a most interesting article on this subject written in a popular manner and yet thoroughly scientific. The reader who is interested in Relativity will find it to be a splendid introduction to the present paper by Dr. Tolman.

Superchargers and Supercharging Engines

By Major George E. A. Hallett, U. S. A.

Chief of Powerplant Section, Engineering Division, Air Service, Dayton, Ohio

The "ceiling" or maximum attainable altitude of an airplane is limited by the engine output. As the available engine power is reduced by the rarified atmosphere at high altitude, it is obvious that a raising of the ceiling by a considerable amount would require either the use of very much larger and heavier engines or some means of supplying the present engines with fuel mixture at sea-level pressure. The latter method is the only one worthy of studious consideration, and consequently much effort has been expended to develop a supercharger or a supercharging engine that will meet the requirements successfully. In the following article, which was delivered as a paper before the Society of Automotive Engineers, January 7 and 8, 1920, the author reviews the work which has been done and outlines the possibilities of the future.—Editor.

The need for aeronautic engines that will deliver the same power at 20,000 or even 30,000 ft. altitude as they develop at sea level is very real and very great, in not only military but also in commercial aviation. Much success has already been attained with supercharging devices in this country and a certain amount of success in Europe. It must be admitted that there have been some failures also. It is the intention to outline past developments in supercharging in this article and to point out the lines of attack which seem to be meeting with most success.

Supercharging, as the term is generally used, means forcing a charge of greater volume than that which is normally drawn into the cylinders by the suction of the pistons in conventional internal-combustion engines.

When Supercharging is Needed

At 20,000 ft. altitude the atmospheric pressure is roughly one half that at sea level; hence about one half the weight of charge is drawn into the engine and less than one half the power is developed. At 25,000 ft. altitude less than 25 per cent of sea-level power is delivered. If at these altitudes air is supplied to the carburetor at sea-level pressure, or approximately 14.7 lb. per sq. in. absolute, the power developed by the engine becomes approximately the same as when running at sea level. The low atmospheric pressure and density at great altitudes offer greatly reduced resistance to high airplane speeds; hence the same power that will drive a plane at a speed of 120 m.p.h. at sea level will drive it much faster at 20,000 ft., and still faster at 30,000 ft. altitude, *and with approximately the same consumption of fuel per horse-power hour*

There is little to be gained by supercharging at sea level to increase the power of a given size engine, because the clearance volume must be made greater than normal to prevent pre-ignition, with consequent decrease in the expansion ratio and comparatively poor fuel economy. The fact that the clearance volume is increased removes the possibility of the engine developing full power at great altitudes unless a supercharging capacity greater than anything heretofore considered feasible is available. Supercharging, therefore, is most useful in maintaining sea-level horse power in engines ascending to or working at great altitudes.

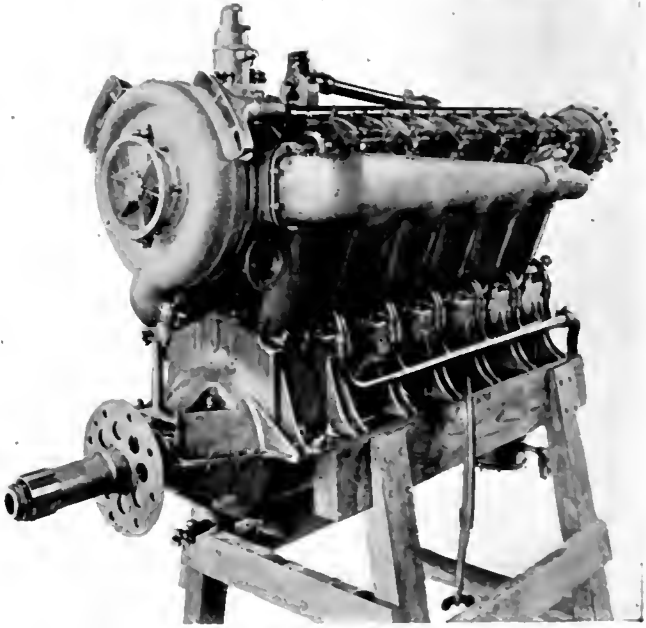


Fig. 1 Twelve-cylinder Liberty Motor with Supercharger of the Type Shown in Fig. 3

Superchargers

Superchargers usually take the form of a mechanical blower or pump and, of course, require a driving gear of some kind The types of blowers or compressors used to date include the reciprocating, Root displacement, and centrifugal types. The reciprocating type was tried by the Royal Aircraft Factory early in the war, on an air-cooled R. A. F. engine, with practically no success. It seems that this type of blower was found to be comparatively heavy and also unsuitable, due to the pulsating pressure of the air delivered.

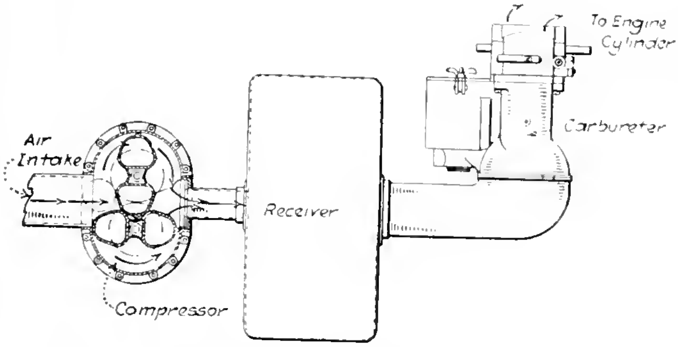


Fig. 2. Root Type Blower so Arranged That Its Air Pulsations Synchronize with the Suction Strokes of the Engine Pistons

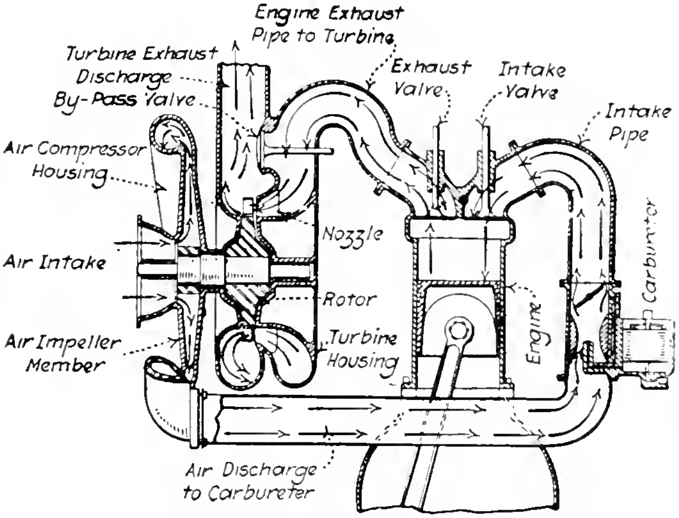


Fig 3. Centrifugal Type Blower Direct Connected to a Turbine Wheel That is Impelled by the Engine Exhaust Gases

The Root type blower was tried by the Royal Aircraft Factory with little or no success. The trouble reported was "rough" running of the engine on account of the pressure pulsations in the air discharged by the blower, which tended to overcharge some cylinders and undercharge others, thus causing uneven impulses. It is reported that mechanical troubles also developed with this type of blower. George W. Lewis, of the National Advisory Committee for Aeronautics, is working on an improved Root type blower, shown in Fig. 2. Here the pulsations in the air discharged are synchronized with the suction strokes of the engine. It will be interesting to note how this develops.

The centrifugal type of blower was used by Prof. Rateau, in France, early in the war. He employed the exhaust gases of the engine to drive a high-speed single-stage turbine direct connected to the centrifugal blower shown in Fig. 3. Some success was had from the start, but he encountered many mechanical troubles. It is claimed in recent reports that some fairly good results are being obtained by the French.

The Royal Aircraft Factory experimented in 1916 and 1917 with a gear-driven centrifugal blower, but as soon as an endeavor was made to run it at speeds that would step up the pressure to the 5 or 6 lb. required, great difficulties were encountered on account of the inertia and momentum of the compressor rotor and the high-speed end of the gear-train, which resulted repeatedly in breakage of the gears when the engine was accelerated or decelerated. To eliminate this trouble a friction clutch, designed to slip under excess torque, was tried, but only partial success was achieved, and the clutch itself gave considerable trouble. Light, flexible vanes were then tried on the compressor impeller, but this expedient has not proved successful to date. Similar experiments were conducted by the A. E. F. in France, but were concluded by the signing of the armistice.

The United States Air Service started work on the Rateau type of turbo-compressor soon after we entered the war. The work was done under the supervision of E. H. Sherbondy, who worked in conjunction with the Rateau-Bateau-Smoot Co. which handled the Rateau patents in this country, and designed a turbo-compressor which seemingly embodied many improvements over the Rateau type. Three of these machines were built and given ground tests on Liberty engines. The arrangement of the engine and the supercharger is shown in Fig. 1. Considerable trouble was encountered due to overheating of the exhaust-driven turbine, and even the use of a special heat-resisting metal in this part did not overcome the trouble. Soon after Mr. Sherbondy began work on the turbo-compressor, Dr. S. A. Moss, of the turbine research department of the General Electric Company, was asked to carry on some work on the same general type. He built one turbo-compressor which was also a modification of the Rateau type, but differed considerably from Mr. Sherbondy's machine. This device was tested on a Liberty engine at the summit of Pike's Peak and developed approximately sea-level horse power there, at an altitude of 14,000 ft. It was capable of making the engine pre-ignite at that height.

After the armistice was signed all work on the development of superchargers was stopped. When the engineering division of the Air Service took over McCook Field and started to plan peace-time development, the supercharger situation was carefully considered. It was decided that it was important to continue development work along this line. It then became necessary to decide whether work should be continued on both the Sherbondy and the Moss machines, and, if not, which one should be developed. It was noted that although Dr. Moss' machine was comparatively crude, it contained some inherent advantages over the Sherbondy type, and no way was seen to overcome the faults of the Sherbondy machine. Therefore, the latter was dropped and the General Electric Company was given a contract to rebuild the old supercharger designed by Dr. Moss. The new device is now being tested in actual flight and is giving very interesting results. Figures on the results obtained with the present Moss supercharger are naturally confidential. The indications are that the turbo-compressor is very durable and probably will outlast an aviation engine.

J. W. Smith, a designer and builder of air-cooled radial engines, located in Philadelphia, is known to have designed a turbo-compressor for this type of engine. The B. F. Sturtevant Co., at Boston, Mass., has at least partially developed a belt-driven centrifugal compressor for supercharging one of its aircraft engines.

Carburetor Locations

There is still some question as to the best location for the carburetor in relation to the blower in supercharged engines. Apparently all positions have been tried:

(1) It is possible to use the centrifugal type of blower as a carburetor by placing a fuel jet within its housing and allowing the rotor to do the mixing. As the rotor usually runs over 20,000 r.p.m., it will certainly mix liquid fuel with air. This system would require a manual fuel adjustment, such as is used with the Gnome engine, for different speeds. With this arrangement there would be danger of an explosion in the blower in case the engine back-fired, because the mixture in the blower would be under pressure higher than atmospheric.

(2) The carburetor can be placed on the suction side of the blower. In this case the evaporation of the fuel will assist in cooling the charge during compression and the action of the compressor will improve the mixing of the fuel, but the danger from explosion remains to be overcome.

(3) When the carburetor is placed in the "normal" position and air is forced through it, it becomes necessary to "balance" the float-chamber with supercharger pressure. This somewhat complicates the feeding of fuel. Pressure gas-feed systems are "banned" in military planes and in any case with a pressure system the tanks would have to be made comparatively heavy to withstand the pressure which would be used at great altitudes. Where gasolene pumps are used it is necessary to regulate their discharge pressure as the plane ascends, because the fuel must reach the float-chamber at a pressure about $2\frac{1}{2}$ lb. higher than that at the supercharger outlet. If the difference in fuel and float-chamber pressures is not kept in constant relation, the quality of the mixture fed to the engine will vary on account of the change in fuel level in the float-chamber. The engineering division has developed a very simple device that solves this problem effectively and is entirely automatic

It would naturally seem at first thought that the extremely low temperatures always found at great altitudes would make possible the easy solution of cooling problems, but in reality the low density of the air reduces its heat conductivity and capacity for heat absorption to such a point that a supercharged engine developing sea-level power at 20,000 ft. requires a little *more cooling surface* than it does when developing normal power at sea level.

The Liberty engine and many others run best with a water temperature of about 170 deg. F. To maintain the cooling water at this temperature in the reduced atmospheric pressure at 25,000 ft. it is necessary to use several pounds of air pressure in the radiator to prevent the water from boiling away. Very effective radiator shutters are needed when the engine is throttled to make a descent from altitudes of over 20,000 ft. to prevent the water in the radiator from freezing before warmer air is reached.

Contrary to expectations, the Moss turbo-compressor now being tested at McCook Field does not complicate the pilot's controls. On a normal engine the pilot handles the throttle and the altitude carburetor control which thins down the mixture as he ascends. With the turbo-compressor the altitude control becomes unnecessary up to the altitude at which the engine can no longer deliver sea-level power but is used, as with a normal engine, if the plane is driven higher.

With the Moss turbo-compressor, when flying at low altitudes, the exhaust pressure is allowed to "waste" through manually operated "gates" in the exhaust pipes. As the plane ascends the pilot closes these gates a little at a time and after he reaches a great altitude he can speed and retard the plane by the use of these gates. He uses the throttle only in case he wants to descend rapidly, when he closes it. In our test flights we have provided the pilot with a sealed altimeter connected only to the supercharger pressure, so that it shows to what altitude this pressure corresponds. When at great altitude the pilot closes the exhaust gates until the pressure in the carburetors causes the altimeter to show sea-level pressure. This makes it unnecessary for him to do any calculating. If he makes the gauge read lower than sea level, the engine will pre-ignite. We have already been able to obtain sea-level pressure in the carburetors at well over 20,000 ft. The exact height cannot be mentioned at present.

With a normal engine the falling off in power as the plane ascends does not cause as much of a drop in propeller speed as might be expected, because of the reduction in density of the air in which the propeller is working. Our best engines do not lose over 75 r.p.m. at 20,000 ft. When an engine is supercharged so that the power remains constant as the plane ascends, the propeller tends to "race" at great altitudes. Therefore it is necessary either to use a variable-pitch propeller or to put on one that holds the engine speed down too low for best performance near the ground, but also does not allow the engine to race too much at great altitude. In our present tests we are using an oversize propeller and are getting surprisingly good results, but we also have variable-pitch propellers about ready for test and should get much better performance with them.

Supercharging Engines

As generally used, the term "supercharging engines" refers to internal-combustion engines in which compression in the crankcase or in the lower end of the cylinders is used to force an additional volume of air or mixture into the working cylinders *after completion of their normal suction stroke.* Early in the war the Army and the Navy each placed an order with the Kessler Motor Co., Detroit, Mich., for several experimental supercharging engines. This type of engine, shown in Fig. 4, supercharged each cylinder by the use of crankcase pressure, as is possible in four-cycle engines. Experiments were made using both air and mixture in the crankcase. Considerable difficulty was encountered in both the design and construction of the engine and so far as the engineering division has learned, no complete tests have been run; and in the small amount of testing that has been done no very large increase in power or brake mean effective pressure has been shown officially. It is believed that the frictional losses will prove to be very high in this type of engine and that the supercharging will be comparatively limited. A similar engine which was tested in this country did show very high frictional loss, due partly to the work of operating the valves which controlled the crankcase air.

An interesting problem in this type of engine when using air in the crankcase is whether a rich mixture should be fed through the regular induction system and an effort made to dilute it with the supercharged air, or a normal mixture should be fed through the induction system and an attempt made to obtain perfect stratification and thus let the supercharged air merely form a cool, elastic and expanding cushion on the piston-head. It is feared that in either case it will be difficult to secure the desired results through a large range of speeds and throttle positions.

There is an English make of supercharging engine in which air is compressed under the piston and by-passed through cylinder ports at the bottom of every stroke (see Fig. 5), supercharging, as in the Kessler engine, at the end of the suction stroke and scavenging at the end of the exhaust stroke. It is claimed by the inventor that this scavenging makes possible the use of higher compression and greatly improves the fuel economy and brake mean effective pressure. It is believed that this engine will give rather limited supercharging and it may prove difficult to control the mixing or stratification of the air and mixture at some speeds.

In an English rotary air-cooled engine the pistons travel out to the cylinder-heads on the scavenging stroke and the beginning of the suction stroke and continue an extra distance inward at the end of the suction stroke, thus taking in a larger charge than that of a conventional engine. The piston reaches only a normal position at the end of the compression stroke and continues an extra distance inward at the end of the suction stroke, all by means of an eccentric crankpin bearing which is rotated on the crankpin by gears of suitable ratio. This type of engine must certainly give a very limited amount of supercharging.

It is believed that supercharging engines will necessarily give a rather limited amount of supercharging. It is also believed that considerable difficulty will be encountered in obtaining the desired stratification in mixing conditions in the combustion chamber through any wide range of throttle positions. Also, some mechanical friction is added in this type of engine and it must be borne in mind that friction is particularly undesirable at great altitudes because it remains nearly constant from the ground up to great altitudes while the power falls off rapidly; therefore, the mechanical efficiency of the engine becomes very low.

The Root type of blower might be interesting for supercharging purposes if the troubles caused by the pulsating nature of its discharge could be eliminated. It is hoped that Mr. Lewis' efforts along this line will meet with success.

It is already frequent practice to build aviation engines with compression so high that the throttle cannot be fully opened on the ground without injury to the engine. In this way, perhaps, the same power is obtained at 5000 ft. as can be obtained on the ground. It has been suggested that this idea be carried further and that an "oversize" engine be built with much higher compression so that the throttle cannot be opened fully until a considerable altitude, such as 10,000 or 15,000 ft., is reached. It has been stated that such an engine could be made lighter, in proportion to the cylinder sizes, than a conventional engine, on account of the fact that the throttle would never be opened near the ground, but it is believed that when this idea is investigated, it will be found that it is the inertia forces quite as much as the explosion forces that determine the necessary strength in most high-speed airplane engine parts and that therefore such an engine could not be built light enough to make it practical. In any case, it is doubtful whether this would give a really good solution for flying at 25,000 or 30,000 ft.

It is possible that centrifugal compressors can be operated satisfactorily by gears or by a belt drive. It is known that some designers are working on both of these problems.

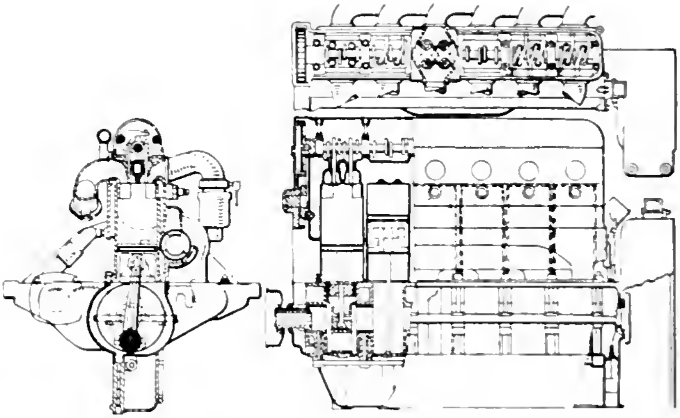


Fig. 4. Specially Designed Engine which is Supercharged by Pressure Developed in the Crankcase

The turbo-compressor in which an exhaust-driven turbine is used for driving the centrifugal compressor seems to present one fairly good way of accomplishing the desired purpose. The turbo-compressor itself is very simple, as there is only one moving part, namely, the rotating element consisting of the turbine wheel and compression impeller. The bearings of this rotating element do not seem to wear noticeably and the device imposes very little drag on the engine when not being used for supercharging. The turbo-compressor is also an effective exhaust muffler.

The Future of the Supercharger

It is believed that when the present type of turbo-compressor now being tested by the engineering division has been more fully developed, it can be built into an engine in a form which will add less weight and less head-resistance than the present machine, and naturally when we know exactly what additional cooling surface is required at a given height, it will not be difficult to build this cooling surface into the airplane in such a form that very little weight and head-resistance will be added.

The uses of the supercharger for military service can be divided into; first, for airplanes in which it is desired to reach extreme altitude; second, for airplanes in which it is desired to increase the rate of climb and horizontal speed and therefore maneuverability at altitudes where it is intended to fight; and, third, for airplanes which carry large loads, such as bombers, which normally are handicapped by having a very low ceiling and whose entire usefulness would, if larger engines were installed to pull them to a higher ceiling, be lost on account of the larger amount of fuel and other material that would have to be carried, thus decreasing their radii of action.

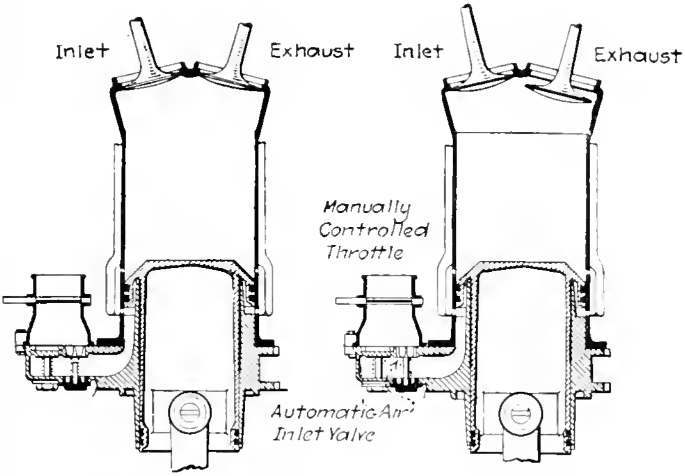


Fig. 5. Cylinder of Specially Designed Engine which is Supercharged by Pressure Developed Around the Piston and Beneath the Rings

In the first case it is believed that a special supercharger can be built that will make feasible much greater altitudes than any that have been attained with the present General Electric turbo-compressor; and it is considered essential that we have airplanes capable of reaching very great heights. In the second case, it is pointed out that military machines not fitted with supercharging engines, when fighting at an altitude of 20,000 ft. or more, are so near their ceiling that their rates of climb, speed, and maneuverability are comparatively poor, but the use of a supercharger seems to overcome this difficulty easily. When a pilot climbs with a normal engine to 20,000 ft. and then levels off in horizontal flight, the engine and propeller speed up perhaps 100 r.p.m. This, of course, enables the engine to develop slightly more power. In the case of a supercharged engine, especially with the turbo-compressor type of supercharger, as the engine speeds up in horizontal flight, the temperature of the exhaust and the power available from the exhaust increase, thus building up the supercharging pressure and giving considerably greater increased power than with a normal engine.

The use of superchargers in commercial airplanes of the future is assured because superchargers will make possible far *more miles per hour* and *more miles per gallon* with a given engine and airplane, and speed is the main advantage of air over other kinds of transportation. It is thought by many qualified judges that, by flying at a sufficient height with a supercharged engine and a suitably designed airplane, a speed of 200 m.p.h. can be maintained.

In the heavy-load-carrying type of plane which must necessarily cross mountains or perhaps fly above storms and clouds, the necessary height can be reached with smaller, cheaper, and more economical engines if they are fitted with superchargers. It is obvious that in really long cross-country flights or trans-continental flights, with mail or passengers, the logical course is to fly at 25,000 or 30,000 ft. altitude where the resistance to speed is low and great speed can therefore be attained provided the engine can deliver high power economically, which it can do if equipped with a supercharger.

As a graphic illustration of the advantage of a supercharged engine, it is pointed out that at 25,000 ft. altitude a supercharged 250-h.p. engine will deliver as much power as a 1000-h.p. engine without a supercharger; and of course the former will weigh many hundred pounds less, its fuel and tankage will weigh very much less, the first cost will be much lower and the structure of the airplane can be made much lighter.

Maintaining Airplane Engine Power at Great Altitudes

By Lieut.-Col. V. E. Clark

Engineering Division, Air Service, Dayton, Ohio

The following is a very brief abstract of Lieut.-Col. Clark's paper presented at the Aeronautic Meeting of the Society of Automotive Engineers, March 10, at New York City. The material omitted in this abstract is principally aeronautical calculations of a rather highly technical nature. These furnish the data for plotting the curves shown in Fig. 1. There seems to be no question but that the supercharger is initiating an era of extraordinary development. In delivering the paper, Lieut.-Col. Clark specifically stated that his calculations referred to the General Electric supercharger and that he computed that during Major Schroeder's recent record altitude flight the plane was performing in accordance with the values stated in this article.—Editor.

In the summer of 1917, the Bolling Airplane Mission to Europe recommended in an official report that our engineers direct especial energy toward the development of means to maintain a high proportion of the power of airplane engines at great altitudes.

The purpose of this article is to indicate the possibilities and limitations of increasing airplane speed by introducing means to maintain high engine power at great altitudes. I have attacked the problem by selecting the De Haviland Four as being an airplane typical of present practice, and by endeavoring to compute approximately the performances that might be obtained at different altitudes with various assumed ratios of actual engine power at the altitude to the total weight of the airplane in every case.

Let us compare the speed of a present-day airplane with that of a hypothetical airplane in which is installed a means of maintaining its power constant at all working altitudes. Looking toward the future, it will be interesting to assume that the total airplane weight is the same in each case, 5000 lb., and the engine develops 500 h.p. at sea level.

Case I. The engine power decreases with an increase in altitude at the normal present-day rate, with no novel means of maintaining it.

Case II. Means are installed for maintaining the engine power constant with changes of altitude.

We will in the second case assume a constant propeller efficiency of 0.80. From a practical standpoint, the maintenance of such an efficiency, constant at various speeds and in different densities, is today impossible. The development of the variable-pitch propeller which, most fortunately, is contemporary with that of the supercharger, is leading in the desired direction, however. The supercharger would, relatively, be of little value without the variable-pitch propeller which, set at a very low pitch, permits climbing away from the ground, and, set at a very high pitch, should show good efficiency at very high airplane speeds, in air of very low density.

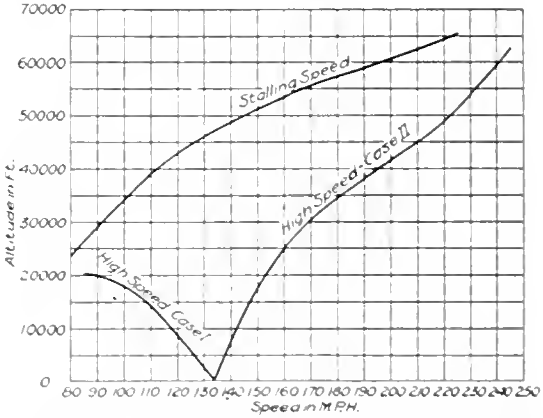


Fig. 1. Stalling Speed and High-speed Curves of a De Haviland Four Airplane with and without a Supercharger Case I without Supercharger; Case II with Supercharger (curve hypothetical)

Computation results in the curves shown in Fig. 1 which present the stalling speed and a comparison between the high speeds of the planes in the two preceding cases at all altitudes.

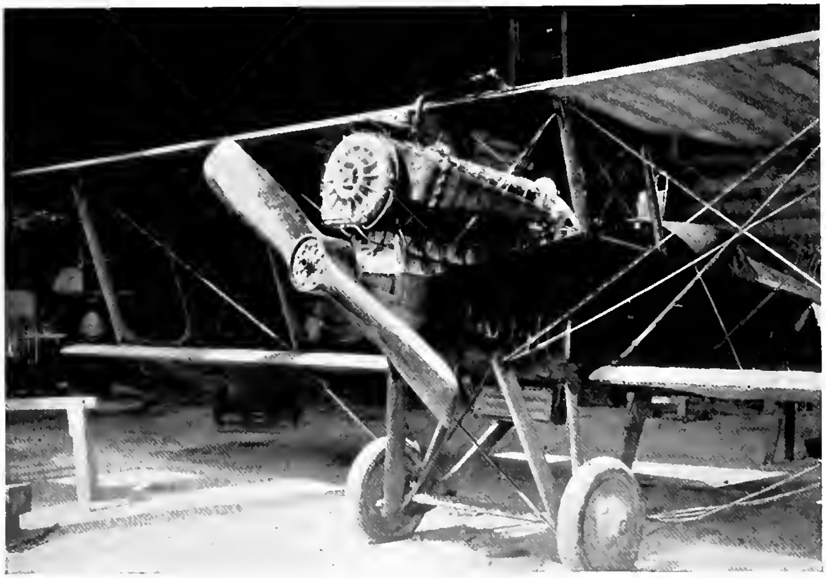
No suggestion will here be made as to the basic principle of the device or means for maintaining power with low density. Among the solutions suggested are a supercharging device at each cylinder to increase the compression and introduce more oxygen, a rotary air compressor driven by an exhaust gas turbine, or through gearing by a shaft, special fuels and the combination of the special fuel with a higher compression, etc. Designers must consider the extreme low temperatures encountered.

Incidentally, the air compressor for the engine intake might also be used to maintain good pressure and introduce extra oxygen in a necessarily sealed compartment occupied by the personnel.

If engineers should go through a few numerical examples, following the method shown (in the full text of this article) and using the curves and noting results, they might become interested in development along this line.

In the general latitude of New York, Chicago and San Francisco, suppose that we could in certain seasons of the year, by rising to an altitude of about 40,000 ft., encounter a wind current having a velocity of 100 m.p.h., whose direction is such as to be "under the tail." If we could maintain a speed through the air of 200 m.p.h. at this altitude our speed over the ground would be 300 m.p.h. We could then, in flying time, go from Chicago to New York in three hours and from San Francisco to New York in nine hours.

Speed of travel or transportation makes for saving in time which, from the practical commercial standpoint, is tantamount to the elimination of space. Bringing San Francisco as near to New York as Pittsburg now is by train, if it can be done, is a matter of tremendous importance. We should, therefore, look well into all means offering even the appearances of feasibility which may be suggested for helping toward this eventual accomplishment.



Le Pere Biplane after trial flight at McCook Field, Dayton, Ohio. The General Electric Supercharger is shown mounted on the head end of the Liberty Motor

The General Electric Turbo-supercharger for Airplanes

By Dr. Sanford A. Moss

Turbine Research Department, General Electric Company

Dr. Moss, who developed the General Electric turbo-supercharger, compares the device with others intended for the same purpose and with supercharging engines. He then explains the design of the General Electric supercharger, and narrates the very interesting history of its development which includes a series of tests on Pike's Peak and also in flight. There is also included a very graphic description of the instruments and method of calculation employed in accurately measuring airplane altitude. The author concludes his article with a description of the performance of the supercharger.—Editor.

Introduction

An airplane flying at high altitude is in an atmosphere of comparatively low density. For instance, at 20,000 ft. altitude the density is practically half that at sea level. This means that a given volume contains half as much actual air by weight. The cylinders of an airplane engine are therefore charged with an explosive mixture which has about half the value of a charge at sea level. The engine actually delivers about half of its sea-level power at 20,000 ft.

Both the low temperature and the decreased pressure at high altitude have effect in fixing the high altitude density. Both the decrease of temperature and the decrease of weight of the charge affect the carburation at high altitude. The fixed clearance volume and the decreased initial pressure give a decrease of compression pressure resulting in a loss of efficiency. There is, therefore, a combination of causes which gives as a net result the decrease in engine power very nearly proportional to the decrease in density.

At high altitude, the resistance of the air to the motion of the airplane is decreased directly in proportion to the decrease of density. The power required for a given airplane speed is therefore greatly reduced. However, the engine power has been so reduced that the usual net result is a considerable decrease in airplane speed. When the engine power is maintained at the sea-level value, there is, however, a considerable increase of speed at high altitude.

Filling the cylinders of an internal combustion engine with a charge greater than that which would normally occur, is called "supercharging." Methods of doing this have engaged the attention of a great many experimenters.

The "gas turbine" is a prime mover in which highly heated products of combustion impinge directly on a turbine wheel. The high thermal efficiency of the gas engine and the rapid displacement of the reciprocating engine by the steam turbine have caused a great deal of effort to be spent upon some combination of the two in the form of a "gas turbine." Many inventors have proposed various types of gas turbines and a number of these have been developed to the point where their operation is successful mechanically. However, no type has yet shown sufficiently good efficiency to warrant commercial use. The engineers of the General Electric Company have very closely followed the various gas turbine developments and have been intimately in touch with the situation for many years.

In 1903 the Company first began work on the "centrifugal compressor." This is an apparatus similar to the fan blower except that the shape of the impeller blades and the passages leading air to and from the impeller are so arranged as to give efficiency very much greater than that of the usual type of fan blower, so that the apparatus forms a satisfactory means for compressing air to appreciable pressures. A line of single-stage centrifugal compressors has been developed for compressing air from one to five pounds per square inch above atmosphere, to be used for many industrial purposes; as well as a line of multi-stage machines for compressing air and gas up to pressures of 30 lb. per square inch above atmosphere.

The turbo-supercharger is a combination of a gas turbine and a centrifugal compressor arranged as part of an airplane gasolene engine. The hot products of combustion from the engine exhaust are received upon the turbine runner and furnish power whereby is driven a centrifugal compressor mounted on the same shaft, which compresses air for supply to the carburetors. A more detailed description is given later.

In the latter part of 1917 the National Advisory Committee for Aeronautics requested the co-operation of the General

Electric Company in the development of the turbo-supercharger in the United States. Our experience with gas turbines and centrifugal compressors led us to be greatly interested and the work was pushed vigorously during the war. An apparatus was constructed and placed in operation on an airplane engine near sea level. After a period of development, the stage was reached where nothing more could be done except at high altitude. However, since the development was not sufficiently advanced to warrant an airplane flight, the entire testing apparatus was taken to the summit of Pike's Peak. Here a further period of development took place. The apparatus was finally gotten into satisfactory working order so that the airplane engine developed the same power at the summit of Pike's Peak as it originally had near sea level. Arrangements had been started for installing the apparatus on an airplane when the Armistice intervened. Examination of the results which had been obtained, by army officials after the Armistice, led to a resumption of the work and the apparatus was finally installed on an airplane. A very good showing was made from the first. The increase of power at high altitude was such as to give an entirely new set of conditions from those under which the airplane originally operated. This required various changes in the entire airplane apparatus and development was made of proper radiators, propellers, gasolene systems, cooling systems, etc. This work has been proceeding satisfactorily for some time.

Development work on the turbo-supercharger is also being carried on in France independently of our work. So far as can be seen from the published accounts of the French work, our apparatus is on a larger scale. We are supercharging a larger airplane motor and are carrying the supercharging to higher altitudes. The mechanical details of the French and General Electric apparatus are quite different. The development of a turbo-supercharger similar to that of the French was started in this country but the design was modified considerably. Work on this apparatus has not been carried to a conclusion, however.

Our work was originally started at the suggestion of Dr. W. F. Durand, then Chairman of the National Advisory Committee for Aeronautics, who knew of our long experience with gas turbines and centrifugal compressors. It has since been carried on under the supervision at various times of Col. J. G. Vincent, Col. T. H. Bane, Major H. C. Marmon, Major G. E. A. Hallett and Major R. W. Schroeder. Major Hallett has had charge of the development since the Armistice, and he has given considerable study to the matter of superchargers in general.

The Turbo-supercharger Cycle

Fig. 3 of the foregoing article by Major Hallett gives a detailed diagram of the principles of the turbo-supercharger. The exhaust of the airplane engine is received by an exhaust manifold which leads it to a nozzle chamber carrying nozzles which discharge it onto the buckets of a turbine wheel. On the same shaft as this turbine wheel is the impeller of a centrifugal compressor. This compresses air from the low pressure atmosphere to approximately normal sea-level pressure and delivers it to an air discharge conduit which supplies the carburetors.

The turbine nozzles are of such area as to maintain within the exhaust manifold and nozzle box a pressure approximately equal to that at sea level. The difference between this pressure and the altitude low pressure gives a pressure drop for the exhaust gases which furnishes the power that operates the system.

Due to the respective temperatures, this power input suffices to give the desired compression and also to supply the inevitable losses. However, in order to avoid back pressure on the engine, above the normal sea-level value, both turbine and compressor must be designed with utmost attention to efficiency.

With an efficient arrangement, the engine when at high altitude exhausts at normal sea-level pressure and receives its air at the carburetor at normal sea-level pressure. Hence, normal sea-level power is delivered at all altitudes up to the maximum for which the supercharger is designed, so that the plane speed will increase uniformly as the altitude density decreases.

In order to reach this ideal there are various auxiliary problems that have to be solved; such as temperature rise of compression, slight deficiency of oxygen at high altitudes, effect of propeller on engine speed, and various other effects. The work thus far accomplished has demonstrated the validity of the fundamental principles and has disclosed the problems of detail.

Mechanical Problems of Supercharging

The General Electric superchargers thus far constructed have been designed to give sea-level absolute pressure at an altitude of 18,000 ft., which involves a compressor that doubles the absolute pressure of the air. This pressure ratio, with the quantity of air involved, requires about 50 shaft horse power input for the compressor. The design of a complete power plant of this size to suit an existing airplane engine, with such weight and location as will not impair the flying characteristics of the plane, has of course offered many problems. The possibility of driving the compressor of the supercharger by engine power, instead of by the exhaust gases, suggested itself. Indeed, observation of an engine exhausting in the usual way into the atmosphere, discharging flames through the short red-hot spouts, with the almost incandescent exhaust valves in view, makes it seem absurd to propose to pass these red-hot gases through pipes with a pressure difference above the surrounding atmosphere equal to its absolute pressure, and more absurd still to obtain power by discharging these red-hot gases onto a turbine wheel rotating at 20,000 r.p.m. Nevertheless the turbo-supercharger has made flight after flight with entirely successful operation, while the mechanically-driven supercharger has never endured in spite of much effort. Much experience with the operation of the gas turbine led the writer to prefer its problems to those of the driving mechanism of a supercharger operated from the engine. The turbine involves merely the addition to the compressor of a single extra wheel, designed for the conditions, with no extra bearings. The engine-driven scheme involves a 50-h-p. transmission with multiplicity of gears, bearings, clutches, belts, and the like. These offer more or less drag on the engine when the supercharger is not in use at low altitudes, and very serious problems of acceleration when the supercharger is to be thrown into action, since the engine will be then running at its full speed of about 1800 r.p.m.

It must be admitted that this is much the simpler proposition, since a turbine wheel has been designed which will endure.

The exhaust manifold and nozzle box have proven to be a very efficient exhaust muffler and conductor. Such a muffler and conductor is needed in any event, and the design of means for withstanding the increased pressure difference of the turbo-supercharger has been successfully accomplished.

Power for Turbo and Engine-driven Superchargers

An efficient turbo-supercharger theoretically deducts from the indicated horse power of the airplane engine an amount corresponding to the difference between sea-level absolute pressure and altitude pressure. There is this additional back pressure during the exhaust stroke. The theoretical power available for driving the turbo-supercharger is greater than this, however, owing to the fact that there is available not only the energy due to the direct pressure difference mentioned, but also the energy of perfect expansion from the higher to the lower pressure. If there were no turbo-supercharger the engine would waste this energy in sudden pressure drop as the exhaust valves open. The turbine can utilize this energy. The sum of these two amounts of available energy, multiplied by the efficiency of the turbine wheel, gives the shaft power delivered to the compressor.

For an engine-driven supercharger compressor there is greater engine indicated power due to a lower exhaust pressure. However, the shaft power for the supercharger compressor must be transmitted through the engine connecting rod and crank shaft, with losses, and then through the supercharger driving mechanism with additional losses. The total shaft power thus subtracted from the engine, multiplied by the efficiencies of these two transmissions, gives the shaft power delivered to the compressor. This is the same as for the turbo-supercharger. For a Liberty motor of about 400 h.p. and sea-level power at 18,000 ft. altitude, this power is 50 h.p.

The comparison then is as follows: The turbo-supercharger subtracts from the engine indicated power, adds power of expansion which would not otherwise be used, and has turbine wheel losses. The engine-driven supercharger puts this indicated power through the engine (with some additional loads on the pins and bearings) and has engine and transmission losses.

With usual efficiency there is probably not a great difference between the gross subtraction from engine power in the two cases. There is then the disadvantage of transmitting the supercharger power through the engine pins and bearings, as well as through some mechanism between engine and supercharger, to be compared with the collection of the hot gases under pressure (with muffling advantages) and delivery to the turbine wheel. As already mentioned, practical success to date is in favor of the turbo-supercharger and the writer feels that this is really due to its innate superiority.

Engine-driven superchargers with positive-pressure blowers have been proposed. These have the additional disadvantage that with the desirable pressure ratios of about two to one there is an appreciable compression loss due to the fact that the machine only displaces air and has no direct means for compression.

It is to be noted that, although the power required to drive the supercharger is subtracted from the engine power, the remainder at high altitude with an efficient supercharger is equal to sea-level power. That is to say, the supercharged engine delivers power enough to drive the supercharger as well as to deliver sea-level power to the propeller. There is of course no way to arrange for full power due to supercharging with the additional power due to exhaust at the low absolute pressure of high altitude and without expenditure of power for supercharging. Without a supercharger the engine has the advantage of a very low exhaust pressure, but the explosive charge is so small that the gross power has the well-known low value at high altitude.

Supercharging Engines

Supercharging engines of various kinds, in which the engine crank case or the engine cylinders themselves are arranged for additional compression, have been discussed by Major Hallett, and shown to give excessive weight and complication as compared with a turbo-supercharger.

A very simple form of supercharging has frequently been used wherein an engine of large displacement, but with very high compression pistons has been fitted to a comparatively small plane. In such a case, the throttle could not be opened wide near sea level because the compression would be excessive and serious pre-ignition would result; to say nothing of the damaging effect on the engine by delivery of the full power corresponding to the displacement with sea-level charge. At altitude, however, a full charge at the altitude density is taken, and on account of the high compression pistons this is compressed to a proper amount for good operation. Some high altitude flights have been made in this way with a single seat plane and engine with a displacement corresponding to 400-h.p. at sea level. The power at high altitude was possibly 100-h.p. A 100-h.p. engine with a turbo-supercharger would give the same power at altitude and weigh very much less.

Since such an engine has normal compression pressure at high altitude, the power will be very nearly proportional to the density of the charge. There will be no loss of efficiency due to decrease of compression pressure. The altitude power will then vary directly with the cylinder displacement and inversely with relative density at altitude.

Major Hallett points out that with such an engine the weight is nearly proportional to the displacement. Hence such an engine will weigh nearly twice as much as a supercharged engine for 18,000 ft. altitude conditions, and nearly four times as much for 35,000 ft. conditions where the density is one fourth that at sea level. There is some deduction from these figures due to the fact that the weight will not go up quite as fast as the displacement and because the supercharger's weight is not negligible. However, the situation in the main is as represented.

Engines have also been proposed with crank-case compression, either with individual connections or with a receiver. With a four-stroke cycle, two crank-case ends supercharge a single cylinder. However, with the minimum crank-case clearance thus far suggested, the maximum compression pressure possible is not sufficient to give supercharging at an appreciable altitude.

Design of General Electric Superchargers

The machines used thus far have been designed to give sea-level pressure at 18,000 ft. altitude, which corresponds to a pressure ratio of about two. The rated speed for these conditions is 20,000 r.p.m. Sea-level pressure has readily been obtained up to 22,000 ft. altitude. The control is entirely by hand operation of waste gates, which permits of free escape of some of the exhaust gases.

The entire apparatus, exclusive of exhaust manifold and air discharge conduit, weighs about 100 lb. The exhaust manifold and air conduits have nearly the same weight as equivalent parts with no supercharger.

The turbine and compressor wheel have diameters somewhat less than a foot. The present design has been hampered by necessity for accommodation to existing engines and planes. It is proposed, however, to construct apparatus in which engine and supercharger are integral, with all parts arranged for the full possibilities of the combination.

The essential features of the design are various arrangements of ducts for cooling the several parts, means for accommodating the temperature expansions, means for handling the temperatures which exist, and design of both turbine and compressor to give utmost efficiency.

History of General Electric Supercharger

The combination of airplane, propeller, engine, radiator, cooling system, and supercharger are so intimately associated that no adequate tests can be made without the complete system in operation at full speed at altitude. Altitude chambers exist for tests of engines alone, but none are arranged for inclusion of the propeller. What tests were possible were first run with steam with the supercharger alone at the Lynn Works of the General Electric Company. Additional tests were run with the supercharger and Liberty motor on dynamometer stands at McCook Field, Dayton, Ohio, the Experimental Station of the Engineering Division of the Air Service. These tests were necessarily made with nearly sea-level initial pressure. Even slight supercharging under such conditions involved increase of compression pressure, and this instantly caused preignition. Both sets of tests gave means for perfecting the mechanical operation of the supercharger, but gave no information as to increase of engine power under altitude conditions. So far as could be seen everything was operating in accordance with scheduled expectations, but there was not sufficient assurance to warrant an airplane flight.

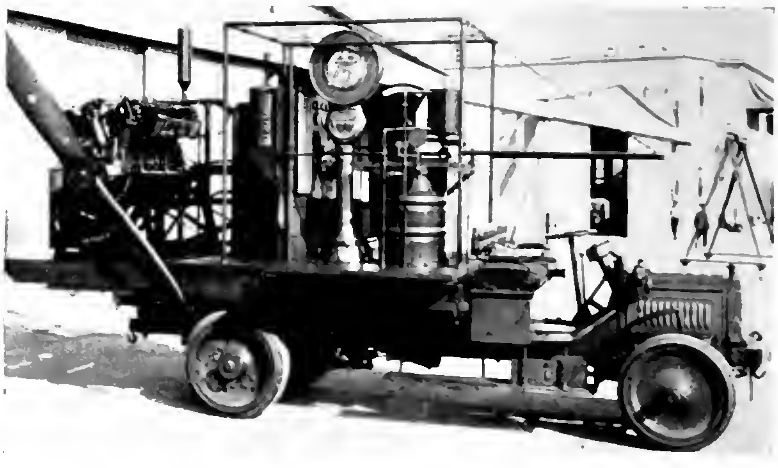


Fig. 1 Motor Truck Carrying Liberty Motor and Complete Equipment for Testing the General Electric Supercharger in Rarified Atmosphere at Pike's Peak

During the initial development of the Liberty motor a testing expedition had been sent to the summit of Pike's Peak, and it was decided to repeat this performance with the supercharger. Fig. 1 shows the motor truck that was prepared for the expedition. The Liberty motor carrying the supercharger was mounted on a cradle dynamometer, with scales and all arrangements for accurate measurement of power, gasolene consumption and the like. In fact, a complete testing laboratory was provided. The motor truck was shipped by rail to Colorado Springs, and then proceeded by its own power to Pike's Peak summit on the "Pike's Peak Auto Highway." This is a well constructed, very tortuous mountain road twenty-eight miles long.

Pike's Peak Summit has an altitude of 14,109 ft. It is the highest point in the United States easily reached by road. The summit is a slightly rounded rocky flat about 100 yds. in diameter. On it are two stone houses, one at the terminus of a cog railroad and the other about one hundred yards distant at the terminus of the auto highway. The motor truck was set up near the latter. Fig. 2 shows the nature of Pike's Peak summit. Fig. 3 shows the way the test car was left after each day's work. Fig. 4 shows its condition on many of the mornings. There were, however, many pleasant days when the testing work could be carried on with facility. Fig. 5 shows the rear of the test car on a pleasant day.

The testing work at the summit lasted through September and half of October, 1918. The usual difficulties with experimental work were, of course, encountered with the addition of many delays, due to the cold and snow, and distance from repair shops. Minor changes were made in a little shack at the summit, but all the machine work and changes of appreciable magnitude were made at Colorado Springs. The apparatus was finally arranged to give good mechanical operation, and a number of tests were run showing the performance of the engine with the supercharger opened up to the maximum limit possible. The supercharger was designed for operation at 18,000 ft with some margin. It was

Fig. 2. Pike's Peak Summit on Which Early Tests Were Made of the General Electric Supercharger at 14,109 ft Altitude

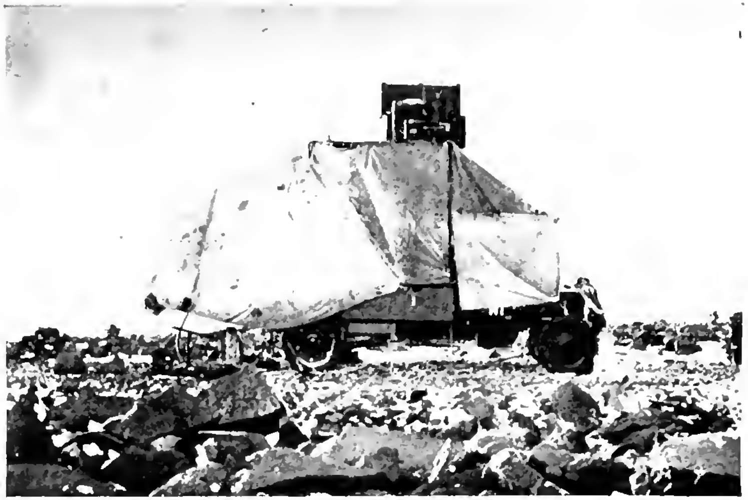


Fig. 3. The Test Car Shown in Fig. 1, as Left for the Night on Pike's Peak

Fig. 4. The Test Car as Found on Many of the Mornings

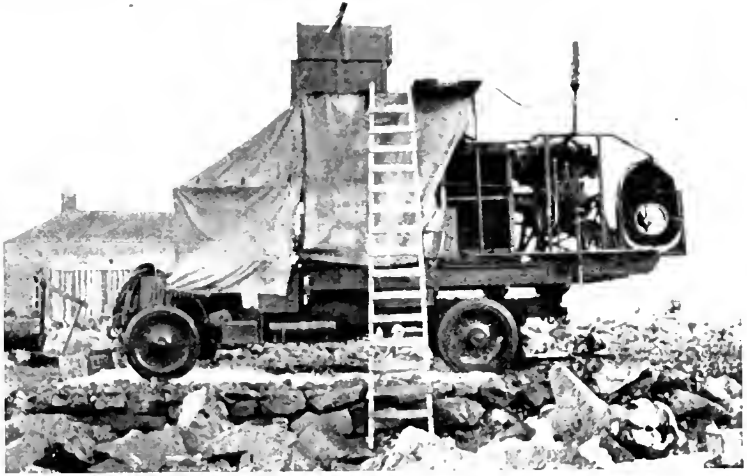


Fig. 5. The Test Car on a Pleasant Day on Pike's Peak

possible at the existing altitude of 14,000 feet not only to supercharge so as to give full sea-level power, but also to overcharge so as to cause the engine to pre-ignite.

It was agreed that results of the Pike's Peak tests warranted the immediate installation of the supercharger on an airplane, and arrangements for doing this were in progress when the Armistice caused a cessation of the work. After the Armistice, careful re-examination of the situation resulted in resumption of the work in the early part of 1919. Various rearrangements were made in view of the experience gained at Pike's Peak and the apparatus was finally installed on an airplane. After a number of tests on the ground, flight tests were made.

Fig. 6 Major R. W. Schroeder, Lieut. G. W. Elsey, and the Author (right to left)

It soon developed that a very appreciable increase of power was easily obtained when the supercharger was opened up. The whole airplane installation was not properly arranged to take advantage of this power, however, and changes were necessary in the radiator, cooling system, propeller system, gasolene tank, and pump system, etc. Changes in these parts have been made from time to time, and this work is still in progress. As the work proceeds more and more power is developed by the engine. Changes have also been made in the supercharger itself.

Many remarkable flight tests have been made. In fact, during the early work a flight record of some kind was broken at every flight. Appreciable progress has already been made, but the full capacities of the apparatus have not yet been reached, and further improvements of performance are to be expected.

Fig. 7 shows the airplane installation, and Fig. 6 shows Major R. W. Schroeder, who has made all of the flight tests to date, together with Lieut. George W. Elsey, who has made all of the flight observations to date. The aviators are of course clothed for the intense cold of high altitudes and carry the parachutes that are now regularly used by the U. S. Air Service in experimental work.

Measurement of Altitude

The altitude of an airplane is measured by an altimeter such as is shown in Fig. 8. This is essentially an aneroid barometer. It comprises a chamber almost wholly exhausted of air, on one side of which is a flexible metal diaphragm. As the atmospheric pressure

Fig. 7. Supercharger Equipped Airplane. The extra long propeller is used to hold the engine speed down to normal in the rarified atmosphere of high altitude

presses on this diaphragm to a greater or lesser extent, the diaphragm moves in or out. This motion actuates a train of mechanism, ending in a needle moving over a scale. The temperature of the instrument itself must, of course, have no effect on the readings. Temperature compensation is arranged for by leaving a certain amount of air in the vacuum chamber and also by use of metal, in one of the levers, which has an appreciable coefficient of expansion. This temperature compensation is never quite exact, however, and a slight correction to the indications must be made, to take account of the actual temperature of the parts of the instrument at the time of an observation.

The reading of the instrument with temperature compensation taken into account gives the absolute pressure at the altitude in question and it is from this absolute pressure that the altitude is computed. Knowing the absolute pressure at the field from which the flight is made, as given by the barometer, the absolute pressure at altitude as given by the altimeter reading, and the temperature of the column of air between these two points at a number of heights, the difference in elevation can be computed by appropriate formula. There exist tables of average values of temperatures at various altitudes to enable this computation to be made approximately for an average case. However, where an actual altitude record is involved, the actual temperatures at various altitudes during the ascent must be observed and inserted in the formula. The determination of the altitude in a record flight is therefore a matter of some complexity. It has been very carefully done in the case of the supercharger flights at McCook Field.

The instrument in Fig. 8 is an indicating instrument. The instruments actually used for the final computation of altitude records are recording instruments called "barographs," which operate on the same principle. Fig. 10 shows the autographic record of such an instrument. After a flight the recording instruments used are removed from the plane and placed under the bell-jar of an air pump, connected with a mercury column, while the clock which causes the rotation of the record paper is still running. Autographic records are thus obtained at a number of known values of absolute pressure, as shown by the mercury column. This gives an accurate calibration and establishes the absolute pressure at the maximum altitude attained. During record flights three independent barographs are used for certainty.

Fig. 9 shows observations of temperatures at high altitudes for a great many of the supercharger flights. From the actual values of these temperatures for a given flight and the barograph record mentioned, the maximum altitude is computed.

Fig. 8. The Instrument which Indicates to the Aviator the Height at which He is Flying

The amount of supercharging is measured by a recording barograph of the same kind, which is not exposed to atmospheric pressure, however, but is enclosed in a sealed chamber connected by a pipe line to the air conduit at the carburetor inlets. By means of the known temperatures the altitudes corresponding to this record are known, so that there is given a record of the equivalent altitude of the engine. This is practically sea level as is shown by the lower curve in Fig. 10.

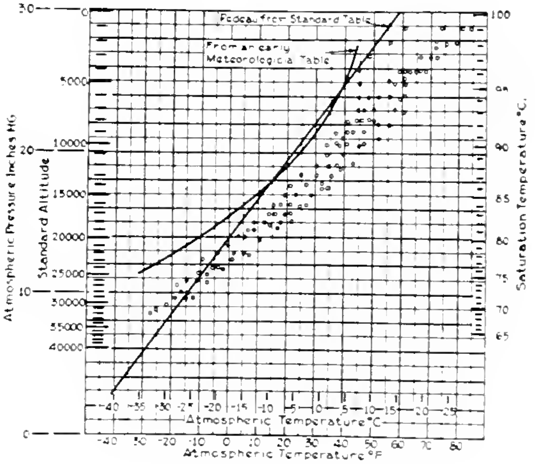


Fig 9. Curves of Temperature at High Altitudes. The plotted points were made during supercharger airplane flights

The upper curve in Fig. 10 gives readings of a Verturi-meter-Pitot-tube arrangement, which gives the air speed. These readings are calibrated by an actual flight near the ground over a measured course of three miles with the use of stop watches.

By these methods very accurate knowledge has been obtained of the performance of the supercharger under many conditons.

Supercharger Performances

The supercharger which has been used to date was primarily designed for high speeds at altitudes of 18,000 to 22,000 ft. The Le Pere plane on which the installation was made had a ceiling of about 20,000 feet with two men, and a speed at this altitude of 70 miles per hour. With the supercharger in use, a speed of about 140 miles an hour has been attained at 22,000 ft. As already pointed out, this has been attained with various parts of the plane installation in a partially developed state. Theoretical computations have been made showing that much higher speeds at high altitudes are to be expected. The progress of the flight tests to date indicates that the theoretical expectations will be fully realized.

The making of high altitude records has been very attractive and the supercharger has, of course, been used for this purpose as well as for the speed courses mentioned. Successively higher altitudes have been reached as experience has been gained regarding the manipulation of oxygen, gasolene, and other details. The highest altitude reached with two men was on October 4, 1919, with Major R. W. Schroeder and Lieut. George W. Elsey. The maximum indicated altitude was 32,335 ft. Various computations from very com-

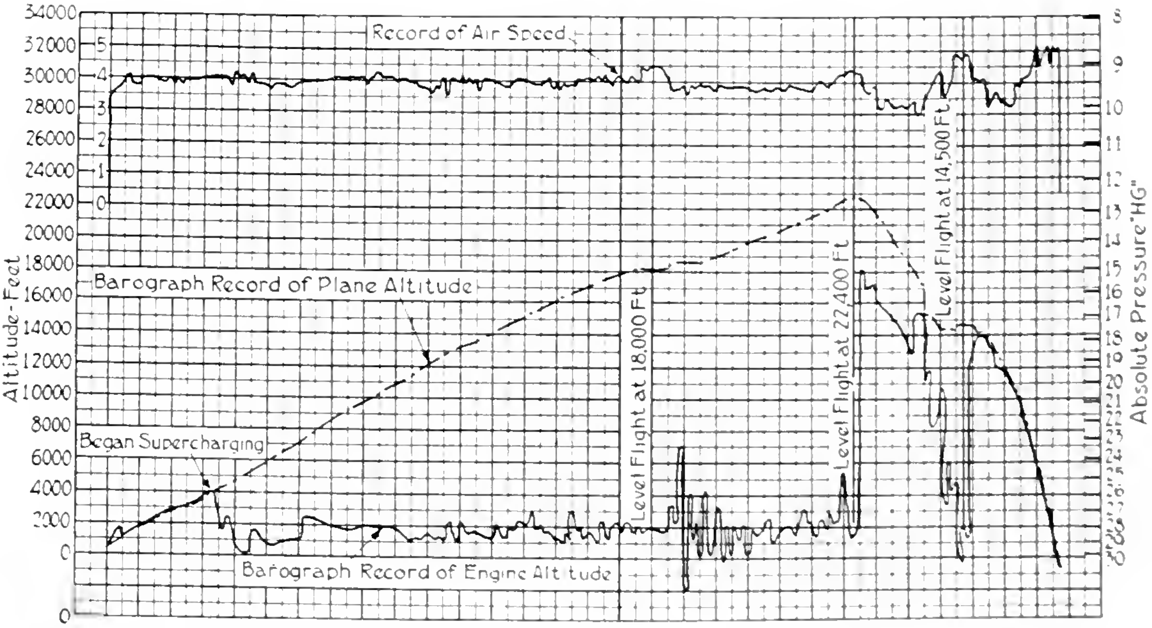
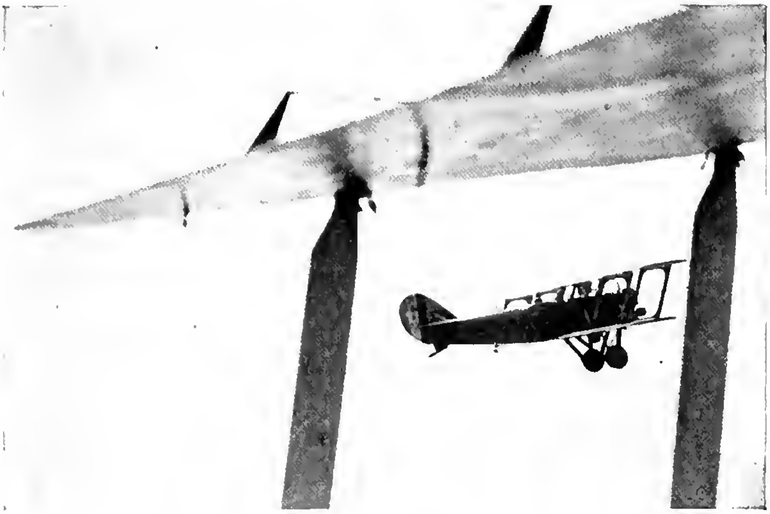


Fig 10 Sample Barograph Curve Record of an Airplane Flight From such a record, and the temperatures as shown in Fig. 9, the true altitudes are calculated

plete observations, give the actual height above the ground as 31,800 ft. Complete details of these computations, as officially verified, are given in *Flying* for January, 1920. This figure is about one mile higher than the nearest two-man altitude record without a supercharger.

On February 27th, Major Schroeder made a flight alone, attaining an actual height above the ground finally computed as 36,130 ft. (6.85 miles). The lowest temperature reached was minus 67 deg. F. At the maximum altitude, Major Schroeder's oxygen apparatus failed and he became unconscious and lost control of the plane. The recording instruments, of course, continued to work and these show that there was an almost vertical fall of about five miles in two minutes (an average speed of fall of 150 m.p.h.). Observers in Dayton saw the plane spinning around as it fell. Major Schroeder became semi-conscious as he neared the earth and, at an altitude of about 3000 ft., he succeeded, in a half-dazed semi-automatic way, in righting the plane and making a good landing in his own field, again becoming unconscious. He was taken to a hospital in a serious condition, but has since almost completely recovered. The supercharger, engine, and plane were in perfect working order after the flight.

At the maximum altitude attained, recording instruments showed that the plane was still climbing at the rate of about 125 ft. per minute and it was estimated that an altitude of 40,000 ft. would have been attained if the oxygen apparatus had not failed.



General Electric Supercharger Equipped Le Pere Biplane photographed from another plane while test flight at McCook Field, Dayton Ohio

Relativity Theories in Physics

By Dr. Richard C. Tolman

Fixed Nitrogen Research Laboratory

The results observed very recently during the eclipse of the sun were so startlingly in accord with Einstein's theory of relativity that the subject at once received universal attention and a great deal of discussion arose in the daily papers over the exact significance of the new theory. The paper by Dr. Tolman is a concise and extremely interesting exposition of Einstein's theory in relation to the older theories of relativity, and is written by one of the best authorities on the subject.—Editor.

In the following paper we shall first present a description of the general nature of relativity theories and then, by way of illustration, shall give brief and hence necessarily incomplete accounts of three relativity theories which have actually been used in physics. The first of these will be the theory of similitude, (or theory of the relativity of size); the second, Einstein's original theory of the relativity of uniform motion; and the third, Einstein's general theory for the relativity of all types of motion, with its applications to gravitation.

The Nature of Relativity Theories

The general idea of relativity arises from the fact that all our quantitative judgments are in the nature of comparisons. To make a quantitative judgment, we compare the phenomenon under consideration as to size, as to position, as to velocity, or what not, with some standard reference system. Our quantitative judgment is thus in the nature of a relation between the phenomenon under consideration and the standard reference system.

Thus I can speak of the length of a table relative to the length of a standard meter-stick, or relative to the length of a foot rule, or relative to the length of any other chosen standard. I can speak of the position of the planet Mercury relative to a system of co-ordinates having the earth at their origin, or relative to a system of co-ordinates having the sun at their origin. I can speak of the velocity of a man in a railroad train relative to the car in which he is located, or relative to a station platform past which the train is moving. To speak of absolute length, absolute position, or absolute velocity, would be meaningless. All quantitative judgments are thus *relative* to the more or less arbitrarily chosen standard system of reference.

It must be particularly noticed that this idea of the relativity of quantitative judgments is such as to make the nature of these judgments depend not only on the properties of the phenomenon to be judged, but also on the particular choice of reference system which is made. In general, a change in reference system will be accompanied by an appropriate change in the quantitative judgment.

For example, suppose I am interested in giving a quantitative description of a circle. If I take as my reference system a set of Cartesian co-ordinates having the center of the circle at its origin, the mathematical equation which gives such a quantitative description of the circle will have the familiar form

$$x^2+y^2=a^2$$

where a is the radius of the circle measured in the particular units of length employed.

If now, however, I change my reference system by choosing a new and shorter standard of length 1/m times as long as the original, the equation describing the circle will be transformed into

$$x^2+y^2=m^2a^2$$

Or if, on the other hand, I change my reference system to a new set of Cartesian co-ordinates parallel to the first, but having its origin not at the center of the circle, the equation for the circle will assume the form

$$(x-x_0)^2+(y-y_0)^2=a^2$$

where x_0 and y_0 are the co-ordinates giving the position of the center of the circle.

As still a further type of change of reference system, I might change from Cartesian to polar co-ordinates, and my equation for the circle would then assume the simple form

$$r=a$$

provided the center of the circle lies at the origin of co-ordinates.

Attention should be paid to the fact that the change in quantitative statements which accompanies a change in reference system may be one either of form, or merely of the numerical values entering into the quantitative statement. Thus, when I change from Cartesian to polar co-ordinates, I have a change in the form of the quantitative statement. By changing, however, from one set of Cartesian co-ordinates to another set of Cartesian co-ordinates, which differs from the first only in the magnitude chosen as unit length, I obtain a change merely in the numerical values entering into the description, but not a change in the form of the description.

Of course, the mere fact that the form and numerical content of the equations of physics are dependent on choice of reference system, is not, itself, sufficient to permit the drawing of definite conclusions as to the nature of physical phenomena. In order to obtain such conclusions, we must know *how* the equations of physics are dependent upon the choice of reference system. This information is usually most succinctly expressed by a statement as to those things which remain *invariant* (i.e., are not changed), when the transformation to the new reference system is made. In fact, any relativity theory can be most conveniently founded on a statement as to the type of change in reference system which is to be considered and a statement as to the invariants for this transformation. On the basis of these two statements, it will then be possible to build up the whole theory of relativity for the particular branch of investigation under consideration.

In carrying out such an application of relativity methods, we are of course at liberty to consider any change in reference system that we may desire. The gist of the problem lies in determining what shall be invariant when the transformation to the new reference system is made. The decision as to this is usually presented in the form of a postulate, which presents our preconceived ideas as to to those things which will not be affected by the change in reference system contemplated.

Theory of Similitude

Let us now consider as a simple example of the application of relativity methods, the theory of similitude,[1] or perhaps, as it might better be called, the theory of the relativity of size.

The fundamental idea of the theory of similitude is that there ought to be no significance in the choice of any particular length as the standard length, in terms of which all other measurements should be made. Since the length of an object is, in any case, merely a relative matter, and since it is meaningless to speak of absolute lengths, it would seem as if the general laws of physics describing classes of phenomena ought to be entirely independent of the choice of standard length, although, of course, the numerical values entering into the description of any particular phenomenon will depend on this choice.

This general idea can be expressed more definitely by the following postulate upon which the theory of similitude may be founded:

A change is possible in the magnitudes of the standards for the measurement of the different quantities of physics, including any desired change in the standard of length, which will leave all the general equations of physics absolutely invariant, both as to form and numerical content.

By the term "general" equations of physics we are to understand those equations which describe classes of phenomena, rather than equations which merely describe one particular phenomenon. Thus, for example, the equation, $C = \pi D$, giving the relation between the circumference and diameter of any circle would be a "general" equation and would be absolutely invariant both as to form and as to the numerical value of the quantity π, for any change in the standard of length. A statement, however, as to the diameter of some one particular circle, such as $D = 24$, would be a "special" equation, and would, of course, not be invariant in numerical content if we changed our standard of length.

In order to satisfy our postulate, we must be able to find a set of equations by which we can transform quantities of length, and such other quantities as may be necessary, to a new set of standards of different magnitude, and yet leave all the general equations of physics absolutely invariant, both as to form and numerical content. Moreover, this set of transformation equations must correspond to any desired change in the standard of length.

As a matter of fact, it has been possible to find such a set of transformation equations. For the five fundamental kinds of quantity—length, time, mass, quantity of electricity, and entropy—the transformation equations have the form:

$$l' = xl' \quad t' = xt \quad m' = \frac{m}{x} \quad e' = e \quad S' = S \quad (1)$$

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(1) See Tolman, Phys. Rev., *3*, 244, 1914; *4*, 145, 1914; *6*, 219, 1915; *8*, 8, 1916; *9*, 237, 1917. Buckingham, ibid., *4*, 345, 1914. Nordstrom, Finska Vetenskaps Soc. Forh., *57*, 1914-15; Afd. A. No. 22. Ishiwara, Science Report of Tohoku Imp. Univ., *5*, 33, 1916. Ehrenfest-Afanassjewa, Phys. Rev., *8*, 1, 1916. Bridgman, ibid., *8*, 423, 1916. Karrer, ibid., *9*, 290, 1917. Davis Science *50*, 338, 1919.

The theory in question was originally called the theory of similitude since the underlying postulate on which it may be founded was first stated in the form:

The fundamental entities out of which the physical universe is constructed are of such a nature that from them a miniature universe could be constructed exactly similar in every respect to the present universe.

In the present paper we take a form of statement for the fundamental postulate which shows more clearly the relation between this and other relativity theories.

Since x may be any desired number, it is seen that these transformation equations correspond to any desired change in the standard of length and, by trial, it can be shown that the substitution of these equations will, as a matter of fact, leave all the general equations of physics absolutely invariant.

Having obtained these equations for the transformation of the five fundamental kinds of quantity, it is easy to obtain transformation equations for any desired kind of quantity merely making use of the definition of the derived quantities in terms of the fundamental quantities. Thus we can write down the following further transformation equations for velocity, energy, frequency, and force, etc.:

$$v' = v \quad E' = \frac{E'}{x} \quad \nu = \frac{\nu}{x^2} \quad f' = \frac{f}{x_2} \tag{2}$$

To illustrate the usefulness of the theory of similitude, we may use these transformation equations to derive a general relation connecting energy and frequency. This was done, as a matter of fact, by Dr. Karrer[1] of the Fixed Nitrogen Research Laboratory, at a time when it was important to supplement our inexact empirical knowledge of the relation between energy and frequency by theoretical investigations.

Let us suppose that our experimental investigations have indicated that there must be some general relation between the energy given up, or absorbed by an oscillating system, and the frequency of oscillation. Expressing this fact, let us write the equation

$$E = \phi\,(\nu) \tag{3}$$

where ϕ is the unknown function, the form of which we wish to determine. In accordance with our postulate, ϕ must be entirely invariant when we change to our new standards of reference. Hence we can obviously also write

$$E' = \phi\,(\nu')$$

where ϕ has the same form as above. Substituting our transformation equations (2) for energy and frequency, we obtain

$$\frac{E}{x} = \phi\left(\frac{\nu}{x}\right) \qquad E = x\phi\left(\frac{\nu}{x}\right)$$

or combining with (3)

$$E = \phi\,(\nu) = x\,\phi\left(\frac{\nu}{x}\right) \tag{4}$$

It will be seen by inspection that the only solution for this functional equation is

$$E = h\,\nu \tag{5}$$

where h is a constant. By this simple process we have thus derived the fundamental equation of the quantum theory.

As another illustration of the usefulness of the theory of similitude, we may note that Newton's equation for the gravitational attraction between bodies is not invariant when we substitute the transformation equations given above. As a matter of fact, the equation

$$f = k\,\frac{m_1\,m_2}{l^2} \tag{6}$$

transforms into

$$f' = x^2\,k\,\frac{m_1'\,m_2'}{l'^2} \tag{7}$$

when we substitute the transformation equations. This alone should make us suspect that Newton's equation of gravitation is not one of the *general* equations of physics. It may give correct numerical results, but its failure to conform with the requirements of the theory of similitude indicates that some more fundamental treatment of gravitation is demanded and this, as a matter of fact, has been provided by Einstein's general relativity theory, which will be described in the last section of this paper.[1]

Einstein's Theory of the Relativity of Uniform Motion

Einstein's first work on the theory of the relativity of motion[2] was based on the general idea that co-ordinate systems in *uniform relative motion* must be entirely equivalent to each other. Since there is no such thing as absolute velocity, it would seem as if one co-ordinate system should be just as good as another, moving relative to the first with some uniform velocity, and that the equations of physics ought to be expressible in such a form as to show their independence of the choice of reference system. In particular, it would seem as if the description of the simplest of all kinematical occurrences; namely, the spreading out of a light disturbance in free space, should be absolutely invariant for all co-ordinate systems in uniform relative motion. This idea may be stated in the form of the following definite postulate:

The general laws of physics are expressible in equations which are invariant, when we change from one set of space-time co-ordinates to another set moving relative to the first with

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[1] loc cit.

[2] In another place, I hope to show the bearing of the theory of similitude on Einstein's solution of the problem of gravitation.

[3] For an English account of Einstein's theory of the relativity of uniform motion, see Cunningham, "The Principle of Relativity," Cambridge University Press, 1914; Silberstein, "The Theory of Relativity," Macmillan, 1914, Tolman, "The Theory of the Relativity of Motion," University of California Press, Berkeley, 1917

uniform velocity; and, in particular, the equation which describes the way light spreads out in free space, is completely invariant in form and numerical content for such a change in reference system.

The latter part of this statement is sometimes called the second postulate of relativity and is stated in the form: The velocity of light in free space appears the same to all observers, regardless of the motion of the source of light and the observer.

This statement, which was originally taken by Einstein more or less as an unproved postulate, has, as a matter of fact, received very satisfactory experimental proof. Thus the Michelson-Morley experiment, which compares the velocity of light perpendicular and parallel to the earth's motion around the sun, may be regarded as showing that the velocity of light is unaffected by a simultaneous motion of source of light and observer through any suppositious ether, and the recent work of Majorana[1] on the velocity of light reflected from a moving mirror, and more recently from an original source set in motion, show that the velocity of light is independent of the relative motion of source and observer.

The revolutionary nature of this postulate must not be overlooked, and no attempt to conceal it can be tolerated. Suppose, for example, that S is a source of light and A and B two moving systems. A is moving towards the source S, and B away from it. Observers on the systems mark off equal distances aa′ and bb′ along the path of the light, and determine the time taken for light to pass from a to a′ and b to b′ respectively. Contrary to what seem the simple conclusions of common sense, the postulate requires that

the time taken for the light to pass from a to a¹ shall measure the same as the time for the light to go from b to b′. Such a consideration makes the path obvious by which the theory of relativity has been led to strange conclusions as to the intercomparison of measurements of length and time made in systems moving relative to each other.

If our postulate is true, it is evident that we must completely remodel our so-called "common sense" ideas as to the nature of space and time, which, however, have been built up through a long ancestral experience which involved such small relative velocities as to make the difference between the correct and the "common sense" ideas of space and time negligible.

Returning now to the statement of the fundamental postulate which we gave above, we can proceed to the development of the original Einstein theory of the relativity of uniform motion.

Using Cartesian co-ordinates, we may obviously write the following equation as a description of the way in which a light disturbance in free space spreads out

$$\left(\frac{dx}{dt}\right)^2+\left(\frac{dy}{dt}\right)^2+\left(\frac{dz}{dt}\right)^2=c^2 \qquad (8)$$

where c is the velocity of light. Multiplying through by dt^2 and transposing, we obtain the equation in the form

$$dx^2+dy^2+dz^2-c^2dt^2=0 \qquad (9)$$

In accordance with our postulate this equation must transform *identically* into itself, when we change to a new system of co-ordinates in uniform motion relative to the first. Our problem is to find a set of transformation equations which will obey this requirement, and which will reduce, at low relative velocities to the form required by our "common sense" ideas of space and time, since these are known to be adequate when we deal with velocities small compared with that of light.

As a matter of fact, if we consider two systems of space-time co-ordinates, S and S′, such that S′ is moving past S in the X direction with the velocity V, it can be shown that the desired transformation equations have the form

$$x'=\frac{x-Vt}{\sqrt{1-V^2/c^2}}$$
$$y'=y$$
$$z'=z$$
$$t'=\frac{t-X/Vc^2}{\sqrt{1-V^2/c^2}}$$

It will be seen by trial that these equations are such as to transform the equation

$$dx'^2+dy'^2+dz'^2-c^2dt'^2=0$$

identically into

$$dx^2+dy^2+dz^2-c^2dt^2=0$$

and that they fulfill the further requirement of reducing to the familiar Galilean form

$$x'=x-Vt$$
$$y'=y$$
$$z'=z$$
$$t'=t$$

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[1] Phil. Mag. *35* 163 (1918) Phil. Mag. *37* 145 (1919).

when the relative velocity of the systems V is small compared with the velocity of light c.

Referring again to our fundamental postulate, Einstein's theory requires not only that the equation for the spreading out of light in free space must be absolutely invariant for the transformation in question, but that all the laws of physics must be expressible in equations which are invariant for this same transformation. This latter requirement has been of great importance in the modern development of theoretical physics, by providing important information as to what must be the nature of the general equations of physics.

These new investigations in theoretical physics have shown that it is possible to retain Hamilton's principle, as the fundamental law from which the equations in the most varied branches of physics can be derived. This has been done by showing that the quantity *Hdt* occurring in Hamilton's fundamental equation

$$\delta \int_{t^1}^{t^2} H\,dt = O \qquad (11)$$

assumes for every branch of physics the same form

$$H\,dt = -\Sigma \frac{E_0}{c} \sqrt{c^2 - u^2}\,dt \qquad (12)$$

where the symbol Σ indicates that we are to sum up the quantity in question for all parts of the system in question[1], E_0 is the energy of each separate portion of the system as measured by an observer at rest with respect to that particular portion of the system, and u is the velocity of that portion of the system.

With the help of this expression, we may now write as the fundamental equation for every branch of physics

$$\delta \int -\Sigma \frac{E_0}{c} \sqrt{c^2 - u^2}\,dt = 0 \qquad (13)$$

To show as a matter of fact that this fundamental equation is invariant for the transformations under consideration, we may note that by introducing the substitution

$$u^2 = \left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2$$

we can transform equation (13) into

$$\delta \int -\Sigma - \frac{E_0}{c} \sqrt{-(dx^2 + dy^2 + dz^2 - c^2\,dt^2)} = 0 \qquad (14)$$

This makes it evident that the same transformation equations which leave

$$dx^2 + dy^2 + dz^2 - c^2\,dt^2$$

invariant will also leave Hamilton's equation unchanged in form. Since this equation can be made the starting point for every branch of physics we have thus shown the general applicability of Einstein's theory of the relativity of uniform motion.

Einstein's Theory of Gravity and General Relativity

Einstein's original relativity theory concerns itself solely with the consideration of systems in uniform relative motion. It is obvious that we wish to be able to employ reference systems having any type of motion relative to each other. Thus, accelerated systems of space-time co-ordinates, rotating systems, or systems moving in any desired manner, ought all to be utilizable for the description of physical phenomena. As a matter of fact, Einstein's theory of general relativity shows that all possible co-ordinate systems are equally justifiable.

As a basis for Einstein's general relativity theory[2] we may take the postulate:

The laws of physics can be expressed in a set of equations which are invariant in form, although not necessarily in numerical content for any possible transformation of space-time co-ordinates.

Since this principle requires invariance merely in form, and not in numerical content[3] it might seem to be of little importance since the well-known theories of curvilinear or generalized co-ordinates have already provided general methods for expressing equations in such a way that their *form* is independent of the choice of reference system. We shall see, however, in what follows, that Einstein is able to relate the change in the numerical content of equations, accompanying a change in reference system, to the change in gravitational field which is also found to accompany changes in reference system. Einstein assumes that the general nature of the relation betwen gravitational field and reference system is such that by using a system of co-ordinates which has the natural acceleration of gravity, the equations of physics with certain restrictions will assume the same form, as in a space free from gravitational action. It is by a combination of the above postulate with this further principle

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[1] For a continuous system the summation will have to be made by a process of integration.

[2] For an English account of Einstein's general relativity theory, see Eddington, Report on the Relativity Theory of Gravitation, London, 1918.

For a discussion of some of the philosaphical implications of relativity, see Wilson, "Space, Time, and Gravitation," *The Scientific Monthly, 10*, 217 (1920).

[3] Owing to the limited nature of the invariance, prescribed by the above postulate, Wilson, Astrophys. J. 45, 244 (1917), would prefer to call this postulate a co-variance principle rather than a relativity principle.

that Einstein is led to his important conclusions.

Returning now to the requirements of our fundamental postulate, Einstein takes as his general equation for the way in which light spreads out when referred to *any* set of space-time co-ordinates, (or in space having any gravitational field) instead of the simple equation

$$dx^2+dy^2+dz^2-c^2\,dt^2=0$$

the more general equation

$$g_{11}dx_1^2+g_{12}dx_1dx_{21}+g_{13}dx_1dx_3+\ldots+g_{44}dx_4^2=0$$

or

$$\sum_1^4 g_{ij}\,dx_i\,dx_j=0 \tag{15}$$

and takes, instead of Hamilton's principle in its earlier form

$$\delta\int-\Sigma-\frac{E_0}{c}\sqrt{-(dx^2+dy^2+dz^2-c^2\,dt^2)}=0$$

the more general equation

$$\delta\int\Sigma\frac{E}{c}\sqrt{g_{11}dx_1^2+g_{12}dx_1dx_2+g_{13}dx_1dx_3+\ldots+g_{44}dx^2_4}=0$$

or

$$\delta\int-\sum_1^4\frac{E_0}{c}\sqrt{\sum_1^4 g_{ij}\,dx_i\,dx_j}=0 \tag{16}$$

In these equations, the four generalized coordinates x_1 x_2 x_3 and x_4 replace the previous co-ordinats x y z and t.

Furthermore, it will be noticed, as is required by our fundamental postulate, that these equations will be transformed into new equations of exactly the same form by any possible transformation of co-ordinates. Thus if we put

$$\begin{aligned}x_1&=x_1\;(x_1'\;x_2'\;x_3'\;x_4')\\x_2&=x_2\;(x_1'\;x_2'\;x_3'\;x_4')\\x_3&=x_3\;(x_1'\;x_2'\;x_3'\;x_4')\\x_4&=x_4\;(x_1'\;x_2'\;x_3'\;x_4')\end{aligned}$$

where the four functional relations may be anything at all, we may then write

$$dx_1=\frac{\delta x_1}{\delta x_1'}dx_1'+\frac{\delta x_1}{\delta x_2'}dx_2'+\frac{\delta x_1}{\delta x_3'}dx_3'+\frac{\delta x_1}{\delta x_4'}dx_4'$$

$$dx_2=\frac{\delta x_2}{\delta x_1'}dx_1'+\ \ldots$$

$$dx_3=\frac{\delta x_3}{\delta x_1'}dx_1'+\ \ldots$$

$$dx_4=\frac{\delta x_4}{\delta x_1'}dx_1'+\ \ldots$$

and substituting into

$$\sum_1^4 g_{ij}\,dx_i\,dx_j$$

it will be found that we obtain an expression of exactly the same form

$$\sum_1^4 g'_{ij}\,dx'_i\,dx'_j$$

thus showing us that the fundamental equations of physics, (15) and (16), are invariant in *form* for any transformation of co-ordinates. It must be noted, however, that in general the *numerical content* of this expression will not be invariant and the quantities g'_{ij} will have different numerical values from the quantities g_{ij}.

Our next problem is to determine the values of these quantities g_{ij}. This has been done by Einstein by obtaining an inter-relation between these quantities and gravitation, his fundamental idea being that the presence and magnitude of a gravitational field is entirely dependent on the particular choice of coordinates made. According to this idea, any observer finds a gravitational field at any point in space, only because he is using a set of co-ordinates which does not have the natural acceleration due to gravity at the point in question. In fact, Einstein's specific assumption is that it is always possible at any point in space and time, for a limited region surrounding that point, to choose a set of co-ordinates such that the equations of physics will all have the simple form found for them in the original simple theory of uniform relative motion. In other words, at any point in space and time it is always possible to choose a set of space-time coordinates such that the expression

$$g_{11}\,dx_1^2+g_{12}\,dx_1\,dx_2+g_{13}\,dx_1\,dx_3+\ \ldots\ +g_{44}\,dx_4^2$$

will reduce to the simpler form

$$dx^2+dy^2+dz^2-c^2\,dt^2$$

These co-ordinates will be called the "natural" co-ordinates for the point in question. It must be noted, however, that Einstein's assumption is, that this particular choice of co-ordinates can be made only for a limited region in space and a limited duration in time.

These ideas as to the inter-relation of gravity and choice of co-ordinate system, and the possibility of transforming away a gravitational field for a limited region in space and time, by a proper choice of co-ordinates, may be illustrated by considering the phenomena inside of a freely falling elevator. It is evident that an observer inside this elevator, using meter-sticks and clocks which have the same downward acceleration as everything else inside the elevator, would obtain for the phenomena inside his limited region, the same laws as would be found by an observer in free space completely removed from any gravitating bodies. The observer inside the elevator would find no evidence of any attraction due to gravity. The floor of the elevator would exert no upward pressure on his feet. Bodies would have no tendency to move downward with reference to the elevator itself and, if thrown across the elevator, would move in straight lines instead of parabolas, referred to the walls of the elevator.

In order now to obtain definite conclusions as to the values that are to be assigned to the quantities g_{ij} which occur in our general equations of physics, we may set in definite form the additional hypothesis used by Einstein as follows:

At any point in space and time it is always possible to choose a set of space-time co-ordinates with reference to which the quantities g_{ij}, and their first differential coefficients will assume the simple values which they have in free space.

This principle has been called by Einstein the equivalence hypothesis, since it requires that at least as far as first order differentials, a gravitational field of force shall be identical with the field of force which can be generated in free space solely by a choice of co-ordinates.

In order to derive from this equivalence hypothesis, definite equations connecting the quantities g_{ij} with x_1 x_2 x_3 and x_4, Einstein has found it necessary to develop a very elaborate mathematical theory, which is beyond the scope of this paper. As a final result, however, using polar co-ordinates, we obtain the following expression for the quantity $\sum_1^4 g_{ij}\, dx_i\, dx_j$, in the neighborhood of a central attracting body such as the sun.

$$\frac{dr^2}{1-\frac{2\,k\,m}{c^2r}}+r^2\,d\theta^2+r^2\,sin^2\,\theta d\phi^2-\left(1-\frac{2\,k\,m}{c^2r}\right)c^2dt^2 \quad (17)$$

In this expression r is the radius from the sun to the point in question, m is the mass of the sun, and k is the gravitational constant.

Substituting this expression into our general equation (15) for the spreading out of a light disturbance, we obtain of course a description of the way light will move in the gravitational field of a central attracting body of mass m, and Einstein has predicted on this basis that a ray of light grazing the sun's limb will be bent inward by the gravitational field so as to give a total deflection of 1.75″. This is the prediction which was recently tested by British astronomers by taking photographs of the sun and the stars surrounding it during the eclipse of May 29, 1919, and comparing the relative positions of the stars with those obtained when the sun was not present. As a matter of fact, the rays of light from stars were bent in towards the sun by an amount almost exactly that predicted.

Substituting the expression (17) for the value of $\sum_1^4 g_{ij}\, dx_i\, dx_j$ in the neighborhood of the sun into (16), we shall obtain a modified form of Hamilton's principle which will permit us to determine the motion of a particle in the gravitational field surrounding the sun. A computation on this basis has been carried out by Einstein, which shows that the path of a planet around the sun should not be quite a stationary ellipse, but that the major axis of the ellipse should gradually rotate. For the solar planets the only case in which this effect is large enough to be determined is for the orbit of Mercury, and Einstein has calculated that the long axis of Mercury's ellipse should rotate 43″ per century, which just removes the previous unexplained anomalies in the orbit of this planet.

These two confirmations of Einstein's theory are certainly very compelling. Einstein has made a further prediction that the frequency of vibration of an atom should depend on the gravitational potential at the point where it is located, and he has calculated that there should be a measurable deflection, towards the red, of lines in the specta which originate from the strong gravitational field at the surface of the sun. This prediction has failed to receive confirmation, although it has been carefully looked for by St. John at the Mt. Wilson Observatory. Further investigation as to the theory and as to the experimental test of this part of Einstein's work must certainly be undertaken.

In conclusion, I wish to express my own feeling that in Einstein's latest theory, allowing for further modifications which will undoubtedly be introduced, he has made a contribution of fundamental importance for theoretical physics. He has shown that *all* the laws of physics can be expressed in equations which are completely *invariant in form* for all possible transformations of space-time co-ordinates. Although the equations of physics are not invariant in *numerical content* for these transformations, nevertheless, he has shown that the changes in numerical content are to be simply accounted for by their relation to the gravitational field, found by the particular observer in question.

Einstein has thus solved the two age-long problems of the relativity of all motion and of the uniformity of gravitation. All systems of space-time co-ordinates are equally justifiable for use in the description of physical phenomena without reference to their state of motion, and all bodies at a given point in space, regardless of the material of which they are composed, will experience exactly the same gravitational acceleration, since this gravitational acceleration is due to the particular choice of space-time co-ordinates made.

The Production and Measurement of High Vacua

PART I

By Dr. Saul Dushman

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The marvelous development during the past few years in the application of hot-cathode devices to the field of wireless telephony and telegraphy has been largely due to the great progress in the art of producing and maintaining extremely high vacua. Simultaneously, because of the knowledge concerning the structure of the atom revealed by investigations at very low gas pressures, added interest has been directed to the whole subject of the production of high vacua. This article, which is the first of a series by Dr. Dushman, discusses the fundamental principles of the kinetic theory of gases which are of importance in connection with the subsequent discussions of methods for the production and measurement of high vacua.—Editor.

INTRODUCTION

"Nature abhors a vacuum." This statement represents the sum total of the knowledge possessed by the ancients of a field of scientific investigation which within the past decade has yielded results of extreme importance. In 1643, Torricelli, a pupil of Galileo, showed that nature abhors a vacuum to a limited extent and the discoverer of the fact that the atmosphere exerts a pressure equivalent to that of a mercury column 32 inches in height, is remembered by the designation "Torricellian vacuum" for the space above the mercury in the barometric tube.

No doubt Torricelli imagined that this space is a "perfect void." We now know, however, that in this space there is mercury vapor at a pressure corresponding to about two or three millionths of an atmosphere and also traces of water vapor and air whose pressure may often amount to one or more millionths of an atmosphere.

In 1654 Otto von Guericke invented the first mechanical air-pump which was subsequently improved by Boyle, Hawksbee, Smeaton and others. During the two hundred years or so that followed, the interest in low pressure phenomena was more or less academic and often that of the dilettante. The paths of glory laid out by Newton, Laplace and Maxwell in mathematical physics, and by Priestly, Lavoisier and Faraday in experimental science, were so enticing that little or no enthusiasm could be aroused in investigations of "empty space." However, with the development of the carbon filament lamp on the one hand, and the discovery by Geissler and others of curious electrical phenomena in gases at low pressures, there began a series of investigations in this field which have not only increased enormously our knowledge of the technique for the production of lower and lower pressures, but have also led to results which have profoundly affected our views of the nature of matter and energy.

When Crookes first observed the phenomena of cathode rays, he thought that he had discovered a fourth, or radiant state of matter. A further investigation of this subject by J. J. Thomson led him, as is well known, to the conclusion that in the conduction of electricity through gases at low pressures, the negative current, or so-called cathode rays, is carried by extremely small corpuscles or *electrons*, whose mass is about one two-thousandths of that of a hydrogen atom, while the charge is exactly the same as that carried by a hydrogen ion in electrolysis, but opposite, of course, in sign. These electrons are the principal carriers of the current in all cases of conduction in gases at low pressures. It was also observed that electrons are emitted from metals under the influence of light, and Richardson showed that electrons are emitted from incandescent metals. The conclusion was therefore drawn that electrons are present in the atoms of all elements—a conclusion which was very soon corroborated by observations on the radio-active elements.

With the discovery by Roentgen of X-rays, the study of so-called vacuum tube phenomena entered upon a new phase which has led not only to increased knowledge of the structure of matter and the nature of X-rays, but also to vast improvements in both the devices for the production of these rays and their application to medical diagnosis and therapy.

The mutual effects of purely scientific discovery and technical achievement have at no other time been better illustrated than in the history of the development of the hot cathode high vacuum devices which play such an important role at the present time in both the application of X-rays and of wireless telephony. The history of this development has been so interwoven with the progress achieved during the past decade in the field of high vacua that a few remarks on this subject may not be out of place in this connection.

It has already been mentioned that electrons are emitted from the surface of incandescent metals. A careful study of the variation in the number of electrons emitted per unit area with change in temperature led Richardson to the theory that the electrons are emitted from the metal by a process quite similar to that of ordinary evaporation. The mathematical relations are the same in both cases and, as in the case of ordinary molecular evaporation, it is also possible to calculate the heat of evaporation of the electrons for different kinds of surfaces.

This view of the existence of an electron emission *per ipse* was opposed by a large number of investigators who maintained that the observed emission of electrons is a secondary effect due to chemical reactions at the surface, between the metal and the residual amount of gas present in the vessel. There was some excuse for this view, as Richardson's experiments were not carried out at very low pressures. The conclusion was therefore quite prevalent that in a "perfect vacuum" the electron emission would disappear.

A similar view was held with regard to the photo-electric effect, in which case electrons are emitted by the action of ultra-violet and ordinary visible radiation.

In order to throw some light on these problems, Dr. Langmuir carried out a series of experiments on electron emission in which special care was taken to obtain extremely low pressures. The results of this investigation showed that not only does the electron emission persist even in the best obtainable vacuum, but that the rate of emission at any given temperature is a specific property of the metal. It was found that the power of emitting electrons is also greatly decreased by slight traces of different gases, even at very low pressures. However, if the vacuum is sufficiently good this electron emission is quite reproduceable and constant, so that further improvement in degree of vacuum causes no increase in emission. It was also observed that at these low pressures the electron emission exhibits space charges effect, that is, the mutual repulsion between the electrons emitted from the hot surface limits the further emission of electrons, and the electron current to the anode is then dependent upon the anode voltage. Such an effect could arise only under such conditions that the number of positive ions formed by collisions between electrons and gas molecules is extremely small, in other words, at very low gas pressures. This accounts for the fact that this phenomenon was not observed by previous investigators.

These discoveries immediately paved the way for the development of the hot cathode X-ray tube by Dr. Coolidge and also led to the development of other hot cathode devices, such as the kenotron, pliotron and dynatron, whose application in wireless telephony and telegraphy has been of immense importance. At the same time the necessity of producing and maintaining high vacua in these devices has led to a vast amount of improvement in methods of exhaust.

While the phenomena of electrical conduction in gases at very low pressures have thus served to arouse a great deal of interest in the subject of high vacua, a number of investigations in other fields of physics and chemistry have also led to greater interest in the same field. The work of Knudsen, Smoluchowsky, Gaede and others on the application of the kinetic theory of gases to low pressures, and the striking results obtained by Langmuir on the mechanism of chemical reactions at low pressures have led to new views upon the nature of chemical and physical forces between atoms and we can look forward, as a result of these investigations, to solving some of the most vexing problems in both physics and chemistry by a study of the phenomena in gases at very low pressures.

Of necessity, as the technique of high vacuum production has improved, methods have been developed for measuring these extremely low gas pressures. A great deal of literature has been published during recent years on this whole subject, and a great deal of information has been gradually acquired in different laboratories about the actual technique of producing and measuring these pressures. In view of the important results to be expected from further investigations of low pressure phenomena it has been thought worth while to describe in a series of articles not only the methods available at present for the production and measurement of high vacua, but also to a lesser extent the more important results which have been obtained by the different investigators who have studied the physical and chemical phenomena exhibited in gases at very low pressures.

KINETIC THEORY OF GASES. APPLICATION TO GASES AT LOW PRESSURES

Laws of Boyle and Gay-Lussac

The state of a gas is ordinarily defined by means of the volume which is occupied by a given mass under definite conditions of temperature and pressure. The three laws of Boyle, Gay-Lussac and Avogadro may be combined in the form of the well-known relation:

$$P V = \nu R T \qquad (1)$$

where P and V denote the pressure and volume respectively, T denotes the absolute temperature (degrees Centigrade+273), ν is the number of mols (mass in grams divided by the molecular weight) and R is a constant for all gases.

The value of this constant is derived from the experimentally determined value of the volume of one mol of an ideal gas at given values of P and T. As standard pressure we shall consider that of 1 *megabar*. By definition, this is equal to 10^6 dynes per cm.², and corresponds very closely to a pressure of 750 mm. of mercury at 0 deg. C., lat. 45 deg., and sea level.

For $T = 273.1$ and $P = 1$ megabar, $V = 22{,}708$ cm.³ per mol.

Hence, $R = 83.15 \times 10^6$ ergs per degree abs. Denoting the weight of gas by m, and its molecular weight by M, equation (1) may therefore be written in the form,

$$P V = 83.15 \times 10^6\, m \frac{T}{M} \qquad (1a)$$

where P is measured in bars (dynes per cm.²) and V in cm.³

Now the pressures which we ordinarily deal with in high vacuum phenomena range from 1 to 10^{-3} bar and even less. It is evident that at these pressures the volume of even a very small amount of any gas may be quite considerable. Thus, by applying the above equation to the case of hydrogen ($M = 2.016$), we find that the volume occupied by 1 milligram of this gas at a pressure of 1 bar and 20 deg. C. (room temperature), is 1.209×10^7 cm.³, while at standard pressure the volume is only 12.09 cm.³

Kinetic Theory of Gases

For a proper understanding of phemonena in gases, more especially at low pressures, it is essential to consider these phenomena from the point of view of the kinetic theory of gases. At the present time we can, as a matter of fact, regard this theory as much more than a mere hypothesis. The evidence of the actual existence of atoms and molecules is so conclusive that very few would care to believe to the contrary. On the other hand, the theory has enabled us to interpret and prophesy so many facts about gases that one naturally uses this point of view in discussing any phenomena in gases.

The kinetic theory of matter, and more especially that of gases, rests essentially upon two fundamental assumptions. The first of these postulates is that matter is made up of extremely small particles or molecules, and that the molecules of the same chemical substance are exactly alike as regards size, shape, mass, and so forth. The second postulate is that the molecules of a gas are in constant motion, and this motion is intimately related to the temperature. In fact, the temperature of a gas is a manifestation of the amount of molecular motion. In the case of solids, at least those that are crystalline, it has been shown by the investigations of Bragg and others that the atoms which constitute the molecules when the substance is in the gaseous state are arranged in definite space-arrangements, and in this case the effect of temperature increase consists in increasing the kinetic energy of vibration of the atoms about their mean positions of equilibrium. But in the case of gases the effect of increased temperature is evidenced by increased translational kinetic energy of the molecules, and a relatively simple calculation based on these assumptions leads to the relation,

$$\frac{MG^2}{2} = \frac{3}{2} RT \qquad (2)$$

where G denotes the so-called *mean velocity* of the molecules at the absolute temperature T.

Substituting for R the value already given, this equation may be written in the form,

$$G = \sqrt{\frac{3RT}{M}} = 15{,}800 \sqrt{\frac{T}{M}} \text{ cm. sec.}^{-1} \qquad (2a)$$

Table I gives the values of the mean velocity at 0 deg. C., and 20 deg. C., for some of the more common gases.

It follows directly from this equation that at constant temperature the rates of flow of different gases through a narrow opening must vary inversely as the square roots of the molecular weights. This conclusion is of importance in connection with exhaust problems since it indicates that heavier gases must be more difficult to pump out than lighter ones.

Maxwell's Law of Distribution of Velocities

It is evident that even if all the molecules in a given volume actually possessed the same velocity at any initial instant, the constantly occurring collisions would disturb this equal distribution of velocities and a non-uniform distribution would soon be established. By applying the laws of probability, Maxwell showed that it is possible to calculate the law according to which the velocities of the molecules would be distributed at any temperature.* The curve shown in Fig. 1 represents graphically the distribution of velocities at any temperature, in terms of the most probable velocity, whose value is taken as unity. The significance of this curve can be understood better by means of the results tabulated in Table II. Under $\triangle x$ is given the range of velocities and under $\triangle y$ the fraction of the total number of molecules which have velocities corresponding to this range. Thus 16.1 per cent of all the molecules have velocities which range between 0.9 and 1.1 times the most probable velocity at any temperature. Similarly it follows that 68.4 per cent of the molecules have velocities ranging between 0.5 and 1.5 times the most probable velocity, while only 3.1 per cent have velocities that exceed 2.5 times the most probable velocity.

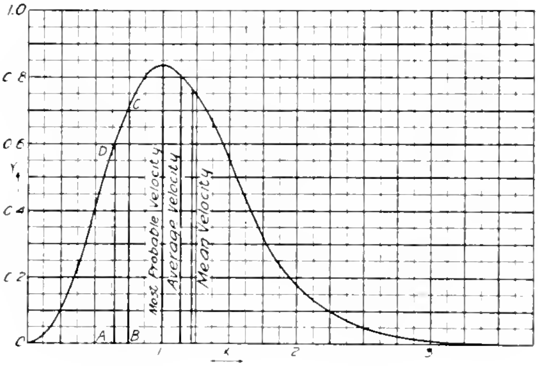

Fig. 1

TABLE II †

$\triangle x$	$\triangle y$	$\triangle x$	$\triangle y$
0 –0.1	0.001	1.3–1.5	0.112
0.1–0.3	.021	1.5–1.7	.078
0.3–0.5	.063	1.7–1.9	.058
0.5–0.7	.112	1.9–2.1	.034
0.7–0.9	.149	2.1–2.5	.030
0.9–1.1	.161	2.5–3.0	.008
1.1–1.3	.150		
0.5–1.5	.684	0 –2.5	.969

As shown in Fig. 1, the most probable velocity (which may be denoted by W) is different from the mean velocity, G, and the relation between these two values of the velocity is given by the following equation, which can be readily deduced from the equation to the curve for Maxwell's distribution law:

$$W = \sqrt{\frac{2}{3}}\,G = \sqrt{\frac{2\,RT}{M}} = 12{,}900\sqrt{\frac{T}{M}} \qquad (3$$

In addition to these values of the velocity, it is important, in connection with a large class of applications of the kinetic theory of gases, to know the arithmetical or average velocity of the molecules at any temperature.

TABLE I ‡

Gas	M	MEAN VELOCITY × 10^{-5} CM. SEC.$^{-1}$		Average Velocity at 20° C.
		At 0° C.	At 20° C	
H_2	2.016	1.838	1.904	1.755 × 10^5 cm. sec.$^{-1}$
O_2	32.00	0.4613	0.4778	0.440
N_2	28.02	.4928	.5106	.471
Air	28.96	.4849	.5023	463
Hg	200.6	.1842	1908	.176
CO_2	44.0	.3933	4076	.376
N_2O	18.016	.6148	6368	.587
A	39.88	.4133	4282	.395
NH_3	17.02	.6328	6554	604
CO	28.00	.4933	5109	471

‡ These data are taken from the author's paper on the Kinetic Theory of Gases, loc. cit

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* For a further discussion of the Distribution Law and other aspects of the kinetic theory of gases the reader may be referred to the following books and articles:

J. H. Jeans, The Dynamical Theory of Gases, 1916.
Meyer, Kinetic Theory of Gases.
K. Jellinek, Lehrbuch der Physikalischen Chemie., I, 1, 1914.
W. C. McC. Lewis, Kinetic Theory of Gases, 1915.
S. Dushman, The Kinetic Theory of Gases, GENERAL ELECTRIC REVIEW, Vol. 18, 1915.

† K. Jellinek, loc. cit., p. 222.

This is usually denoted by Ω and may be calculated by means of the relation,

$$\Omega=\sqrt{8/3\pi\ G}=\sqrt{\frac{8\ RT}{M\pi}}=14{,}500\sqrt{\frac{T}{M}} \qquad (4)$$

The values of the average velocity at room temperature for some of the more common gases are given in the last column of Table I.

Number of Molecules Per Unit Volume

According to Avogadro's law the number of molecules per gram-molecular weight of any gas ought to be the same. The problem of accurately determining the value of this constant, which we shall denote by N_0, has naturally been the object of a large number of investigations, and a number of different methods have been used in order to determine it. The phenomena of Brownian movement, the accurate determination of the charge on an electron, counting the number of alpha particles expelled from a gram of radium, and finally the study of the laws of black body radiation—all these methods have led to approximately the same value for N_0. According to Millikan, whose determination is undoubtedly the most accurate we have, this constant has the value of 6.062×10^{23}. From this value it is readily calculated that the number of molecules per cubic centimeter of an ideal gas at a pressure of 10^6 bars and 0 deg. C., is 2.67×10^{19}.

Let us now attempt to interpret this magnitude. The highest vacua attainable at present range around 10^{-4} bar. Even at this extremely low pressure, which would ordinarily be regarded as a "perfect vacuum," the number of molecules per cm.^{3}, at 0 deg. C., is still 2,670,000,000, a number which is, roughly speaking, of the same order of magnitude as the total population of the earth.

Rate at Which Molecules Strike a Surface

It was shown by Meyer that the number of molecules of a gas at rest as a whole that strike unit area per unit time is equal to $\frac{1}{4}\ n\ \Omega$, where n denotes the number of molecules per unit volume, and Ω denotes the average velocity.

Substituting for n and Ω the values previously given, we obtain the relation.

$$\begin{aligned}1/4\ n\ \Omega&=1/4\frac{N\ P}{R\ T}\sqrt{\frac{8\ RT}{\pi\ M}}\\&=2.653\times10^{19}\frac{P}{\sqrt{MT}}\end{aligned} \qquad (5)$$

For air at 20 deg. C., and 10^6 bars, the number of molecules striking 1 cm.^{2} per second, is 2.88×10^{23}.

Equation (5) may also be expressed in terms of the mass (w) of gas that strikes 1 cm.^{2} per second.

Let ρ denote the density of the gas.

Then,

$$\begin{aligned}w&=1/4\ n\ m\ \Omega=1/4\ \rho\ \Omega\\&=\frac{M\ P}{4\ R\ T}\Omega=43.74\times10^{-6}\frac{P}{\sqrt{MT}}\end{aligned} \qquad (6)$$

For air at 20 deg. C., and 10^6 bars,

$w=13.8$ gm./cm.^{2} sec.

As has been shown by Langmuir, equations (5) and (6) are extremely useful in the consideration of rates of evaporation of metal in vacua, and also in the study of the kinetics of chemical reactions at low pressures.*

Mean Free Path of Molecules

While the individual gas molecules in a gas at rest possess very high velocities, as shown above, it is a matter of ordinary observation that gases diffuse into each other very slowly. This is explained on the kinetic point of view by assuming that the molecules do not travel continuously in straight lines, but undergo frequent collisions. The use of the term "collision" naturally leads to the notion of *free path*. This may be defined as the distance traversed by a molecule between successive collisions. Since, manifestly, the magnitude of this distance is a function of the velocities of the molecules, we are further led to use the expression "mean free path" (denoted by L), which is defined as the average distance traversed by all the molecules between successive collisions.

Simple considerations show that the value of L must vary inversely as the total cross-sectional area of the molecules per unit volume. Taking into account Maxwell's distribution law and the fact that the molecules exert attractive forces on each other, it can be shown that L is given by the relation,

$$L=\frac{1.402}{\sqrt{2}\ \pi n\ d^2\left(1+\frac{C}{T}\right)} \qquad (7)$$

where d denotes the molecular diameter, and C is a constant for each gas (Sutherland's

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* Phys. Rev., *2*, 329, 1913, also Jour. Am. Chem. Soc., *37*, 1139, 1915.

constant) which is a function of the attractive forces between the molecules.*

The value of the molecular diameter may be derived, as shown by van der Waals, from the critical temperature and pressure of the gas. This value of d can then be used to calculate L by means of the above equation. It is, however, more usual to calculate L from the coefficient of viscosity, or heat conductivity of the gas, for it is evident that whether it be transference of momentum from one layer to another, as in viscosity, or transference of increased kinetic energy, of the molecules, as in heat conductivity, the rate of transference must depend upon the number of collisions which each molecule experiences as it passes from point to point. It should be observed in this connection that in the case of air especially, and of most other gases, the value of the coefficient of viscosity (denoted by η) has been determined with a high degree of accuracy.

The general relation between L and η is of the form,

$$\eta = k\,\rho\,G\,L, \tag{8}$$

where ρ denotes the density, and G the root-mean square velocity. For approximate calculations the value of k is ordinarily taken as $^1/_3$. Boltzmann and Meyer have both derived different values of k by taking into account Maxwell's distribution law. According to the latter the relation is,

$$\eta = 0.3097\,\rho\,\Omega\,L \tag{9}$$

while Boltzmann derived the relation,

$$\eta = 0.3502\,\rho\,\Omega\,L. \tag{10}$$

From the above equations it follows that the magnitude of L varies inversely as the pressure, that is, the lower the pressure, the greater the value of the mean free path. Table III, taken from the writer's paper on the kinetic theory of gases, gives the values of L at room temperature and standard pressure, for different gases. Under these conditions, the length of the free path for most gases is about 10^{-5} cm. But at 1 bar the value of L is as much as 10 cm., so that the molecules travel considerable distance without suffering any collisions. We shall show, in a subsequent section, how this conclusion is in splendid agreement with the phenomena observed at low pressures.

TABLE III

Gas	$L \times 10^5$ cm., at 20° C., and 10^6 bars	Collision-frequency $\Omega\ L \times 10^{-6}$
Air	9.376	4940
H_2	17.44	10060
He	27.45	4545
N_2	9.287	5072
O_2	9.931	4432
A	9.879	3998
CO_2	6.148	6115
CO	9.232	5101
NH_3	6.60	9152

From the values of L and Ω, the value of the collision-frequency, $\frac{\Omega}{L}$ may be derived. This number thus expresses the number of collisions per molecule per second. The values for some of the gases, at room temperature and standard pressure, are given in the last column of Table III.

Molecular Diameters

Using the above values of L, it is possible, from equation (7) to calculate the molecular diameters for different gases. Owing, however, to the fact that different investigators have used different values of the constant in the numerator of equation (7), there is no exact agreement with respect to the values of d thus derived. Table IV gives a summary of the values obtained by different methods of calculation. Under I are given the values calculated by the writer by means of equations (7) and (10), using the values of C as deduced by Sutherland. Column II gives the values assigned by Jeans as the mean values derived from three different methods of calculation.† Sackur has also attempted to deduce the value of d by several different methods‡, and concludes that the most probable values are those given in column III. Heydweiller's values,§ obtained by using equation (7) with the substitution of 1.319 for the constant 1.402, and combining this with equation (9), are given in the last column

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* See the writer's articles on "The Kinetic Theory of Gases," GENERAL ELECTRIC REVIEW, *18*, 1042-48, 1915, for a more detailed discussion of the derivation of this equation and of the following equations for the calculation of L, from the coefficient of viscosity. Heydweiller, Ann. Phys., *42*, 1273, 1913, uses the constant 1.319 instead of 1.402, as above, and combines this with equation (9) below, for the calculation of the molecular diameter.

† Dynamical Theory of Gases, 1916, p. 341

‡ O. Sackur, Ann. Phys., *40*, 97, 1913

§ A. Heydweiller, Ann. Phys., *42*, 1273, 1913

TABLE IV

Gas	MOLECULAR DIAMETERS (d x 10^8 cm.)			
	I	II	III	IV
H_2	2.403	2.68	1.90	2.176
He	1.905	2.16		1.77
N_2	3.146	3.76	2.40	
O_2	2.975	3.62	2.30	
A	2.876	3.64		2.68
CO	3.190	3.78	2.50	
CO_2	3.335	4.54	2.76	
Cl_2		5.36	3.30	3.693
Br_2			3.74	
I_2			4.52	
H_2O		2.27	2.26	
NH_3	2.967			

General Considerations Regarding Gases at Low Pressures

As has already been stated, the pressures which interest us in the study of high vacuum phenomena usually range below 1 bar. At these pressures the mean free paths of the molecules are at least of the same order of magnitude as the dimensions of the vessels used in experimental work. Thus, at 1 bar the mean free paths for most gases are about 10 cm. (Table III). It therefore follows that the majority of the molecules travel in straight lines as far as the dimensions of the vessels will allow, and the number of inter-molecular collisions per second becomes relatively small as compared with the rate at which the molecules strike the walls. The following considerations will probably serve to explain the significance of this statement more fully.

Consider a cube, whose volume is D^3 cubic cm., and let n denote the number of molecules per cm.^{3}. The number of collisions between gas molecules, per second is

$$C = n\,D^3\,\frac{\Omega}{L}$$

The total number of molecules striking the walls of the cube in each second is

$$A = 6D^2\,n\,\frac{\Omega}{4}$$

Hence, $\frac{A}{C} \infty \frac{L}{D}$. That is, the ratio between the rate at which the molecules strike the walls and the rate at which they collide with each other is given by the ratio between the lengths of the mean free path and of the side of the cube. It can be readily shown that no matter what the shape of the vessel, the ratio $\frac{A}{C}$ is proportional to that of $\frac{L}{D}$, where D is the distance between the walls. Thus, if D is of the order of magnitude of 10 cm., A is greater than C when L is greater than 10 cm., that is, when the pressure is lower than 1 bar (approximately). Consequently we should expect to find that at pressures of 1 bar and lower, the molecules travel in straight lines toward the walls of the containing vessel.

A very common illustration of this fact is the production of sharp shadows in vacuum type incandescent lamps. As has been shown by the investigations of Langmuir and Mackay[*], the blackening of ordinary tungsten lamps is due to the evaporation of metal from the filament. The pressure in this type of lamp under operating conditions is less than 0.01 bar[†], so that the mean free path of the tungsten atoms is of the order of several hundred centimeters. Consequently, collisions between these atoms and molecules of residual gas are very rare, and the tungsten atoms travel directly to the sides of the bulb, where they are immediately condensed. By interposing some object between the filament and the walls, very sharp shadows can be produced, if the vacuum is good. On the other hand, the shadows are very much blurred if there is present in the bulb a pressure of even several bars of some inert gas like argon. Similar phenomena are observed in the evaporation of other metals, like mercury and sodium.[‡]

Laws of Molecular Flow

It is evident from the above considerations that at very low pressures the rate of flow of gases through tubes or narrow apertures must be limited solely by the frequency with which the molecules strike the walls of the tube or aperture and may thus be thrown back in the direction of incidence. At higher pressures the rate of flow of gases through narrow tubes is governed by Poiseuille's law. If Q_1 denotes the amount of gas (measured in terms of $P.V$) which flows per second through a tube of diameter D and length l, and η denotes the coefficient of viscosity, Poisouille's law may be expressed by means of the equation,

$$Q_1 = \frac{D^4\,(P_2 - P_1)P}{128\,\eta\,l} \tag{11}$$

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[*] I. Langmuir, Am. Inst. Electr. Eng. Trans., also, Phys. Rev., *2*, 329, 1913.

[†] S. Dushman, Phys. Rev., *5*, 223, 1915.

[‡] L. Dunoyer, Les Idees Modernes sur la Constitution de la Matiere, p. 215, 1913. This article contains a very interesting discussion of low pressure phenomena, especially of Knudsen's Work (see p. 500).

where P is the pressure at which Q is measured and $P_2 - P_1$ denotes the difference in pressure at the two ends of the tube. At very low pressures this relation is no longer valid, and for a reason which is self-evident. At ordinary pressures the rate of flow of gases must be limited by the frequency of collisions between molecules, hence the necessity for introducing the coefficient of viscosity in the formula for the rate of flow. At very low pressures, however, where the length of L, the mean free path, is much greater than that of D, it is meaningless to speak of a coefficient of viscosity and it is therefore necessary to discard the hydrodynamical equations upon which Poiseuille's relation is based, in order to arrive at a more accurate relation for the rate of flow of gases through tubes. A similar difference has been observed for the laws of heat flow in gases at low and high pressures. For pointing out the manner of attacking both these problems and deducing a number of relations which are applicable to gases at low pressures, we are indebted to the theoretical and experimental investigations of M. Smoluchowsky, M. Knudsen, and W. Gaede, who, since 1908, have published a large number of papers dealing with this subject.

The term "molecular flow" was suggested by Knudsen to designate the condition of gases flowing through tubes at such low pressures that collisions between the molecules are infrequent as compared with collisions at the walls. As has been shown above, at these pressures L is much greater than D and the ratio $\frac{L}{D}$ increases with decrease in pressure, so that any molecule striking the inner surface of the tube at any point is repelled all the way across the tube until it strikes the opposite wall. Knudsen now assumes that any plane surface, no matter how smooth it may appear, consists in reality of teethlike projections which are probably due to one or more atoms being irregularly piled up above the surrounding atoms; that is, these projections are of molecular dimensions, and they are irregularly distributed over the surface. Consequently, "a gas molecule on striking the surface is repelled in a direction which is totally independent of the direction of incidence, and the distribution of directions of an infinitely large number of molecules after reflection from a surface follows Lambert's cosine law for the reflection of light from a glowing body."

Introducing Maxwell's distribution law and Meyer's equation for the number of molecules in a gas at rest that strike unit area, Knudsen arrives at the following relations for the case in which the diameter of the tube or aperture is infinitesimally small as compared with the length of the mean free path.[*]

In the case of a circular tube of diameter D, and length l, the quantity of gas, Q_2, which flows through per second, with a difference of pressure $P_2 - P_1$, is given by the equation.

$$Q_2 = \frac{P_2 - P_1}{W_1 \sqrt{\rho_1}} \tag{12}$$

where

$$W_1 = \frac{6\,l}{\sqrt{2\pi}\,D^3} = \frac{2.394\,l}{D^3} \tag{13}$$

and ρ_1 denotes the density at 1 bar pressure and the temperature of the tube.

From the gas laws it follows that,

$$\rho_1 = \frac{M}{83.15 \times 10^6\ T}$$

It will be observed that equation (12) is analogous to Ohm's law, so that we may speak of the term $W_1 \sqrt{\rho_1}$ as the resistance to flow of the tube at the temperature T for a given gas. For different gases, the value of the resistance varies as the square root of M.

For the case of a circular opening in a thin plate, equation (12) is still valid, but the value of W_2, the "resistance" is given by the equation,

$$W_2 = \frac{\sqrt{2\pi}}{A} = \frac{3.184}{D^2} \tag{14}$$

where A is the area of the opening, and D its diameter.

Hence, where we have a tube of diameter D and length l connecting two vessels at low pressures, the total resistance to flow of this tubing for a gas of unit density, is

$$W = \frac{2.394\,l}{D^3} + \frac{3.184}{D^2} \tag{15}$$

By means of equations (12) and (15) it is possible to calculate the quantity of gas that can flow through any given tube or opening at low pressures. The value of Q is obtained in terms of PV, that is, the volume in cm.^{3} at a given pressure P, in bars. As an illustration of the application of the above equation, Table V gives the volumes (in cubic cm.)

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[*] Ann. der Phys., 28, 75, 1908, and 28, 999, 1908. Also M. L. Dunoyer, loc. cit.

TABLE V

l	D	W	Q_2 (Air)	Q_2 (Hyd.)
1	1	5.578	5204.	19710.
10	1	27.124	1070	4053.
1	0.1	2712.4	10.70	40.53
10	0.1	24258.4	1.196	3.60

of air or hydrogen (at 1 bar pressure) that would flow through different sizes of tubing for a difference of pressure of 1 bar, and room temperature. For air at 293 deg. abs. and 1 bar pressure, $\rho = 1.189 \times 10^{-9}$ and for hydrogen, under the same conditions, $\rho = 8.271 \times 10^{-11}$.

From equation (15) and the data in Table V it is evident that for long tubes of very small diameter (capillaries) the end correction is negligible. The values of Q_2 for air and hydrogen may then be derived from the data in the table for $l = 10$ and $D = 0.1$ by applying equation (13).

These examples illustrate the effect of narrow tubes on the rate of exhaust at low pressures, and it is therefore absolutely essential that in experiments at low pressures where maximum speed of exhaust is desired, the connecting tubing should be as large in diameter as practicable, and also as short as possible.

Laws of Flow at Higher Pressures

The equations given above are strictly accurate only at such low pressures that $\frac{D}{L}$ is infinitesimally small. Actually it has been found by Knudsen that the equations are accurate to within 5 per cent even at pressures where $\frac{D}{L} = 0.4$. For air at room temperature and 1 megabar, the value of L is 9.4×10^{-6} cm., and at a pressure P, $L = \frac{9.4}{P}$. So that in case of a tube 1 cm. in diameter, the equation for molecular flow would be accurate to within 5 per cent for all pressures below about 3.76 bars.

It is of interest in this connection to discuss briefly the manner in which the rate of flow of gas through a tube varies at higher pressures. If we denote the ratio, $\frac{Q_2}{(P_2 - P_1)}$ by F, it is evident from the above discussion that for very low pressures this ratio is constant and *independent of the pressure*. As, however, the pressure is increased the value of F is observed to decrease at first until it reaches a minimum value which is about 0.95 of its value at very low pressures. As the pressure is increased still further, F increases and the rate of increase with pressure is given by Poiseuille's law. From experiments over a large range of pressures with different gases, Knudsen has derived the following semi-empirical relation which is found to hold at all pressures:

$$F = a\,P + b\frac{(1 + c_1 P)}{(1 + c_2 P)} \qquad (16)$$

where,

$$a = \frac{\pi\,D^4}{128\,\eta l} \quad \text{(Poiseuille's constant)}$$

$$b = \frac{1}{W\sqrt{\rho_1}} \quad \text{(Coefficient of molecular flow)}$$

$$c_1 = \frac{\sqrt{\rho_1}\,D}{\eta} \quad \text{and} \quad c_2 = \frac{1.24\sqrt{\rho_1}\,D}{\eta}$$

For ordinary pressures this equation assumes the form already given for Poiseuille's law, equation (11), while at very low pressures it becomes identical with equation (12). In order to illustrate the application of equation (16) and also show the effect of pressure on the rate of flow of gases it is of interest to calculate by means of this equation the value of F at different pressures for air flowing through a tube 10 cm. long and 1 cm. in diameter, at room temperature. In Table VI, F expresses the volume in cubic cm., measured at 1 bar pressure and room temperature that flows through the tube for a difference of pressure of 1 bar at the ends and an average pressure of P bars.

TABLE VI

$a = 135$-6, $b = 1070$	$c_1 = 0.19033$	$c_2 = 0.2360$
P (bars)	F (equation 16)	$F - 1070$
10^6	13.56×10^6	13.56×10^6
100	2227	1157
50	1555	485
20	1160	90
10	1058.1	—11.9
5	1025.7	—44.3
4	1023.6	—46.4
3	1025.2	—44.8
1	1043.6	—26.4
0.1	1065.4	— 4 6
0.01	1069.6	— 0.4

These results have been plotted in Fig. 2. It is seen that the minimum value in F occurs at about 4.5 bars. Even at this pressure the difference between the value calculated by means of equation (16) and that calculated by applying the simple equation (12) combined with equation (15) is less than 5 per cent of the value, $F = 1070$, calculated by the last mentioned method. Table VI also shows that the resistance of tubes is very much greater at extremely low pressures than at ordinary pressures.

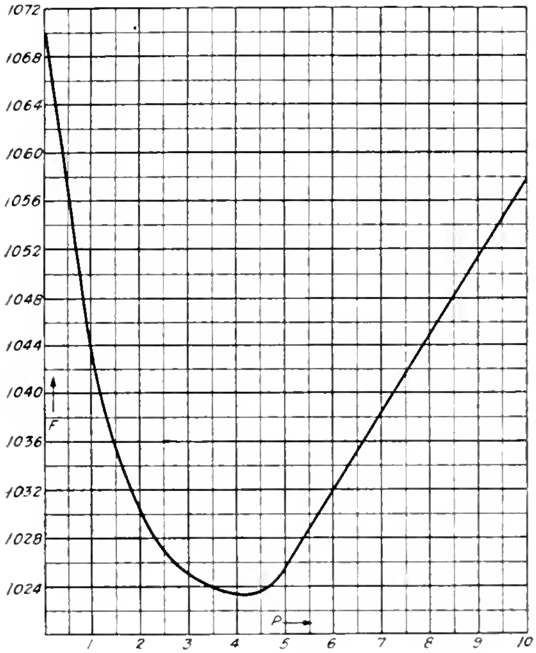

Fig. 2

Thermal Molecular Flow

In experiments on gases at low pressures it is often the practice to keep different parts of a system at different temperatures. A usual case is where an appendix or trap connected with the vessel to be exhausted, is kept immersed in liquid air, while the pressure in the system is read by some form of sensitive gauge. If the pressure is so low that $\frac{L}{D}$ for the connecting tube is very high, gas is observed to flow *from the colder to the hotter parts* until a sufficient pressure is developed to check it. The condition of equilibrium of pressures in the two parts of the system is then given by the relation,*

$$\frac{P_1}{P_2} = \sqrt{\frac{T_1}{T_2}} \text{ or } \frac{\rho_1}{\rho_2} = \sqrt{\frac{T_2}{T_1}} \qquad (17)$$

As the pressure increases, the amount of flow from the colder to the hotter parts gradually decreases to zero and then reverses, so that at ordinary pressures the condition of equilibrium is

$$P_1 = P_2 \text{ or } \frac{\rho_1}{\rho_2} = \frac{T_1}{T_2}$$

Equation (17) is immediately applicable to the case mentioned above where a trap connected to an exhaust system is immersed in liquid air ($T = 88$ approx.). The pressure in the latter is then $\sqrt{\frac{88}{293}} = 0.55$ of that in the rest of the system.

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* Knudsen, Ann. Phys., *31*, 205 and *33*, 1435, 1910.

G. D. West, Proc. Phys. Soc. (Lond.) 31, 278 (1919). This paper gives a critical discussion of the laws of thermal transpiration over the whole range of pressures.

(To be Continued)

Fundamental Phenomena in Electron Tubes Having Tungsten Cathodes

PART I

By Irving Langmuir

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As a result of the pressing need for electron tubes during the war, the development of these devices has proceeded rapidly in the last few years. The phenomena upon which the operation of these tubes depends are so different from those of most electrical devices that confusion has frequently arisen as to the interpretation of their various characteristics. The author discusses the fundamental factors, such as the electron emission from the filament, the effect of space charge, the disturbances caused by the current passing through the filament, etc., and endeavors to clear up many of the mysterious effects that have been observed. This article was read as a paper last November at a symposium on electron tubes held in Chicago by the American Physical Society.—Editor.

In a paper* published in 1913, it was shown that in a two-electrode thermionic device having only a negligible gas residue, and operating with relatively large currents, the characteristics consists essentially of two parts.

In one part of the characteristic the current is practically independent of the applied voltage, but increases rapidly if the temperature of the filament is raised. This part of the characteristic we will refer to as the "saturation region." The current is primarily determined by the electron emission from the cathode.

In the second part of the characteristic the current increases with the applied voltage, usually about in proportion to the three-halves power of the voltage, but the current is practically not affected by a change in filament temperature. This part of the characteristic we will refer to as the "space charge region." Under these conditions the current is limited primarily by the electrostatic field of the electrons in the space between the electrodes.

In discussing the fundamental phenomena in electron tubes, we must keep clearly in mind the distinct nature of each of the two factors just mentioned. It will therefore be desirable to discuss these factors separately and later consider how they may co-operate to determine the characteristics of a given device.

The fundamental phenomena underlying the two different parts of the characteristics are (1) the *electron emission* from the cathode, and (2) the *space charge* between the electrodes.

Electron Emission. When a metal is heated to high temperature in an extremely high vacuum, electrons are emitted from its surface. These electrons are emitted with certain initial velocities, depending on the temperature of the heated metal or cathode. It has been shown by Richardson and others that these initial velocities depend only on the temperature of the cathode and not on the material of which it is constituted. All the electrons emitted do not have the same velocities—the velocities of the individual electrons are distributed around an average value according to the laws of probability. In this particular case the distribution of velocities is expressed by a law derived by Maxwell and usually known as Maxwell's Distribution Law. The average kinetic energy of the emitted electrons has been found to have the same value as that of gas molecules in a gas at the same temperature as the cathode, and the distribution of the individual velocities around this mean value is also the same.

Although the actual average velocity of emitted electrons is very high when expressed in ordinary units, such as miles per second, the effects produced by these velocities are strikingly small. Because of the very large electric charges on the electrons and their small masses, these initial velocities do not enable the electrons to move against anything but small retarding potentials. For example, the average kinetic energy of the electrons emitted from a cathode heated to 2400° K.† is only sufficient to allow the electrons to

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* Langmuir: Phys. Rev. *2*, 450 (1913). Two other papers giving some new data and a clearer discussion of the theory were soon afterwards published in the Physikalische Zeitschrift Vol. 15, pages 348 and 516 (1914). A review of the history of these theories and a discussion of their application to electron tubes for use in radio work were published the following year. General Electric Review, *18*, May, 1915, and Proc. Inst. Radio Engs. *3*, 261 (1915).

† The temperature of filaments are expressed on the absolute or Kelvin scale as denoted by the symbol °K. The method of determining the temperatures from the characteristics of the filaments have been published: Langmuir, Phys. Rev. *7*, 302, (1916) and General Electric Review 19, 208 (1916).

move against a retarding potential of 0.31 volts; with a filament at 1200° K. the average velocity corresponds to 0.15 volts. To illustrate the meaning of Maxwell's Distribution Law applied to the case of a filament at 2400° K. the following figures are given: 90 per cent of the emitted electrons are capable of moving against 0.022 volts; 75 per cent can move against 0.059; 50 per cent against 0.143; 25 per cent against 0.29; 10 per cent against 0.48; 1 per cent against 0.95; while only one out of a thousand can move against 1.42, one out of a million against 2.85 and only one out of a billion against 4.27 volts. The higher the temperature of the filament the greater the voltages against which the electrons can move; in fact, this voltage increases directly in proportion to the absolute temperature of the filament.

The number of electrons emitted from a given cathode in high vacuum depends to a very marked extent on the nature of the material constituting the cathode, on the condition of its surface and on the temperature. The way in which the electron emission varies with the temperature is usually given with satisfactory accuracy by an equation which was derived in 1901 by Richardson. This equation is

$$i = a\sqrt{T}\,e^{-\frac{b}{T}} \qquad (1)$$

Here i is the current emitted per unit area from the cathode. In other words, i is proportional to the number of electrons emitted per unit area per second; T is the absolute temperature of the cathode, a and b are constants depending on the nature and condition of the surface of the cathode, and e is the base of the natural system of logarithms, which is 2.718.

In deriving this equation it was assumed that the number of electrons per unit volume in the metal remains substantially constant while the temperature has been raised, and that the external electric field produced by a positive anode is without effect in drawing electrons out of the metal. In order that the current obtained in any actual device may correspond with the above equation it is necessary that the conditions be so chosen that all of the electrons which are emitted are able to flow to the anode. If this is the case and if the external field does not cause an increase in electron emission, then the current passing through the tube is independent of the voltage applied to the anode and the current is said to be saturated and is usually referred to as the saturation current.

For the case of a filament of pure tungsten in a very high vacuum the electron emission is given by the equation:

$$i = 23.6\times 10^{6}\sqrt{T}\,e^{-\frac{52500}{T}} \qquad (1)$$

where i is expressed in amperes per sq. cm. From this equation the values of i given in Table I are calculated.

TABLE I

ELECTRON EMISSION FROM PURE TUNGSTEN

Absolute Temp.	Amperes per Sq. Cm.	Absolute Temp.	Amperes per Sq. Cm.
1500	0.58×10^{-6}	2300	0.1377
1600	5.42×10^{-6}	2400	0.365
1700	37.8×10^{-6}	2500	0.891
1800	214×10^{-6}	2600	2.044
1900	0.00103	2700	4.35
2000	0.0042	2800	8.33
2100	0.0151	2900	17.1
2200	0.0483	3000	31.7

Although it is frequently possible under experimental conditions to obtain saturation currents which remain constant over wide ranges of voltage, there are two factors which, even in the complete absence of gas effects, may cause the current to increase with the voltage over that part of the volt-ampere curve where ordinarily the saturation current is to be expected. The first of these effects has been experimentally found by several observers and particularly by Schottky (Phys. Zeit. *15*, 872, 1914). Schottky has given both theoretical and experimental reasons for believing that with potential gradients of the order of magnitude of a million volts per centimeter, the electron emission from a metal can be very greatly increased because of an actual pulling of the electrons out of the metal by these fields. Although fields of this order of magnitude can be rather easily obtained experimentally, most practical devices utilizing thermionic currents do not have electric fields around their cathodes sufficient materially to increase the current in this way.

The second effect is caused by heterogeneity in the surface of the cathode.

When a metal which gives a high electron emission is in electric contact with another metal giving smaller electron emission, there is a contact difference of potential between these metals, and there is an electric field produced in the space between the surfaces of these metals. This contact difference of potential has been the subject of discussion for nearly a hundred years, but within more recent years, through the work of Richardson and others, has assumed increased importance.*

According to this theory a small surface of very high electron emission (which we will refer to as an active surface) will have a positive potential with respect to surrounding areas having lower electron emission (inactive surface). If the active surfaces are small in extent compared to the inactive ones the electric field close to the surface of the cathode will be largely determined by the negative field of the inactive areas. Since the electrons escaping from the active areas must pass through these negative fields, the effective electron emission may be greatly cut down unless an external field is applied sufficient to counteract or neutralize the negative field produced by the inactive areas. A mathematical analysis† shows that when the sizes of the active and inactive areas are of molecular dimensions or rather are of the dimensions which one might expect by a random distribution of active molecules over the surface, very large external fields are necessary in order to get saturation current. When to this effect of active and inactive areas we add the geometrical surface irregularities such as small elevations and depressions due to crystalline structure, etc., it is apparent that conditions should be expected to arise in which the volt-ampere characteristics may increase with the applied voltage in a complicated way over the range usually called the saturation region.

Among the numerous experiments which have confirmed these theoretical conclusions, I will mention only one in detail. A thermionic device having a tungsten filament containing a trace of thorium and made up in such a way that a particularly high vacuum is maintained, can be treated so that the filament acts in one case like a pure tungsten filament, and in a second case like a pure thorium filament (as far as electron emission is concerned), while in a third case a fraction of the surface of the cathode is covered with thorium atoms so that the surface is not homogeneous. These changes in the condition of the cathode can be brought about at will merely by heating the cathode at a series of different temperatures in the highest vacuum. For example, if the filament is heated for a short time to 1900° K., thorium diffuses from the inside of the filament to the surface and gradually completely covers the surface of the filament with a layer of thorium. On the other hand, when the filament is heated for a few minutes at 2800 or 2900° K., all the thorium distills off the filament, leaving a surface of pure tungsten. If, however, the thorium be distilled from the filament at a lower temperature or for a shorter time, it is possible to leave the surface covered partly with tungsten and partly with thorium.

When the surface is entirely covered with thorium the electron emission at a given temperature is many thousands of times greater than that from the pure tungsten surface. By lowering the temperature of the thorium covered filament it is possible to get the same emission in the two cases. It is then found that under both of these conditions a very definite saturation current is obtained. That is, there is a wide range of voltage over which the current remains practically constant.

On the other hand, if the surface of the cathode is made heterogeneous by having both tungsten and thorium present on the surface it is found that no well defined saturation current is obtained, but the current gradually increases as the voltage is raised. The volt-ampere characteristic is very markedly different from that which is found in either of the two previous cases. This test is best made by adjusting the filament temperature so that the current that flows with an anode voltage of 200 is the same in each case. These experiments can only be made in an exceptionally high vacuum because even slight traces of gases such as water vapor, or oxygen entirely destroy the activity of a surface of thorium and slight traces of positive ionization produce a disintegration of the surface to such an extent that the minute traces of thorium are removed from the surface. It is clear from these experiments that the failure to reach saturation is no indication whatever of the condition of the vacuum within the tube. With one and the same tube, without change in vacuum conditions, the volt-ampere characteristics can either be made flat, giving a good saturation current, or be made to curve continually upward even at high voltages so as to give little indication of a definite saturation value. Other experiments seem in a general way to indicate that Wehnelt cathodes as ordinarily made are far from homogeneous, and that even in the highest vacuum it is difficult to get a well defined saturation current.

This effect also explains the results obtained by Schlichter‡ in which he found that with a

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* For a general discussion of contact potentials and for references to the earlier literature see Langmuir, Trans. Amer. Electrochem. Soc. *29*, 125 (1916).

† This work will probably be published within the next year.

‡ Annalen der Physik *47*, 573 (1915).

contaminated platinum surface no definite saturation was obtained at a hundred volts, while with a clean surface saturation was reached at five volts or less.

In determining the saturation current in a particular device it is usually necessary to take great care that the temperature of the cathode remains constant. The electron emission ordinarily increases so extremely rapidly with the temperature that a very few degrees change in temperature of the cathode will cause a relatively large change in the electron emission, and therefore in the saturation current. In cases where fairly large currents are made to pass through a thermionic device and fairly high voltages are used, the heat generated at the anode and radiated from it may be sufficient to cause changes in the temperature of the cathode, and in this way, unless extremely sensitive methods of determining and checking the cathode temperature are employed, it may happen that this cause produces an apparent increase in the saturation current when the voltages applied to the anode are increased. An effect of this kind is apt to be particularly important in those cases where the cathode operates at a low temperature, as for example where a Wehnelt cathode is used. Either by careful control of the cathode temperature or by making measurements of the electron emission by momentary application of voltage to the anode, it is possible to distinguish between an apparent increase in saturation current due to this heating effect and a real increase in electron emission due to heterogeneity of the filament surface or to other causes.

Very minute traces of impurities in the filament or on its surface may cause great changes in electron emission, and as the condition of the surface may change during the heating of the filament it may happen that the saturation current changes markedly with the time so that irregularities in the volt-ampere characteristics may result.

Space Charge. When a positive potential is placed on an anode, in proximity to a heated cathode in a high vacuum, and the filament is heated to a low temperature so that it emits relatively only few electrons, the velocity of the electrons increases steadily as they move between cathode and anode. However, with a given voltage on the anode the velocity which the electrons acquire is perfectly finite so that the electrons take a certain time to pass across this space. When the temperature of the cathode is raised and the electron emission increases, the number of electrons in the space between cathode and anode at any given time increases at first in proportion to the electron emission. Now these electrons in the space tend to repel those which are leaving the cathode, and it is clear that as we increase the total number of electrons carrying the current, a point must ultimately be reached at which the repulsive force caused by the electrons in the space will be sufficient to neutralize the attractive force caused by the positive potential on the anode. Under these conditions the current still flows to the anode because of the initial velocities of the electrons, but if the current should then increase enough so that the repulsion of the electrons in the space is able to exceed the attractive force due to the anode sufficiently to counteract the effect of the initial velocities, then any additional electrons emitted by the cathode will be forced to return to the cathode. The current flowing from cathode to anode will thus reach a definite limit at any given voltage on the anode. In other words, the space between cathode and anode has a finite current-carrying capacity for a given anode voltage. No mere increase in electron emission from the cathode can cause the current through the device to increase beyond that set by this limitation to the current.

The quantitative theory of the volt-ampere characteristics of an electric discharge in which the current is carried by ions of only one sign was worked out by Child (*Physical Review*, 32, 192 [1911]). For the case of a discharge occurring between two parallel plane electrodes Child obtained the equation *

$$i = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\,\frac{V^{3/2}}{x^2} \qquad (2)$$

Here i is the current flowing between the electrodes per square centimeter of surface.

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* This equation was independently derived by the writer (Phys. Rev. 2, 450 [1913]) and applied to the case of conduction by electrons.

Lilienfeld (Phys. Rev. 3, 364, [1914]) claims to have found the law that the current increased with the 3/2 power of the voltage in some of his work published in 1910. A careful study of Lilienfeld's data shows, however, that in his experiments the current did not even approximately vary with the 3/2 power of the voltage. The original data upon which Lilienfeld bases his claim are those given on page 698 of his 1910 article (Annalen der Physik, Vol. 32). It there appears that no current flowed until the voltage between the sounding electrodes was 102 volts and when the voltage increased from 102 to 116 volts there was a 17 fold increase in current.

The current thus increased with the 22nd power of the voltage instead of with the 3/2 power. At higher voltages the rate of increase became gradually less, but over the range in which Lilienfeld claims to have found the relation, the 3/2 power law is not even approximately fulfilled. What Lilienfeld did find was the purely empirical relation that, beginning from 102 volts in his device the current increased in proportion to the 3/4 power of the quantity $(V - V_0)$, where V is the difference of potential between two sounding electrodes and V_0 is 105 volts. At the higher voltages before V became very large compared to V_0, Lilienfeld found that even the above empirical relation did not hold.

e is the charge on the ion; m is the mass of the ion; V is the difference of potential between the anode and cathode; and x is the distance between these electrodes. Child derived and used this equation in connection with a discussion of the maximum current that could be carried by positive ions in a gaseous discharge.

When equation (2) is applied to the case of a discharge carried by electrons only, the value of $\frac{e}{m}$ is very much larger than in the case of discharge carried by positive ions. If we take the value of this ratio as found for the electrons and substitute in the equation and adopt as our units the volt, ampere and centimeter the equation becomes

$$i = 2.33 \times 10^{-6} \frac{V^{3/2}}{X^2} \qquad (3)$$

In this equation, i represents the current-carrying capacity of the space between the electrodes in amperes per square centimeter when the difference of potential V is applied to the electrodes, and the distance between the electrodes is X centimeters.

For the entirely analogous case of a pure electron discharge from a straight cylindrical filament to a co-axial cylindrical anode, I have derived the equation

$$i = \frac{2\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{V^{3/2}}{r} \qquad (4)$$

where i is the current per centimeter of length along the axis and r is the radius of the cylindrical anode.

If the units are expressed in volts, amperes and centimeters this equation becomes

$$i = 14.65 \times 10^{-6} \frac{V^{3/2}}{r} \qquad (5)$$

This gives the maximum current-carrying capacity of the space between the cathode and anode in amperes per centimeter of length for the case of a small heated wire in the axis of a cylindrical anode of radius r centimeters, having a positive potential of V volts with respect to the cathode.

Assumptions Underlying the "Space Charge Equations"

In deriving the above equations, Child, Langmuir, Schottky, and presumably Arnold, made two fundamental assumptions; first, that the initial velocities of the electrons had a negligible effect under the conditions to which the equations were to be applied, and secondly, that the temperature of the cathode and therefore its electron emission were so high that a further increase in temperature would not cause an increase in the current. This second assumption is equivalent to assuming that the filament is at such a temperature that it emits a surplus of electrons. It is necessary to make some such assumption in order to bring into the mathematical equations the fact that we wish to consider the space charge limitation of current instead of that due to the electron emission from the cathode.

We have already seen that the average initial velocity of the electrons emitted from the filament at 2400° K. is only sufficient to cause electrons to move against a negative potential of 0.31 volts. Since the space charge equation is ordinarily used in connection with thermionic devices, in which voltages of from 10 volts up to many thousands of volts may be used, it is clear that the initial velocities are very small compared to those produced by the applied voltages. In general, therefore, it would seem that we are justified in neglecting these initial velocities. Of course, what actually happens is that, when the electron emission from the cathode exceeds the current-carrying capacity of the space, some of the electrons begin to return to the cathode. When this occurs there is at the surface of the cathode an opposing electric field, and the potential in the space at a short distance from the cathode surface is negative with respect to the cathode itself. The electrons which return to the cathode are naturally those which were emitted from it with the lowest velocities. There is thus directly in front of the cathode a place where the potential is a minimum and it is at this place that the potential gradient is zero.

In the derivation of the space charge equations the assumption of negligible initial velocities introduces an error which is roughly proportional to the ratio of the few tenths of a volt to the applied anode potential. The assumption that the potential gradient at the surface of the cathode is zero is strictly only permissible when we neglect the initial velocities. If the initial velocities were actually zero, then there is no question that the potential gradient at the surface of the cathode would be zero when the current is limited by the current-carrying capacity of the space. If we assume that this zero potential gradient does not exist at the surface of the cathode, but exists at the point of minimum potential at a distance of a thousandth of an inch or so from the cathode, then the assumption is entirely permissible.

It is also apparent that this assumption of zero potential gradient taken together with an assumed zero initial velocity, is merely equivalent to stating that a surplus of electrons is emitted at the cathode, and it is essential to make this assumption if we wish to have the resulting equation give us the maximum current-carrying capacity of the space.

Of course, there are various other tacit assumptions which are made in the derivation of the space charge equations (2) to (5), such as, for example, that the whole of the cathode is at one potential, that the electrons do not lose energy by collisions with gas molecules, that there is no magnetic field which interferes with the free motion of the electrons, etc.

The space charge equation (3) giving the current between parallel plane electrodes is not of a form which can be readily tested experimentally because it is difficult to work with a plane cathode surface of large area.* The fact, however, that this equation indicates that the current when limited by space charge should increase in proportion to the three-halves power of the voltage is the most significant feature.

The equation (5) dealing with the case of a straight cathode wire in the axis of a cylindrical anode is one which can be tested experimentally with high accuracy. A large number of experiments by Dushman† and by Schottky have shown that this equation holds with a very satisfactory degree of accuracy, the experiments being made of course under conditions of very high vacuum. This agreement is not only accurate in regard to the current increasing in proportion to the three-halves power of the voltage over a wide range, but also in regard to the actual numerical values of the current obtained at a given voltage.

By a general method of reasoning published in 1913,‡ it was concluded that the three-halves power relation derived directly for the case of the parallel plane electrodes and the cylindrical electrodes should also hold for electrodes of any shape, provided that every part of the cathode surface is heated to a temperature high enough so that a surplus of electrons is emitted, and that the boundaries of the space through which the discharge takes place are either at the potential of the cathode or at the potential of the anode. In the argument given in support of this relation it was not made clear that the rigorous derivation depends upon the assumption of negligible initial velocities and also upon the fact that the paths which the electrons take under these conditions remain the same if the potentials of the bounding surfaces are all increased in the same ratio. Schottky (Phys. Zeitsch. *15*, 526 [1914]) criticised this conclusion and maintained that the 3/2 power law should hold only for those cases in which the electrons travel in straight lines from the cathode to the anode. As a result of correspondence, however, Schottky recognized that the paths of the electrons remain unchanged when the voltage is raised, and therefore admitted the general validity of the 3/2 power law for all cases where the effects of initial velocities were negligible.

By far the best indication, however, that the three-halves power relation does hold for electrodes of even complicated shapes is the experimental proof that it holds over wide ranges of voltages in actual thermionic devices in which the filaments and even the anodes are in the form of wires twisted into a great number of irregular shapes. In fact, the experiments seem to show that except under unusual conditions the relation holds very nearly as well as for the case of concentric cylinders. This experimental proof justifies the assumptions made in the derivation of the general equation. In devices with three electrodes it is usually found that the three-halves power relation holds satisfactorily either when both cold electrodes are connected together as anode or when one is used as anode and the other is connected to the cathode. In this latter case, however, the range over which the relation holds is usually more restricted. The reason for this will be discussed below.

Of course, it is only to be expected that the space charge equations will apply only when the electron emission from the cathode is so great that a surplus of electrons is emitted from every part of the cathode surface. Even under these conditions there are various factors which may cause deviation from the three-halves power law or which may cause the current-carrying capacity of the space to vary, even without change in the anode potential.

We will discuss these various factors.

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* Germershausen (Physik. Zeitsch. *16*, 104 [1915]) applied Equation (3) to electron current between a plane Wehnelt cathode and a parallel anode and obtained good agreement.

† Dushman, Phys. Rev. 4, 121 (1914).
Schottky, Physik. Zeitsch. *15*, 624 (1914).

‡ Langmuir, Phys. Rev. 2, 450 (1913).

‖ See footnote on page 874 of Schottky's subsequent paper (Physik. Zeitsch. *15*, 872, [1914]).

Effects Due to Initial Velocities of the Electrons

I have already discussed how with the parallel plane electrodes the initial velocities of the electrons produce a small deviation from the three-halves power relation when the voltage applied to the anode is not very large compared to the voltages of a few tenths of a volt corresponding to the initial velocities. Of course when voltages below two or three volts are used on the anode these deviations from the three-halves power law become relatively large. In the case of coaxial cylindrical electrodes the electric field around the cathode is particularly strong close to the surface of the cathode, and the effects due to initial velocities are thus less important than in the corresponding case of the parallel plane electrodes. Still with anode voltages of less than five or ten volts, the initial velocities cause quite perceptible, and at very low voltages, relatively large deviations. In the general case of electrodes of any shape whatever it is not always true that the initial velocities have the same relatively small effect as in the two simple cases of the plane and cylindrical electrodes. Wherever the design of the apparatus is such that there is a strong electric field close to the surface of the cathode the deviations from the three-halves power relation are not greatly different from those in the case of the concentric cylindrical electrodes. Thus, the cathode instead of being straight can be bent into complicated shapes, such as a rather open helix or a V, U or W shape. The anode also may have various shapes of this kind, and yet in all these cases the three-halves power ratio may be found to hold over a very wide range of voltages and even hold fairly accurately at voltages as low as five volts. That is, the current at five volts may differ only by a small percentage from the current calculated by extrapolating from the volt-ampere curve at higher voltages according to the three-halves power law.

In those cases, however, where the apparatus is so designed that the electric field close to the surface of the cathode is made abnormally small by the presence of an auxiliary electrode or the walls of the vessel, the effect of the initial velocities of the electrons is exaggerated so that marked deviations from the three-halves power law may hold at comparatively high voltages. Such an effect, for example, is observed when a standard Coolidge X-ray tube, having a focusing shield nearly surrounding the cathode, is operated at potentials of only a few hundred volts, that is, under conditions far removed from those at which it ordinarily operates. The presence of this focusing screen or shield, which is connected to one end of the cathode filament, makes the electric field close to the surface of the cathode very small indeed compared with what it would be if the shield were not present. Under these conditions the number of electrons which escape from the cathode and pass to the anode depends very greatly on the initial velocities of the electrons. Thus, with voltages on the anode much less than those needed to give saturation, the current flowing through the tube is found to depend to a considerable degree on the temperature of the cathode; in other words, on the initial velocities. Furthermore, the current is found to increase with the voltage considerably more slowly than corresponds to the three-halves power law even at voltages of several hundred volts. However, as the voltage is raised the slope of the volt-ampere characteristic gradually approaches closer to that corresponding to the three-halves power law, so that at 2000 volts there is reasonably good agreement with this law.

Another case in which the effect of initial velocities may be abnormally increased is that in which the grid of a pliotron is connected to the negative end of the filament, while various positive potentials are applied to the plate or anode. The shielding action of the grid has an effect similar to that of the focusing shield in the Coolidge tube, although the effect is usually not nearly so marked. Under normal conditions it is usually found that the current flowing to the anode follows the three-halves power law quite satisfactorily under these conditions over a wide range of voltage, but that as the anode voltage is lowered deviations from this law begin to occur at, for example, 20 to 50 volts on the anode, instead of five or ten volts as in the case where the grid and anode are connected together.

A simple analogy may make clearer the reason for the effect of initial velocities being so greatly exaggerated when the field around the cathode is made small. Suppose, for example, a man stands on the ground holding a handful of sand and throws this up into the air while the wind is blowing. The sand will evidently be carried away by the wind. This condition is rather analogous to the case of electrons emitted from a filament surrounded by an electric field which tends to draw the electrons away. The wind corresponds of course to the electric field. Under these conditions, it is clear that the particular velocity with which the man throws the sand upward is not important so long as the velocity is sufficiently great for the sand to leave his hand. Consider now the case of a man standing at the bottom of a well, with the wind blowing over the ground around the well: If the man throws the sand up as before, it will all fall to the bottom of the well because it is protected from the action of the wind. If, however, he throws it upward with sufficient velocity so that some of it rises above the level of the ground, it will then be carried away by the wind. The amount that is thus carried will depend entirely on the velocity with which the sand is thrown upward. This is analogous to the case of the Coolidge X-ray tube in which electrons are emitted at the bottom of a depression which protects the surface of the cathode from the action of the external electric field.

Experiments have shown that if a tube is made up exactly like a standard Coolidge X-ray tube, except that the focusing shield is omitted, the three-halves power law then applies with very satisfactory accuracy down to comparatively low voltages.

Effects Due to the Charging Up of the Walls of the Vessel

In cases where the anode does not nearly surround the cathode some of the electrons emitted from the cathode are able to pass to the surface of the glass until a negative charge develops on the glass sufficient to prevent any further flow of electrons to the glass. In other words, the glass will become slightly negatively charged with respect to the cathode. The actual potential which the glass may reach in this way depends mainly on how good the insulating conditions are, and, as we shall see later, depends to an extraordinary degree on the presence of even relatively minute amounts of gas ionization. According to Maxwell's Distribution Law, there is no definite upper limit to the velocities with which the electrons are emitted from the hot cathode, but, as has been shown, only about one out of a million of the electrons is able to move against 2.85 volts, and only one out of a billion against 4.27 volts. Such extremely small currents as those corresponding to this last figure would not ordinarily be able to make up for the electric leakage from the surface of the glass. Under usual conditions, therefore (and this is in general accord with experiment), the glass walls, and, in fact, any well insulated electrode placed within the vessel, charges up to potentials in the neighborhood of about two volts. But under exceptional conditions of high vacuum, etc., this negative charge may be a couple of volts greater.

Where the anode nearly surrounds the cathode the slight negative potentials on the glass have, of course, relatively little effect on the electric field between the electrodes, and therefore are not important in their effect on the current-carrying capacity of the space. In those cases, however, where the anode is relatively small, or is placed at a considerable distance from the cathode so that a relatively large surface of glass is exposed, the effect of the charges on the glass frequently becomes of the utmost importance in modifying and increasing the effect of the space charge, and in weakening the field around the cathode. In this way it may happen that the effects of the initial velocities may be exaggerated, just as in the case of the presence of an auxiliary electrode close to the cathode. In the case where the anode and cathode both consist of small U-shaped filaments placed at some distance apart in a rather large glass bulb, the effect of the charging-up of the walls may become so great as entirely to stop the current that flows between the two electrodes even when several hundred volts are applied to the anode. Such effects as this can be observed when the greatest effort is made to obtain a high vacuum and the entire bulb is completely immersed in liquid air so as to improve the vacuum and decrease the electric conductivity of the glass surfaces. Under slightly poorer vacuum conditions, where effects of this kind may occur, but are less marked, it may happen that no current will pass from cathode to anode until a certain critical voltage is applied to the anode. Above this point the volt-ampere characteristics correspond accurately under ordinary conditions to the three-halves power law. These effects can be eliminated by rendering the glass walls electrically conducting, as for example, by distilling tungsten, copper or other metallic substance on to them from the filament and by connecting this conducting surface to the anode or cathode in such a way as to prevent the accumulation of negative charges.

In properly constructed thermionic devices effects of this kind usually do not occur at all under normal conditions. These effects have, however, misled a great many scientific investigators and have undoubtedly led Pring and Parker in their work on thermionic emission from carbon, and Hallwachs in his work on photo-electric emission, to conclude that in a very high vacuum the thermionic emission and photo-electric emission vanish. Of course, subsequent work has entirely disproved these conclusions.

Effects Due to the Current Used to Heat the Cathode

Under the usual operating conditions ordinary thermionic devices have a cathode which is in the form of a filament and is heated by the passage of current through it. There is thus a potential drop along the filament and the current through the filament produces a magnetic field surrounding the wire. There are thus three ways in which the current flowing through the filament may influence the volt-ampere characteristics and cause deviations from the three-halves power law:

(*A*) The potential drop along the wire makes the potential difference between the anode and cathode vary for different parts of the cathode surface.

(*B*) If the different portions of the cathode are in close proximity to each other, two parts having marked difference of potential produce an effect exactly like that caused by the grid of a pliotron.

(*C*) The magnetic field causes changes in the paths of the electrons.

Let us discuss these effects separately:

(*A*) *Potential Drop Along Cathode.* As an extreme case where the potential drop along the wire influences the characteristics of the discharge, let us consider a long straight filament placed in the axis of an equally long cylindrical anode. We will assume that the voltage drop along the wire is 100 volts. If, now, we give the anode a potential of ten volts (positive) with respect to the negative end of the filament, it is clear (neglecting initial velocities) that current will flow only from that part of the cathode which is negative with respect to the anode. The current will thus flow only from a section of the cathode located near the negative end of the filament, which is one tenth of the length of the cathode. If, on the other hand, the anode is charged to plus 20 volts with respect to the negative end of the filament, then current will flow from two tenths of the length of the cathode while the other eight tenths will be entirely inactive as far as contributing to the total current is concerned. For each small section of the cathode the three-halves power law will apply with reasonable accuracy, but the total effective length of the filament also increases in proportion to the applied voltage. From this it is readily seen (and this is confirmed by more rigorous mathematical analysis) that as long as the potential of the anode does not exceed that of the *positive* end of the cathode, the total current increases in proportion to the five-halves power, that is, the two and one-half power of the voltage. With anode voltages higher than that of the positive end of the filament this relation will no longer hold, but the slope of the volt-ampere characteristic will gradually approach more and more closely to that corresponding to the three-halves power law as the voltage is raised beyond this point. It is thus seen that the maximum effect of the voltage drop along a straight filament with the anode at a constant distance from it is not greater than that corresponding to an increase of the exponent from 3/2 to 5/2.

It is clear that in studying the characteristics of a device in which there is a large voltage drop along the filament, the voltage applied to the anode should be measured from the negative end of the filament, because most of the electron emission, and in some cases all of the electron emission, comes from this end of the filament.

(*B*) *Grid-like Action of One Part of the Filament on Another.* With special construction of the cathode by which the two ends of the cathode are brought close together, or where the cathode is made as a double helix, this grid-like action may become fairly marked. It is still more pronounced where one end of the filament is supported by a framework in proximity to the filament or to the path that the electrons take between the cathode and anode. This framework corresponds exactly to a grid connected to one end of the filament. The current-carrying capacity of the space between cathode and anode depends upon the direction in which the current is made to pass through the cathode, the voltage of the anode with respect to the negative end of the filament being kept constant. Thus, if the framework is positive with respect to the rest of the filament, the current-carrying capacity of the space will be greater than if the framework is negative with respect to the rest of the filament. In general the 3/2 power relation will hold more accurately if the framework is connected to the negative end of the filament than if it is connected to the positive end. Furthermore, with a given potential on the anode (always with respect to the negative end of the filament) the current-carrying capacity of the space will vary with the current flowing through the cathode, because the potential on the positive end of the filament is thus made to change and this alters its effect as a grid. In case the anode is maintained at a given potential with respect to the positive end of the filament (which is not customarily done) this may readily lead to a decrease in the current-carrying capacity of the space when the filament temperature is increased. This effect is simply due to the negative end of the filament becoming more strongly negative when the filament temperature is raised.

(*C*) *Effect of Magnetic Field.* Richardson[*] has pointed out that the magnetic field produced by the current flowing through the cathode tends to interfere with the free motion of the electrons and tends in fact to cause them to return to the cathode. This effect is particularly marked when the cathode is such that it requires large heating currents of many amperes, and is also more marked when the electrons are moving under the influence of a weak electric field, that is, when the anode voltages are low.

For the case of a straight filament carrying one ampere the electric field needed to draw the electrons through this magnetic field is only 0.2 volts. The effect is thus of the same order of magnitude as that due to the initial velocities of the electrons. With filaments, however, which take 10 or 20 amperes to heat them, this effect would be quite serious except when high anode voltages are used.

Elimination of Effects Caused by Current Passing Through the Cathode

All of the effects caused by the current passing through the cathode can be entirely eliminated by making measurements of the volt-ampere characteristics during short intervals of time during which the current flowing through the cathode is interrupted. If these time intervals are made of the order of a hundredth of a second or less, the filament temperature remains practically constant. This may be accomplished by use of a rotating commutator. This method was apparently first used for measurement of thermionic currents by O. von Baeyer[†] and was subsequently used by Schottky (Annalen der Physik *44*, 1021 [1914]). This simple method of determining the characteristics of a thermionic device eliminates all the rather complicated secondary effects produced by (*A*) the potential drop along the cathode; (*B*) the grid-like action of one part of the cathode on another; and (*C*) the magnetic field caused by the current flowing through the cathode.

Effects Caused by Lack of Uniformity in the Temperature of the Cathode

The filament used as cathode is cooled at its ends by the leads which carry the current to it, and it is also cooled by any supports used to hold the filament in place. Although the central part of the filament may be heated to such a high temperature that it emits more electrons than can be carried through the space with a given voltage on the anode, the ends of the filaments are always cooled to such a low temperature that they emit practically no electrons. A mathematical and experimental analysis has shown that under ordinary conditions the cooling effect at the two ends of a tungsten filament lowers the total electron emission from the filament by an amount that corresponds roughly with the electron emission from a length of filament having a voltage drop of 1.4 volts. Thus, if the voltage used to heat the cathode is 14 volts, the cooling effect of the leads normally decreases the total electron emission by about 10 per cent below that which would be obtained if the entire length of filament were heated to the same temperature as that which exists at its middle. With a filament, however, requiring only 4.2 volts the cooling effect of the leads would reduce the total electron emission by about one third. These results are given simply to indicate the order of magnitude of the effect produced by the cooling of the leads.

With filaments which take three volts or less the relative decrease in electron emission for a given heating current is much greater than would be calculated by the above simple rule.

In the derivation of the space charge equations particularly that derived for the case of electrodes of any shape, it was assumed that every part of the cathode surface was heated to a temperature at which a surplus of electrons was produced. Now, in all cases in which we are dealing with actual filaments there is a short length of filament near the ends on which the electron emission is so small that there is not a surplus of electrons. In fact, over this region of the filament the current flowing from it will be saturated. This causes a slight deviation from the 3/2 power law, but with filaments requiring three or four volts or more this particular cause of deviation is an extremely small effect. This is

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[*] "The Emission of Electricity from Hot Bodies" (1916), by O. W. Richardson, p. 67.

[†] Physik. Zeitsch *10*, 168 (1909).

proved by observation of the actual characteristics of electron discharge devices having filaments of this character. It is found that the volt-ampere characteristics do follow the 3/2 power law over a wide range of voltage. Of course the higher the voltage used in the filament the smaller this effect becomes, but the evidence seems to indicate that even for the filaments having the lowest drop used in practice this particular effect is negligible in causing departure from the 3/2 power law.

The cooling effect of the leads, however, has a more marked effect on the characteristics in causing a change in the current-carrying capacity of the space because of the change in the area of the heated part of the filament when different filament temperatures are used. Thus the higher the filament temperature the longer the section of the filament which will be heated hot enough to emit a surplus of electrons. With filaments in which the voltage drop is only three or four volts and operating at normal temperature a marked increase in filament temperature will increase the length of the heated region sufficiently to cause several per cent increase in the current-carrying capacity of the space, simply because it increases the cross-section of the space through which the electrons pass. With filaments in which the voltage drop is larger, however, this effect becomes proportionally less.

This effect of the cooling of the leads sometimes causes the apparent current-carrying capacity of a given device to depend on the cathode temperature. This should not be mistaken for an effect due to the initial velocities. The effect due to initial velocities is noticed particularly with low anode voltages, whereas that due to the cooling of the leads is effective at all anode voltages practically equally. The volt-ampere curve in this latter case still corresponds to the 3/2 power law, but the coefficient K in the equation $i = KV^{3/2}$ increases as the filament temperature is raised simply because the length of the heated region changes with the temperature of the filament.

Effect of External Magnetic Field

If a thermionic device is placed in a magnetic field, as, for example, by bringing an electro-magnet or permanent magnet close to the bulb, the paths of the electrons are changed in a way similar in principle to that caused by the magnetic field due to current flowing through the cathode. With ordinary thermionic devices of the type I am considering an external magnetic field usually decreases the current-carrying capacity of the space for a given anode voltage. The lower the voltage on the anode the more marked this effect becomes. As a result of this an external magnetic field usually causes the current to increase with the applied voltage on the anode more rapidly than when the magnetic field is absent. Thus, in the ordinary device the 3/2 power law holds accurately over a wide range when there is no field, but a strong magnetic field has the effect of making the current increase more rapidly than the 3/2 power law requires. An effect of this kind is ordinarily only noticeable when rather strong external fields are applied, and weak fields like that of the earth's magnetic field are negligible in their effects.

(To be concluded in July issue)

Electron Power Tubes and Some of Their Applications

By William C. White

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The interest and activity in radio transmission is on the increase and this fact has focused attention on the three-element electron tube, otherwise the pliotron. In this article there is given a very thorough exposition of the factors of design and construction that determine the output of three-element power tubes. This is followed by a description of a typical pliotron power tube, after which are discussed the properties of oscillating circuits for these tubes. The article is concluded with descriptions and illustrations of radio transmitting sets.—Editor.

There is a considerable field of application for three-element electron tubes as oscillators or amplifiers to give outputs of several hundred to several thousand watts.

For this purpose it is possible to utilize a very large number of small tubes operating in parallel, but for reasons of expense, complexity, liability to breakdown of units, and space required, such a solution of the problem is impracticable and becomes increasingly so the greater the power output required.

In radio transmitting apparatus particularly, there is a field for continuous wave high frequency outputs of about one kilowatt.

Excluding amateur installations, the greater proportion of radio transmitting sets are of the so-called medium power type giving outputs of high frequency energy of 250 to 2500 watts into the antenna. With the usual size of antenna employed and the logical organization of wave lengths, operation in the wave length range of 300 to 2000 meters (1,000,000 to 150,000 cycles) is usually desired.

At the present time spark sets, mostly of the quenched gap type, are used for this class of transmitting equipment.

The adoption of continuous wave transmission to supersede damped wave transmission has brought about wonderful improvements in the case of very low power and very high power installations.

Spark sets of the medium power class mentioned above cannot be replaced by the type of apparatus used on the high power continuous wave sets.

Neither the high frequency alternator, the Poulsen arc nor the so-called timed spark systems are practical for this particular class of stations, principally because of their inability to operate at the short wave lengths required and also due to lack of flexibility of wave length in the case of the alternator and poorer characteristics of the arc at low power.

Also in the case of radio telephony, voice control is a comparatively simple matter with three-element electron tubes.

Therefore it is logical to believe that this class of medium power transmitting equipment is a particularly promising field for the three-element vacuum tube.

There are also several other fields of application, some of which will be described later.

Since the three-element power tube itself is the basis of such equipments, its characteristics and the features required for power output will be first considered.

THE THREE-ELEMENT POWER TUBE

There are a number of factors in the design and construction of a three-element vacuum tube which may limit its output.

(1) Dissipation of energy in the form of heat at the anode so great that deterioration of the vacuum results, or certain of the parts lose their mechanical strength, or even melt.

(2) Insufficient electron emission, resulting in a definite limitation of plate current and therefore limiting the input energy to the tube.

(3) Insufficient exhaust treatment.

(4) Insufficient dielectric strength in the materials holding the electrodes in place and in the lead-in wires or terminals.

(5) Insufficient mechanical strength of the electrodes or their parts, so that the high anode voltage causes a displacement and probable short-circuiting, due to the mechanical force of the electrical field.

(6) Improper geometrical design or construction so that the electrical constants of the tube are incorrectly proportioned to the conditions of operation. This allows the factors which cause the first five limitations to be at values above the possible minimum.

These factors will now be taken up more in detail together with comments relating thereto.

(1) Dissipation of Energy from the Anode

Of the input to the plate circuit of the tube a portion appears as output and practically the entire remainder is lost as heat at the plate.

In the types of oscillating circuits used at the present time the output approximates 50 per cent of the input, actual values ranging from 25 per cent up. Therefore, in the design of the anode and bulb provision must be made to dissipate more energy than is produced.

The heat energy leaves the anode or plate mostly by radiation, but a certain proportion is carried away by conduction through the plate supports. The necessary plate area acting as anode is more or less determined by the desired electrical characteristics, but its actual area, to facilitate radiation of heat, may be increased by vanes or other forms of attached surfaces. It is good practice to make the plate out of the same piece of metal as the vanes, as it is surprising how poor the heat conductivity between two pieces of metal may be that are in intimate contact by a process such as riveting. This effect is often plainly apparent in plates that are running at a red heat by the difference in color of parts supposedly in intimate contact.

In the choice of material for the plates of power tubes the use of tungsten or molybdenum is very desirable, as it gives the following advantages of energy dissipation for a given area:

(1) These metals, in the form of vacuum tube plates, can be freed from gas to a greater extent than any other metal.

(2) They retain good mechanical strength at a bright red heat.

(3) The rate of evaporation of the metal which would cause blackening of the bulb is very small, even at a bright red heat.

(4) On account of their very high melting points they can stand up under very high inputs of energy over a short period of time. This is important in safeguarding the tube from excessive inputs with no output when, from some accidental cause, a high voltage power tube stops oscillating and the plate current is only limited by the electron emission.

The writer has noted this latter defect in many foreign power tubes. Their rated operating condition is so near the absolute limit which the tube will stand that any change in conditions is liable to spoil the vacuum, or a mishap stopping oscillations almost instantly causes destruction of the tube by excess dissipation of energy. It certainly is not good engineering practice to so rate vacuum tubes. This defect in tubes of foreign design is usually accentuated by the fact that the design is of rather low impedance for the voltage employed, thus making the plate current at full rated plate voltage greatly in excess of the normal load current in the oscillating condition.

When a tube fails to function properly and the characteristic blue glow of excessive ionization appears, this gas usually comes from the metal of the plates, the glass, or from other metal portions of the tube, such as plate supports, grid frame, or supporting sleeves.

Extravagant claims are often made as to the output of a vacuum tube. If the tube is used in the usual types of circuits, so that the efficiency is of the order of 50 per cent, an examination of the size and material of the anode gives very good evidence as to the power capabilities of a tube, assuming it is satisfactory in all other respects.

A little experience with tubes of various designs gives a person a very good idea of the approximate amount of energy which can be liberated from any form of anode of particular material without either rendering it too weak mechanically, or too hot so that excessive evaporation takes place.

(2) Insufficient Electron Emission

When a tube is delivering alternating current energy, either as an amplifier or oscillator, a certain average direct current is supplied to the plate from the direct current source.

Electrons, of course, cannot be "stored up" and used even a short period of time after their emission. Therefore, there must be a constant emission of them sufficient to meet the maximum demand portion of the plate current cycle.

With a pure sine wave form of plate current an emission corresponding to double the average plate current is required to give the peak value. Also during the period of the cycle when the plate current is maximum the grid voltage and therefore the grid current is at a positive maximum. A direct current meter placed in the grid circuit of an oscillating tube supplying energy under proper adjustments shows a current of roughly 10 per cent of the average plate current. Therefore the peak value of electron current to the grid is several times this value, running up as high in certain cases as the average plate current itself.

It is desirable to have a certain excess electron emission so that the tube will deliver practically full energy over the range in variation of filament current that is liable to occur in actual supply circuits or through the limits of variation of a filament current-regulating device.

Also slight differences in the dimension of filaments for different tubes of the same type necessitates usually a further allowance of excess emission.

These factors taken together usually require that the emission at rated filament current be three to five times the average current while oscillating, as measured on a direct current instrument.

There is also an effect which is negligible on receiving and other low power tubes, but which is an important factor on high voltage power tubes. This is the effect on filament temperature, and therefore upon the electron emission, of the electron current of the plate circuit, adding to or subtracting from the filament current.

If the filament is operated from a direct current source through a series resistance in the circuit the electron current will add to the filament current if the negative of the plate voltage source is connected to the negative filament terminal and it will subtract from it if connected to the positive filament terminal. This effect will not be uniform over the entire length of the filament but will be variable, being a maximum or minimum at the end of the filament to which the negative terminal of the plate source is connected.

When it is remembered that the average plate current of a tube usually has a value between 2 and 7 per cent of the filament current and that a 3 per cent increase or decrease in the heating current of a tungsten filament respectively halves or doubles the filament life, the importance of allowing for this is apparent.

This filament heating effect of the plate current also has another important aspect. If for any reason a high voltage power tube stops oscillating, the plate current will usually rise to a value limited only by the filament emission. If the return or negative of the plate source is connected to the negative end of the filament this abnormal current flow will increase the temperature and therefore the emission which in turn increases the plate current, this effect being accumulative, often destroying the filament in a few seconds.

Therefore, on a high voltage power tube with direct current filament excitation it is advisable to connect the negative terminal of the plate voltage source to the positive end of the filament.

If possible, alternating current should be used for filament excitation with the regulating rheostat in the power side of the transformer circuit and the return of the grid and plate circuit made to a center tap on the winding supplying the filament.

This connection assures minimum disturbance in the plate and grid circuits from the frequency of the filament source.

The plate circuit current in this case divides evenly between the two filament legs. Also the direct electron current and the alternating filament current add at a 90 deg. displacement to give the combined heating current so that the additive effect is much smaller. For instance, a one-ampere electron current added to a four-ampere filament current would give a five-ampere heating current at the hottest part of the filament if it were d-c., and only 4.13 amp. if a-c.

For a tungsten filament there is a definite relation between the electron emission current, filament heating watts and temperature.

A curve is shown (Fig. 1) giving the plot between milliamperes emission current per watt of filament heating energy and absolute temperature of the filament. This relation holds for any diameter or length of filament, but its values are subject to some modification for particular cases owing to the cooling effect of lead wires and filament supports and

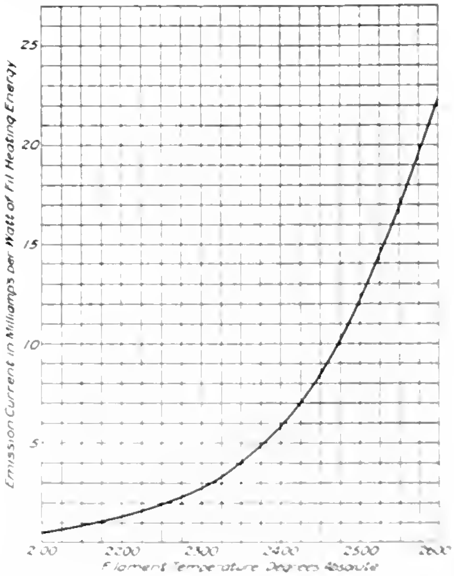

Fig 1 Variation of the "Efficiency" of Electron Emission with Temperature for Tungsten Filament Cathode

also variations in emissivity factor for different samples of tungsten. This curve is plotted from Dr. Langmuir's published data.*

In types of high power tubes in which the plates are of tungsten or molybdenum and are located close to the plate and operated at a bright red heat, the filament temperature will be higher than when the plates are cold. Therefore in the operation of such a tube the filament current may be reduced after the plates have come up to their normal operating temperature.

Although in vacuum tube circuits it is advisable to include a voltmeter or ammeter in the circuit of the filament or filaments, such an instrument should not be wholly relied upon for filament adjustment.

The best practice is to operate tubes at the lowest filament temperature consistent with satisfactory operation. In this way maximum tube life will be obtained.

(3) *Insufficient Exhaust Treatment*

As is now well known, it is not only necessary to reduce the gas pressure in the bulb to a minimum, but it is even more important to free the internal parts from gas so that the pressure of gas in the bulb remains low throughout the life of the tube.

The exhausting process for a vacuum tube increases in difficulty the higher the power of the tube and the higher the voltage at which it is to operate.

This condition arises at higher powers and voltages, owing to the fact that the positive ionization effects are greater and the temperature of the parts higher.

Keeping the glass walls of the tube cool by artificial means will help to better the vacuum, because it not only prevents the glass from liberating gas, but may actually enable it to absorb some gas that might be liberated from other parts of the tube.

(4) *Insufficient Dielectric Strength in the Materials Holding the Electrodes and in the Lead-in Wires or Terminals*

In a three-element oscillating tube the maximum voltage occurs between the grid and plate and may easily reach a value three times the normal operating plate voltage. This is due to the fact that with a pure inductance in the plate circuit the current may vary between zero and twice normal value each cycle, and therefore the voltage between filament and grid may vary between zero and twice normal. At the same time there is a 180 deg. relation between grid and plate voltage; therefore, with a tube of low amplification constant the grid voltage may easily reach the value of average plate voltage.

It will therefore be seen that with a tube operating at a plate voltage of several thousands, the dielectric strain may be considerable. Owing to the temperature at which power tubes operate this factor is made more serious.

A high vacuum is the best insulator under these conditions and air at atmospheric pressure also is a good insulator.

Glass, however, is necessarily used for supports. The dielectric strength of glass decreases rapidly with increase of temperature. This is true of all grades of glass but the effect is much more marked in some grades than in others.

Hot glass is conductive and acts like an electrolytic solution. Bubbles of gas form at the negative electrode and if this electrode is one of the seal-in wires leakage of air soon results.

It is interesting to note that in a tube in which the leads are brought through a pinch seal the electrolysis is much more serious with the tube oscillating than with the tube operating non-oscillating with the same plate voltage and energy loss in the tube.

With the best grades of glass at a temperature of about 400 deg. C. the dielectric strength at high frequency is less than a layer of air of equal thickness.

Therefore, in the design of a high power tube it is necessary to have the electrical path between electrodes through the glass as long as possible and located in one of the cooler parts of the bulb.

Under certain conditions of improper adjustment of the oscillating circuit the voltage between grid and filament may rise very high. This necessitates careful insulation between these leads both in the tube and in the base.

Related to this question of dielectric strength between electrodes is the question of high frequency dielectric losses in the material employed, such as the glass of the tube and the insulating materials of the bases. This factor becomes very important because often these dielectrics are subjected to an intense electric field of high frequency.

If the materials used have a high dielectric loss heat will be generated at the points of loss, adding to the liability of breakdown and also decreasing the efficiency of oscillation.

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* "The Characteristics of Tungsten Filaments as Functions of Temperature," by Irving Langmuir, G. E. REVIEW, Vol. 19, No. 3, March '16.

(5) *Insufficient Mechanical Strength to Withstand the Mechanical Force Due to the Electric Fields*

The filament and grid mesh are most subject to this strain, because of their comparatively small size. The most usual effect of this strain is a contact between filament and grid or grid and plate.

On several occasions the writer has seen double helix spiral filaments pulled into almost two parallel strands by this force. Also, if the plates are operated by alternating current of a commercial frequency, some of the grid strands may have mechanical resonance to this frequency and vibrate to destruction.

When operating an audible frequency oscillator it is not uncommon to have the tube emit a distinctly audible tone of the frequency generated.

(6) *Improper Geometrical Design or Construction*

If the value of the amplification constant is too low, an excessive grid excitation voltage is required for power oscillation. This makes more difficult the problems of mechanical and dielectric strengths.

If the value of plate impedance is too high for the voltage used or for the output desired, the grid current will be excessive while oscillating because the grid must be carried to a high positive value to obtain the necessary maximum of plate current.

In this case also greater emission will be required to supply the added grid current.

This question of proper proportioning of the electrodes to obtain the best electrical constants is not within the scope of this paper. These two examples were stated to give an idea of some of the factors involved.

As in most cases of design, the final choice of constants is a compromise which, it is believed, will give the best results under the conditions of service.

In the case of a power vacuum tube, certain practical considerations usually decide the electrical design rather than the choice of the electrical constants for absolute maximum output.

In the case of a tungsten filament type of tube the plate voltage is chosen as high as possible consistent with the operating conditions and procurability of the voltage source.

The desired power output being decided upon, and knowing the probable efficiency, the input direct current is then determined. It is then best to design the elements of the tube so that at full plate voltage, with the filament at a maximum temperature, the plate current will not exceed two or three times normal oscillating value when the grid is at zero potential.

Although a design made in this way will show a higher impedance and therefore a somewhat lower output than the use of a lower impedance, the ease of handling and safety to the tube during telegraphic operation and particularly while making adjustments more than compensate, it is believed, for the loss in maximum output.

For efficient operation and use of the tube as a modulator, as large a value of amplification constant as possible is advisable; this choice, of course, assuming a value of impedance as chosen above.

In the foregoing it is understood that by impedance is meant the value obtained from the slope of the plate-voltage plate-current curve. This, of course, is not the apparent resistance of the tube found by dividing the plate voltage by plate current for a given value of grid voltage.

It is possible that future developments in the vacuum tube art might make maximum output a better criterion than ease and safety of operation, the latter being gained by auxiliary and protective devices.

The question of the possible efficiency of the vacuum tube as a generator of oscillations is dependent to some extent on the proper tube design, but much more largely on the circuit employed. This question has been quite thoroughly investigated and reported upon in a very interesting paper recently presented.*

DESCRIPTION OF PLIOTRON POWER TUBE

As an example of a three-element power tube, the Type P pliotron will be described.

This tube is rated at 250 watts output with 1500 volts on the plate. The filament consumes about 80 watts. The plate current at full load is approximately 300 milliamperes. This tube is shown in Fig. 2, a view of the grid filament and plate elements being also included.

The bulb and glass parts are constructed of Pyrex, a special strong heat resisting glass. The globular part is 5 in. in diameter and there are two arms extending from opposite sides, making, when based, a total overall length of approximately 11¼ in.

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* "The Vacuum Tube as a Generator of Alternating Current Power," by J. H. Morecroft and H. T. Friis. Presented before the Philadelphia meeting of the A I E E, October 10, 1919.

The cathode arm is 2½ in. and the anode arm 1½ in. in diameter. The net weight is approximately 25 ounces. For shipment the tubes are crated individually.

There are three terminals in the base at the cathode end. The center blade is the grid terminal, the two pins being the filament terminals. The anode terminal is the cap at the anode end.

The filament is of ductile tungsten wire W-shaped in form. The range of filament current used is 3.5 to 4.0 amp.

The U-shaped grid frame and the wire forming the grid mesh are of tungsten and are freed from gas by the exhaust treatment.

The anode or plate are of tungsten supported by molybdenum rods. The plates and these rods are, of course, thoroughly freed from gas during the exhaust treatment.

Under normal operating conditions the plates run at a dull red heat. During exhaust treatment they are brought up to a brilliant red heat by electron bombardment dissipating nearly 2 kw. of energy. An average characteristic curve plotted between grid voltage and plate current for this type of tube is given in Fig. 3.

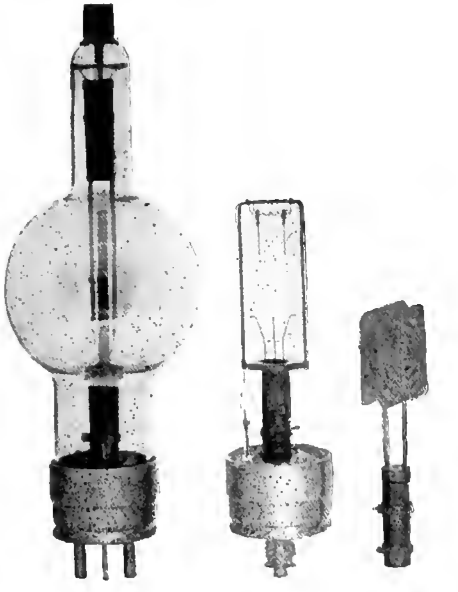

Fig. 2. Large Type of Pliotron Tube, Assembled and Disassembled

It is interesting to estimate the future development in size and output of the three-element power tube.

In the opinion of the writer, the physical dimensions of the glass bulb pliotron are somewhere near their limits. This is because large glass constructions are expensive to build, difficult to safely ship, and a very slight mishap such as a small crack or leak practically destroys the total value of the tube.

It is believed that the much-to-be-desired increase in power output per tube unit will be obtained in one or more of the following ways:

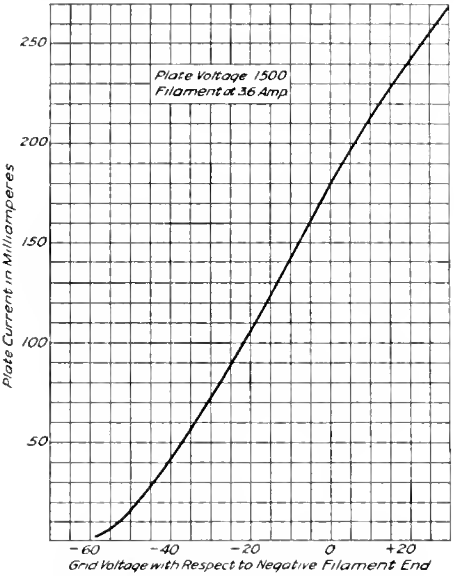

Fig. 3. Typical Characteristic Curve for the Type of Pliotron of Fig. 2

(1) Increase of plate voltage for the glass tubes up to the neighborhood of 100,000 volts, or whatever limit is set by the feasibility of the production and use of such a high voltage. By the use of these high voltages in special circuits, which seem possible of development, a very high efficiency is probable so that possibly 100 kw. may be generated by a pair of tubes each not much larger except for terminal arms than the Type P tube described.

(2) By the use of a hermetically sealed metal tube.

(3) By the use of a metal or glass tube or combination in which the vacuum is maintained by a continual or intermittent method of exhaustion.

In any case the use of as high a voltage as practical is desirable.

The advantages of increased voltage are due to the fact that for a given output the currents are smaller, thus simplifying the problems of emission and space charge. The outputs and efficiencies can be made higher because more voltage is available for the output circuit and a smaller proportion is lost in the tube.

OSCILLATING CIRCUITS FOR POWER TUBES

A great deal has been published on this subject and the principles involved are pretty widely understood. However, such publications have dealt mostly with receiving circuits in which the requirements are somewhat different.

Some general considerations from the viewpoint of power tube operation will be given and these points explained in connection with a typical circuit.

In practically all the forms of oscillating circuits used at the present time three fundamental adjustments are necessary in order to get full output at the best efficiency and desired frequency. In some forms of circuits the variation of one factor will change another, making the complete adjustment a complex matter.

These three fundamental adjustments are:

(1) Variation of inductance or capacity or both in the resonance portion of the circuit to obtain the frequency desired.

(2) Adjustment of the ratio of transformation between the plate circuit and the load circuit.

(3) Adjustment of the voltage value, phase relation and normal d-c. potential of the energy fed back to the grid for self-excitation.

The first and probably the third of these adjustments are well known and need no further explanation; but the second one, the adjustment of the ratio of transformation between the plate circuit and the load circuit, is not as well understood as it should be.

Since power tubes are used mostly for radio transmission, an antenna as a load will be considered.

For energy calculations the antenna may be replaced by a resonant circuit having concentrated inductance and capacity. In an artificial circuit of this sort the energy radiating property of the antenna is replaced by a resistance and it is customary to consider a resistance in series with the inductance and capacity rather than a higher resistance shunted across the two.

For instance, ten amperes flowing in an antenna circuit of 0.001 microfarad and one millihenry at the resonant frequency of 159,000 cycles (1885 meters wave length), will give an energy dissipation of 1000 watts if the series resistance is ten ohms. An equivalent dissipation in energy would take place if the series resistance of ten ohms were replaced by a resistance of 100,000 ohms shunted across the capacity.

For every condition of operation of a three-element tube as an amplifier or oscillator, there exists a particular value of plate impedance and the use of this value of resistance in the plate circuit will give a maximum output of energy. This is a well known fact and has been brought out by many writers.

Now supposing the normal operating impedance of the tube to be 5000 ohms, it is very apparent that the voltage generated by the tube is not at all suitable for direct excitation of the antenna. Therefore, a transformer or its equivalent must be placed between the plate circuit and the antenna circuit.

In the case mentioned the ratio of transformation between impedances of 5000 and 100,000 would be the square root of this ratio or approximately 1 to 4.5.

The actual turn ratio would be considerably higher than this, owing to the fact that in most radio frequency transformers the voltage ratio falls below the turn ratio.

An equivalent to a step-up transformer is a variable coupling, but in this case the plate circuit must be made resonant by the addition of a capacity shunted across the plate inductance.

In order to get full output from a tube it is necessary to have only resistance effective in the plate circuit. Any excess value of inductive or capacity reactance means a heavier current for the same energy delivered (the so-called wattless component) and this component gives an added loss in passing through the necessary impedance of the filament to plate path in the tube.

In any circuit built to energize an antenna at a number of quite widely different wave lengths, this ratio must be varied for each wave length in order to get best results, because the effective antenna resistances will vary. The tube impedance under fixed operating conditions remains quite constant except through very extreme ranges of frequency where the capacity effects between electrodes becomes appreciable.

One form of typical oscillating circuit quite widely used for energizing a radio transmitting antenna is shown in Fig. 1

The first variation mentioned, that of change of inductance or capacity to get the desired wave length, is accomplished in this case by variations of the inductance of *LA*.

The inductance L_p and L_a have a fixed close coupling and the second adjustment, that of variation in ratio, is accomplished by variation by taps in the number of turns of L_p. In most cases the ratio of L_p to L_a is a step-up one; but if the tube impedance is unusually high and the antenna resistance (expressed in the usual way as equivalent series ohms) rather higher than the average, the ratio in the direction as above stated may be slightly step-down.

If a direct current ammeter is placed in one of the leads from the direct current source E_b, so as to indicate the average plate current I_b and an ammeter inserted in the antenna it is very easy to set the transformer ratio at the proper value.

Starting with a large number of turns on L_p, other adjustments being properly made, both the value of plate current I_b and antenna current I_a will be low.

As the number of effective turns on L_p is decreased the values of I_b and I_a rise. Since E_b is held constant while antenna voltage increases with increase of I_a, the rate of increase of I_a will be less for a constant value of efficiency.

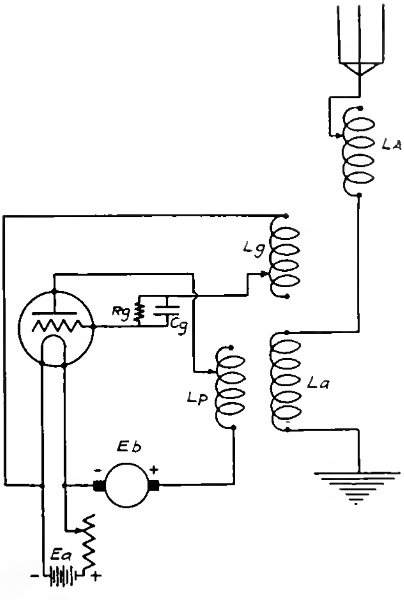

Fig. 4. Typical Oscillating Circuit for Energizing a Radio Transmitting Antenna

In most cases of high voltage power tubes, the adjustment is made for best efficiency considering the maximum safe load on either the tube or the source of supply at E_b. In either case the value of L_p is adjusted until the ratio of $\frac{I_a^2}{I_b}$ is a maximum. If the number of effective turns of L_p is decreased beyond the best point there will be an increase of I_b with little or no increase in I_a. Finally, if the number of effective turns of L_p is unduly decreased, the oscillations will usually stop and I_b take up a value dependent upon the static characteristics of the tube.

Of course as in the case of transformer design at commercial frequencies it is not only the ratio of turns between L_p and L_a that is important, but also the actual number of turns used on the coil L_p. Too few turns will give an excessive exciting current relative to normal load current and too many turns an excessive impedance to the load current. Owing to the fact that air with its uniform magnetic permeability is usually used for the magnetic circuit of the coils the permissible range of design variation is increased over that of commercial frequency transformers.

If a variable coupling between L_p and L_a is employed rather than variable turn ratio, a condenser must be placed across L_p to form a resonant plate circuit if full output is desired. If this condenser or an equivalent is not used there will be an excessive inductive reactance in the plate circuit.

The third adjustment, that of grid excitation voltage, is accomplished by variation of L_g, its coupling to L_a and the value of R_g (see Fig. 4).

In the actual arrangement of a circuit of this type incorporated in a finished piece of apparatus, there are several features which are of interest.

In radio telegraphy the telegraphic dots and dashes require rapid make and break of the energy to the antenna. This is usually accomplished by placing a key in series with the high grid resistance R_g of Fig. 4. In this way it is only necessary to make and break the relatively low current and low potential of the grid circuit. Opening the circuit at this point allows the condenser C_g to charge up so as to give the grid a high negative value of potential, thus cutting off the flow of plate current to the tube which in turn reduces the input and therefore the output to zero.

Now, the condenser C_g has usually a small value of capacity of the order of a few hundred micro-microfarads. Therefore, the rate of its charging up and the resultant rate of decrease of the plate current I_b is extremely rapid, much more rapid than the opening of a pair of contacts because there is no arcing or sparking.

In most power tube work the source E_b is a high voltage, direct current generator. In such a machine the number of turns in an armature coil is large and therefore the armature inductance is high. If the flow of current through this inductance is suddenly interrupted there naturally follows a considerable step-up of voltage across the armature terminals.

Therefore, there is an abnormal instantaneous voltage strain liable to cause a breakdown, which breakdown of insulation usually occurs between some point on the armature coil near the plus end and the core of the armature, because the negative armature terminal and frame are at, or near, ground potential.

As an example, a certain more or less standardized form of high voltage direct current generator rated at 1500 volts, 2 kw., 1800 r.p.m., had an armature inductance of approximately one henry. The full load current was 1.33 amperes and it is readily seen what a high surge of voltage was caused when this current was brought to zero in a very small fraction of a second.

It is therefore necessary to put some form of protective device across the terminals of E_b which will pass current when the voltage arises above a certain predetermined value.

Aluminum cell lightning arrester equipment* has proved to be an excellent form of protective device and it has been found advisable to use them when the energy input exceeds 500 watts at 500 volts or over. For the lower powers a condenser of as large a value as practical should be shunted across the source E_b.

When a circuit is incorporated in a finished piece of apparatus in which the wiring is more or less complicated by the requirements of operation, it is often noticed that the adjustments, particularly that of the grid excitation, are more critical than in a similar but simple experimental circuit. This can be usually accounted for by the capacity effects between adjacent wires and inductive effects between wires of different circuits which are naturally closer spaced and of greater number than on an experimental layout.

In operating tubes of the larger type in parallel it is usually advisable to include a fuse and ammeter in the plate circuit of each tube. The ammeter allows the location of a defective tube to be noted and the fuse throws out of circuit a tube drawing excessive current.

In the parallel operation of tubes, trouble is often experienced with sudden values of excessive plate current. One cause of this is the oscillation of the tubes at a very high frequency, the value of which is determined by the capacity between the electrodes and the inductance of the leads to the grid and plate. In order to avoid these occasional abnormal plate currents it has been found advisable to insert in the grid circuit of a few of the tubes a very small inductance of only a few microhenries value. This precaution prevents the operation of the bank of tubes at this ultra frequency. Such a coil is inserted in the grid circuit as near the grid terminal of the one or two tubes as possible.

Where a considerable number of power tubes are operated in parallel the total plate impedance may reach a rather low value of the order of a few hundred ohms. Also at very high frequencies as small an inductance as 10 microhenries is closely comparable to the tube impedance, and therefore under these two conditions of high frequency (1,000,000 cycles or more) and low total plate impedance it is important that the total plate impedance be as far as possible localized

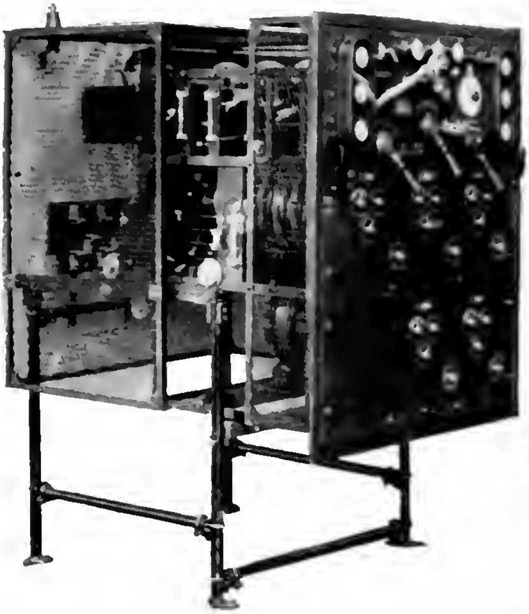

Fig. 5. Pliotron Radio Transmitting Set In the Open Position Shown All Circuits are Disconnected

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*"The Construction and Maintenance of Aluminum Cell Arresters," by R. T. Wagner, GENERAL ELECTRIC REVIEW, Vol. 16, January, 1913.

in the tubes and output transformer. Ten or fifteen feet of plate circuit wiring may have a very appreciable effect under these conditions.

For this reason it is usually advisable to bridge the d-c. power leads by a capacity as near the tubes and output transformer as practical; this capacity of course to have an impedance (at the frequency used) low in comparison with the tubes.

RADIO TRANSMITTING SETS

Brief descriptions and illustrations of pieces of apparatus used in the application of pliotron power tubes to various fields, follow.

Description of Power Tube

In Fig. 5 is shown a radio transmitting set arranged for radio telephony or either continuous wave or modulated wave telegraphy. Six Type P pliotrons are used, and for continuous wave telegraphy a maximum antenna radiation of 12 to 15 amperes is obtainable in a six-ohm antenna.

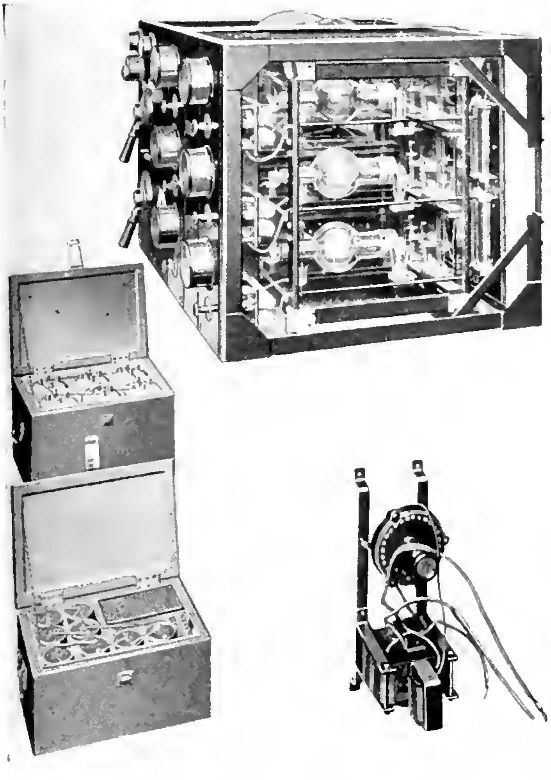

Fig. 6. Another Multiple Pliotron Set Arranged for Only Three Wave Lengths

A plate voltage of 2000 is used, obtained from a double commutator direct current generator of $3\frac{1}{2}$ kw. capacity. Because of this high voltage the set is completely screened in. To gain access to the set it is mounted on wheels running on rails in the supporting frame and when pulled forward to the open position as shown in Fig. 5 all circuits to the set are disconnected. This is following the modern engineering practice of removable switchboard panels of the truck type.

The particular set illustrated is equipped for five wave lengths, any one of which may be instantly put into use by a shift of the dial lever switch to the right of the panel.

It will be noted that there are four adjustments for each wave length. These adjustments correspond to those previously outlined.

(1) Adjustment by change of antenna inductance to the exact wave length desired.

(2) Adjustment of transformer ratio between the plate circuit of the tubes and the antenna circuit.

(3) Adjustment of grid excitation voltage by:

(*a*) Coupling of grid coil.

(*b*) Amount of inductance in grid circuit.

Means are also provided for conveniently adjusting the value of grid resistance (R_g of Fig. 4) which controls the value of normal operating negative grid potential. A dial switch is provided for this purpose which can be operated from the front of the panel.

On the upper one of the three panel sections are mounted various controls and instruments. The plate current ammeters for individual tubes are located in the oblong protective cases. These protective cases are used because these instruments are located in the positive or "high side" of the plate circuit. The other instruments are for plate voltage, total plate current, filament voltage and antenna radiation current.

The white circular disk to the right side of the panel is a wavemeter condenser for determining the wave length of the transmitted energy. The transmitter for telephone operation and the key for telegraphic operation are shown in operating position in Fig. 5. This view also shows two of the individual tube plate fuses mentioned in a previous paragraph.

Fig. 6 shows another multiple pliotron tube set, of simpler design, as it is equipped for only three wave lengths and has no adjustments from the front of the panel for best operating conditions.

This view shows the method of tube mounting in a spring suspended cradle so that the set may be operated under conditions of mechanical shock or vibration.

Fig. 7. Pliotron Panel for 50,000 Cycles

This view also shows three auxiliary pieces of apparatus, the aluminum cell protective device in the upper box, dry batteries for transmitter excitation and normal grid voltage in the lower box, and the transformer for filament lighting from an a-c. source with a center tap connection to minimize the a-c. potential effect.

Equipment for Production of High Frequency Energy

Two views of pliotron panel equipment for supplying 50,000-cycle energy are shown in Fig. 8.

Instruments are provided for indicating filament voltage, plate voltage, plate current, grid current and high frequency output current.

Means are provided for filament regulation, a slight variation of output frequency, and for an adjustment of grid excitation voltage and ratio of transformation between tube and load.

The dial switch for this latter adjustment of transformer ratio can be seen on the left side of the set in Fig. 7.

In this same view, at the bottom of the left side, a spark gap is shown. This is for protection of the resonance condenser of the load against over-voltage.

If a large number of pliotron tubes are to be operated in parallel, it is best to arrange the design so that there are unit panels each controlling a certain number of tubes. By combining these panels an equipment of any size can be provided for.

These unit panels contain only the pliotron tubes and their individual auxiliary pieces of control apparatus, the inductance capacities and generating equipment being separate units.

Such a unit panel for six large tubes is shown in Figs. 8 and 9.

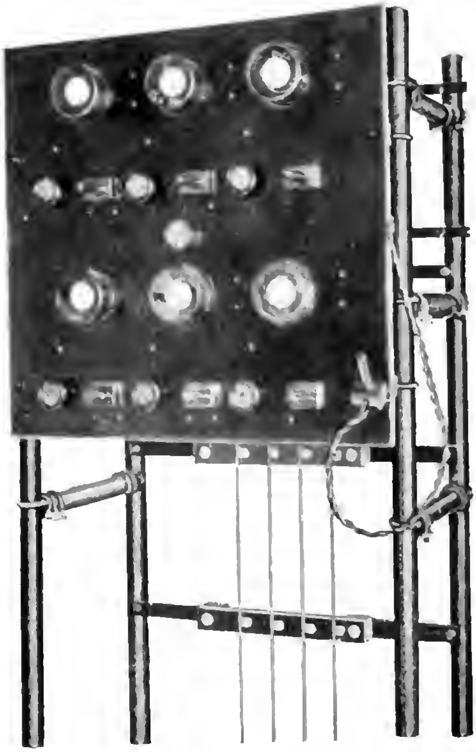

Fig. 8 Pliotron Unit Panels Containing Only Pliotrons and Individual Control Apparatus

Referring first to Fig. 8, each tube position is equipped with the following devices:

(1) Plate ammeter, under a protective cover.

(2) Individual filament rheostat, the control knob being located below and

slightly to the left of each plate ammeter.

(3) A plug switch for throwing in or out of circuit each filament.

A similar plug having the contacts connected to an ammeter through flexible leads is provided. By this means the filament current of any tube may be individually adjusted to the desired value. This ammeter is located in the center of the panel and the plug is in its holder near the lower right-hand corner of the panel.

Referring now to Fig. 9:

(4) Individual plate fuses are provided. The white porcelain fuse blocks showing plainly on the back of the panel.

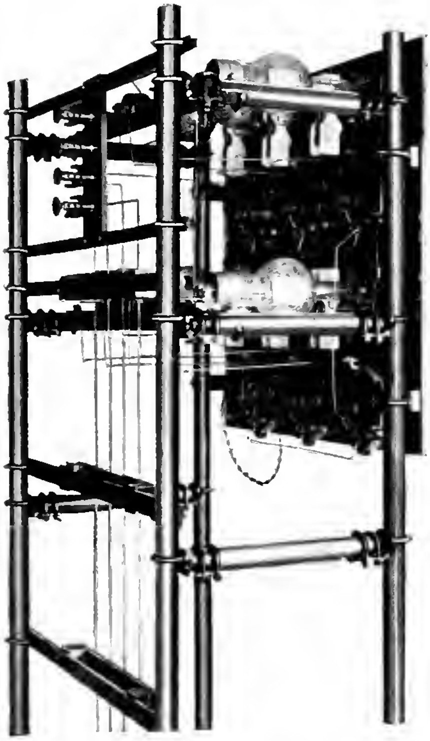

Fig. 9. Rear of Panel Shown in Fig. 8

All filaments, grids and plates are each connected in parallel and brought out to terminal posts mounted at the rear of the framework. Such units are used for either amplifier or oscillator equipment.

A typical power control panel for use in connection with the above unit is shown in Fig. 10.

From left to right the instruments are:

Filament volts, filament amperes, plate volts (in hecto-volt scale divisions) and plate current in amperes. The left switch is for the field circuit of the filament generator and the right switch for the separately excited field of the high voltage d-c. plate source generator.

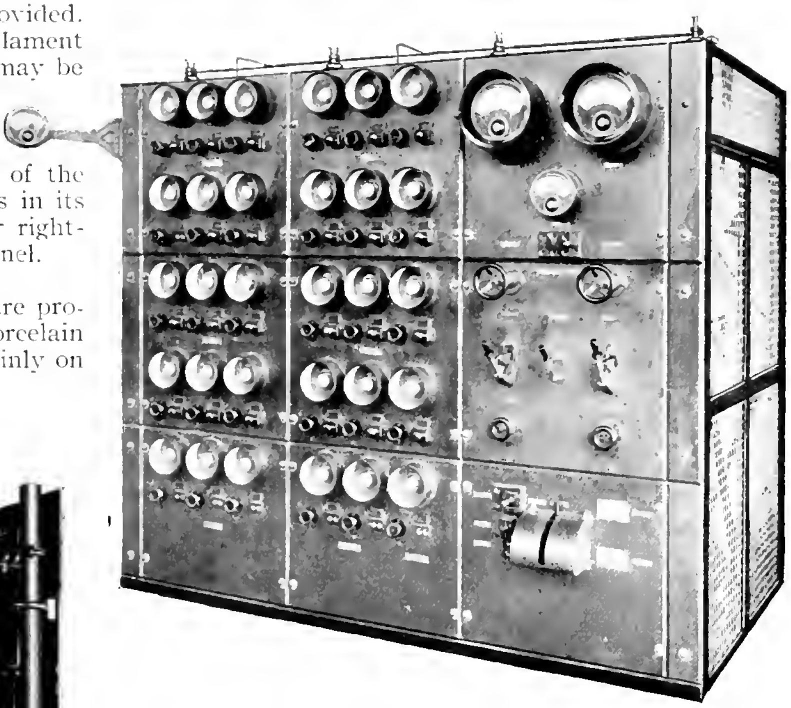

Fig. 11. Thirty-tube Pliotron Panel

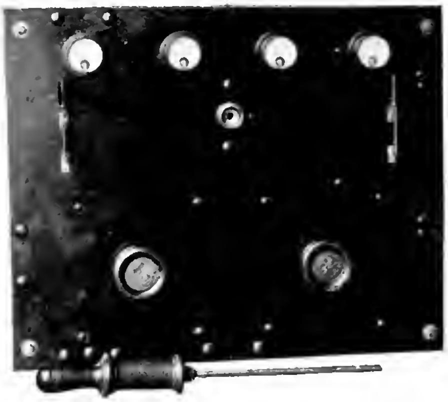

Fig. 10. Power Control Panel for Use with Pliotron Units Shown in Figs 8 and 9

A high voltage plug switch is used in the plate circuit to absolutely disconnect the high voltage source to insure safety when handling the circuits.

The lower left-hand rheostat knob is for filament voltage adjustment and the right-hand rheostat knob is for plate voltage adjustment. In general, therefore, filament control is on the left and plate voltage control on the right.

On the rear of the panel is located the rheostats, plug switch mechanism, fuses, voltmeter resistances and terminals.

Power Tube Amplifier Equipment

A panel equipment of this type containing 30 pliotron power tubes is shown in Figs. 11 and 12. The tube panels are made up on the unit plan previously described.

In Fig. 11 the power panel is the right-hand one and contains instruments and control apparatus for filament and plate sources of supply.

In this equipment forced cooling is used because of the large number of tubes in close proximity. The blower and air ducts are plainly shown in Fig. 12.

This equipment operates normally with a direct current plate voltage of 2300, the total plate electron current averaging about two amperes.

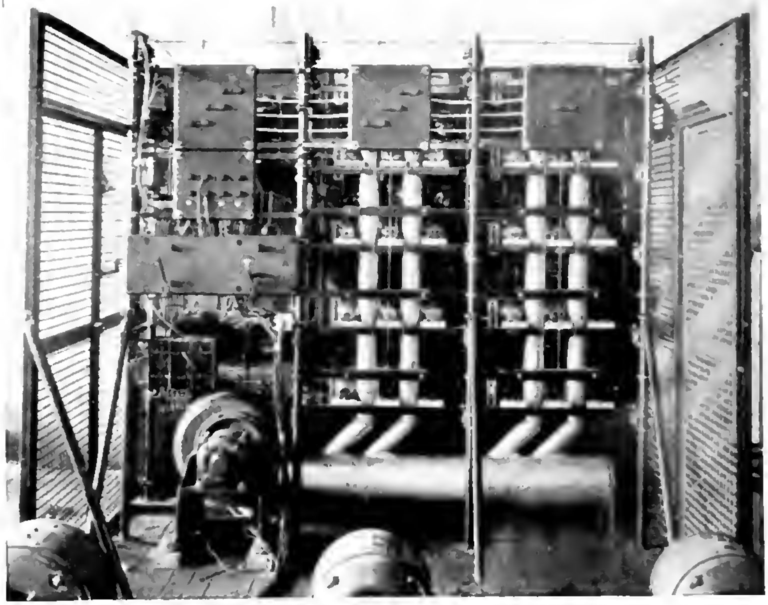

Fig. 12 Rear View of 30-tube Pliotron Panel Shown in Fig 11

Artificial Daylight for Merchandising and Industry

By G. H. Stickney

Engineer Lighting Service Department, Edison Lamp Works, General Electric Company

The great difficulty in approximating daylight by artificial means is owing mainly to the indefiniteness of the term daylight. Daylight, as we know it, is a combination of direct sunlight and reflected skylight and varies widely, depending on the degree of cloudiness, state of atmosphere, the angle at which sunlight enters the atmosphere, etc. The closeness with which artificial light should approach average daylight varies for different purposes, and the requirements are arranged in three groups by the author. The needs of the silk dyer are most exacting and are closely followed by the requirements of the woolen industry. Other industries involving color matching come in the second classification; while the color matching needs of the merchant are the least exacting and form the third class. The quality of artificial lighting demanded by the first class is produced by expensive and inefficient color matching units. A more efficient light source of lower color accuracy is provided by the daylight Mazda, and in conclusion the author mentions a number of specific applications where modified light by means of this lamp can be employed to advantage.—Editor.

Introductory

In view of the lack of a general understanding of the features of lighting for the purpose of inspection or selection of colored materials, it seems desirable to present a general review of the subject.

For ordinary purposes the color of artificial light is not highly important so long as it is pleasing and does not depart too far from that of daylight. In fact, a yellow tone in light is often desirable, on account of artistically pleasing qualities. On the other hand, there are certain applications in connection with the manufacture, inspection and sale of colored materials where it is highly important that they be viewed under an illumination that is much closer to daylight in color than is the illumination from ordinary lamps.

Since the appearance of colored objects varies more or less with the color of the light falling on them, it is important, especially for artistic articles which are seen under daylight, that color determinations and selections be made under a light of daylight quality. This is especially the case with garments in which different materials, such as woolen cloth, silk linings, braids and buttons, are combined, as the apparent colors are not always affected similarly or in the same degree by a change of light. In such a case, parts which harmonize under one light may clash under another. It should be noted also in this connection, when such articles are likely to receive their principal use in the evening, that the colors should be inspected under the predominating artificial light.

Color of Natural Light

Although daylight is universal, and almost as intimately experienced as gravity, few realize how complex it is in its composition, nor the extent to which it is subject to variation in intensity and color.

Light emitted by the sun traverses the 92,000,000 miles of space with presumably no apparent color change. However, on entering the earth's atmosphere it becomes modified. Small particles of water, vapor, clouds and dust in the atmosphere tend to deduct, especially the short waves or blue rays, from the direct sunlight. Part of this light is scattered and received as skylight, so that we receive a combination of direct filtered sunlight and skylight. It is evident, therefore, that the character of daylight, as we know it, depends to some extent upon the state of cloudiness, the angle at which sunlight enters the atmosphere, etc. In interior lighting other factors enter: for example, the position of the sun with reference to the window exposure, and the color of nearby buildings which may be reflecting light into a room. Fortunately some of these factors tend to compensate for each other, and the variation is usually less than might be expected.

While the variation of daylight colors is sufficiently large to render accurate determinations difficult, it must be remembered that they are small compared with the difference between average daylight and unmodified light of practically all artificial illuminants.

For accurate color matching purposes, experts have always preferred the light from the north sky—i.e., that from which direct sunlight is always absent. The apparent advantage of this is that it is subject to less variation than any other natural light. Such light contains more blue than average daylight, and undoubtedly the latter would have been preferred if it were obtainable as a fixed standard. Artificial lighting can be and has been produced which is more accurate as a color standard, but such lighting is expensive and therefore practicable only where the value of the accuracy is great or the areas to be lighted small.

Demands for White Light

Observations of the practical use of daylight lead to the conclusion that there is a wide range of demands as to accuracy of color matching. That the silk dyer needs an accurate standard is evidenced by the pains taken, even at considerable expense, to work always under unobstructed north light.

The woolen industry apparently has a slightly less exacting demand, and the cotton industry less yet, although compared with most industries these (i. e., textile manufacturing), along with the manufacture of celluloid, ivory, and a few other things, may be classed in a separate group with exacting demands.

Nearly all other color industries find daylight from any direction acceptable, and very few take pains to eliminate colored light reflected from buildings. These fall in a second grade as to color accuracy.

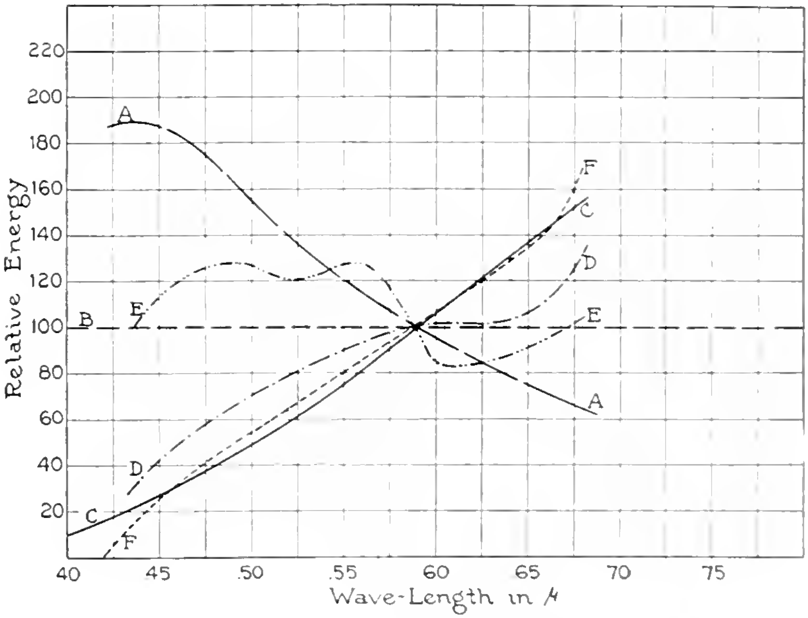

Fig. 1 Spectrophotometric Curves of Typical Color Modifying Glass Energy Intensity for Various Wave Lengths

A—Blue sky
B—Average daylight (black body at 5000° K)
C—Mazda lamp at 19 lumens per watt (black body at 2850° K)
D—Daylight Mazda lamp
E—Accurate color matching type unit
F—Typical daylight enclosing globe

When we come to the sale of all these goods, we find a much lower standard of accuracy acceptable. Many of the finest dry-goods stores are in the business centers, where the surrounding buildings must necessarily modify the light to a considerable extent and subject it to variation through the more or less direct reflection of sunlight from adjacent structures. Still further is the light modified by window shades and hangings, as well as wall finishes, mahogany furniture and other woodwork, so that it is evident that store managers have not recognized any such demand for color accuracy as have the manufacturers. Thus, a third grade is formed.

In artificial lighting, the production of daylight color is usually secured at the expense of efficiency, the sacrifice depending upon the degree of accuracy required. There is, therefore, a demand for several compromises, depending upon the relative importance given to these two elements, viz., cost of light and color accuracy.

Since there is today a relatively small demand for a highly accurate light and a much larger demand for a more efficient light, even though less accurate, it is evident that ordinary demands can readily be taken care of by the modified light from the incandescent lamp, especially since the Mazda C lamp has made a much whiter light source available. Particularly for the general lighting of large interiors, such as salesrooms, efficiency and attractive appearance, as well as color accuracy, are of great importance, and the more accurate unit used for localized lighting of small areas will not so adequately meet the requirements.

Method of Modifying Artificial Light

In modifying the light of an illuminant for color matching purposes, the best method at present available is that of passing the light through glass so colored as to absorb part of those radiations which are in excess, so as to produce approximately the same balance of light rays as exists in daylight. This means that the intensity and therefore the efficiency is reduced. While a considerable modification can be made with relatively little loss, further correction involves much larger sacrifices. It is no simple matter to produce glass suitable for this purpose, since ordinary glasses absorb too much of one color and not enough of another.

It is not so difficult to produce a light which appears white or displays a few colors correctly. This does not seem to be understood by many who are manufacturing and selling glass for this purpose, so that it is necessary to use considerable discretion in the selection of color screens. The only safe method of determining the correctness of the glass filter is to supplement careful spectrophotometric tests by the practical demonstration of the light on a large number of colored samples selected throughout the range of colors.

Accurate Color Matching Units

There are two or three makes of color matching units which employ Mazda C lamps with colored glass screens very accurately chosen to modify the light in such a manner as to produce a mean between north skylight and average daylight. Such a unit is relatively expensive and inefficient, but this form has proved satisfactory where the most exacting color requirements are encountered. In general, these accurate color matching units consist of a metal reflector arranged to concentrate the light downward through a blue green glass filter plate. They are available in sizes from 150 to 500 watt. Such fixtures are ordinarily employed to light a table top, or an area of 6 to 8 sq. ft. on which colored material is inspected. They have been employed in commercial dye-houses, for cotton grading, color printing, paint and ink mixing, and many other industrial purposes. They have also been used in lighting color booths in silk and dress goods departments of dry-goods stores, haberdasheries and tailor shops. As a rule such units are not sufficiently economical for general lighting of stores. Some of the fixtures are so designed that either artificial daylight or ordinary incandescent lighting can be obtained by the mere throw of a switch, enabling the goods to be examined under both conditions of use.

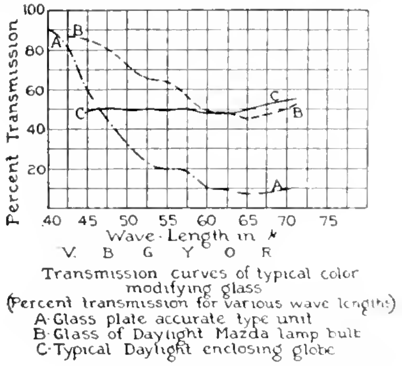

Fig. 2. Transmission Curves of Typical Color Matching Glass

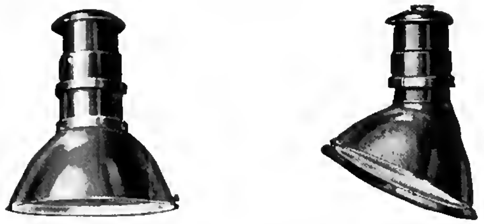

Fig. 3. Accurate Color Matching Units for Industrial Purposes Light from a Mazda C Lamp is Reflected Downward Through a Glass Color Screen. The unit on the right, of the angle type, produces high illumination on vertical surfaces

The Daylight Mazda Lamp

As before pointed out, there is a very large demand for a more efficient, although less accurate degree, of color modification. This is obtained with the Daylight Mazda lamp. This lamp is provided with a scientifically determined blue glass bulb, while the filament is run at a higher temperature, giving a whiter light than produced by the regular Mazda C lamp. Daylight Mazda lamps are made in sizes from 75 to 500 watt, and, while the efficiencies of the various sizes are slightly different, they correspond approximately to those of the larger Mazda B lamps. The lamps, therefore, are applicable to general lighting.

As pointed out in the article on the "Effect of Color of Walls and Ceilings on Resultant Illumination,"* where Daylight Mazda lamps are used in semi-indirect or other ornamental glassware, it is important that the glass and reflecting surfaces, such as the walls and ceilings, be white; yellow tinted glass or room

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* "Effect of Color of Walls and Ceilings on Resultant Illumination," by A. L. Powell, G-E REVIEW March, 1920.

finish tends to counteract the effect of the bulb thereby lessening the special advantage of the light for color purposes.

In the case of the Daylight Mazda lamp, in spite of the popular opinion to the contrary, the blue bulb does not add anything to the color of the light, but on the other hand subtracts a certain percentage of the rays which are predominant in the unmodified light. It is evident from this that the efficiency of the Daylight Mazda lamp is necessarily lower than that of the regular Mazda C lamp. This fact must always be borne in mind when installing Daylight Mazda lamps, since it will be necessary to use approximately 35 per cent more wattage than when clear bulb Mazda C lamps are installed to obtain the same illumination.

Fig. 4. A Counter Type Color Identification Unit Showing the Application in Merchandising Greatly Simplifying the Selection of Colored Materials

Color Modifying Globes

Besides the units already described, there is on the market a considerable variety of enclosing glassware sold for color matching purposes. Some of these equipments have considerable merit. The majority have little advantage beyond an apparent whitening of the light. Some, however, while having a considerable absorption, actually lessen the color matching value of the light of the Mazda C lamp. Unfortunately, there are manufacturers of such glassware who claim in their advertising "perfect color matching effect." Such claims tend to discredit all such publicity and injure other similar products which have considerable merit.

This situation is ameliorated, however, by the fact that many merchants who think they desire color matching illumination really are better off with a light of yellowish tint which has the advantage of producing a more cheerful appearance in the store.

In conclusion, it may be noted that, while there seems to be a general impression that an exact duplication of daylight color is needed in lighting, there is in reality a wide diversity of requirements, relatively few of which include a high degree of accuracy. Even where colored materials are handled and sold, the common illuminants without color modification meet the large majority of cases.

Specific Applications of Modified Light

Stores.—Daylight Mazda lamps find a wide field of application in store lighting. This type of illuminant will never supplant the regular Mazda C lamp for general illumination; for the public, as a whole, prefer the somewhat warmer hue of the latter, as it makes the store look cheerful and inviting. Prominent merchants have stated that, in over 90 per cent of their sales, color matching is not an element. They feel it desirable to sell goods under the conditions most favorable to their best appearance. Many of the finest garments will be worn at night and are designed to be most attractive under average night illumination such as furnished by the regular Mazda lamps. Nevertheless, there are certain goods which should be lighted with a nearer approach to daylight than furnished with clear bulb lamps. In this class fall those which would be worn largely out of doors.

Daylight Mazda lamps used for general store illumination give a distinctive appearance to the store which has a distinct advertising value. In fact, some stores so lighted make it a feature in their newspaper and other advertising calling attention to the "Daylight" store. Even though Daylight Mazda lamps are not used for general illumination throughout, there are certain departments which will require such a light to display the goods to the best advantage, for example, men's clothing (particularly blues and blacks), linens, which appear pure white rather than slightly yellowish, furs, jewelry, silks and shoes.

Many of the most progressive stores in the country have supplemented the general illumination with the accurate type of color matching units over the counters and in other parts of the store where color matching is an important element. Larger types of these same units are employed over the triplicate mirrors in the clothing department with very satisfactory results.

Fig. 5. A Color Identification Unit Placed Above the Triplicate Mirror in a Clothing Establishment. Confidence in purchasing garments is much greater when artificial daylight is available

These units provide local lighting of the high intensity suitable for the critical examination of colored fabrics. It is not necessary to enclose such devices in a booth, for the amount of light directly beneath the fixture is so much greater than the illumination necessary for the store as a whole that the mixture of color of light does not affect the result. Where accurate color comparison units are installed the customer can have absolute confidence in his judgment. These save a great deal of the clerk's and customers' time by avoiding the necessity of carrying merchandise to the doorway or window for inspection, and are a decided economy in store operation.

Show Windows.—Daylight Mazda lamps in the show windows cause them to stand out prominently in comparison with other forms of illumination. While they are not necessary as standard show window equipment, every store of any appreciable size should have a complete set for at least one window, so that when displays requiring such a quality of light are in place they may be employed.

Laundries.—Spots and stains on goods are usually of a brownish or yellowish tint. If the light source is rich in yellow, then these blemishes tend to fade into the white background and are hard to detect. Daylight Mazda lamps in steam laundries over the folding and inspection tables enable the operator to catch many an improperly cleaned piece and thus keep up the standard quality of the work.

Textile Mills.—Without doubt, most of the processes here are carried on without regard to color. After the warp is made up and the shuttles filled with thread of the proper color, operations proceed almost automatically, but there is the liability of the mixing of color which may throw out an entire piece. Daylight Mazda lamps are being installed over looms in a number of instances to avoid this difficulty. It must be borne in mind that the color of light produced by these lamps is not accurate enough for color matching as the term is used in the dye-house, and the more accurate units should be recommended for such work. Color matching devices are also very desirable in the final inspection departments, bleacheries and show-rooms.

Concentrating Plants.—Iron and zinc streaks must be recognized as they are found on the concentrating tables. The zinc is of a rusty gray color and the iron of rusty red brown color. In a mill lighted by ordinary types of lamps it is difficult to tell these colors apart, yet it is necessary to separate most of the iron ore from the zinc. Some of the mines in the West have installed Daylight Mazda lamps for localized lighting over the tables for this purpose.

Chemical Laboratories and Sugar Refineries.—Daylight Mazda lamps have given quite satisfactory service in illuminating the centrifugal machines in use in the laboratory. They assist in the discriminations of color necessary for the grading and matching of cane sugar. Some prominent chemical manufacturers are employing Daylight Mazda lamps for watching changes of color in their testing departments, particularly in connection with titrating. There are also numerous places about the chemical plant where very definite demands for constant north sky color quality exist, and with the devices mentioned this can be satisfactorily met.

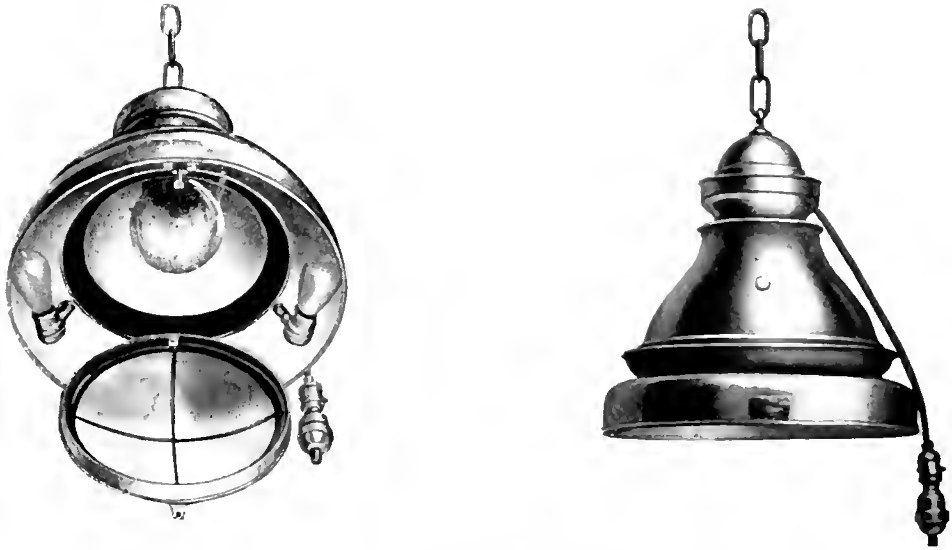

Fig. 6. A Color Identification Unit in Which a Large Mazda C Lamp Housed in the Center Produces Accurate Color Matching Light After Passing Through a Large Circular Color Screen at the Bottom. Small Mazda B lamps at either side provide a convenient means of comparing artificial lighting color effects with daylight

Photographic Supplies.—Some manufacturers of photographic materials are employing Daylight Mazda lamps for examining the quality and color of prints; correct shades of blues, blacks and sepias can be determined far more readily with this type of illuminant. Daylight Mazda lamps are also used for microscopic and lower power photomicography and in connection with the spectrograph for determining color sensitiveness of photographic emulsions. Where a high degree of accuracy is required the accurate type of color modifying device is essential

Printing.—It is quite difficult to detect the yellow half-tone from the white background when illuminated by regular Mazda lamps, and other colors are not shown in their true relation. Some of the large lithographing companies are using Daylight Mazda lamps to light the receiving end of the presses and also in the proof room and artist's workshop. The accurate type of color matching units, however, are particularly adaptable to the final inspection and for the absolute assurance of satisfactory night work. By the proper use of modified light, overcast and short days put no check on the art or press work in the lithographing plant.

Cigar Factories.—Cigars are graded according to shade, and minor differences in color must be detected in inspecting and sorting. The Daylight Mazda lamp assists in this work. A high quality of product can be obtained in the factory lighted with these lamps. This factor alone offsets the slight additional cost of operation.

Miscellaneous Industries.—Other fields in which modified light has proved useful are oil refineries, where it is necessary to determine the difference between grades of oil; in fruit packing houses, where oranges and lemons are sorted according to color as well as to size; in paper mills, where the sample room is so illuminated; in the jewelry trade, for the critical examination of stones such as diamonds and pearls; in metal working, for the selection of brass by color; and in miscellaneous places about flour mills, rubber goods and garment factories, button factories, potteries, paint factories, etc

Medical.—The Daylight Mazda lamp has proved quite a boom to the medical profession, in the chemical laboratories and assisting in microscopic examination. For diagnosis of skin disease and retina examinations, prominent specialists have employed this form of illuminant. In the operating room, the various tissues are revealed more accurately when examined under the light of the Daylight lamp—as, for example, when operating on a jaundiced patient whose tissues are yellow and whose blood gives all the tissues of the body a yellow tint a yellow light would be unsatisfactory. During operations for gall stones, yellow bile ducts, red arteries and blue veins must be distinguished one from the other.

One of the first uses for which the Daylight Mazda lamp was placed was the examination of X-ray negatives. A suitable light for this purpose is necessary, for, after the plate is developed, it is necessary to inspect this very carefully to determine the ailment or discover the fracture. The negative is in general illuminated by very diffused light from the rear, and experience has proved that the whiter the light the greater the ease of the examination. Diffused light for this purpose is obtained by using what is practically indirect illumination. A box or frame to hold the negatives is painted flat white on the interior surface. Lamps are concealed from view and equipped with reflectors to direct the light on this white background. From here it is reflected to an opalescent ground glass plate covering the opening or mouth of the box.

In dental work the Daylight Mazda lamps used for general illumination of the office or in the concentrating spot lamp assist materially in detecting decayed spots and diseased conditions. Many accurate color matching units are used by the dental supply companies for the matching, grading and sorting of artificial teeth.

Art Galleries and Museums.—Daylight Mazda lamps are used in many instances with splendid results for illuminating paintings. The artist paints his pictures under natural light; he places the colors on his canvas with particular relation to each other. Each small area of the picture is blended with the next and viewed as a whole. If the color of light is such as to materially modify the relation between these various areas of the picture, then his object is defeated. Portions may be intensified; others dulled. The better the painting, the greater the demand for suitable lighting. Many of the art exhibits throughout the country are visited at night by the general public, and for this reason the question of the correct artificial illumination is of much importance.

Hotels.—The field of application of Daylight Mazda lamps is far broader than one can imagine and it would be out of the question to attempt to enumerate all the various applications for which they find use in the hotel. If the sample room is fitted with Daylight Mazda lamps, then the critical examination of goods on display is facilitated. In the linen department they enable the help to readily detect spots on tablecloths and napkins. Over the cigar counter they present the display in more nearly its true value.

BIBLIOGRAPHY

The following list indicates some of the leading articles on the general question of artificial daylight and kindred subjects which have appeared in the technical magazines during the past few years:

"Color Values of Light from Electric Lamps," G. H. Stickney, *Trans. I. E. S.*, Vol. 5, p. 431.

"Daylight and Artificial Light," E. L. Nicols, *Trans. I. E. S.*, Vol. 3, p. 301.

"Daylight Efficiency of Artificial Illuminants," H. E. Ives, *Bulletin Bureau of Standards*, Vol. 6, p. 231.

"The Subtractive Production of Artificial Daylight," H. E. Ives and M. Luckiesh, *Electrical World*, May 4, 1911.

"The Relation Between the Color of the Illuminant and the Illuminated Object," H. E. Ives, *Trans. I. E. S.*, Vol. 7, p.62.

"Color of Illuminants," L. A. Jones, *Trans. I. E. S.*, Vol. 9, p. 687.

"Artificial Daylight: Its Production and Uses," M. Luckiesh and F. E. Cady, *Trans. I. E. S.*, Vol. 9, p. 839.

"Development of Daylight Glass," E. J. Brady, *Trans., I. E. S.*, Vol. 9, p. 937.

"Some Data on Artificial Daylight Units," C. H. Sharp, *Trans. I. E. S.*, Vol. 10, p. 219.

"A Gaseous Conductor Lamp for Color Matching," D. McFarlan Moore, *Trans. I. E. S.*, Vol. 11, p. 192.

"Colored Glass in Illuminating Engineering," H. P. Gage, *Trans. I. E. S.*, Vol. 11, p. 1050.

"Commercial Uses of Filtered Light," C. E. Clewell, *Electrical Review*, April 7 and 14, 1917.

"Mazda C-2 Lamps and Their Applications," A. S. Turner, Jr., *National Electrical Contractor*, October, 1917.

"The Color of Artificial Light in the Medical Profession," A. L. Powell, *Medical Times*, October, 1917.

"Mazda C-2 Lamp and Its Applications," A. L. Powell, *Electrical Engineering*, December, 1917.

"Artificial Daylight in the Industries," M. Luckiesh, *Electrical World*, September 28, 1918.

"A Color Symposium," *Trans I. E. S.*, Vol. 13, p. 1.

"Symposium on Camouflage," *Trans. I. E. S.*, Vol. 14, p. 216.

"The Daylight Mazda Lamp in the Psychological Laboratory," G. J. Rich, *American Journal Psychology*, July, 1919.

Enclosed Carbon Arc Lamps *vs.* Novalux Mazda Units

By H. E. Butler

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During the period of the war and during the coal strike, street lighting was curtailed in this country in the interests of economy. Two very important truths have been revealed as the result of this experience: first, that reduced street lighting is accompanied by an increase in crime and accidents; second, that an appreciable waste of power exists in street lighting systems because of the use of the enclosed carbon arc lamp. The author takes up this second matter and by detailed analysis shows the fallacy of the policy of keeping in service obsolete forms of lighting units. The author's conclusions are accepted by the most progressive central stations in the country, but there still appears to exist an opportunity for education among others in the industry.—Editor.

A few years ago it was estimated that approximately a half million series enclosed carbon arc lamps were in use for street lighting. This number has been materially reduced during the past few years, but there are still in use throughout the country many of these obsolete lamps. It is for the purpose of illustrating the inefficiency and poor economy of these lamps that the following data have been prepared.

The enclosed carbon arc lamp was developed to overcome the disadvantages of the open arc lamp; viz., short life of carbons and poor distribution of light on the street surface. However, the long life of the carbon trims and the steady and relatively uniform distribution of light from the enclosed lamp were obtained at a sacrifice of efficiency. These characteristics are now available in the luminous arc lamp and Novalux fixtures but at an efficiency very much greater than existed in the earlier lamps. The luminous arc lamp is a more efficient producer of light; however, as this article is to cover data only on incandescent lamps and obsolete enclosed carbon arcs the luminous arc lamp will not be discussed.

In Figs. 1, 2, 3 and 4, the enclosed carbon arc lamp is compared with the 250, 400, 600 and 1000-c-p. series Mazda lamps respectively. These charts indicate the relatively low efficiency of the carbon arc as compared with the incandescent equipments. Another feature which shows the Mazda lamp to advantage is the rated life per trim for the carbon arc as compared with the rated life of the Mazda lamp. It is well, however, to remember that, while the life of a series incandescent lamp is rated at 1350 hours, it is not economical to allow the lamp to remain in service without attention until its life is spent. Periodic visits should be made for the purpose of cleaning the equipment; otherwise a serious loss of light will result from the accumulation of dirt on the glassware. It will be further noted from these charts that a wider range of lamp sizes and a greater choice in types of light distribution are available with the Mazda lamp than with the carbon arc lamp. The illumination data in this article comprise a picture of the unit, the candle-power distribution curves, and the calculated illumination curves; the latter give the average and minimum foot-candles and the uniformity of illumination for various size lamps and spacings. The uniformity factor is the ratio of minimum to maximum foot-candles.

From these curves, the following are some of the questions that may readily be answered:

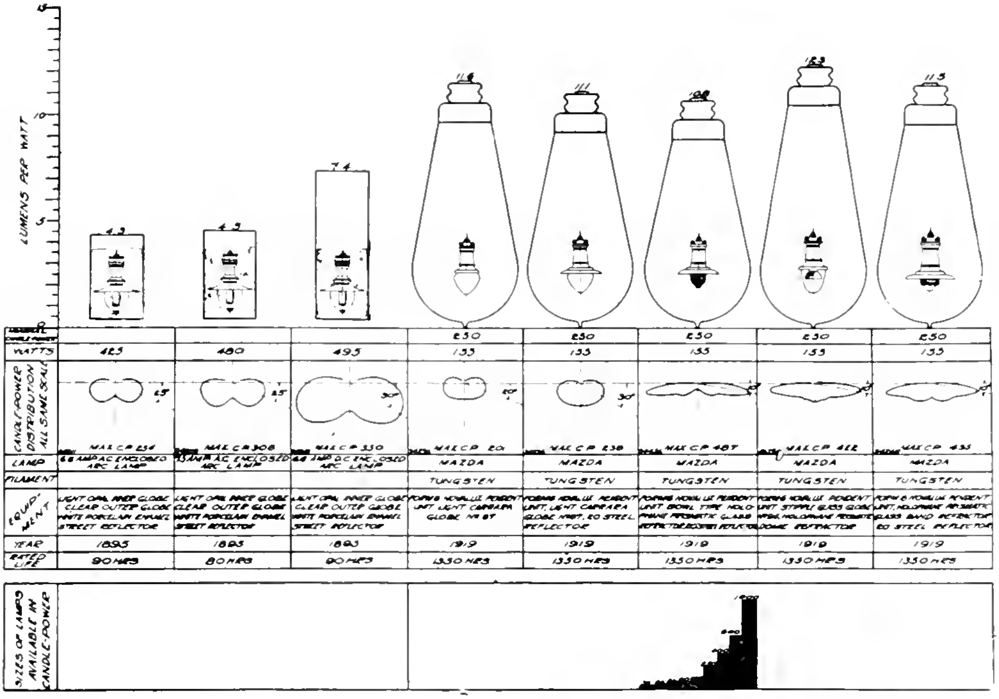
With a specified spacing and equipment, what will be the average and minimum illumination and the uniformity on the street?

Taking equal average or minimum intensity of illumination as a basis, what will be the spacing required for the various units with their different equipments?

From this and the wattage, what is the power consumption per linear foot?

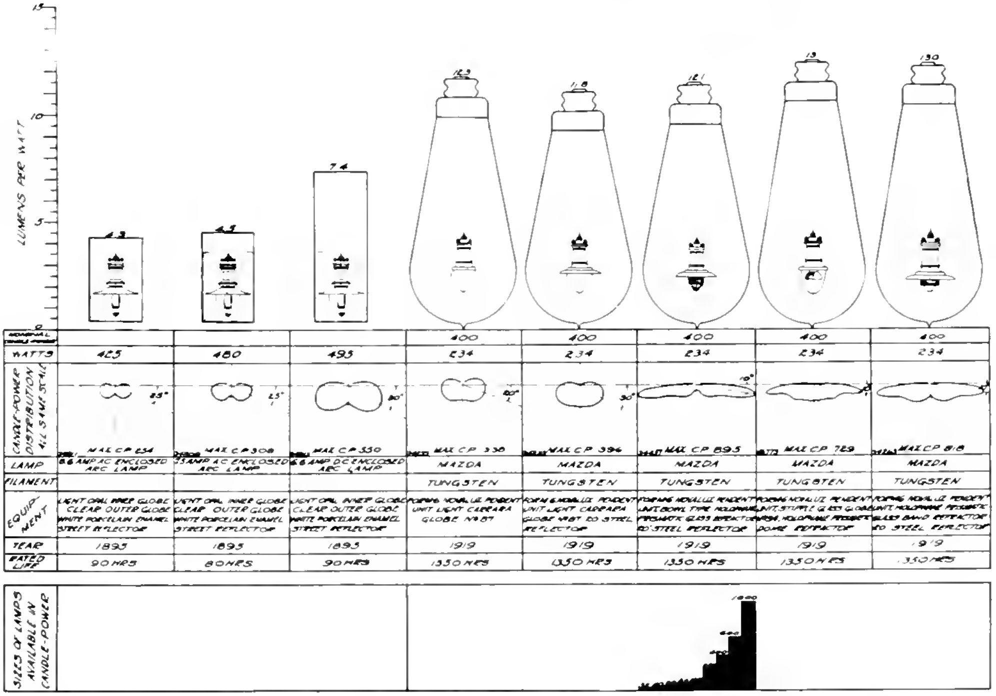
Taking equal uniformity of illumination as a basis, what will be the spacing required?

The candle-power distribution of the enclosed carbon arc lamps are shown in Fig. 5, together with curves giving the average minimum illumination and the ratio of the minimum to the maximum foot-candles for various spacings on the street. The alternating-current series enclosed carbon arc lamp is less efficient than the direct-current enclosed carbon arc lamp because the alternate cooling of the electrodes in the former lamp causes an additional loss of heat and consequently a lower temperature of the carbon points. It is interesting to compare the photometric curve in Fig. 5 with those of the incandescent equipments in Figs. 7, 8, and 9. The angle of maximum candle-power in



NOMINAL CANDLE POWER				250	250	250	250	250
WATTS	425	480	495	155	155	155	155	155
CANDLE-POWER DISTRIBUTION ALL SAME SCALE	MAX CP 254	MAX CP 306	MAX CP 330	MAX CP 201	MAX CP 238	MAX CP 487	MAX CP 422	MAX CP 435
LAMP	6.6 AMP AC ENCLOSED ARC LAMP	7.5 AMP AC ENCLOSED ARC LAMP	6.6 AMP DC ENCLOSED ARC LAMP	MAZDA	MAZDA	MAZDA	MAZDA	MAZDA
FILAMENT				TUNGSTEN	TUNGSTEN	TUNGSTEN	TUNGSTEN	TUNGSTEN
EQUIPMENT	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	FORMS NOVALUX PENDENT UNIT LIGHT CARRARA GLOBE No 87	FORMS NOVALUX PENDENT UNIT, LIGHT CARRARA GLOBE No 87, 20 STEEL REFLECTOR	FORMS NOVALUX PENDENT UNIT BOWL TYPE HOLOPHANE PRISMATIC GLASS REFRACTOR & 20 STEEL REFLECTOR	FORMS NOVALUX PENDENT UNIT STIPPLE GLASS GLOBE WITH HOLOPHANE PRISMATIC DOME REFRACTOR	FORMS NOVALUX PENDENT UNIT, HOLOPHANE PRISMATIC GLASS BAND REFRACTOR 20 STEEL REFLECTOR
YEAR	1895	1895	1895	1919	1919	1919	1919	1919
RATED LIFE	90 HRS	80 HRS	90 HRS	1350 HRS	1350 HRS	1350 HRS	1350 HRS	1350 HRS

Fig. 1. Obsolete Series Enclosed Carbon Arcs Compared with Novalux Unit Equipped with 250-c.p. Series Incandescent Lamp



NOMINAL CANDLE POWER				400	400	400	400	400
WATTS	425	480	495	234	234	234	234	234
CANDLE-POWER DISTRIBUTION ALL SAME SCALE	MAX CP 254	MAX CP 306	MAX CP 330	MAX CP 330	MAX CP 394	MAX CP 895	MAX CP 729	MAX CP 818
LAMP	6.6 AMP AC ENCLOSED ARC LAMP	7.5 AMP AC ENCLOSED ARC LAMP	6.6 AMP DC ENCLOSED ARC LAMP	MAZDA	MAZDA	MAZDA	MAZDA	MAZDA
FILAMENT				TUNGSTEN	TUNGSTEN	TUNGSTEN	TUNGSTEN	TUNGSTEN
EQUIPMENT	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	LIGHT OPAL INNER GLOBE CLEAR OUTER GLOBE WHITE PORCELAIN ENAMEL STREET REFLECTOR	FORMS NOVALUX PENDENT UNIT LIGHT CARRARA GLOBE No 87	FORM 6 NOVALUX PENDENT UNIT LIGHT CARRARA GLOBE No 87 20 STEEL REFLECTOR	FORMS NOVALUX PENDENT UNIT BOWL TYPE HOLOPHANE PRISMATIC GLASS REFRACTOR 20 STEEL REFLECTOR	FORMS NOVALUX PENDENT UNIT, STIPPLE GLASS GLOBE WITH HOLOPHANE PRISMATIC DOME REFRACTOR	FORMS NOVALUX PENDENT UNIT, HOLOPHANE PRISMATIC GLASS BAND REFRACTOR 20 STEEL REFLECTOR
YEAR	1895	1895	1895	1919	1919	1919	1919	1919
RATED LIFE	90 HRS	80 HRS	90 HRS	1350 HRS	1350 HRS	1350 HRS	1350 HRS	1350 HRS

Fig. 2. Obsolete Series Enclosed Carbon Arcs Compared with Novalux Unit Equipped with 400-c.p Series Incandescent Lamp

The 15-amp. 400-c-p. Mazda series lamp is operated from an auto-transformer

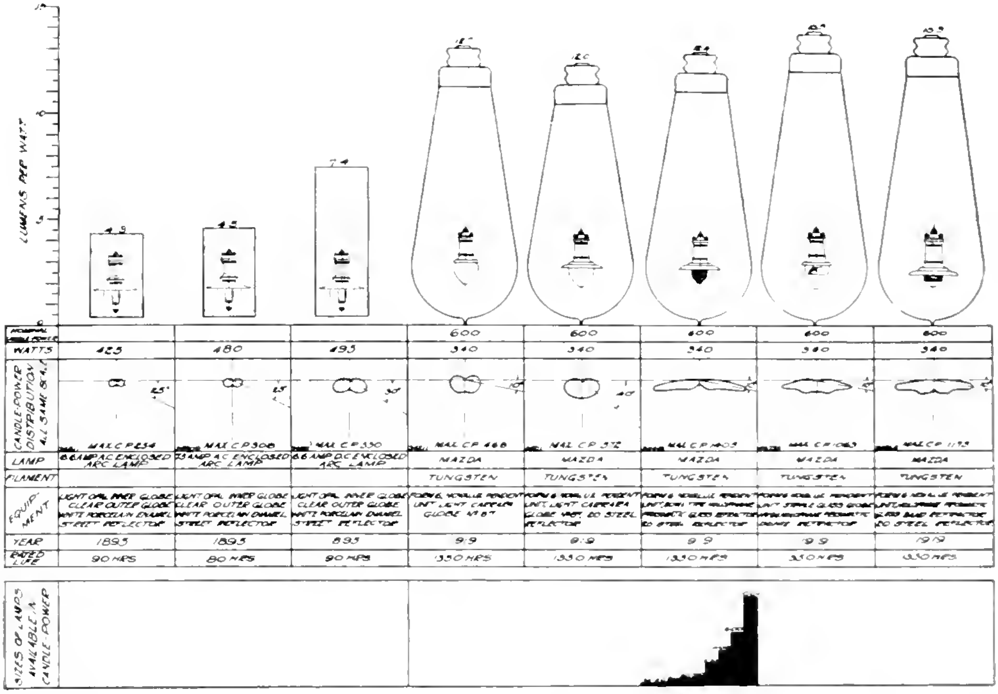


Fig 3. Obsolete Series Enclosed Carbon Arcs Compared with Novalux Unit Equipped with 600-c p Series Incandescent Lamp

The 20-amp 600-c p Mazda series lamp is operated from an auto transformer

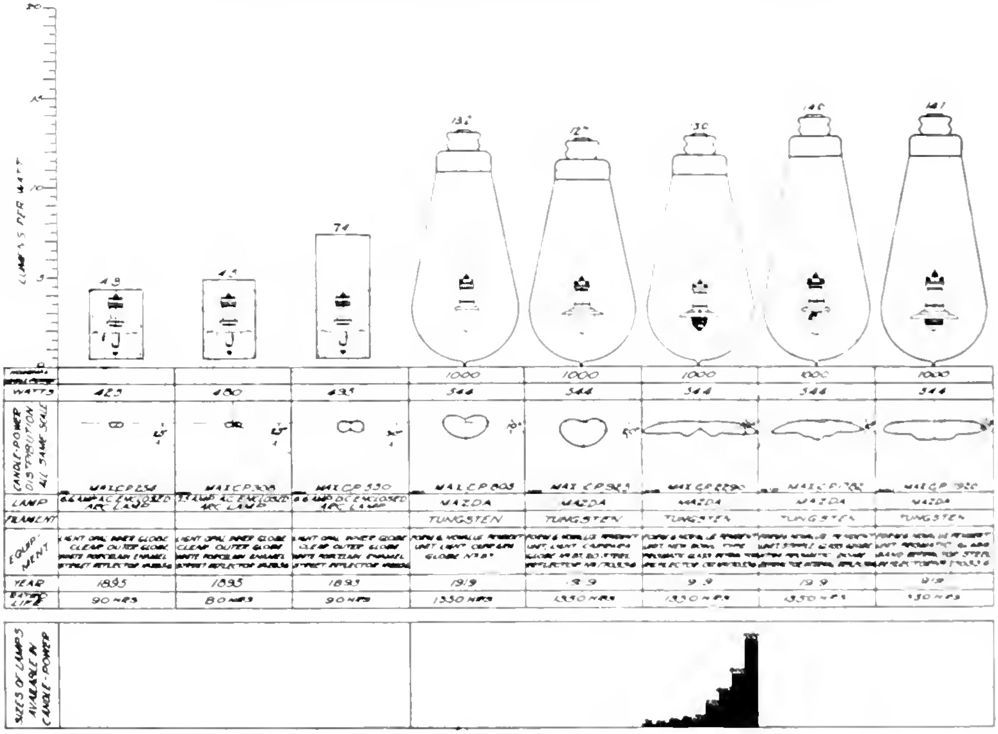


Fig 4 Obsolete Series Enclosed Carbon Arcs Compared with Novalux Unit Equipped with 1000-c p. Series Incandescent Lamp

The 20-amp 1000-c p Mazda series lamp is operated from an auto-transformer

Fig. 5a. Enclosed Carbon Arc Lamp with Light Opal Glass Inner Globe, Clear Glass Outer Globe, and Street Reflector

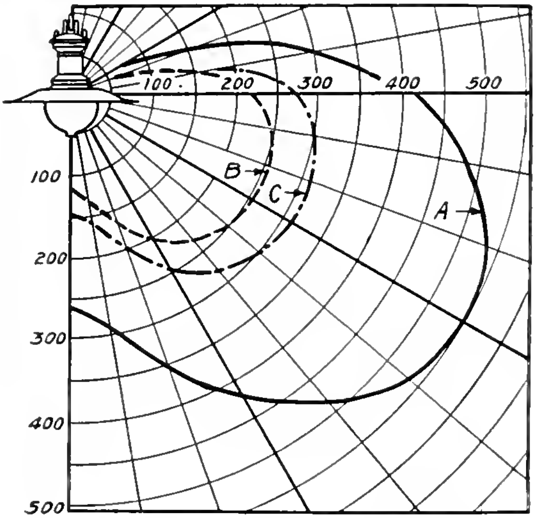


Fig. 5b. Initial Distribution of Candle-power in a Vertical Plane of the Unit Shown in Fig. 5a

Curves *A*, *B*, and *C* correspond to the lamps named in Fig. 5c

the incandescent units is brought closer to the horizontal, and therefore those rays which have to travel the greatest distance possess the greatest intensity. This results in greater uniformity of illumination on the surface of the street, as may be seen by the curves of the ratio of minimum to maximum illumination. On residential streets, parkways, and

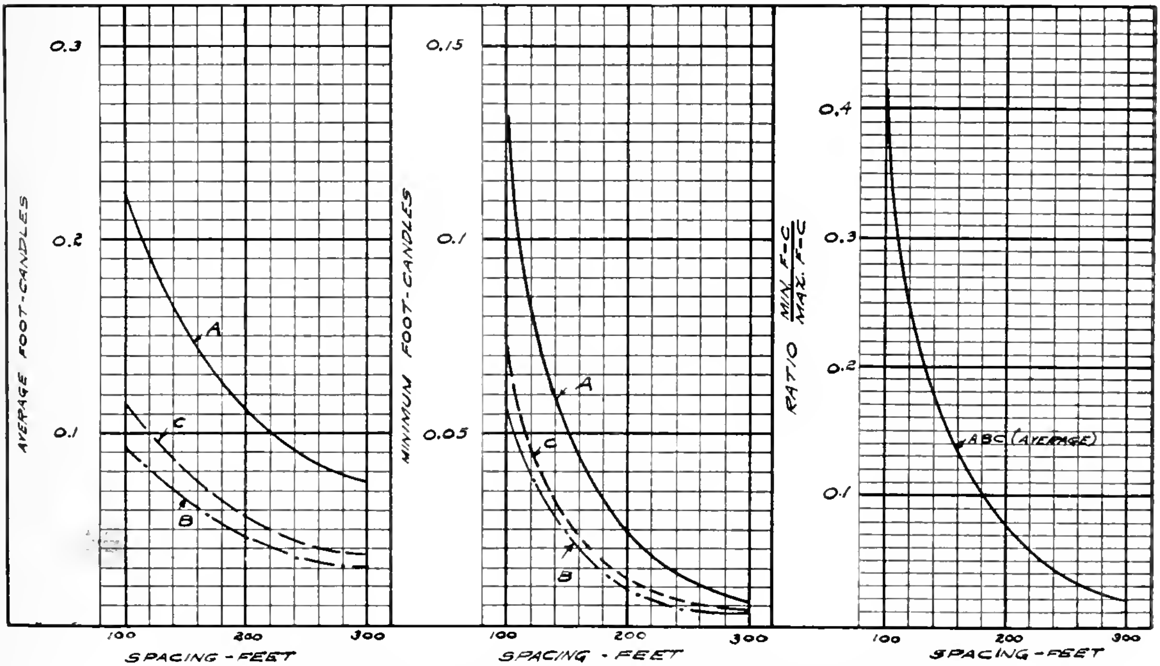


Fig. 5c. Calculated Illumination Values on Street Surface Along Center Line of Street

Lamps on one side of street only, on 4-ft. bracket arm. Height, 25 ft. Width of street, 60 ft.

A: 6.6-amp. d-c. series enclosed carbon arc lamp *B:* 6.6-amp. a-c. series enclosed carbon arc lamp

C: 7.5-amp. a-c. series enclosed carbon arc lamp

Fig 6a. Novalux Pendent Unit with Diffusing Glass Globe Reflector Used with 250-, 400-, 600- or 1000-c.p. Mazda Series Lamp

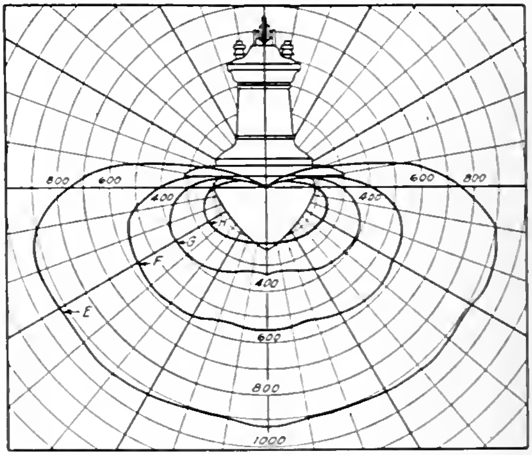


Fig. 6b. Initial Distribution of Candle-power in a Vertical Plane of the Unit Shown in Fig. 6a.

Curves *E, F, G* and *H* correspond to curves *A, B, C,* and *D* in Fig. 6c

boulevards where it is possible to space the units close, diffusing glassware will give satisfactory illumination and eliminate the glare which is so often experienced with other equipments, and also more ornamental and pleasing effects will be obtained. For such service a distribution similar to that shown by Fig. 6 is most suitable. It is not possible, however, to make general statements covering the use of illuminating glassware, as each problem requires a careful study of existing conditions.

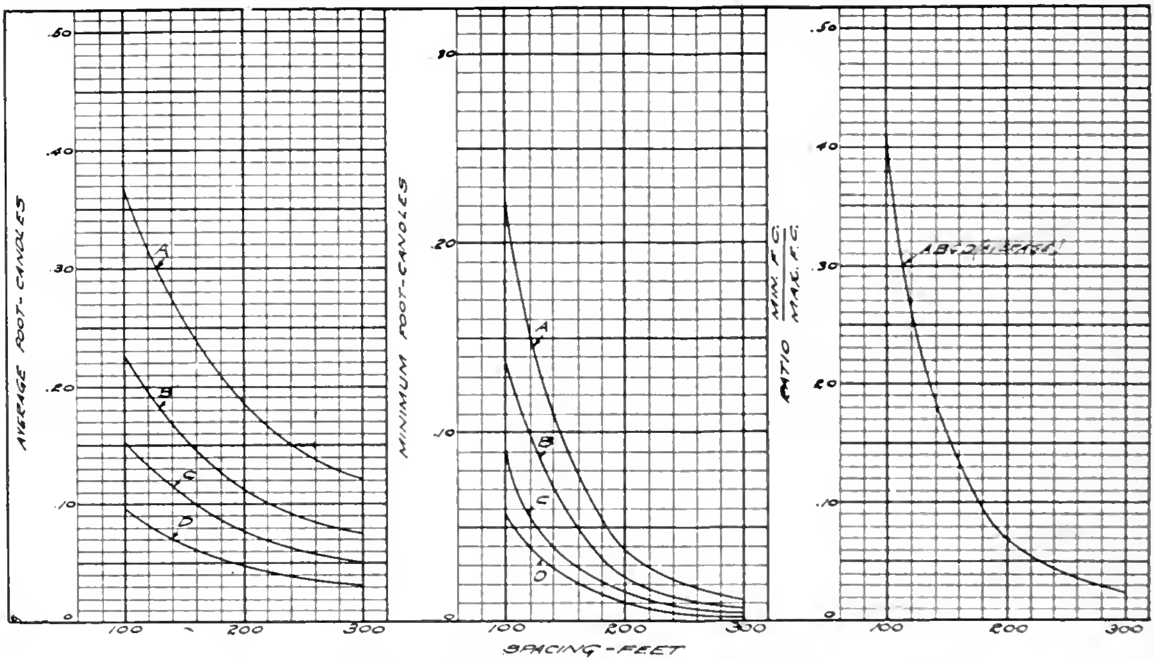


Fig 6c. Calculated Illumination Values on Street Surface Along Center Line of Street

Lamps on one side of street only, on 4-ft. bracket arm. Height, 25 ft. Width of street, 60 ft.

A, B, C, D: Diffusing Glass Globe and Steel Reflector

A: 1000-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb
B: 600-c-p., 20-amp. Mazda Series Lamp, SP-40 bulb
C: 400 c-p., 15 amp. Mazda Series Lamp, PS-40 bulb
D: 250-c-p., 6.6-amp. Mazda Series Lamp, SP-35 bulb

Fig. 7a. Novalux Pendent Unit with Bowl Refractor and Reflector Used with 400-, 600-, or 1000-c.p. Mazda Series Lamp

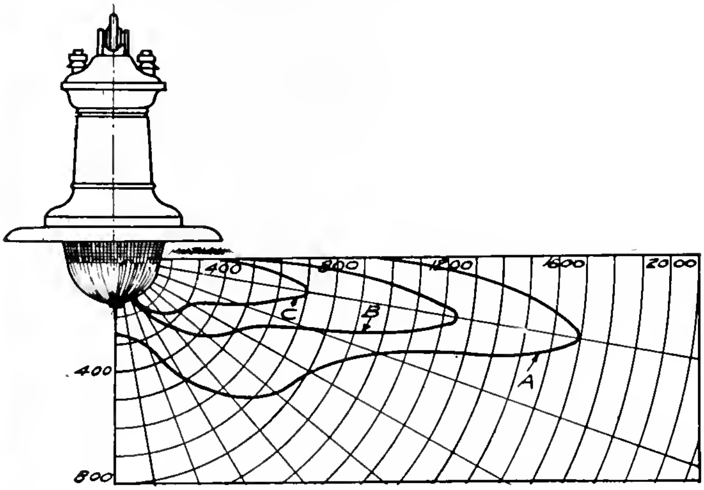


Fig. 7b. Initial Distribution of Candle-power in a Vertical Plane of the Unit Shown in Fig. 7c

Curves *A*, *B* and *C* correspond to the lamps named in Fig. 7c

The general order of illumination intensities for utilitarian street lighting where pendent type lamps are appropriate is as follows:

	Average Hor. Ill. in Foot-candles
Important side streets	0.10 to 0.25
Residential streets	0.01 to 0.05
Suburban roads	0.005 to 0.01

The most useful basis of comparing illuminants is, perhaps, the total lumens or light flux delivered by lamps as it is usually possible by selecting proper refractors, reflectors, and glassware to distribute the light in the manner most suitable for the particular conditions at hand. These lumen values are

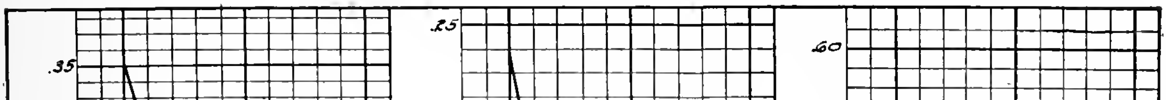


Fig. 7c. Calculated Illumination Values on Street Surface Along Center Line of Street

Lamps on one side of street only, on 4-ft. bracket arm. Height, 25 ft. Width of street, 60 ft.

A, B, C: Prismatic Glass Bowl Refractor and Steel Reflector

A: 1000-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb *B:* 600-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb

C: 400-c-p., 15-amp. Mazda Series Lamp, PS-40 bulb

Fig. 8a. Novalux Pendent Unit with Dome Refractor and Stippled Glass Globe* used with 250-, 400-, 600- or 1000-c.p. Mazda Series Lamp

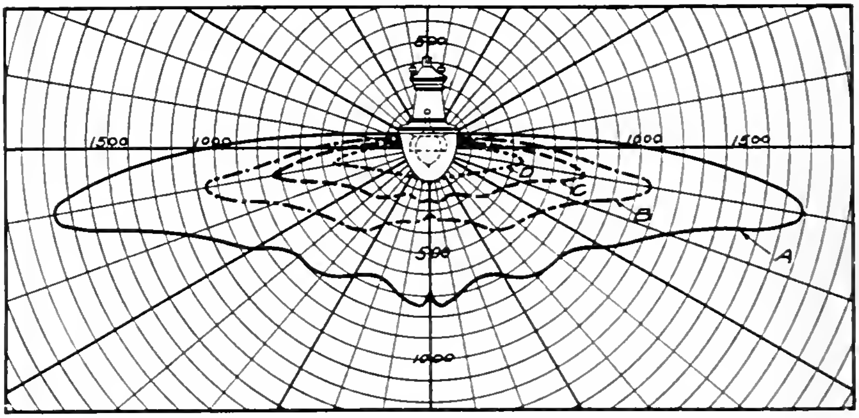


Fig. 8b Initial Distribution of Candle-power in a Vertical Plane of the Unit Shown in Fig. 8a

Curves *A*, *B*, *C* and *D* correspond to the lamps named in Fig. 8c

given in Fig. 10 for the following lamps which are considered in this article:

ENCLOSED CARBON ARC LAMPS

6.6-amp. a-c. enclosed carbon arc, light opal inner, clear outer, standard reflector.

7.5-amp. a-c. enclosed carbon arc, light opal inner, clear outer, standard reflector.

6.6-amp. d-c. enclosed carbon arc, light opal inner, clear outer, standard reflector.

NOVALUX UNITS WITH MAZDA LAMPS

Form 6 pendent Novalux unit with 250, 400, 600, and 1000-c-p. Mazda series lamps, diffusing globe with and without reflector.

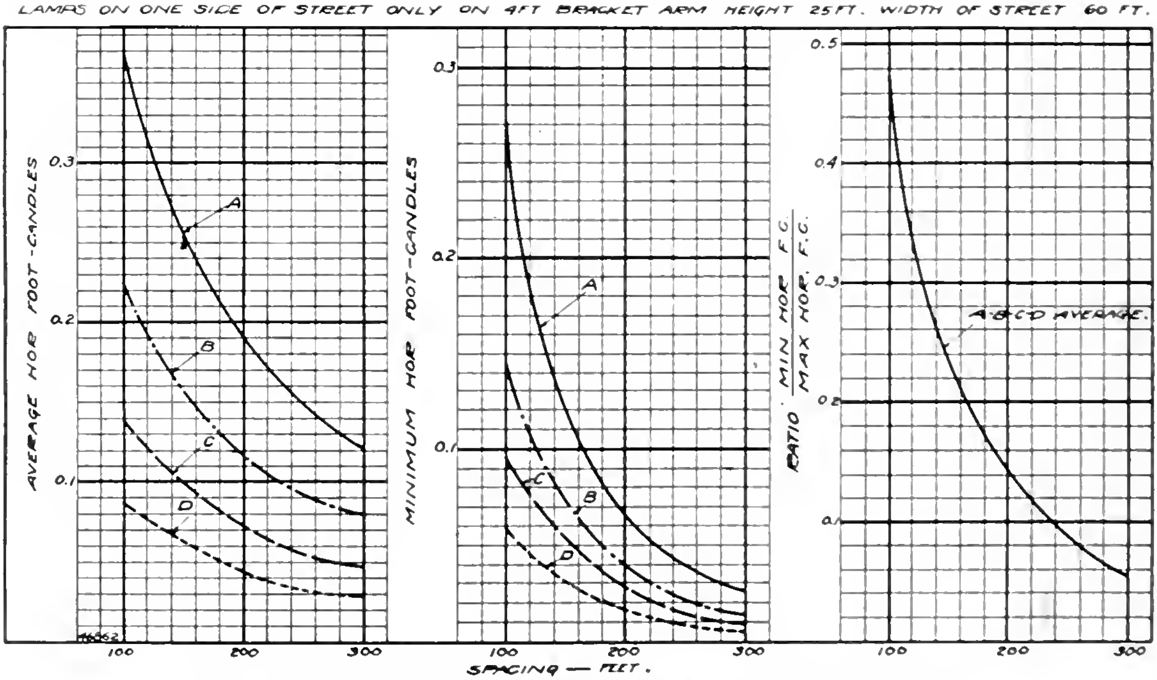


Fig. 8c. Calculated Illumination Values on Street Surface Along Center Line of Street

Lamps on one side of street only, on 4-ft. bracket arm. Height, 25 ft. Width of street, 60 ft

A, B, C, D: Prismatic Glass Dome Refractor and Stippled Glass Globe*

A and *E:* 1000-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb
B and *G:* 600-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb
C and *G.* 400-c-p., 15-amp. Mazda Series Lamp, PS-40 bulb
D and *H* 250-c-p., 6.6-amp. Mazda Series Lamp, PS-35 bulb

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* The illumination on the street will be practically the same for a rippled glass globe

Fig. 9a. Novalux Pendent Unit with Prismatic Refractor and Reflector Used with 250-, 400-, 600- or 1000-c-p. Mazda Series Lamp

Form 6 pendent Novalux unit with 250, 400, 600, and 1000-c-p. Mazda series lamps, equipped with bowl refractor and reflector.

Form 6 pendent Novalux unit with 250, 400, 600, and 1000-c-p. Mazda series lamps, equipped with Holophane prismatic dome refractor and stippled glass globe.

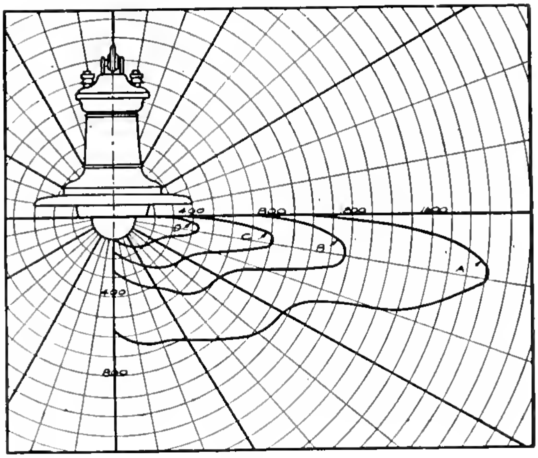


Fig. 9b. Initial Distribution of Candle-power in a Vertical Plane of the Unit Shown in Fig. 9a

Curves *A*, *B*, *C* and *D* correspond to the lamps named in Fig. 9c

Form 6 pendent Novalux unit with 250, 400, 600, and 1000-c-p. Mazda series lamps, equipped with Holophane prismatic band refractor and reflector.

The comparative figures of lumens reveal the inferiority of the enclosed carbon arc. The best that can be obtained from the en-

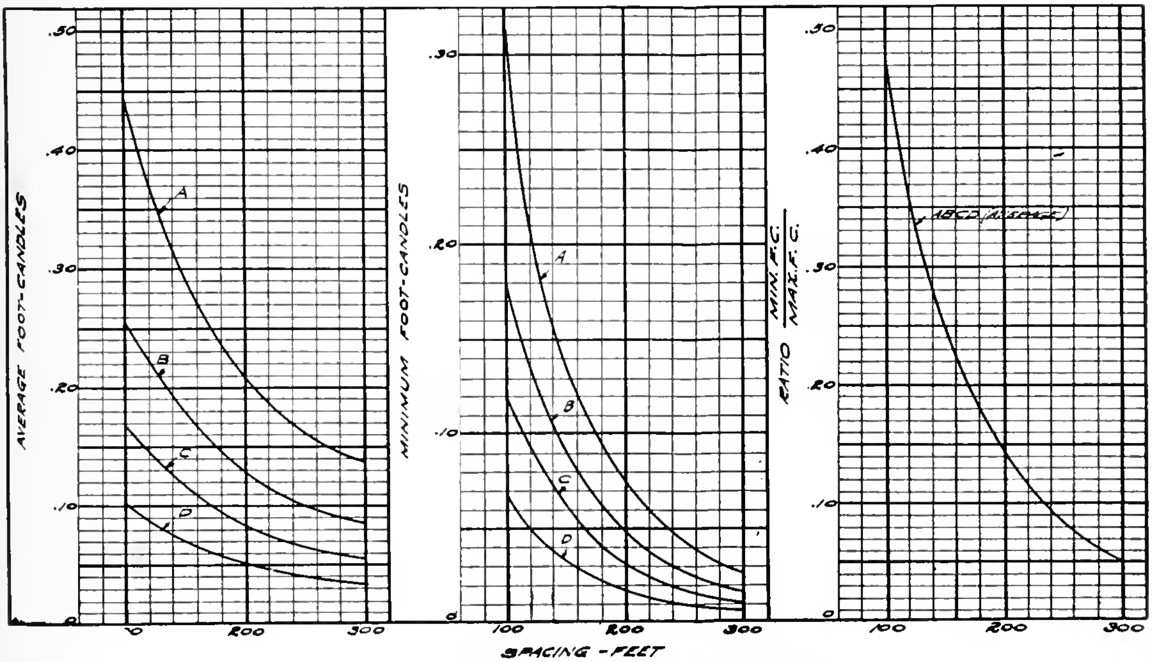


Fig. 9c. Calculated Illumination Values on Street Surface Along Center Line of Street

Lamps on one side of street only, on 4-ft. bracket arm. Height, 25 ft. Width of street, 60 ft.

A, B, C, D: Prismatic Glass Band Refractor and Steel Reflector

A:	1000-c-p., 20-amp. Mazda Series Lamp, PS-40 bulb	*B:*	600-c-p., 20-amp. Mazda Series Lamp, SP-40 bulb
C:	400-c-p., 15-amp. Mazda Series Lamp, PS-40 bulb	*D:*	250-c-p., 6.6-amp. Mazda Series Lamp, SP-35 bulb

closed carbon arc lamps (direct-current series type) is 7.4 lumens per watt as compared with 10 to 14 lumens per watt for the incandescent units, depending upon the size of lamp and equipment. A general idea of the relative appearance of an incandescent and an enclosed arc installation may be had from Figs. 11 and 12. These are actual photographs and illustrate very forcibly the non-uniform illumination on the street surface from the arc installation as compared with the Novalux system.

Table I shows the electrical data relating to the several systems considered in this article and also the saving in power and the relative power cost data of the carbon arc and incandescent systems. An examination of these data, together with the photometric data previously referred to, will convince the most skeptical that it is poor economy to continue operating the enclosed carbon arc lamp in lieu of the more modern incandescent equipments. Due to the advancement in the efficiency of street illuminants and equipments, it is possible to maintain higher standards of illumination than was possible with the series enclosed carbon arc lamp for the same expenditure of money. W. D'A. Ryan, Director of the Illuminating Engineering Laboratory, has advocated higher

TABLE I

ELECTRICAL DATA

Type of Unit	6.6 Ampere A-C. Series Enclosed	7.5 Ampere A-C. Series Enclosed	6.6 Ampere D-C. Series Enclosed	Form 6 Novalux 250 C-P.	Form 6 Novalux 400 C-P.	Form 6 Novalux 600 C-P.
Line Amperes	6.6	7.5	6.6	6.6	6.6	6.6
Lamp Amperes	6.6	7.5	6.6	6.6	15	20
Volts at Lamp Terminals	77	77	75	23.4	37.1	51
Watts at Lamp Terminals	425	480	495	155	234	340
Line Loss	5%	5%	5%	5%	5%	5%
Efficiency of Constant-current Transformer	96%	96%		96%	96%	96%
Efficiency of Brush Arc Generator Driven by Synchronous Motor			86%			
Combined Efficiency	91.2%	91.2%	81.7%	91.2%	91.2%	91.2%
Watts Supplied at Switchboard	468	527	605	170	257	373
Hours Lamps Burn Each Year	4000	4000	4000	4000	4000	4000
Kw-hr. Consumed per Lamp per Year	1872	2108	2120	680	1028	1492
Total Lumens per Lamp:						
With light opal inner globe, clear outer globe, and street reflector	1810	2170	3645			
With light Carrara globe and reflector				1725	2750	4070
With bowl type Holophane prismatic refractor and reflector				1670	2820	4225
With Holophane dome refractor and stippled glass globe*				1913	3060	4580
With Holophane band refractor and reflector				1780	3040	4510

* The illumination on the street will be practically the same for a rippled glass globe.

SAVING IN KILOWATT-HOURS AND MONEY PER LAMP PER YEAR BY REPLACING ENCLOSED CARBON ARC LAMP WITH NOVALUX UNIT AND MAZDA SERIES LAMP

Power at 1.5 Cents per Kw-hr.

	FORM 6 NOVALUX					
	250 c-p.		400 c-p.		600 c-p.	
	Kw-hr.	Money	Kw-hr.	Money	Kw-hr.	Money
6.6 Amp. A-c. Series Enclosed Carbon Arc	1192	$17.88	844	$12.66	380	$ 5.70
7.5 Amp. A-c. Series Enclosed Carbon Arc	1428	21.42	1080	16.20	616	9.24
6.6 Amp. D-c. Series Enclosed Carbon Arc	1740	26.10	1392	20.88	928	13.92

The 1000-c-p. lamp is not considered in this table, as its size confines it very largely to high intensity White Way lighting where local conditions preclude installing the luminous arc lamp.

standards of illumination for many years and has shown the many advantages in their use. His recommendations of higher standards of street illumination have been accepted by some of the largest cities in this country and in foreign countries and they have installed street lighting installations which have more than doubled the old standards of intensities.*

The simplicity, flexibility, and efficiency for the incandescent system extends beyond the lighting unit itself to the station equipment where we find a variety of apparatus suited to all possible conditions of service. The illustrations shown in Figs. 13a and 13b indicate the general structure of two types of constant-current transformers; and Figs. 13c, 13d, and 13e a complete line of auxiliary transformers.

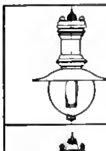
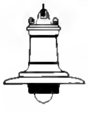
	EQUIPMENT		DOWNWARD LUMENS	UPWARD LUMENS	TOTAL LUMENS	TOTAL LUMENS PER WATT
	6.6 AMP A.C. SERIES ENCLOSED ARC WITH LIGHT OPAL INNER CLEAR OUTER GLOBES AND REFLECTOR		1460	350	1810	4.3
	7.5 AMP A.C. SERIES ENCLOSED ARC WITH LIGHT OPAL INNER CLEAR OUTER GLOBES AND REFLECTOR		1830	340	2170	4.50
	6.6 AMP D.C. SERIES ENCLOSED ARC WITH LIGHT OPAL INNER CLEAR OUTER GLOBES AND REFLECTOR		3020	625	3645	7.4
	FORM G NOVALUX PENDENT UNIT WITH LIGHT CARRARA GLOBE No. 87	250 C.P. (6.6 AMP)	1162	633	1795	11.6
		400 C.P. (15 AMP)	1915	965	2880	12.3
		600 C.P. (20 AMP)	2850	1470	4320	12.7
		1000 C.P. (20 AMP)	4640	2560	7200	13.2
	FORM G NOVALUX PENDENT UNIT WITH LIGHT CARRARA GLOBE No. 87, 20" STEEL REFLECTOR	250 C.P. (6.6 AMP)	1390	335	1725	11.1
		400 C.P. (15 AMP)	2260	490	2750	11.8
		600 C.P. (20 AMP)	3370	700	4070	12.0
		1000 C.P. (20 AMP)	5530	1370	6900	12.7
	FORM G NOVALUX PENDENT UNIT WITH BOWL TYPE HOLOPHANE PRISMATIC GLASS REFRACTOR 20" STEEL REFLECTOR	250 C.P. (6.6 AMP)	1510	160	1670	10.8
		400 C.P. (15 AMP)	2540	280	2820	12.1
		600 C.P. (20 AMP)	3870	355	4225	12.4
		1000 C.P. (20 AMP)	6550	500	7050	13.0
	FORM G NOVALUX PENDENT UNIT WITH STIPPLED GLASS GLOBE HOLOPHANE PRISMATIC DOME REFRACTOR	250 C.P. (6.6 AMP)	1672	241	1913	12.3
		400 C.P. (15 AMP)	2675	385	3060	13.1
		600 C.P. (20 AMP)	3910	670	4580	13.5
		1000 C.P. (20 AMP)	6610	1040	7650	14.0
	FORM G NOVALUX PENDENT UNIT WITH HOLOPHANE PRISMATIC GLASS BAND REFRACTOR AND 20 STEEL REFLECTOR	250 C.P. (6.6 AMP)	1645	135	1780	11.5
		400 C.P. (15 AMP)	2850	190	3040	13.0
		600 C.P. (20 AMP)	4220	290	4510	13.3
		1000 C.P. (20 AMP)	7120	560	7680	14.1

Fig. 10. Light Flux Values of A-C. and D-C. Series Enclosed Carbon Arcs and Novalux Series Units for Street Lighting

Fig. 13a shows the station type air-cooled constant-current transformer design in sizes from 3 to 80 kw. to operate series street-lighting circuits. These transformers are standard for 2300 volts, 60 cycles primary, 6.6 amp. secondary and for one and two circuits. They may be designed for any circuit or commercial frequency. This type of transformer is recommended in places where the streets that are to be lighted are economically close to the station or substation. Otherwise, the pole type constant-current transformer, as shown in Fig. 13b, is recommended. The features of the station type constant-current transformers are as follows:

1. Constant current within one per cent of normal from full load to short circuit, regardless of fluctuations in primary voltage, lamp failures, grounds, or short circuits.
2. Automatic regulation; no change in taps for variations in load; no adjustments necessary.
3. Instantaneous regulation; balancing mechanism supported on ball bearings.
4. Maximum insulation between all parts.
5. High efficiency and power-factor.
6. Ventilated, air-cooled, impregnated windings.
7. All parts visible and easy to keep clean.

Fig. 13b illustrates the use of the pole type constant-current transformer. This transformer adds another important link to the chain of constant-current transforming devices. The demand is urgent and the field is wide.

Series street lighting systems require constant current, and constant-current transformers have always required a substation with control panels and an attendant, therefore, it has been difficult to provide street lighting for smaller towns and villages where the revenue derived would not be sufficient to warrant the installation of a substation and attendant.

Larger cities also have experienced difficulty in solving the demand for higher intensities and more units in their suburbs. The growth of these outlying districts has been so rapid that it has been almost impossible to keep pace. When it becomes impracticable to run circuits from the control station because of the distance and the copper required, it is not always advisable to erect a substation, but if it is, the growth is usually so rapid that there is an interval before the substation can be erected when the lighting service is apt to be inefficient or ineffectual.

The type of transformer shown in Fig. 13b has been designed for such service. It is entirely automatic and positive in action. It does not require a substation or an attendant, and it can be controlled by an oil time switch. These features are combined with as close current regulation through as wide a range as offered by the best station type constant-current transformer. The current from

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*"Intensive Street Lighting," by W. D'Arcy Ryan, GENERAL ELECTRIC REVIEW, May, 1920, page 362.

full load to no load is maintained within one per cent of normal. This feature alone practically guarantees the life of the Mazda lamps operating on a circuit controlled by such a transformer. The efficiency is the same as for the station type transformer and the power-factor is 20 per cent higher than for any previous design of pole-type regulating transformer.

For the operation of Mazda C lamps, this transformer is ideal. The high internal reactance serves to protect the lamps at starting and acts instantaneously to check surges on the line which would tend to shorten the life of the lamps. The moving secondary coil with its high repulsion gives almost perfect regulation from full load to dead short circuit. It protects the lamps not only from changes in current due to changes in secondary load, but also from fluctuations in primary voltage.

The construction of this transformer contains no untried features, but simply combines various features incorporated in several

Fig. 11 Night View Showing Street Illuminated with Obsolete Enclosed Carbon Arc Lamps

Fig. 12 Night View Showing Street Illuminated with Pendent Type Novalux Units Equipped with Refractors

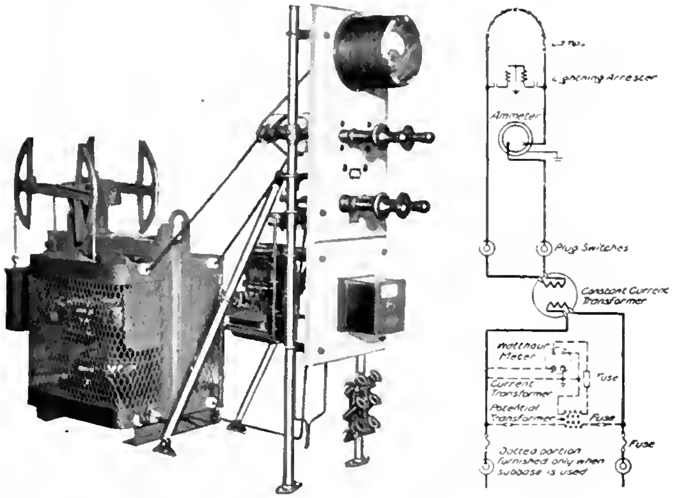


Fig. 13a. Illustrating the Station Type Constant Current Transformer and Its Application

different types of transformers which have been in production for a long time. The core is the standard, three-legged construction with coils surrounding the center leg. The primary coil is fixed at the bottom of the core, and above is the floating secondary coil. The balancing mechanism, however, has been modified so that an exact line up of the coils is not necessary for satisfactory regulation.

In order to give protection to the lamps at starting, the minimum reactance of the transformer is made fairly high. This results in a motion of the coil of only a few inches, while at the same time the repulsion of the coils is high, thus giving excellent regulation. This transformer may be tipped 10 deg. from the vertical in any direction without affecting the regulation. This is much more than the transformer would be called upon to stand in actual service. The coils are liberally designed so that temperatures come within A.I.E.E. requirements. A single adjusting lever permits adjustment of the secondary current to the desired value. The final current adjustment is made in the factory and no further change in adjustment should be necessary.

After being installed this transformer requires no more attention than one of the constant-potential type. It is used in sizes from 1 to 20 kw., 6.6-amp. secondary, and for any commercial frequency.

Fig. 13c illustrates the series transformer designed for the purpose of operating series circuits of low-voltage in conjunction with the main series circuit. This is accomplished by using a series transformer having a one to one ratio, the secondary being well insu-

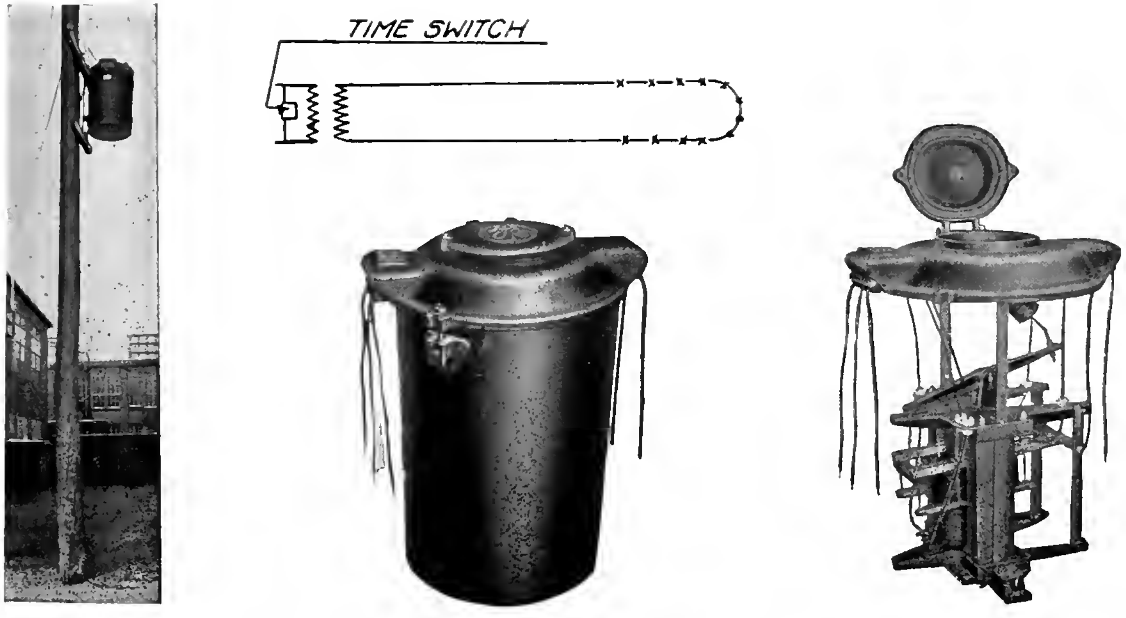


Fig. 13b. Illustrating the Pole Type Constant Current Transformer and Its Application

lated from the primary. The primary winding is connected in series with the main series circuit so that, under all conditions of load on the secondary, the primary carries the full current of the main circuit which is maintained at its normal value by a constant-current regulating device. Series transformers of such construction are made in many sizes from 0.04 to 10 kw.

With this type of transformer, the installation can be arranged so that all street lamps will come on at the same time and the

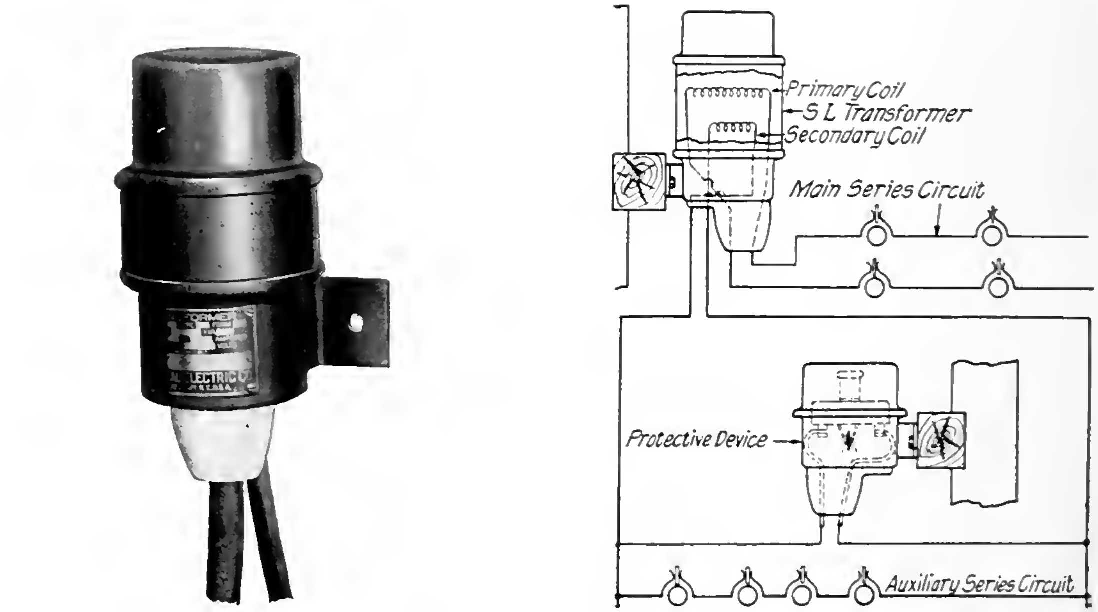


Fig. 13c. Illustrating Low Voltage Series Circuit with Constant Current Transformer and Its Application

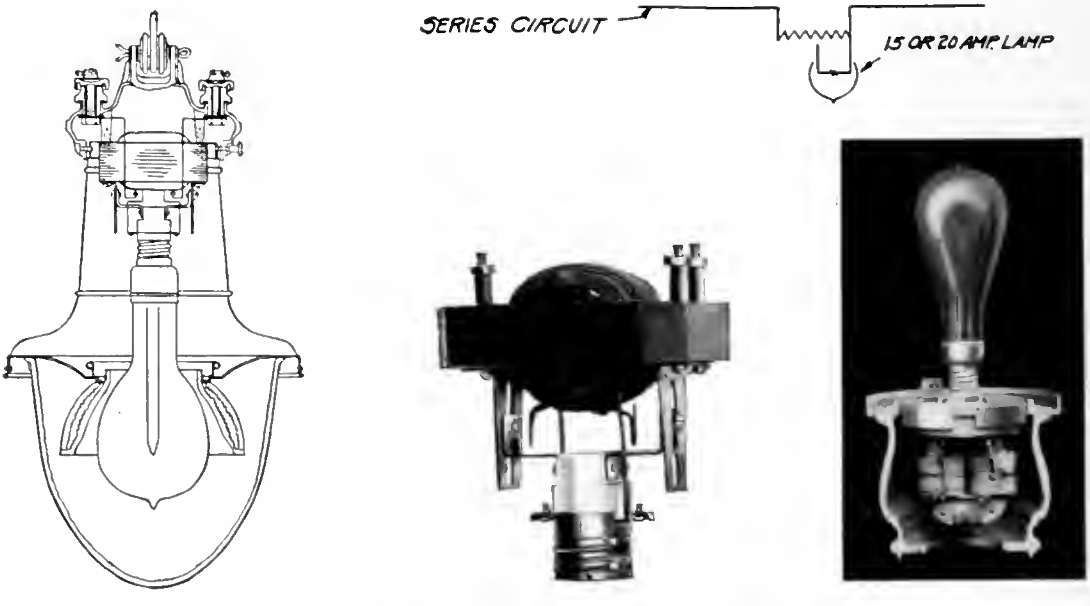


Fig. 13d. Illustrating the Series Auto Transformer and Its Application

expense of switching on by hand can be eliminated. The transformer permits the use of the series lamp which is more efficient than the multiple lamp. It is used for supplying current to one or more lamps connected in series and located where the high potential of the ordinary constant-current series circuit would be objectionable.

These transformers are operated on loaded series systems and, consequently, if the secondaries become open-circuited, are subjected to sinusoidal excitation which gives a high distorted voltage. With the larger sizes of transformers where this open circuit voltage may become dangerous to the insulation or to operators, film protective devices are used. Film cutouts are not employed with the smaller sizes of transformers as these will operate without overheating or breakdown on open circuit.

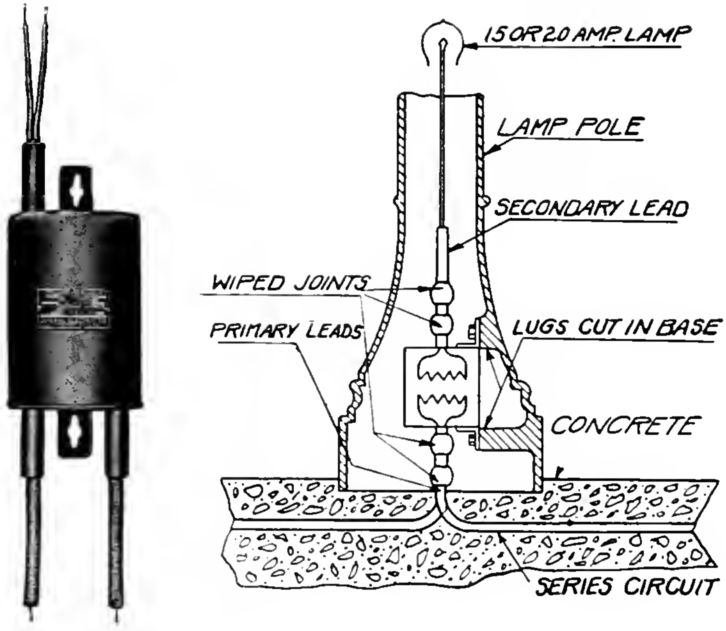


Fig. 13e. Illustrating the Single Lamp Series Transformer and Its Application

The protective devices are designed with clips to short circuit the secondary system when the handle is removed. A second pair of clips in the handle holds the films which, on account of the relatively high voltages encountered, are of a new type. The films for higher voltages consist of plates of soft metal cemented to the two sides of a fiber disk through which a hole is pierced. The thickness of the fiber determines the strength of the air gap which, being protected, is very uniform. When the gap breaks, the metal flows and fills the hole so as to form a short circuit across the transformer. When the handle containing the film is inserted in the holding clips, the protective device circuit is opened and the film left in position to operate in case the system is open-circuited. The protective devices are mounted in steel cases adapted to either pole or subway use in accordance with the arrangement of the transformer with which they are used.

As these transformers are designed to operate from a circuit where the current is held constant, the field for them necessarily lies in the vicinity of constant-current series circuits.

Certain classes of lighting require lower potential than that existing on series arc or incandescent circuits and, to provide for this, companies would be compelled to run multiple circuits from the Central Station, often at a considerable expense, if it were not for this transformer. Some of this low-voltage lighting is supplementary to the regular street lighting system and, filling the same function, it is desirable to control it simultaneously with the street lights. This transformer affords the ideal method for this control as the low-voltage circuit is turned on and off with the closing or opening of the main constant-current transformer circuit.

Places where this transformer can be used to advantage are as follows:

1. Isolated side streets or alleys where it is desired to install series incandescent lamps and where the only available circuit is the alternating-current series circuit.

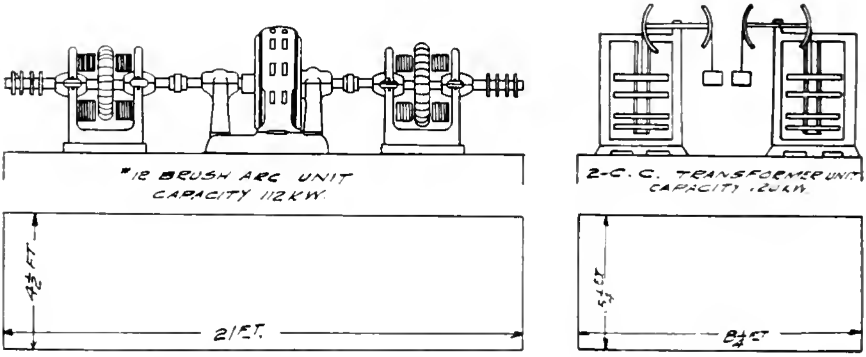


Fig. 14. Comparative Floor Area and Efficiencies of the Brush Arc Generator *vs.* the Constant Current Transformer System Based on Approximately Equal Capacity

2. In places where high potential is impracticable; e.g., where the line would be installed on telephone poles, or where a few small units in a building are required and a multiple circuit is not available.

3. On bridges where it is necessary to eliminate high potential.

4. For underground circuits leading to ornamental poles.

These transformers are designed in sizes from 0.4 to 1.0 kw. and for any current or frequency, having a ratio of the primary amperes to the secondary amperes of 1:1. The secondary is highly insulated from the primary.

Fig. 13d illustrates the use of the series auto-transformers designed for operating high current Mazda series lamps such as the 15-amp. 400-c-p., 20-amp. 600-c-p. and 20-amp. 1000-c-p. lamps. It is designed primarily to operate these lamps at high current density to obtain the advantage in efficiency over straight current lamps. They are made for both pendent and ornamental Novalux units.

There is one winding and taps come out for the lamp, as shown in Fig. 13c, therefore the circuit to the lamp is not insulated from the high potential series circuit.

For aerial work there are no particular objections, and for ornamental lighting the auto-transformer is placed in the casing mounted on the pole shown in Fig. 11 and is recommended where high voltage going through the pole is not objectionable or the appropriation is limited so that a safer transformer cannot be used such as is shown in Fig. 13e. When the auto-transformers are used, the underground highly insulated cables are carried up the post to give proper protection against grounds.

Fig. 13e illustrates the use of the single-lamp series transformer also designed for operating high current Mazda series lamps. It is built in capacities to take care of 400, 600 and 1000-c-p. lamps. Standard primary windings are for 6.6 amp. and standard secondaries for 15 amp. 400 c-p., or 20 amp. 600 and 1000 c-p.

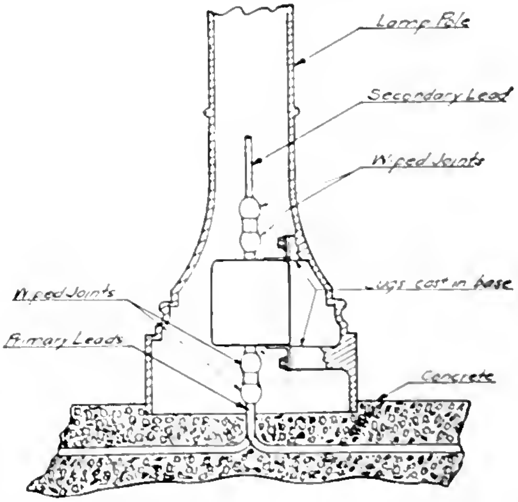


Fig 15 Series Transformer Mounted in Base of Pole on Strap Iron Support Embedded in Concrete

They are entirely enclosed in steel casing and are weatherproof. Two types are used; subway and aerial. Leads on the subway type are brought out through galvanized iron wiping sleeves so that the lead sheath can be readily wiped on. For aerial use the leads are brought out through porcelain bushings. These have the following advantages:

1. High efficiency series lamps can be used where high potential is impracticable.

2. They protect the lamp from surges in the line.

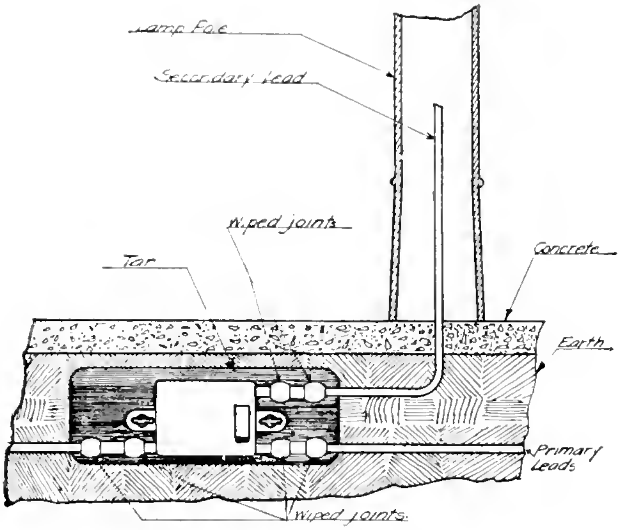


Fig. 16. Series Transformer Buried in Ground

3. They are a valuable adjunct to "Safety First" in ornamental street lighting, due to the fact that the secondary is highly insulated from the primary and permits the use of high efficiency series lamps in business districts where ordinances prohibit high tension wire above street surface.

4. They save the expense of high-voltage conductors, heavy insulation and high tension cutouts, which materially assists in liquidating the difference between the first cost of auto-transformers and series transformers, the latter being naturally somewhat higher priced. Furthermore, this low voltages eliminates 75 per cent of all the line trouble which occurs between the pole and the lamp.

When lamp wattage varies between 8 per cent above and 20 per cent below normal, the secondary current will not vary more than 1 per cent with normal current and frequency.

An interesting comparison of the floor space required for Brush arc machines operated by synchronous motors, which supply current to direct-current enclosed carbon arcs, as against the constant-current transformer equipment (the latter to supply current to the incandescent lamp), is shown in Fig. 14. The Brush machine may be found in many of the cities that are still using the carbon arc lamp.

It will be obvious to any central station manager, after reviewing these data, that the time has arrived to replace the enclosed carbon arc lamp with more efficient equipment. Their continued use can be attributed to no other cause than backwardness and failure to realize the opportunity for increased efficiency, increased capacity, and better service offered by the later developments in street lighting equipment.

350-ton Hammer Head Fitting Out Crane

By J. A. Jackson

Power and Mining Engineering Department, General Electric Company

The massiveness of the armament and machinery of our modern battleships is well indicated by the capacity of the huge crane described in this article. It seems scarcely probable that the maximum capacity of this crane, 350 long-tons, will ever be required for a single load, but we are progressing at such a rapid rate that another two or three years may produce a need for a crane having a capacity greatly in excess of the one described here.—Editor.

There was recently put into service at the League Island Navy Yard, Philadelphia, Pa., the largest hammer head type fitting out crane which has ever been built. The crane is approximately 250 ft. high overall and can handle a 350-long-ton load at 115 ft. radius, and a 50-long-ton-load at a 190 ft. radius.

The maximum lift of the main hook from the deck of the pier on which the crane is located is 145 ft., but the drum holds sufficient cable so that the hook can be lowered 25 ft. below the deck of the pier, making a total lift for the main hook of 170 ft. The 50-ton hook has a maximum lift of 180 ft.

The total length of the swinging jib is 300 ft. of which 100 ft. is on one side of the center line and contains the machinery house and counterweight, while the other 200 ft. is on the opposite side of the center line and contains the runways for the trolley carriages.

The machinery house has a floor space of approximately 70 ft. by 50 ft. and is served by an overhead travelling crane of 35 tons capacity and approximately a 50-ft. span. The runway for this crane is extended outside the machinery house so that the crane can run out through a motor-operated sliding door and lower its hook to the pier deck when necessary to lift anything from the ground to the machinery house.

The machinery house contains all the machinery and electrical equipment with the exception of the slewing motor, drum controllers, and the master switches. The slewing motor is located in a motor house about 50 ft. from the ground at the lowest part of the revolving member of the crane. All master switches and drum controllers are located in an operator's cab, so placed as to have a clear view of the crane hooks at all times.

The revolving member, which with its live load weighs approximately 5,500,000 lb., is supported at the top of the stationary member on a roller bearing, which bearing can be readily inspected by raising the entire revolving member by means of hydraulic jacks permanently located on the crane. The revolving member is carried down to approximately 50 ft. of the ground, where it terminates in a large ring running on rollers located on the stationary part of the crane. A rack is also fastened to this ring, which rack is connected to the slewing motor through a suitable train of gearing.

There are two entirely independent main hoists, each having a capacity of 175 tons and each main hoist has its own independent trolley. The hoisting engines, however, for both the two hoists and the two trolleys, are arranged so that they can be coupled together mechanically so as to operate as a single unit. When thus operating, the two master switches for the hoist motors have their shafts coupled together so that they operate in unison from one handle. The two drum controllers for the two trolley motors are similarly coupled together.

The drum for each main hoist has right and left hand grooves, from which two ropes lead off through suitable guiding sheaves to the trolley wagon. At this point each rope is reeved through four sheaves, giving an eight part line between the trolley wagon and the hook. After passing through the sheaves, the two ropes are taken to an equalizer sheave to insure equal division of the load on the two ropes.

There are four gear reductions between the drum and the motor pinion, and an actual test with a 350-ton load showed an efficiency of 52 per cent from the hook to the motor pinion. The crane was designed for a hook speed of 2.5 ft. per min. when hoisting full load, but an actual test showed a speed of 2.62 ft. per min.

Each main hoist is also equipped with a gear change which increases the hook speed from 2.5 ft. per min. to 10 ft. per min. for handling lighter loads at higher speeds. Each main hoist drum weighs approximately 37 tons.

All the trolley wagons are rope driven from hoisting engines located in the machinery house, and in the case of the two main trolleys, the hoisting engines have gear changes which give a speed of 12 ft. per min. in low gear and 100 ft. per min. in high gear. Actual tests, however, with full load on the hook, give a speed of about 19.3 ft. per min. in low gear.

The auxiliary hoist is geared for a hook speed of 12 ft. per min. with a 50-ton load and its trolley is geared for 100 ft. per min. The auxiliary trolley runs on separate tracks from the main hoist trolleys so that its operation is entirely independent of them.

The slewing motor is geared to give one revolution of the crane jib in 12 minutes, but an actual test showed one revolution in approximately 9 minutes with a 125 per cent load on the hook.

One MDS-107 mill-type motor is used on each of the main hoists, the auxiliary hoist and on the slewing motion, while each of the three trolleys is equipped with an MDS-104 motor. All motors are series wound. Tests showed that all motions are conservatively motored, especially the slewing motion. It was considered advisable, however, to use the same size motor on the slewing motion as on the hoist motions, on account of the spare part situation.

The control equipment for all hoist motions consists of a standard contactor panel slightly modified to obtain additional points of control, which were required by the government specifications.

Each hoist master switch gives six-hand points in each direction and all lowering points give both power and dynamic braking, depending on the load requirements.

Extra heavy duty resistors were necessary to meet the severe dynamic braking conditions encountered when a load is lowered throughout the maximum lift as required by government tests.

The lowering speed with full load on the hook was approximately 3 ft. per min.; thus it required about 57 min. to lower through the maximum lift. Each hoist equipment has a geared type limit switch to prevent overtravel.

The slewing motion has straight reversible magnetic control with a five-point master switch. The panel contains plugging relays and the resistor is laid out to give safe plugging.

All three trolley motions are controlled by drum type manual controllers with vertical operating handles. Resistors are laid out for plugging.

Track type limit switches limit the travel of all trolley motions. The protective panel is a standard panel with two gravity reset overload relays in each motor circuit. The protective panel also contains contactors on which the trolley motion limit switches operate.

Series wound solenoid brakes are used on all motors, those on the slewing and trolley motions being set for very low retarding torque values.

The operator's cab is equipped with complete electric bell signaling devices to signal to the ground or to the machinery house, and it is also equipped with indicators to show the exact position of each of the trolleys on the runway.

The crane is equipped with a passenger elevator which starts at the bottom of the revolving member and runs to both the operating platform and on up to an observation tower at the highest part of the crane.

The crane was subjected to a very severe series of acceptance tests by the government, which included the handling of a 25 per cent overload throughout the maximum lift with the trolley run out to the maximum radius. It passed all tests successfully and the cover illustration of this issue of the REVIEW shows the crane at the completion of the test.

QUESTION AND ANSWER SECTION

The purpose of this department of the REVIEW is two-fold.

First, it enables all subscribers to avail themselves of the consulting service of a highly specialized corps of engineering experts, or of such other authority as the problem may require. This service provides for answers by mail with as little delay as possible of such questions as come within the scope of the REVIEW.

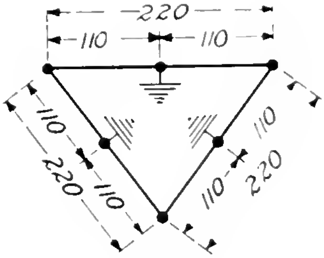
Second, it publishes for the benefit of all REVIEW readers questions and answers of general interest and of educational value. When the original question deals with only one phase of an interesting subject, the editor may feel warranted in discussing allied questions so as to provide a more complete treatment of the whole subject.

To avoid the possibility of an incorrect or incomplete answer, the querist should be particularly careful to include sufficient data to permit of an intelligent understanding of the situation. Address letters of inquiry to the Editor, Question and Answer Section, General Electric Review, Schenectady, New York.

GROUNDS: THREE-WIRE THREE-PHASE DELTA

(215) Ordinarily, 220 110-volt three-wire systems have their neutral grounded. However, the grounding of a three-phase delta three-wire secondary distribution system, as illustrated in Fig. 1, would cause a circulating current through the ground from each phase to the other two, due to the 110-volt delta potential. Should such a system be grounded; if so, how should the grounds be connected?

The National Electric Code states that circuits should not be grounded in such a manner that the ground connection will carry an appreciable amount of current. Obviously, the ground connections shown in Fig. 1 (or even only two) could not be used for they would short circuit half the voltage of the delta. There have been a few cases known where the middle point of one phase only was grounded, dependence being placed upon this to furnish sufficient ground connection for the other phases.



(215) Fig. 1

If the transformers are single-phase and each phase is separated from the other two on the secondary side, the middle points of the individual phases could of course be grounded.

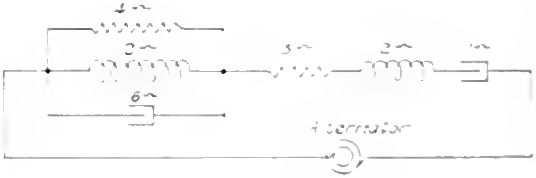
F. R. F.

CALCULATION: INDUCTANCE, CAPACITY AND RESISTANCE IN SERIES AND IN PARALLEL

(216) Please solve by the method of complex quantities the problem given in Q. & A. No. 190.

The question referred to asked: "What is the total impedance of the circuit illustrated in Fig. 1? Explain the method of calculation."

As in the two methods of solution previously published,* the following solution by the complex quantity method will be divided into distinct parts: (*1*) the impedance of the parallel group, (*2*) the impedance of the series group, and the combination of these two.



(216) Fig. 1

(*1*) Impedance of the parallel group.

This is composed of three impedances in parallel

$$Z_1 = r_1 + jx_1$$

$$Z_2 = r_2 + jx_2$$

$$Z_3 = r_3 + jx_3$$

in which

$r_1 = 4 \quad x_1 = 0$

$r_2 = 0 \quad x_2 = 2$

$r_3 = 0 \quad x_3 = -6$

Hence

$$Z_1 = 4,\ Z_2 = j2,\ Z_3 = -j6$$

The corresponding admittances are

$$Y_1=\frac{1}{Z_1}=\frac{1}{4};\ Y_2=\frac{1}{Z_2}=\frac{1}{j2}=-j\frac{1}{2};$$

$$Y_3=\frac{1}{Z_3}=-\frac{1}{j6}=j\frac{1}{6}$$

In complex quantities, the joint admittance of a number of parallel-connected admittances is equal to the sum of the individual admittances, thus

$$Y_a=Y_1+Y_2+Y_3=\frac{1}{4}+j\left(\frac{1}{6}-\frac{1}{2}\right)=\frac{1}{4}-j\frac{1}{3}$$

and the impedance of the parallel group is

$$Z_a=\frac{1}{Y_a}=\frac{1}{\frac{1}{4}-j\frac{1}{3}}$$

$$=\frac{1}{4}\left(\frac{1}{(\frac{1}{4})^2+(\frac{1}{3})^2}\right)+j\frac{1}{3}\left(\frac{1}{(\frac{1}{4})^2+(\frac{1}{3})^2}\right)$$

$$Z_a=\frac{1}{4}\times\frac{144}{25}+j\frac{1}{3}\times\frac{144}{25}=1.44+j1.92.$$

(2) Impedance of the series group:

$$Z_b=r+jx=3+j(2-1)=3+j$$

Combination of the two groups:

The joint impedance of a number of series-connected impedances is equal to the sum of the individual impedances, thus the total impedance of the system is

$$Z=Z_a+Z_b=3+1.44+j(1+1.92)$$

$$=4.44+j2.92$$

and the absolute value is

$$Z=\sqrt{(4.44)^2+(2.92)^2}=5.314$$

The complex quantity method furnishes a more exact solution than does either the graphical or the arithmetical method.

L.G.

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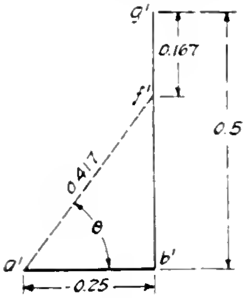
* These appeared in the December, 1916, REVIEW, p. 1135, but are repeated in the following for the sake of completeness, and for the benefit of those who were not subscribers at that time.—EDITOR.

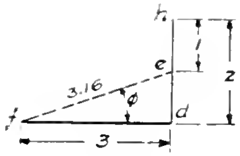
One method is based on graphics: this is by far the simpler mode. The other employs only arithmetic; this method furnishes a more exact answer than does the former.

Since there are two distinct combinations of the resistance, magnetic reactance, and capacity reactance in the circuit, the problem will be divided first into two parts, viz., (*a*) the impedance of the parallel group and (*b*) the impedance of the series group. The combination of these two impedances will then be the total impedance of the circuit.

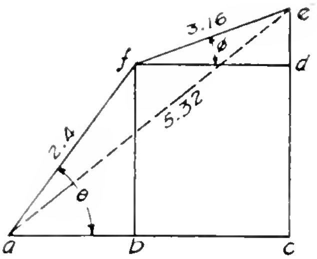
The impedance of a parallel circuit is equal to the reciprocal of the vector sum of the reciprocals of the ohmic values of the sub-circuits. The impedance of a series circuit is equal to the vector sum of the ohmic values of all the parts of the circuit.



(216) Fig. 2



(216) Fig. 3



(216) Fig. 4

Graphical Method

(Assume the vector direction for resistance to be horizontally to the right, for magnetic reactance to be vertically upward, and for capacity reactance to be vertically downward.)

(*a*) For the parallel group lay out the vectors, as shown in Fig. 2, equal to the reciprocal of the ohmic values of the conductors, i.e., for resistance draw *a'b'* $\frac{1}{4}$ or 0.25 of a unit to the right, for magnetic reactance *b'g'* $\frac{1}{2}$ or 0.5 upward, and for capacity reactance *g'f'* $\frac{1}{6}$ or 0.167 downward. The vector, *a'f'*, that joins this last point to the first will be at some angle θ to the horizontal and will scale 0.417 in length. The impedance of the parallel group will therefore be $\frac{1}{0.417}$ or 2.4 ohms.

(*b*) For the series group lay out the vectors, as shown in Fig. 3, directly equal to the ohmic values of the conductors, i.e., for resistance draw *fd* 3 units to the right, for magnetic reactance *dh* 2 upward, and for capacity reactance *he* 1 downward. The resultant vector, *fe*, will be at some angle ϕ to the horizontal and will scale 3.16 ohms, which will be the impedance of the series group of the circuit.

Combination of the two groups:

Lay out a vector, *af*, 2.4 units in length at the angle θ to the horizontal, see Fig. 4. From the end of this line lay out a vector, *fe*, 3.16 units in length at the angle ϕ to the horizontal. The line bridging these two vectors from end to end, *ae*, will represent the total impedance of the circuit, the value of which will be found to be 5.32 ohms by scaling the length.

Arithmetical Method

This method employs the general formula:

"Impedance equals the square root of the sum of the resistance squared and the arithmetical difference between the magnetic and capacity reactances squared."

(a) For the parallel group the reciprocal of the ohmic values of the sub-circuits are used, the reciprocal of the resultant giving the impedance. This coincides mathematically with the graphical method described in Method I (*a*).

$$\text{Impedance}=\sqrt{\frac{1}{(\frac{1}{4})^2+(\frac{1}{2}-\frac{1}{6})^2}}$$
$$=2.4 \text{ ohms.}$$

(b) For the series group the general formula is applied directly

$$\text{Impedance}=\sqrt{3^2+(2-1)^2}$$
$$=3.16 \text{ ohms.}$$

Combination of the two groups:

Since the influence of the parallel group on the power-factor is not the same as that of the series group, the respective resultant ohmic values of the two groups must be added in accordance with the difference in phase angle, in order to obtain the total impedance.

This is best accomplished by squaring the arithmetical sum of the two resistance components of the two groups, adding to this the square of the arithmetical sum of the resultant magnetic or capacity reactance of the two groups, and determining the square root of the whole. In the symbols of Fig. 4 this is

$$ae=\sqrt{(ab+bc)^2+(cd+de)^2}$$

$$ab=2.4\times\frac{a'b'}{a'f'}\text{ (from Fig. 2)}=2.4\times\frac{0.25}{0.417}=1.44$$

$$bc=fd\text{ (from Fig. 3)}=3$$

$$cd=bf=2.4\times\frac{b'f'}{a'f'}\text{ (from Fig. 2)}=$$

$$2.4\times\frac{(0.5-0.167)}{0.417}=1.92$$

$$de=2-1\text{ (from Fig. 3)}=1$$

Impedance therefore, equals

$$\sqrt{(ab+bc)^2+(cd+de)^2}$$
$$=\sqrt{(1.44+3)^2+(1.92+1)^2}$$
$$=5.32 \text{ ohms.}$$

E. C. S.

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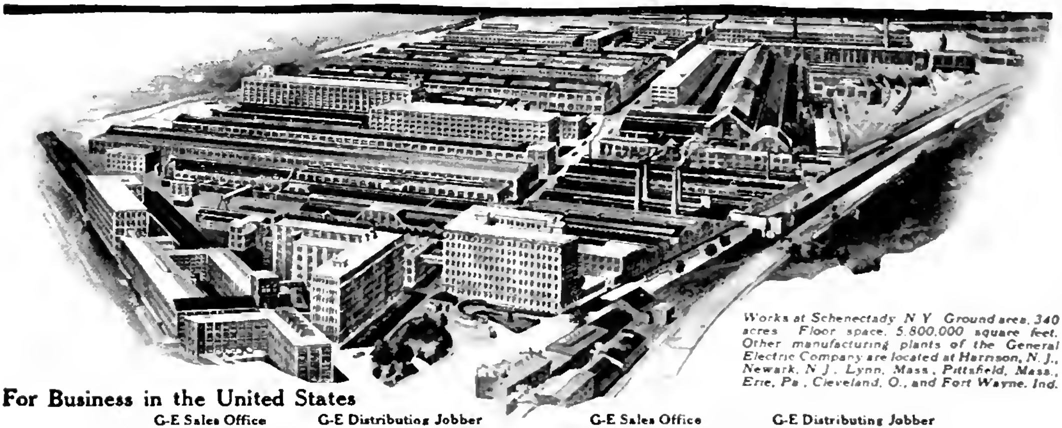

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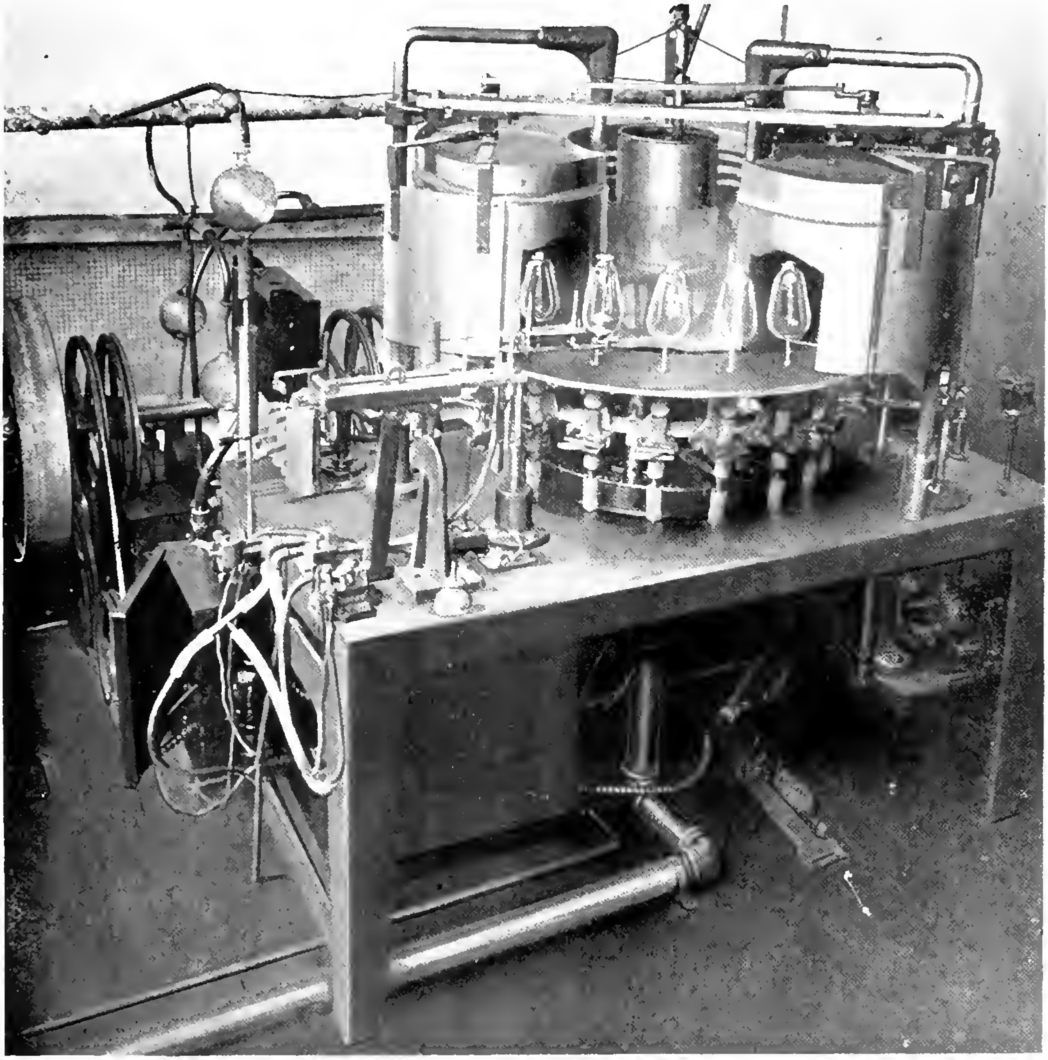

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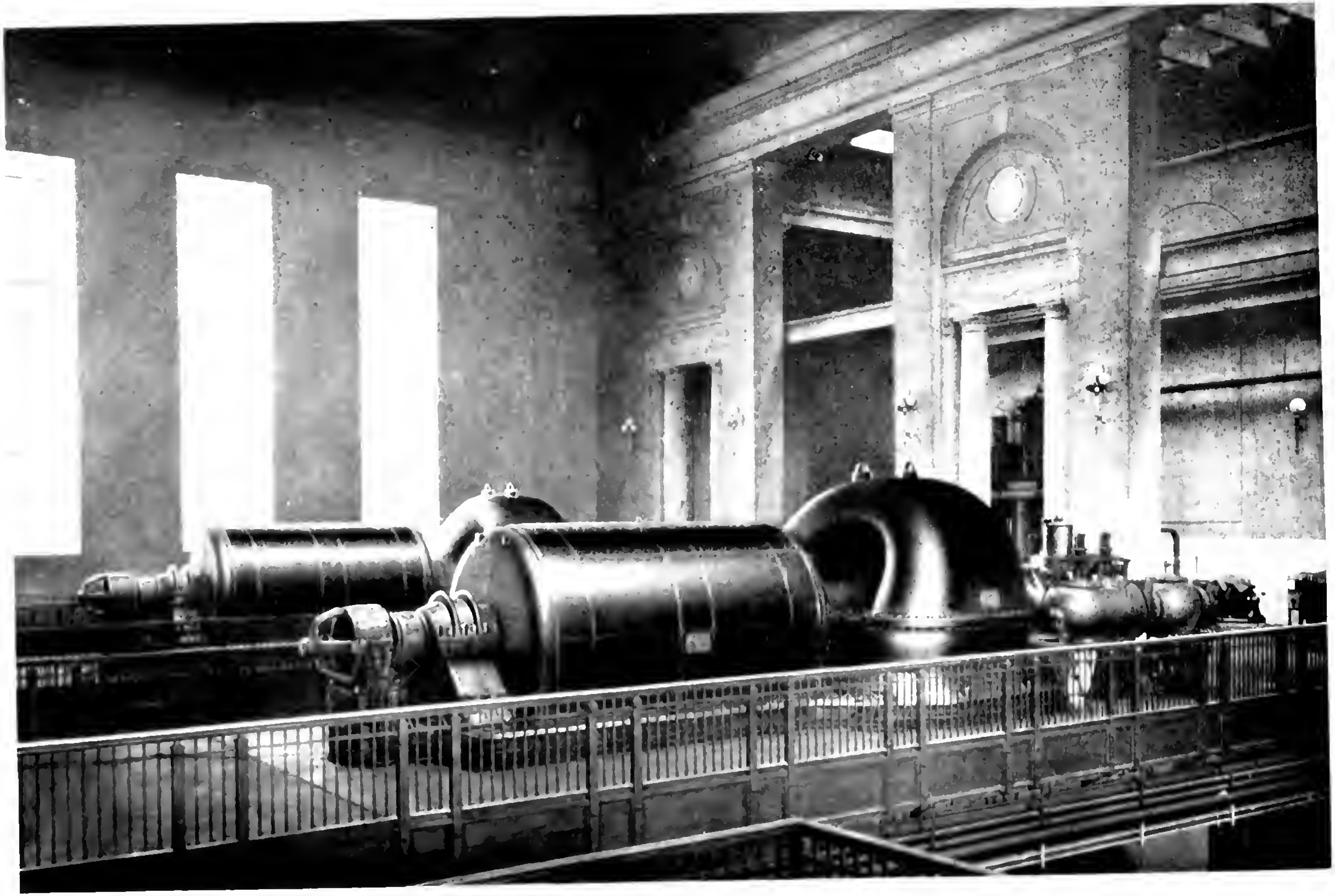

30,000 kw. Turbine Generator Sets Consisting of Curtis Turbines and 33,333 kv-a., 1800 r.p.m., 11,000 volt Generators in the Chester Power House of the Philadelphia Electric Company (For a Discussion of Temperature Problems See Page 560)

GENERAL ELECTRIC REVIEW

TEMPERATURES IN LARGE ALTERNATING-CURRENT GENERATORS

Temperature is a matter of so great importance in rotating electric machinery that all standardization of the American Institute of Electrical Engineers is now based upon it. The approved ratings of machines are determined by considerations of the temperature rises as related to the materials employed. Hence it has come about that designers of electric machines have given great attention to the ventilation problem. This is most commendable in itself, and has resulted in a decided advance in the construction of machines.

It often happens that wrong ideas exist regarding machines when established rules are applied. For instance, there is a prevalent notion that any electric machine is underrated if the temperatures when operating at the rating given to it by the manufacturer are lower than those designated by the rules of the A.I.E.E. for the type of insulation used. Temperature rises are often less than those permissible for the reason that purchasers of machines also insist upon certain other desirable characteristics.

The temperature of an electric machine, or any electrical apparatus, is the resultant of two factors: first, the quantity of energy in the form of heat losses that are attendant upon the operation of the apparatus, and, second, the effectiveness of the dissipation of this heat energy. It therefore happens that of two machines of the same rating, operating at the same load under the same conditions, the one showing higher temperatures may be the more efficient. This is undoubtedly contrary to the general notion regarding the matter. It is simply necessary to reflect that a machine that is constructed as a good blower and passes through itself a large quantity of air, can remove from itself a much greater amount of energy in the form of heat than can one that is sluggish in its air circulation.

Another idea that is generally prevalent is that the facts taken as the basis of standardization are established beyond dispute. In the case of electric machines, it is generally believed that the temperatures specified in the rules for different classes of insulation represent the dividing point between what is safe and what is dangerous, and that it is perfectly safe to operate below the specified temperature and unsafe to operate above it; whereas, as a matter of fact, there is no hard and fast division point and, consequently, it is often sensible to operate at temperatures quite a little below those allowable. It is the life of the machine, the freedom from renewal of parts and from repairs in general, that should be considered in connection with the original cost and the efficiency at which the machine operates.

As yet no accurate method of determining the real internal temperatures of insulated windings has been developed for the regular commercial operation of machines. These internal temperatures could be derived with a high degree of accuracy from measurements on the outside of the insulation and from laboratory determinations of temperature drop through insulations made up of various materials, were it not for the impossibility of determining the actual quantity of heat to be removed. It is quite generally known that in most electric conductors there are other losses than that represented by the flow of current against resistance. Most alternating-current generators, even of the largest size, can be designed with these parasitic losses so small in quantity as to make the internal temperatures so low that the deterioration of insulation will be slow. This fact has been demonstrated in many instances by high-voltage generators, having only varnished cloth insulation, operating from 15 to 20 years without a single breakdown.

EXCITERS AND EXCITATION SYSTEMS

At the annual convention of the American Institute of Electrical Engineers held at White Sulphur Springs, June 29th to July 2nd, a session under the auspices of the Power Stations Committee was devoted to papers on exciters and systems of excitation.

A complete analysis of the factors determining the selection and general design of exciter systems was presented by J. T. Barron and A. E. Bauhan, both of whom are connected with large operating companies. A shorter paper was presented by Messrs. Parker and Meyer, of the Detroit Edison Company, which discusses briefly the advantages and disadvantages of various excitation schemes and outlines the essential requirements from a broad point of view as power house designing engineers.

A paper by H. R. Summerhayes, of the Engineering Department of the General Electric Company, gives a broad discussion of the advantages and disadvantages of various types of exciters and of exciter drive, and refers to past practice and to the trend of present practice in the selection of exciters. Mr. Summerhayes' paper will be found in this issue.

Papers by Messrs. Cox and Michener, of the Southern California Edison Company, describe the excitation arrangement used in existing and proposed plants of that Company, and J. D. Ross, of Seattle, Wash., gave data on the exciter practice in a number of hydro-electric plants in the Northwest.

A paper by Messrs. Boddie and Moon, of the Westinghouse Company, calls attention to a number of characteristics of design of exciters to be used with automatic regulators, and characteristics affecting parallel operation; also the advantages of shunt exciters as compared to compound.

Thus, the field of exciter systems was covered by a number of papers from manufacturers, from operators, and from engineers having to do with the design of new stations. It was noticeable that all of the authors attempting classification of exciter systems divided them into two general classes, first, the common bus system with exciters operating in parallel, and second, separate exciters or individual exciters for each generator not operating in parallel. This division was independent of the method of drive. The general conclusion reached from the opinions expressed in the papers and brought out in the discussion was that for plants where the speed is not too low or too high to obtain a good design of exciter, the direct-connected individual exciter provides a most reliable form of excitation at the lowest cost. There are some engineers, however, especially those connected with large city central stations, who still prefer the common bus exciter system on account of the fact that a storage battery can be operated on this bus at all times, ready to take up the excitation load in case of exciter trouble. The general opinion, however, and the trend of present practice is toward the individual direct-connected exciter, which has the advantage that its circuit to the generator field is short and simple and not liable to trouble, that its method of drive is exceedingly reliable and efficient, and that trouble on the exciter affects only one generator. Proof of the reliability of direct-connected exciters for hydro-electric generators is given in the decision of the Southern California Edison Company, as described in the paper by Cox and Michener, to supply in their latest plant one direct-connected exciter without any operating alternate exciter, although a spare direct-connected exciter ready to be mounted will be kept in stock. The use of direct-connected individual exciters with large steam turbines was also favored by Messrs. Parker and Meyer on account of the reliability of such units, as proved in actual experience.

Mr. Summerhayes points out that in planning power stations, engineers sometimes call for direct-connected exciters on steam turbines large enough to excite more than one turbine. This practice is undesirable, since such a large exciter, if over-hung, may require a shaft extension so long, and the weight of the exciter may become so great, that it interferes with the operating balance of the main unit. The exciter drive should not be permitted to introduce any uncertainty into the operation of the main turbine unit and for this reason the size of exciters should be limited to those which may be safely overhung on the turbine shaft. When common bus excitation is used this bus should not be used for the supply of auxiliaries, or for working electrically-operated switches in a plant where continuity of service is essential, since troubles on the auxiliaries or on the bus may affect the excitation, and vice versa — because in case of short-circuit on the alternator high voltage may be induced in the field circuits which may affect the control circuits.

SPEED AND POWER-FACTOR CONTROL OF LARGE INDUCTION MOTORS

In the early days of electric power transmission the motor problem and the generator problem were the same, and the universal answer to both was the d-c. commutator machine, whose voltage control as generator and whose speed control as motor could be economically attained with a field rheostat. But the transmission problem demanding small currents and their accompanying high voltages, and the generation and utilization problem demanding low voltage, forced the development and almost universal use of the constant-voltage constant-frequency polyphase a-c. system. Then came the polyphase induction motor—rugged, simple, efficient, with high starting torque (especially when used with external resistance and wound rotor) and low starting current, well nigh perfect except for two characteristics, viz.: for its excitation the line has to furnish magnetizing current; and it has but one economical speed, and more serious still, one stable speed, synchronism, which it approximates either loaded or light.

These limitations have not overcome its advantages, and therefore the induction motor has had a marvelous growth in size and numbers. But the recent attention that has been given the indirect costs of poor power-factor has brought one of these disadvantages to the foreground, while the urgent need of varying the speed of many large induction motor units (especially in rolling mills) which are supplied with a-c. power has kept the problem of speed control of large induction motors in a prominent position pending a satisfactory solution.

For the solution of the latter numerous schemes have been advanced, but so far only two have assumed any real commercial importance, aside from the arrangements which may be classed as multi-speed motors where two or more motors of different speeds are combined in one mechanical structure. One of the schemes involves the conversion of the slip ring energy of the induction motor into mechanical power by means of a rotary and d-c. motor, and is somewhat loosely called the "Kraemer" system. The other involves the conversion of the slip ring energy into mechanical power by a polyphase a-c. commutator machine, and is commonly called the "Scherbius" system.

Thus, in order to regulate the speed economically, recourse is had again to the commutator. Why? In the synchronous machine, there is a relation of proportionality between speed and voltage; but speed and frequency are also in fixed proportion, so that to vary the speed by merely changing the field strength is not possible, and the attempt to do it results in magnetization or de-magnetization by wattless current from the line. In induction machines, the speed can be varied independently of primary voltage and frequency if voltages are introduced into the secondary at slip frequency. Secondary resistance drop can thus be used to reduce the speed, but this gives poor efficiency and unstable speed.

Only in commutator machines can be had frequencies capable of changing without a change in speed, and *vice versa*; and by placing the commutator machines in the secondary circuit of the induction motor to be regulated, the commutator machines can be made of reduced capacities, and if desired, can be removed from the main motor, as contrasted to placing the commutator on the main driving machine. This of course vastly simplifies the design problem, cheapens the drive, and increases its dependability. In the Kraemer system the rotary converter speed is of course determined by the slip frequency, but in this case the desired variation between slip frequency and speed is between slip frequency and the speed of the d-c. regulating motor. As so far developed commercially, the Kraemer or "rotary converter" system regulates the speed only below synchronism, so that the motor may be operated without the auxiliaries only at its top speed. This also characterizes the Scherbius system as built in Europe and as first built in the United States. John I. Hull, who is the author of an article on the subject in this issue, has however developed this system to a point where it is possible to regulate the induction motor above as well as below its synchronous speed, so that the normal speed of the motor lies in a much used part of the speed range, permitting the regulating set to be shut down and its wear and losses avoided during a great number of operations. Clearly this affords many operating advantages, while decreasing the size of the auxiliaries and increasing the overall efficiency.

Temperatures in Large Alternating-current Generators

By W. J. Foster

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When solving the temperature problems that arise in the design of large alternating-current generators, the first factor to be considered is the relationship between the space occupied by the object and the total heat losses to be dissipated. Other factors are those of the heat density and thermal conductivity of the various materials and the construction employed. In the following article, which was delivered as a paper at the annual Convention of the A. I. E. E. June 29–July 2, the author calls particular attention to certain advantages to be gained by reversing the present usual practice of ventilating large hydro-electric generators by taking in air directly from the generator room and piping it out of doors or to some point in the building remote from the generators.—Editor.

What shall be considered a large generator; 5000, 10,000, 15,000, or 20,000 kv-a.? Shall it be the rating alone that is considered, or shall we take such factors as speed into account?

Undoubtedly, a large proportion of the general public think of a large machine as one that occupies a large space compared with other machines used for the same purpose. They judge largeness by physical dimensions alone. At the same time, it is safe to say the more intelligent of the general public think of size in terms of the work that can be done. Probably a machine of 10,000 kw. or more is regarded by them as a large machine. To the engineer, largeness involves the difficulties inherent in design and construction. A 1000-kv-a., 10,000-cycle alternator is a large one; a 5000-kv-a. generator of 3600 r.p.m. is large. Considered strictly with reference to the temperature problem, the engineer would hardly consider a 20,000 kv-a. generator a large one if the periodicity and potential were those in regular commercial use and the speed were 100 r.p.m. or thereabouts. However, for the purpose of this article we will consider a 20,000-kv-a. machine as large.

There are two principal factors in the temperature problem in every case; first, the total losses or the amount of heat energy to to be disposed of and its concentration; and, second, the means that can be provided for dissipating the heat in such a manner as not to cause damage to any part of the machine. The problem may be attacked along the lines of reduction of losses or of devising such constructions that the heat may be more effectively dissipated.

In a rotating dynamo-electric machine three sources of heat are always involved; first, hysteretic losses in the magnetic material; second, the resistance to flow of current losses in the windings; and, third, the frictional losses in the bearings and the windage. The first two are electrical in their nature; the last is mechanical.

Combined with hysteresis losses in the magnetic material are more or less eddy current losses. The total losses in the magnetic material are dependent upon such factors as the degree of lamination employed, the character of the insulation between laminations, the amount of pressure employed in clamping the cores, as well as the character of the steel employed. In like manner, the resistance losses in the copper are frequently accompanied by eddy current losses, the amount of which is dependent upon such factors as the stranding of the conductor, the pitch of the winding, and the arrangement of the turns. The windage losses, or the losses that result from either the fan action of the rotating parts or from the disk action or rubbing of a revolving body on the surrounding air, are dependent upon the peripheral speed and the details of design of the parts that are producing fan action.

In considering the temperature problem, the first and most fundamental consideration is the relation of the space occupied by the object to the total heat losses to be dissipated. A 20,000-kv-a., 100-r.p.m. machine compared with one of the same output at 1800 r. p.m., has its losses generated in a space eight times as great in terms of cubical space occupied, or approximately two times in the projected area occupied. We may well think of the temperature problem in terms of heat losses to space occupied. Below a certain value of this constant it is absurd to use ventilation housings, no matter how great the rating of the machine, as such housings have the effect of preventing the natural means of heat dissipation; viz., convection and radiation, and ventilation housings in such cases result in higher temperatures, unless forced draft is provided, which results in a decrease in the efficiency of the unit and can be justified only on the score of reduction of noise or some similar reason.

Second in importance to the space factor comes the heat density factor. By this we mean the quantity of heat energy passing through a unit area of material.

The third factor is the thermal conductivity of the various materials; a factor which depends not only upon the thermal properties *per se* of the materials but also upon the manner in which the materials are put together.

Classification of Machines with Respect to Ventilation

Attempts have been made to standardize various classes of machines with respect to ventilation, but the writer thinks it safe to say that nothing yet has been suggested which appeals to engineers in general as entirely satisfactory. Possibly it is desirable to have a large number of classes of machines to fill in the gap between the extremes of the lowest speed small capacity machine that requires no special provision and may be said to depend upon *natural* ventilation alone, and the highest speed machine that requires the most careful artificial ventilation. It is difficult to classify the types that have already been developed to fill in this gap as they blend into one another.

The points to be kept in mind in the design and construction of machines in general, not particularly those standing at the extreme ends, are: first, the obtaining of a supply of cooling air from a region well removed from the space into which the outlet air is discharged; second, the placing of barriers or bafflers to assist the flow of air and to prevent re-circulation; third, the providing of ample cross section in all parts of the paths of flow of cooling air and the avoidance of sharp contrasts in the cross-sectional area of the paths, especially the avoidance at any point of greatly reduced cross-section that would introduce great resistance; and, fourth, the avoidance of "churning of air," or internal circulations, which are often hard to prevent by reason of the irregular shapes of the different parts of the machine.

Closed and Semi-closed Ventilated Machines

In almost all large generators, whether hydraulic or steam turbine, it is necessary either to pipe air to the machine or away from it, or both to and away from it. Probably the most common practice is to pipe air to the machines, allowing it to escape through the stator frame into the dynamo room, the escape often being arranged so as to be upwards, which is preferable on account of the greater comfort to the operators, the reduction in noise and the slight reduction in temperature obtained by the lower temperature of the air immediately around the machine.

The writer wishes to call attention to certain advantages that would result in reversing the common practice of the present time, in the ventilation of large generators in hydraulic units, and to take the air in directly from the room and pipe it away either to some point in the building removed from the machine or to out of doors. The advantages of this arrangement have already appealed strongly to the operators of some of the largest hydraulic generators, and such a system is now in use in a few plants. It is a much simpler matter to draw air into the rotor direct from the room at the two ends of the generator than to provide the necessary space for the air conduits and the housings required either at the one end or the two ends, which almost invariably involve greater distance between bearings and, consequently, an increase in both the diameter and length of the shaft and corresponding parts. A great advantage of the scheme of piping air away is the more comfortable temperature of the dynamo room in hot weather. It is never necessary to be in an atmosphere of higher temperature than that existing out of doors, whereas, in case of the more common practice, the air surrounding the machine has its temperature raised several degrees above that of out of doors, due to the heat that has been added to it when passing through the machine.

Water Cooling

Water is an ideal agent for cooling purposes. At first thought it seems strange that it has not been made greater use of in removing heat from large machines. A small quantity of water, on account of its high specific capacity, would suffice to remove heat from a large generator, but the difficulty is in arranging jackets that will prove safe and can be located in close enough proximity to the parts in which the losses are generated to remove such losses without a considerable drop in temperature through the intervening walls of material. It is apparent at once that water-cooling is much better adapted to the stationary than to the revolving parts. While it is possible to arrange for a flow of water through the revolving parts, it is probably not possible to so arrange the flow of water as to cool the surfaces where most of the heat is generated. Hence, a system of water-cooling would be dependent upon the joint action of air-cooling and would require a design that would re-circulate the air surrounding the rotor in such manner as to most effectively carry the heat from the surfaces of the rotor to the surfaces of the water piping in the stator. Another objection is the danger of injuring a machine in case the water circulating system becomes leaky. Still another is the danger of too great an accumulation of dampness due to condensation, at certain times, of the moisture in the air on the water-cooled parts. It is doubtful whether water-cooling can ever be a competitor of air-cooling in dynamo electric machines.

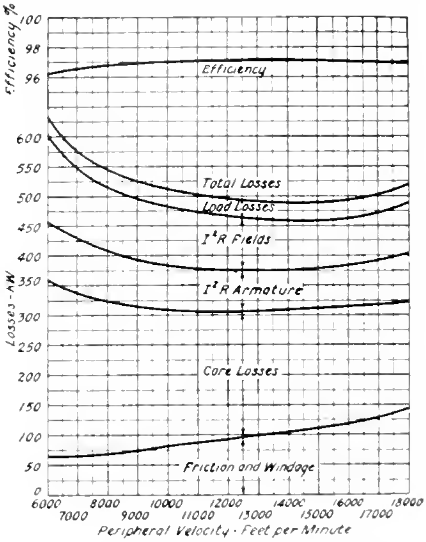

Fig. 1. Losses and Efficiencies as Affected by Choice of Diameter for a 20,000-kv-a., 11,000-volt, Three-phase, 360-r.p.m., 60-cycle, 0.8-power-factor, Two-bearing Generator

Peripheral Speed of Rotor

It is possible that the electrical advantage of higher peripheral speed in almost all designs of large generators is not fully appreciated by many designers themselves. The losses in both the iron and the copper are almost universally less at the higher peripheral speed in any practical problem. Assuming the same characteristics electrically in all respects, such as saturation curve, armature reaction per unit pitch, etc., the losses in the armature teeth are less at the higher peripheral speed. They are exactly inversely as the peripheral speed, while the core losses proper remain practically constant. Copper losses in both armature and field are less at the higher peripheral speed, unless the speed is carried to an absurd limit. The windage losses will be increased. Hence, considered electrically, the most efficient design will be that where the windage losses begin to increase so rapidly as to offset the combined reduced losses of core and windings. For the purpose of illustration, the curves in Fig. 1 have been worked out for a 20,000-kv-a., 60-cycle, 360-r.p.m., 3-phase, 11,000-volt generator at peripheral speeds varying from 6000 to 18,000 feet per minute.

The variation in the segregated losses, as affected by different rotative speeds, is illustrated by the curves added in Fig. 2 which show such losses for 20,000-kv-a. generators throughout the range 100 to 600 r.p.m. It should be understood that these generators are designed with identical electrical characteristics and have the same temperature rises; viz., those corresponding to the A.I.E.E. Standard for Class "A" insulation. They are what the writer considers normal in design for the output at the several speeds.

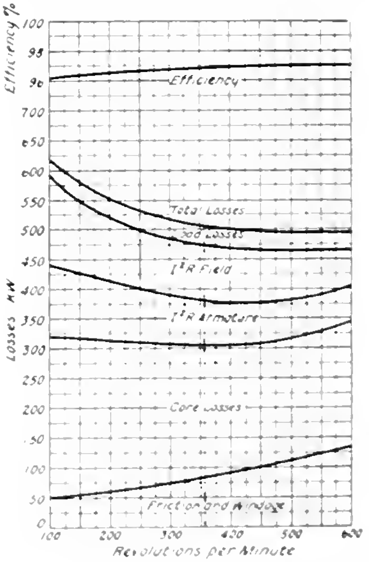

Fig 2 Losses and Efficiencies as Related to Rotative Speed of a 20,000-kv-a., 10,000-volt, Three-phase, 60-cycle, 0.8 power factor Generator for Speeds from 100 to 600 r.p.m.

The 100-r.p.m. generator has a peripheral velocity of about 7500 ft. per min.; the 600-r.p.m., 15,000 ft. per min. The first has its losses generated in a space of approximately 2200 cubic feet, the last in approximately 550 cubic feet. The total losses of the first are 620 kw., or 270 watts per cubic foot of space occupied; of the last, 495 kw., or 900 watts per cubic foot of space occupied. Hence, the ventilation problem is quite different in the two cases. The first might be of the open type, drawing its ventilating air from the room and returning it directly to the room; the last must be enclosed, preferably totally enclosed.

Ventilation Ducts in Armature Cores

The common practice for ventilating armatures is to provide at short intervals in the laminated core, a narrow passage, usually $^{3}/_{8}$ in. or ½ in., for the air to be driven through radially by the fan action of the rotor, or in special cases by an external fan. The flow of air is in any special case dependent upon the details of construction, such as the character of the space blocks, how these are located with respect to the coils in the slot; the niceties introduced at the entrance from the airgap in the way of treatment of the retaining wedges of the windings, the exact location of the end of the spacers, etc.

Good results are usually obtained by having a ventilating duct about every two inches, the most efficient spacing being dependent upon such factors as the radial depth of the core, the length of the core, and the pressure of the cooling air. In long cores the spacing may be graded and the sections of core at the middle made smaller than at the ends. There are two reasons for this arrangement; first, some of the heat at the ends travels to the head of the core where the cooling conditions are usually good and, second, the ventilating air gathers up heat as it passes in from the head towards the middle and hence is not as good a cooling medium when it enters the ventilation duct as the air in the ducts nearer the head. When fans are mounted at the two heads of the rotor and end housings are placed on the stater so as to establish a good air pressure, the pressure in the ventilating ducts increases from the head to the middle. Hence, the quantity of air passing through is greatest in the duct at the middle, decreasing toward the heads. The curve in Fig. 3, entitled "Velocity of air at entrance to air duct," was plotted from air pressure readings made on a large turbo-generator with equally spaced ventilating ducts. The other curves were determined from a consideration of the heat dissipation problem. In like manner, Fig. 4 shows curves for a later turbo-generator with stator core sectionalized in such a manner as to equalize the temperatures throughout the length of the core.

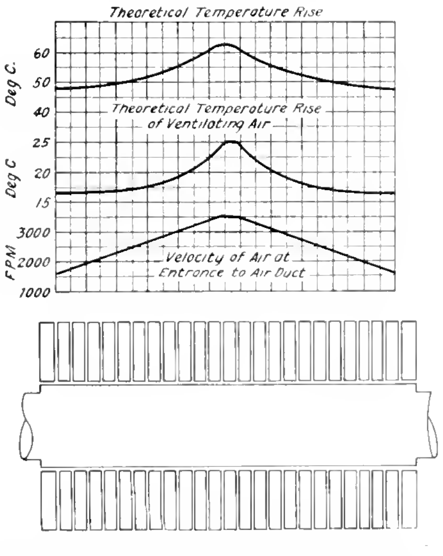

Fig. 3. Ventilation of Stator Core Having Ducts Equally Spaced and the Air Admitted at the Two Ends of the Air Gap

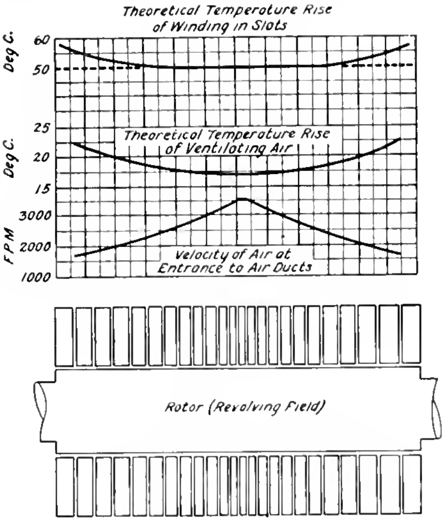

Fig. 4. Ventilation of Stator Core Having Ducts Unequally Spaced and the Air Admitted at the Two Ends of the Air Gap

Giving Direction to Cooling Air

It is quite wonderful what improvements are sometimes accomplished in cooling machines by very simple expedients. Sometimes it is advisable to arrange a machine so that it is obliged to take all of the cooling air in at one end and to discharge it at the other. This, as a rule, is especially helpful to the rotor.

But, in general, machines arranged with a radial system of air ducts through the core should draw the air in equally from both ends. Often a machine that seems at a casual glance to be symmetrical as to the two ends proves to be a surprise in taking practically all its air from one end. In such case, little, if any, air passes outward through the radial air vents; in fact, sometimes the air will pass inwards in some of the vents. The remedy is usually very simple; any little barrier interposed in the path of the axial flow will restore the desired circulation and often reduce the temperature several degrees.

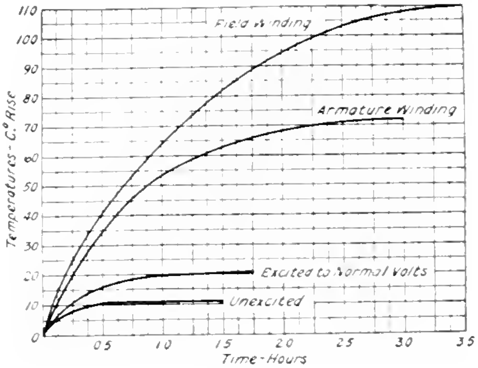

Fig. 5. Time Required to Reach Constant Temperature in an 18,750-kv-a., 11,000-volt, Three-phase, 60-cycle, Cylindrical-rotor Generator Operating at Overload as a Synchronous Condenser

The poles themselves act as fan blades on the rotors of many salient pole generators, and no fans or fins for additional fan effect are required. It may not be generally known that even in cases where carefully designed fans similar to those used in large cylindrical rotor turbo-generators are employed, the poles themselves contribute more to the blower action than the fans. The problem of ventilation in salient pole machines is more complicated than in cylindrical rotor machines, where the blower action is more largely due to fans designed for the purpose.

Heat Flow

The most efficient ventilation of a large electric generator requires circulation of the cooling air in such manner as to bring it in contact with large surfaces of the solid materials in which heat is being generated and close to the sources of the heat generation.

The heat resistance of the various materials entering into the construction, such as copper, magnetic steels, and various insulating materials, is quite well known.

An analysis of heat flow in a 30,000-kv-a. generator from the inside of an armature coil at the middle point of the core to the ambient cooling air is as given in Table I for the following four designs:

(a) 4000-volt mica-insulated coils to withstand A.I.E.E. high-potential tests.

(b) 11,000-volt mica-insulated coils to withstand A.I.E.E. high-potential tests.

(c) 11,000-volt mica-insulated coils with copper density same as in 4000-volt design.

(d) 11,000-volt mica-insulated coils to withstand high-potential test of three times normal, instead of two times plus 1000 volts (A.I.E.E. Standard), with coils of same external dimensions as those of (b), so as to be assembled in the same slots.

TABLE I

TEMPERATURE DROP IN DEGREES C.

Coil Design	(a	(b)	(c)	(d)
Drop through insulation	21	30	48	67
Drop through core	6	4	6	5
Drop at surface	16	11	16	14
Drop in cooling air	15	15	15	15
Total drop	58	60	85	101

Heat Storage

Heat storage must be reckoned with when ratings for intermittent loads are to be given to a generator; but for continuous load service, as in nearly all large commercial generators, the heat capacity properties are chiefly of scientific interest, except when the duration of heat runs in acceptance tests is under consideration. Fig. 5 shows curves of time required to reach constant temperature, in the case of an 18,750-kv-a. turbo-generator at overload corresponding to about 20,000 kv-a., which may be taken as typical of the modern large cylindrical rotor generator. This set of curves represents three runs under widely different conditions. The curves, "Field winding" and Armature winding," were determined in the same run. The curve, "Unexcited" shows the rate of temperature rise when the heat is generated by windage alone, as measured by detectors embedded in the armature slots. The curve, "Excited to normal volts," shows the rate of rise measured in the same manner, when the heat is that of core losses on open circuit in addition to the windage. Fig. 6 gives curves of temperature rise in a single run on a salient pole generator. Comparing the two sets of curves, it is interesting to note the quicker rise in the field winding of the salient pole machine, where nearly all the heat passes directly into the cooling air from the surface of the bare copper, over that of the cylindrical rotor machine where the field winding of each pole consists of several coils embedded in slots in the magnetic material.

High vs. Low Temperature Generators

Undoubtedly any machine, electric generator or strictly mechanical machine, such as the steam turbine, would be better off if it could always maintain the same temperature in all its parts. A rise of temperature beyond certain limits, repeated often enough, results in deterioration in most electric generators. This is due primarily to an effect of heat that is mechanical in its nature; viz., a change in size. Much can be done to minimize the deleterious effects of change in size of the various parts by introducing constructions in detail parts that automatically adjust for changing size. But it is extremely difficult in certain parts to protect materials of quite frail mechanical nature, like many insulations, from the effects of change in compression or what is more serious, slight movements of different degree in different places. Looked at in this way, it is desirable to have a generator of low temperature rise. But it is not always convenient or possible to build low temperature generators if machines are to be produced equal in capacity to prime movers. Furthermore, high temperature machines are justified in cases where increased efficiency or lower cost will more than offset the shorter life.

With reference to relative efficiency and cost, it is quite apparent that the high temperature machine has the advantage in the case of a generator whose insulations are suitable for the higher temperature, and whose efficiency is still rising with increase of load, as in most alternating-current generators, and whose cost is only slightly increased by enlarging the shaft and other mechanical parts involved.

It may be laid down, as a rule, that the high temperature machine costs less, but it must not be taken for granted that its efficiency is better. In fact, most of the lower speed machines of low temperature rise have better efficiency than corresponding machines of high temperature, unless the designer has been grossly careless in taking care of the ventilation of the former.

It is possible to design most machines for low temperature rise without great additional cost, and to have decidedly better efficiency. This condition obtains especially in connection with large salient pole generators of low speed and low or medium potentials. As a rule, machines of this class, designed for 50 deg. C. rise, permit of decided increases in the amount of copper in both armature and field without any change except slightly larger slots in the armature. In addition, a higher grade of magnetic steel may be used than that called for by temperature considerations. Often one per cent in efficiency at full load may be gained at an increase in cost of 10 to 15 per cent. In other cases as much as $\frac{1}{2}$ per cent efficiency can be gained. The resulting generators may have only 35 or 40 deg. C. rise at rated load.

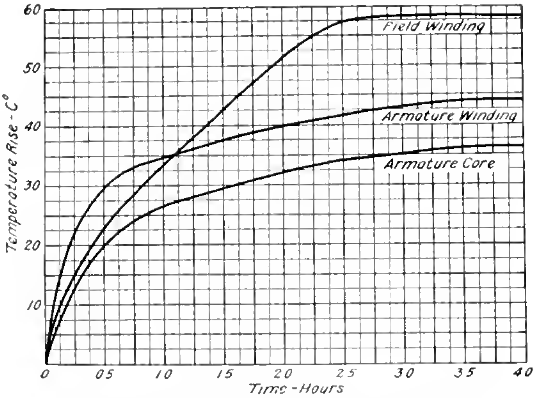

Fig. 6. Time Required to Reach Constant Temperature in a 12,500-kv-a, 22,000-volt, 50-cycle Synchronous Condenser Having a Salient Pole Rotor

Possibly the author is on dangerous ground in discussing the advantages of generators that do not conform to the Standardization Rules of the A.I.E.E. However, it is not for a moment his intention to reflect in the slightest on the standards that have been set, but he wishes to point out gains to the user to be had by following along more conservative lines in certain cases. Again, he realizes the possibility of trouble to himself and his ilk from urgent requests that may be in store from buyers of generators, when generators are under consideration that cannot economically be built for temperatures below the Standards of the A.I.E.E. in the high and low temperature classes. It is well to add that designing certain sizes for low temperatures, where only slight gain or no gain whatever in efficiency results, often involves hardship and results in certain risks being taken that are wholly unjustified.

Exciters and Systems of Excitation

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The continuity of service rendered by a generating station is directly affected by the reliability of its excitation system. Therefore, in the selection of a system, first cost and economy of operation are of lesser importance. In the following article, which was read as a paper at the annual convention of the A.I.E.E. June 29 to July 2, systems of excitation are grouped and discussed as common excitation plants and as individual exciters. In addition to a comparison of these two systems and a comparison of shunt, compound, and commutating-pole exciters, there is included a discussion of such related factors as: method of exciter drive, voltage, rheostats, field switches, batteries, voltage regulators, and station auxiliaries.—**Editor.**

In laying out the excitation system for the generators of a central power station the primary requirement is reliability; that is, continuity of service. First cost and economy in operation are secondary, but, nevertheless, must be given consideration.

To meet the first requirement:

(1) The exciters should be machines of good design and liberal size.
(2) The method of drive should be reliable.
(3) All electrical connections and wiring should be as short and simple as possible, and located and supported so as to be safe from external injury.
(4) The method of control should be simple and reliable, and the operation convenient.
(5) Reserve capacity should be supplied and reserve driving source.

The systems of excitation which have been used or proposed may be divided into two general classes:

(1) Common excitation plant (exciters operating in parallel on a bus supplying excitation to all generators).
(2) Individual exciters (not operating in parallel).

The first system was for many years the standard American practice for both steam and hydro-electric plants, excepting in some small plants where belted individual exciters were commonly used.

European practice, on the other hand, has shown a preference for individual exciters, and in recent years American practice has tended toward their use, for reasons which will be discussed

One reason for the American preference for a common excitation plant may have been the use of large alternators driven by low-speed Corliss engines, on which it was relatively expensive, in cost and floor space, to arrange for direct-connected exciters.

At the same period, European plants were installing high-speed vertical engines, for which the exciters on account of the high speed were of small dimensions and weight and could readily be overhung on extended shafts.

When steam turbines came into general use, manufacturers were somewhat unwilling to lengthen their shafts and to complicate their problems of balance, expansion, etc., for the purpose of adding direct-connected exciters, and for vertical shaft turbines there was the further objection that the exciter would be in an inaccessible location. There was also the conservatism of power plant engineers and the general appreciation of the reliability of excitation afforded by having a battery floating on the common excitation bus.

It is interesting to note, however, that of the steam turbines, 7500 kv-a. and over, sold by one manufacturer during the last five years, about 45 per cent were equipped with direct-connected exciters; and of the generators, 1000 kv-a., and over for waterwheel drive, made by the same manufacturer, 75 per cent had direct-connected exciters.

Some of the hydro-electric generators of low speed and large size without direct-connected exciters were equipped with individual exciters driven by motors.

COMPARISON OF VARIOUS PLANS OF EXCITATION

Common Excitation Plants

Common excitation plants in which the exciters are operated in parallel on a common bus have the advantage, as compared with individual exciters, that the bus voltage is kept constant so that a storage battery may be kept floating on the bus at all times ready to take up the excitation load in case of exciter trouble; also that the constant voltage exciter bus offers a source for the supply of lighting, auxiliaries, and sometimes the control of electrically operated switches. If automatic voltage regulators are used directly on the exciters this constant voltage is no longer maintained and this advantage disappears unless a regulator is used on a booster between

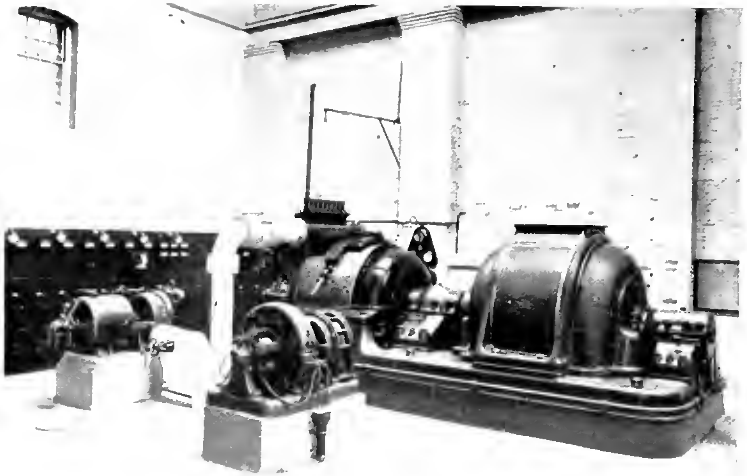

Fig. 1 Motor-driven and Turbine-driven Exciter Sets, together with a 3000-kw. Curtis Steam Turbine Generator

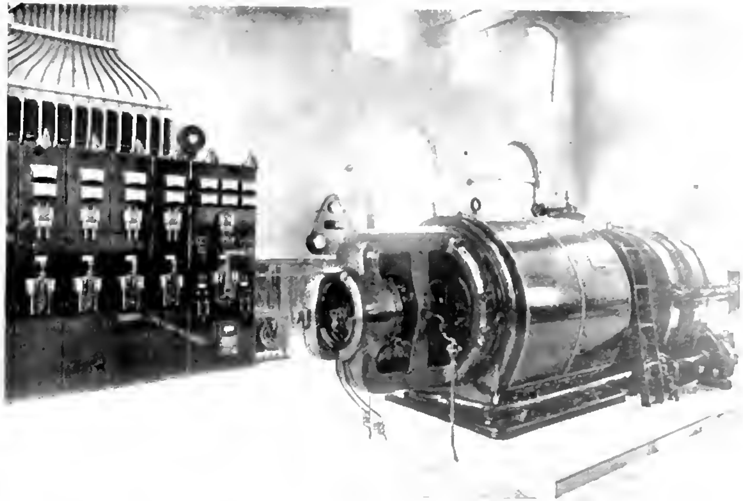

Fig 2. Exciter Direct-connected to a 1250-kw., 3600-r p.m., 2300-volt Curtis Steam Turbine Generator

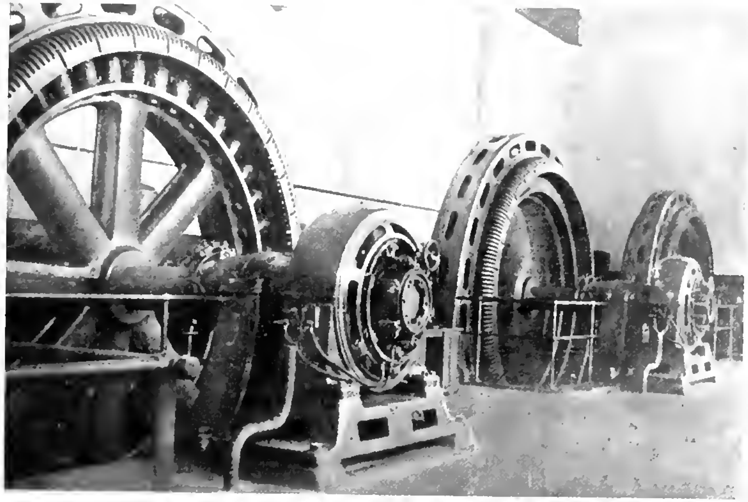

Fig. 3. Exciters Direct-connected to 3333-kv-a., 150-r p.m , 2500-volt Waterwheel-driven Generators

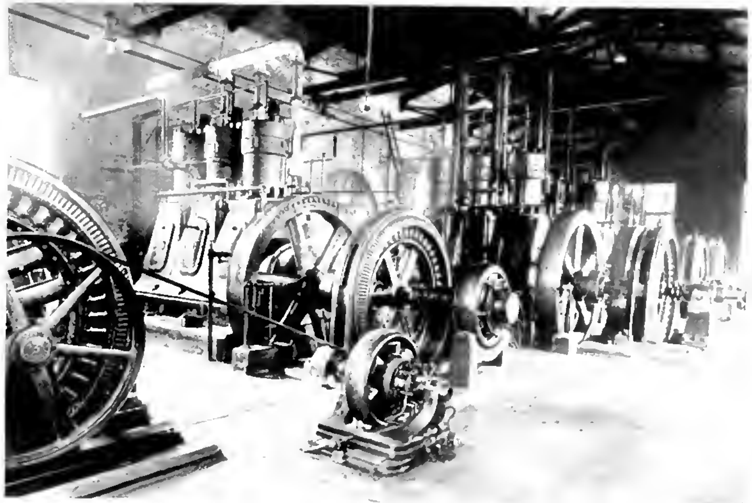

Fig. 4. Belt-driven and Direct-connected Individual Exciters

the constant-voltage exciter bus and a varying voltage bus to which the generator fields are connected. These common excitation plants have the disadvantage that any trouble on the main exciter bus may cause a shut down on the entire generating station.

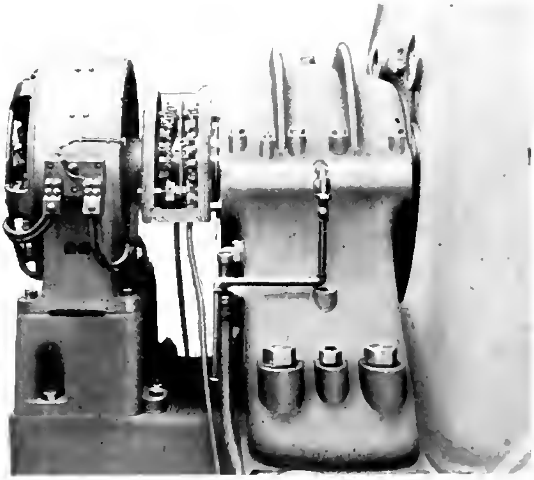

Fig. 5 Direct-connected Exciter Mounted at the Generator Bearing and Collector End of Shaft

Individual Exciters

In the case of individual exciters, where one exciter is supplied for each machine and the exciters are not normally operated in parallel, trouble on one exciter circuit will affect only one generator. The exciter circuits are short and simple and are not liable to trouble.

Methods of Driving Exciters

Whether the common excitation plant or individual exciters are used, the method of drive is important.

For individual exciters usually only two methods of drive are used, namely, exciters directly connected to the generator shafts and exciters driven by motors.

In the latter case the motors may be connected to the main bus or preferably they should be connected to an auxiliary bus supplied by an alternating-current generator driven by a prime mover. Transformers are also furnished, so that the motors may be supplied from the main bus in emergency. This method of driving individual exciters is used chiefly for large hydro-electric plants where, on account of the low speed of the vertical shaft generators, direct-connected exciters become too expensive.

For individual exciters it may be said that those which are direct connected are preferable on account of cost, reliability of drive, and shortness and simplicity of wiring.

Direct-connected exciters large enough to excite two units are sometimes specified. For steam turbines, such large exciters may be undesirable on account of their weight and size being too great to overhang on the extended shaft. The exciter drive should not be allowed to jeopardize the continuity of operation of the main turbo-generator. For turbines up to 1800 r.p.m. direct-connected exciters are reliable machines and have given good service records. For turbines of 3600 r.p.m. direct-connected exciters are often used, but in order to obtain the best results as to commutation, and to make such machines as reliable as those of lower speed, great care must be exercised in manufacture.

Exciter Drive in Common Excitation Plants

In the case of common excitation plants a number of arrangements for driving the exciters are in use. The most reliable and efficient arrangement is the direct-connected exciter, unless there are reasons, such as too high speed or too low speed, against using it. Belted units are widely used in small plants where the engine speeds are low and the use of a belt involves very little risk or trouble. On account of the low engine speed a considerable saving of cost and space is made by using belted instead of direct-connected exciters. Geared exciters have been proposed for large, low-head, hydro-electric plants.

The plan generally adopted for a common excitation plant is to have some of the exciters motor-driven through transformers from the main alternating-current bus and some of them driven by separate prime movers.

Another plan which has been used in connection with some large steam plants is to have the exciters motor-driven from an auxiliary alternating-current bus supplied by auxiliary generator units designated as "house turbines." Transformers connecting the auxiliary bus to the main bus are supplied for emergency use or for adjusting the power on the auxiliary bus for heat balance purposes. This auxiliary bus is used also for the supply of auxiliary power for the whole station, such as circulating water, air and hot-well pumps, stoker motors, economizer and draft fans, coal crushers and conveyors, etc. In very large stations an auxiliary bus and its generating unit may be supplied in connection with each main generating unit on the system.

An arrangement commonly used in hydro-electric plants and used occasionally in steam plants is to have each exciter connected to a prime mover and to an alternating-current motor supplied from the main bus, so that the exciter may be driven by either or both.

This arrangement has been used in steam plants of moderate size and in hydro-electric plants for the following reasons:

The reason which applies to both cases, is to have two separate sources of power for the exciter drive. In hydro-electric plants for high head where the exciter waterwheel nozzles on account of their small size are likely to become blocked, it has been for many years the practice to have an induction motor connected to the bus mounted on the same shaft as the exciter and the waterwheel, so that when the waterwheel fails to carry the load the induction motor will take it up. In steam plants the chief reason for using this arrangement is to provide means of adjusting the amount of exhaust steam available to heat feed water, which is done by adjusting the governor of the exciter unit to take more or less power, the remainder being supplied from the motor.

This arrangement in steam plants has the disadvantage that to obtain an efficient turbine the speed must be high, possibly too high for the proper design of the direct-current generator, or of the motor, necessitating sometimes a geared connection which of course is disadvantageous for a high-speed continuous running unit.

The plan of using direct-connected exciters on the main generator shaft, exciters not operating in parallel, the voltage of each generator controlled by the exciter field, appears to be the most reliable and simple method of excitation for large plants wherever the speed requirements are not prohibitive.

For all large stations using individual exciters, it is desirable to have an emergency excitation bus with a reserve exciter driven by a separate steam turbine, waterwheel, or motor, so that any generator field may be thrown on this bus in case of trouble with one of the individual exciters. The question as to whether a storage battery is necessary will depend on the number of units in the plant and on the importance of the service.

VOLTAGE OF EXCITER PLANT

For many years the standard excitation potential has been 125 volts and this pressure is still standard for small and medium size plants. In recent years 250 volts has been coming into use and has now become standard for large plants for the following reasons:

The difficulty and expense of building high-speed commutators for 125 volts, especially turbine-driven exciters, or waterwheel exciters which stand double speed. The space occupied by the commutator is reduced at 250 volts. The expense of busbars, machine leads, circuit breakers, etc., to carry the large currents necessary at 125 volts, especially in large stations where the field currents are heavy and in long stations where the distances are great.

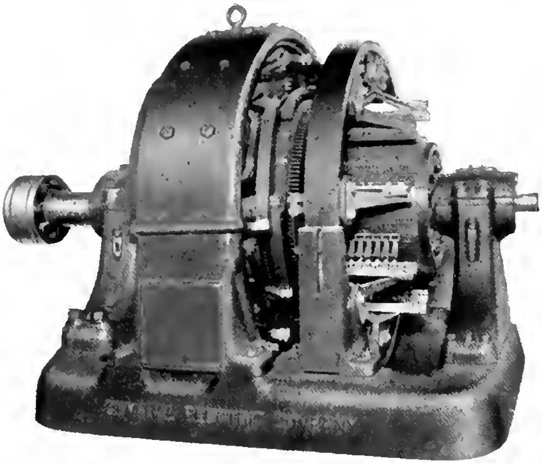

Fig. 6. Waterwheel-driven Exciter of 600-kw. Capacity 600-r.p.m. and 220-volts

EXCITATION REQUIREMENTS OF ALTERNATORS

Voltage Range

In steam turbine generators the armature reaction may be about equal to the no-load ampere-turns. This means that with 100 amp. field current required to give full voltage at no load, 200 amperes would be required to maintain full voltage at full load at the rated power-factor. Since the alternator fields must be designed to take not over 125 volts at rated power-factor full load and maximum temperature, and because a margin must be allowed in the design for variation in the material, etc., the actual machines may meet their requirements at 90 to 115 volts across the field, and this means that at no-load full alternating-current voltage the exciter pressure may go as low as 40 or 50 volts, or about 30 or 40 per cent of the rated voltage. The exciters and their rheostats and regulators must be designed for this range of voltage.

For synchronous condensers the range of exciter volts is down to 10 per cent or less of full pressure, and for synchronous motors the range depends on the range of power-factor for which they are designed.

Kilowatts Required

The excitation requirements of alternators vary according to the design, but for modern standard lines may be summarized as follows in per cent of the kilovolt-amperes alternator rating:

	Per Cent
Steam Turbo-generators	
1000 to 5000 kv-a.	0.5 to 0.3
7500 to 35,000 kv-a.	0.4 to 0.3
Waterwheel-driven Generators	
1000 to 5000 kw. low speed	1.5 to 0.8
1000 to 5000 kw. high speed	1 to 0.5
7500 to 20,000 kv-a. low speed	0.7 to 0.5
7500 to 20,000 kv-a. high speed	0.5 to 0.4
Motor Generators	
1000 to 5000 kv-a.	1 to 0.5

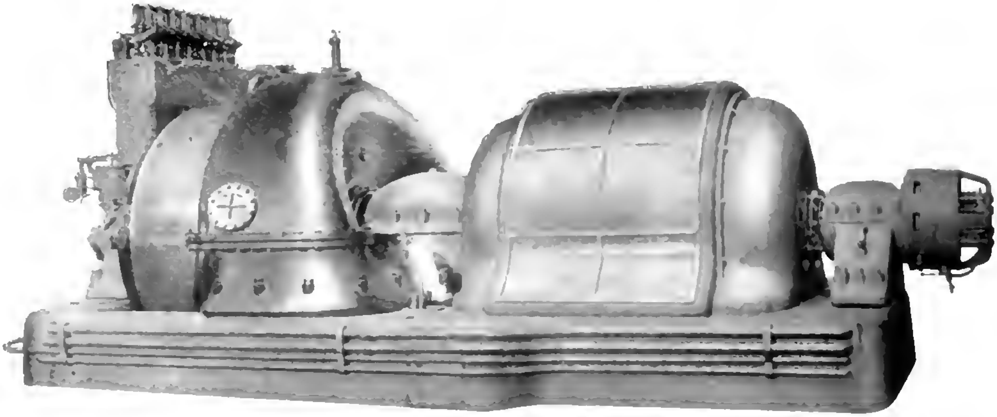

Fig. 7. Exciter Direct-connected to a 7500 kw., 1800-r.p.m., Curtis Steam Turbine Generator Set

RHEOSTATS FOR EXCITERS

For small exciters hand-operated rheostats mounted on the back of the switchboard, or operated by chain drive from a handwheel on the switchboard, are generally used.

For large plants the alternator field and the exciter field rheostats are nearly always electrically operated and this method of operation is recommended for any plant where an electric control circuit for operating rheostats is available and where the main control board is on another floor or distant from the machines. For all such plants convenience of operation, location and wiring, as well as cost considerations, will usually give electrically operated rheostats the preference.

For operation with automatic voltage regulators the exciter field rheostat is generally made three to four times the ohmic resistance of the exciter shunt field winding, or from two to two and one half times the resistance furnished with ordinary direct-current generators not used for exciter purposes.

For a common excitation plant with hand voltage regulation, where the alternating-current voltage is controlled by the alternator field rheostats, the exciter rheostats may be of ordinary design with resistance points closely graduated from 85 to 100 per cent of full exciter voltage and further apart for lower voltage ranges.

For individual exciters, non-automatic voltage control, where no generator field rheostats are used, the exciter rheostats should have closely graduated resistance steps all the way down to 30 per cent of the voltage and may have as many as 100 to 150 steps. When this method of regulation is used, the alternator field rheostats may be dispensed with, but it is considered better practice to install them for emergency use in case some other source of excitation is resorted to; and it will usually be found that more stable operation at the lower ranges may be obtained by the use of these field rheostats to a certain extent to enable the exciters to work at somewhat higher voltage. If the alternator rheostats are used there is a slight sacrifice of efficiency.

CIRCUIT BREAKERS AND FIELD SWITCHES

As a general principle no automatic overload circuit-breaker or fuse should be installed in exciter circuits. When the alternator is short-circuited the alternator field current may rise to several times normal in the normal direction and an automatic circuit-breaker under such conditions might interrupt the exciter circuit, which must not be allowed. Short circuits in the generator field circuits.

or on the exciter busbars, are an infrequent occurrence and should be taken care of by the operator. It is considered better to risk injury to the exciter than to install overload devices which may operate at the wrong time.

With exciters operating in parallel it is desirable to have circuit-breakers between the exciters and the direct-current busses operated by reverse current in case of trouble in an exciter or its prime mover.

Alternator field switches should be equipped with discharge resistances. Field switches and exciter switches should be electrically operated in all large plants and in other plants when dictated by convenience of operation, location, and wiring. It is desirable, of course, to keep the field switches as near to the alternators and the exciter switches as near to the exciters as possible, and to locate the exciter as near to the generator as possible in order to keep the exciter circuits short, since the shorter they are the less the chance of trouble and the better the economy. Hence, hand-operated field and exciter switches may be used even in large plants if operated by the floor men, but it is generally desired to operate them from the central switchboard.

Field switches should never open on overload, but may be made to open automatically when the main alternating-current circuit breaker opens by the action of reverse power or differential relays in the main alternator leads.

When individual exciters are installed, automatic throw-over switches may be used to throw the alternator field over to a reserve exciter bus in case of failure of the individual exciter.

EXCITER BATTERIES

In most large steam stations, and in some large hydro-electric stations, a storage battery is provided capable of carrying the excitation requirements of the station for thirty minutes to an hour. This battery may be used as follows:

(1) Floating on the constant-voltage exciter bus.

(2) In reserve on the emergency bus.

(3) Battery separated into halves, each floating through a high resistance on the variable voltage exciter bus with automatic switches to cut out resistance and throw the two halves of the battery in series when required for excitation.

Charging a battery may be provided for by an exciter set designed for high voltage, by a special booster or a charging set, or by separating the battery in two halves and charging through resistance from the exciter bus.

In many stations the exciter bus is used to supply current for the control bus for the working of motor and solenoid operated circuit-breaker switches, field rheostats, indicating lamps, etc. It is now considered better practice to provide a separate control bus, for the reason that during short circuits on the main generators transient high pressure of the order of several hundred volts may exist in the generator field circuits and alternating currents of normal or double frequency are superimposed on the field currents.

It is difficult to insulate the multiplicity of switches, lamp sockets, wiring, etc., in the control circuit for such high voltages, owing to the limited space requirements for control boards. For these reasons, in large stations a separate control bus with a small battery and motor-generator charging set is generally installed.

SHUNT *VERSUS* COMPOUND-WOUND EXCITERS

The relative advantages and disadvantages of shunt and compound-wound exciters have been frequently discussed; and the selection

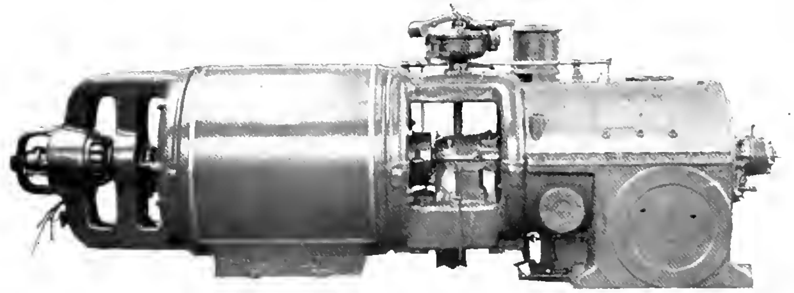

Fig. 8. Exciter Direct-connected to a 300-kw., 3600-r.p.m., 2300-volt Curtis Steam Turbine Generator Set

has sometimes been dictated by the type of excitation plant used; sometimes by individual preference of engineers.

The matter may be summarized under the following headings:

"A": *Small belted exciters operating in parallel; no battery*

Compound-wound machines are generally used to keep the exciter bus voltage constant with variation in excitation load due to either variation in the alternating-current load or to a change in the number of alternators in service. With shunt exciters such variations would require adjustment of exciter field rheostats as well as generator field rheostats; and consequently the compound machines are usually preferred for convenience in operation.

If voltage regulators are used either shunt or compound exciters can be handled equally well. For this class of exciters standard belted generators are used, which are manufactured and stocked in large numbers compound wound, so that reducing the varieties stocked is another reason for the choice of compound winding.

"B": *Motor, engine, or waterwheel-driven exciters operating in parallel; no battery*

The compound winding is preferred for same reason as stated under "A."

"C": *Exciters direct connected to the main generating units; operating in parallel; no battery*

The compound winding is preferred for above reasons, but stock requirements do not apply excepting in small units.

"D": *Exciters operating in parallel, with storage battery floating on the exciter bus*

In this case either compound or shunt windings may be used.

The compound has the advantage of keeping the bus voltage constant with a change in the excitation load, and the disadvantage of possible reversal and motoring of an exciter in case of failure of its source of power. This contingency may be provided against by reverse-current relays, so far as motoring is concerned, but this may not prevent reversal of the polarity of the exciter due to the sudden reversal of the current in the series field.

Shunt exciters are safer, when in parallel with a floating battery, as regards possible overspeeding due to motoring in case of failure of reverse-current relays. They are certainly less liable to be reversed in polarity when an exciter slows down due to trouble with its drive. They require more frequent adjustment of the exciter field rheostats, but have the advantage of omitting the equalizer bus with its extra switches and connections. Commutating pole shunt-wound exciters should be adjusted to have a drooping characteristic at all operating voltages, not only for proper parallel operation, but in order to reduce the liability of reversal.

Individual Exciters

The shunt winding appears preferable for individual exciters, whether the alternating-current voltage regulation is accomplished by the alternator field rheostat or the exciter field rheostat. In the former case there is no reason for compound winding unless for manufacturing or stock convenience in the smaller sizes. In the latter case, when the exciter has to operate down to a low voltage the shunt winding has more stability, particularly in exciters of the commutating pole type. The shunt exciter is also less susceptible to reversal by discharge from the alternator field, or by residual magnetic effect from the alternator field.

REVERSAL

The reversal of polarity of an exciter, due to failure of driving power, has been discussed in the foregoing. It appears likely that in case of compound-wound exciters the chances of reversal due to this cause may be reduced by exciting the shunt field from the busbars instead of across the exciter brushes.

The reversal of an exciter has been occasionally observed at the time of shutting down an alternator. The possibility of reversal at this time is apparent only on an individual exciter direct connected or otherwise driven from a main generating unit. In one case a steam turbine unit with individual direct-connected exciter was taken out of service, the field being left closed to bring the machine to rest quickly, and the field opened after the machine had reached a standstill. It appears probable that residual magnetism in the generator field structure would persist to a lower point of speed than that in the magnetic circuit of the exciter. The flux would be varied in passing the armature slots, causing weak alternating currents to flow in the field circuit, which may account for the reversal of the exciter.

Assuming that the field current does alternate or reverse, it is apparent that a series field on the exciter would be effective in reversing the residual magnetism of the exciter.

In the case of a commutating-pole exciter, the position of the brushes would determine the influence of the commutating field on reversal.

EXCITERS USED WITH REGULATORS

When a vibrating-contact regulator is used to control the alternating-current pressure through the exciter field there appears to be little choice whether the exciter shall be shunt or compound wound, so far as the action of the regulator is concerned. For shunt-wound machines, the field current handled by the regulator is greater. For compound-wound machines, the field current is less, but a greater range of voltage must be applied to obtain the same speed of regulation.

The shunt across the series field makes the latter a damper winding, which impedes sudden flux changes, but this is partially neutralized by the action of the series field with changes in current.

For sensitive regulation the shunt machine is undoubtedly better, since the entire field is controlled by the regulator, and on account of the absence of the damper formed by the series winding. For most plants the compound exciter is satisfactory with a regulator, since its period is usually faster than that of the alternator field.

COMMUTATING-POLE EXCITERS

Some years ago, during the first period of experience with commutating-pole exciters, some troubles were encountered in operating them in parallel. These were due to incorrect design or to incorrect adjustment of the commutating field strength or to the position of the brushes.

Shunt generators to operate in parallel with proper division of load must have a drooping characteristic, and compound machines to operate in parallel must have a drooping characteristic without the series winding. Machines having a rising voltage characteristic without the series winding in operation will be liable to give trouble in parallel operation, either as shunt or compound generators, unless the regulation of their prime movers is sufficiently poor to overcome the rising characteristic of the generator.

With commutating pole exciters it was soon found that if compounded flat in test at 125 volts full load, 125 volts no load, then when operated at lower voltages (as frequently happens under control of a regulator) they had a rising characteristic and were therefore unstable in parallel operation. This trouble was sometimes made much worse by the slight backward brush shift required for good commutation when the commutating field was too strong.

To take care of this the expedient adopted for a time in one manufacturing plant was to flat compound the exciters in test at 80 volts, thus insuring a drooping characteristic at higher pressures, the division of load at lower pressures not being so important.

This expedient involved carrying in stock generators for ordinary purposes compounded flat at 125 volts and generators for exciter purposes flat compounded at 80 volts, or the delay of testing and adjusting the shunt after the receipt of an order.

With further knowledge of the characteristics of commutating-pole machines and more nearly correct designs, the foregoing expedient was abandoned, and it is the present practice to proportion the commutating field so that the machine is not over compensated; the design is such that some range of brush shifting is allowable, and the brushes are given a slight forward shift so as to obtain a drooping characteristic at all voltages within the range where parallel operation is required. With this arrangement, exciters when compound wound may be compounded flat at 125 volts and still operate properly in parallel at lower voltages.

The stability of a commutating-pole machine depends greatly on the brush position, the commutating-pole field strength, and the voltage at which it operates with regard to the saturation curve of the unit. These three factors affect equally the stability of the shunt and the compound-wound unit. In addition, the compound-wound unit is affected by the amount of compounding, the nature of the compounding curve, and the size of the equalizer connection, also the amount of resistance in the equalizer circuit.

Many engineers feel that brush position alone changes the characteristic of the commutating-pole machine and, whenever a change is desired, the first resort is always to change the brush position. In many cases, the desired effects can be secured in this way, but nearly always a change in commutating field strength, together with a change in brush position, if necessary, will obtain the results required in a more satisfactory manner.

It is a well-known fact that shifting the brushes back from the direction of rotation on a commutating-pole generator improves the voltage regulation of the machine, and, on some machines, it is possible to obtain practically a flat voltage characteristic curve on a shunt-wound unit, and, in exceptional cases, it is possible to obtain a rising voltage characteristic curve. The latter is obtained by a combination of over-compensated commutating field and backward shifting of the brushes. In fact, the two act together in that to hold commutation with a backward shift of the brushes it is necessary to use a stronger commutating field than would be required with the brushes on neutral with proper compensation.

The over-compensated commutating field tends to magnetize the main pole, and, therefore, has a compounding effect. The magnetizing effect is due to the short-circuit current in the coil undergoing commutation. The reverse is true for under-compensation, since the short-circuited current in the coil is reversed for this condition.

We have never found an instance where successful parallel operation could not be obtained after the brush position, as well as the commutating-pole field strength, where properly adjusted for shunt-wound machines, and where these two conditions were met and the equalizer connections properly made on compound-wound machines.

In this connection also it is desirable to arrange the switches of a machine so that the equalizer switch is closed with the line switches and not before. If closed before the machine on the bus is operating with an additional shunt across its series field and the incoming machine is operating with series as well as shunt excitation, resulting in a lower shunt excitation and, therefore, a chance for instability when the series part of the excitation is changed in amount, and, in extreme cases, in direction.

VOLTAGE REGULATORS

Large city central stations supplying power from the generator busbars at generator voltage through a multiplicity of feeders have seldom found it necessary to resort to automatic voltage regulation, because the sudden changes of load are small in proportion to the generator capacity.

Exceptions are noted, such as the plants at Philadelphia, Baltimore, and Pittsburg, where unusual requirements in intermittent loads exist, due to the supply of main railway electrification or steel mill loads.

In hydro-electric plants, on the other hand, the power is usually carried through a few large transmission lines, the interruption of any one of which means the loss of a large proportion of the station load, thus necessitating automatic voltage regulation of the generators. The vibrating contact forms of regulators devised by Tirrill are the only ones in wide use in this country, and no others will be discussed.

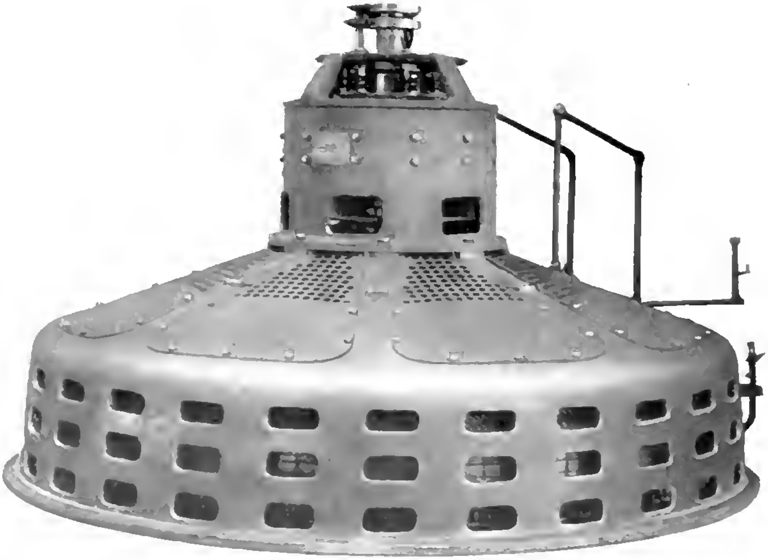

Fig. 9. Vertical Exciter Mounted on an 850-kv-a., 144-r.p.m., 2300-volt Waterwheel-driven Generator

These regulators can be made to take care of exciters operating individually or in parallel in sizes up to the largest which it has been found necessary to use. The exciter field current is controlled through relay contacts; the relay coils themselves being actuated by direct current passing through the main regulator contact. Up to about four amperes at 125 volts a single relay handles the exciter field current; for larger exciters, the field rheostat is divided into sections short circuited by a number of relays, the general rule being that each relay will take care of two amperes field current; that is to say, for a total of ten amperes field current there will be at least five relays. At 250 volts half the current is handled. To obtain the best results the output per exciter should not be more than 25 kilowatts per relay. When the field current is more than 20 amperes, it is generally desirable to split the field, so as to keep the actual field current handled by the relays below 20 amperes.

Since a 12-relay regulator will handle about a 300-kw. exciter, and regulators have been made with as many as 48 relays, which could handle four such exciters in multiple, it is evident that the regulator can be made to take care of very large excitation plants.

For still larger plants, if such should be contemplated, other methods of application of the vibrating contact regulator may be used, so that we can say there is no limit to the size of plant which can be regulated on this principle.

A single regulator may be used to control a number of exciters operating in parallel, or to control a number of invidiclual exciters not operating in parallel when the alternators excited run in parallel. It is also possible to use individual regulators in the latter case. The proper division of the reactive component among the alternators is then accomplished by a compensating coil on the regulator supplied from a current-transformer connected in such a way that the current is at a right-angle phase relation to the voltage which the regulator is maintaining. This last arrangement is favored for large hydro-electric plants having individual exciters, as the individual regulator may be mounted near each exciter.

Stops may be provided on regulators to limit the field current of an alternator and this is always done when a regulator is used with a synchronous condenser to keep the voltage of the receiving end constant up to the limit of output, which is determined by a limiting field current.

Regulators for large plants are provided with accessories, such as over-voltage relays and over-current relays, which cut in an extra block of resistance in the exciter field, so that in case of over-speed of the generators or of the relay contacts sticking, unduly high voltage will be prevented and in case of short-circuit the action is to prevent over-excitation of the fields.

DISCUSSION OF VARIOUS PLANS OF EXCITATION

In selecting a plan of excitation for any plant the local conditions will govern to some extent. In either steam or hydro-electric plants there will be a certain amount of auxiliary power about the station which must be supplied. In a hydro-electric plant the requirements for auxiliary power are not very exacting as to continous operation unless motor pumps are supplied for the step bearings. Most other motors about such plants are for intermittent operation and may be taken care of by an auxiliary bus supplied by step-down transformers from the main bus.

In a steam plant the continuous operation of many of the auxiliaries is of vital importance; and since variable-speed motors are supplied for many of the auxiliaries in order to obtain economical operation at part loads, direct-current motors are frequently used for part of the auxiliaries. At first sight, the best source of power for such auxiliaries would appear to be the exciter bus and, thus, the question of choice of excitation plans becomes involved with the other auxiliaries in the station.

The earlier practice in this country was to operate all of the auxiliaries, such as the circulating water pumps, hot-well pumps, feed pumps, stokers, draft fans, etc., by steam power, thus insuring an ample supply of exhaust steam to heat the main feed water. In some cases this provided too much steam and some steam had to be wasted; and in any event the driving of many of the auxiliaries by individual steam turbines or engines is somewhat wasteful, since the small machines consume steam per horse power output at a rate several times that of the main turbine. If a certain number of pounds of exhaust steam is required to heat feed water it is evidently more economical to use that steam first in a large and efficient turbine, so as to get as many horse power as possible out of it before passing it into the feed-water heater. Modern practice is now tending toward the operation of as many of the auxiliaries as possible electrically, particularly on account of the convenience, reliability and freedom of repair of the electric motor itself, and partly on account of the high efficiency obtained by this method of operation, whether the electric power for the auxiliaries is derived from the main busses or from a separate auxiliary generating source of high efficiency.

The main boiler feed pumps are usually run by steam, but if all the other auxiliaries are electrically operated, as appears to be the modern tendency, there will not be sufficient exhaust steam from the feed pumps to heat the feed water. If the electrical auxiliaries are operated from the main bus the feed water may be supplied by bleeding the main turbine at an intermediate stage and drawing off sufficient steam to heat the feed water.

This is an efficient method of operation, since the steam is used very efficiently in producing mechanical power in the main turbine before it is drawn off. Such an arrangement should be operated on the unit system; that is to say, with a certain bank of boilers supplying a certain turbine, the steam drawn from such a turbine should be used to heat the feed water for its own bank of boilers.

This method has the disadvantage that in case of trouble on the main bus many of the station auxiliaries may be interrupted.

The house turbine arrangement in which a house turbine with its own boilers supplying power to an auxiliary bus is installed for each main generating unit, or one house turbine for two main generating units in a very large plant, appears to possess many advantages. When the main units are 15,000 to 30,000-kw. each, each house turbine may be 1000 to 2000-kw., large enough to obtain efficiency in the use of steam. The auxiliary bus may be connected by transformers to the main bus with automatic relay arrangements, so that in case of trouble on the main bus the auxiliary bus is cut off and supplied only by its own power.

This arrangement possesses the advantage that the supply of power for the auxiliaries, including the excitation, is independent of the main supply, and also the advantage that the heat balance is readily adjustable by adjusting the amount of power supplied by the auxiliary generating unit, so that the amount of steam exhausted by it is just sufficient to bring the feed water to the proper temperature, the remainder of the auxiliary power being supplied from the main bus, which is operating in parallel.

When such an auxiliary house plant is supplied it is generally of alternating current and the excitation for the main unit may be supplied from a motor-generator set run from the auxiliary bus. It would seem desirable that these exciter busses for separate units of the power house should not be operated in parallel, but provision may be made for connecting them in parallel and to obtain the greatest safety a reserve exciter unit and storage battery with emergency bus may be supplied to which any generator field may be connected.

For the very largest steam station such a plan appears desirable, but it is a still better plan, when an auxiliary house plant is used, to supply the excitation for the main units from direct-connected exciters on the main units. There should still be installed a reserve exciter bus with battery and reserve exciter driven from the auxiliary bus, with automatic throw-over switches, so that in case of trouble with any direct-connected exciter the field of that alternator is disconnected from the exciter and thrown on the reserve excitation bus. With this plan the excitation is kept separate from other auxiliaries and the exciter bus is not liable to trouble originating in a motor, also the exciter and field connections are kept short and simple as possible. This plan has the further advantage that the alternating-current voltage may be controlled by the exciter fields and the losses in the main field rheostats eliminated. It is desirable, however, to supply main field rheostats for emergency use.

In connection with an auxiliary house plant generating alternating current for the supply of most of the auxiliaries, motor-generator sets have been installed fed from the auxiliary bus to produce direct current for the variable-speed auxiliaries. This complication of an extra direct-current bus may be done away with if an alternating-current motor with good adjustable-speed characteristics were available. Such a motor is now coming into use. It is a three-phase commutator motor with three sets of brushes on the commutator and the speed is varied by shifting the brushes, which may be done by distant control by a small motor geared to the brush shifting yoke. The motor has a series characteristic and is, therefore, well adapted for driving fans or centrifugal pumps, but it is not as good as an adjustable-speed shunt-wound motor for applications where it is desired to adjust the speed through a wide range and to keep the speed constant for varying load.

There has been some experience with such motors in continuous operation driving mine fans, which indicates that they are as good as direct-current motors with a possible disadvantage of more brush wear. Further experience will undoubtedly justify their use for the exacting requirements of power-house service for such purposes as fans and centrifugal pumps.

Gaseous Conduction Light from Low-voltage Circuits

By D. McFarlan Moore

Edison Lamp Works of the General Electric Company

The first artificial electric light produced was of the gaseous conduction type, as were its immediate successors. Later, the solid conductor or filament lamp came into being and rapidly outdistanced the gaseous conduction lamp in development and application. The development of the filamentless lamp has not been neglected, however, as is evidenced by Mr. Moore's description of it in the following article that was presented last March at a New York meeting of the A.I.E.E. The author explains the problems that have arisen and describes the various types of lamps produced, concluding with the latest type which is of a size comparable with the standard Mazda lamp, starts and operates on low voltage without auxiliary equipment, and furnishes light of an amount useful for many purposes.—Editor.

The production of artificial light is one of the most important activities concerning the welfare of humanity. It is a very large subject, since both its practical and theoretical aspects cover vast fields, yet there are less than a dozen distinct methods of making light artificially and some of them are not developed commercially, although theoretically they possess great possibilities.

This article is written to consider some of these methods of producing artificial light, that have to do with electricity and that come under Item 5 of the following list:

1. Torch (and candle)
2. Oil
3. Gas
4. Solid electric conductors
5. Gaseous electric conductors.

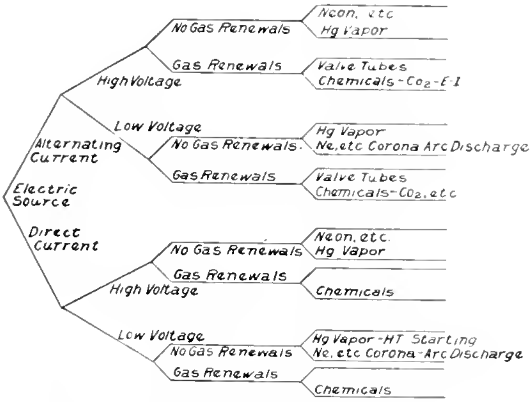

Fig. 1. Diagram Illustrating the Extension of the Varieties of Gaseous Conductor Lamps

Electricity can be used to agitate solids, liquids, or gases into light. The light of the incandescent lamp is due to electrically-heated solids; and when electricity is conducted by a gas under suitable conditions, light also results. Many varieties of lamps of this nature, both in design and construction, are indicated in Fig. 1, the scope of which can be enlarged almost indefinitely; for example, by the use of many other gases and vapors.

High-tension lamps require special auxiliary transforming apparatus to generate the high potential.

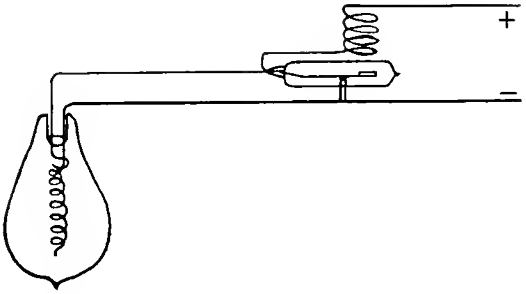

Fig. 2. Connection Diagram of Gaseous Conductor Lamp and Vibrator Employed in 1895

The two major factors in all of these types are: (1) the electrodes, and (2) the gaseous conductor.

Both electrodes of alternating-current lamps can be similar, but in direct-current lamps the cathode differs from the anode. Electrode materials differ with the gas used. It is therefore seen that the construction and design of each one of the scores of lamps indicated is a distinct and difficult problem, the solution of many of which have hardly been seriously attempted.

As might be surmised, the specific type of lamp I wish to emphasize is the one in which I have been most interested recently, but in order to give it its proper setting, it is necessary to review the past. The first natural electric light was lightning, or the aurora.

The first artificial electric light was due to gaseous conduction and was produced with the revolving glass sphere of Hawksbee in 1750.

A hundred years later, Geissler first operated his small tubes from an induction coil.

In 1879 Crookes modified them in many ways, including obtaining high vacua.

About 1891 Nickola Tesla delivered his famous lectures on "High Voltage and High Frequency."

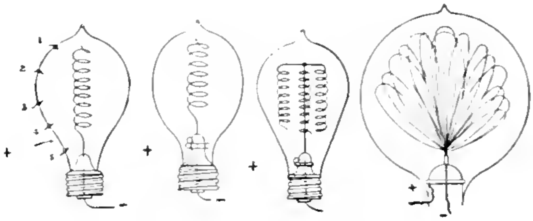

Fig 3. Various Designs of Early Negative Glow Lamps

Due to the rapid and very objectionable blackening that was deposited over the inside of incandescent lamp bulbs in 1893, I first began thinking and talking about the possibility of constructing a lamp without a heated filament— a filamentless lamp.

In connection with the American Institute of Electrical Engineers, I explained that I meant a bulb form of lamp, the light source of which was to be not an incandescent solid conductor but an enclosed gas or vapor electrically agitated by the low-tension circuits in common use.

During the twenty-six years that have intervened, this simple thought has never left me, though the tortuous road has been very dark at times, but it is now brighter than it has been before.

Fig 4 Special Negative Glow Lamps Designed for Advertising Purposes

In order that I may not be misunderstood, I must hasten to say, perhaps sorrowfully, that it is still far too dim even to think of its competing in brilliancy with that splendid array of present day commercial illuminants led by the incomparable tungsten lamp.

My first attempts in 1893 to obtain any light from a lamp without a heated filament on 220 volts resulted in no light whatever. All known gases were unsuccessfully tried. Light from many of the common gases proved very interesting; for example, the bluish-white light from CO_2, the pinkish, hot and almost non-luminous light of hydrogen, the efficient orange-yellow light of nitrogen, and the dull whitish light of oxygen; also many mixtures were tried, together with chlorine, bromine, etc., and various vapors like those of sulphur and mercury. The prediction was made that progress would result only after the discovery of some of the gases indicated by the table of the periodic law of the elements. It was necessary therefore, in 1894, to resort to the high voltage of an induction coil, in order to obtain some light from the first gaseous conductor bulb lamp. In 1895, the vacuum vibrator displaced the induction coil, and on direct-current circuits the bulb lamps were filled with negative glow light. Fig. 2 shows the vibrator and connections. Fig 3 shows the negative glow lamps, and Fig 4 depicts the use of negative glow for advertising purposes, and the means for increasing its intensity. Detailed information of this nature will be found in some of my previous papers.*

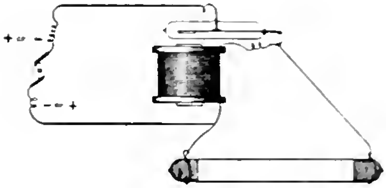

Fig 5. Seven-foot Vacuum Tube Lamp with External Electrodes and Vibrator

After neon had been discovered as hoped for, and nineteen years later I had made the first low-voltage gaseous conductor lamp, there was a certain satisfaction in proving that my original conception of utilizing the feeble light of the almost despised negative glow was correct.

In 1896, seven-foot vacuum tubes, Fig 5, with external electrodes displaced the bulb

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* A New [illegible] I.E.E. 189[illegible], S[illegible] 2[illegible]

Re[illegible] D[illegible] Vacuum Tu[illegible] A.I.E.E. 898 Apr. 2[illegible]

[illegible] A.I.E.E. [illegible]

lamp. The vacuum rotator succeeded the vibrator in 1897 and 1898. Fig. 8 shows the interior of the historical "Moore Chapel." The first 220-volt direct-current tubes, started with a higher potential from both vibrator and rotators, were then made and used. Fig. 6 shows the 5-foot tube which was used in taking the first instantaneous electric portrait—Chauncey M. Depew being the first subject.

The anticipated discovery of neon was announced in 1898, but even samples of it were impossible to obtain in America. Sir Wm. Ramsey, Lord Raleigh, Travers and their brilliant contemporaries announced in rapid succession the five new monatomic elements, argon, helium, neon, xenon, and krypton, all of which will probably ultimately take important places in the world of commerce and some of which have already done so.

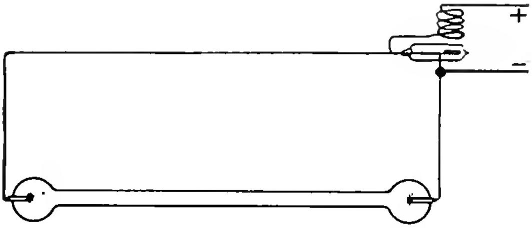

Fig. 6. Five-foot 220-volt Tube Lamp

Vacuum-breaks were displaced in 1899 for a combination of resonance coils and a low-frequency generator and later high-frequency generator.

In 1902, the "long tubes" (about 100 feet) appeared, and they were improved in 1903 with internal electrodes.

The beauty of the first long tube was admired by thousands.

The first rotary high-vacuum oil pump was developed for the exhaustion of the long tubes built *in situ*.

Also a 24-inch CO_2 tube lamp provided with a carbon filament cathode was started with higher potential on 220-volt direct-current and the resultant light was highly efficient.

Other, though similar, tubes and lamps had metallic cathodes buried in lime, etc., and it was noted that, when operated on alternating current, rectification took place. These interesting types of lamps are shown in Fig. 7.

It was a great advance in 1904 and 1905 to discontinue the use of a special generator with each "long tube" installation and to obtain brilliant illumination from the distribution street circuits by the use of nitrogen gas. An installation of such lamps is shown in Fig. 9.

Special electrodes were also constructed with auxiliary circuits, similar to those later used in rectifiers, pliotrons, and X-ray tubes.

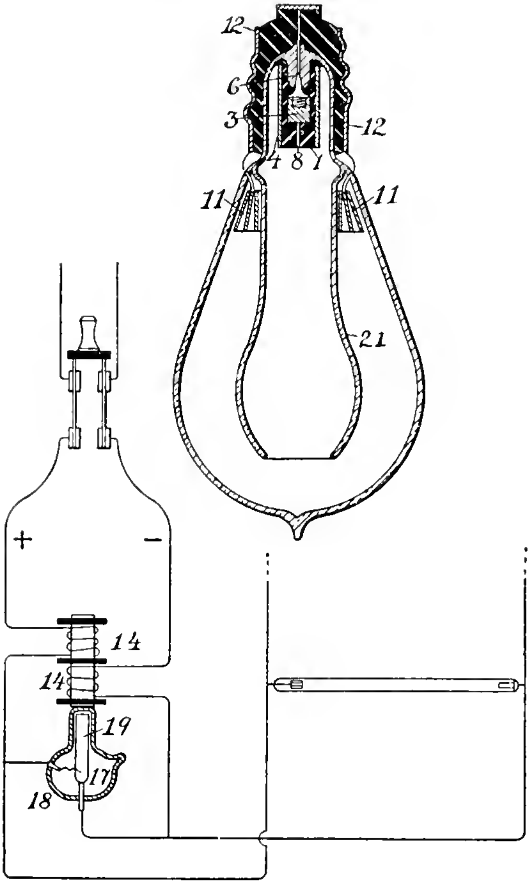

Fig. 7. Hot Cathode Luminous Discharge Lamp and Its Connections

The life of these long tubes was extended to 10,000 hours during the period of 1906 to 1909 by the invention of the electromagnetic feed valve and over four miles of light-giving tubing were commercially installed. The lobby of Madison Square Garden is shown in Fig. 10. Fig. 11 shows the details of the magnetic feed valve. No light source known today equals in efficiency a neon tube 1¾ inches in diameter and 200 feet long. The long-tube system is theoretically correct in so far as it provides means for generating light at the exact intensity most suitable for the eye; this in contra-distinction to the generation of concentrated light at an enormous intensity and temperature that must, before

Fig. 8 Interior of the Moore Chapel Lighted by Gaseous Conductor Lamps

Fig. 10. Lobby of Madison Square Garden Illuminated with Low-voltage "Long-tube" Lamps

Fig. 9 Installation of Low-voltage "Long-tube" Nitrogen Conductor Lamps

it can be used by the eye, be either greatly reduced in intensity by means of some kind of semi-transparent or diffusing screen, or widely scattered by a reflector. Fundamentally the first cost of a long tube system is less than that of a complete incandescent lamp system and its life is longer with a resulting lower maintenance cost. It is also simpler.

During 1910 and 1911, the long tubes in the form of portable artificial daylight windows made their appearance. One of these is shown in Fig. 12.

Between 1913 and 1915, several types of small tube lamps dependent upon the new chemical gas feed principle were invented and marketed for color matching purposes. Such lamps are shown in Figs. 13 and 14. The spectrum of this type of color-matching lamp will never be surpassed as a standard light by which to judge colors.

Simple neon tubes operable from transformers were designed and made in many varieties. Some were equipped with screw lamp bases. These outfits consume 13 watts and are light enough to be screwed into an ordinary incandescent lamp socket. Lamps of this kind have run without change for over 4000 hours.

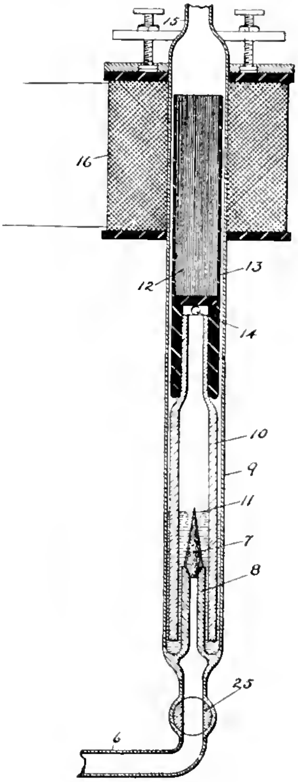

Fig. 11. Cross-sectional Drawing of the Electro Magnetic Feed Valve

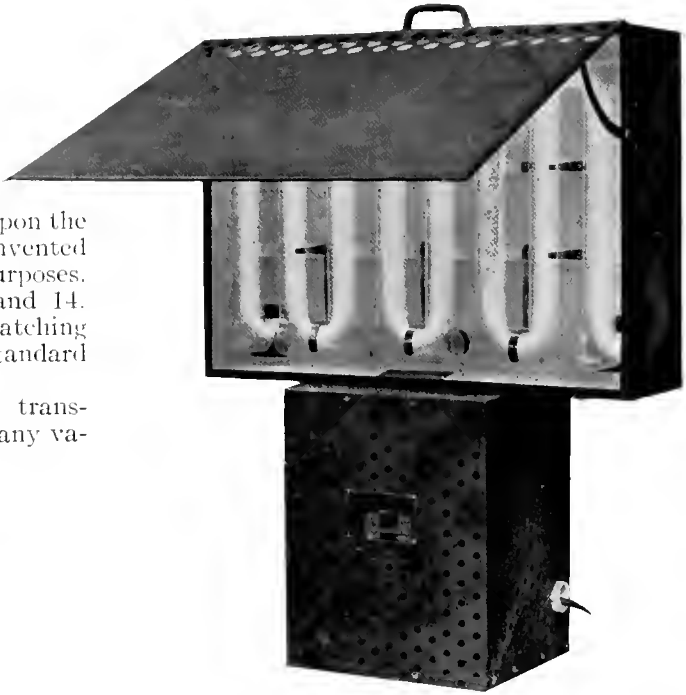

Fig 12. Compact Form of "Long-tube" Outfit for Portable Use

In the fall of 1916, there was exhibited the first portable and thoroughly commercial neon tube outfit of high intensity and efficiency operated from a step-up sixty-cycle transformer. It resembles those shown in Figs. 13 and 14 except that the tube housing is twice as long. The tube is in the form of a hairpin and has a total gas column length of 101 inches at ⅞ inches diameter. The specific efficiency of this type of lamp is 0.74 watts per spherical candle-power.

Even this high efficiency can be improved considerably by using purer neon (that is, neon gas that does not contain 25 per cent helium and other impurities) together with a longer gas column and of greater diameter. Also the electrode losses can be reduced. But the photometric measurements of this brilliant type of tube lamp showed a total of 180 mean spherical candle-power of 2260 lumens with 0.162 amperes passing through the gas column. Simple straight tubes about $1\frac{3}{4}$ inches in diameter and 8 feet long could be arranged as a continuous line of light and used for the lighting of large interiors or for streets.

The initial installations would have great advertising or display worth. The red rays will also be valuable for signaling purposes, etc.

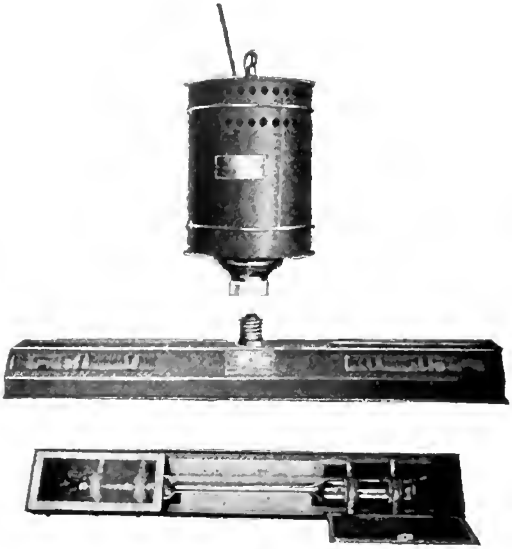
Fig 13. Color Matching Tube Lamp Operating on the Chemical Gas Feed Principle

Various alternating-current tube lamps provided with two similar electrodes were also made to operate on 220 volts alternating current without a step-up transformer, but they need a momentary higher voltage to start the gas column discharge which is most simply obtained by short-circuiting a series inductance. The length of the gas column of this type of lamp is too long (about 3 inches) to permit 220 volts to pass any current, but it will maintain the discharge, which is positive, for an indefinite length of time after once started. The necessity for starting apparatus is an objectionable feature of this particular type of lamp. When the gap or gas column between the electrodes of a tube lamp on 220 volts alternating current is less than about $1\frac{3}{4}$ inches, the light is negative glow.

The direct-current lamp, of the type requiring high potential for starting, involves even when filled with neon gas a special cathode of mercury of a KNa amalgam.

Still another type of 220-volt direct-current neon tube was started by using an auxiliary current to raise to a high temperature a portion of the cathode. Space will not permit the listing of many other varieties of gaseous lamps.

However, attention is to be called to the type of lamp that has cold electrodes and is designed to start and operate without using high potential.

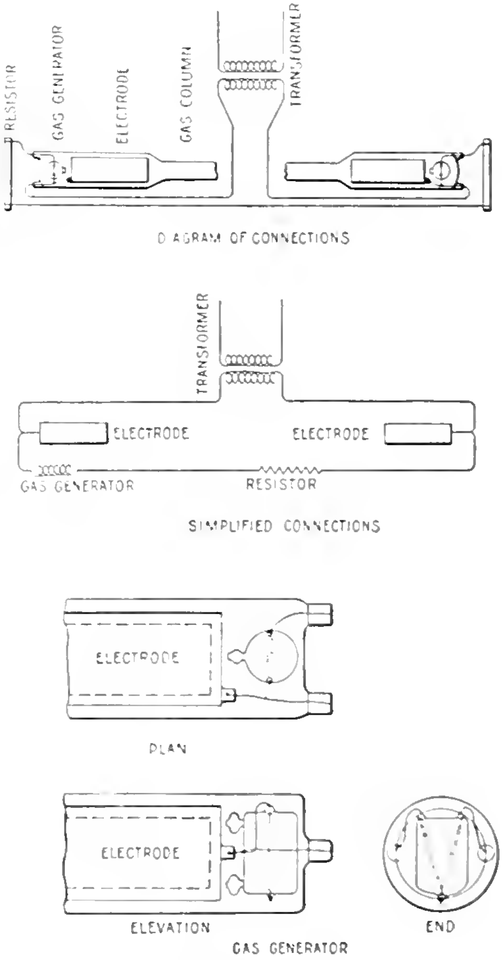

Fig 14 Connection Diagram of the Type of Lamp Shown in Fig. 13

The current of a 220-volt circuit passes through the neon gas and causes it to give light. No potential-raising transformer is used. When the particular problem was the production of small units of light, its satisfactory solution by the use of the transformer was commercially impracticable but it seemed for many years impossible to obtain any light without using a transformer.

Fig. 15 shows a form of this type of lamp, for alternating circuits. Scores of modified designs have been made. It is a novel type of lamp. I hope that many will see in it, with me, the possibilities of a lamp of this kind. In fact, diligent inquiry among scientific men has failed to find anyone who did not agree that all theory seemed to indicate the great probability that artificial light of high efficiency will result from the further development of lamps of this kind. The handwriting on the wall seems to unmistakably indicate that to further increase the luminous efficiency of light sources in general we shall need to resort to gaseous radiation, by which means it may be possible to reduce to about one tenth the energy now required.

Since the ice on the problem now seems to be broken, it is my earnest hope that many of the ablest inventors will become actively interested and that by the combined knowledge, experience and ingeniousness of all who have studied and worked on gaseous conduction phenomena, the many problems involved will be solved. I believe that a very great deal remains to be learned and discovered.

The lamp shown in Fig. 15 resembles an incandescent lamp in outward form and perhaps is far more simple, yet it is not an incandescent lamp. Four electrodes made of aluminum, each 6 in. long, $\frac{5}{8}$ in. wide, and $\frac{1}{16}$ in. thick, are mounted in a 3-in. straight sided bulb about a common center. A glass hub, provided with radial arms of glass, supports the electrodes, which have holes in them and through which the arms extend. The capacity of the solid radiators is objectionable and yet the effect of a solid radiator is approached by radiators made of very small mesh netting.

In designing this lamp, an effort was made to take advantage of every factor that required minimum voltage so that it would operate on 220 volts or less.

The potential is least (volts per centimeter) for the negative glow. All of the light radiated from this new type of lamp is produced by the negative discharge; not by the positive column as is the light in all of the long vacuum tubes when in operation on either a-c. or d-c. circuits. All text books and investigators have heretofore considered that the amount of light given by the negative glow in any vacuum tube discharge was so small as to make it entirely negligible as a light source.

An ordinary long tube discharge consists of: (a) next to the cathode, the short first dark space; (b) the short and not bright negative glow; (c) the short second dark space; (d) the long brilliant positive column extending to the anode. But in the lamps herewith described, the positive column has been practically eliminated and substantially the only luminous discharge in the lamp is the negative glow which appears in the form of a velvety glow or corona of yellowish light over the entire surface of the alternating-current electrodes and also a uniform gaseous radiation throughout the interior of the bulb.

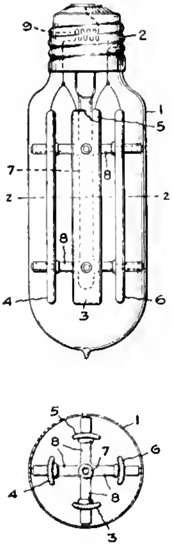

Fig. 15. Negative Glow Lamp Capable of Starting and Operating on Low Voltage Without Auxiliaries

The lamp shown in Fig. 15 is designed for operation on 220-volt a-c. circuits. From the line it uses about 0.11 amperes and 21 watts, but of this amount 3.6 watts at 33 volts is used by an ohmic resistance about 1 in. long placed in the skirt of the lamp base, because due to the impurities principally in the neon gas and the aluminum radiators a slight blackening may form between them in time and may cause the lamp to short circuit.

The finished lamp will probably require no series resistance, but at the present time the use of such a resistance affords a convenient method of adjusting the total watts consumed, the life, and the intensity. The specific efficiency of this particular type of lamp is low. When this lamp is consuming 17.4 watts, it gives approximately 1.16 s.c.p., which corresponds to 15 watts per s.c.p. Therefore, the most important problem still to be solved is how to decrease the number of heat waves and increase the number of luminous radiations.

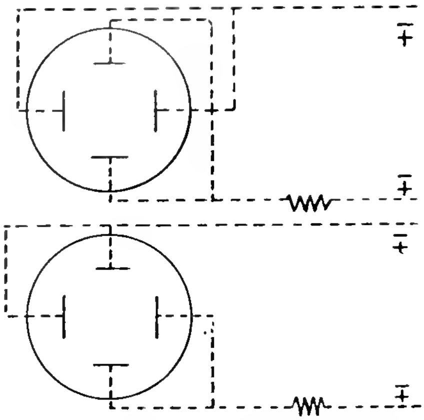

Fig. 16. Two Methods of Connecting the Radiators When Four Are Used in a Lamp

When the line voltage was reduced to 135, the light was suddenly extinguished.

The neon used had a helium content of about 25 per cent, but if it had had a nitrogen impurity of a fraction of one per cent, the neon lines would have been greatly reduced. The pressure of the gas when sealed off was 3.5 mm.

The bulb temperature is about 40 deg. C., but of course is increased when the watts are increased.

The color of the light is a beautiful yellow.

Some of the important factors to which special attention has been given in the design of this new lamp are:

1. The attempt to use a gaseous conductor of maximum conductivity.
2. Electrodes that are subdivided and of as large a total area as possible.
3. A gas column (discharge gap) as short as possible.
4. The planes of the electrodes of opposite polarity placed parallel to each other.
5. The length of the radiator electrodes greater than the gas column and perpendicular to it.

Since the light is entirely due to negative glow, cathodic disintegration of the electrodes is one of the problems in connection with this type of lamp, but it is practically nil when the cathode fall equals its minimum value. It is greater at lower gas pressures and increases as the square of the current, assuming a constant electrode area and gas pressure, but it is not an essential to transmission of current and seems to be largely due to the occluded gases, particularly hydrogen. The bulb blackening is far less with aluminum radiators than tungsten, nickel, copper, etc. Carbon in pure form is difficult to obtain. Iron radiators, as well as various radiators combined with fluorescent coatings, offer promise.

One of the troubles connected with the use of the carbon was the difficulty of removing all of the occluded gases. However, this may be overcome by heating not only carbon electrodes but all other varieties of radiators. Radiators of whatever material should be as pure as possible and be cleansed in the best manner.

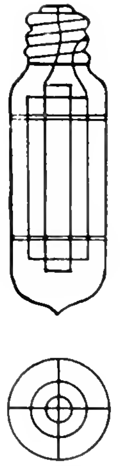

Fig. 17. Direct-current Lamp with Concentric Radiators, the Outer of Which Emits the Light

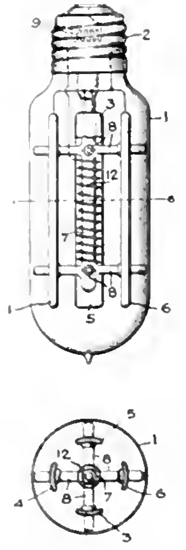

Fig. 18. Another Variation of the Direct-current Radiator Lamp, the Positive Being Wound as a Spiral

This corona type of lamp produces a luminosity that is not due to arcing or even pure discharge phenomena, but is due to the glow of light emanating from electrodes or radiators that normally have a temperature below red heat. According to the theory of ionization, the temperature within the negative glow is higher than within the positive column and the velocity of the negative ion is greater than that of the positive, and this is one reason why the potential required to produce a luminous discharge from a negative pole is less than from a positive, together with the fact that in the negative glow the number of positive and negative ions are about equal.

The exceptional luminous efficiency of neon makes it unique among light sources. Immediately upon the announcement of its discovery in 1898, I proposed its use for lighting purposes. Its great scarcity until recently has made rapid progress impossible. Within the last few days announcement has been made that it can now be bought in almost any quantity and of a high degree of purity. Its luminous spectrum is almost ideally located to effect the eye in a maximum manner. It is a splendid example of selective emission or radiation that eliminates the long and therefore inefficient waves.

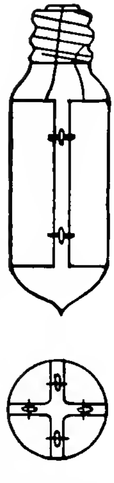

Fig. 19. A Simple Form of Alternating-current Lamp Having Four Radiators of Aluminum Netting

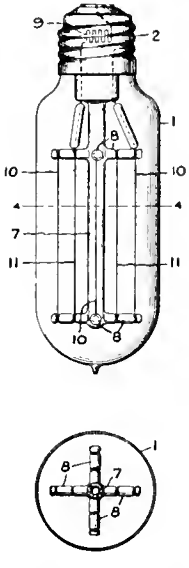

Fig. 20. A Form of Gaseous Conductor Lamp Which in Construction Resembles the Standard Incandescent Lamp

It does for gaseous conductors just what the Welsbach mantle or the impregnated arc lamp electrode does for heated solids.

The maximum emission is between wave lengths 590 and 650 which is one of the remarkable properties of this gas. It produces over a hundred times as much luminosity for the same watts as does argon for example. Its dielectric cohesion is 5.6 which is extremely low when compared with air at 419. It has less than one half the resistance of nitrogen. It is fortunate that the color of the negative glow of neon is different from that of the positive column.

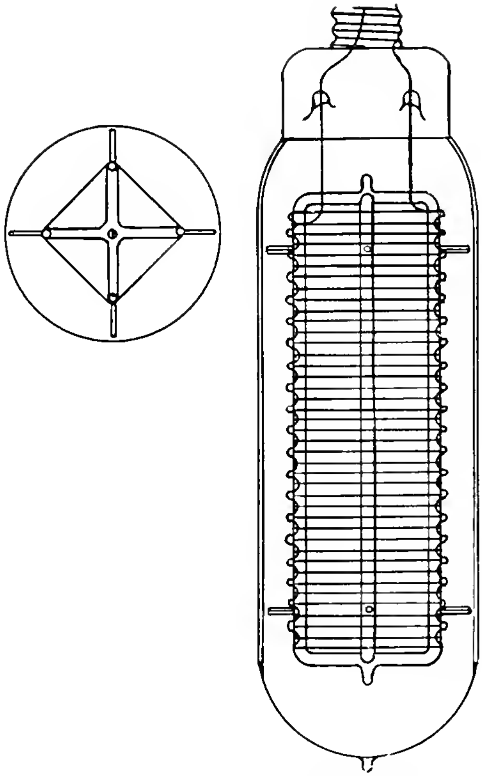

Fig 21. Lamp with Wire Electrodes Wound Parallel in the Form of a Square Spiral

Neon gas when used as a positive column of light has a color so reddish that it would be objectionable for many purposes; but when the same gas is used as a negative glow, the color is yellowish. It has no blue or violet or indigo lines and very few infra-red rays. It is four times better as a light producer than the yellow-white light of helium or the violet of xenon, both of which have many infra-red rays.

The characteristic crimson of neon has been displaced by a uniform mass of soft yellow light that somewhat resembles the color of a high class oil lamp, or that from the electric incandescent carbon lamp, the intrinsic brilliancy of which is theoretically too great.

The connections of the four radiators are shown in the upper diagram of Fig. 16, but the total flux of light is not very much less when the connections are as in the lower diagram of Fig. 16.

Scores of modifications and varying designs have suggested themselves. For example, such a type of lamp that is suitable for alternating circuits will differ from a properly designed direct-current lamp. But all alternating-current lamps will give some light on a direct current of the same voltage. That is, only one of the radiator poles (the negative) will give any light. Therefore, in the case of the lamp shown in Fig. 15, only two of the four radiator plates will be luminous.

Fig. 22 A Tube Variation of the Radiator Lamp

The positive poles will remain absolutely dark. This fact is given recognition in the design of the direct-current lamp, shown in Fig. 17. The inner cylinder is of sheet aluminum and the outer cylinder is of aluminum netting and made the negative pole.

Fig. 18, which is taken from the United States Patent No. 1,316,967, and which was applied for November 30, 1917, shows the positive electrode in the form of a spiral on the axis of the lamp.

Fig. 19 shows a very simple lamp for alternating circuits that is constructed by inserting into a three-inch straight-sided glass bulb four right angles made of aluminum netting of 0.052 wire having a mesh of eight wires per inch. Each right angle is 5 inches long. Eight glass buttons or spacers keep all portions of these four angles at a uniform distance of $\frac{3}{16}$ in. from each other, and they are all held in place by the walls of the bulb.

Just as a final mechanical form for the major designs of the tungsten lamp was arrived at, so also will doubtless be the case with lamps or tubes based on the corona principle. These lamps should be so designed mechanically that a maximum amount of the light that is generated has free exit or is reflected in the best manner.

Fig. 20 has a construction that closely resembles that of a standard tungsten incandescent lamp.

Fig. 21 shows wire electrodes wound parallel to each other on a glass drum.

Fig. 22 shows such a lamp in the form of a tube.

The dozen most important factors involved in the design of these lamps should be examined theoretically and a definite conclusion reached concerning each one, so as to determine definitely its possibilities.

Some of the important variables are:

The gas pressure; for (a) efficiency, (b) life.
Electrodes; material, form (wire), and area best suited for a definite voltage, life, wattage, intensity, and efficiency.
The exhaust program.
The length of the gas column; that is, the distance between radiators of opposite polarity.
Volume and shape of the bulb.

When the gas pressure is too high (about ten millimeters) no light appears; but at six millimeters it consists of a velvety or luminescent glow that closely envelops the radiators and extends further and further from them as the pressure grows less until it fills the entire bulb with a suffused glow, which, however, becomes thinner and less luminous when the pressure is still further reduced.

It seems advantageous to subdivide the radiator of each negative pole. The lamp made in accordance with Fig. 23 shows that far more light is generated between such subdivisions than between areas attached to opposite poles.

It is apparent that a brighter lamp is desirable. Photometric measurements of lamps constructed as in Fig. 21, showed 2.59 spherical candle-power on 220 volts alternating current. The higher the voltage, the easier is this problem. Therefore, perhaps it would be best first to develop a lamp for the commercial 500-volt circuits. When the voltage is raised abnormally on most of these lamps, they will arc destructively even though the

Fig 23 A Form of Lamp with Subdivided Electrodes

air gap is large. Oftentimes there seems to be less tendency to this destructive "ball discharge" arcing when the air gap is small than when it is large, because then the ohmic series resistance can be greater. The lamp shown in Fig. 15 has a discharge gap of $\frac{5}{8}$ in. but in other lamps it varies from $\frac{1}{32}$ in. to one inch.

The lamps that gave the most light on 110 volts are those whose radiators were made of wire of small diameter and small total area as shown in Fig. 20.

Photometric data of various types of these corona lamps have been obtained by the use of an 80-inch sphere. Color corrections were made by the following procedure:

1. Hold Moore lamp at 220 volts and adjust comparison lamp to Moore lamp color.
2. Set galvanometer on zero and maintain comparison lamp at above color.
3. Adjust Mazda "B" lamp to comparison lamp color and note voltage.
4. Ascertain horizontal candle-power of Mazdz "B" lamp at above voltage.
5. Horizontal candle-power of Mazda "B" lamp × 0.785 – spherical candle-power of Mazda "B" lamp.
6. Read Mazda 'B" lamp and all direct-current or alternating-current Moore lamps against comparision lamp as set.
7. Multiply Moore lamp readings by ratio of Mazda "B" reading to Mazda "B" spherical candle-power.

The tabulation in Table I shows, first, the performances of four lamps constructed approximately as in Fig. 15 on alternating current, and then follows the test data of several lamps of varying constructions.

Table II shows most of these lamps when operating on direct-current circuits, under which circumstances of course but one pole gives any light.

TABLE I

ALTERNATING-CURRENT LAMPS

Lamp Nos.	LINE		LAMP				LINE		SERIES
	Volts	Amps.	Volts	Watts	Spherical Candle-power	Watts per Spherical Candle-power	Watts	Watts per Spherical Candle-power	Resistance
547	155 (min.)								
	164	0.03	149	5	0.234	21	4.5	24	500
	221	0.105	168	15.5	0.594	26	21	35.5	
	264	0.16	184	24.5	1.04	23.5	37.5	36	
595	135 (min.)								300
	166	0.045	153	3.9	0.258	15	4.5	17	
	220	0.11	187	17.4	1.15	15	21	17	
	265	0.18	211	32.9	2.44	13.4	42.6	17	
594	127 (min.)								300
	167	0.045	153	4.4	0.392	11.2	5.0	12	
	220	0.135	180	21	1.24	17	26.4	21.2	
	265	0.215	200	37.2	2.4	15	51	21.2	
430	220	0.13	155	17	0.715	23.5	26	34	500
605	220	0.11	188	16.7	0.897	18.5	20	22	300
609	220	0.245	195	53	1.825	29	58	32	100
600	220	0.095	172	14.1	0.715	19.8	18.6	26	500
647	220	0.185	164.5	24.5	0.870	28	34.5	39	300
270	220	0.205	179	29	1.047	27	37.5	36	200
669	220	0.135	193	15.9	0.645	24	19.5	30	200
675	220	0.085	126.5	19	0.601	31	16.5	27	1100
673	220	0.22	176	30.3	0.847	35	40	47	200

It is safe only to consider these data, however, as indicating very broad generalizations because no two lamps have been made alike, even as regards their mechanical construction, and they also differ as regards the purity of the gas and its pressure, the exhaust programme, etc. There were also encountered difficulties as regards the photometrical and electrical measurements; for example, when such a lamp is consuming less than two watts the amount of the light seems considerable to the eye in a dark room.

Nevertheless, I believe that complete and exact specifications should be determined upon for an ideal lamp of this nature entirely independent of its comparative relations to other and seemingly far superior forms of artificial light.

Some of the conclusions that may be drawn are as follows:

1. The efficiency of these lamps is about the same whether operating on alternating-current or direct-current circuits.
2. The efficiency is about the same on alternating-current circuits over a wide voltage range.
3. The efficiency is about the same on alternating-current circuits over a wide range of intensities.
4. The spherical candle-power varies approximately with the wattage on either alternating current or direct current.

TABLE II

DIRECT-CURRENT LAMPS

Lamp Nos.	LINE Volts	LINE Amps.	LAMP Volts	LAMP Watts	LAMP Spherical Candle-power	LAMP Watts per Spherical Candle-power	LINE Watts	LINE Watts per Spherical Candle-power	SERIES Resistance
547	165	0.017	156.5	2.66	0.158	16	2.8	17.8	500
	220	0.066	187	12.3	0.444	27	14.5	32.7	
	265	0.124	203	25.1	0.880	28	32.8	37.3	
595	165	0.013	161.1	2.0	0.178	11.7	21.1	12.1	300
	220	0.072	198.4	14.2	0.792	17.8	15.8	20	
	265	0.134	224	30	1.88	16	35.8	18.9	
594	165	0.014	160.8	2.2	0.178	12.3	2.3	12.9	300
	220	0.061	201.7	12.3	0.633	18.7	13.4	20.2	
	265	0.13	261	33.9	1.53	22	34.4	22.5	
605	165	0.015	160.2	2.5	0.217	11.5	2.6	12.2	300
	220	0.078	196.6	15.2	0.787	19	17.1	21.8	
	265	0.146	221	32	1.48	22.3	38.7	26	
609	220	0.16	204	32.4	1.48	21.5	35	23.5	100
430	219	0.105	166	16.2	0.796	22.5	21.9	27.4	500
600	220	0.04	198	8	0.387	20.5	8.8	22.5	500

5. The lamps with a reasonably pure neon color were not as efficient as those in which gas impurities made the color whiter.
6. The general lamp performance is not very sensitive to wide variations in the length of the gas column or gap.
7. The same lamp equipped with the same resistance and operating at the same voltage takes a considerably higher line wattage on alternating current than on direct current, which doubtless is principally due to the light radiating area being double.
8. The candle-power is greater with radiators of large area.
9. The power-factor of these lamps is about 85 per cent.

This new form of lamp demonstrates that useful gaseous conductor light, that to say the least has advertising value, can now be produced in a simple manner from ordinary commercial circuits. Special uses will be found for such lamps, for example, as polarity or potential indicators. Since the internal parts are all below red heat, gas explosions will not be caused by bulb breakage. Gaseous light, due to electrical agitation, has to a limited extent been emancipated from all necessity for an heretofore ever-present high potential either for starting or normal operation. The basic conception of using a gas to supplant the heated filament in an ordinary lamp seemed wholly impossible, yet this new type of lamp makes it at least a partial reality. It constitutes an advance in that it adds to our knowledge of a very little developed subject. A new epoch in the history of Gaseous Conduction Lighting has been reached. It is my hope that the great cause of new and better lighting methods in which my deep interest has been centered for years may be spurred to rapid advancement in a new direction that gives promise of reward to an unlimited number of worthy investigators and inventors.

Fundamental Phenomena in Electron Tubes Having Tungsten Cathodes

PART II

By Irving Langmuir

Research Laboratory, General Electric Company

The preceding section of this article appeared in our June issue. In the present and concluding installment, the author first treats of the fact that electrons impinging on solid surfaces frequently cause the emission of relatively large numbers of secondary electrons. He then discusses how such phenomena may play a prominent part in the operation of vacuum tubes and describes striking experiments illustrating these effects. In the remainder of the article he deals with the manner in which the various fundamental phenomena co-operate to determine the operating characteristics of electron tubes.—Editor.

Secondary Electron Emission from the Walls of a Discharge Tube

With relatively high-voltage electron discharges in high vacuum, particularly when the walls of the vessel are of unusual shapes, so that the distance between the electrodes is large and the walls of the vessel interfere with the free passage of electrons between the electrodes, it may happen that the bombardment of the walls of a vessel by high velocity electrons and the consequent emission of secondary electrons becomes a phenomenon of vital importance.

When a surface of glass is struck by electrons with relatively high velocities corresponding to 20 to 100 volts or more the energy of the impact may cause other electrons already present in the glass to be knocked off or emitted. Of course, these electrons leave the glass with less energy than that of the primary electrons which struck the glass, and a large part of the energy of the primary electrons is converted into heat, thus heating the walls of the vessel subject to this electron bombardment. Under ordinary conditions, with a discharge tube in which the walls of the tube are not so shaped as to interfere directly with the passage of electrons between the two electrodes, phenomena of this kind become important only at extremely high voltages, of the order of magnitude of 50,000 volts or more, although in the presence of small amounts of gas the effects of secondary electron emission are often a serious disturbing factor at voltages of the order of magnitude of 10,000 volts.

A glass tube with cylindrical walls, about two inches in diameter and about eight inches long, contained a V-shaped tungsten cathode placed at about the center of the tube, and a disk-shaped anode of tungsten placed perpendicular to the axis of the tube at a distance of about an inch or a little more from the tip of the V of the tungsten filament. This tube was exhausted to a particularly high vacuum, the tungsten anode having been heated to brilliant incandescence by use of a high-voltage discharge. It was found that this tube could be operated in either one of two ways: (1) If a voltage of a few hundred volts was applied to the anode and the temperature of the cathode was gradually raised, it was found that the tube operated in a normal manner, the energy of the discharge being liberated at the anode and causing a heating of the anode, the walls of the tube remaining relatively cold, receiving only heat that was radiated to them from the anode. Under these conditions the current between anode and cathode, because of the space charge and because of the negative charge which accumulated on the walls of the vessel, was limited to a comparatively small value. (2) If a switch in the circuit carrying current to the anode was opened and then immediately closed again, it was found that the characteristics of the discharge were entirely different. The current flowing to the anode was now much greater than before, but the heating of the anode was less than before, and the energy of the discharge was liberated in greater part on the walls of the vessel surrounding the space between two electrodes.

It was found repeatedly that it was possible to change from one type of discharge to the other. With the second type of discharge there was a tendency for the vacuum to become poorer, as was indicated by a decrease in the electron emission from the cathode. These simple experiments, together with practical experience obtained in connection with the manufacture of Coolidge X-ray tubes and the exhaustion of a large number of thermionic devices, have indicated clearly that secondary electron emission from the walls of the glass under influence of bombardment is responsible for phenomena of this kind.

In the second type of discharge the sudden application of the voltage to the anode causes some high velocity electrons to strike the walls of the vessel. These high velocity electrons cause the emission of large numbers of low velocity secondary electrons from the surface of the glass, so that the walls of the glass lose a larger amount of negative electricity than they received, and thus tend to become positively charged. The discharge therefore maintains itself, the electrons flowing from the cathode to the surface of the glass, thus causing the emission of other electrons which then pass to the anode. This discharge, of course, soon reaches a stationary condition in which the number of electrons emitted from the glass is equal to the number of electrons which strike the glass. The potential of the glass is then intermediate between that of the anode and cathode, usually much more nearly that of the anode than that of the cathode. The fact that the glass surface, which has a large area compared to that of the anode, becomes decidedly positively charged with respect to the cathode, greatly increases the current-carrying capacity of the space between the two electrodes, in much the same way that a positively charged grid in a three-electrode device increases the current that can flow between the cathode and anode.

When devices are made up in which the glass walls play even a more prominent part than in the tube that I described, for example, where the anode and cathode are separated to considerable distances and the vessel forms a rather long, narrow tube connecting the spaces around the two electrodes, the phenomena due to secondary electron emission have a still more controlling effect on the characteristics of the discharge. The most striking difference between the characteristics of a tube of this kind and one in which secondary electron emission plays no part is that the walls of the tube become heated by the secondary electron bombardment, instead of the whole of the energy of the discharge being liberated in the form of heat at the anode. The bombardment of the walls of the tube and the resultant heating tend to liberate gas from the walls, so that if a tube of this kind is to have constant characteristics, particularly great care must be used in freeing the walls of the vessel from gases which might otherwise be evolved while the discharge is passing.

Lilienfeld* has made an elaborate study of discharges taking place in high vacuum through long, narrow tubes connecting two bulbs, one of which is provided with a hot cathode, while the other contains an anode. He measured the potential drop between sounding electrodes placed in the tube about three centimeters apart.

The energy of the discharge was consumed in heating the walls of the tube. This heating together with the fluorescence of the tube walls, and the uniform potential gradient along the tube prove that the discharge depended upon the emission of secondary electrons resulting from the electron bombardment of the walls. Lilienfeld, however, interprets his results as indicating that empty space is dissociated into positive and negative electrons by passage of current through it. By repeating Lilienfeld's experiments, Dr. A. W. Hull and I have found that the characteristics are of just the kind that are to be expected as a result of secondary electron emission. No measurable discharge takes place in high vacuum with a tube like Lilienfeld's until voltages above 1000 volts are applied between the anode and cathode. The current then begins suddenly. At much higher voltages the current increases about in proportion to the square of the voltage. This type of electron discharge is radically different from that in the pliotron or kenotron, where the electrons pass directly from cathode to anode and liberate all their energy at the anode in the form of heat.

Dr. A. W. Hull* has constructed a device called the dynatron, in which secondary electron emission from a metallic anode is made use of to produce a true negative resistance.

The device consists essentially of a filament, a plate, and a perforated anode (or grid) located between the filament and plate. The anode being maintained at a positive potential of, say 200 volts, attracts the electrons from the cathode, but most of these pass through the perforations of the anode and strike the plate unless this is at too low a potential. If the plate is at a potential of over 25 volts, some secondary electrons of low velocity are emitted and these pass to the anode. The emission of the secondary electrons thus decreases the current to the plate. When the plate voltage is raised to about 100 volts,

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* Annalen der Physik 32, 673 (1910); Leipziger Berichte 63, 31 (1911); Annalen der Physik 53, 21 (1914)

the number of secondary electrons emitted is about equal to the number of primary electrons striking the plate, so that the plate loses about as many electrons as it gains, and the current falls to zero. With a further increase of plate voltage the number of secondary electrons exceeds that of the primary, so that the effect of the electron bombardment of the plate is to cause it to give up more electrons than it receives. Thus the current to the plate flows in the opposite direction to the applied potential, but under certain conditions is proportional to this applied voltage. Thus the plate circuit has a characteristic exactly like that of a negative resistance.

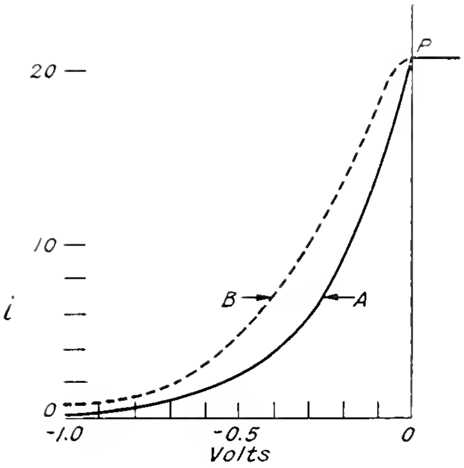

Fig. 1

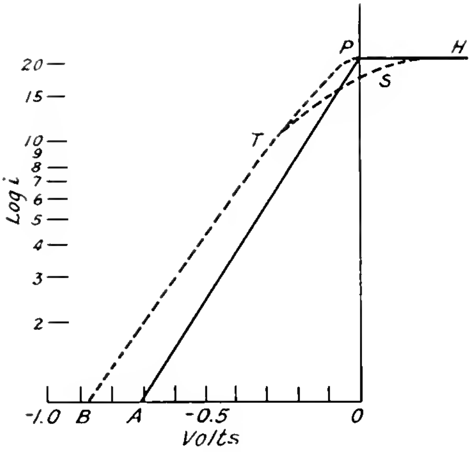

Fig. 2

This secondary electron emission is not normally of importance in the pliotron, but under exceptional circumstances, as for instance, when very high grid potentials are used, the secondary emission from the grid may produce very remarkable results. Thus with very high grid voltages the grid current may reverse in direction, so that electrons flow from the grid to the anode. If there is sufficient impedance in the grid circuit the grid thus becomes still more positively charged until its potential approaches that of the anode. In high power tubes this may lead to extreme electron bombardment of the grid and undue heat production. Such effects are easily avoided by limiting the positive potentials of the grid to reasonable values.

Volt-ampere Characteristics

If we determine the volt-ampere characteristics of any two-electrode electron device or kenotron, over a wide range of voltages, including negative anode voltages, we obtain, in general, a curve consisting essentially of three parts:

(*a*) A region in which the current is determined by the initial velocities of the electrons; (*b*) a region where the current is determined by space charge; and (*c*) the saturation region in which the current is determined by the electron emission from the cathode. The laws of variation of current with voltage and with temperature in these three regions are totally distinct from one another.

(a) Current Limited by Initial Velocities

With negative anode voltages the current varies with the voltage according to a law derived from Maxwell's Distribution Law.

In this region the current is dependent on the number and velocities of the electrons emitted and is therefore extremely sensitive to filament temperature.

In applying Maxwell's Distribution Law it is necessary to know exactly the shapes of the electrodes.[†]

In the ideal case of parallel plane electrodes, the current should increase exponentially with the voltage of the anode, that is, for each increment of voltage, the current should increase in the same ratio. Fig. 1 illustrates more clearly the way that the current varies

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[*] Phys. Rev. 7, 141 (1916); Proc. Inst. Radio Eng. *6*, 5 (1918).

[†] See Richardson, Phil. Mag. *16*, 353, 890 (1908); *17*, 813 (1909); *18*, 681 (1909).

with the voltage. The curve A P is an exponential curve. In this curve the anode voltage is plotted as abscissa and the current passing to the anode is given as ordinate. It is seen that this Maxwell's Distribution Law is observed only with negative anode voltages.

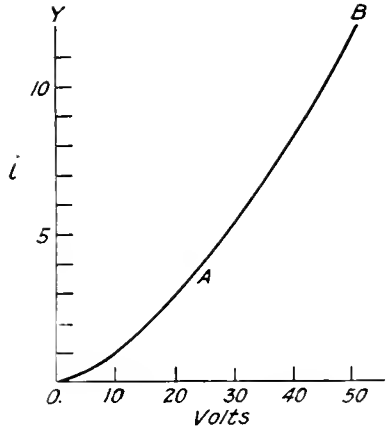

Fig. 3

For each increase of 0.2 volt in the anode voltage the current increases by a little more than two-fold.

If now, instead of plotting this curve as current against voltage, we plot the logarithm of the current against the voltage, we obtain a straight line as is shown by the line A P of Fig. 2.

The slope of the line A P in Fig. 2, is not arbitrary, but can be calculated by Maxwell's Distribution Law. The slope is inversely proportional to the temperature of the cathode. It is apparent at once that there is a very great advantage in plotting the volt-ampere characteristics over this range as in Fig. 2, that is, plotting the logarithm of the current instead of the current itself.

The simplicity of the relationship denoted by the line A P in Fig. 2 is due to the fact that between parallel plane electrodes it is only the velocity component perpendicular to the surface which determines whether the electrons emitted from the surface of the cathode are able to pass to the anode. When the anode or cathode are not in the form of parallel planes their relationships are in general more complicated.

With a small cathode which might practically be considered as a point, at the center of a spherical anode, it is evident that all the electrons striking the anode are moving in a direction perpendicular to the surface of the anode. Under these conditions it is not the velocity component in the given direction among the electrons escaping from the cathode which is important but rather the total velocity. This velocity is distributed according to a somewhat different law from that which applies to the velocity component, so that another form of Maxwell's Distribution Law must be applied.

By the dotted line B P in Fig. 2 it is shown approximately how the characteristics of a device in the region where the current is limited by the effect of initial velocities is modified by the use of electrodes which are not in the form of parallel planes. The exact shape of this curve depends on the shape of the electrodes, but in general the curve is horizontal where it meets the axis O P at the point P, and tends to be parallel to the line A P for the larger negative voltages.

Schottky* has discussed in detail the characteristics of a thermionic device having a straight filament mounted in the axis of a cylindrical anode. He avoided complications due to the end effects in the cylinder by having two auxiliary cylinders placed at the ends of the main cylinder; he also avoided complications due to the potential drop along the filament by using a rotating commutator.

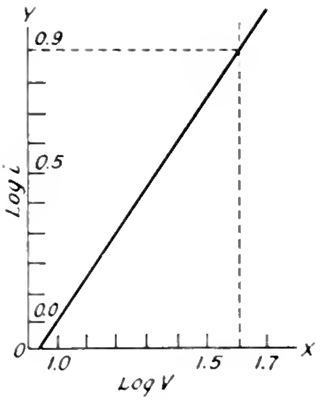

Fig. 4

He found that with currents of the order of magnitude of one tenth of a milli-ampere the experimental curves depart considerably from the theoretical curves because of the space charge effect. With currents as low as 10^{-6} ampere this effect is, however, not appreciable.

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* Annalen der Physik 44, 1011, 1914.

Where the effect is absent the curve is of the type shown by B P H of Fig. 2.

The part of the curve represented by the horizontal line P H corresponds to the saturation current, and is therefore determined by the electron emission solely. Schottky finds that in general there is a transition curve such as that shown by T S H in Fig. 2, between the part of the curve where the current is limited by the effect of initial velocities and the part where it is limited by electron emission.

With electron tubes which operate with currents of the order of milliamperes, the part of the curve in which the current is limited by the initial velocities is only a very negligible part of the whole curve.

(b) Current Limited by Space Charge

In the second region the current increases in proportion to the 3/2 power of the applied voltage, and is practically independent of the filament temperature. In this range where the current is limited by space charge the relation between the current and the voltage is like that shown in Fig. 3. If instead of plotting the volts and the amperes we plot the logarithm of the current against the logarithm of the voltage, or if we plot the current and the voltage on logarithmic paper, we obtain a straight line as indicated in Fig. 4. The slope of this line is not arbitrary but is always 3/2, that is, for any given increment of the abscissæ the increase in the ordinates is 1.5 times as great. It is readily seen that the law according to which the current increases with the voltage, as shown by Fig. 4, is very different from that which applies to the current limited by initial velocities (Fig. 2). In the latter case in order to obtain a straight line, the logarithm of the current was plotted directly against the voltage, whereas in the present case it is plotted against the logarithm of the voltage. Furthermore, it should be noted that in Fig. 4, which applies to space charge, the slope and position of the line are independent of the cathode temperature, while the slope of the line in Fig. 2 is inversely proportional to the temperature, and the position of the line is also affected by the temperature since the line must pass through the point P (Fig. 2) and the ordinate of this point increases in proportion to the electron emission.

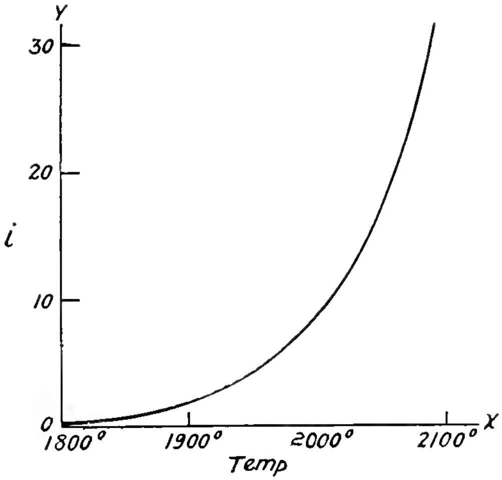

Fig 5

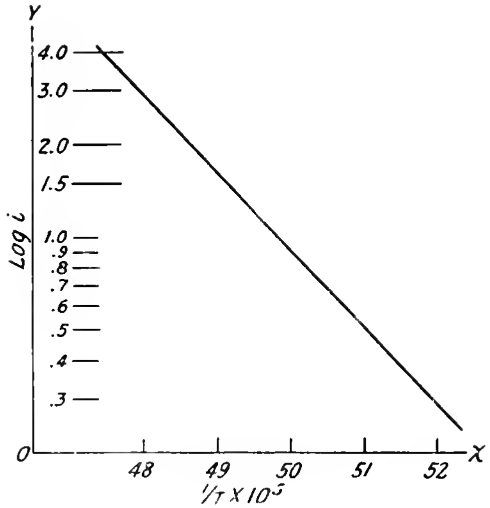

Fig. 6

Current Limited by Electron Emission

In the third region the current is independent of the applied voltage but varies with the temperature according to Richardson's equation and thus increases extremely rapidly with the temperature.

The curve which represents the variation of current with voltage is thus a straight horizontal line. The current increases with the temperature very rapidly, as shown in Fig. 5. The ordinates represent the current and the temperatures are plotted as abscissæ. This rate of increase with temperature is very much more marked than that shown in Fig. 3.

Furthermore, the curve approaches the axis O X asymptotically and practically coincides with it for all temperatures below a certain value. Above that temperature it departs very rapidly and curves upward at a high rate.

In Fig. 6 is plotted the same curve as that shown in Fig. 5, except that the logarithm of the current is plotted against the reciprocal of the temperature, so that we obtain a straight line.*

Let us now consider how the three types of characteristics just discussed combine to form the complete volt-ampere characteristic of an electron tube. With three-electrode tubes or pliotrons let us assume at first that the grid is connected to the anode.

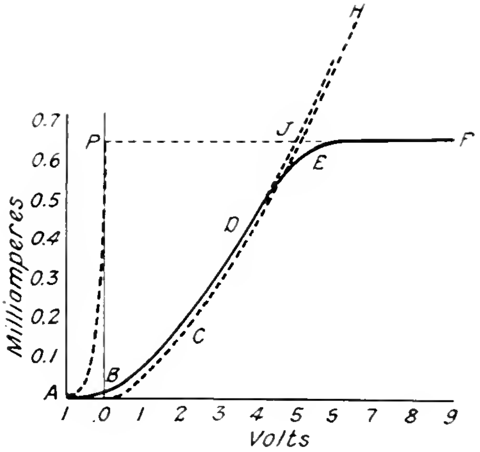

Fig. 7

With very low filament temperature, where the saturation current is of the order of a microampere or less, the space charge effect is practically absent. For negative anode voltages the current is thus determined by the initial velocities, while at positive anode voltages the current is saturated. The volt-ampere characteristics are thus of the type shown in Figs. 1 and 2. There is normally a transition curve as indicated by T S H in Fig. 2 between the region in which the current is (*a*) limited by initial velocities and that in which it is (*c*) limited by electron emission.

When the filament temperature is raised so that the saturation current is of the order of milliamperes, the volt-ampere characteristics undergo a very fundamental change. The space charge then becomes the predominating factor. As an example, let us consider the characteristics of a kenotron having a cylindrical anode one inch in diameter and two inches long with a tungsten filament of 0.005 inches diameter in its axis.

The full line A B D E F in Fig. 7 gives the characteristics to be expected for such a tube when the filament temperature is 1980° K., giving a saturation current of 0.65 milliamperes. The dotted line A P shows the limitation of current calculated from Maxwell's Distribution Law. This curve corresponds exactly to the curve A P of Fig. 1. Thus, if it were not for the space charge effects the current would vary with the voltage according to a curve A P J F. As a matter of fact, if large negative potentials are applied to the anode so that the current flowing is very small (of the order of 10^{-6} ampere) the volt-ampere curve does actually follow accurately the curve A P, but as is seen by inspection of Fig. 7, the ordinates of the curve with such low currents are entirely invisible when plotted on the scale used in Fig. 7.

If the effects of initial velocities were wholly negligible no current would begin to flow until a positive potential is applied to the anode. The current would then increase according to Equation 5, that is, the current would increase in proportion to the 3/2 power of the voltages as shown by the curve O C H of Fig. 7, until the current is limited by the electron emission from the cathode. In other words, under these ideal conditions, the current increases according to the curve represented by the dotted line O C J and then follows J F representing the saturation current.

Actually, however, because of the initial velocities there is a certain current flowing to the anode even when the potential of the anode is zero. The current under these conditions is dependent not only on the initial velocities, but to an even greater degree on the space charge produced by the electrons flowing across the space due to their initial velocities. The actual volt-ampere characteristic is therefore of the type given by the curve A B D E F of Fig. 7.

The deviations of the curve A B D from the curve O C H are due to initial velocities. The curve A B D theoretically follows the curve A P until a current of a few microamperes is reached; the curve then departs radically from the curve A P and takes the course indicated by A B and tends to approach the curve O C

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*Strictly speaking, the logarithm of the current divided by the square root of the absolute temperature should be plotted in order to get Richardson's equation. However, this square root term produces an effect that is hardly perceptible in any ordinary plot.

or rather tends to become parallel to it, differing from it only by a value corresponding to a few tenths of a volt.

Let us now consider the case where the filament temperature is raised, so that the electron emission from the filament is 50 milliamperes. This requires a filament temperature of about 2360° K., which is rather lower than the normal operating temperature of the filament on an ordinary tungsten lamp.

If we substitute in equation 5, $i = 0.010$ amperes per centimeter of length (corresponding to 50 milliamperes for a five-centimeter length) and place $r = 1.25$ centimeters and solve the equation for V, we find $V = 90$ volts. This indicates that a voltage of 90 volts is required to overcome the space charge effect when a current of 50 milliamperes is used, assuming the initial velocities of the electrons to be negligible. The volt-ampere characteristic is thus given by the curve A D F in Fig. 8.

The curve O D J H in this figure represents the $3/2$ power relation calculated from Equation 5. For voltages above a few volts the volt-ampere characteristics of the device considered should follow the theoretical curve so closely that on the scale used for Fig. 8 the difference between the two curves would be hardly visible. If the filament temperature were so high that a large surplus of electrons was produced the current would increase indefinitely along the curve O D J H. Actually, however, since the filament at 2360° K. emits only 50 milliamperes, the current cannot increase above the line represented by P F.

If the voltage on the anode is zero the effect of initial velocities is to cause some current to flow to the anode. This current is limited, however, mainly by space charge although it is larger than at lower filament temperatures.

The curve corresponding to the distribution of the initial velocities of the electrons according to Maxwell's law is represented in Fig. 8 by the dotted line A P, which corresponds exactly to A P in Fig. 1. For negative voltages on the anode of such magnitude that the current is of the order of microamperes or less, the actual volt-ampere characteristic represented by the line A D will theoretically approach the line A P, but of course currents as small as this represented on the scale of Fig. 8 would give ordinates much too small to see.

From the foregoing discussion it is clear that the volt-ampere characteristics of two electrode devices consist essentially of the three parts in which the currents are limited respectively by (*a*) initial velocities of the electrons, (*b*) space charge, and (*c*) total electron emission. However, over certain parts of the characteristic two factors may operate simultaneously. Thus there are transition curves like those shown in Fig. 2 by T S H, in Fig. 7 by A B and D E F, and in Fig. 8 by D E F. This latter form of transition curve, namely, that between the space charge and the saturation regions is the one that concerns us most directly in electron tubes. The extent or length of this transition curve depends upon several factors of which the following are probably the most important:

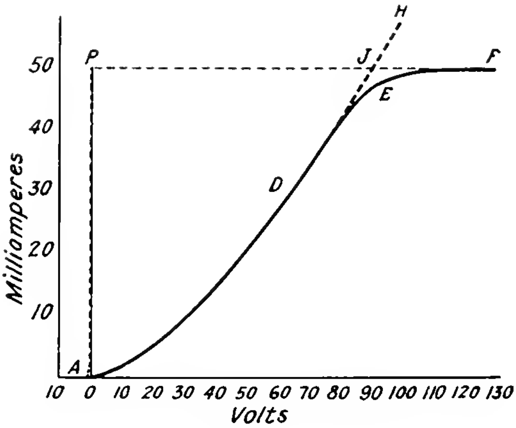

Fig. 8

Non-uniformity of the Field Around the Cathode

In the case of a straight filament in the axis of a long cylindrical anode, the field around the cathode is greater at one end than at the other, because of the effect of the voltage drop along the filament. Thus as the voltage of the anode is gradually raised, the current from some parts of the cathode becomes saturated before that from other parts, and this effect tends to extend the range of the transition curve. A similar effect occurs in case the strength of field around the cathode is made non-uniform in any other way. Thus, if the filament is in the form of a V or W some parts may be closer to the anode than other parts. Or again, the grid-like effect of one part of the cathode or another part may cause differences in the field strength.

Lack of Uniformity of Filament Temperature

The cooling effect of the leads causes difference of temperature in the filament and the current from some parts becomes saturated before that from other parts. This also extends the range of the transition curve.

Heterogeneity of the Surface of the Cathode

This effect, which has been discussed at length in connection with the electron emission from filaments, is of particular importance in affecting the transition curve between the space charge and the saturation regions.

The Effect of the Grid in Pliotrons

The action of the grid is to modify the effect of the space charge. A positive charge on the grid partly neutralizes the space charge of the electrons and thus increases the current-carrying capacity while a negative charge has the reverse effect.

In general, when the current is limited by space charge the electron current I depends on the anode voltage V_a and the grid voltage V_g according to the equation*

$$I = K\ (V_a + kV_g)^{3/2} \qquad (6)$$

Here K and k are constants depending on the construction of the electrodes.

By taking the logarithm of this equation and differentiating we can readily find that the exponent n according to which the current increases with the anode voltage is

$$n = \frac{d\ log\ I}{d\ log\ V_a} = \frac{3}{2}\,\frac{1 + k\dfrac{d\,V_g}{d\,V_a}}{1 + k\dfrac{V_g}{V_a}} \qquad (7)$$

Thus, if the grid is at the potential either of the cathode or of the anode, the exponent is 3/2. The same is true if the grid voltage is increased in proportion to the anode voltage, V_g/V_a remaining constant. If, however, the grid voltage is kept constant while the anode voltage is varied, Equation 7 becomes

$$n = \frac{3}{2}\,\frac{1}{1 + k\,(V_g/V_a)} \qquad (8)$$

Thus, when the grid is positive with respect to the cathode the exponent n is less than 3/2 while for negative grid voltages n becomes greater than 3/2. Measurements of the characteristics of tubes show this relation clearly. A receiving tube (pliotron) with zero volts on the grid gave for the exponent n the value 1.54. For a positive grid potential of 2 volts the exponent was 1.3 while for a negative potential of two volts it was 1.9 and for ten volts it was 3.6.

If the grid and the filament are of different materials there will be in general a contact difference of potential between them even when they are connected together. Thus, if the grid is of nickel and the cathode is of a material having a much higher electron emission (such as a Wehnelt cathode or thoriated tungsten cathode), the grid will have a negative potential with respect to the cathode. The exponent should thus be greater than 3/2 if the grid is connected to the cathode. In order to bring the grid to the same potential as the cathode, a positive electro-motive force should be applied to the grid sufficient to compensate for the effect of the contact potential. In the case of a nickel grid and a Wehnelt cathode this contact difference should be about 2.2 volts,† so that there should be a material effect on the exponent n.

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* Langmuir, Proc. Inst. Radio Engs. *3*, 278, (1915) GENERAL ELECTRIC REVIEW *18*, (1915).

† The constant b of Richardson's equation for a Wehnelt cathode (50 per cent BaO and 50 per cent SrO) has been given by W. Wilson (Phys. Rev. *10*, 79 [1917]), as approximately 25,000 degrees corresponding to 2.14 volts. According to a method of calculation given by Langmuir (Trans. Amer. Electrochem. Soc. *29*, 165-166 [1916]), the probable value of b for nickel is 50,000 degrees, corresponding to 4.32 volts. The contact potential is the difference of these or 2.18 volts.

The Safety Car

By W. D. Bearce

Railway and Traction Engineering Department, General Electric Company

Some five years ago a movement was started toward a reduction in car weights and the consequent reduction in operating cost. In order to provide equipment to compete with the jitney automobiles then thriving in the West and Southwest the so-called safety car was made unusually light with ample power for rapid acceleration and was handled by a single operator. The success of the venture was immediately apparent and engineers and car designers then started the standardization which has since been attained in this equipment. Necessarily the preliminary information that was available regarding the safety car was based on engineering estimates; and while these figures were reasonably accurate actual operating results are much more convincing. In the following article the author has included figures of this kind from all parts of the country.—Editor.

During the past few years the electric railways of the country have been confronted with rapidly increasing cost of operation while their gross income has remained practically unchanged. A vast amount of study and attention has been given by the engineering and financial interests to assist the railways in the continuance of business under the existing unfavorable conditions.

The most encouraging results achieved by these studies have been the development and the many successful installations of the one-man light-weight safety car. Examples of what may be accomplished by this radical departure from the ordinary method of street railway transportation may be found in almost every section of the United States. Briefly stated, the reasons for the success of this innovation are:

1. Improvement in service.
2. Freedom from accidents.
3. Increase in riding habit.
4. Lower maintenance cost.
5. Reduction in labor cost.
6. Reduction in power consumption.

As a result of these features, the operating company's net income has shown a marked improvement in almost every case. This increase in gross receipts, combined with the marked reduction in cost of operation, effects sufficient saving to insure profitable operation of roads previously run at a loss.

Report of A.E.R.A. Committee

The conclusions of the committee on one-man car operation presented to the American Electric Railway Association in October, 1919, represent the findings of a competent body of operating men on this subject:

1. The safety car is one of the most important improvements in street railway service that has appeared for many years. Its valuable features in the order of their importance are:

(a) Greatly improved service to the public, both as to frequency and safety.

(b) Increased earnings for the company.

(c) Decreased operating expenses.

2. One-man operation alone, while useful in saving platform expense in the smaller communities, is not comparable with the improved service that can be obtained by the light-weight safety car with its more frequent headway and greater average speed.

3. The savings obtainable from one-man cars should be shared with the trainmen in the form of a higher hourly rate for the operators of such cars than is paid to the trainmen on two-man cars.

4. When inaugurating one-man car service, it is good policy to assure the trainmen that no one will lose his job due to putting in the new cars. They are installed, as a rule, on a line at a time; and experience has proved that the company is not burdened with extra men through this policy.

5. From the nature of the traffic available, the safety cars can accomplish more in a large city than in a small one, for the reason that the possibilities of increasing riding in the small community are limited. This statement is made to correct the erroneous impression existing in some minds that the safety car is useful only for saving expense in the smaller cities.

6. Where traffic is believed to be too heavy on the peak to be successfully handled by safety cars, the larger, heavy cars may be used for tripper service on the peak, thus making the light cars handle the long hour runs.

7. Similarly, where snow storms require the use of the heavier equipment at rare intervals, the safety cars can still be used to advantage during other times.

8. The safety car, though light, is just as substantial and with the same care in maintenance should last just as long as the former types of car. It has a steel frame and thoroughly modern, ventilated, interpole motors.

9. Regarding the matter of standardization, your Committee was not unanimous, but the majority opinion favored adhering to the present standard design of the safety car in the interest of cheaper costs through quantity production.

10. Experience has shown that the overwhelming majority of both riding public and trainmen favor the one-man safety car; that it can, at one and the same time, improve the public's service, increase the trainmen's wages, and raise the company's profits; that it can be operated for about half the cost of an ordinary car; and that most of the companies that have tried it want more. We predict an increasingly rapid extension of the use of a device that can make a showing like the above.

Fig. 1. Safety Car in the Business District, Gary, Ind.

Fig. 2. Safety Car Built for the Eastern Massachusetts Street Railway Company, Boston, Mass.

Fig. 3. Safety Car on the Lines of the Austin Street Railway Company, Austin, Tex.

Fig. 4. A Few of the 66 Safety Cars Handling City Traffic in Terre Haute, Ind.

General Features of the Safety Car

The standard safety car which is most commonly used is approximately 28 feet in length and seats 32 passengers, when arranged for double-end operation. By utilizing the rear end, three additional seats can be obtained when the car is desired for single-end operation only. The body is mounted on a single truck with 26-inch wheels and a wheel base of about eight feet. The construction of the truck is such that the car has excellent riding qualities and it is possible to use accelerating speeds comparable to those of the competing automobile without discomfort to the passengers.

The safety car, completely equipped, weighs about eight tons. It is of all steel construction and is built to a standard form and size. The roof is of the arched type and the sides are of steel with windows arranged for opening when desired. The platform is on the same plane as the body floor and folding doors and steps are equipped with mechanical opening and closing devices under the control of the operator.

The electrical equipment of the car consists of two 25-h.p. ventilated type railway motors, a controller, special light-weight grid resistors, and a motor-driven air compressor having a capacity of 10 cu. ft. per minute. The air brakes include various safety features and labor saving devices. The safety control equipment is especially adapted to one-man operation; the brakes, doors, steps, and sanders being controlled by a single brake handle and mutually interlocked.

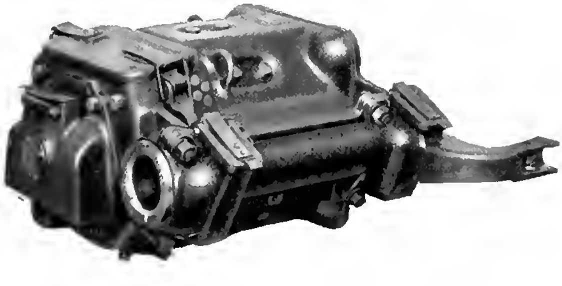

Fig. 5. 25-h.p. Railway Motor Equipped with Ball Bearings for Light Weight Safety Car

As may be gathered from the foregoing and from the following detailed description of the air brakes and safety devices, the requirements of this type of car have been studied out with great care; and to quote again from the report of the American Electric Railway Association the development of this equipment has resulted in:

> The creation of an entirely new type of car of low weight, greatly improved safety, and more rapid acceleration and deceleration. This car of the light-weight safety type not only saves platform and accident expense, but permits of an improvement in service, such as well nigh to revolutionize the street railway business.

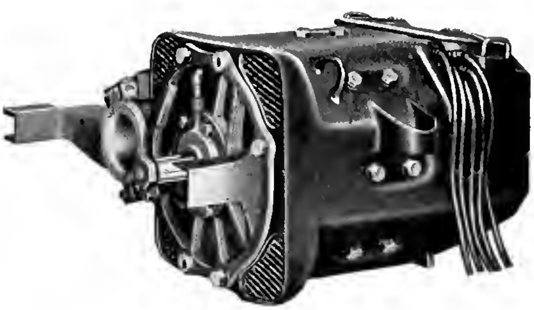

Fig. 6. 25-h.p. Railway Motor for Light Weight Car Equipped with Standard Sleeve Bearings

Improvement in Service

The effect of improved service by the use of safety cars is best shown by the actual results in Table I.

TABLE I

	Per Cent Increased Service	Per Cent Increased Gross Receipts
Houston, Texas	80	60
El Paso, Texas	44	43
Tacoma, Wash.	45	41
Seattle, Wash.	55	67
Gary, Ind.	62	46
Terre Haute, Ind.	77	44
Tampa, Fla.	51	51
Bridgeport, Conn.	125	100

Power Consumption

Because of the increased cost of power, due to the high price of coal, labor, and materials, the reduction in energy consumption secured by the use of light-weight safety cars is an important factor in their success. In some cases the adoption of this equipment has actually postponed indefinitely the purchase of additional power equipment. The power consumption is, of course, dependent upon the weight of the car, the number and duration of the stops, the speed profile of the line, etc. It is, therefore, difficult to make any definite statement as to the actual power consumed, except for a specific case, but it is evident that a car weighing eight tons with two motors should operate with an energy consumption of approximately one third that of a 24-ton car equipment with four motors. The average consumption on most city railway systems is approximately three kilowatt-hours per car mile. According to the A.E.R.A. report, the actual figures from forty-five companies show the energy consumption of safety cars to range from 0.8 to 1.75 kilowatt-hours per car mile.

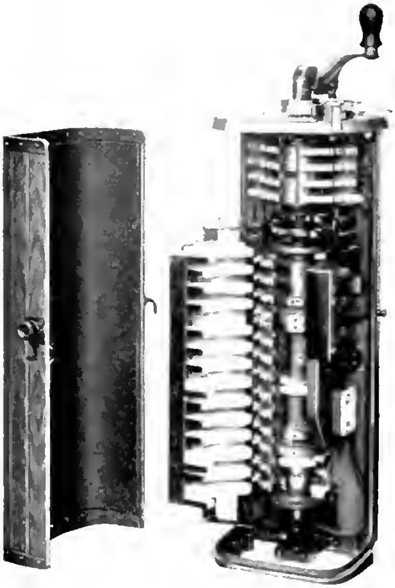

Fig. 7. Standard Platform Type of Controller Used on Safety Cars

Safety Car Installations

The total number of light-weight safety cars in operation and on order in the United States at the present time is approximately 3400, not including rebuilt cars, many of which have been equipped with safety features and are operated by one man. In general, the rebuilt cars have been used only on lines of light traffic, and their general use is not recommended.

By taking the results of many investigations as a basis it is possible to make a study of the financial results of replacing the ordinary types of heavy rolling stock, using present-day costs of operation, and thus secure a fairly accurate idea of what return can be counted upon for an investment made in safety cars. All such studies so far made, confirmed by actual results in every existing installation, indicate that the majority of roads cannot well neglect placing some of these cars in their service.

For instance, there are thousands of standard city cars which weigh about 40,000 lb. and seat an average of 40 passengers. The safety car weighs 16,000 lb. and seats 32 passengers. Its motive power consumption is approximately 40 per cent that of the heavier car. Its maintenance will be about 40 per cent less. In many instances, where the cars replaced are exceptionally old or obsolete, the saving in maintenance will be much greater. The power ratio of about 40 per cent has been repeatedly checked and verified; and the maintenance records of the earliest installations indicate that the ratio shown is accurate after the cars have been in service from two to three years.

Table II shows the saving in equipment maintenance and power which can be secured by the use of safety cars.

TABLE II

POWER AND MAINTENANCE CHARGES

Cents per Car Mile

	40,000-lb. Car	16,000-lb. Car
Equipment maintenance	3.5	2
Power	4.2	2
Total	7.7	4

A car operating 18 hours daily on an 8.5 m.p.h. schedule, which is the average for city service in practically all parts of the country, will run approximately 56,000 miles a year. The heavy car costs for power and maintenance, when making this mileage, $4312; the safety car $2240, a saving of $2072.

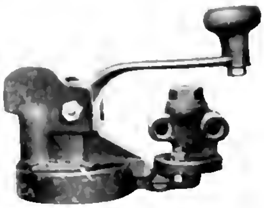

Fig 8 Operating Handle for Safety Car Controller with Base and Pilot Valves

The platform expense for a two-man car averages $1.20 per car hour. An all-day car, including a five per cent allowance for reporting and lay up time, will run approximately 6900 hours per year, costing in wages $8280.

It has been customary to pay the operator of a one-man car a higher wage than either member of a two-man car. The average platform expense for a safety car is 66 cents per hour. At this rate the platform expense for the safety car would be $4554 annually, or a saving of $3726 as compared with a two-man car.

Car for car, therefore, the safety car on all-day runs can save over $5700 per year and would pay for itself within 14 months. Car for car replacement is not recommended, as the best results are obtained by operating more cars on shorter headway thus providing improved service. Experience has proved that most lines will stand at least 40 per cent improvement in service. This can best be accomplished by operating about 30 per cent more cars and increasing the schedule speed 10 per cent. For instance, instead of operating ten cars on a ten-minute headway, operate thirteen cars on a seven-minute headway, giving 8.5 cars per hour instead of six, a 40 per cent increase. Reduced stops and the higher accelerating and braking rates of the safety cars enable such a schedule speed increase to be easily made.

The costs and effect of such an increase can be shown as follows, assuming that only the regular all-day cars are replaced, using existing equipment for rush-hour trippers:

Ten old cars, running 8.5 m.p.h. make 560,000 car miles annually at a cost for power, maintenance, and crew wages of $122,200.

Thirteen safety cars at 9.3 m.p.h. make 795,000 car miles per year; their cost for power, maintenance, and crew wages will be $88,300, a saving of $33,900, while providing 40 per cent more service.

The average receipts per car mile on street railways in the United States is 37.7 cents.

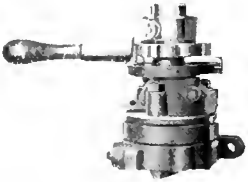

Fig. 9. Air Brake Valve for Safety Car Control Equipment

The total receipts, therefore, for the ten old cars in this case will be $211,120. Experience shows that a 40 per cent increase in service means approximately a 40 per cent increase in receipts. Assuming only a 20 per cent increase, this amounts to $42,200. The combined effect of reduced cost and increased gross income is a net increase in earnings of $76,100, or approximately $7600 per car annually for each heavy car displaced, which is equivalent to an annual return of 78 per cent on the first cost of fifteen safety cars. This provides two spare cars. Taking increased fixed charges on the increased capital account at 18 per cent to cover interest, depreciation, taxes, and insurance, there is still left a profit to the purchaser of better than 58 per cent annually—enough to wipe out their cost in approximately two years.

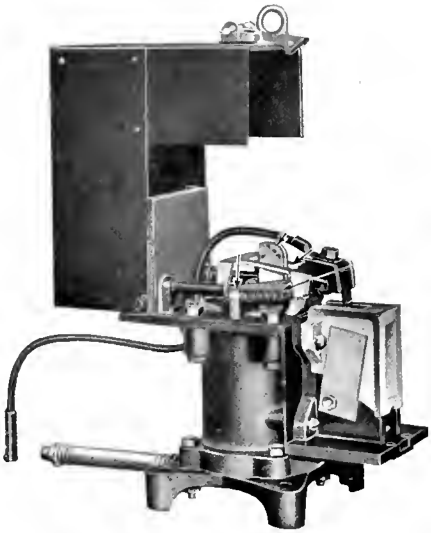

Fig. 10. Automatic Air Compressor Governor Controlling Operation of Motor-driven Compressor

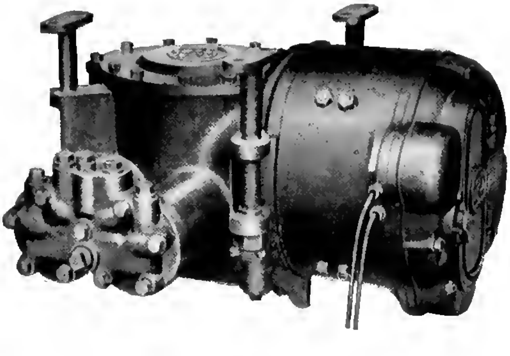

Fig. 11. Standard 10-cu ft. Air Compressor with Tee Bolt Suspension

Where traffic does not warrant increased service and the replacement is made car for car, 11 cars would probably be sufficient for a ten-car line. The net savings would be approximately $58,000 which is equivalent to an annual return of approximately 80 per cent of the first cost of 11 safety cars.

Probably in wide-spread applications some lines would fall into one category, some into the other. An average result would unquestionably show, after paying all increased fixed charges including amortization, between $5000 and $6000 profit for each car displaced, a sum sufficient to pay the interest at 6 per cent on $80,000 to $100,000 worth of securities.

The data in Table III illustrate the economies and increased earning possibilities for each car displaced. The figures in column *A* are based on running equal mileage with no increase in cars; those in column *B* are based on running 40 per cent more mileage with 30 per cent more cars.

TABLE III

Savings Made With	A Equal Mileage	B 40 Per Cent Increase
Maintenance of equipment, annual saving	$ 840	$ 370
Power	1232	760
Crew wages	3726	2280
Total savings	$5798	$3410
Increased receipts at 20 per cent		4222
Increase in net earnings	$5798	$7632
Annual return on cost of safety car, approximately	80%	78%

The foregoing values are based on average costs for labor and on the replacement of the heavier types of city cars. Average wage scales in many properties are materially lower and power consumption less. Many, moreover will show lower average receipts per car mile. Under such conditions the savings of the safety car become less, but are still remarkable as is evidenced by the figures in Table IV, representing about the lowest costs anywhere in the country today; they are the averages of representative roads operating in the smaller cities of the middle west and south. The average weight of the cars is 30,000 lb.; their average platform expense is 11.3 cents per car mile and their average receipts 30 cents per car mile.

Even under these circumstances, the new cars would pay for themselves in less than two years; or if from these increased earnings be deducted interest, depreciation, taxes, and insurance, there remains a clean profit of from $3500 to $5000 for each car displaced.

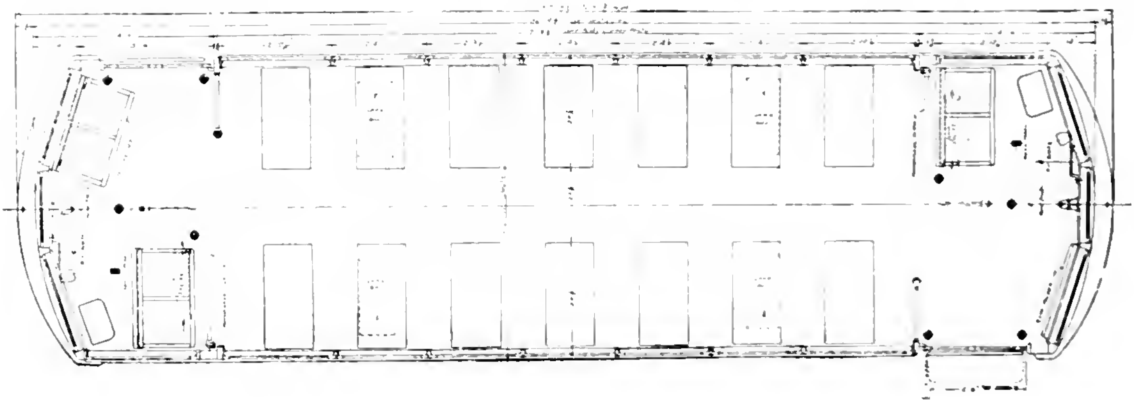

Fig. 12 Floor Plan of Standard Safety Car

Motor Equipment

The electrical equipment developed for the safety car by the General Electric Company includes two 25-h.p. railway motors, a light-weight platform type controller adapted for use with standard safety features, special light-weight grid resistor, modified straight air brake equipment, also suitable for use with safety devices, and a ten-cubic-foot air compressor for supplying the air brake and accessory requirements.

Two types of motors have been most generally adopted for use on safety cars.

These were designed for this service and are, for their capacity, the lightest weight railway motors manufactured. One has ball bearings on the armature shaft and weighs approximately 885 lb. The other has sleeve bearings of liberal design and weighs approximately 1000 lb. The continuous capacity of these machines is so great that they operate at unusually low temperatures, and their performance during the past five years has been extremely satisfactory. This controller was designed for use on light-weight cars, is compact, occupies the minimum of platform space and weighs only 135 lb.

Air Brake and Safety Features

The air brakes with safety features and labor saving devices are of special importance when the responsibility for the operation of a car is placed in the hands of one man instead of the usual crew of two. In the design of this equipment, every effort has been made to guard against accidents that might be caused by the disability or the inattention of the operator.

This equipment is a modification of the well-known straight air brake with emergency features and safety devices which provide for bringing the car to a standstill automatically should the operator by reason of sudden physical or mental disability be unable to

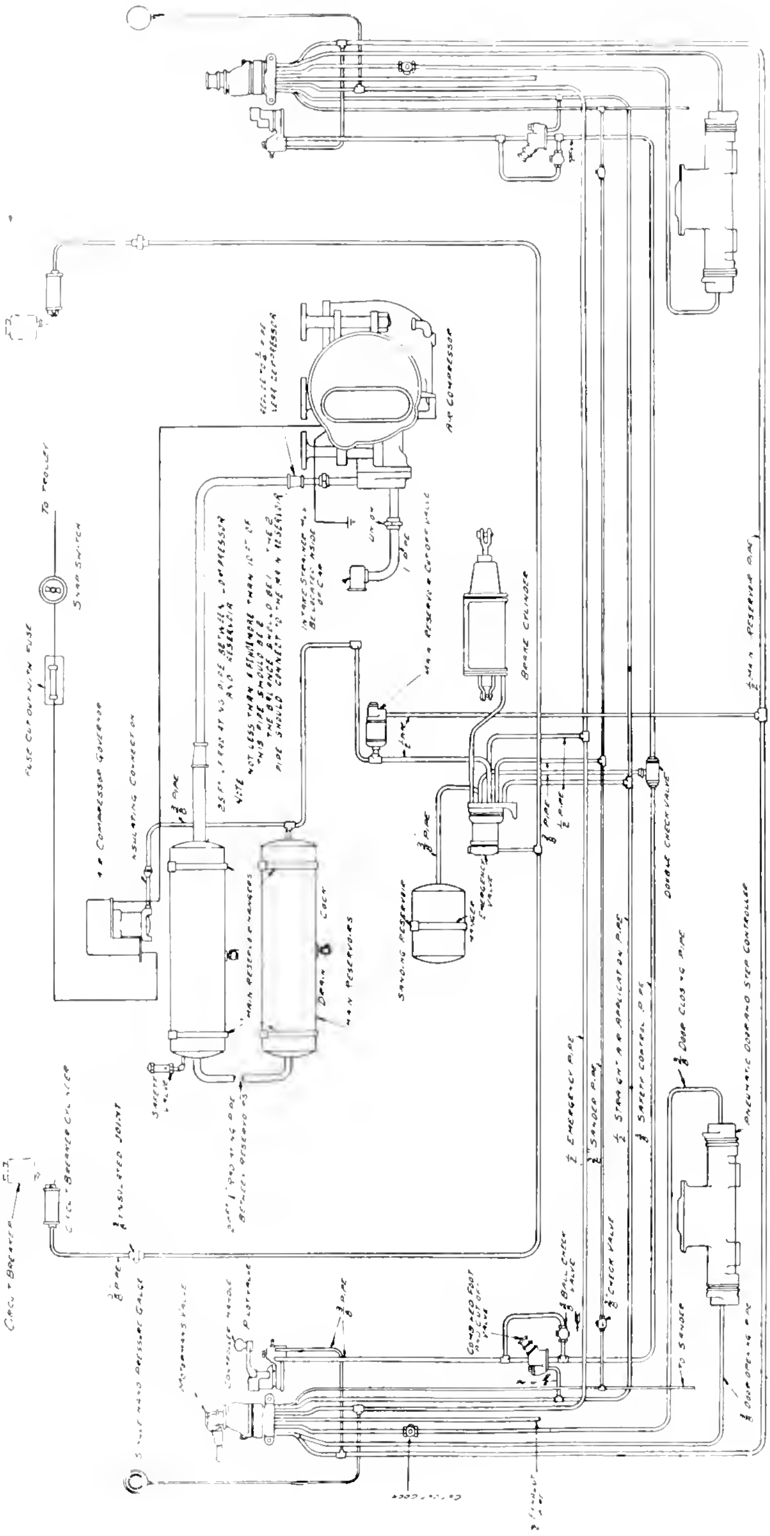

Fig. 13. Diagram of Double End Air Brake Equipment Used on Standard Safety Car

perform his duties properly. Normally, the brakes, doors, steps, and sanders are controlled by the operator by means of a single brake valve, making it unnecessary for him to remove his hand from the brake valve handle to open the doors after the car has been brought to a stop, to close them when he is ready to proceed, or to manipulate the automatic sander. The brake valve is so constructed that a downward pressure on the handle in any of the several positions will cause sand to be applied to the rail.

The safety controller handle, which is an important part of this equipment, is so interlocked pneumatically with the brakes, doors, steps, sanders, and a circuit breaker tripping device as to cause the brakes to be applied automatically with full force if the operator removes his hand from it without having first made a brake application. In addition, the circuit breaker is opened, sand is applied to the rail and the doors are balanced so that they may be opened manually, if desired.

To relieve the operator of the necessity of keeping his hand on the controller handle at all times while the car is in motion, a relief valve known as the combined foot and cutoff valve is provided. This valve is installed in the safety control pipe and is located on the platform in such a position that the operator can reach it with his right foot. By holding this valve closed, the "dead-man" feature is transferred from the controller handle to the foot valve. The latter is automatically held closed when a brake application of sufficient force to insure bringing the car to a stop has been made.

It is impossible for the brakes to "leak off" through carelessness on the part of the operator in leaving the car with the brake valve handle in the "lap" position by reason of the fact that the combined foot and cutoff valve will automatically open if the brake cylinder pressure falls below a safe minimum. The opening of the foot valve under these conditions will result in emergency operation under which the brakes are applied with full force and maintained against leakage.

An emergency valve, which is located inside the car, automatically controls the brakes, door engines, sanders, and circuit breaker cylinders under emergency conditions. This valve is actuated by a sudden reduction in pressure in either the safety control pipe or emergency pipe, hence it will operate: (1) if the operator removes his hand from the controller handle (or his foot from the foot valve) when the brakes are not applied, (2) if the operator moves the brake valve handle to the emergency position, or, (3) if the pipe on either end of the car is accidentally broken or ruptured.

In all positions of the brake valve, except the door-opening position, the door-closing pipe is connected to the emergency line, hence when emergency operation takes place from any cause, pressure is automatically removed from the closing side of the door engines which permits of the doors being opened manually.

TABLE IV

OPERATING COSTS

Cents per Car Mile

	30,000-lb. Car	Safety Car
Maintenance of equipment	2.5	1.5
Power	3.4	2
Total	5.9	3.5
Platform expense	11.3	6.23

All-day Service

Savings Made With	Equal Mileage	40 Per Cent Increase
Annual savings on maintenance	$560	$210
Annual savings on power	780	320
Annual savings on platform expense	$2840	$1870
Annual savings on total	4180	2400
Increased receipts at 20 per cent		3360
Increased net earnings	$4180	$5760
Annual return on cost of safety car, approximately	58%	63%

In the normal position of the emergency valve, the sander reservoir is connected to the main reservoir, thus keeping the former fully charged. When the emergency valve operates, the sander reservoir is connected to the sanders and sand is blown onto the rail until the pressure in the sander reservoir is exhausted. This arrangement limits the time of automatic sanding in emergency and thus avoids an undue waste of sand.

Motor-driven Air Compressor

As compressed air is used for operating the brakes and all of the safety devices, it is imperative that the air compressor be of such design and construction as to insure continuity of service. The center-gear type air compressor is in successful operation on approximately 1000 safety cars in all parts of the country and has fully demonstrated its many superior qualities in this class of service where schedule speeds are high and the demand for air is greater than heretofore.

These machines have duplex cylinders fitted with single acting trunk type pistons, and are driven through herring-bone gearing by series-wound motors having four salient poles.

Air Compressor Governor

The functions of the air compressor governor are to start and stop the air compressor automatically so as to maintain the air pressure in the main reservoir within predetermined maximum and minimum limits. Air compressor governors were developed after a careful study of the rigid requirements of electric railway service, and are in successful use on thousands of cars throughout the country.

This type of governor is essentially a single-pole switch of the contactor type operated by means of a rubber diaphragm, a piston, and a set of levers. The interrupting switch is provided with an arc chute of highly refractory material, an effective blowout, and easily renewable contacts. The principal bearings are provided with hardened knife edges to reduce friction to a minimum, and to insure a quick snap action.

The Production and Measurement of High Vacua

PART II

METHODS FOR THE PRODUCTION OF LOW PRESSURES

By Dr. Saul Dushman

Research Laboratory, General Electric Company

This installment and the one which will appear in our succeeding issue describe some of the different types of pumps that have been developed for the production of high vacua. The August installment will deal mainly with the Langmuir condensation pump and will contain an appendix which gives detailed information regarding the actual set-up and operation of an exhaust system.—Editor.

Classification of Methods for the Production of Low Pressures

The methods for the production of low pressures may be classified conveniently under the following headings:

- I. *Mechanical Pumps*
  1. Piston pumps
  2. Toepler and Sprengel mercury pumps
  3. Rotary mercury pumps
  4. Rotary oil pumps
  5. Gaede "Molecular" pump
- II. *Mercury Vapor Pumps*
  1. Gaede "diffusion" pump
  2. Langmuir condensation pump
- III. *Physical-Chemical Methods*
  1. Charcoal or other absorbing agent at low temperature
  2. Clean-up of residual gases by chemical reactions
  3. Clean-up of gases by ionisation methods

General Theoretical Considerations Regarding Vacuum Pumps[1]

In comparing vacuum pumps it is necessary to consider the following factors, which are the main characteristics of a pump:

1. *Exhaust Pressure.* This is the pressure against which the pump may be operated. In general, the higher the degree of vacuum desired on the "fine" or intake side of the pump, the smaller the exhaust pressure should be. The low exhaust pressure is then obtained by means of another (so-called "rough") pump in series with the high vacuum pump. Two or more rough pumps may be used in series in order to obtain a sufficiently low exhaust pressure for the fine pump.

2. *Degree of Vacuum Attainable.* "This is the lower limit of pressure which may be attained in a closed vessel connected to the pump. With most types of pump the degree of vacuum attainable depends to a large extent on the exhaust pressure used. This is usually due to leakage through the pump." In the cases of the mercury vapor pumps, to be described in the next installment, there is theoretically no lower limit to the pressure

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[1] In writing this section, the author has made extensive use of the article by Dr. Langmuir on "The Condensation Pump," in General Electric Review, Dec., 1916, p. 1060.

which may be attained, while in the case of the Gaede molecular pump the limiting pressure bears a constant ratio to the exhaust pressure.

3. *Speed of the Pump.* The law for the rate of decrease in pressure in a closed vessel connected to a pump is quite similar to that of chemical and physical reactions of the first order. It may be stated as follows: If p_0 denote the lower limit of pressure attainable with the pump, then the rate of decrease in pressure at any instant is proportional to $p-p_0$, where p denotes the pressure at that instant. That is,

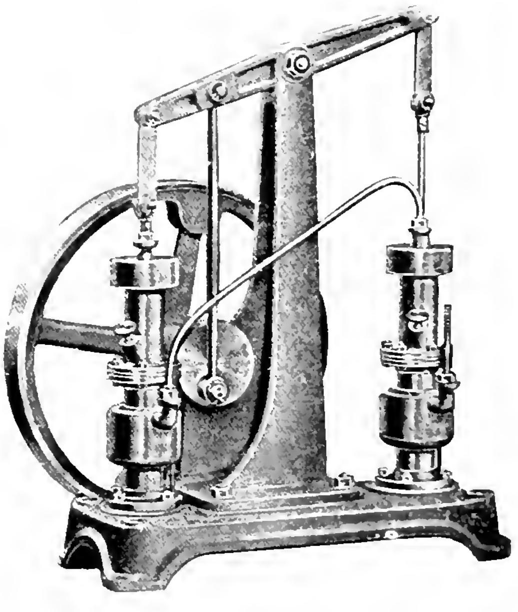

Fig. 3. Geryk Vacuum Pump, Power Drive

$$-\frac{dp}{dt} = k(p-p_0) \qquad (18)$$

where k is a constant. Further consideration shows that with a given pump the rate of exhaust must vary inversely as the volume (V) of the vessel to be exhausted. Thus we can write

$$-\frac{dp}{dt} = \frac{S}{V}(p-p_0) \qquad (18a)$$

where S is a *constant* for the given pumping system, that is, pump and connecting tubing. Integrating the last equation we obtain the relation,

$$S = \frac{V}{t}\,ln\left(\frac{p_1-p_0}{p_2-p_0}\right) \qquad (19)$$

where t is the interval of time required to reduce the pressure in the volume V, from p_1 to p_2.

Gaede has defined S as the *speed of the pump*, and it is ordinarily measured in cubic cm. per second. It is readily seen that from the above equation S may also be defined as follows:

With a pump of speed S, it is possible to reduce, in each second, the pressure in a volume S cm.^{3} by 63.2 per cent of the maximum possible decrease in pressure.

It is necessary to distinguish between the speed as defined in this manner and the actual speed of exhaustion, which we may denote by E. The latter is defined thus:

$$-\frac{dp}{dt} = \frac{E}{V}p$$

or

$$E = \frac{V}{t}\ln\frac{p_1}{p_2} \qquad (20)$$

It is only when $p_0=0$, that S and E are identical, and remain constant during the whole period of exhaust. In all other cases the speed of exhaust gradually decreases from the value S which it has at the beginning, and as the pressure in the vessel approaches the limiting pressure, p_0, E decreases rapidly until it becomes zero when the pressure has decreased to p_0.

The actual speed of exhaust depends not only upon the design of the pump but also upon the diameter and length of the connecting tubing between pump and vessel to be exhausted. The pump and tubing together really constitute a system which is the equivalent of a pump of lower speed. Mention has been made in a previous section of the results of Knudsen's investigations on the resistance to flow in tubes. According to these results, the quantity of gas, Q, flowing through a narrow tube is given by the relation

$$Q = \frac{p_2-p_1}{W\sqrt{\rho}} \qquad (12) \text{ and } (15)$$

where $W\sqrt{\rho}$, is the "resistance," and p_2-p_1 is the difference in pressure at the ends.

Let us now assume that the volume of the tube is negligible compared to the volume of the vessel to be exhausted, and that the limiting pressure for the pump, $p_0=o$. Let p_2 denote the pressure in the vessel and p_1 the pressure at the pump intake (end of the tube). Also let S_1 denote the speed of the pump itself, and S_2 the speed of pump and connecting tubing. Then since the quantity of gas taken out each second by the pump is the same as that flowing through the tube, we have the following relations:

$$Q = \frac{p_2-p_1}{W\sqrt{\rho}} = S_1\,p_1 = S_2\,p_2$$

Eliminating p_1 and p_2 from these equations, we obtain the equation,

$$\frac{1}{S_2}=\frac{1}{S_1}+W\sqrt{\rho_1} \tag{21}$$

which shows the effect of the added resistance of the tube on the speed of the pumping system. It will be observed that $\frac{1}{S}$ has the same dimensions as $W\sqrt{\rho_1}$, that is, the speed of a pump may also be looked upon as the *reciprocal of a resistance* to flow of gases through it, and by analogy with electrical usage we may define $\frac{1}{S_1}$ as the "impedance" of the pump itself and $\frac{1}{S_2}$ as the impedance of pump and tubing. Similarly we may regard S_1, S_2 and $1/W\sqrt{\rho_2}$, as "admittances."

It follows logically from these considerations that "in operating vacuum pumps of high speed it is essential to use tubing of large diameter (and short length) between the pump and the vessel to be exhausted if full advantage is to be taken of the speed of the pump." As an illustration of the effect of narrow tubes in diminishing the effective speed of a pump, let us consider the case of a tube 10 cm. long and 1 cm. diameter connected with a pump of speed $S_1=1400$ cm.^{3} per second (which is the value for a molecular pump under ordinary operating conditions).

The "resistance" of such a tube has been calculated in a previous section.[2] For air at room temperature $1/W\sqrt{\rho_1}=1070$. Applying equation (21) it follows that $S_2=606$, that is, the speed of the pumping system is about 43 per cent of that of the pump alone.

With a pump which has a speed of 4000 cm.^{3} per second (such speeds are easily attainable with mercury vapor pumps) the same piece of tubing would diminish the actual speed of exhaust to 844 cm.^{3} per second. In order to make effective use of the speed of this pump, it would be necessary to use very much larger tubing. Thus, let us assume that the connecting tube has a diameter of 3 cm. and a length of 30 cm. (To use tubing larger than this is usually impracticable, while the length given is about as short as would be practical.)

$$W\sqrt{\rho_1}=10^{-4}\times 1.04$$
$$1/S_1=10^{-4}\times 2.5$$

Hence, $S_2=2825$ cm.^{3} per second.

These results indicate how seriously the speed of a mercury vapor pump may be limited by the resistance of the tubing unless this is of very great size. It also follows from the above considerations that in the case of a low speed pump such as the Gaede diffusion pump ($S=80$) or a rotary oil pump ($S=100$), the resistance of the tubing, as long as it is not too large, is not nearly as important a factor as in the case of high speed pumps.

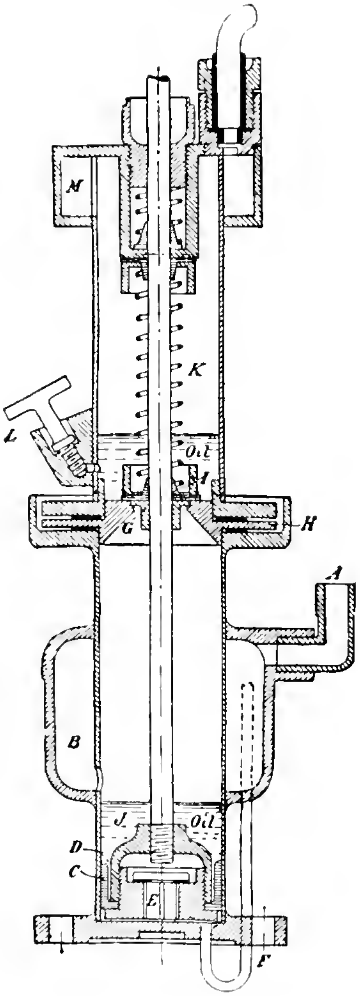

Fig. 4. Details of Construction of Geryk Vacuum Pump

MECHANICAL PUMPS

The early forms of exhaust pumps were of the piston type. As they have been largely superseded in modern practice, especially for high vacuum work, no detailed mention of them need be made in this connection. More-

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[2] See Q_2, Table V, Part I.

over, they are described in most elementary text-books on physics.

Geryk Vacuum Pump

This is a modern form of the piston type of pump (see Fig. 3), made by the Pulsometer Engineering Co. The illustration (Fig. 4) and the following description are given by E. H. Barton:[3]

"Referring to this figure, A is the suction pipe, B the air port into the cylinder above the piston, C is the piston whose bucket leather is kept up to the cylinder wall by oil pressing in the annular space D. E is the piston valve, F an air pipe to relieve the piston on the first few strokes. G, H and I collars and cover forming a good joint and delivery valve combined.

"When the piston is at the bottom of its stroke as shown, there is a perfectly free opening from A to B. As the piston rises the port B is cut off and the cylinder full of air irresistibly carried up to outlet valve G. No air can get back past the piston as it is covered with oil. When the piston approaches the top of its stroke, it lifts the valve G off its face and gives a free outlet for the air. The oil on the piston then mingles with that shown above G, but the right quantity returns with the piston on the closing of G. L is the plug for filling up with oil, which is very non-volatile, moistureless and non-solvent of air and fills all clearance spaces and seals the valves."

With a single-cylinder pump of this type it is claimed that a pressure of about a quarter of a millimeter of mercury can readily be obtained.

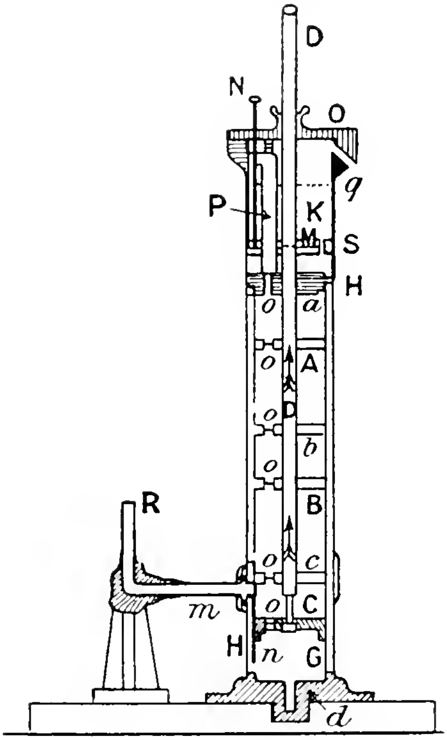

Fig. 5. Gaede Piston Pump

Gaede's Piston Pump[4]

This form, shown in Fig. 5, consists really of three piston pumps in series. The vessel to be exhausted is connected at *R*. As the piston rod *D* moves upwards, it carries with it the three pistons A, B, and C. The air is thus forced from *X* (which communicates with the tube *M*) through the valves *O* in the stationary partitions *c*, *b*, and *a* into the chamber *K* from which it is ejected into the air by the vent *q*. The top chamber *K* also contains a small amount of oil which forms an emulsion with the water and other vapors condensed above the piston A. "This emulsion is forced, together with the air, through the valve *o* in the cover *a*, through the tube *P* above the valve, and thence into the chamber *K*. This chamber is filled with a fibrous mass by which the oil and water emulsion is separated into its components. In consequence of its greater density, the water collects on the bottom *M* of the chamber, and may be pumped off as often as necessary by means of a glass syringe and rubber tube connected to the tube *X* extending upwards out of the pump. The oil overflows through the tube *S* into the space between *a* and *M*, whence it re-enters the pump barrel to combine with fresh quantities of water vapor."

According to Gaede's published account it is possible with this pump to obtain a pressure as low as *0.00005 mm. mercury; i.e. 0.067 bar.*, when exhausting into atmospheric pressure.

Sprengel Pump

The use of a water-jet as a suction pump is quite familiar. With this pump, the minimum pressure obtainable is that corresponding to the vapor pressure of water at the temperature which it has in the supply line; i. e.

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[3] An Introduction to the Mechanics of Fluids, p. 197 (Longmans, Green & Co., 1915).

See also Encycl. Britannica, 11th Edition, Vol. 22, p. 646.

[4] W. Gaede, Phys. Zeits. *14*, 1238, 1913.

See also E. H. Barton, loc. cit. pp. 198-9, from whose books the following description is quoted.

from 5 to 10 mm. mercury. As the vapor pressure of mercury at ordinary temperatures is only about 1 to 2 bars it is possible by means of a stream of mercury to obtain fairly low pressures, and by interposing a refrigerating chamber between the vessel to be exhausted and the nozzle which communicates with the mercury stream it is possible to obtain still lower pressures. The *Sprengel* mercury pump operates on this principle, and some of the simpler forms are described in most elementary text-books.[5]

G. W. A. Kahlbaum[6] has described a form of Sprengel pump which he states to be capable of exhausting a 400 cubic cm. bulb in 30 minutes to 0.004 bar. In a subsequent paper[7] he gives the following data with regard to the speed of exhaust of a 500 cubic cm. bulb:

3 minutes to 0.5 mm. mercury
15 minutes to 0.000165 mm.
30 minutes to 0.000069 mm. = .092 bar

With special care he states that he was able to get a pressure as low as .0024 bar. This pressure is evidently that of residual gas, and does not include the pressure of the mercury vapor itself, which, as stated above, would be between 1 and 2 bars.

Geissler-Toepler Pump[8]

The principle of this pump is fundamentally the same as that used by Torricelli in his famous experiment. In this type (Fig. 6) mercury forces the piston and also opens and closes certain ports, so that no valves are needed except one rough glass valve (*g*) to prevent the mercury from entering the vessel, E, which is being exhausted. The essential parts of the pump are made of glass and the air from E is exhausted by alternately raising and lowering the mercury reservoir R which is connected to the tube of barometric length below B. At each upward "stroke," the gas in B is closed from E and forced through the tube F, into the atmosphere at M. Then on the downward stroke, the pressure in E is lowered by expansion of the gas into B. E. Bessel-Hagen[9] has described a modified form of Toepler pump with which he claims to have obtained pressures of residual gas as low as 0.016 bar.[10]

Both the Sprengel and Toepler pumps have rendered very useful service in high vacuum investigations, and there is no doubt that with care it is possible to obtain pressures as low as .02 to .01 bar by their use.

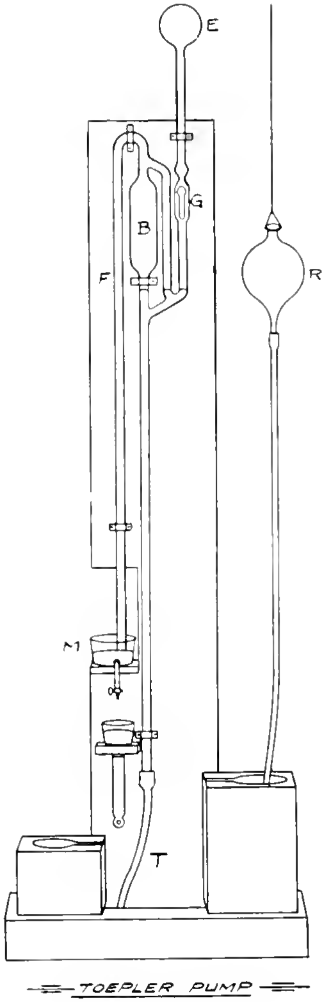

Fig. 6. Toepler Pump

The great disadvantages of these pumps are, however, two-fold. First, they require constant personal attention during the exhaust and second, the speed of exhaust is extremely slow, as it depends upon the rate at which the mercury can be raised and lowered alternately. It is of interest to note in this connection the results obtained by

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[5] See Encycl. Brit. loc. cit., also Winkelmann, Handbuch der Physik, I, 2, pp. 1314-1332, contains a very detailed description of the different forms of Sprengel and Toepler mercury pumps.

[6] Wied. Ann. *53*, 199 (1894).

[7] See also L. Zehnder, Ann. d. Phys. *10*, 623 (1903), for a description of an improved form of Kahlbaum's pump.

[8] See Encycl. Britannica and Winkelmann, loc. cit., also Barton loc. cit., from whose books Fig. 6 is taken.

[9] Wied-Ann. *12*, 425, 1881.

[10] Other forms of Toepler pump are described by a A. Stock Ber. deutsch. chem. Ges. *38*, 2182, 1905, and E. Grimsehl, Phys. Zeits. *8*, 762, 1907.

Scheel and Heuse[11] in their investigation of the degree of vacuum attainable with different types of pump. They used a 6 liter bulb and measured the speed of exhaust by means of a very sensitive McLeod gage. (See subsequent section for description of this gage.) In the experiments with a Toepler pump, each stroke actually required two minutes, and two more minutes were allowed between each stroke for equalization of pressure. Table VII gives the pressures at the end of different intervals of time.

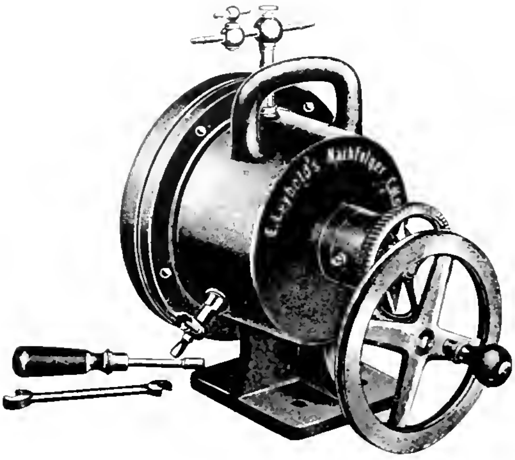

Fig 7. Gaede Rotary Mercury Pump

The last column gives the "speed of exhaust" as calculated by Gaede's formula. Compared with the speed of even 100 cm.^{3} sec. obtained by a Gaede rotary mercury or an ordinary oil pump (described below) the speeds given in Table I, are manifestly very low. Considering, furthermore, that in the case where gas is continually evolved from the walls, the minimum attainable pressure is given by the ratio S/q where q denotes the rate of gas evolution, it is seen that in actual practice it would be very difficult to obtain pressures below .01 bar by means of a Toepler pump.

Similar results were obtained by Scheel and Heuse in investigating the rate of exhaust of a 6 liter bulb by means of a Sprengel pump (Zehnder's form).[12]

TABLE VII

t (minutes)	press (mm. Hg.	$E = \frac{2.3\,V}{60\,t} \log \frac{p_1}{p_2}$
0	0.0645	0.40
2	0.0399	
24	0.0254	0.38
48	0.0107	0.35
60	0.00705	
108	0.00141	0.35
120	0.00033	
180	0.00024	0.39
192	0.00015	
240	0.000053	0.28
252	0.000038	
264	0.000032	0.06
300	0.000025	

Gaede Rotary Mercury Pump

An automatic form of Toepler pump has been described by U. von Reden,[13] with which he claims to have exhausted a 500 cm.^{3} bulb in 13 minutes to a pressure of .00001 mm. From his data, the speed of exhaust is found to be about 20 cm.^{3} sec.

In 1905, W. Gaede designed a rotary mercury pump which has been used to a very large extent in the commercial exhaust of incandescent lamps and Roentgen tubes until quite recently. The pump as described in the first publication[14] and illustrated in Fig. 7, consists of an iron casing (with glass front) partially filled with mercury, in which a porcelain drum is made to rotate. A rough pump producing a vacuum of 10 to 20 mm. is used as fore-pump. Fig. 8 shows a vertical section of the pump, and Fig. 9 a front view. The iron case is shown at g, and G is a heavy glass plate through which pass the tubes R and r which connect to the vessel to be exhausted and the fore-pump respectively. The porcelain

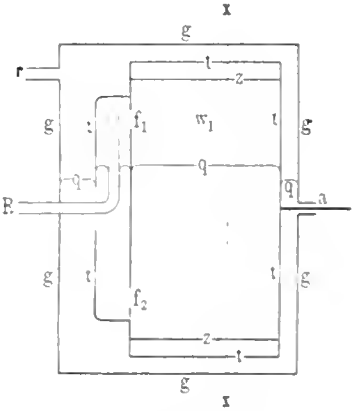

Fig. 8. Gaede Rotary Mercury Pump, Vertical Section

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[11] Zeits f. Instrumentenkunde, *29*, 47, 1909.

[12] Ann. d. Phys. *10*, 623 (1903).

[13] Phys. Zeits. *10*, 316, 1909

[14] Verh. d. deutsch. Physik. Ges. *7*, 287, (1905). Phys. Zeits. *6*, 758-760, (1905).

drum *t* is built up of two (or more) sections as shown in Fig. 9 and rotates on the axis *a*. As the drum rotates in the direction of the arrow the compartment W is at first increased in volume and thus sucks in the gas at the opening *f*, from the vessel to be exhausted. During the second part of the revolution, the opening *f* becomes covered with mercury, as shown at f^2, and the gas is then forced out under pressure from the compartment w_2 into the space between the walls Z_1 and t_1 and into the rough pump connection at *P*.

Fig. 10 shows an improved form of the pump in which the opening to the rough pump *r* is brought in through the iron casing. The vessel to be exhausted is connected at *E*, and a side tube *t* is provided with P_2O_5 to take up water-vapor. The tube MOF acts as manometer and also makes it possible to exhaust with the rough pump alone at the beginning. As the vacuum improves, the mercury in *o* rises and seals off the connection to the rough pump through $a\ s_1$. The system is then ready for exhausting to lower pressure by means of the mercury pump.

Gaede gives as an illustration of the operation of the pump the following data. With a pump rotating at 20 r.p.m., and a volume of 6,250 cm.³, the pressures during exhaust were as follows:

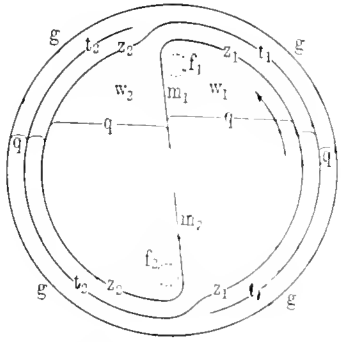

Fig. 9. Gaede Rotary Mercury Pump, Diagrammatic View

t (min.)	P (mm.)	$E = \frac{2.3\ V}{60\ t} \log \frac{p_1}{p_2}$
0	9	
5	0.03	94.5
10	0.0018	46.5
15	0.00023	34.0
20	0.0001	13.8
25	0.00007	6.9
30	0.00007	0.0

The speed of this pump is therefore approximately 100 cm.³/sec. at the maximum, while the degree of vacuum attainable is about .00007 mm. or 0.1 bar.[15]

Rotary Oil Pump[16]

Figs. 11 and 12 show the construction of a pump of this type designed by Gaede primarily for the purpose of acting as a fore-pump to the rotary mercury pump described above. It is also shown in Fig. 15 at the right hand side. The pump consists of a steel cylinder A which rotates eccentrically inside a steel casing. The projections at S are held tightly against the inner wall by means of springs, so that as the cylinder rotates the air is sucked in at C and forced out through the valve D into the oil chamber O and from there into the atmosphere at J. The oil serves as automatic lubricant and also helps to prevent air from leaking back into the fine pump side, by forming a film between the rotating and stationary members.

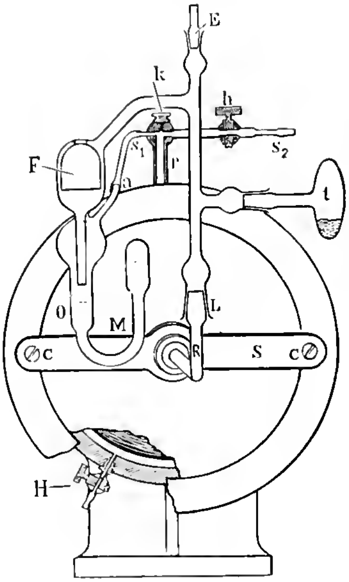

Fig. 10. Improved Form Gaede Mercury Pump

Fig. 13 illustrates a standard form of rotary oil pump used in incandescent lamp factories and which can also be used as a fore-pump to higher vacuum pumps such as Gaede's Molecular or Langmuir's Condensation pump. With a rough side pressure of about 1 cm. mercury, such a pump is capable of exhausting to a pressure of approximately

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[15] Later improvements in this pump have been described in Verh. d. deustch. Physik. Ges. *9*, 639 (1907), and Phys. Zeits 8, 852, (1907).

[16] G. Meyer, Verh. d. deutsch Phys. Ges. *10*, 753 (1907).

1 bar, and with two pumps in series the fine side pressure may be lowered to 0.1 bar.[17]

With a pump of this type operating at about 400 r.p.m., the speed of exhaust is 100–150 cm.^{3} per second.

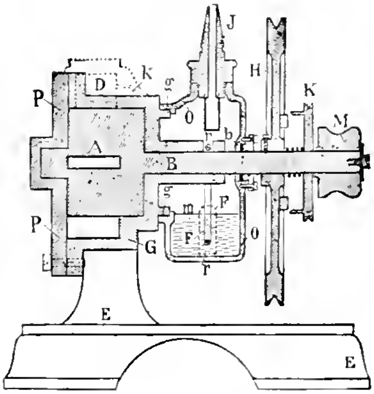

Fig. 11. Gaede Rotary Oil Pump, Side View

Gaede Molecular Pump

The Gaede Molecular pump undoubtedly marks a distinct advance in the design of pumps for the production of high vacuum. The difference between his pump and the types previously constructed has been well described by Gaede himself in the paper which he published in 1913:[18]

"All high vacuum pumps known up to the present consist of an exhaust arrangement which, according to the original idea of Otto von Guericke, separates a definite volume of gas from the vessel to be exhausted, and then gives it up to a fore-vacuum or the atmosphere. It is absolutely essential in these pumps to separate the rough side from the higher vacuum side as much as possible. This is accomplished in the mechanical pumps by tight-fitting pistons and valves, and in the case of mercury and oil pumps by means of the liquids themselves. On the other hand, in the case of the molecular pump there is no separation, whether piston or fluid, between the high-vacuum and fore-vacuum." The gas is dragged along from the vessel to be exhausted into the fore-vacuum by means of a cylinder rotating with high velocity inside a hermetically sealed casing. The pump thus represents a logical development and application of the laws of flow of gases at very low pressures as investigated by Knudsen, Smoluchowski, and Gaede himself.

The fundamental principle of the pump may be illustrated by means of Fig. 14. The cylinder A rotates on an axis *a* (in the direction of the arrow) inside the air-tight shell B and drags the gas from the opening *n* towards the opening *m*, so that a pressure-difference is built up in the manometer M, as shown by the mercury-levels at *o* and *p*. Between *m* and *n* there is a slot in the case B as shown in the diagram, while at every other point A and B are very close together. Now, at ordinary pressures the viscosity is independent of the pressure. Under these conditions, as Gaede shows, the difference in pressure at *o* and *p* depends only on the speed of rotation *u*, of the cylinder, the co-efficient of viscosity of the gas, *n* the length of the slot *L* and *h* the depth measured radially, according to the following relation:

$$p_1 - p_2 = 6\,Lun\;h^2$$

At low pressures, however, the number of collisions between gas molecules becomes relatively small as compared with the number of collisions between the gas molecules and the walls. Under these conditions the molecules therefore tend to take up the same direction of motion as the surface against which they strike, if the latter is in motion.

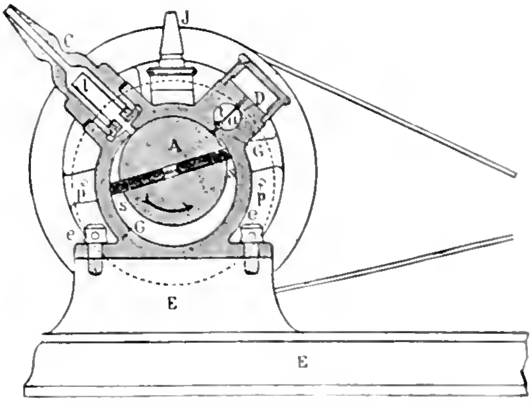

Fig. 12 Gaede Rotary Oil Pump, Front View

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[17] K. T. Fischer, Verh. deutsch. Physik. Ges., 7, 383 (1905), has described a form of rotary oil pump for use in commercial exhaust operations. With two pumps in series exhausting into atmospheric pressure he states that a pressure of about 2 bars may be obtained.

[18] W. Gaede, The Molecular Air Pump. Ann. d. Phys., 41, 337-380 (1913). This paper contains a complete discussion of the theory and construction of the pump. Briefer descriptions may also be found in the following:

W. Gaede, Physikal. Zeits. *13*, 864-870 (1912), and Verh. d. deuts. Phys. Ges., *14*, 775-787 (1912).

K. Goes, Physikal. Zeits., *13*, 1105, and *14*, 170-2 (1913). Description of some experiments with the pump and precautions in using it.

Electrician (London), *70*, 48-50 (1912).

K. Jellinek, Lehrbuch d. Physikal. Chemie, I, 1, pp. 330-333 (1914).

M. L. Dunoyer, Les Idees Modernes sur la Constitution de la Matiere, pp. 215-271 (1913).

This conclusion is based upon the investigations of Knudsen on the laws of molecular flow, which have been discussed in a previous section. The relation deduced above is therefore found to be no longer true and instead of the pressure-difference remaining constant at constant speed of rotation, the *pressure-ratio* is now constant and independent of the pressure in the fore-vacuum. Gaede shows that at very low pressures,

$$P_1/P_2 = \frac{ku}{c} = K$$

where K is a constant whose value depends upon the nature of the gas and the dimensions of the slot in the casing B of the pump, so that at constant speed of rotation, u, the ratio between the pressures on the two sides of the pump is constant.

The construction of the actual pump based on the above principles is illustrated in Figures 15 and 16, while Fig. 17 shows the pump connected in series with a Gaede rotary oil pump.

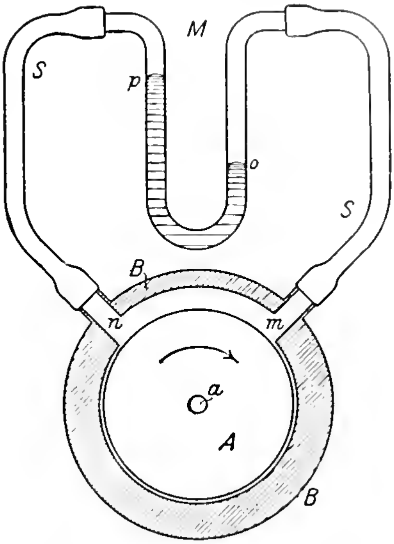

Fig. 14. Diagram Explaining Operation of Molecular Pump

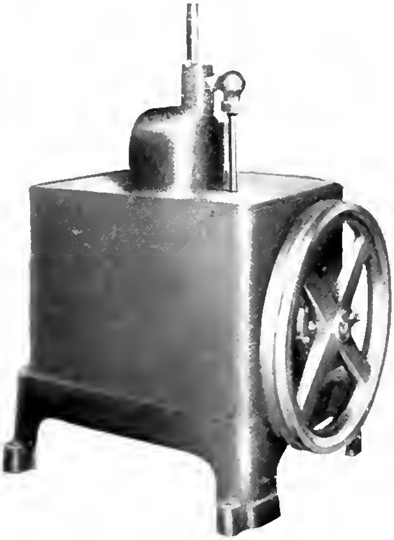

Fig. 13. Standard Form of Rotary Oil Pump

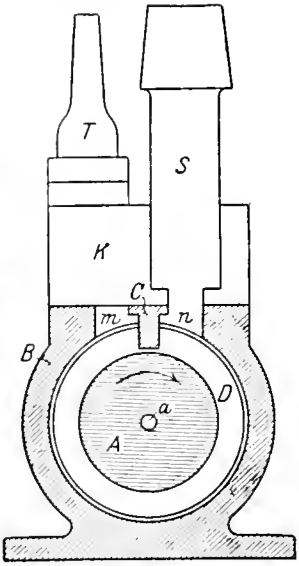

Fig. 15. Gaede Molecular Pump, Front View

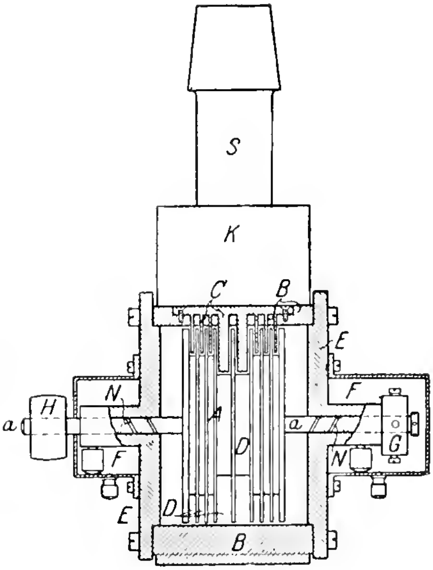

Fig. 16. Gaede Molecular Pump, Side View

The rotating cylinder A (Figs. 15 and 16) has 12 parallel slots around the circumference, into which project the extensions C from the outer casing. If A rotates clockwise, the pressure at m is greater than that at n, and in order to increase this pressure different sections are connected in series. The distance between the outer edge of the cylinder A and the inside of the shell B is about 0.01 cm. The over-all radius of A is 5 cm., and the depth of the slots vary from 0.15 cm. in the outer section to 0.6 cm. in the inner ones. With the cylinder rotating clockwise as indicated, the vessel to be exhausted is connected at S, while the opening T is connected to an ordinary mercury or oil pump capable of exhausting to a pressure of less than 0.05 mm. *Hg*. As the speed of rotation of the cylinder is very high (about 8000 r.p.m.) oil cups are provided at F, and the shaft N is so designed that the oil in the spiral slot is driven outwards by the centrifugal action. The slots in the rotor are so arranged that the lowest pressure is in the center, and the pressure increases uniformly outwards until the ends, where it is equal to that produced by the rough pump.

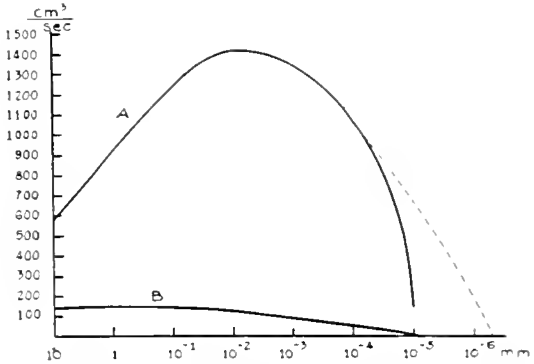

Fig. 13. Effect of Rough-pump Pressure on Speed of Gaede Molecular Pump

The effect of varying the speed of rotation or the rough pump pressure on the degree of vacuum produced by the molecular pump, is shown in Table VIII.

TABLE VIII

Speed of Rotation R.P.M.	Rough-pump Press. mm. Hg.	Press. on Fine Side mm. Hg.
12000	0.05	0.0000003
12000	1	0.000005
12000	10	0.00003
12000	20	0.0003
6000	0.05	0.00002
2500	0.05	0.0003
8200	0.1	Not measurable
8200	1.	0.00002
8200	10	0.0005
6200	0.1	0.00001
6200	1.0	0.00005
4000	1.1	0.00003
4000	1	0.0003

The pressures on the fine side were measured with an extremely sensitive type of McLeod gage except in the case of the first result given in the table which was estimated. The writer's own experiments[19] with the Gaede molecular pump at 8000 r.p.m. have shown that with a rough pump pressure of 20 mm. the fine side pressure was 0.0004 mm., so that the ratio of the pressures was 50,000—a result which is in accord with figures given by Gaede above.

The speed of the pump as defined by the relation,

$$S = \frac{V}{t} \ln \frac{p_1}{p_2}$$

has been found by Gaede to vary with the magnitude of the rough-pump pressure. The curve A in Fig. 18 shows that the maximum speed is about 1400 cm.³ per second with a fore-vacuum of 0.01 mm. For comparison Gaede also shows the curve *b* for his rotary mercury pump, which has a speed of about 130 cm.³ per sec., at the maximum.

(To be Continued)

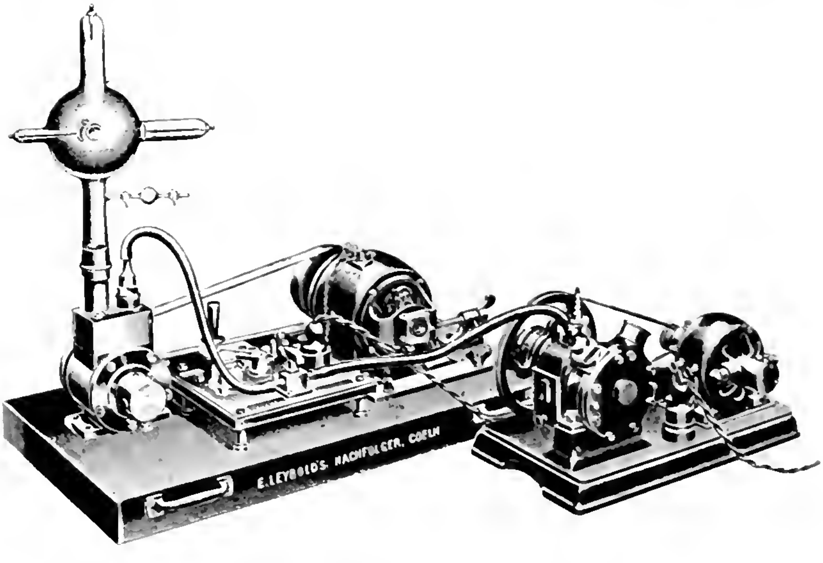

Fig. 17. Assembly of Gaede Molecular and Gaede Rotary Oil Pumps

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[19] S. Dushman, Phys. Rev. 5, 224 (1915).

Two Years' Service of Battleship *New Mexico*

The battleship *New Mexico*, pride of the United States Navy, and first of Uncle Sam's fighting fleet equipped with the electric drive, has recently completed her second year of active service.

Commander S. M. Robinson, fleet engineer of the Pacific fleet, of which the *New Mexico* is flagship, reviews this two years of electric propulsion in the following report:

"The *New Mexico* has been operating for nearly a year in company with two sister ships, the *Idaho* and *Mississippi*, which have hulls identical with that of the *New Mexico*. During this time it has been possible to get an accurate comparison of the relative economy of the three ships and also the relative maneuvering qualities. In the latter respect, the *New Mexico* is decidedly superior, and the remarkable part of it is that nearly all of the maneuvering in restricted waters has been done with our turbo-generator. When this installation was first proposed, its opponents maintained that, while a ship like the *Jupiter* could be satisfactorily operated with the screws on both sides of the ship running at exactly the same speed, it would not be possible to get satisfactory operation with that arrangement on a ship which had to operate in formation. But exactly the reverse has proved to be true; it has been found that more satisfactory operation is obtained when using one generator than when using two, and it is customary, when in dangerous waters where it is desired to take all possible precautions, to use one generator for driving the ship and to keep the other turning over idle. If the ship is getting under way from an anchorage and has to turn, as soon as the anchor is away the signal is given for standard speed ahead on one side and the same speed astern on the other; with this arrangement the ship will turn absolutely on her wheel without gaining ground either ahead or astern.

"The advocates of electric propulsion have always claimed that it was very superior to all other forms of propulsion at the cruising speeds, but even the most enthusiastic of these have been surprised by the remarkable showing made. This is doubtless due to the fact that no one made sufficient allowance for the saving due to shutting down one generator and all the auxiliaries that go with one of the condensing plants. At a speed of 10 knots the *New Mexico* uses about 16.7 per cent less oil than her sister ships, or, putting it another way, her sister ships use about 20 per cent more than the *New Mexico;* at 13 knots the figures are 29.9 per cent, or 42.7 per cent; at 16 knots the figures are 32.3 per cent, or 47.8 per cent; at 19 knots the figures are 28.6 per cent, or 40.1 per cent; at full power the figures are 24.4 per cent, or 32.2 per cent. At 19 knots, also at full power, the *New Mexico* uses about .975 lbs. of oil per shaft horse power, and at 15 knots she only uses 1.1 lb. of oil per shaft horse power per hour. This is a remarkable uniform economy.

"In regard to the reliability of the machinery, the *New Mexico* has had nothing but the most minor troubles with her electric plant and there have been no navy yard repairs whatever."

Electric Power in the Oil Fields as a Central Station Load

By W. G. Taylor

Power and Mining Engineering Department, General Electric Company

In our May, 1919, issue, Mr. Taylor thoroughly explained to the oil producer the advantages of motor drive. In the present article, which was delivered as a paper at the N. E. L. A. Convention, Pasadena, Calif., May 20-22, the author discusses the subject from the standpoint of the central station. He gives detailed information as to the nature of oil field load, the motor equipment for various local conditions, the cost of installation, and the power consumption. In comparing electric drive with gas-engine drive, tables are included showing the time saved by the former, the increased production, and the lower operating expense. Full consideration is given to the electrification of gathering and line pumps, vacuum pumps, compressors and circulating pumps for casing-head gasolene plants, dehydrators, machine shops, and lighting.—Editor.

Oil companies have in general reached a very receptive mood toward electric drive for oil field operations. This is particularly the case in the California, Mid-continent, and Texas fields, comprising between 70 and 75 per cent of the productive wells of the United States and producing over 80 per cent of the crude oil in this country and more than half in the world. Not only are several thousand wells now being pumped in these fields by electric power, but motor drive has also been successfully used for several years in California for drilling, and has been recently introduced in the Mid-continent field for this work with notably good results.

The other principal applications of electric power in the oil fields are to:

Water pumps,
Gathering and line pumps,
Vacuum pumps,

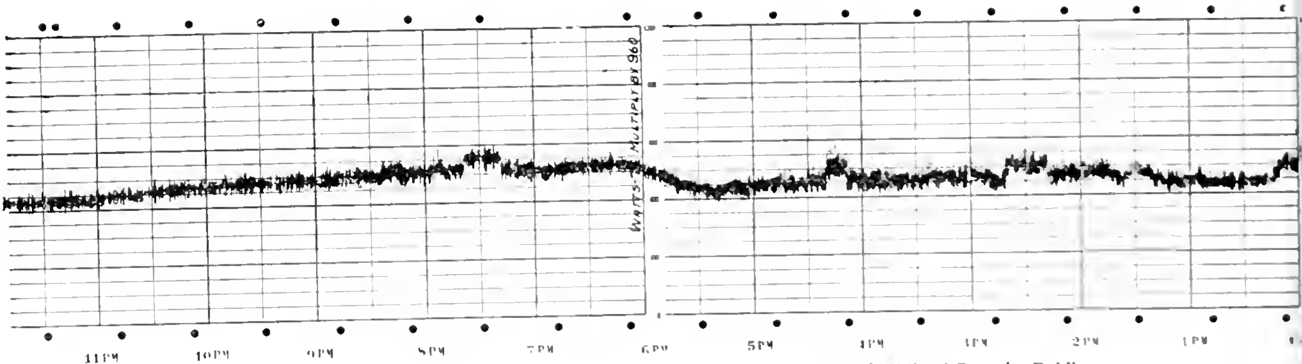


Fig. 1. Twenty-four hour Load Curve of Substation of Midland Counties Public

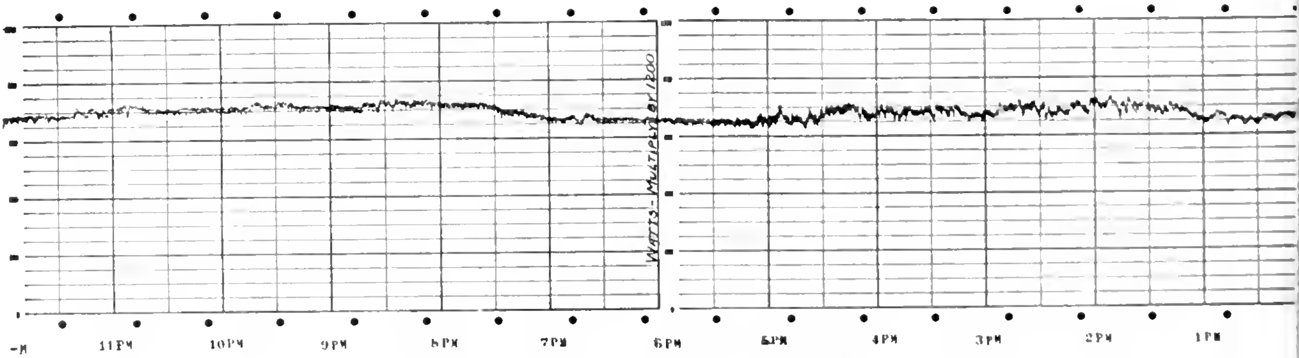


Fig. 2. Twenty four-hour Load Curve of Substation of San Joaquin Light and

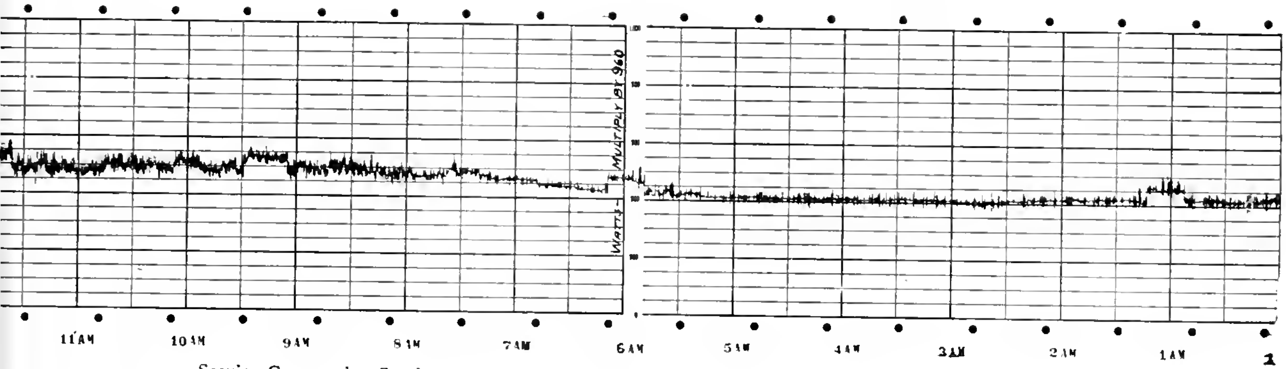
Compressors for casing-head gasolene plants,
Circulating pumps for casing-head gasolene plants,
Dehydrators,
Machine shops,
Lighting.

Refining and other operations not directly concerned with oil production are not covered in this article.

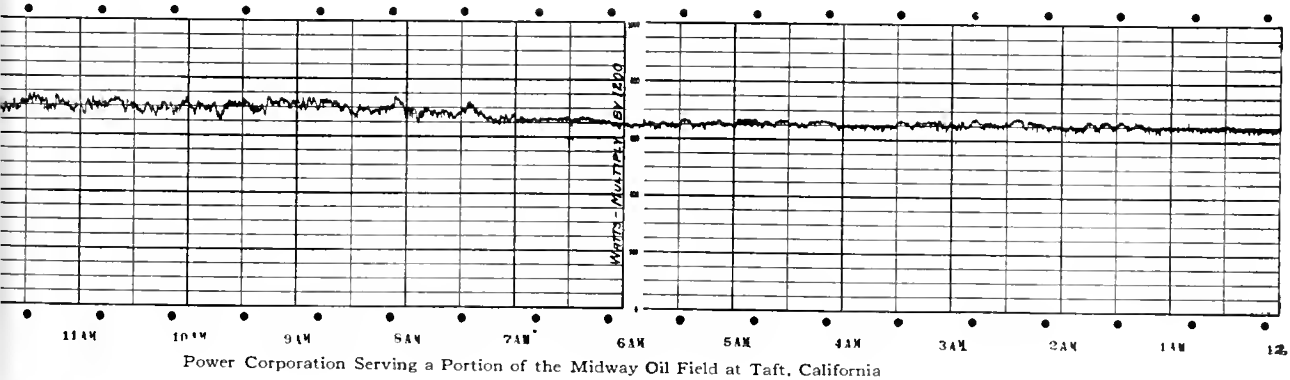
NATURE OF OIL FIELD LOAD

The almost ideal nature of an oil field load is well presented in Figs. 1 and 2 by actual curve-drawing wattmeter records of substations serving typical oil fields in California. The load is practically constant twenty four hours a day every day in the year, without any material seasonal variation. A slight rise in the load curve at night is due to electric lighting. At any individual installation of oil well motors, there are of course relatively large load fluctuations, as illustrated by Figs. 3, 4, and 5, but the diversity factor of a large number of installations prevents the peaks from being felt at either the generating station or substations.

Oil well pumping comprises the largest percentage of an oil field load, and accordingly is the chief factor in determining its character. The quite varied operations necessary for the maintenance of a producing well require a very versatile motor, and these requirements are fully met only by the two-speed oil-well motor with both speeds variable, which has become the standard machine for this work. Although its chief duty is to pump the well, the motor is frequently called upon for other work, particularly when the well is cleaned out and the rods and tubing must be pulled. This hoisting work demands power, for short periods, several times greater than that required for pumping. Although the motor develops this high power at its high speed and is designed for pumping conditions at its low speed, it is not practicable for it to have as high a power-factor under these circumstances as can be expected of an ordinary industrial motor, and therefore the power-factor of the system is correspondingly affected. An oil field load for this reason generally has a power-factor, without correction, of about 60 to 65 per cent.



Service Corporation Serving a Portion of the Coalinga Oil Field in California



Power Corporation Serving a Portion of the Midway Oil Field at Taft, California

The cost of correcting this power-factor in the low-voltage distribution system would be prohibitive on account of the scattered nature of the load and the small capacity of the units involved. The most economical correction is therefore obtained by the installation of synchronous or condenser equipment in the primary circuit, after the load has developed to such an extent that correction becomes advisable.

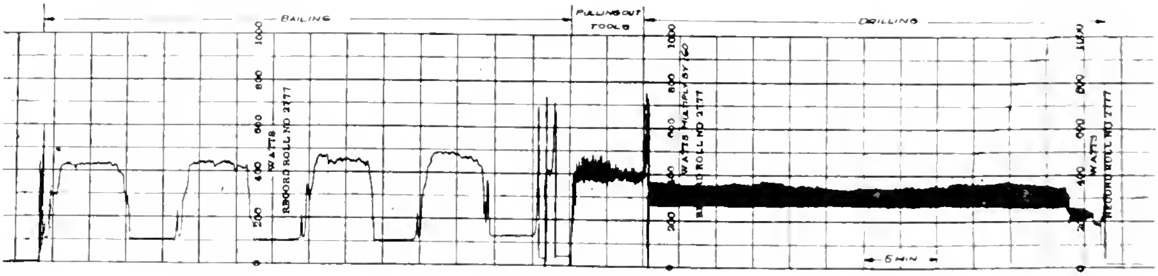


Fig. 3. Wattmeter Record of Drilling with Standard Tools and Bailing in a 10-in. Hole at a Depth of 2025 Ft.

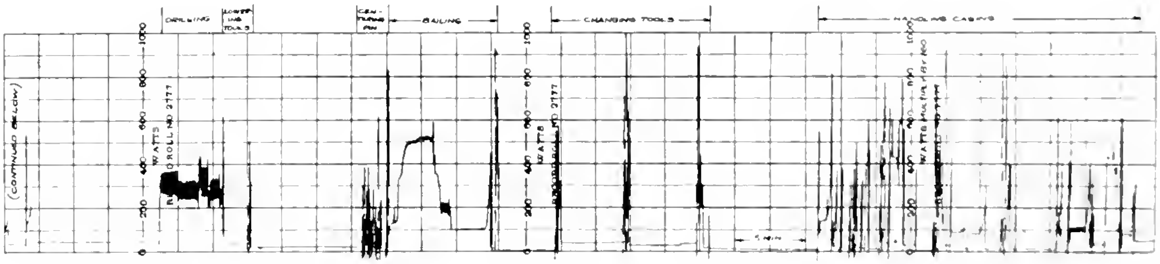


Fig. 4. Wattmeter Record of Miscellaneous Work in Connection with Drilling a 10-in. Hole with Standard Tools at a Depth of 1840 Ft.

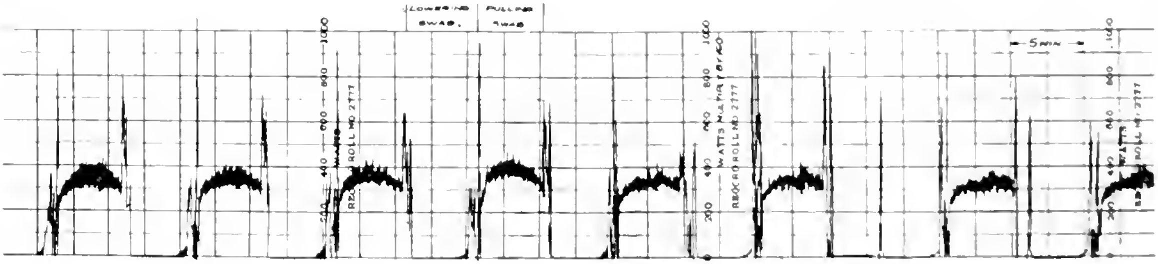


Fig. 5. Wattmeter Record of Swabbing in 4½-in. Casing at a Depth of 2165 Ft.

The standard distribution voltage is 440 volts. The cost of both the motor equipments and the distribution copper would be increased by the use of any lower voltage, and there would be no compensating advantages; while on the other hand, high voltage at the motor is impracticable on account of the necessity of handling line current in the controller for reversing the motor.

Six large power companies furnish nearly all of the electric power at present used in the American oil fields, these being the Southern California Edison Co. and the San Joaquin Light and Power Corporation in California, the Kansas Gas and Electric Co. in Kansas, The Oklahoma Gas and Electric Co. and the Oklahoma Power Co. in Oklahoma, and the subsidiaries of the American Power and Light Co. in Texas. The large increases in station capacity and power line extensions, which are now being undertaken by these companies to reach and carry additional oil field load, furnish good evidence of its desirability.

MOTOR EQUIPMENTS FOR OIL WELL PUMPING

Pumping the well requires continuous operation of the motor usually for weeks at a time without change or shut down, with a low power demand and at a comparatively low speed of the rig. Speed control is necessary to adjust the number of strokes per minute to the changing conditions at each well. Pulling rods and tubing, which is necessary at intervals to clean out the well or to replace broken or worn parts, as well as all of the other roustabout work, is done at high speed to save time, and demands the characteristics of a high-torque hoist motor. The two-speed slip-ring induction motor with both speeds variable, which has proved to be especially adaptable to all these operations, has all the flexibility of engine drive and is an improvement over it in numerous respects. Figs. 6 and 7 show typical installations.

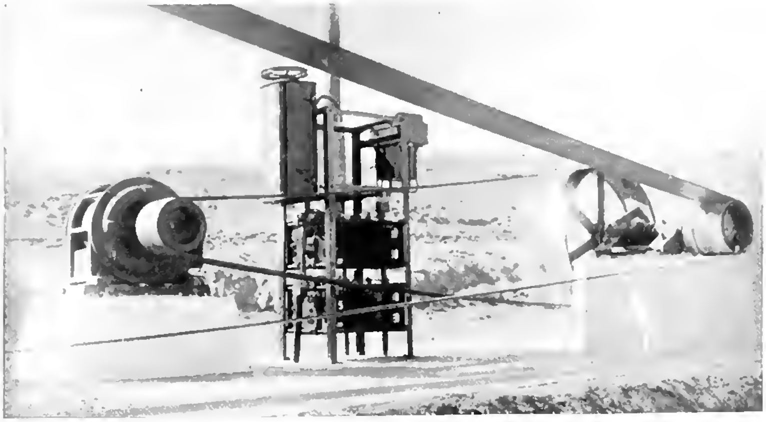


Fig. 6. Typical Installation in California of a Two-speed 30/15-horse power Oil Well Pumping Motor Equipment Before Completion of Housing

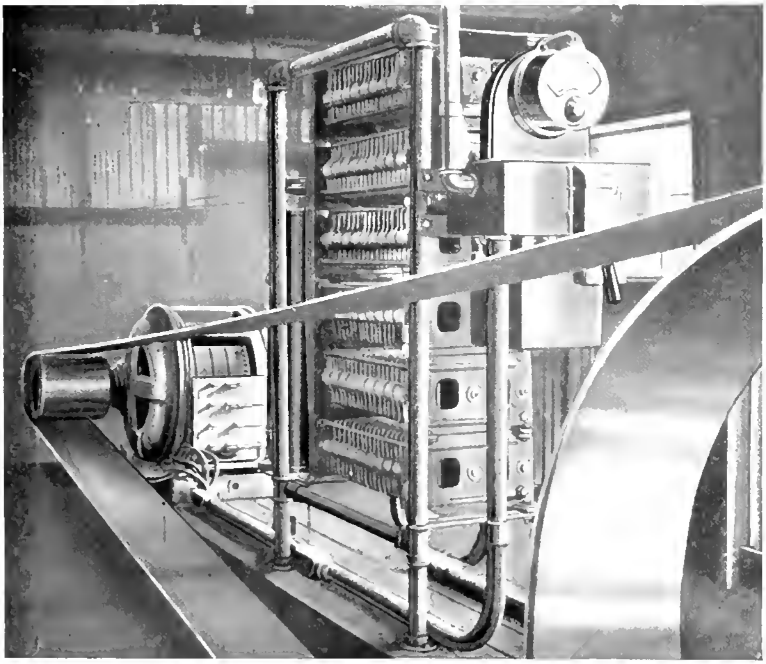


Fig. 7. A Kansas Installation of a Two-speed 30/15-horse power Oil Well Pumping Motor Equipment, This Being Typical of Those in the Mid-continent Field

A number of wells of moderate depth are equipped with 25/10-h.p. motors, but the machine which meets the greatest variety of conditions is rated 30/15 h.p. In California, one of these is pumping a 4800-foot well. The higher rating is developed at a synchronous speed of 1200 r.p.m. for pulling, bailing, and similar work; and the lower rating at 600 r.p.m. for pumping duty. By means of a pole-changing switch mounted on the frame of the motor, the speed is readily changed as desired for the work to be done.

A drum controller and specially designed secondary resistor give the required speed variation at either high or low speed. The controller is installed near the motor and is operated by a rope wheel from the "headache post" at the derrick.

The motor is fully protected by an oil circuit breaker having under-voltage release and overload trip The overload trip coils are double-wound to provide protection on both pumping and pulling duty, these coils being electrically interconnected with the pole-changing switch on the motor frame in such a manner that the coils are always connected to trip the circuit breaker at an overload corresponding to the motor rating in use. This makes it impossible for the motor to be left without adequate protection, particularly when running unattended on low speed for pumping.

An automatic device can be placed in the base of the controller, if desired, to prevent the controller from being moved past an intermediate point until after the current has dropped below a predetermined value. An unskilled operator can thus be prevented from abusing the equipment, and can at the same time be automatically taught to handle the controller in the proper manner to get the best results.

Many of the installations in the Mid-continent field are equipped with an ammeter mounted on the cover of the oil circuit breaker. This is of assistance when counterbalancing the well and serves as an indication of the condition of the well when pumping. The ammeter is not in circuit when the motor is connected for high speed. On most leases a watthour meter is installed at each well, and this enables the operation to be watched more closely from month to month.

Required Motor Capacity for Pumping

There is no apparent way to calculate the power required to pump a well which will give figures at all consistent with actual results, because of the difficulty of determining the effect of varying well conditions. For instance, a large amount of sand in the oil will increase the power necessary to pump it; while on the other hand, gas may be encountered which will help lift the oil. No numerical value can be placed on these conditions, so the motor capacity is determined largely by comparison with results obtained at other wells; and a proper selection depends largely upon the data at hand and the judgment of the engineer or salesman.

Other conditions being equal, the power required for pumping will vary directly as,

(a) The length of stroke.
(b) The number of strokes per minute.
(c) The square of the diameter of the tubing.

The following figures may serve as a guide in estimating the motor capacity for pumping individual wells. Owing to changeable conditions always encountered, it is best to have some reserve capacity in the motor on the pumping connection.

In California, the following data have been obtained on 213 wells, but cannot be considered representative of conditions in deep territory:

Depth of wells	900 to 3110 ft. (av. 1430)
Length of stroke	29 to 32 in. (2nd hole in crank)
Strokes per minute	20 to 30 (av. 24)
Diameter of tubing	3 in.
Daily production per well	10 to 230 bbl. (av. 122 bbl.)
Power required per well	1 to 5 h.p. (av. nearly 4.0 h.p.) Exceptional wells have required more, some as high as 17 h.p.

In Louisiana, some heavy pumping wells have been encountered. One well in the Jennings field required the following:

Depth of well	2000 ft. (approx.)
Depth of pumping	1100 ft.
Length of stroke	30.5 in. (3rd hole in crank)
Strokes per minute	40
Diameter of tubing	2.5 in.
Daily production	600 to 800 bbl., 90 per cent water
Power required	9.5 h.p.

Another well in Louisiana in the field at Hosston required the following:

Depth of well	1050 ft. (approx.)
Depth of pumping	1000 ft.
Diameter of tubing	3 in.
Daily production	500 bbl. (av.), over 90 per cent water.

Length of Stroke	Speed	Counterbalance Used	Average Horse Power
37.5	25	No	11
37.5	38	No	17.5
30.5	40	No	15
30.5	40	Yes	13

Compared with the California data, these Louisiana wells have a longer stroke, higher speed, larger percentage of water, less gas, and therefore require higher horse power. The Hosston well, compared with the Jennings well, has a lower speed but less gas and larger tubing, therefore requires a somewhat higher horse power.

From 10 other wells in the Jennings field in Louisiana, the following data were obtained:

Depth of wells	2050 ft. (approx.)
Depth of pumping	1100 ft.
Length of stroke	31 in. (except in a few cases)
Strokes per minute	18 to 44 (av. 27.5)
Diameter of tubing	2.5 in., 3 in. and 3.75 in.
Daily production per well	600 bbl. (av.), 90 per cent water
Power required per well	5.2 to 8.6 h.p. (av. 6.4 h.p.)

In the Louisiana field near Hosston, data on 11 other wells were obtained as follows:

Depth of wells	1050 ft.
Depth of pumping	980 to 1000 ft.
Length of stroke	30 to 36 in. (3rd hole in crank)
Strokes per minute	28 to 38 (av. 34)
Diameter of tubing	3 in.
Daily production per well	500 bbl. (av.), 90 per cent water
Power required per well	7.5 to 15 h.p. (av. 10 h.p.)

In Texas, 74 wells in the Goose Creek field furnished the following figures:

Depth of wells	2800 ft. (av. 3400 ft. (max.)
Length of stroke	29 to 32 in. (2nd hole in crank)
Strokes per minute	28
Diameter of tubing	2.5 in.
Daily production per well	100 bbl. (av.) max. water 10 per cent
Power required per well (motor input)	5.1 to 5.5 kw.

These wells produce a considerable amount of sand.

In Kansas, the power required for pumping five wells in the El Dorado field was as follows:

Depth of wells	2500 to 2940 ft. (av. 2730 ft.)
Length of stroke	28 in.
Strokes per minute	19 to 22 (av. 21)
Diameter of tubing	3 in.
Daily production per well	300 to 600 bbl. (av. 460 bbl.)
Power required per well	6.9 to 9.7 h.p. (av. 7.9 h.p.)

These Kansas records were obtained about three years ago on comparatively new wells. Records were checked a year ago on another group of about 60 wells, and the average per well was 5 h.p., the maximum being 8 h.p. Similar operating conditions prevailed but the production had materially declined.

In Oklahoma, at Shamrock, the following pumping data were obtained from seven wells:

Depth of wells	2660 to 2920 ft. (av. 2810 ft.)
Length of stroke	29 in. (2nd hole in crank)
Strokes per minute	18 to 28 (av. 23)
Diameter of tubing	2 in.
Daily production per well	60 to 100 bbl. (av. 80 bbl.)
Power required per well (motor input)	4.1 to 6.4 kw. (av. 5.2 kw.

Capacity of Motor for Pulling

As a guide for determining the maximum depth of well at which a motor of a given rating can safely be installed for pulling work, the following formula is of much service. It is based on the maximum torque of the motor, but has been found sufficiently conservative that the motor heating will normally not be excessive under the usual operating conditions.

$$\text{Maximum depth of well} = \frac{R\times E\times L\times K}{w\times d}$$

in which, R = ratio of motor speed to corresponding bull-wheel speed.

E = mechanical efficiency of the rig (usually varies from 0.5 to 0.7).

L = number of load lines used in the tackle for pulling the tubing.

w = weight of tubing in lb. per ft.

d = diameter of bull-wheel shaft in inches.

K = a constant, depending upon the motor used.

The constant K is determined as follows:

$$K = \frac{1260\times h.p.\times T}{r.p.m.}$$

in which, $h.p.$ = horse power rating of motor on high speed.

T = max. torque of motor in per cent of full-load torque.

$r.p.m.$ = full-load high speed of motor.

The extreme condition which may be encountered is pulling rods and tubing together with the tubing full of oil. This may be taken into account by determining the total weight per foot of this load and using this figure for w in the formula.

Power Consumption for Pumping Operations

The kilowatt-hour consumption for deep wells is no more in many cases than that for shallow wells. The most influential factors are the length of stroke, the speed of pumping, the diameter of the pump barrel, the gravity of the oil, and the fluid level in the wells. This is indicated in Table I.

The data in Table I do not represent all or even average conditions in California, and it would be a difficult matter to determine them. It is of interest to note, however, that there are a large number of wells in both the Midway-Sunset and the Coalinga fields with a depth from 1000 to 2500 feet which

TABLE I

COMPARATIVE POWER CONSUMPTION OF SELECTED GROUPS OF ELECTRICALLY OPERATED OIL WELLS IN CALIFORNIA

	Case 1	Case 2	Case 3	Case 4	Case 5
Number of wells	50	5	6	4	6
Location (California)	Kern	Casmalia	Casmalia	Cat Canyon	Santa Maria
Average depth (feet)	1000 to 1100	1800	2000	2900	2800 to 3000
Pumping Speed (strokes per min.)	27	18	20	22	20
Hole in Crank—used for pumping	1st, 2nd & 3rd	1st	1st	1st	1st
Gravity of oil (Deg. Baumé)	12.5 to 14.9	10 to 11	12	15	19 to 21
Size of tubing (inches)		$4\frac{1}{2}$	$2\frac{1}{2}$ and 3		$2\frac{1}{2}$
Water	Much	Much			
Gas			Very Little	Some	Yes
Number of months	4	3	3	3	3
Kw-hr. per well per month	5252	4403	3927	4229	3941

use between 2000 and 3300 kw-hr. per well per month. An average obtained for 366 of these wells was 2600 kw-hr.

In Kansas there is not such a wide variety of conditions. Aside from a number of shallow wells pumped by "powers," the following are about the average operating conditions:

Depth of wells	2400 to 2950 ft.
Pumping speed	15 to 20 strokes per min.
Hole in crank used for pumping	2nd
Gravity of oil	38 deg. B.
Size of tubing	3 in.
Some water	
No gas to lift the oil.	

In March, 1918, the records of 82 wells showed a monthly power consumption per well of 3030 kw-hr. For the following month, the average for 96 wells was 3340 kw-hr. In October, 1918, 26 wells, not included in those just mentioned, required an average of 2430 kw-hr., but seven of these pumped only part time. The average for the 24-hour wells was 3110 kw-hr. A later record of 79 wells, some of which pumped only part time, gave an average of 2220 kw-hr. per well per month.

In the Burkburnett field in Texas, conditions are about as follows:

Depth of wells	1650 to 1800 ft.
Pumping speed	15 strokes per min.
Length of stroke	26 in.
Gravity of oil	38 deg. B.
Size of tubing	2 in.
No water or sand.	

In the Townsite pool in this field, wells are pumping on the beam for the full 24 hours a day and require approximately 3000 kw-hr. per well per month.

In the Northwest pool, with practically the same field conditions, most of the wells are still being swabbed from 3 to 10 hours a day, with a power consumption anywhere from 2500 to 9500 kw-hr. a month.

The Goose Creek field in Texas is a deep pool from which the following figures have been obtained:

Depth of wells	2800 (av.) 3400 ft. (max.)
Pumping speed	28 strokes per min.
Hole in crank	2nd
Gravity of oil	20 deg. B.
Size of tubing	$2\frac{1}{2}$ in.
Considerable water and gas.	
Monthly kw-hr. per well	3500 to 4000

Motor for Driving "Powers"

The well-known method of pumping wells in a group from a central "power," with shackle rods extending from the "power" to the jack at each well, is very well adapted to motor drive and a large number of such applications have been made. No special electrical features are necessary, and constant-speed duty is usually all that is required. Such wells are pulled by portable hoisting outfits, to which small hoist motors have been applied in several instances.

The number of wells in a group and the length of time each is pumped daily vary so widely that no good general data can be given. A motor load of about 2.5 h.p. per well and an average power consumption from 30 to 45 kw-hr. per well per day is a rough estimate of about what may be expected.

ADVANTAGES OF ELECTRIC POWER FOR OIL WELL PUMPING OPERATIONS

For oil well pumping, motor drive has a number of special advantages which have already been discussed in detail,* but which can well be summarized here:

Increased Production

Fuel Saving

The oil fuel consumption for steam-engine pumping of individual wells is from 3 to 15 barrels per well per day. This is saved by electrification and thus in fact amounts to an increase in net production. More gas is available for the market where motors replace gas engines.

Decrease of Shut-downs

Elimination or reduction of many avoidable shutdowns in oil well pumping operations can be accomplished by using motors, and production can thus be increased in many cases as much as 15 per cent. Evidence of this is given in Table II.

TABLE II

COMPARISON OF PUMPING TIME LOST FROM SHUT-DOWNS WITH GAS ENGINE AND ELECTRIC DRIVE UNDER SIMILAR NORMAL OPERATING CONDITIONS IN KANSAS, PUMPING ON THE BEAM

	GAS-ENGINE DRIVE AUGUSTA FIELD		ELECTRIC DRIVE EL DORADO FIELD	
	Nov., 1917	Feb., 1918	Oct., 1918	Nov., 1918
No. of wells	208	216	26	27
Percentage of available pumping time lost, all causes	23.3	28.2	10.7	9.8
Percentage of available pumping time lost, engine or electric troubles only	4.8	8.15	1.98	0.63

Experience has demonstrated that the value of motor drive in accomplishing these results lies in the following points:

(a) Electric troubles do not cause over two per cent loss in time due to shut-downs.

(b) There are no gas, water, or freezing troubles with electric drive.

(c) The time lost from rod breakage is usually cut in half when motors are installed.

(d) Valve and cup troubles are reduced several per cent with motor drive.

(e) There are occasionally some other troubles which electric operation remedies to a considerable extent.

Time Saving

By reducing or eliminating many delays, electric drive makes more pumping time available and thus increases the production. In this respect the following are included among the advantages of a motor over a gas engine or steam engine.

(a) No delay from steam lines full of water after an idle half hour.

(b) No time required to get up steam after long idle periods.

(c) A motor cannot stick on dead center.

(d) A motor, unlike a gas engine, will always start without difficulty.

(e) A motor does not materially slow down on the heavier "pulling" work and hence pulls the first "stand" of tubing as fast as the last one.

(f) The more accurate control obtained with motors results in quicker work in handling rods and tubing.

(g) After drilling is completed, less than an hour is ordinarily necessary to change to electric pumping when the proper arrangements are made. Production lost at the flush period during the long time required to set a pumping engine is thus nearly all saved.

Uniform Pumping Speed

Production is much reduced by variations in engine speed. The more uniform speed of a motor maintains full output of every well. Actual examples are given in Tables III and IV.

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*"The Operation of Oil Wells by Electric Power and the Resulting Gain to the Oil Producer," by W. G. Taylor, GENERAL ELECTRIC REVIEW, vol. XXII, May, 1919, p.384.

TABLE III

COMPARATIVE PRODUCTION WITH STEAM ENGINE AND ELECTRIC DRIVE UNDER IDENTICAL OPERATING CONDITIONS ON THE SAME WELL, PUMPING BY ENGINE AT NIGHT AND BY MOTOR IN DAYTIME. BURMA OIL COMPANY, SINGU FIELD, UPPER BURMA, INDIA

	Aug., 1916		Sept., 1916	
	Bbl.	Per Cent	Bbl.	Per Cent
Oil pumped by motor	1311	42.5	1310	45.4
Oil pumped by engine	1777	57.5	1587	54.6
	Hrs.	Per Cent	Hrs.	Per Cent
Total time motor operation	271	36.5	270	37.5
Total time engine operation	473	63.5	450	62.5
Barrels per hour, motor	4.84		4.82	
Barrels per hour, engine	3.75		3.52	
Increase in production due to motor drive		28.5		36.0

TABLE IV

INCREASE OF PRODUCTION OBTAINED WITH ELECTRIC DRIVE BY AN OIL COMPANY IN THE SPINDLETOP FIELD, TEXAS, PUMPING FROM A "POWER"

	Total Bbl.	Bbl. Per Day	Bbl. Per Well Per Day
Eight wells on steam, January and February, 1918	9346	158.4	19.8
Same eight wells, electric power, March and April, 1918	10,791	176.9	22.1
Increase (11.6 per cent)		18.5	2.3

Lower Operating Expenses

Operating figures for a number of oil companies have been published to show the comparison between engine and motor drive, and they all indicate a remarkably large saving with the latter. Four different companies, for example, show savings respectively of 22 per cent (12 wells), 21 per cent (12 wells), 40 per cent (107 wells) and 63 per cent (number of wells not stated). Comparisons for five other companies show average savings, obtained when electric drive was substituted for steam engines, varying from $450 to $2775 per well per year, the average for all these being approximately $1275. As the complete cost of a standard two-speed oil well pumping motor installed is from $1600 to $2000 per well, depending upon the kind of installation, the comparisons indicate that in nearly all cases this can be fully paid for from the savings in less than two years, even though the greatly diversified conditions encountered in the oil fields cause a wide variation in the costs of operation.

The items taken into consideration in these comparisons are only those affected by the change; viz., fuel, power, labor, water, and maintenance. A few comments on each of these will be of interest.

Fuel and Power

As previously mentioned, the oil field consumption for steam-engine pumping operations is from 3 to 15 barrels per well per day. The electric power usually required is from 60 to 150 kw-hr. per well per day, though in exceptional cases it may reach about 200 kw-hr. maximum. From this it is clear that at prevailing power rates electric power is much the cheaper. It may also be cheaper than gas fuel where the latter has any market value.

Labor

Motors require much less labor expense than engines. One pumper can usually look after 15 or 20 motors, but cannot properly handle more than 8 to 12 gas engines or 10 to 15 steam engines under the same conditions. One electrician can take the place of several gas-engine and boiler repair men, and firemen are needed only in proportion to the number of boilers retained on the lease.

Water

Water is scarce and expensive in many oil fields, and such as is obtainable is usually bad for boilers. The use of motors eliminates it at a saving often in excess of the cost of electric power.

Maintenance

The average annual repair expense on oil well motor equipment does not reach one per cent of the first cost, even over periods of operation up to 12 years or more. Gas engine equipments not over four or five years old have an average annual maintenance expense of more than 11 per cent. A low figure for steam engines and boilers is five per cent. Another important matter is the investment necessary for a suitable stock of repair parts. For motors, this is not over 25 per cent of that required for gas engines, due to the lower rate of depreciation and the fewer wearing parts.

Other Advantages of Motors

(1) A motor cannot run away when the rods part.
(2) Explosions are eliminated and the fire risk is reduced, thus lowering insurance rates.
(3) Accidents are fewer.
(4) More reliable speed control is obtained.
(5) Better motion of cleaning-out tools is produced by motors than by gas-engines.
(6) Motors have a simpler method of control than engines.
(7) Electric power consumption can be accurately measured.
(8) Electric drive is cleaner and quieter than engine drive.

MOTOR EQUIPMENTS FOR OIL WELL DRILLING

A different type of electrical equipment is used for drilling than for pumping. Drilling requires a motor of larger capacity than is necessary on a producing well, and the method of control is somewhat different. It is therefore the practice to use separate equipments exclusively for drilling, and, as each well is completed, to put in a pumping motor as a permanent installation, moving the drilling motor and control apparatus to the next new rig.

For standard cable-tool drilling, an ordinary slip-ring induction motor gives the best results. An auxiliary controller provided in addition to the main controller gives the very fine adjustment of speed necessary to make the movement of the walking-beam accord with the natural period of vibration of the drilling line. The two controllers are operated independently by rope-wheels from the headache post, Fig. 8.

In cable drilling the beam must overspeed and allow a "free drop" of the tools on the down-stroke to get the most effective blow. To accomplish, this the motor must slow down on the up-stroke and speed up on the down-stroke. This characteristic is very satisfactorily obtained by so proportioning the pulleys that some secondary resistance is in circuit when the motor is operating at the proper drilling speed.

For rotary drilling the same type of motor is used for the draw-works and turntable, but very fine speed control is not necessary. The slush pumps are also driven by standard slip-ring motors.

Drilling itself is a fairly steady load on the motor, but the other work, particularly the handling of casing, is heavy and very intermittent in character. This may be seen in Figs. 3, 4, and 5. For wells much over 2000 ft. in depth, a 75-h.p. motor has been found by experience to be of suitable size. It has been used for drilling to a depth of 4412 ft. in California and apparently has ample capacity for still deeper drilling. For 2000 ft. or shallower wells, 50 h.p. may be sufficient, depending upon local conditions.

Power Consumption for Drilling Operations

It has been found that after a well has reached a depth of 300 or 400 feet, the amount of energy required per hundred feet increases with the depth of the well. As the well grows deeper the drilling tools used are smaller in diameter and lighter in weight, and a larger amount of water is usually carried in the hole, so that the power required to swing the tools grows less. On the other hand, the length of time required for bailing increases in proportion to the depth, and the "dashpot" effect in pulling out the bailer increases due to the larger amount of water in the well. It is also usually necessary to work the casing more frequently as the depth increases, in order to keep it from "freezing." Both of these conditions cause a considerable increase in energy consumption. Furthermore, progress becomes slower as the well deepens. The power consumption as a whole, therefore, increases more rapidly than in direct proportion to the depth.

Mr. W. G. Lane recently published* very reliable power consumption figures which are based on actual meter readings taken not only over a considerable period of time, but also on a number of different rigs in various fields. These show the average energy consumption per 24-hour day to be as follows:

1000-ft. territory......	150 to 170 kw-hr.
1500-ft. territory......	180 to 215 kw-hr.
2000-ft. territory......	200 to 235 kw-hr.
2500-ft. territory......	230 to 270 kw-hr.
3000-ft. territory......	250 to 285 kw-hr.
Over 3000-ft. territory......	265 to 350 kw-hr.

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*"The Application of Electricity to the Production of Crude Oil," by W. G. Lane, *The Oil Age*, vol. XVI, Jan. 1920, p. 10.

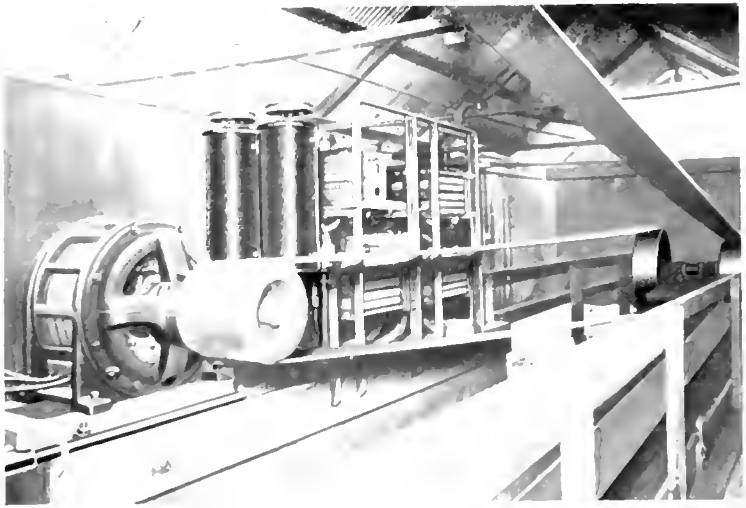

Fig. 8 A Complete 75 h.p. Oil Well Drilling Motor Equipment Operating Standard Tools in California

Fig. 9. Electrically Pumped Oil Wells on the Famous "25 Hill" in the California Midway-Sunset Field, Located in the Desert of the San Joaquin Valley

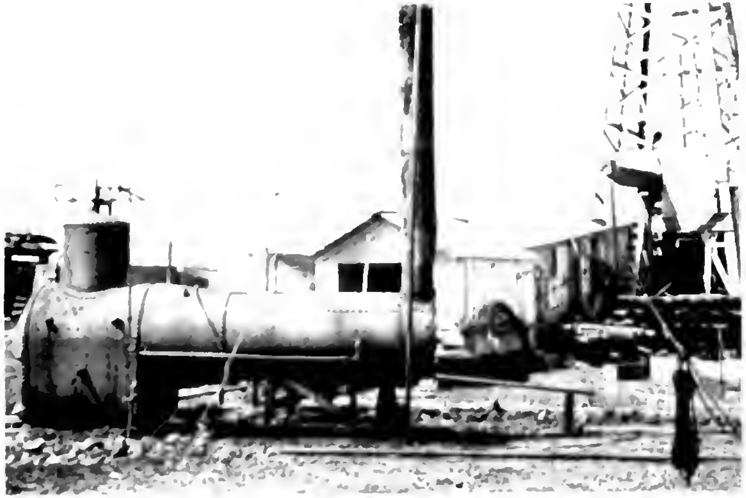

Fig. 10 The Usual Installation for Oil Well Drilling by Steam Power. Electric Drilling Eliminates the Enormous Loss of Heat and Consequent Waste of Fuel

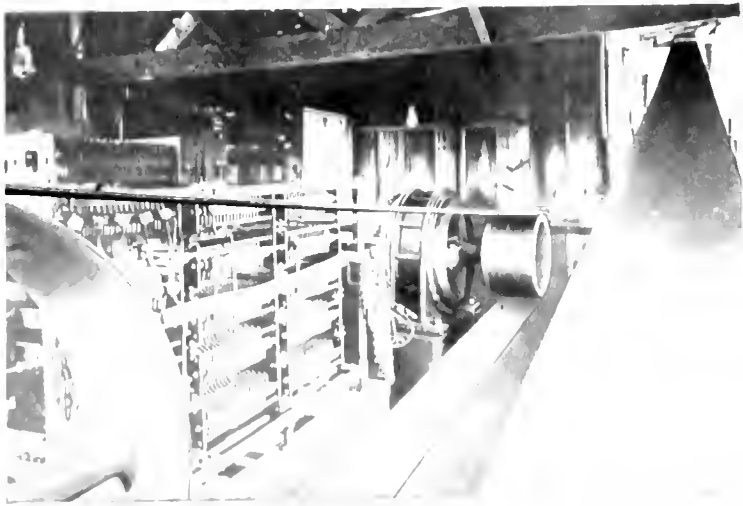

Fig. 11 The 75 h.p. Oil Well Drilling Motor Equipment Used by the Empire Gas and Fuel Company on the First Electrically Drilled Well in the Kansas Oil Fields

Advantages of Electric Drilling

To the power company it is of advantage to introduce electric drilling and thus get power lines into the fields early in the game. Electric pumping then follows as a logical step, as oil men all consider it more feasible to adapt motor drive to pumping than to drilling operations.

As to the success and advantages of drilling by electricity, a large oil company in the Mid-continent field recently published* convincing comments and data. It was stated that "results obtained in the drilling of Stokes No. 27 and a subsequent well show conclusively that a combination of motor and control apparatus has been perfected to a degree that causes even experienced drillers to say electric equipment is superior to steam." The driller himself reported: "Having worked on Stokes No. 27 from start to finish, my candid opinion is that electric power for drilling is great. From a standpoint of economy and reliability it has no equal. In spudding, drilling, bailing water, pulling tools or landing casing, the motor gave us not the slightest difficulty."

The cost of installing and operating this drilling equipment compared with what it would have been with steam-engine drive is given in Table V.

WATER PUMPS

Practically all oil companies using motors pump their own water with electrically driven pumps, and it has often been the case that these were the first motors put in. In the aggregate this amounts to a considerable power load, but for any particular property a small unit furnishes all the water necessary. The large companies usually have an extensive water supply system.

Fig. 12. Pumping 450 Barrels of Oil a Day From a Depth of 1900 ft. with a Two-speed Oil Well Motor in the California Midway Field

TABLE V

COST OF INSTALLATION AND OPERATION OF MOTOR EQUIPMENT FOR DRILLING 2440-FOOT WELL, COMPARED WITH STEAM-ENGINE DRIVE

	Boiler and Engine	Motor	Loss	Saving
Initial cost	$1,862.00	$1,625.00		$ 237.00
Cost of installation (including belts, etc.)	432.50	*768.03	$335.53	
Estimated depreciation per well	290.00	32.50		257.50
Cost of water	480.00	60.00		420.00
Estimated cost of fuel oil at $36 per day	2,160.00			
Cost of electric power		574.93		
Saving in cost of power				1,585.07
Saving in installing pumping motor in same house, on same foundation				186.16
Saving in oil production during change to pumping				1,305.00
Totals			$335.53	$3,990.73
Net estimated saving of electric drilling over steam				$3,655.20

*The installation charge of the motor drilling equipment was high, due to the fact the equipment was new and changes had to be made which involved labor charges that will not be necessary in future outfits. It also includes the cost of building the motor house.

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*"Drilling by Electricity" in *The Empire* (published by Empire Gas and Fuel Co., Bartlesville, Okla.), Oct. 30, 1919.

GATHERING AND LINE PUMPS

Pumps requiring motors up to 100 horse power, and often built for high pressures, are used for gathering crude oil from the wells and sumps and transferring it to the pipe lines or tank farms. These furnish a considerable power load, though it is not large in comparison with oil well pumping. The small units generally use squirrel-cage motors, but slip-ring machines are necessary to obtain variable speed on the larger pumps on account of the variable pressure encountered in cold and hot weather.

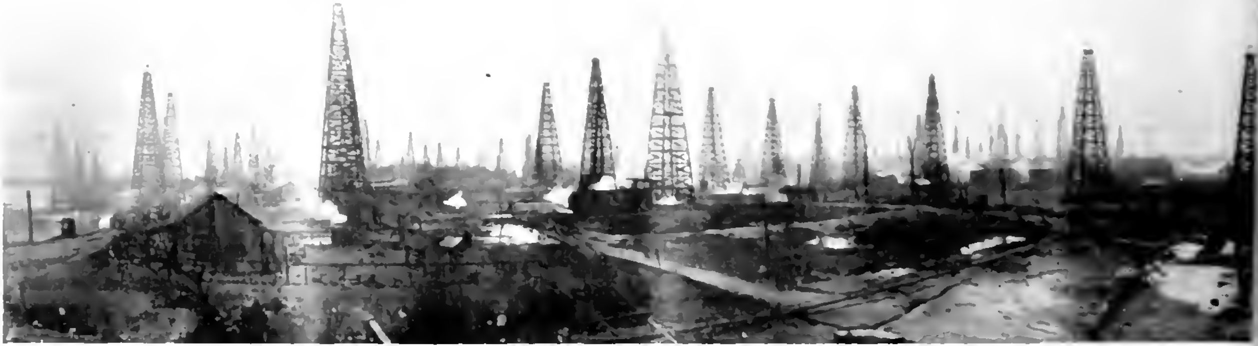
The application of electric drive to main pipe line pumping makes a very desirable load for the central station, but current is seldom available at every pumping station along the line. The general tendency up to the present has been to install uniform pumping equipment at all stations on a pipe line, and accordingly there are only a few instances where motor-driven pumps have been installed. The larger stations require several hundred horse power and the load is uniform and practically continuous. Power companies will therefore be warranted in making strong efforts to obtain this desirable load.

VACUUM PUMPS, COMPRESSORS AND CIRCULATING PUMPS FOR CASING-HEAD GASOLENE PLANTS

The electrification of casing-head gasolene plants is a comparatively recent development, but in some fields, particularly in Oklahoma, it has promise of exceeding oil well pumping as a central station load. In the Drumright field alone there is more than 32,000 horse power in gas and oil engines in these plants, and there are good reasons for anticipating that many of these will be changed to electric drive within a brief period.

Most casing-head gasolene plants are now driven by gas-engines and use the residue gas for fuel. In many cases this gas would be blown off and wasted if not so used, and it would accordingly be expected that motor drive would receive scant consideration. However, engine troubles are found to be the cause of a big loss in gasolene production, this more than offsetting the cost of the electric power which would be consumed. The engines are not only shut down several days a month for repairs, but their speed variation results in reduced output of the compressors. It is very necessary that a definite speed be maintained at all times in order to handle the maximum amount of wet gas.

One example of the better results obtained with motor drive is a plant at Los Angeles. Three 200-horse power gas engines driving the compressors were replaced, after less than a year's operation, by three 200-horse power slip-ring induction motors. An average shut-down of about four days per engine per month was thus eliminated and this increased the production an amount just



Panoramic View of the Goose Creek Oil Field in Texas, Where about sufficient to pay the monthly power bill. In addition, the steadier speed at which the motors drove the compressors resulted in greater production per day. This convinced the operating company of the superiority of electricity and they accordingly electrified their entire lease.

Operators consider motor drive for vacuum pumps even more necessary than for compressors. This is due to the fact that if the vacuum pumps are not operated continuously at a fixed speed, a loss in vacuum results which enables the neighboring leases to secure the gas and also a certain amount of oil. Every engine trouble which causes a shutdown means a probable loss in production to the plant for 10 to 18 hours, this being the time required to again build up a vacuum on the lines so that it balances that of the neighboring companies.

ELECTRIC DEHYDRATORS

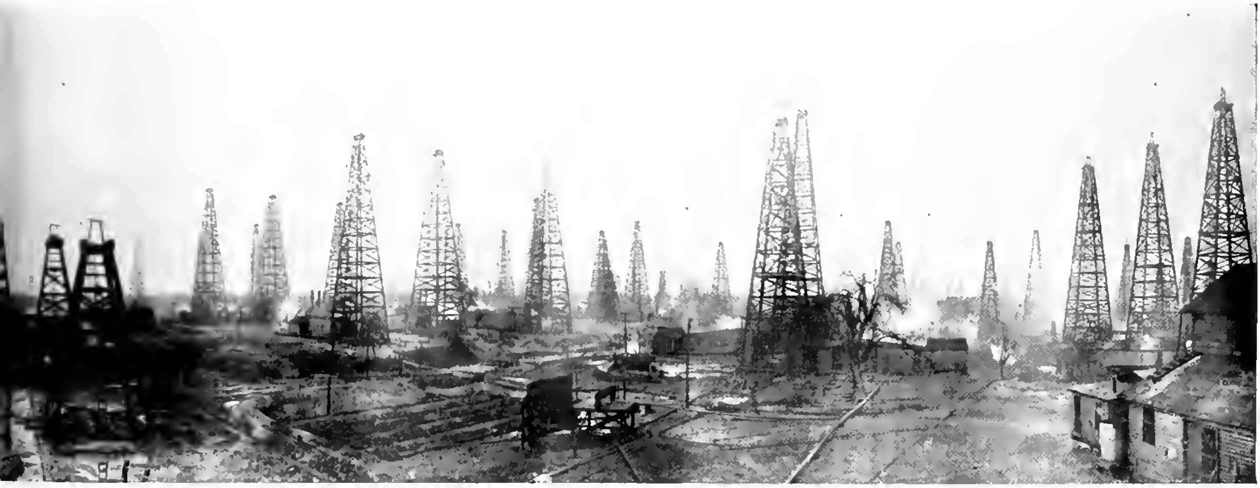
Electric dehydrators were developed to provide a more economical method than that usually employed for breaking up emulsions of water and oil which cannot be separated by settling. The oil containing the emulsion is passed through an electric field, between two electrodes having a difference of potential of about 11,000 volts. The discharge between the electrodes breaks down the emulsion and the water then settles out. This raises the Baumé gravity of the oil to practically its original figure and thus increases its market value. The saving thereby made is usually sufficient to pay for the treater within a period of operation of nine months or less.

The average power consumption is in the neighborhood of 2000 kw-hr. per month, though it may vary with the conditions from 1200 to 5000 kw-hr. The amount of power required per barrel of cleaned oil ranges from 22 to 65 watthours. The power-factor is about 98 per cent leading, due to the condenser effect of the highly charged electrodes. The dehydrators may consist of from two to eight treater units, but this does not affect the power consumption to any great degree.

MACHINE SHOPS AND LIGHTING

Little need be said about these applications of electric power in the oil fields, as they present no unusual features. A machine shop is a necessity in oil field operations and motor-driven tools have well-known advantages.

The fire risk is of course an important consideration in connection with oil production and for this reason electric lighting, particularly in gassy territory, is especially favored. When it is necessary to keep all wiring as far away from a drilling rig as possible and to avoid even the danger of ignition from the breaking of a bulb, flood lighting furnishes practically the only safe method of illumination.



Wells are Now Pumped by Two-speed Oil Well Motors

Theory of Speed and Power-factor Control of Large Induction Motors by Neutralized Polyphase Alternating-current Commutator Machines

By John I. Hull

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This article discusses the theory of induction-motor control under the headings of: single-range (below synchronism only) speed and power factor control by means of a constant-speed series commutator motor, by means of a constant-speed shunt commutator motor, by means of a constant-speed compound excited commutator motor; double-range (all speeds above or below synchronism) speed and power factor control by means of a constant-speed shunt commutator motor; and double-range (either above or below synchronism) operation remote from synchronism. This article was presented as a paper at the A.I.E.E. convention, White Sulphur Springs, W. Va.—Editor.

A stationary polyphase wound-rotor induction motor is merely a static transformer arranged so that the primary coils are all on one part of the magnetic circuit, and the secondary coils on another part of the magnetic circuit, the two parts thus being arranged so as to permit relative motion. The reluctance of the magnetic circuit is kept as low as possible by imbedding both primary and secondary winding in slots, thereby permitting the "teeth" between the slots of the primary iron to come as close to the "teeth" of the secondary iron as safe mechanical clearance permits. The necessity of some clearance or "air gap" makes the reluctance, hence, the magnetizing current and kv-a. larger than for the static transformer of similar capacity, voltage and frequency, while the separation of the primary winding from the secondary winding and the imbedding of both in slots make the leakage reactances larger than for the corresponding static transformer. It is thus evident that the induction motor may logically be considered from the point of view of a transformer so arranged as to permit the forces set up in the secondary conductors to cause rotation, at the cost of an increase in the magnetizing current and the leakage reactance.

The flux common to both and set up by the resultant of the primary and secondary magnetomotive forces is the link of mutual influence between the primary and secondary. This influence manifests itself as electromotive forces set up in proportion to the effective number of turns, the flux, and the frequency in the circuit in question. (Of course, this is rigorously true only with the usual assumptions of sine wave distribution, etc.)

The torque is proportional to the summation of the products of the secondary turns, and the components of current in quadrature with the common flux of each, and to the common flux.

The usual theory of the induction motor takes into account only the phenomena within the motor itself, performance with adjustable external secondary resistance being analyzed by considering it to be merely an addition to the normal resistance of the secondary.

In Fig. 1, we reproduce a circle diagram, a vector diagram for analyzing induction motor performance, which lends itself to the introduction of electromotive forces etc., of concatenated machines.

$AH = I_1$ (proportional to primary current) represents the flux linking primary and secondary which would be produced by the primary current alone. (Saturation neglected.)

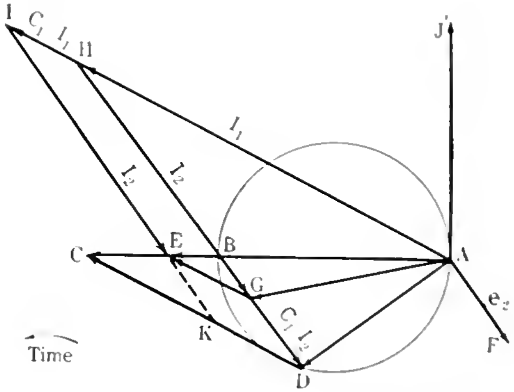


Fig. 1. The Circle Diagram of an Induction Motor

$HI = C_1 I_1$ represents primary leakage flux.

$HG = IE = I_2$ (proportional to the secondary current) represents the flux linking secondary and primary which would be produced by the secondary current alone. (Saturation neglected.)

$GD = C_2I_2$ represents secondary leakage flux.

AE is thus the resultant of all the primary flux and that secondary flux, linking the primary, so that neglecting primary resistance drop E is a fixed point for constant line voltage and frequency, as AE is the flux which generates the counter e.m.f. to balance the applied voltage e_1.

HG intersects AE at B, and as

$$AB/AE = \frac{I_1}{I_1(1+C_1)}$$

we see that AB is constant, making B also a fixed point. AD is resultant of I_1 and $I_2+C_2I_2$ and therefore generates all secondary electromotive forces except resistance drop which is, therefore in phase opposition to the voltage e_2, set up in the secondary in quadrature to flux AD. This makes AF parallel to HD and to IE and further makes ADH a right angle, which taken in connection with the fact that, as shown above, A and B are fixed points, demonstrates that the curve traced by point D is the arc of a circle.

A line parallel to AI from point D intersects prolongation of AE at C and prolongation of IE at K.

$$CD = CK + KD$$

$$\frac{CK}{EK} = \frac{AI}{IE}$$

$$CK = \frac{C_2I_2 \times I_1(1+C_1)}{I_2}$$

$$= I_1C_2(1+C_1)$$

$KD = HI = C_1I_1$ (since they are parallels intercepted by parallels)

$$CD = I_1[C_1+C_2(1+C_1)]$$

$$BD = BG + GD$$

$$\frac{BG}{EG} = \frac{IE}{IA}$$

$$BG = \frac{EG \times IE}{IA} = C_1I_1 \times \frac{I_2}{I_1(1+C_1)}$$

$$= I_2 \times \frac{C_1}{1+C_1}$$

$$GD = C_2I_2$$

$$BD = I_2\left(C_2 + \frac{C_1}{1+C_1}\right)$$

$$= \frac{I_2}{1+C_1} \times [C_1+C_2(1+C_1)]$$

EA is the flux whose counter e.m.f. balances all the applied line voltage as noted above. Let it be designated I_m. BA is the *mutual flux* at running light and, if denoted by I_0, we have

$$I_0 = \frac{I_m}{1+C_1}$$

$$CB = CE + EB$$

$$\frac{CE}{EA} = \frac{EK}{EI}$$

$$CE = EA \times \frac{EK}{EI} = I_m \times \frac{C_2I_2}{I_2} = I_mC_2$$

$$\frac{EB}{EA} = \frac{IH}{IA} \qquad EB = I_m \times \frac{C_1I_1}{I_1(1+C_1)}$$

$$= I_m \times \frac{C_1}{1+C_1}$$

$$CB = I_m\left(C_2 + \frac{C_1}{1+C_1}\right)$$

$$= \frac{I_m}{1+C_1} \times [C_1+C_2(1+C_1)]$$

$$= I_0[C_1+C_2(1+C_1)]$$

Further, C is a fixed point since:

$$\frac{CE}{EA} = \frac{EK}{EI} = \text{Constant} = C_2 \times I_2/I_2$$

$$CA = EA + CE = I_m + I_m C_2 = I_m(1+C_2)$$

$$= \frac{I_m(1+C_2)[C_1+C_2(1+C_1)]}{C_1+C_2(1+C_1)}$$

Summing up we have:

$$CD = I_1[C_1+C_2(1+C_1)]$$

$$DB = \frac{I_2}{1+C_1} \times [C_1+C_2(1+C_1)]$$

$$CB = \frac{I_m}{1+C_1} \times [C_1+C_2(1+C_1)]$$

$$= I_0[C_1+C_2(1+C_1)]$$

$$CA = \frac{I_m(1+C_2) \times [C_1+C_2(1+C_1)]}{C_1+C_2(1+C_1)}$$

$$EA = I_m$$

$$BA = I_0$$

With proper scale, I_m could be made to represent the magnetizing current for a total flux I_m, (which is the quantity commonly calculated, as the primary reactance and resistance drop are usually omitted) I_0 could be made to represent the true running light current, primary reactance drop considered, I_1 the primary current and I_2 the secondary current. If we now change the scale of the diagram by the factor $C_1+C_2(1+C_1)$, we may say that magnetizing current i_m divided by $1+C_1$ equals CB, equals true running light current i_0; primary current i_1 equals CD; secondary current divided by $1+C_1$ equals DB.

At standstill, with zero secondary resistance AD, the resultant secondary flux must, of course, be zero, as its generated voltage is zero, which means that D coincides with A and $CD = CA$, so that we have the ideal short-circuit or standstill current, with zero secondary resistance, equal to CA.

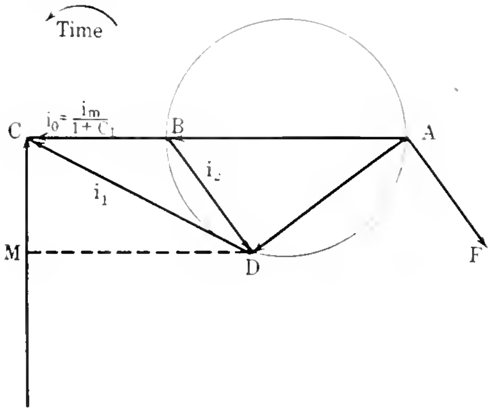


Fig. 2. Simplified Diagram

As $C_1 I_1$ is defined as primary leakage flux, the primary reactance drop with current i_m is $C_1 e_1$, since i_m produces a total flux whose e.m.f. is equal to e_1. The primary reactance drop is further equal to $i_m X_1$, if X_1 be the primary reactance, thus:

$$C_1 e_1 = i_m X_1$$

$$C_1 = \frac{i_m X_1}{e_1} \text{ and similarly}$$

$$C_2 = \frac{i_m X_1}{e_1}$$

Thus, to draw the diagram of the motor, we need to know the primary and secondary reactances X_1 and X_2 and the nominal magnetizing current i_m. We need then only so much of Fig. 1 as is shown in Fig. 2.

Having chosen a scale, lay off:

CB equal to i_0

CA equal to $\frac{i_m(1+C_2)}{C_1+C_2(1+C_1)}$ and

draw a circle with BA as diameter. CM is the in phase or watt component of input current for any considered lead. MD parallel to CA then locates D and the remainder of the diagram. The primary current is then $i_1 = CD$ and the secondary current i_2 is then $(1+C_1)DB$, or if we use as the unit for i_2 the unit denoting the other currents divided by $1+C_1$, we can let $DB = i_2$.

To find the secondary voltage $e_2 = AF$, we can first determine its value reduced to full frequency. The voltage generated by flux AE of Fig. 1 is e_1, and that generated by AB is, therefore, $\frac{e_1}{1+C_1}$. So in Fig. 2, knowing e_1, we can say that AB units of length correspond to $\frac{e_1}{1+C_1}$ volts, and can regard AB, etc., as measures of voltage. So AD is $\frac{AD}{AB}$ times $\frac{e_1}{1+C_1}$ volts at standstill frequency. If the secondary resistance is known, the actual value of secondary induced voltage e_2 is, of course, $i_2 r_2$, so that per cent slip is $s = \frac{i_2 r_2}{AD}$.

"Synchronous watts" torque is BD times AD, output is $(1-s)BD \times AD$, efficiency $(1-s)$ $BD + \frac{AD}{e_1} MC$, power factor $\frac{MC}{CD}$.

If the ratio of secondary turns to primary turns is other than 1 to 1, the diagram is, of course, of necessity drawn for all factors reduced to either primary or secondary terms, secondary terms being usually used for work of the present sort. Thus, the primary voltage to be expressed in terms of secondary must, of course, be multiplied by ratio of secondary to primary effective terms, primary reactance by the square of this ratio, etc

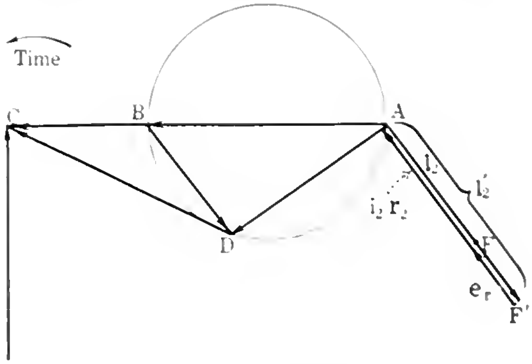


Fig. 3. Induction Motor Diagram

With neutralizing voltage e_r introduced into secondary in phase opposition with $i_2 r_2$ [illegible]

In the demonstration of Figs. 1 and 2, it was pointed out that point D traces the arc of a circle whose diameter is BA, because ADB is a right angle, due to the phase opposition of e_2 and $i_2 r_2$ when the only e.m.f. in the secondary circuit, other than that induced by the total secondary flux, is resistance drop. If as in Fig. 3, another e.m.f. than the resistance drop as e_r be introudced, then D will still trace the circle with the diameter $A\ B$ when and only when the introduced e.m.f. is in phase with or in phase opposition to e_2. In this case, for given values of i_1, i_2, etc., e_2 must be equal and opposite to the algebraic sum of $i_2\,r_2$ and the introduced voltage; hence, since the inducing flux of e_2 is determined by the currents,—its inducing frequency and the slip and speed must follow variations in the algebraic sum of $i_2\,r_2$ and the introduced voltage. It is, therefore, evident that varying the introduced voltage, while maintaining it in phase with e_2 gives a means of varying the speed of the motor without effecting its power factor torque, etc.

If now, as in Fig. 4, the introduced e.m.f., e_r be of different phase from that of e_2, point D departs from the circumference of the circle whose diameter is $B\ A$, as shown at D' because i_2 is no longer in phase opposition to e_2, hence, $A\ D'\ B$ is no longer a right angle. It is seen that in addition to regulating the speed, the power factor of the motor may also be regulated by proper selection of phase as well as magnitude of the introduced e.m.f.

It is clear, of course, that the frequency of the introduced or regulating e.m.f. must at all times be exactly that of e_2, in order to maintain the phase relation shown.

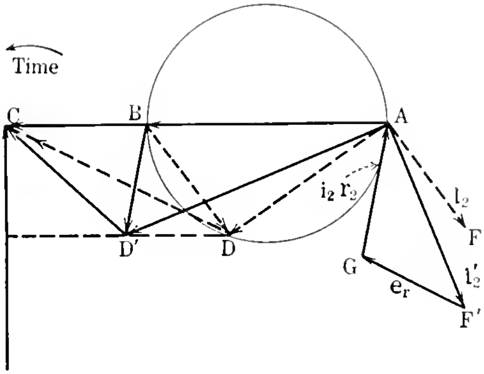


Fig. 4. Induction Motor Diagram

With regulating voltage e_r introduced into secondary out of phase with total induced e.m.f.

Thus, if we can introduce at exact secondary frequency a regulating voltage of controllable phase with respect to e_2 and controllable magnitude, we shall be able to regulate either speed, power factor or both.

Single-range (Below Synchronism Only) Speed and Power-factor Control by Means of a Constant-speed, Series Commutator Motor

In Fig. 5, we show schematically at D, a three-phase series neutralized commutator machine whose terminals are connected to the secondary slip rings of main motor A. The speed of D is held practically constant by generator E.

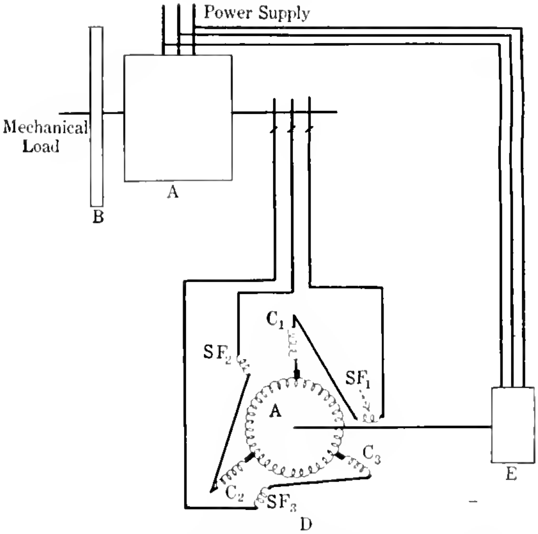


Fig. 5. Neutralized Series-excited Three-phase A-c. Commutator Machine and Connections for Automatic Single-range Regulation of Induction Motor Equipped with Flywheel to Reduce Peaks on Line

Neutralizing winding C_1, C_2, C_3 balances the armature reaction (magnetomotive forces) of armature A_w, and so of necessity neutralizes the e.m.fs. set up in A_w by the transformer action of the fluxes induced by series exciting windings SF_1, SF_2, SF_3. (C_1, C_2, C_3 being in series with A_w carry the same currents as A_w, hence, for a balanced condition of magnetomotive forces must have an equivalent and opposite number of turns, so the e.m.fs. also cancel.) Thus the e.m.fs. appearing at the terminals of D are the leakage reactance drop, resistance drop and the rotation e.m.f. induced by the rotation of the armature A_w. The rotation e.m.f. is, of course, proportional to the flux and the speed of rotation, the flux, neglecting saturation being proportional to the main currents which flow through series exciting windings SF_1, SF_2, SF_3. This arrangement can then be seen to be such that the speed of A will be reduced with the increase of load, provided the rotation voltage, as e_r in Figs. 3 and 4, be given a suitable component in phase with the resistance drop, thereby having the same effect on the main motor speed, as increasing the resistance.

Up to the point of the magnetic saturation, two laws may be seen to inhere in the machine *D*.

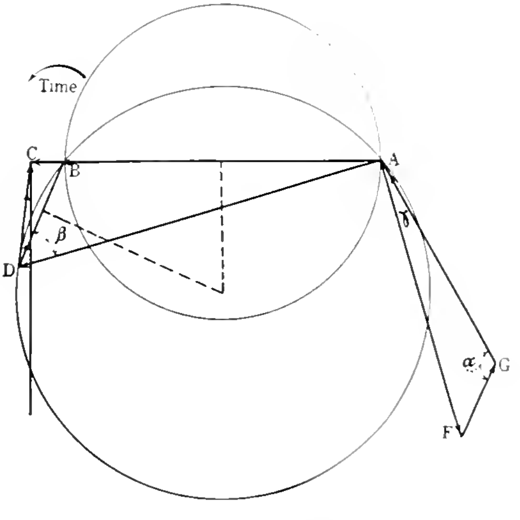


Fig. 6. Circle Diagram of Induction Motor with Constant-speed Series A-C. Commutator Regulating Machine

1. The flux, hence the rotation voltage at constant speed, is proportional to the current.

2. The phase angle between the current and the rotation voltage (hence, the angle between resistance drop and rotation voltage) is constant (it can only be changed by changing the construction of the machine).

These are the basis of the circle diagram of Fig. 6.

Points *A*, *B*, and *C* are determined exactly as in Fig. 1, except that for X_2 we now substitute X_{2+c+c_s} where $X_{2+c+c_s} = X_2 + X_c + X_{c_s}$ and X_c = leakage reactance of regulating motor at primary frequency

$$X_{c_s} = \frac{\text{kv-a. required to excite regulating motor}}{i_2^2 \times \sqrt{3}}$$

The kv-a. is at primary frequency and unsaturated iron of regulating motor is assumed. Obviously the performance of an induction motor is not changed for our purposes, having a part or all of the rotor leakage reactance external to the machine. Angle $\alpha = F\,G\,A$, between resistance drop $F\,G$ and rotation e.m.f. $G\,A$ is constant by law No. 2, and $G\,A$ is by law No. 1 proportional to $B\,D$ and hence to $F\,G$. For these reasons angle $G\,F\,A$ is constant and since angle $B\,D\,A = 90$ deg. $-$ angle $G\,F\,A$, we see that β = angle $B\,D\,A$ is also constant.

Thus, as *A*, *B*, and *C* are fixed points, point *D* traces a circle whose center must be at the intersection of the perpendicular bisectors of *A B* and *B D*.

We have remarked that Figs. 1, 2, 3, 4 and 6 are rigorous when and only when the iron of the machine is unsaturated, that is, when the flux may be regarded as proportional to the ampere turns. This condition is closely enough approximated in the main induction motor so that saturation may be neglected without much loss of accuracy. For the series machine of Fig. 6, however, to be of economical proportions, considerable saturation will be attained within the working range; hence, it becomes desirable to investigate its effects. In Fig. 7, *A*, *B*, *C* has been determined as was done for Fig. 6, and *B D A* is the corresponding circle determined by angle *B D A*, which is determined by ratio $\frac{A\,G}{F\,G}$ and design angle α, saturation neglected.

Now with current *B D*, we can calculate a new value for X_{2+c+c_s} which will hold only for this one current, since in expression

$$X_{c_s} = \frac{\text{kv-a. to excite regulating motor}}{i_2^2 \sqrt{3}}$$

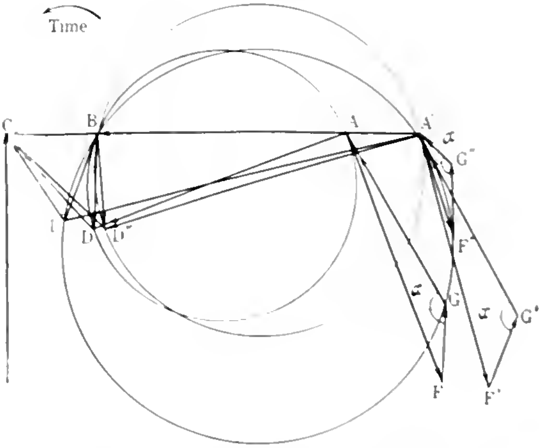


Fig. 7. Diagram of Induction Motor and Constant-speed Series A-C. Commutator Regulating Machine

Taking account of saturation of iron of regulating machine

we can determine kv-a. (at full frequency, of course) from the known or assumed magnetizing curve of the regulating machine. With this new (and decreased) value of X_{2+c+c_s} we calculate $A'\,C$ instead of $A\,C$. If the new value of X_{2+c+c_s} were constant, our new circle would be $B\ D'\ A'$, but as it varies, D' may be the only load point upon it. Triangle A', F', G' is, of course, equal to triangle $A\ F\ G$, and angle $B\ D'\ A'$ is equal to angle $B\ D\ A$.

A second effect of the saturation is that the ratio of rotation e.m.f. to field current (field current being the same as the main current for a series machine) is reduced, so considering this, $A'\ G''\ F''$ is the e.m.f. triangle with angle $A'\ G''\ F''$ still equal to angle $A\ G'\ F'$ and $A\ G\ F$.

Since $A'\ G''$ is less than $A'\ G'$ and $G''\ F'' = G'\ F'$ with constant α we see that angle $G''\ F''\ A'$ is less than angle $G'\ F'\ A'$, hence, angle $B\ D''\ A'$ greater than angle $B\ D'\ A'$ and the circle, if X_{2+c+c_s} and $\frac{A\ G''}{G''\ F''}$ were constant, would be $B\ D''$ A'.

We thus see that the two effects of saturation of the regulating machine partially offset one another, as the reduction of X_{2+c+c_s} makes the imaginary circle larger and the power factor more leading, while the reduction of ratio $\frac{A'\ G'}{G'\ F'}$ to $\frac{A'\ G''}{G''\ F''}$ makes the imaginary circle smaller and the power factor more lagging.

The point D'' cannot be located by rule and compass unless we calculate triangles $A'\ D''\ B$ and $A'\ F''\ G''$ which can be done as follows:

$A'\ G''$, $G''\ F''$ and angle $A'\ G''\ F''$ are known.

$$A'\ F'' = \sqrt{A'\ G''^2 + G''\ F''^2 - 2 \times A'\ G'' \times G''\ F'' \times \cos A'\ G''\ F''}$$

$$\sin A'\ F''\ G'' = \frac{A'\ G'' \times \sin A'\ G''\ F''}{A'\ D''}$$

Angle $F''\ A'\ G''$

$= 180$ deg.—(angle $A'\ F''\ G'' + A'\ G''\ F''$) determining triangle $A'\ F''\ G''$.

In triangle $B\ D''\ A'$, $B\ A'$ and $B\ D''$ are known and angle $B\ D''\ A' = 90$ deg.—angle $A'\ F''\ G''$.

$$\sin B\ A'\ D'' = \frac{B\ D'' \times \sin B\ D''\ A'}{B\ A'}$$

Angle $D''\ B\ A'$

$= 180$ deg.—(angle $B\ A'\ D''$ + angle $B\ D''\ A'$)

$$A'\ D'' = \frac{B\ D'' \times \sin D''\ B\ A'}{\sin B\ A'\ D''} \text{ or } \frac{A'\ B \sin D''\ B\ A'}{\sin B\ D''\ A'}$$

Knowing, thus, A D'' and $B\ D''$, we can find point D'' with compass.

We can now construct the curve traced by D'' by assuming values of current $B\ D''$, calculating for each value $A'\ B$, $A'\ G''$ and $A'\ D''$ as described.

For the designs ordinarily encountered, this yields a curve so closely approximating for the working load the original circle $B\ D\ A$ in which saturation is neglected, that it is not necessary to go beyond the construction of $B\ D\ A$ to get a good idea of the characteristics except slip which is $\frac{A'\ F''}{A'\ D''}$. If the scale used for $A'\ F''$ is not that of $A'\ D''$, then, of course, slip is $\frac{A'\ F''}{A'\ D''}$ multiplied by the proper ratio of scales.

The combination in Fig. 5 is suitable to service in which there are rapid and wide fluctuations in load which it is desired to absorb as much as possible by the flywheel B. This arrangement is superior to the use of a resistance across the slip rings because instead of being wasted as in the resistance, the slip energy can all be returned to the power system except for the machine losses of D and E. When applied to a motor with secondary resistance the flywheel reduces the peak loads by delivering torque as it is retarded. The return of most of the slip energy to the line by the regulating set decreases the peak loads still more. A further advantage for the regulating set is the means which it affords of materially improving the power factor of the main motor.

Single-range (Below Synchronism Only), Speed and Power Factor Control by Means of a Constant-speed, Shunt Commutator Motor

The series regulating set is, of course, the simplest form, but it is not adjustable without tapping the field winding or external apparatus and as it imparts to the main motor the characteristic of a material reduction of speed with the assumption of load, it is not suited to the majority of industrial uses in which variable speed from large induction motors is required. In the greater number of cases, it is desired to adjust the speed to a value suited to the momentary requirement of the process, and have the speed remain at approximately the adjusted value irrespective of load variation.

The total induced secondary e.m.f. of an induction motor including the secondary reactance drop is proportional to the "rotor field" (see $A\ D$ of Fig. 1) and the slip. So, as is well appreciated, within the working range the slip is about proportional to the torque as the torque is about proportional to the rotor current, the current being proportional to the total induced rotor voltage. If at a given load we obtain speed reduction by an increase in resistance or by the use of a "series" regulating set, in which cases an increase in secondary induced e.m.f., hence, slip is required to overcome the additional resistance drop, or the rotational e.m.f. of regulating set, plus resistance drop, then, as soon as the load disappears, the main motor speeds up to synchronism, since the secondary resistance drop and the rotational e.m.f. of the regulating motor vanish with the current. If the rotational e.m.f. of the regulating motor could be made independent of the load and of the slip, then with the departure of load it would remain constant, so that the speed would only rise enough to make the total induced secondary e.m.f. equal to the rotational voltage of the regulating motor, leaving no resultant to circulate load current. With load fluctuations, the speed would then fluctuate by only such small amounts as to cause at all times the small difference between total induced secondary e.m.f. and the rotational e.m.f. of the regulating motor to overcome the small resistance drop of the windings; usually only a few per cent of synchronous speed.

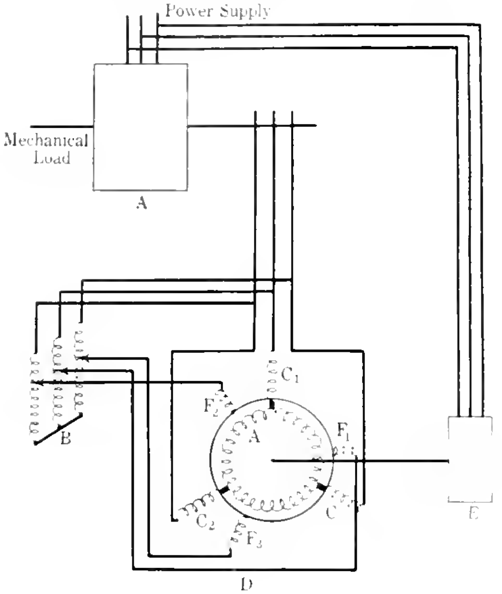


Fig. 8. Neutralized Three-phase Shunt Constant-speed A C. Commutator Machine and Connections for Adjustable Speed Control of Induction Motor Below Synchronism

In Fig. 8 is shown an arrangement to approximate these conditions. *A* is the main motor, *D* a neutralized three-phase shunt commutator motor, whose speed is held practically constant by generator *E*, returning the energy derived from *D* to the line. *B* is an auto transformer excited from the slip ring circuit and provided with suitable taps to apply pre-determined percentages of the slip ring e.m.f. to the shunt exciting windings F_1, F_2, F_3. Assume that the resistance drop in the F_1, F_2, F_3 circuit is negligible and that "*B*" applies to F_1, F_2, F_3 the selected percentage of the total secondary induced e.m.f. This with the further assumption that the reactance drop of the regulating motor is included in the slip ring e.m.f. (which is supplied to *B*) and that the resistance drop of the main motor rotor is not included in the slip ring e.m.f., will give what may be termed for our purposes, "pure shunt excitation." The effects of these assumptions will be pointed out later. The counter e.m.f. of F_1 F_2, F_3 thus consists of the e.m.f. set up by the flux excited by it, and is, therefore, proportional to the flux and the frequency (frequency itself being proportional to slip *s*).

$$i.e., e_c = k \times \phi \times s$$

The e.m.f. applied to the field is proportional to the total induced e.m.f., as remarked above, and the total induced e.m.f. is equal to its own standstill value for the main motor current (hence torque) in question times the slip, so we see that, total induced e.m.f. at standstill $\times s = k \times \phi \times s$.

ϕ is thus independent of frequency and proportional only to total standstill induced e.m.f. Referring to Fig. 9 *A*, *B*, *C* is constructed exactly as Fig. 1, including the leakage reactance of the regulating motor with that of the secondary of the main motor, so that instead of X_2, we shall have $X_{2+r} = X_2 +$

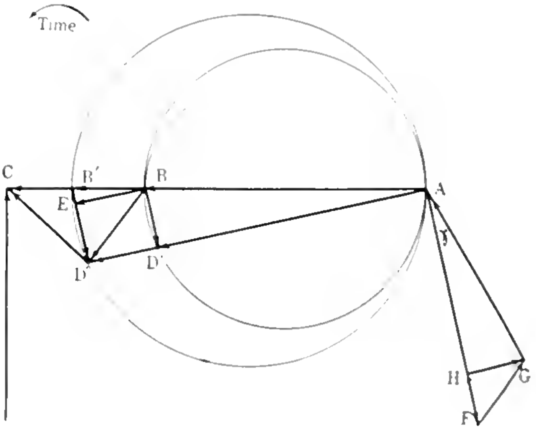


Fig 9 Circle Diagram of Induction Motor and Pure Shunt Excited Constant-speed A C. Commutator Machine

X_c and instead of C_2, we shall have C_{2+c}. The circle B, D, A would thus apply with regulating set D and E of Fig. 8, stationary. With the regulating set running, we get secondary current $B\ D'$, total induced e.m.f. $A\ F$ of main motor secondary proportional to slip and the $A\ D'$ and rotation e.m.f. of regulating motor $A\ G$ proportional to $A\ D'$ and at a constant angle γ from $A\ F$, angle γ being determined by the connections of the transformer B and exciting winding F_1, F_2, F_3 of Fig. 8.

Resolve resistance drop $F\ G$ into the component $F\ H$ in phase opposition to $A\ F$ and $H\ G$ in quadrature to $A\ F$, the corresponding components of secondary current $B\ D'$ being $B\ D$ and $D\ D'$.

$D\ D'$ is proportional to $H\ G$, $H\ G = A\ G \sin \gamma$, so $H\ G$ is proportional to $A\ G$ (γ constant) which is proportional to $A\ D'$, hence, to $D\ D'$ is proportional to $A\ D'$.

$A\ D = A\ D' - D\ D'$, hence, $A\ D$ is proportional to $A\ D'$.

$B\ D$ and $B'\ D'$ are both perpendicular to $A\ D'$, hence, $\frac{A\ B'}{A\ B} = \frac{A\ D'}{A\ D} =$ constant, and B' is fixed point. So curve traced by D' is a circle.

Slip "s" is equal to $\frac{A\ F}{A\ D'}$.

At running light (zero torque) $B\ D$ and $H\ F$ become zero. (For proof of this see Fig. 1. The torque of the motor is proportional to the mutual flux $A\ G$ and the component of secondary current in quadrature with it. This is the same thing as the total secondary current and the component of the mutual flux in quadrature to the current, which component is equal to $A\ D$, the "rotor field." The torque is, therefore, zero when $B\ D$ is zero, and in Fig. 9, $B\ D$ is the torque producing component of $B\ D'$.)

Thus, running light slip $s_0 = \frac{A\ H}{A\ D'}$, and the additional slip s_1, due to the load is thus, $\frac{H\ F}{A\ D'}$.

It is thus seen that at running light the main motor runs at slip s_0, determined by the angle γ, and the ratio $\frac{A\ G}{A\ D'}$, which conditions are adjusted by the connections at B, Fig. 8. The load slip s_1, is the same for all values of s_0, provided angle γ be so chosen that $\frac{H\ G}{A\ D'}$ remains constant, and is the same as would obtain for a normal motor whose circle is $B'\ D'\ A$ and whose short-circuited secondary has the resistance corresponding to the current $B'\ D'$ and the drop $H\ F$. Thus it is evident that the main motor, regulated as in Figs. 8 and 9 would retain practically the same load slip-torque, power factor-torque and input-torque characteristics as with short-circuited slip rings, but would have no-load speeds equal to the synchronous speed $\times \frac{1-s_0}{1}$.

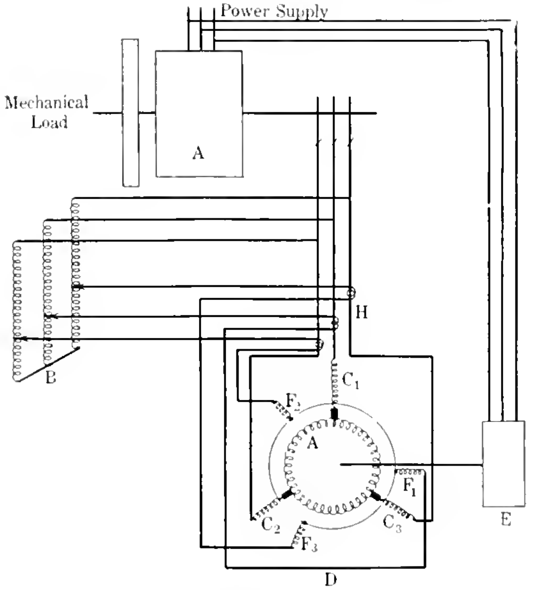


Fig. 10. **Neutralized Compound-excited Constant-speed Three-phase A-C. Commutator Machine and Connection for Adjustable-speed Single-range Speed Control of Induction Motor Giving Automatic Drop in Speed With Increase of Load**

It will be noted from Fig. 9 that the primary power factor can readily be improved and that at the same time the pull-out torque of the main motor can be increased.

Single-range (Below Synchronism Only) Speed and Power Factor Control by Means of a Constant Speed, Compound Excited Commutator Motor

Occasionally, in processes where the peak loads are high and of brief duration and of sufficient magnitude in proportion to the capacity of the supply system to be objectionable, it becomes desirable to have a larger drop in speed due to load than would be obtained with a shunt commutator motor, so that a fly-wheel can be effectively added to smooth out the peak loads, and at the same time retain the adjustability of the speed. Fig. 10 illustrates a method of compounding the regulating motor.

In the shunt excitation, neglect the same factors as in the case of the shunt regulating motor, (the secondary resistance drop of the main motor and the absence of the reactance drop of the regulating motor). In order to get the compounding action it would not do merely to put in some series turns as in a d-c. machine, since there is applied to the shunt field a fixed percentage of the total induced secondary e.m.f., which means a flux proportional to the rotor field of the main motor as already pointed out. Thus, the ampere turns of the series winding would merely be balanced by a change in the shunt current, F_1, F_2, F_3 serving as the primary of a transformer. It, therefore, becomes necessary to change the field voltage in response to load, in order to change the flux and hence the rotation e.m.f. This is done by the series transformer H, which has an air gap in the magnetic circuit, so that its flux is proportional to the resultant of the primary and secondary ampere turns. Of course, a proportionate effect upon the flux of the regulating motor, will accompany any changes in the flux in the series transformer (slip transformer) since the alteration in flux produces a proportionate alteration in voltage applied to regulating motor field, and this in turn a proportionate change in flux thereof. This then means that the rotation e.m.f. will contain a component proportional to the resultant ampere turns of the series transformer, which component, of course, may itself be resolved into components corresponding to the components of the resultant ampere turns of the series transformer.

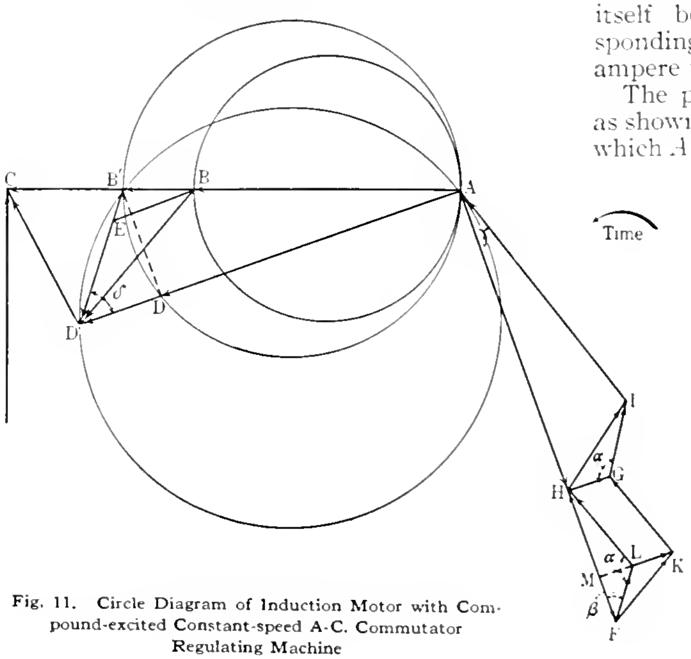


Fig. 11. Circle Diagram of Induction Motor with Compound-excited Constant-speed A-C. Commutator Regulating Machine

The performance of the motor, controlled as shown in Fig. 10, is illustrated in Fig. 11, in which A, B and C are again found as for Fig. 1, including the reactance of machine D with that of the secondary of A. B is the no-load point, such that $B\ B'$ is the no-load secondary current, and D' is the load point under consideration. Resolve secondary current $B\ D'$ into component $B\ E$ parallel to $A\ D'$ and $E\ D'$ part of $B'\ D'$. Component $B\ E$ produces no torque. $I\ A$ is the rotational e.m.f. of regulating motor at constant angle from total induced secondary e.m.f. $A\ F$ of main motor and bearing constant ratio to $A\ D'$ being due to the application of total induced e.m.f. $A\ F$ to the shunt field circuit of D, Fig. 10. $H\ G$* is resistance drop of $B\ E$ and $I\ G$ is the rotation e.m.f. produced by D of Fig. 10 by the voltage introduced into the field circuit by the existence of current $B\ E$ in primary of H. The transformer flux component due to the secondary current of H (magnetizing current of D) may clearly be regarded merely as field leakage flux, and has no significance except for the value of the still constant ratio $\frac{I\ A}{A\ D'}$. The angle α ($I\ G\ H$) is determined by design and is, of course, constant, as is the ratio $\frac{G\ I}{H\ G}$.

$F\ K$ is total resistance drop, and $F\ L$ and $L\ K$ are components, due to $E\ D'$ and $B\ E$. $K\ G = L\ H$ is compounding effect, due to $E\ D'$, just as $G\ I$ is due to $B\ E$, so angle $H\ L\ F$ = angle $I\ G\ H = \alpha$ and is constant. Further $\frac{H\ L}{L\ F}$ is constant, so angle $L\ F\ H = \beta$ is constant and as $F\ L$ is parallel to $B'\ D'$ and $A\ F$ is perpendicular to $A\ D'$, angle $B'\ D'\ A = \delta = 90$ deg. $- \beta =$ constant.

Therefore, D' traces the arc of a circle.

---

*Point H is on $A\ F$ because at zero load $B\ E$ becomes $B\ B'$, the total secondary current and $H\ G$ and $G\ I$ the only e.m.fs. to close the gap between $I\ A$ and $A\ F$. As $B\ E$ is proportional to $A\ D'$ and hence $A\ I$ and at constant angle thereto, H must remain on $A\ F$.

The slip S is equal to $\frac{A\ F}{A\ D'}$ and at running light (zero torque) $E\ D'$, $F\ L$, $H\ L$ and $K\ G$ become zero $\frac{A\ I}{A\ D'}$ and angle γ are constant. Angles of triangle $I\ H\ G$ being constant and $G\ H\ A$ being 90 deg., we see that $I\ H\ A$ is also a constant angle, hence angle $A\ I\ H$ is constant. So $\frac{A\ H}{A\ D'}$ is constant and as this is the expression for S_0, the running light slip where $H\ F$ is zero, we see that the slip, due to load $S_1 = \frac{H\ F}{A\ D'}$, consisting of $L\ F$, due to the resistance and $H\ L$, due to the compounding action of the slip transformer. We thus see that the running light slip S_0 is adjustable by means of B in Fig. 10, while the load slip S_1 has been increased from $\frac{M\ F}{A\ D'}$ to $\frac{H\ F}{A\ D'}$ by the slip transformer. Further, it is apparent that by controlling the angle α we can make the power factor get more leading or more lagging as load comes on, and thus, also, increase or decrease pull-out torque of the motor.

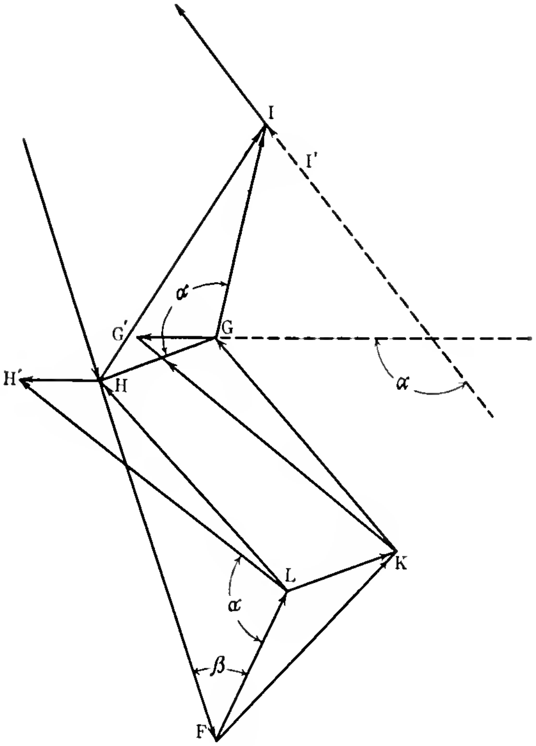


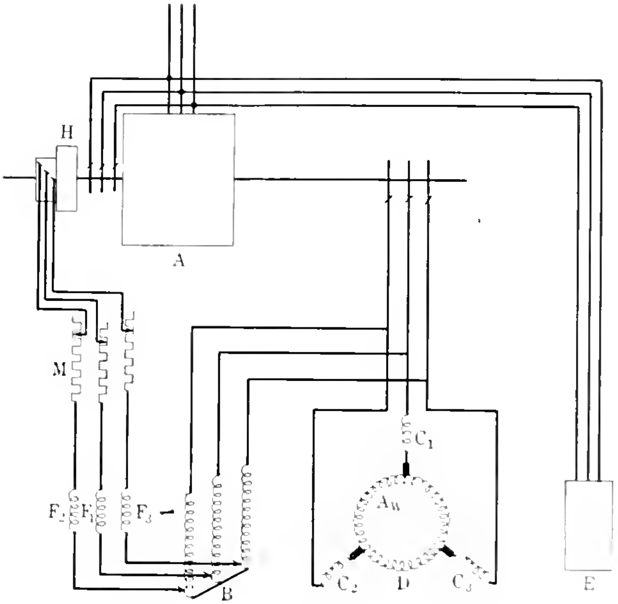
Fig. 11a. Effect on Fig. 11 of Correctly Locating Resistance of Main Motor Secondary and Reactance of Regulating Machine

In defining the conditions assumed for Fig. 10, we mentioned that the leakage reactance drop of the regulating motor was supposed to be included in the voltage applied to the exciting winding. The actual effect of excluding it from this circuit can now be shown in Fig. 11a, a modification of part of Fig. 11. The reactance in the regulating motor is, of course, not applied to its field, and hence the actual rotation e.m.f. for shunt excitation should not include $I'\ I$, the rotation e.m.f., due to the application of reactance drop of $B\ E$ to the shunt field. Note that $I'\ A$ is the rotational e.m.f. of pure shunt excitation, and that as triangle $B\ E\ B'$ is similar to triangle $A\ D'\ B'$, $\frac{B\ E}{A\ D'} = \frac{B\ B'}{A\ B'}$, hence $I'\ I$ is proportional to $I\ A$ and to $A\ D'$ so that $A\ H$ is still proportional to $A\ D'$. $G\ G'$ and $H\ H'$ are the rotational e.m.f. due to application of reactance drop of $E\ D'$ to shunt field, and hence proportional to $E\ D'$, so they may be excluded from $K\ G'$ and $L\ H'$, and for them may be used instead $K\ G$ and $L\ H$. As angle $G'\ G\ K$ and $H'\ H\ L$ are fixed and as $H\ H'$ and $G\ G'$ are proportional to $H\ L$ and $G\ K$, we see at once that $H\ L$ is proportional to $L\ F$, angles $H\ L\ F$ ($=$angle $H\ L\ H' + \alpha$) and $H\ F\ L$ are constant, hence, $\delta = B'\ D'\ A = 90$ deg.$-\beta$ is constant and D' still traces a circle.

Thus when we consider the actual effect of the leakage reactance of the regulating motor we see that it is merely to alter the amount of compounding. Hence, to consider this in the case of Fig. 9, would mean to change it to a diagram like Fig. 11, with a small amount of compounding, the "pure shunt excitation" being only a hypothetical condition.

The magnetizing current of the regulating motor has so far been neglected. Neglecting regulating motor saturation, this is proportional to and in phase with $A\ D'$ of Fig. 11. As it flows through the armature and compensating windings of the regulating motor only, its reactance drop can be added to the compounding just as was done in Fig. 11a at $I\ I'$ and its resistance drop, proportional to $B\ E$ can be added to the resistance drop of $B\ E$. Thus, we still would get our circle diagram. However, it does not usually pay to consider so small an element except as an interesting theoretical consideration.

The effect of the inclusion of the main motor resistance drop in the voltage applied to the regulating motor field of Figs. 8 and 9 may be treated similarly, providing we confine ourselves to operation so far from synchronism and at such a range of loads, that s_1 is a fairly small part of s_0, in which case the component of rotation e.m.f. caused by the resistance drop is approximately proportional to the current components.



[Fig. 12. Neutralized Three-phase Shunt A-C. Commutator Machine and Connections for Adjustable-speed Control of Induction Motor for Operation Both Above and Below Synchronism

Further the accuracy of the diagram developed so far hinges on the assumption that the values of S (distance from synchronous speed) are so great as to cause the variations in the relative values of the resistance and reactance drops of the shunt field circuit to be relatively small, which will mean a small variation in $H\ G$ of Fig. 9, since variations in the phase relation of field current and "total induced e.m.f." $A\ D'$ means variations in angle γ. As the resistance drop is larger and larger compared to the reactance drop the smaller the slip and frequency, it therefore appears that Figs. 9 and 11 are accurate only at fairly large values of slip, and small ratios of resistance drop to reactance drop in the field circuit, becoming inaccurate as synchronism is approached. Consideration of these effects has lead the writer to the use of a constant voltage frequency changer and adjustable resistance for overcoming and regulating the resistance drop of the field circuit, and of an auto-transformer with taps (and alternative devices) for overcoming the reactance drop, leading in turn to a feasible way of regulating the main motor through and above its synchronous speed as well as below.

Double-range (All Speeds Above or Below Synchronism) Speed and Power Factor Control by Means of a Constant-speed Shunt Commutator Motor

Several advantages of regulating the main motor speed above as well as below its synchronous value appear at once. The capacity of the regulating set for a given maximum speed variation and maximum speed is reduced 50 per cent, provided the synchronous speed of the main motor is half way between the extremes. For if, S_{max}, S_{min} and S_s, represent the maximum, minimum and synchronous speeds of the main motor and $H\ P_{max}$ be the horse power capacity at speed S_{max}, we have for single range,—$S_s = S_{max}$ and capacity of set is:—

$$H\ P_{set} = H\ P_{max} \times \frac{S_{max} - S_{min}}{S_{max}}$$

Now for double range, as above, we have:—

$$2\ (S_{max} - S_s) = S_{max} - S_{min}$$

$$H\ P_{set} = H\ P_s \times \frac{S_{max} - S_s}{S_s} =$$

$$\frac{H\ P_s}{S_s} \times \frac{S_{max} - S_{min}}{2}$$

But as $\frac{H\ P_s}{S_s} = \frac{H\ P_{max}}{S_{max}}$ we have,

$$H\ P_{set} = 1/2\ H\ P_{max} \times \frac{(S_{max} - S_{min})}{S_{max}}$$

showing that the capacity of the double-range set is one half that of the single range. Thus, not only will the first cost be materially less, but the machine losses will also be greatly decreased.

A second important advantage is that the synchronous speed of the main motor is in the middle of the speed range, so that often times many processes may be carried out running as plain induction motor with the set shut down, with consequent saving of wear and tear on it.

The apparatus, shown in Fig. 12, is the same as Fig. 8, except that instead of going to a star point the ends of shunt field coils F_1, F_2, F_3 are carried through the adjustable resistance M, to the frequency changer H mounted upon the shaft and wound for the same number of poles as main motor A. This machine has a single primary winding connected to a commutator exactly as in the armature of a d-c. machine, and has collector rings tapped in at points 120 electrical degrees apart (for three-phase power). The secondary is a smooth laminated ring without windings which may or may not rotate with the primary. Obviously a "revolving field" is set up in this machine, which at standstill, rotates at synchronous speed of A and H. With 120 electrical degrees brush spacing on the commutator, we get three-phase full frequency voltage of the same value as we apply to the collectors neglecting machine drop, and the phase relating between the commutator and collector currents depends upon the position of the brushes on the commutator. Assume A to rotate synchronously in opposite direction to the rotation of flux of H, which carries said flux backward mechanically at the same rate that it is turning electrically, leaving it stationary in space, and permitting H to produce direct current at commutator like a synchronous converter.

Thus, it is seen that H is automatically a source of constant voltage at exact slip ring frequency.

If we regulate A at no-load (for simplicity) we see that the rotation e.m.f. of D, hence both its flux and field current are proportional to slip s. Hence the reactance drop component of the impedance drop of the field circuit, being proportional frequency as well as flux is proportional to s^2 while the resistance drop is merely proportional to the field current and to s. By connecting to taps of B whose distance from the star point is proportional to s, we get a voltage proportional to s^2, since the total e.m.f. of B is itself proportional to s. By changing taps on resistance M so that the entire resistance of the circuit is proportional to $1/s$, we just permit constant voltage frequency changer H to supply the resistance drop balancing e.m.f. while autotransformer B furnishes reactance drop balancing e.m.f. In practice, one set of switches can be arranged to vary both M and B simultaneously.

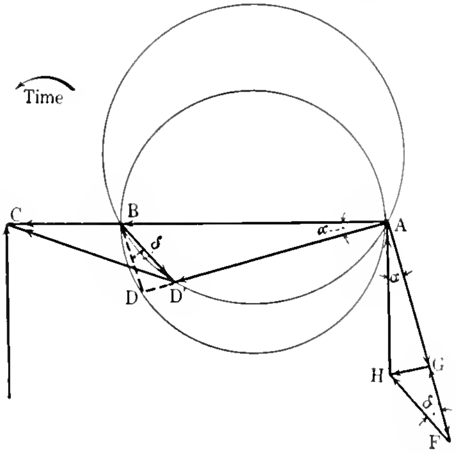


Fig. 13. Circle Diagram of Induction Motor Running Below Synchronism with Regulating Machine Receiving Constant Shunt Excitation Without No-load Power Factor Improvement

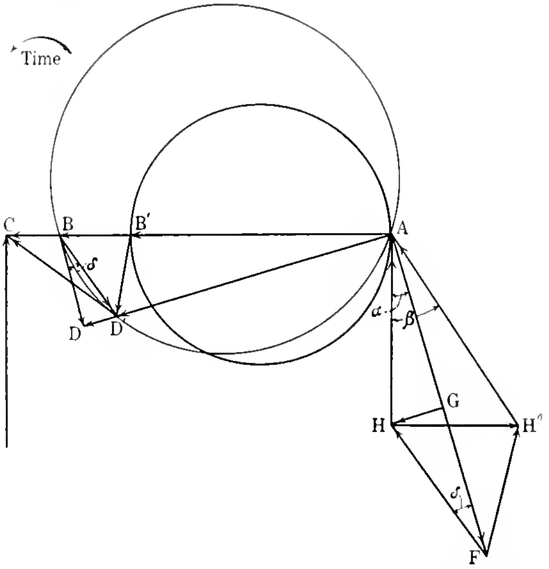


Fig. 14. Circle Diagram of Induction Motor Running Below Synchronism with Regulating Machine Receiving Constant Shunt Excitation, Such as to Give No-load Power Factor Improvement

With M operating at a considerable distance from synchronous speed, the field resistance drop can be exactly balanced for a given load by H, so that as B supplies the reactance drop, the conditions previously assumed are attained. From Fig. 9 it will be noted that the phase of A F alters with load, while that of the voltage from H in Fig. 12 remains fixed. This only introduces a comparatively small discrepancy for working loads, the main effect being a slight alteration of the load slip.

Let us now, on the other hand, consider the case of running near synchronism, where the reactance drop of the field, varying as s^2, and very nearly balanced by B has become practically ineffective. Fig. 13 is the simplest circle diagram for these conditions, the constant excitation of D, Fig. 12, from the frequency changer H being so chosen that, in

Fig. 13, rotational e.m.f. $H\,A$ is perpendicular to line $A\,B\,C$ found as usual. $A\,F$ is the total induced e.m.f. of main motor secondary, $F\,H$ the resistance drop in main secondary circuit for secondary current $B\,D'$.

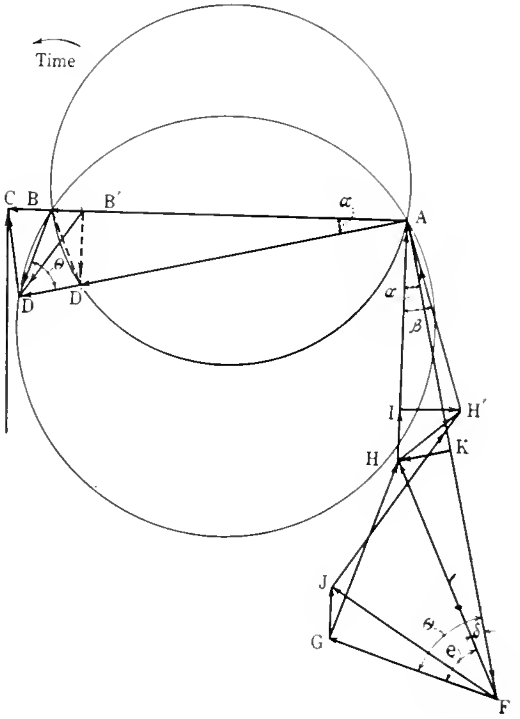


Fig. 15. Circle Diagram of Induction Motor Running Below Synchronism with Regulating Machine Compound-excited, the Shunt Excitation Being Constant and Having No-load Power Factor Improvement, and the Series Excitation Yielding E.M.F. 90 Deg. Ahead of the Current

Resolve $F\,H$ into components $F\,G$ in phase opposition to $A\,F$ and $G\,H$ perpendicular to $A\,F$ and $B\,D'$ into corresponding components $B\,D$ and $D\,D'$, (Point D, thus traces the circle of the main motor with regulating motor reactance included, but with $A\,H$ left out of the circuit)

$$G\,H = H\,A \sin\alpha$$

$$F\,H = \frac{G\,H}{\sin\delta} = \frac{H\,A\sin\alpha}{\sin\delta}$$

$$B\,D = A\,B\sin\alpha$$

$$B\,D' = \frac{B\,D}{\cos\delta} = \frac{A\,B\sin\alpha}{\cos\delta}$$

Further, $B\,D' = \dfrac{F\,H}{r_{2+c}}$

So $\dfrac{H\,A\sin\alpha}{r_{2+c}\times\sin\delta} = \dfrac{A\,B\times\sin\alpha}{\cos\delta}$

And $\tan = \dfrac{H\,A}{A\,B}\times\dfrac{1}{r_{2+c}}$

As $H\,A$, $A\,B$ and r_{2+c} are constant,

Angle δ must be constant.

Angle $B\,D'\,A$ is 90 deg. $+\,\delta$, hence D' traces a circle.

In Fig. 14, we have given the excitation, and hence, the rotation voltage $A\,H$ a shift β from its position in Fig. 13, so as to improve the power factor.

Resolve the resistance drop $F\,H'$, of the secondary current $B'\,D'$ (A, B' and C being the usual fixed points) into $H'\,H$ perpendicular to $H\,A$ perpendicular to $A\,B$, and $F\,H$, corresponding current components being $B\,B'$ and $B\,D'$. Since $H'\,A$ and angle β are constant, H and B are fixed points. Now resolve $F\,H$ into $F\,G$ along $A\,F$ and $G\,H$ perpendicular to $A\,F$, also $B\,D'$ into corresponding components $B\,D$ and $D\,D'$. D' may now be shown to trace arc of circle $B\,D'\,A$ as in Fig. 13. We note the power factor and pull-out torque are better than for Fig. 13.

As we are considering operation at rather small values of slip where the shunt excitation is all from H and M of Fig. 12 and is not effected by B, we can compound by the use of plain series windings as with d-c. machines without interference by transformer action.

In Fig. 15, we have shown the effect of such compounding, brought about by making changes in the neutralizing winding C_1, C_2, C_3. It can be demonstrated that a polyphase armature turning above its own synchronous speed in the field, set up by its own reaction generates a rotation voltage leading the current by 90 deg. Hence, by weakening $C_1\,C_2\,C_3$, we can get this sort of compounding in any desired degree.

$A\,B'\,C$ denote the usual fixed points of the main motor with reactance of regulating motor included. $H'\,A$ is the fixed excitation from frequency changer and rheostat and $B'\,B$ is running light secondary current, due to $H'\,I$, $B'\,D$ being load current considered. $A\,F$ is the total secondary induced e.m.f.

The secondary current $B'\,D$ consists of a constant component $B'\,B$ and variable component $B\,D$. $I\,H'$ is the constant resistance drop and $H\,I$ the constant leading rotation e.m.f. due to component $B'\,B$, making H a fixed point. $G\,H$ is resistance drop and $F\,G$ leading rotation e.m.f. of variable component $B\,D$. Now the resistance drop and the variable rotation e.m.f. are each proportional to the current (the iron of the regulating motor is always at low densities for these near synchronism conditions) hence, angle $H\ F\ G = c$ is constant. Since H is a fixed point, angle $H\ F\ K = \delta$ can be shown to be constant as in Fig. 13. Angle $K\ F\ G = \theta = c + \delta =$ constant. Angle $B\ D\ A$ is also equal to θ, since $A\ D$ is perpendicular to $A\ F$ and $B\ D$ is perpendicular to $F\ G$. So D traces are of a circle, passing through A and B.

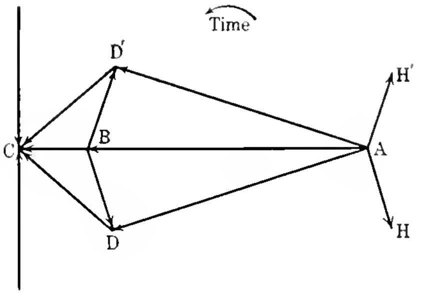


Fig. 16. Diagram of Induction Motor Running Loaded at Synchronous Speed

The same conditions are represented as infinitesimally below and as infinitesimally above synchronism.

It will be seen then that the power factor and pull-out torque can be improved as well as the speed regulated by this method, when regulating near synchronism, as well as remote therefrom. When we regulate the speed, we so adjust the taps of B, Fig. 12, as to get the desired percentage of slip voltage from $F_1\ F_2\ F_3$ to overcome the reactance drop and then so adjust resistance M that the field current corresponding to the desired conditions will have a resistance drop equal to the voltage supplied by H. As the field current is about constant over the working range of loads we can thus get an even better approximation to Figs. 9 and 11 than without H and M. As we regulate the speed, we thus transfer gradually from the condition of Figs. 9 and 11 to those of Figs. 13, 14 and 15.

We have drawn Fig. 16 to examine the phenomenon of regulating the speed of the main motor while loaded from an infinitesimal amount below synchronism to an infinitesimal amount above synchronism. As the slip is negligible, the total induced e.m.f. is also negligible and the rotational e.m.f. of the regulating set $A\ H$ just supplies the resistance drop $H\ A$, the main motor being assumed to be a trifle below synchronism. Let us now assume it to be an infinitesimal amount above synchronism.

All vectors are referred to the secondary whose phase rotation has been reversed, although the physical conditions in the motor remain unchanged. If we select the phase of $A\ C$ as the phase of reference for both phase rotations, then the components of all vectors in phase with it will not be altered by reversal of the phase rotation, but the quadrature components of all vectors will be reversed, as a vector which would not reach its maximum until 90 deg. after $A\ C$ will, in reversed phase rotation, reach its 90 deg. ahead of $A\ C$. This law yields us $H'\ A\ D'\ B\ C$ to represent the same phenomena in terms of reversed phase rotation as are shown by H, A, D, B, C with original phase rotation in the secondary.

In Fig. 17, D is a load point with motor nearer synchronism than its natural slip, as the rotation e.m.f. of the regulating motor $H\ A$ has been reversed so as to have a large component in phase with the total induced e.m.f., $A\ F$. The bulk of the resistance drop $F\ H$ is, therefore, supplied by $H\ A$, so that $A\ F$ and consequently the slip are reduced. In these conditions the motor would pass through and above synchronism as the load dropped off.

Let us now increase $H\ A$ until the main motor runs above synchronism (with reversed secondary phase rotation). As $H\ A$ was in quadrature to $A\ C$, the line of the phase of reference, its new value will be shown with reversed direction at $H'\ A$. Load point D' is above line $A\ C$ for motor torque for the same reason. The total induced e.m.f. would

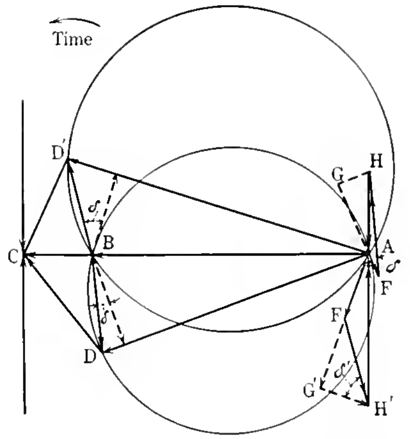


Fig. 17. Circle Diagram of Induction Motor and Constant-excitation Regulating Machine with One Value of Excitation Such That Speed for the Load Point Shown is Nearer Synchronism Than the Natural Slip Value and Another Value of Excitation Such That Speed for the Load Point Shown is Above Synchronism

also be represented with its quadrature component above $A C$ instead of below, but its direction is actually reversed, as shown at $A F'$, since at any instant any given conductor now cuts the flux in the opposite direction.

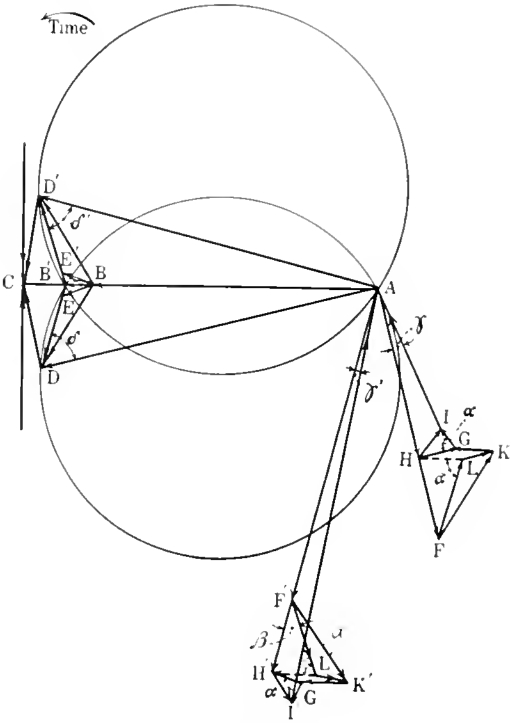


Fig. 18. Circle Diagrams of Induction Motor Running Below Synchronism and Above Synchronism with the Same Characteristics, Controlled in Each Case by a Compound Constant-speed Regulating Machine

NOTE.—For the development of the circle diagram, particular mention should be made of the works of Behrend, Blondel and Arnold-LaCour. Meyer-Delius has also written concerning what the writer has termed Single-Range Regulation.

We note that with no initial quadrature or power factor component in $H A$, and $H' A$, the motor characteristic when running above synchronism is better than below in respect to power factor and maximum torque, while for the generator characteristic the converse is true.

Double-range (Either Above or Below Synchronism) Operation Remote from Synchronism

In Fig. 18, we represent operation both above and below synchronism, with the same speed—torque and speed—power factor conditions. The configuration indicated by the plain letters is for using a compound commutator motor similar to that of Fig. 11 except that angle α has been decreased so that the compounding is mostly in the way of power factor improvement and adds very little to the slip. The primed letters indicate the relations for operating above synchronism and angle $A D' B'$ equals can be shown to be constant just as in the case of angle $A D B'$. Keeping the phase of $A C$ as the phase of reference, we note as before that the representation in secondary terms with reversed phase rotation requires the reversal of the components in quadrature with $A C$ of all vectors, and as $A F'$ is further actually reversed in passing above synchronism, we see that its quadrature components are still in phase with that of $A F$. But as the regulating machine must furnish power to the main motor secondary in order to satisfy the conservation of energy, the total current $B D'$ must have a component in phase with the rotation e.m.f. $I' A$, which we see is the case, thus requiring that $I' A$ be larger than $A F'$ fulfilling the condition that the regulating machine function as a generator.

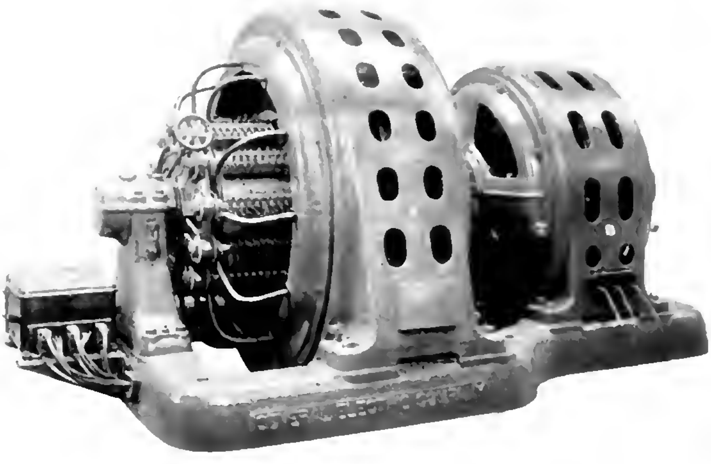


Fig. 19 Speed-regulating Set for a 1600 h p Motor

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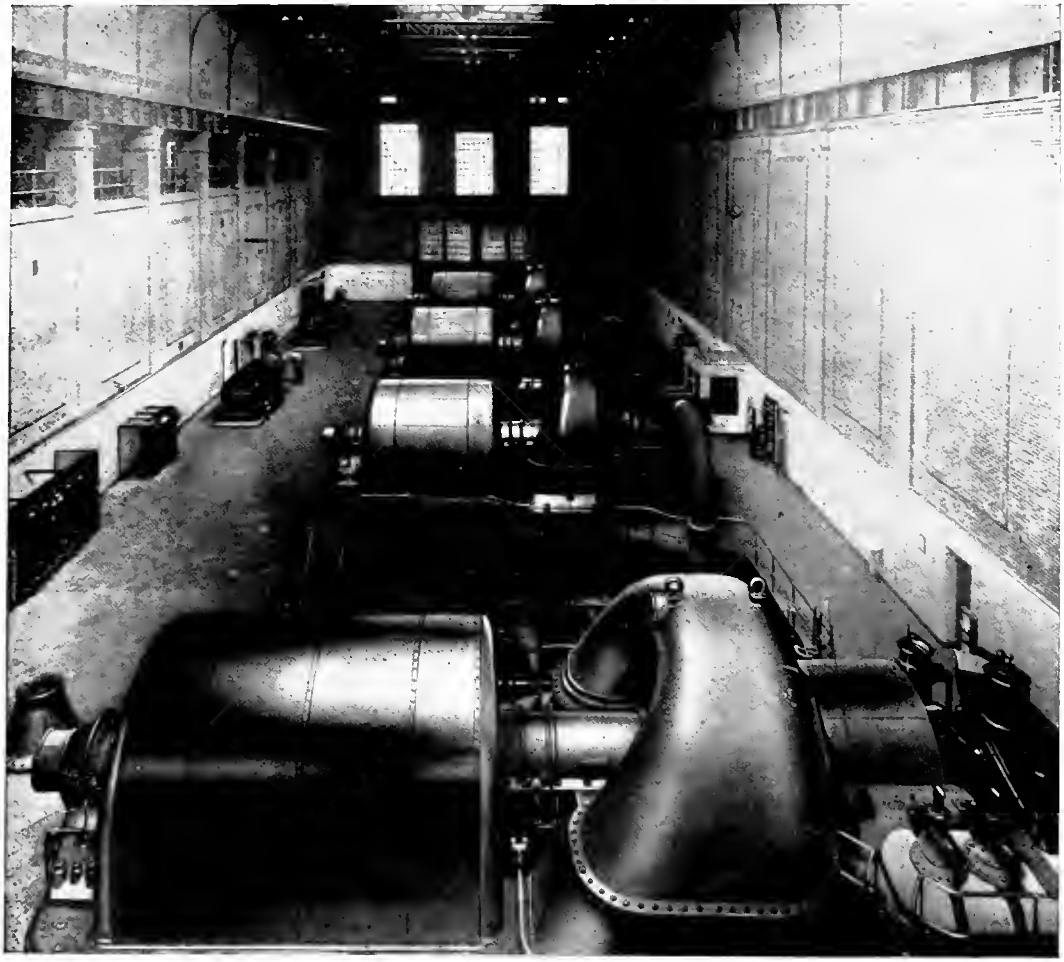

One 35,000-kw. and Three 20,000-kw. Curtis Turbine Generator Units in the River Station of the Buffalo General Electric Company. The stable parallel operation of high-power stations is discussed by Dr. Steinmetz in this issue

GENERAL ELECTRIC REVIEW

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August, 1920

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Buffalo Electric Show Illuminated by Five Thousand White Mazda Lamps. This type of lamp was developed to eliminate the objectionable glare that in many cases results from the use of clear glass bulbs. See page 711

GENERAL ELECTRIC
REVIEW

CONTROL AND STABILITY OF STATIONS IN PARALLEL

We are today well entered upon the fulfillment of the prediction that our steadily increasing national demand for power will be satisfied by electric power generation, transmission, and distribution. In this development, from the small electric light station of a few horse power capacity—still within the memory of our generation—to our present generating systems having over half a million horse power machine capacity, problem after problem had to be solved; old problems, which worried the central station man of a generation ago, vanished, but new problems and difficulties arose in their stead, and sometimes these were practically the antithesis of their predecessors. For instance, in the early days of lighting, foremost attention was given to attaining good inherent regulation, that is, constancy of voltage under great and sudden variations of load. This problem vanished when our station capacities rose into the hundred thousands of kilowatts, and in its place arose the reverse problem, the limiting of the amount of power that can accidentally be concentrated at any point in the system, and the reduction of its destructiveness. The need for such protection is apparent when it is considered that a system having a capacity of several hundred thousand kilowatts, but no power-limiting equipment, may concentrate several million kilovolt-amperes at a fault—a power as large as that of Niagara. With the growth of the central station, experience with the increasing destructiveness of short circuits forcibly impressed upon the engineer the need for the solution of this problem.

It was solved ten years ago by the introduction of power-limiting reactors, in generators, busbars, tie lines, and feeders. Power-limiting reactors have come into general use in high-power systems, and have made it possible to increase indefinitely the size of the system without any increase of danger from power concentration.

These ten years experience with the use of power-limiting reactors have proved their value in limiting the effect of short circuits and other troubles; as a result of this experience, we are able now to determine the proper and most economical value of power-limiting reactors for the various service conditions with far greater certainty than when their use was first introduced. At the same time, experience has shown a number of effects of the use of power-limiting reactors, which were not contemplated ten years ago, some advantageous, some disadvantageous, particularly in their effect on synchronous operation. Since all our modern high-power generating equipment is of the synchronous type, as is also much of our power load, it is essential that stable operation of these machines be maintained under all conditions, even such abnormal ones as short circuits. The effect which power-limiting reactors exert on synchronous operation, the limitations with regard to power, speed, stability, etc., thus are worthy of extensive study. The importance of this was forcibly impressed upon engineers by troubles connected with synchronous operation, experienced by high-power systems and referred to in Dr. Steinmetz's article in this issue. It can be seen that reactors, in limiting the destructive short-circuit power which may flow across them from station bus to station bus, also may limit the synchronizing power between the stations, where this has to pass over the reactors, and thus under certain conditions may reduce the stability. On the other hand, power-limiting reactors, by limiting the power flow at times of accident, tend to localize the voltage drop, to maintain higher voltage on the station busbars, and to give a more rapid voltage recovery after short circuit, any of which will increase the synchronizing power and thus tend toward an increase of stability.

Thus these mattters are of great importance and are being studied by the most prominent engineers, with the view of adjusting the distribution characteristics of large stations operating in parallel, for the purpose of securing with safety a more economical and reliable supply of power. In this issue of our magazine and in the one following, we are presenting a comprehensive analysis and discussion of the subject by Dr. Steinmetz.

Commercial Statistics and Their Value to the Executive

By G. P. Baldwin

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This article is developed along the following line of thought: The executive of today has grown up with his job and therefore has a first-hand and intimate knowledge of its workings; the executive of tomorrow cannot be prepared according to this program, and therefore for guidance in his management will have to depend mainly upon reports prepared for him by his subordinates; the figures of these reports comprise Commercial Statistics, from which special compilations will reveal the status of any matter under consideration; statistics may be presented in figures but usually are amenable to a more ready conception by a graphic type of display, such as a map, chart, curve, etc.—Editor.

It has been said that a good executive is a man who decides quickly and is sometimes right. If asked the reason why he gives a certain decision, that same executive would reply that it is based on his best judgment. Judgment ranges in degree from prejudice to profound reason depending upon the proportions possessed by the man who makes the decision.

As a rule our present executives are extremely fortunate in that they have grown up with their jobs. They have grown bigger as their jobs grew bigger. They have had experience in various departments, have been close observers of the operations of others, and have seen the trend towards a greater degree of specialization, a greater division of labor, and a greater consolidation of executive direction.

It is questionable whether the executive of the future can be made by this process for business has assumed proportions that practically make it impossible. The executive of the future will be compelled to resort to statistics, which will be prepared in shape and form for his instantaneous use; and his ability to analyze them will be one of his qualifications as a good executive.

All concerns whose magnitude is great and whose product is diversified are susceptible to the application of a great amount of statistical data, and these statistics can be built up and summarized into a few that are vital. For example, of the statistics that guide the directors of various departments, the few that represent the gist are extracted to compile the statistical report of the single manager of those departments and so on up the scale until the collective activity of the entire organization is co-ordinated and represented by a single sheet of abbreviated statistics.

CLASSIFICATION OF STATISTICS

Product, Orders and Expenses, and Customers

Electrical sales department statistics for the use of the executive readily segregate themselves into three classes: those that have to do with the product, with the orders and expenses, and with the customers.

We may further state that the product is susceptible to further segregation; into large apparatus, small and fractional horse power motors, supplies, renewal parts, and lamps. Expenses segregate themselves into departments: sales department, order department, credit department, collection department, etc.; and customers into classes: industrial customers, lighting customers, railway customers, and merchandise customers. It is possible to get through the use of these segregations a large number of combinations. For instance, a segregation of renewal parts into customer's classifications will show where that type of business is coming from. The activities of the sales department when segregated into components will show what its branches produce along their special lines. It's possible to combine these features into any number of combinations which are of infinite use. It would be interesting to know for instance what the clerical expense would be in connection with an apparatus order, a supply order, and a lamp order when sold to an industrial customer, a lighting customer, or a merchandise customer. Orders, volume, and expenses can be combined in any amount of detail.

Units and ratios are derived from the foregoing classifications. We should bear in mind however that it would not be altogether fair to compare cost-of-sales ratios among districts because the mechanics of selling is affected by many factors. The three

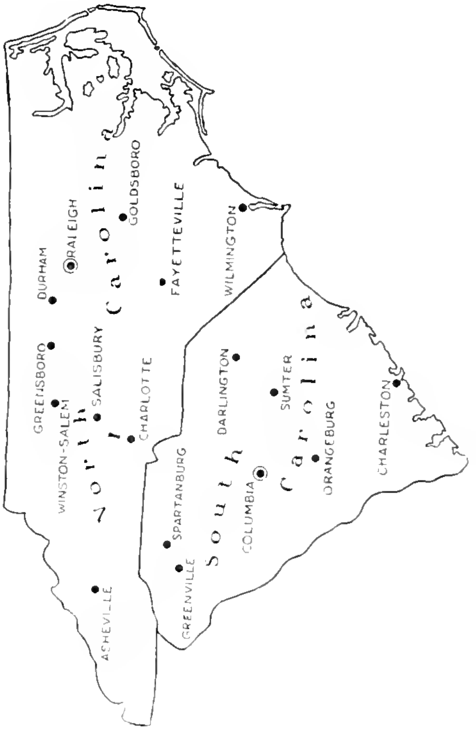

Fig. 1 Simple Geographical Map of the States of North and South Carolina

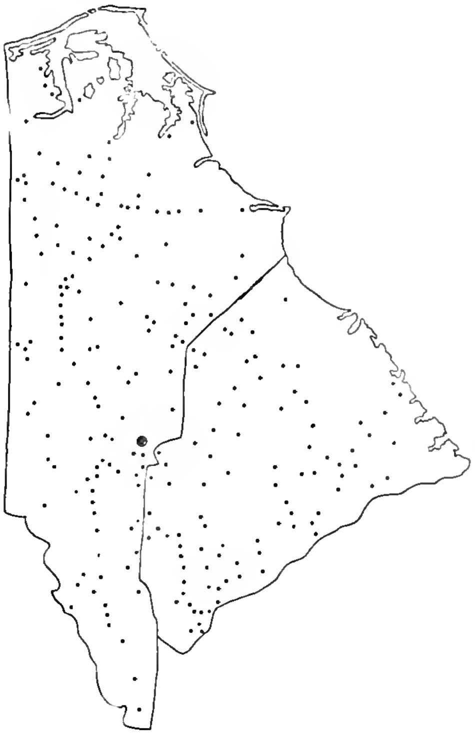

Fig. 2. Special Map of North and South Carolina Indicating the Number and Location of Central Stations Supplying the Territory

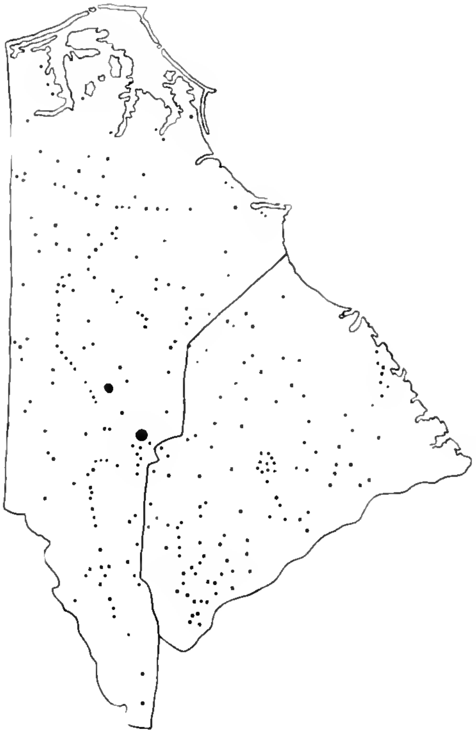

Fig. 3 Special Map Indicating the Electrical Communities in the Territory

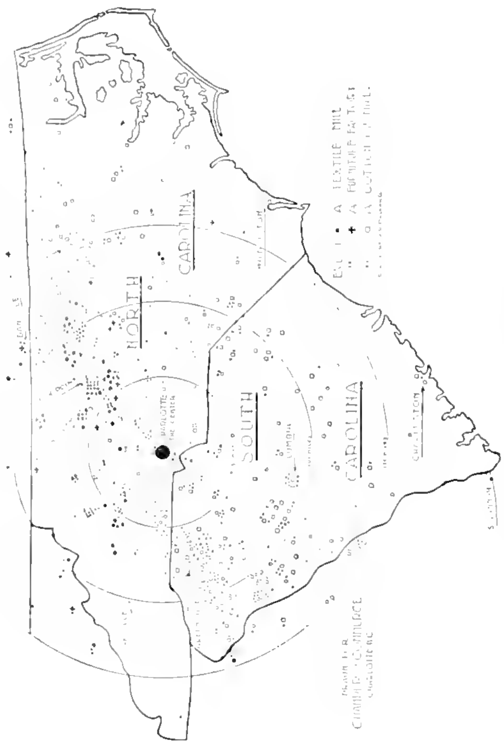

Fig. 4 Special Map Indicating the Industrial Plants in the Territory

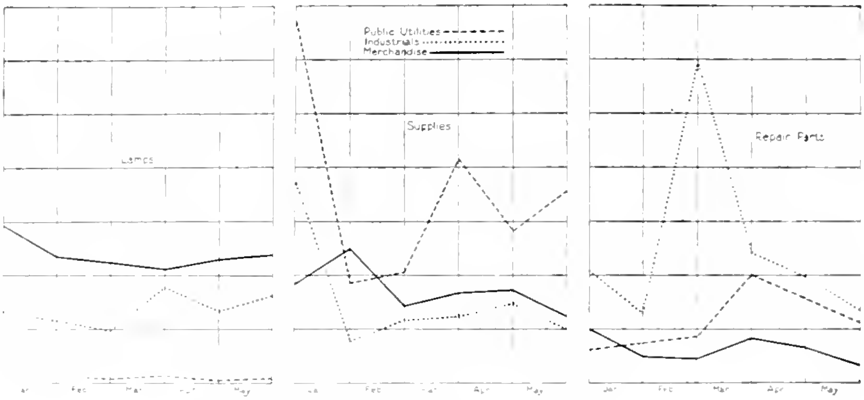

Fig. 5. Curves Plotted to Represent the Monthly Trend in the Sales of Three Commodities Segregated with Respect to the Classification of the Purchasers

principal ones are: the electrical population, the application of electricity to the predominant industries, and the geographic area.

Electrical Population

The electrical population (being the population served by central stations) varies from 94 to 21 per cent in different states. The total population of the State of New York according to the last census was about 60 per cent greater than that of the States of Pennsylvania, Virginia, West Virginia, Maryland, Delaware, and North Carolina. The electrical population was about the same. There are approximately 390 central stations in the State of New York and 670 in the other territory just mentioned. The geographic area of these states is $3\frac{1}{2}$ times as great as that of New York; therefore, to get a given volume of sales from them (assuming that the organizations are equally effective), there are more customers to receive attention, more territory to be covered, and more relations to be established. It will require more people in the sales organization and consequently more expenses.

Electrified Industries

Data as to the source of the orders furnish an extremely interesting sheet and this will show that the largest volume comes from the predominating industries. It will also show some enlightening comparisons between supply and apparatus sales. It will demonstrate that supply sales do not vary in direct proportion to apparatus business; in fact, as a territory becomes more thickly settled and more industrial business becomes established, the proportion of supply business from the industrials as against the total will be constantly accelerating. One may therefore draw the conclusion that in a sparsely settled territory the supply business will come from utilities rather than from

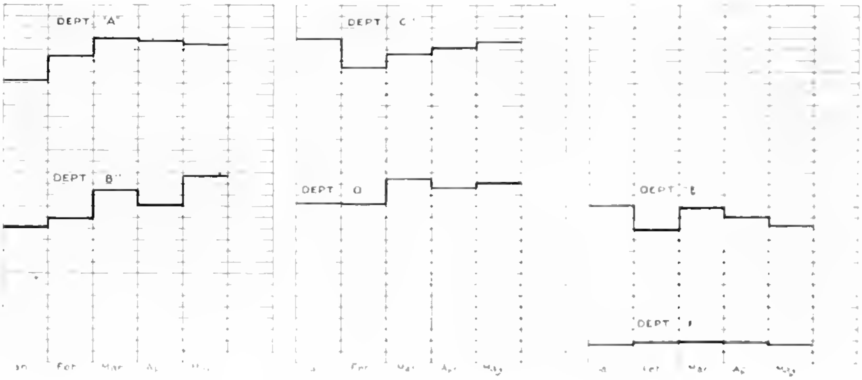

Fig. 6. A Graphical Record of the Departmental Expenses of a Sales Organization

industrials; and as the population grows and industrials become established, business with them increases. This is a fact that probably everyone who has looked into the subject knows and realizes, but very few realize its proportions, and it is possible to realize these proportions only by the examination of statistics.

It is interesting to note some of the ideas of supply salesmen in this connection. If one were to ask how much of their time they spent on industrials, on utilities, and on merchandise customers, the answers would vary, but an average of the replies given by twelve experienced men was that they spent about 50 per cent on utilities, 25 per cent on industrials, and 25 per cent on merchandise customers. However, an exact check on their calls showed that they spent 75 per cent of their time on utilities, 10 per cent on industrials, and 15 per cent on merchandise customers. Here, then, was an enormous supply business from industrial customers being received with comparatively very little direct supply solicitation.

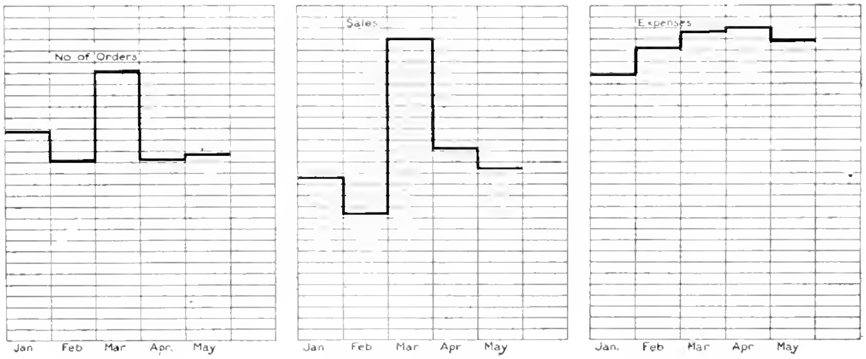

Fig. 7. Statistics of the Number of Orders Taken, the Amount of Sales Made, and the Expense Incurred by a Sales Office as Plotted for the Information of Its Manager

Whether solicitation is necessary, and to what extent, is of course another question. To answer this question, statistics according to classification of product would become involved. However, they would probably show that direct solicitation was necessary in specialties and special application, and that specialties and special application for industrials were comparatively few as compared with those used by the utilities and merchandise customers. They would probably also show what is necessary for the further development of industrial business, particularly in small orders, and that it is necessary to keep the manufacturer's name constantly and favorably before the trade.

The number of orders received by one district as against another would show a yearly comparison that can be listed against the number of industries and the number of customers, and can be developed to show a unit that will indicate the progress made. Incidentally, if the number of orders is compared with the number of quotations it would bring to mind that the number of quotations made in large order business will compare rather favorably with the number of orders received; but with small order business the number of orders received will greatly exceed the number of quotations, as much in some cases as 300 or 400 per cent; while with a specialized commodity like lamps there is an enormous volume of sales built up with practically no special quotations. In other words, quotations largely disappear in small order business and that element of cost is eliminated.

Geographic Area

If we would take a given territory and make three special maps, one of which we will call a central station map, another an electrified community map, and another an industrial map, the combination would indicate rather clearly the target of the sales department. Typical maps of this character are shown in Figs. 2, 3, and 4. In the territory illustrated there are 250 central stations, about 400 electrical communities, and over 1000 industrials. Such facts as these are not shown by the ordinary geographical map, Fig. 1, and therefore it would not occur to anyone that in that territory there are located industries of such magnitude and volume as the special maps indicate. It may even be further stated that should one pass through this territory on a train it wouldn't occur to him that six of the largest individual plants of their type in the world are located in this section; at the same time the territory is comparatively isolated. It is not in what we would call a metropolitan district, and the electrical population is about 21 per cent of the total.

Application of Charts and Curves to Present Statistics

An immense amount of thought and time has been devoted during the last few years to charts and curves; to graphic methods of illustrating facts. The eye is more receptive to a curve than to a mass of figures. More information can be presented on a given sheet, fluctuations are immediately observed, and tendencies are indicated at a glance. The curves in Fig. 5 show the source and changes in local lamp, supply, and renewal part sales. From such curves as these the eye can read the situation at a glance, and on comparison with earlier curves can readily observe the trend from year to year Fig. 6 indicates the contributing expense of a sales organization; the various clerical departmental expenses. It will show that they are increasing in some lines and not in others. Fig. 7 presents curves of orders, sales, and expenses for a local office, showing that the orders are remaining about the same, but have a tendency to decrease in the last few months, so is the volume of sales, but the expenses are increasing.

Curves of this character are of inestimable value to an executive. He obtains a knowledge of the situation at a glance. If he has data of all his districts on a like basis he can prepare for his own use a chart which will show his total expenses, and when conspicuous variations are noted he can by means of these segregated curves trace the changes to the exact point where they occurred. If orders are decreasing and volume is increasing it should mean comparatively less clerical expense, and the executive immediately has a reference on which to check his opinion.

There is no question but that among his other qualifications the executive of the future must be able to assimilate and digest statistics and direct accordingly; and, obviously, management must take its cue from the auditor, the accountant, the statistician, or from some one who is specifically charged with this duty.

The executive cannot proceed without the auditor, nor the auditor without the executive for that matter; but perhaps it is well to remember that none of us can proceed without the customer. Therefore, in the application and use of statistics, the human element must not be forgotten.

If we are going to know the value of our relations individually, collectively, and comparatively and what they produce we cannot neglect the value of statistics.

Flywheel Effect for Synchronous Motors Connected to Reciprocating Compressors

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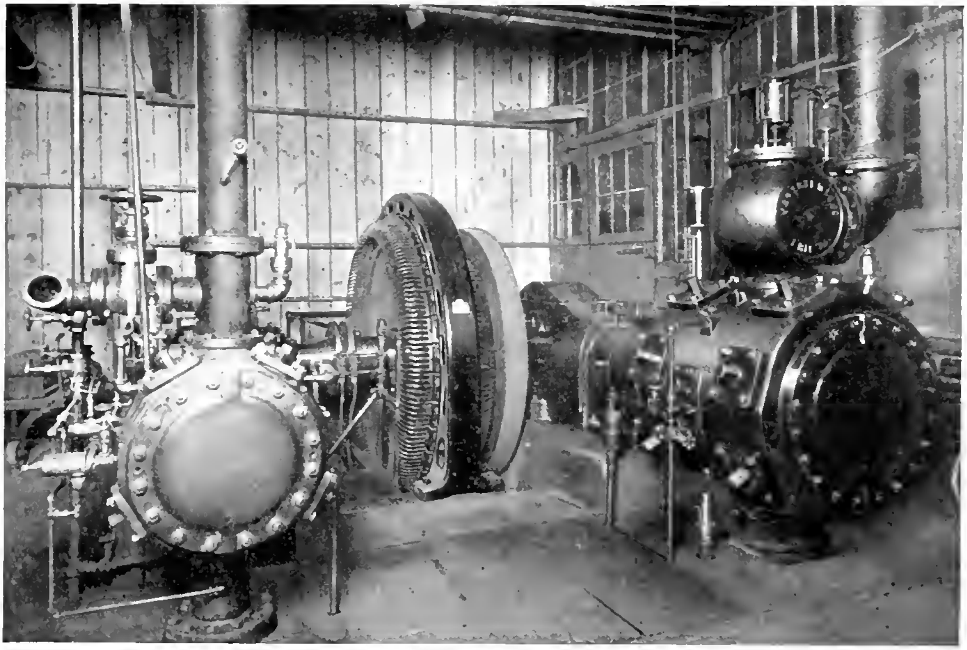
When driving reciprocating machines by synchronous motors it is important to avoid a condition that will produce hunting, or a periodic oscillation of the revolving element ahead of and behind the normal position. In cases where the natural oscillating frequency of the motor is near the frequency of the predominating impulses of the reciprocating machine, hunting may occur of such amplitude to throw the motor out of step. The remedy lies in the selection of the correct flywheel. This whole subject is very clearly explained by Mr. Doherty with the aid of mechanical analogies, and a general method for determining the proper flywheel effect for any given set of conditions is outlined. The performance of some installations is very puzzling and troublesome, and this article will prove of great assistance in attacking problems of this sort.—Editor.

The purpose of this paper is to show why flywheels are necessary on synchronous motors which drive reciprocating compressors, and to outline the method of determining the proper flywheel weight.

For convenience in analyzing the problem I shall divide the discussion into two parts, dealing first with the mechanical aspects and later with the electrical. I do not wish to impart the idea that they are entirely separate matters, for they are not, as I shall presently explain, but it is convenient to treat them separately.

When the torque developed by a synchronous motor is just equal at all times to the torque consumed, the speed must be constant. This means that at any given instant the rotating member of the motor has a definite position in space. To illustrate this point, consider an analogy. In Fig. 1, two trains are running side by side at constant speed and abreast of each other. At any instant of time these two trains will occupy a definite position along the track and will remain abreast of each other. Under such conditions the driving force of the trains is exactly equal to the opposing forces of friction, windage, etc. The position thus held may in the analogy be termed the "stable position" and corresponds to the space position



Air Compressor Driven by a Synchronous Motor. The Flywheel for Effecting Stable Operation is Shown to the Right of the Synchronous Motor of the motor referred to. It is important to hold in your mind the idea of this stable position as the necessary reference to which varying motion may be referred.

Referring again to Fig. 1, assume that trains "A" and "B" are running abreast of each other and at constant speed, and that at an instant designated by O the driving force on A is instantly increased by an amount indicated in the figure, and that this excess force, existing for a time t, is suddenly removed. Let us inquire how this affects the velocity and relative displacement of trains A and B.

In Fig. 1a, the excess force, which is consumed entirely in the acceleration of the train, can also, if drawn to proper scale, represent the acceleration of the train. Therefore the area under the curve, representing the product of acceleration and time, represents the accumulated excess velocity. Plotting in Fig. 1b ordinates which represent the accumulated area in a will give a curve of the excess velocity at any instant during the time t. Likewise, since the area in Fig. 1b is the product of velocity and time, ordinates representing the accumulated area at any instant, when plotted in c, give the curve of excess displacement of train A ahead of train B. That is, at the end of time t train B will have reached m, whereas train A will have gone further, that is, to point n. The excess displacement mn is represented by the maximum ordinate at the end of curve c. The idea here is that it is possible to find the change in both velocity and displacement from the curve of unbalanced force impressed upon a body simply by integrating the area of the loops in the unbalanced force diagram. The first integration gives velocity, the second gives displacement.

Carrying the illustration further, assume that instead of the momentary excess force described, a periodically varying force is applied. That is, at equal intervals of time first an excess force and then an insufficient force is applied to train A such that the resulting average velocity of train A is the same as the constant velocity of train B. In other words, train A will alternately and at equal successive intervals have an excess and insufficient driving force impressed upon it. This is represented graphically in Fig. 1d. Since the area of the first excess loop at any instant represents added velocity, it follows that at the end of the first interval the velocity must be a maximum, and that likewise at the end of the second interval the velocity must be a minimum. The resulting curve of velocity will therefore be as shown in e. By the same process the displacement curve showing the position of train A first ahead and then behind the stable position is shown in f.

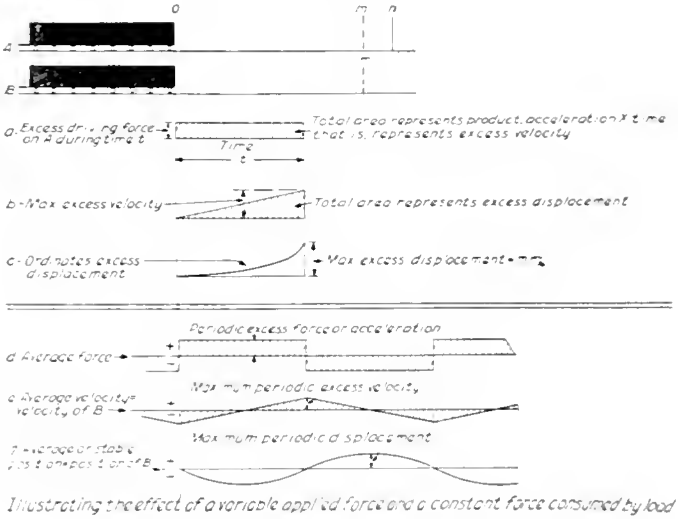


Fig. 1 Diagram Showing How Periodic Relative Displacement of Two Trains is Derived from Curve of Unbalanced Driving Force

One part of the problem of determining the proper flywheel effect for synchronous motors direct-connected to reciprocating compressors is illustrated in this way, viz.: that it is required to find what mass train A must have in order to limit to a definite amount the plus or minus displacement as shown in f when a given periodic variation in the driving force is impressed upon the train A.

The idea of angular deviation of the synchronous motor can now be approached from a more direct point of view. Consider two duplicate synchronous machines, one driving an air compressor, the other driving a blower. The latter will have constant speed, the former, on account of the pulsating torque of the compressor, will have a pulsating speed. Suppose that reference arrows are placed on corresponding poles of these two machines. In this case, just as in the case of two trains, the variable torque on the motor which drives the compressor will cause it to be displaced first ahead and then behind the position of the reference arrow on the other motor.

For electrical reasons, explained later, it is necessary to set limits to this displacement or deviation. The larger the number of poles on the motor the smaller correspondingly must be the limit. That is, in the case of a 60-pole motor, the allowable angular displacement is one half of that for a 30-pole motor, because the allowable value is a function of the electrical, not mechanical angle. Therefore, the problem is to determine how much flywheel is required to keep the angular displacement within given required limits. This is easily worked out from the turning effort diagram of the compressor.

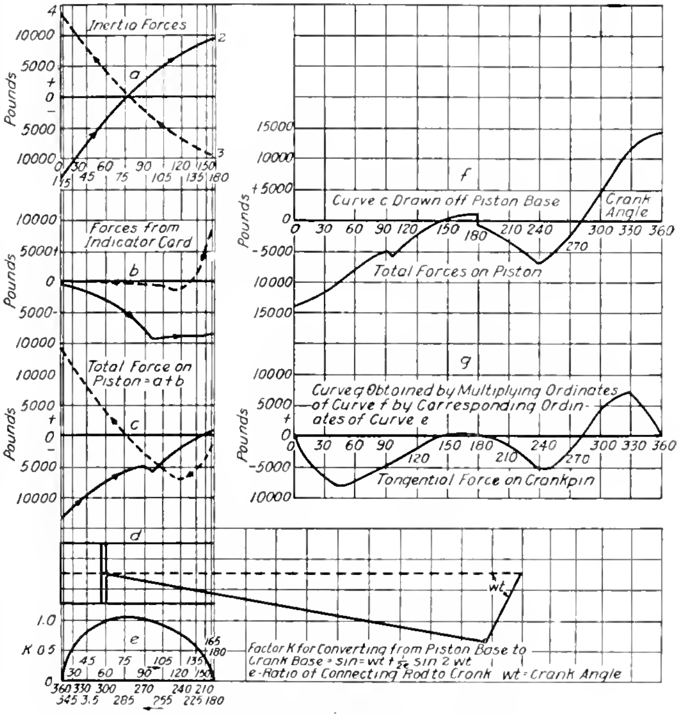


Fig. 2. Method of Determining Tangential Effort on Crank Pin from the Indicator Card and Inertia Forces

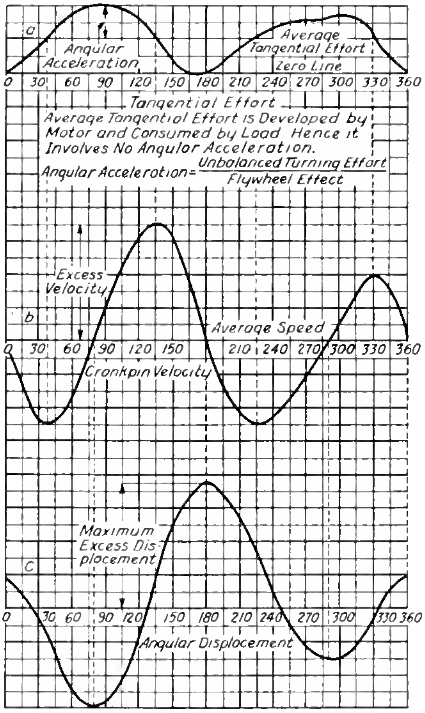


Fig. 3. Velocity and Displacement Curves as Derived by Successive Integrations of Tangential Effort Curve

The process of obtaining the turning effort curve for a reciprocating compressor is illustrated in Fig. 2. For simplicity, the case of a single crank single acting compressor is chosen. *a* represents the inertia forces, that is, the forces required to stop and start the reciprocating masses. Positive forces are taken as those tending to maintain motion, negative as those tending to retard motion. *b* shows the forces taken from the indicator card, that is, the forces acting on the piston. *c* shows the sum of *a* and *b*, all plotted on the piston base. Curve *f* shows the forces in *c* developed on the piston base. These forces on the piston are converted to tangential forces on the crank pin by multiplying the different ordinates of curve *f* by corresponding ordinates in curve *e*. The resulting curve, shown in *g*, is the turning effort curve or tangential force on the crank pin. Most compressors are, of course, double acting. This simple case was taken merely for an illustration.

Fig. 3a shows the tangential force of an actual double acting machine. By integrating the areas under the plus and minus loops of this curve in the manner as described in Fig. 1, the velocity curve is obtained as shown in Fig. 3b. Integrating the loops of this curve in like manner gives the ordinates of the displacement curve, as shown in Fig. 3c. Thus it is possible, with a given flywheel effect in the motor, and a given tangential curve as shown above, to determine accurately what angular displacement would occur under the assumed conditions; or conversely, what flywheel effect would be required to limit the angular displacement to a definite value.

Inasmuch as the integration of the loops of the crank effort and velocity curves by planimeter is a very laborious process it is rarely resorted to. Yet any method that does not involve a proper integration of the entire curve is at best an approximation. We have found the analytical method to be very useful. This gives the same results as the graphical integration. It consists in expressing the unbalanced component of the crank effort diagram, which to proper scale is the acceleration diagram, into a Fourier's series of sines and cosines, and integrating this equation twice for displacement. Thus the unbalanced crank effort or torque can be expressed as,

$$T = (a_1 \sin \omega t + a_2 \sin 2\,\omega t + a_3 \sin 3\,\omega t + \ldots + b_1 \cos \omega t + b_2 \cos 2\,\omega t + b_3 \cos 3\,\omega t)$$

Where $\omega = 2\,\pi nt$

n = revolutions of crank per second

t = time

The angular acceleration is

$$^{*}\ \alpha = \frac{T}{I}$$

Where I = moment of inertia of rotor.

Thus the velocity equation is

$$v = \int \alpha\, dt = \frac{1}{\omega I}\left(-a_1 \cos \omega t - \frac{a_2}{2} \cos 2\,\omega t - \frac{a_3}{3} \cos 3\,\omega t - \ldots + b_1 \sin \omega t + \frac{b_2}{2} \sin 2\omega t + \frac{b_3}{3} \sin 3\omega t +\right)$$

And the angular displacement in mechanical radians is

$$\theta = \int v\, dt = \frac{1}{\omega^2 I}\left(-a_1 \sin \omega t - \frac{a_2}{4} \sin 2\,\omega t - \frac{a_3}{9} \sin 3\,\omega t + \ldots - b_1 \cos \omega t - \frac{b_2}{4} \cos 2\,\omega t - \frac{b_3}{9} \cos 3\,\omega t -\right)$$

The coefficients $a_1\, a_2, a_3 \ldots\, b_1, b_2, b_3 \ldots$ are obtained from an analysis of the crank effort curve by the use of a schedule shown in Fig. 4.

By proper substitutions the maximum angular displacement in electrical degrees becomes,

$$\theta = \frac{10^7\, K\, f\, r\, Z_m}{S^3\, WR^2}$$

K = lb. on crank pin per inch scale of crank effort curve.

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[*] This scheme is described by H. C. Lehn, GENERAL ELECTRIC REVIEW, March, 1915.

ANALYSIS OF CRANK EFFORT CURVE
FOR 2 STROKE CYCLE

y = a₀ + a sin ωt + b cos ωt + a₂ sin 2ωt + b₂ cos 2ωt + a₃ sin 3ωt + b₃ cos 3ωt + a₄ sin 4ωt + b₄ cos 4ωt
y = ordinates of crank effort curve in inches

		a₁		b₁		a₂		b₂		a₃		b₃		a₄		b₄	
ωt	y	sin ωt	y sin ωt	cos ωt	y cos ωt	sin 2ωt	y sin 2ωt	cos 2ωt	y cos 2ωt	sin 3ωt	y sin 3ωt	cos 3ωt	y cos 3ωt	sin 4ωt	y sin 4ωt	cos 4ωt	y cos 4ωt
0		+ 0		+1000		+ 0		+1000		+ 0		+1000		+ 0		+1000	
15		+ 258		+ 965		+ 500		+ 866		+ 707		+ 707		+ 866		+ 500	
30		+ 500		+ 866		+ 866		+ 500		+1000		+ 0		+ 866		- 500	
45		+ 707		+ 707		+1000		+ 0		+ 707		- 707		+ 0		-1000	
60		+ 866		+ 500		+ 866		- 500		+ 0		- 1000		- 866		- 500	
75		+ 965		+ 258		+ 500		- 866		- 707		- 707		- 866		+ 500	
90		+1000		- 0		+ 0		-1000		-1000		- 0		- 0		+1000	
105		+ 965		- 258		- 500		- 866		- 707		+ 707		+ 866		+ 500	
120		+ 866		- 500		- 866		- 500		- 0		+ 1000		+ 866		- 500	
135		+ 707		- 707		-1000		- 0		+ 707		+ 707		+ 0		-1000	
150		+ 500		- 866		- 866		+ 500		+1000		+ 0		- 866		- 500	
165		+ 258		- 965		- 500		+ 865		+ 707		- 707		- 866		+ 500	
180		+ 0		-1000		- 0		+1000		+ 0		- 1000		0		+1000	
195		- 258		- 965		+ 500		+ 866		- 707		- 707		+ 866		+ 500	
210		- 500		- 866		+ 866		+ 500		-1000		- 0		+ 866		- 500	
225		- 707		- 707		+1000		+ 0		- 707		+ 707		+ 0		-1000	
240		- 866		- 500		+ 866		- 500		- 0		+ 1000		- 866		- 500	
255		- 965		- 258		+ 500		- 866		+ 707		+ 707		- 866		+ 500	
270		-1000		- 0		+ 0		-1000		+1000		+ 0		- 0		+1000	
285		- 965		+ 258		- 500		- 866		+ 707		- 707		+ 866		+ 500	
300		- 866		+ 500		- 866		- 500		+ 0		- 1000		+ 866		- 500	
315		- 707		+ 707		-1000		- 0		- 707		- 707		+ 0		-1000	
330		- 500		+ 866		- 866		+ 500		-1000		- 0		- 866		- 500	
345		- 258		+ 965		- 500		+ 866		- 707		+ 707		- 866		+ 500	
Σy =		Sum		Sum		Sum		Sum		Sum		Sum		Sum		Sum	
		[illegible] Sum		[illegible] Sum		[illegible] Sum		[illegible] Sum		[illegible] Sum		[illegible] Sum		[illegible] Sum		[illegible] Sum	
a₀ = [illegible]		a₁ = [illegible]		b₁ = [illegible]		a₂ = [illegible]		b₂ = [illegible]		a₃ = [illegible]		b₃ = [illegible]		a₄ = [illegible]		b₄ = [illegible]	

Acceleration = α = [illegible] [a sin ωt + b cos ωt + a₂ sin 2ωt + b₂ cos 2ωt + a₃ sin 3ωt + b₃ cos 3ωt + a₄ sin 4ωt + b₄ cos 4ωt] Electrical degrees per sec²

Velocity = v = [illegible] [a cos ωt + b sin ωt − a₂/2 cos 2ωt + b₂/2 sin 2ωt − a₃/3 cos 3ωt + b₃/3 sin 3ωt − a₄/4 cos 4ωt + b₄/4 sin 4ωt] Electrical degrees per sec

Displacement = θ = [illegible] [a sin ωt − b cos ωt − a₂/4 sin 2ωt − b₂/4 cos 2ωt − a₃/9 sin 3ωt − b₃/9 cos 3ωt − a₄/16 sin 4ωt − b₄/16 cos 4ωt] Electrical degrees

S = Rev per min K = lb on crank pin per inch scale of crank effort curve q = No of poles of generator WR² = Total lb ft² r = Crank pin radius [illegible] feet

Fig. 4. Schedule for Determination of Coefficients of Fourier's Series Expressing the Tangential Effort as a Function of Time

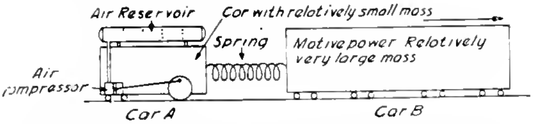
f = frequency of supply voltage in cycles per sec.
r = crank pin radius in feet.
Z_m = maximum value of bracket quantity in equation of displacement, that is, maximum value of the series.
S = r.p.m.
WR^2 = total flywheel effect in lb. ft.^{2}

It is not my purpose, as intimated at the outset, to explain in detail the derivation and application of formulas, because that is a long story in itself, but rather to outline what the problem is and show the nature of the solution.

The foregoing considerations cover what I have chosen to call the mechanical aspects of the problem, and describe one part of what seems to be the most practical method of getting at the complete solution. There is an additional part which will now be discussed as the electrical aspects of the problem.

As already stated, there are really not two separate phenomena involved. There is only one, as shall presently be shown; but as a matter of convenience both in presenting the problem and in the practical solution of any given case, it is desirable to consider that there are separate parts. In the first, the effect of the electro-magnetic force (usually called the synchronizing force or torque) is neglected. In the second this force is taken into account.

Consider the character of this force. Have you ever watched an electric motor whirling in space, receiving energy into the stationary member and delivering that energy to the rotating member, with no mechanical connection between the two members—have you ever watched such a motor and wondered just what was going on in the small air space between the members, and also what was the character of the medium through which that energy transfer takes place? It is very much as if one end of invisible rubber bands or small spiral springs were attached to the poles on the rotating member, and the other ends of these elastics were carried circumferentially around the face of the stationary member at constant speed. At no load there would be no stretch in the elastic elements, and the rotor would maintain a definite stable position in rotation. Suppose a constant load is put on the shaft, the ends of the elastic elements would nevertheless continue to be carried around the stator face at an unaltered speed. Since the other ends are attached to the poles, the rotor would be pulled along also at the same speed, but on account of the stretch in the elastic due to the added load, the rotor would assume a new and lagging position in space, such that the forces in the stretched elastics balance the load. Obviously, if the rotor is displaced from the no load position, whether by load or by some momentary impulse, *there is a force exerted upon the rotor that is proportional and opposite to the displacement. This is the characteristic of synchronizing force.** The magnetic lines of force emanating from the surface of the poles and entering the stationary member are elastic like rubber bands or springs, and behave in a similar manner, and they constitute the medium through which the energy is transferred from the stationary to the rotating member.



Car A with spring, represents a synchronous motor driving an air compressor. The mass of the car corresponds to the flywheel effect of the motor, the spring represents the magnetic flux Car B, represents the large power system which supplies power to the synchronous motor

Fig. 5. Analogy Representing an Air Compressor Driven by a Synchronous Motor Which is Connected to a Large Power System

I wish to emphasize another mechanical analogy as a fixture to which subsequent ideas may be attached. Fig. 5 is intended to show a heavy railway car which runs at constant speed regardless of what else happens. It draws, through a spring connection, a smaller and lighter car which has a drive wheel connected to an air compressor. That is, the source of energy for the work of compressing air is the large car. The variable force exerted on the drive-wheel by the compressor is obviously reflected in the spring tension. As an analogy, the large massive car running at constant speed represents the power supply system to which the motor is connected. The small car with spring represents the synchronous motor; the mass of the car corresponds to the flywheel effect; and the spring to the magnetic lines of force. The entire small car equipment represents a synchronous motor driving an air compressor. The speed of the drive wheel corresponds to the speed of the motor. The analogy is practically complete. As load is added the spring stretches; the car assumes a new, lagging position with respect to the large car. The variable torque exerted on the drive wheel

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* Direct proportionality ceases at large angles, but holds for the range considered here.

by the compressor produces periodic displacement alternately ahead and behind the average, or stable position. If it were possible to add more and more load the strain or stretch in the spring would increase, until ultimately the elastic limit would be reached, the spring would give way, and the car would stop. Just so with the motor. If the load is increased sufficiently, whether momentarily or gradually, the elastic limit of the magnetic lines of force is reached and the motor breaks out of step.

The speed of the large car corresponds to the voltage, the spring tension to the electric current and the product of the two obviously corresponds to the power. Thus the variable load, as represented by the varying spring tension, is manifested at the switchboard by swinging meter needles. It is beginning to be clear, therefore, why angular displacement must be limited. It is a question of setting a limit to the pulsation of power which we are willing to accept. This will be discussed later on.

Another extremely important point to be drawn from this analogy is that *if a sudden change in load occurs it will be attended by an oscillation, and the oscillation will be at a definite frequency.* This follows from the characteristic of synchronizing forces already explained. Suppose, for convenience of illustration, that both cars are stationary; that the connecting rod of the compressor is temporarily disconnected from the drive wheel; and that the small car is pulled back from the large car, stretching the spring, and is then released. Obviously the result will be an oscillation of the small car with respect to the large car, and, as in the case of a pendulum, there will be a definite number of oscillations per minute. The same thing would happen even if the cars were traveling forward. Imagine, then, the two cars to be running along the track at, say fifteen miles an hour, and the small car to be oscillating or "hunting" with respect to the large one; you will then have a physical conception of the hunting of a synchronous motor. Moreover, if the drive-wheel is now connected to the compressor, bringing its variable torque into action, you will have the disturbing influence which, under certain unhappy conditions can cause excessive hunting or surging. For instance, a sudden change in load starts an oscillation which as already stated occurs at a definite frequency. Suppose that each time the small car swings back and forth in oscillation relative to the large car, it receives, in perfect time harmony, impulses from the compressor which are in a direction to amplify the swing. Little by little the oscillation will build up to large amplitude, that is, will become violent. These conditions exist if the natural oscillating frequency (oscillations per minute) is exactly equal to the revolutions per minute of the drive-wheel. If, however, the impulses occur either faster or slower than the oscillations, so that now and then the impulse acts against, instead of with, the oscillation, the result will obviously be less violent oscillation. And as the frequency of impulse, that is, the speed of the drive-wheel is made to differ more and more from the oscillating frequency, the amplitude of the oscillation becomes less and less. Although by the method described in Fig. 1 (neglecting the effect of the spring) the relative displacement of the small car with respect to the large one may have been calculated as, let us say, two inches, we nevertheless find that at resonance between the impulses and natural oscillations the actual displacement becomes many times larger; also, that as the difference between the impulses and oscillations becomes greater the displacement becomes less, ultimately approaching the value calculated as in Fig. 1 (assuming that the unbalanced forces acted on a free mass, that is, neglecting the effect of the spring). All of this applies to a synchronous motor driving a reciprocating compressor.

The characteristic that synchronizing force, like spring tension, is proportional and opposite to the displacement of the rotor from the no load position, leads us to the very convenient fact that the motion of the rotor in oscillation must be harmonic. Hence the well known formula for the period of simple harmonic motion can be applied, and the natural oscillating frequency for any combination of synchronizing force and flywheel effect can be calculated. This formula will be given later.

Such oscillations of the small car as are described above can be limited to some extent by the use of a damping device, such as a dash pot. For instance, in Fig. 5, if an adequate dashpot were placed between the two cars so that any relative movement between the cars would involve a change in the dashpot piston, the free swings or oscillations (that is, those occurring at the natural frequency) would be damped out, leaving only the increased displacement occurring at each impluse. But even this displacement, although less than that without dashpot, is many times that which would occur if the natural oscillating frequency were considerably different from the impulse frequency. Such a dashpot represents the amortisseur winding in the pole face of a synchronous motor in its action of damping out oscillations.

Fig. 6 illustrates this condition. It shows the angular displacement for different values of flywheel effect, first, in the dotted line, neglecting the effect of synchronizing force, and second, in the full line curve, including the effect of synchronizing force, and assuming the free oscillations to be damped out. Since, as intimated above, the oscillating frequency is a function of synchronizing force and flywheel effect, it is possible to plot the natural oscillating frequency, as well as flywheel effect, as abscissæ. The curve assumes a 250-r.p.m. compressor connected to a synchronous motor whose synchronizing force corresponds to 10 kw. per electrical degree displacement. You will observe two peaks of displacement, much in excess of the dotted line values.

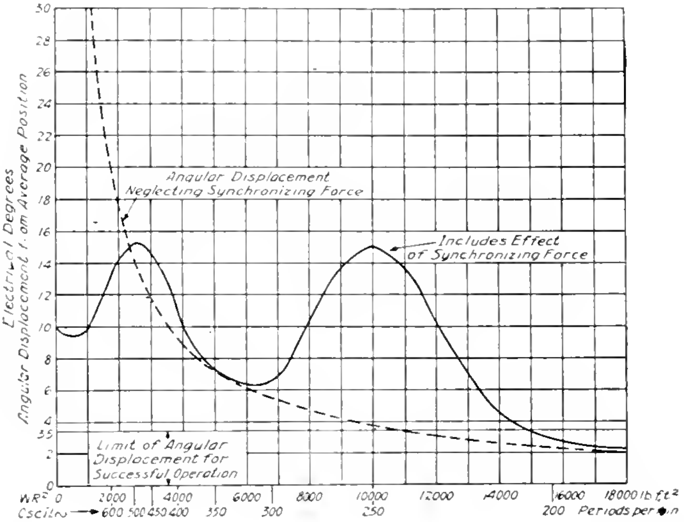

Fig 6. Curve Showing Approximate Effect of Synchronizing Force Upon Angular Displacement for Different Values of Flywheel Effect. Drawn for an Assumed Compressor Unit of 250 r.p.m. Synchronizing Force Corresponds to 10-kw per Electrical Degree Displacement

These correspond to a natural oscillating frequency equal respectively to the revolutions of the crank, that is, 250 per minute, and to twice the revolutions, or 500 per minute. Beyond 15,000 WR^2 and between the peaks, the displacement is about the same as the calculated value, neglecting synchronizing force. The beginning of this curve is interesting. Suppose the small car in Fig. 5 had zero mass, then whatever instantaneous variations occur in the torque on the drive-wheel would be impressed in full and in phase upon the spring; but there is nothing impossible about this except the zero mass. I mean that the periodic displacement from the average position would obviously not be infinite, but a value determined by the constant of the spring. Thus, if the momentary excess torque is, say 50 per cent of normal, then with zero mass the spring at that instant would simply be stretched 50 per cent more than at normal torque. Thus, in Fig. 6, starting at zero flywheel effect, there is a definite periodic displacement determined by the momentary load and the synchronizing force. Adding WR^2 reduces the displacement until, by approaching a critical natural oscillating frequency, the displacement is again increased, passing through a peak at resonance—and so on. Observe that when a difference of 20 to 25 per cent exists between the impulse frequency and the natural oscillating frequency, say at 16,000 WR^2 or at 6000 WR^2, the displacement approaches the values as calculated, neglecting synchronizing force.

Thus in going over a whole range of values of WR^2, we find that the problem is really one connected story, not two; yet at the same time the story itself suggests a division for practical calculation. It is this:

(1) Calculate from the crank effort curve the value of WR^2 required to limit angular displacement to a given value, neglecting the effect of synchronizing force.

(2) Then see if this WR^2 causes the natural oscillating frequency to fall in a critical range, that is, within 20 per cent of the revolutions, thus causing greatly increased displacement. If so, the WR^2 must be increased until the required difference is obtained.

For reasons discussed later, the present limit for angular displacement which we consider necessary for satisfactory operation is plus or minus 3.5 electrical degrees.* For instance, in Fig. 6 the calculated WR^2 required to limit the displacement to plus or minus 3.5 electrical degrees is, by dotted curve 10,500. But this value would cause a natural frequency, as noted on abscissa, equal to about 250, that is, equal to the revolutions per minute. Hence the WR^2 must be increased to about 15,000.

The formula for calculating the oscillating frequency is simple, but the determination of one of the factors in it is a very difficult matter. It has been shown that the characteristic of synchronizing force is, for our consideration, the same as that of a spring. That is, *this force on the rotor at any angular displacement is proportional and opposite to the displacement*. This is the definition of harmonic motion. Hence the well known formula for the period of harmonic motion can be used. Thus, the period is

$$T = 2\pi\sqrt{\frac{I}{\sigma}} \text{ seconds}$$

where,

I = moment of inertia

σ = ratio of torque to angular displacement.

With proper substitution, the formula for natural frequency of oscillation becomes,

$$F = \frac{35200}{RPM}\sqrt{\frac{P_0\ f}{WR^2}} \text{ periods per min.}$$

where,

P_0 = factor depending upon synchronizing force.

f = frequency of supply voltage in cycles per second.

WR^2 = flywheel effect on lb. ft.^{2}

For motors with uniform airgap the factor P_0 is easily determined from calculation or test. But in salient, or definite pole machines, which constitute practically all that are now built, this factor is extremely difficult to calculate and can be determined experimentally only by very elaborate tests. An investigation extending over some three years has given a method of calculating P_0, and necessary tests have been made to confirm the calculation. Hence, although the calculation is rather involved, it is nevertheless worthwhile, if we would keep out of trouble.

I have outlined the factors which are involved in the determination of the proper flywheel effect; or in other words, have stated the problem, and also have indicated roughly the method which has been found to be the most practical one for solving any particular case. I shall now touch upon some of the more general aspects of the problem.

The problems for those of us to answer who are interested in the electrical side of this problem (which includes the customer) is this: What value of power pulsation are we willing to accept as reasonable? This is the equivalent of asking: What periodic angular displacement are we willing to allow? To answer these questions we must make inquiry as to what harm such power pulsations produce. The first thing that naturally comes to our mind is the disagreeable feeling which seizes us when we see an ammeter or wattmeter needle surging across the scale, a feeling that tells us at each new pulsation that something serious is certainly going to happen at the next swing. But it never happens, at least rarely happens. I have never seen a motor "kick" out of synchronism *as a result of surging or hunting*, although, of course, such a thing is possible. The point is, it is an extremely rare occurrence. We therefore face this interesting point: If we have to look at the ammeter to tell whether there is trouble, can we justly call that trouble? Moreover, the complete absurdity of the point is brought out by the fact that ammeters can be made, and are made and used, which will not follow the pulsations. The current may vary 100 per cent from the average, yet the ammeter may

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* To reduce this to mechanical degrees divide by one half the number of poles.

show only 5 per cent. Hence, in such cases meter swinging in itself surely cannot be taken as the cause of any contention. *Conversely, and this is very important, we must not assume that just because the ammeter is quiet there are no power pulsations.* We must therefore drop this point as of no value in determining a limit for angular displacement.

However, there are good reasons for setting a limit. The principal one is the vibration of certain parts of the motor caused by the pulsation, and all that the vibration leaves in its wake. I think it is true that almost any machine, of whatever manufacture, designed for normal service would ultimately fail if subjected to incessant, serious vibration. The failure may be either mechanical or electrical. Parts which are mechanically strong enough and adequately held for normal service, may, when subjected to such vibration, gradually work loose. On the other hand, the pulsating torque, exerted on the armature coils, may cause them to work loose in the slot. *Breathing* of the projecting portion of these coils will cause chafing of the insulation, and ultimate failure. Even if the projecting portions were bound firmly to supporting rings (which construction on the slow speed motors in question is not required for any other reasons) the continued reversal of stress in the insulation, just as in metal, would gradually produce fatigue, in this case both mechanical and dielectric fatigue, with the result that the life of the coil would be seriously shortened.

Serious pulsation also lowers the efficiency and causes unnecessary heating of the armature coils. A pulsating current, delivering the same average power as a steady current, will cause more loss in the windings than the latter. Moreover, the oscillations cause loss in the amortisseur or damping winding in the pole face. Another point is that the pulsating current taken from the line may cause corresponding fluctuations in the line voltage, if the impedance of the supply lines is appreciable. This, however, is not a serious matter if the motor is connected to a large power supply system through low impedance feeders.

What, then, shall we call the limit? In the early days 2.5 electrical degrees, plus or minus, was established. Step at a time, and guided by experience, we have raised that limit to 3.5 degrees. We know that with the average run of machines one degree deviation will cause from 3 to 6 per cent of full load current; hence the above limit means a pulsation of about plus—minus 10 to 20 per cent, a total variation of from 20 to 40 per cent. Present experience indicates that this limit should not be exceeded. It is, however, entirely a matter of experience, which the future may modify.

Fig 7. 32-pole Rotor for Synchronous Motor Showing Construction and Amortisseur Winding

Melbourne Suburban Electrification, Australia*

By W. D. Bearce

Railway and Traction Engineering Department, General Electric Company

Before selecting the equipment to be used in electrifying the extensive suburban steam lines out of Melbourne, Australia, a careful analysis was made with the result that high-voltage direct-current equipment was decided upon in view of the fact that this system of electrification would not entail so great an initial outlay and annual expense as would the single-phase system. The analysis is of especial weight because of the magnitude of this suburban enterprise—one involving the electrification of 336 single-track miles (153 route miles), the equipping of 400 motor cars and 400 trailer cars, and the installation of 15 substations having a total ultimate capacity of 81,000 kw. Mr. Bearce has, in the following article, summarized the principal features of the electrification.—Editor.

The electrification of the Victorian Railway lines radiating from the City of Melbourne, Australia, is the most extensive suburban steam road conversion in the world. The project was initiated in 1913 by the State of Victoria, which operates all of the steam roads in this State. The decision to electrify was followed by exhaustive study of the available systems by Merz and McLellan, Consulting Engineers, and a decision to use 1500-volt direct current as the most economical both in first cost and cost of operation. Estimates of the relative cost of 1500-volt direct-current and 11,000-volt single-phase equipment were published in December, 1912, by the Consulting Engineers after a thorough analysis of proposals submitted by twenty different manufacturers. These figures included the cost of power plant, transmission, substations, overhead distribution, rolling stock and alterations to existing equipment.

The following figures, taken from this report, show the relative cost of installation and annual cost of operation (including power, maintenance, and interest charges).

	Direct Current	Single Phase
Initial Cost.	$11,636,964	$14,857,137
Annual Expense.	1,235,286	1,578,211

The recommendations of the General Electric Company as to the general features of the electrification were accepted in practically every respect, and the motor and control equipment of the 400 motor cars is of standard General Electric design.

General Features

The Melbourne Suburban System consists of approximately 336 single-track miles including parallel tracks and sidings. A larger part of the system is equipped with double track and there are some four and six-track lines, distributed as shown in Table I. This table also indicates a total of 153 miles of route.

TABLE I

MILES OF ROUTE AND SINGLE TRACK MELBOURNE SUBURBAN RAILWAYS.

	Miles Single Track Basis	Miles Route
6 track	18.90	3.15
4 track	21.44	5.36
3 track	6.69	2.23
2 track	220.00	110.00
1 track	33.00	33.00
Sidings	36.00	
Total	336.03	153.74

The standard construction consists of 100-lb. T section rails double spiked to untreated ties 9 ft. by 10 in. by 5 in. and spaced 2 ft. 10 in. centers with 1 ft. 8 in. spacing at joints. The road bed is rock ballasted to a depth of 15 in. and the tracks are located 11 ft. 8 in. apart. The track gauge is 5 ft. 3 in. and the curvature is limited to a maximum of approximately 10 deg. which occurs on the Flinders Street viaduct. The line between Sandringham and Broadmeadows, which includes the initial electrically operated line, may be taken as typical of the system. This branch contains a maximum grade of 2 per cent, and for a distance of approximately 9 miles the average grade is 0.85 per cent. The maximum speed allowable on this section is 52 m.p.h. with slow downs on some of the curves. Practically all of the curves have a 150-ft. easement approach.

The contracts for electrification which were made in 1913 contemplated the electric operation of this entire suburban district. Owing to the precipitation of the European War actual construction was seriously handicapped, and the official opening took place May 28, 1919. The first electrical operation

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* Abstracted from a series of articles in *The Commonwealth Engineer* (Melbourne), by E. P. Grove, in charge of the installation for Mertz & McLellan, Consulting Engineers.

included the section of line between Sandringham and Essendon. This line extends approximately due north from the Flinders Street terminal to Essendon and south to Sandringham. With the exception of the portions around the terminal station, the line is practically all double track.

The population of the city of Melbourne, including suburbs, according to the 1912 census, was approximately 700,000. There is a large outlying residential district which is supplied with frequent and high-speed train service, handling a very heavy suburban traffic. Electrification was adopted in preference to the construction of additional lines and parallel tracks to handle the rapidly increasing business.

Instead of locomotives and trailing passenger coaches, the entire passenger traffic will be handled by multiple-unit motor-car trains. At present no provision is being made for handling freight traffic; and steam loco-

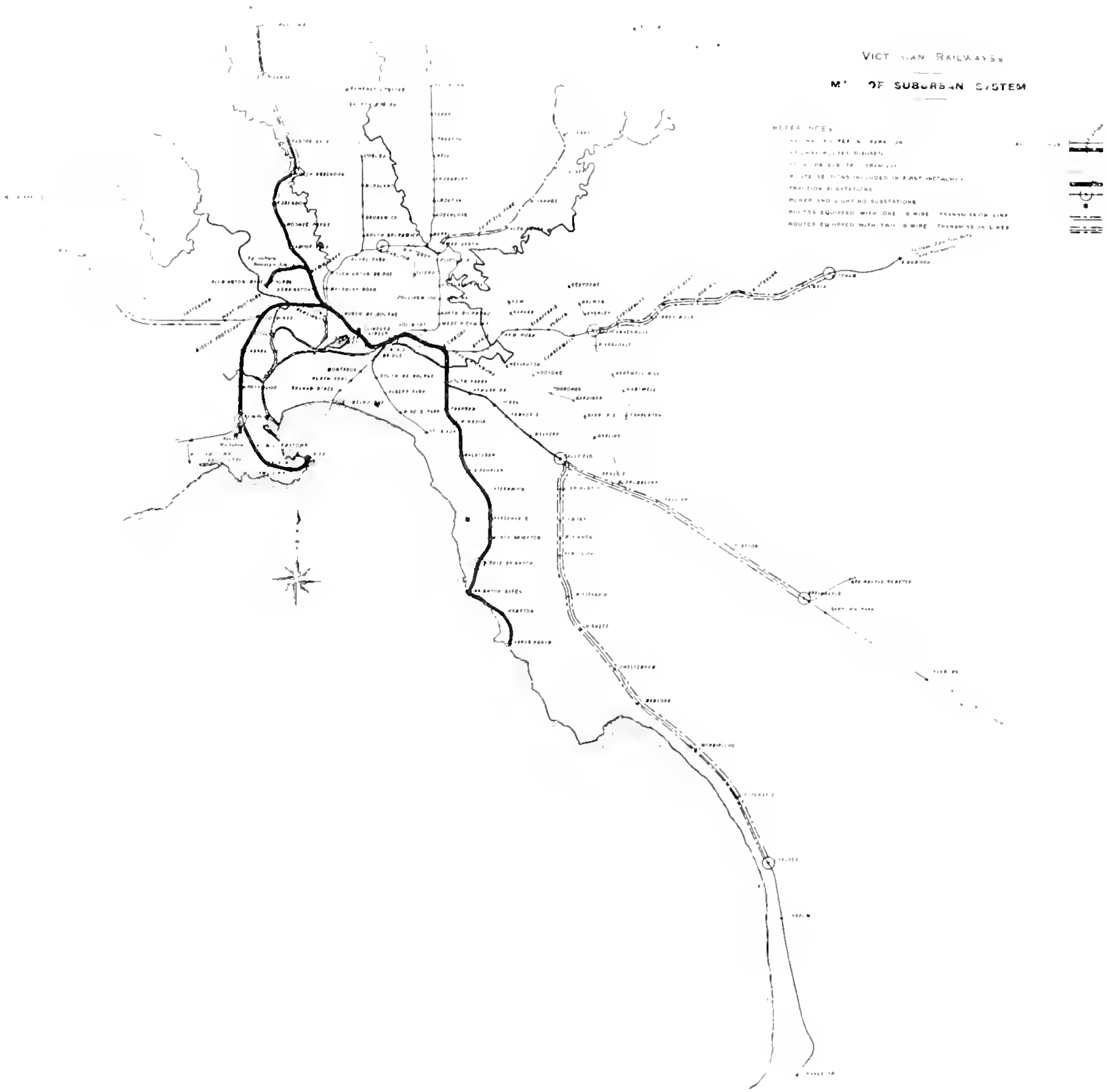

Fig. 1. Map of Electrified Lines

motives will be employed for this purpose until the passenger service has been fully taken care of.

Rolling Stock

The suburban trains on the Melbourne system are made up of units each consisting of a motor car and a trail car which can be operated from either end. The normal six-car train will thus be made up of three-units (three motor cars and three trailers). The initial orders for rolling stock included the equipment for 400 motor cars and 400 trail cars adapted to operate either from the motor car or trailer. About 45 per cent of these cars are of the compartment type with swing doors, the remainder being of a combination type with sliding doors and cross seats, and a corridor running the full length of the passenger section. A larger part of these cars are partitioned into sections to form smoking and non-smoking compartments. The seating accommodation and weights of the cars are as given in Table II.

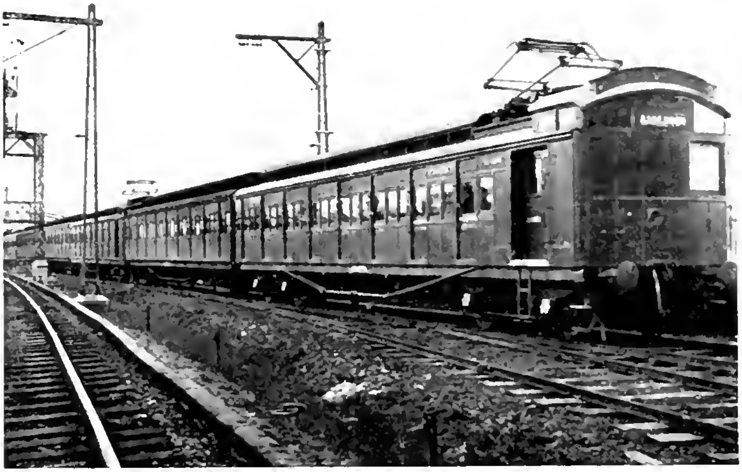

Fig. 2. Multiple Unit Passenger Train on 1500-volt Electric Zone

TABLE II

	Seats	2000-lb. Tons Equipped
Sliding door motor car	84	53.57
Swing door motor car	80/70	52.41
Sliding door driving trailer	84	30.88
Swing door driving trailer	80/70	29.43
Sliding door non-driving trailer	94	30.69
Swing door non-driving trailer	90	28.48

The number of cars at present equipped for electric traction is as shown in Table III.

Electrical Equipment

The electrical equipment for the 400 complete motor coaches and 400 trailer coaches was furnished by the General Electric Company and consisted briefly of the following:

Sixteen hundred GE-237, 140-h.p. 750/1500-volt ventilated motors with gears and pinions.

Four hundred current-collecting equipments including sliding pantograph with devices for raising and lowering and accessories.

Four hundred Sprague GE type M control equipments including circuit breakers, contactors, reversers and master control equipment.

Four hundred auxiliary equipments including dynamotor, air compressor, auxiliary devices for control and lighting circuits.

Each motor car is equipped with four GE-237 motors, the motors on each car being connected two in series for operation on the 1500-volt trolley. The field coil windings are provided with taps so that 20 per cent of the field can be cut out

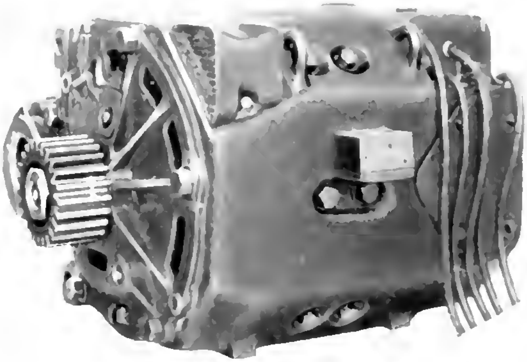

Fig 3. GE-237 Ventilated Railway Motor

TABLE III

	Swing-door Type	Sliding-door Type	Total
Motors	164	195	359
Driving trailers	27	29	56
Non-driving trailers	126	161	287
	317	385	702

automatically for high-speed running. The gear ratio is 74 23, giving maximum speed of approximately 52 miles per hour on level tangent track.

The collector is of the pantograph type having two sliding pan shoes. These shoes are spring supported and free to move independently. Each shoe has two strips of contact copper about 2 in. wide and $\frac{3}{16}$ in. thick, so arranged as to form a pan between them which is filled with graphite grease. The contact strips are replaceable, and the design is such that the greatest amount of surface is provided in the center where the maximum running occurs. The over-all width of the contact surface is 45 in. The upward pressure of the pantograph on the contact wire is approximately 25 lb. and with a reasonably clean wire a current of considerably more than 500 amp., the maximum normal operating current for each motor coach, can be collected without sparking. The working range is from 14 ft. 6 in. to 21 ft. 6 in.

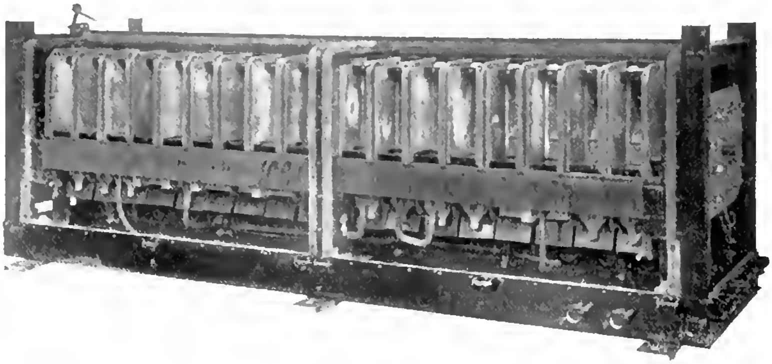

Fig. 4. 1500-volt Contactor Box for Type M Control

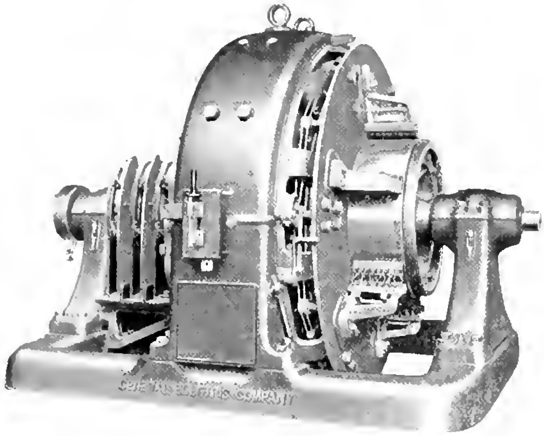

Fig. 5. One of the 1500-kw., 1500-volt Synchronous Converters Installed in Jolimont Substation

The pantograph is raised by admitting compressed air to the working cylinder mounted on the base of the collector. The valves controlling this cylinder are of the electro-pneumatic type, mounted near the master controller, and they can be remotely controlled from the leading cab so that pantographs can be raised or lowered on all cars simultaneously.

Control current at approximately 750 volts is supplied by the dynamotor for operation of the various control circuits and for lighting accessories. The main contactors are actuated from the master controller containing a single-contact cylinder with stationary fingers. The action of the contactors is automatic, the master controller having only four points forward and two reverse. These points are known as switching, series, parallel lap, and parallel. The switching and lap positions include resistances in circuit. Each car is provided with an automatic line circuit breaker, which is also used to make and break current to the motors, being the last switch to close the motor circuit and the first to open. When tripped by overload, this switch is reset by an electro-magnet controlled from the motorman's cab.

The reverser is of the drum type, also electrically operated and is controlled by two electro-magnets, one for each position. This switch is connected to reverse the fields of the motors. Train acceleration is entirely automatic, being controlled by current-limiting relays which insure the completion of each step before the next step is taken.

The air compressor is of the standard General Electric center-gear type operated

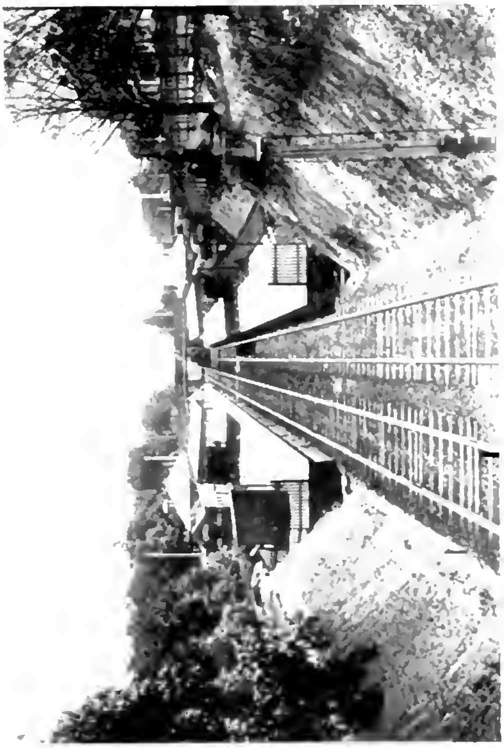

Fig. 6. Typical Suburban Station

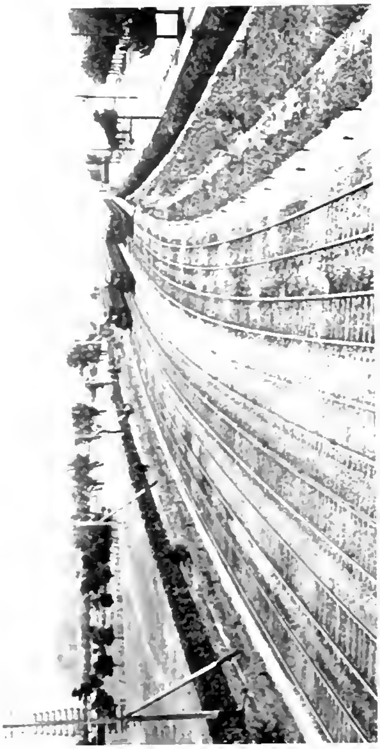

Fig. 7. Main Lines of the Victorian Railways Before Electrification

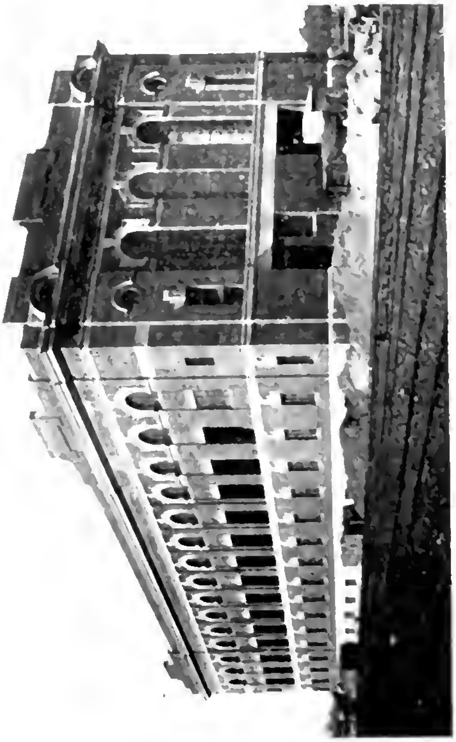

Fig. 8. Exterior of Jolimont Substation

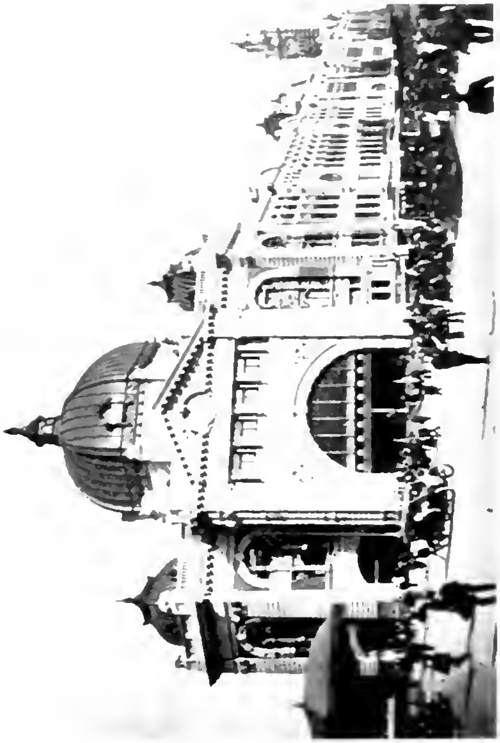

Fig. 9. Entrance to Central Railway Station, Flinders Street, Melbourne

directly from the 1500-volt trolley. It has a capacity of 25 cu. ft. of free air per minute, and is controlled automatically by an air compressor governor operated by an air cylinder. The normal pressure on the reservoirs is 100 lb. per sq. in. The air brakes are of the compressed air type commonly used in the United States for multiple-unit train service. Two pipe lines are installed, one connecting the reservoirs and the other known as the train pipe line. The air compressor governors are arranged to operate simultaneously so that the work is uniformly divided between the several compressors.

Power Station

The central power station for the system is located at Newport on the River Yarra. This location is also adjacent to an arm of Port Phillip Bay, from which a plentiful supply of cold water can be obtained for condensing purposes.

The electric power is obtained from steam-turbine generator sets which deliver three-phase 25-cycle alternating current at 3300 volts. Provision is made for six 10,000-kw. units operating at 210-lb. steam pressure with a normal vacuum of $28\frac{3}{4}$ inches.

The 3300-volt three-phase current is stepped up through a bank of three single-phase transformers, for each generating unit, to 20,000 volts. The 20,000-volt feeders are 13 in number, all three-phase lead-covered armored cable. These feeders are laid underground in trenches in the congested parts of the district, while overhead transmission lines are used on some of the outlaying portions of the distribution network. Coal is brought in from Spotswood over a branch line from the main tracks. There are two boiler houses, each equipped with 12 boilers of the Babcock and Wilcox marine type. Coal bunkers are provided with a total capacity of 3000 tons. Coal from these bunkers is fed by gravity chutes direct to the chain grate stokers.

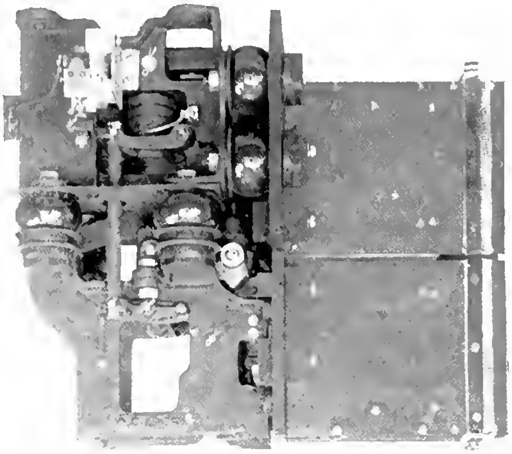

Fig. 10. 1500-volt Direct-current Line Breaker

TABLE IV

1500-VOLT DIRECT-CURRENT SUESTATION EQUIPMENT

Substation	No. Units Ultimate	Size Units Kilowatts	Total Kilowatts
Jolimont	6	3000	18000
Middle Brighton	4	1500	6000
Newmarket	3	3000	9000
Glenroy	2	750	1500
Newport	3	1500	4500
Albion	3	750	2250
North Fitzroy	3	3000	9000
Reservoir	2	750	1500
Macleod	2	750	1500
East Camberwell	3	3000	9000
Mitcham	2	750	1500
Caulfield	3	3000	9000
Springvale	2	750	1500
Mentone	3	1500	4500
Seaford	3	750	2250
Total	44		81,000

Substation Equipment

The present plan for electrification includes the construction of 15 substations for delivering 1500-volt direct current to the various sections of the line. These stations are located as shown in Table IV.

In addition there are one or two 600-volt substations connected to the transmission line for supplying local tramway systems. Owing to the delays caused by war conditions, only five of these stations have so far been placed in service. In the Jolimont station four 1500-kw. General Electric units are operating temporarily, pending the receipt of 3000-kw. units for this station. These machines are of the standard commutating-pole type, starting from high-voltage taps on the transformers, and wound for 1500 volts direct current per commutator. Two 1500-kw. units of English manufacture have also been installed in the Middle Brighton substation and two 3000-kw. units in the Newmarket station. There are also three 1500-kw. units installed in the Newport substation and similar equipment at North Fitzroy. The total substation equipment provided under the plans now drawn includes 44 units with a total capacity of 81,000 kw

Direct-current Distribution

The 1500-volt current is transmitted to the motor cars through overhead contact conductors of the catenary type. Over the main suburban tracks the normal construction consists of a 0.25 sq. in. hard-drawn grooved copper contact wire supported from a stranded hard-drawn copper cable of either 0.25 sq. in. or 0.375 sq. in. cross section. This gives an equivalent sectional area of 0.5 or more square inches, corresponding to from 650,000 to 800,000 circular mils section. There are no paralleling feeders other than the catenary supporting wire. Owing to the poor conducting quality of the flexible supporting droppers which employ a section of link chain to obtain flexibility, the catenary support is connected to the contact wire at intervals of about 600 ft. The contact wire is maintained in constant tension at 2500 lb. per sq. in. by cast-iron weights arranged at each end of sections about 3000 ft. in length. This scheme is intended to provide for changes due to temperature variations. The overhead construction is supported on steel bridges with anchor structures approximately 3000 ft. apart on which the tensioning device is located. The intermediate supports are located at intervals of 300 feet on tangent track with somewhat closer spacing on curves. Special construction is necessary where the structures are required to carry signal equipment and also on the four and six-track sections.

The construction on sidings is similar to the main line, except that a contact conductor of 0.125 sq. in. is used, and a stranded steel messenger.

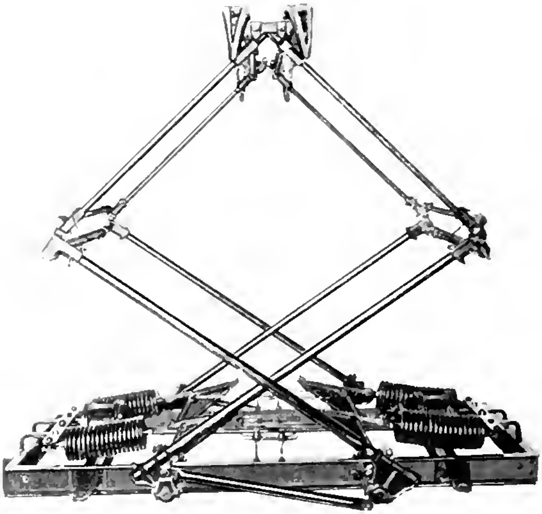

Fig. 11. Slider Pantograph Collector

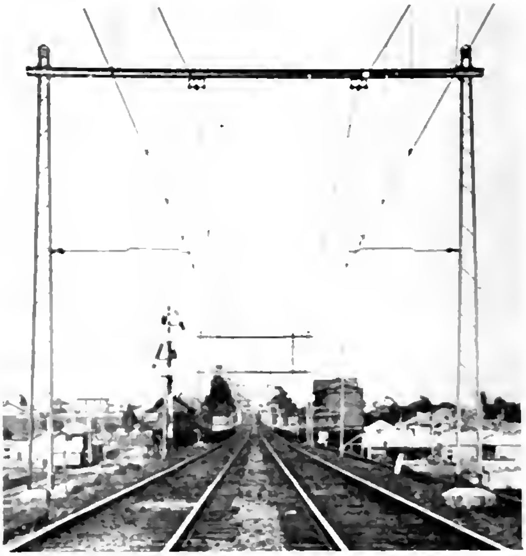

Fig. 12 Double Track Section in Electric Zone

All of the electrical equipment for the rolling stock including motors, control and compressors and auxiliary switching is of General Electric design. The General Electric Company has also furnished some of the substation equipment The remainder of the installation has been supplied from firms in Great Britain and from local Australian manufacturers. The engineering and design for the complete system has been carried out under the direction of Merz and McLellan, Consulting Engineers of New Castle, England, under the direction of E. P. Grove.

A New Short-circuit Calculating Table

By W. W. Lewis

Power and Mining Engineering Department, General Electric Company

A description of an entirely new development for calculating short-circuit currents in large power networks was published in the General Electric Review for October, 1916. This calculating table was later improved and enlarged, and a description of the table and methods of employing it for the calculation of short-circuit problems was published in the General Electric Review for February, 1919. The value of this calculator was at once recognized by large power companies and a number of them have been built and sold to companies operating large transmission systems, although the device was not originally developed as a commercial article. Further improvement in this calculating table is described and illustrated in this article.—Editor.

The short-circuit calculating table and its use have been described in previous issues of this magazine.* Since the original table was built in 1916, many improvements have been made to increase its accuracy and simplify its operation.

A new table has recently been installed in the Power and Mining Engineering Department of the General Electric Company which, for the present at least, is the last word in this sort of device. It is well illustrated in Figs. 1 and 2, which show respectively front and rear views. The rheostats consist of tubular resistance elements with taps brought out and connected to buttons on the back of the board. On the front of the board is an etched dial plate calibrated in per cent reactance. Each rheostat has two handles, the right-hand one giving a ten per cent setting and the left-hand one a one per cent setting, so that it is possible by this means to set accurately on the nearest per cent reactance. A total of 104 rheostats are provided, 20 of these being connected as generators and 84 as lines. Six of the line rheostats may be converted into generator rheostats by small switches on the horizontal part of the table. The network to be studied is set up in miniature with the assistance of telephone cords, plugs and jacks.

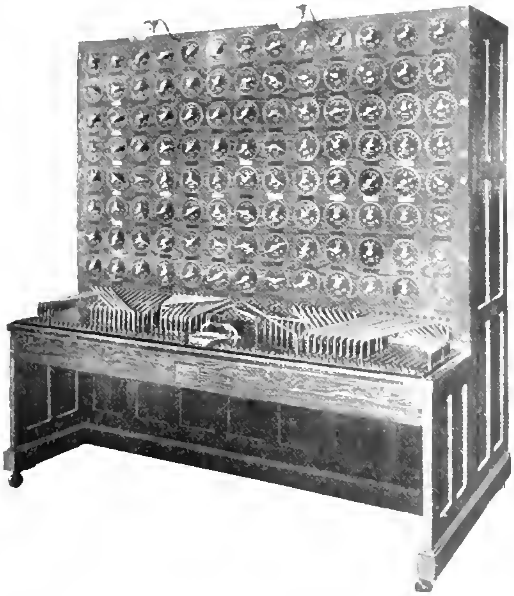

Fig. 1. Short-circuit Calculating Table with Set-up of System Shown in Diagram, Fig. 3

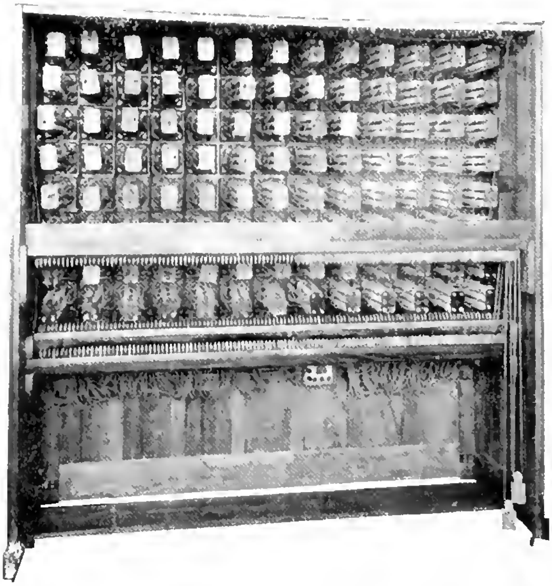

Fig. 2. Back View of Short-circuit Calculating Table Shown in Fig. 1

When the telephone cords are not in use they are held out of the way by weights, only the plugs protruding from the front of the board. Each rheostat is wired to an ammeter bus and by pressing a button the current passing through any rheostat may be read. Thus the total short-circuit current, the current given by each generator, and the

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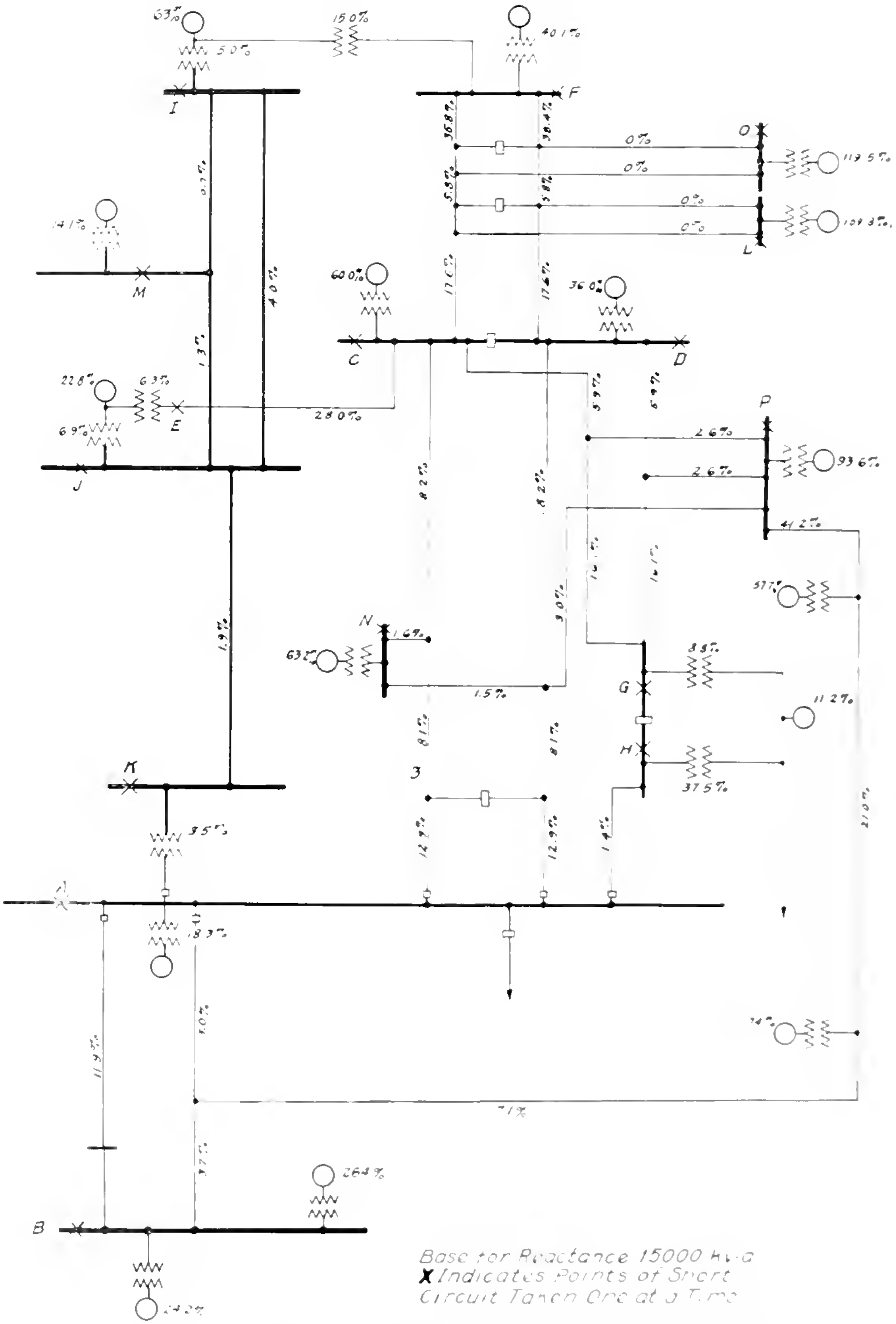
*General Electric Review, Oct., 1916, p. 901; Feb., 1919, p. 141.



Base for Reactance 15000 kv-a
X Indicates Points of Short Circuit Taken One at a Time

Fig. Diagram of Transmission System as Set up on Calculating Table and Illustrated in Fig.

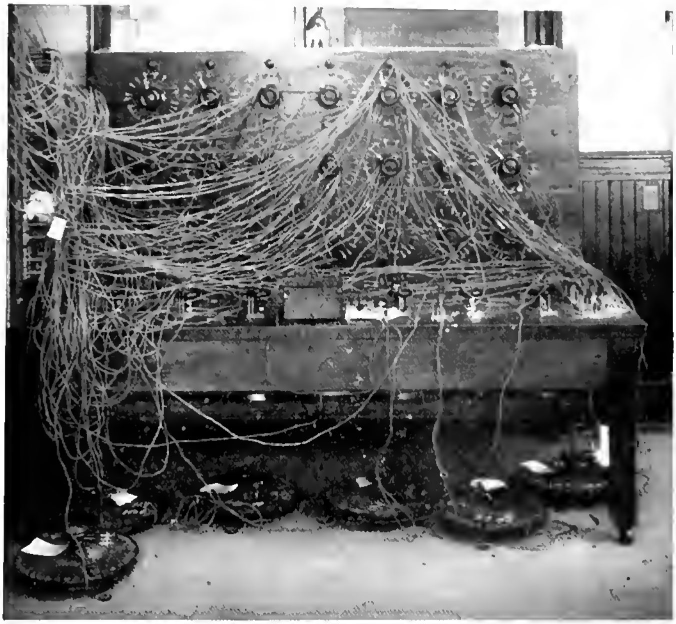


Fig. 4. Enlarged Calculating Table Made by Adding to the Original Table Built in 1916

current passing through each portion of the circuit, may be read in a very short time after the system is set up. A three-position switch gives three ranges on the ammeter and a switch is provided for reversing the polarity. A key is also provided for converting the ammeter into a voltmeter for reading the potential of the supply circuit.

The table is designed for operation on a 100- to 125-volt, two-wire, direct-current circuit. A small lamp over the ammeter serves to light the instrument and also acts as a voltage indicator. Switchboard lamps at the top of the table furnish general illumination.

Fig. 3 shows the diagram of the transmission system which is set up on the calculating table illustrated in Fig. 1.

Two sizes of tables have been designed, the one previously described with 104 rheostats and a smaller one with 50 rheostats. They can also be made with fixed instead of adjustable resistors. These are suitable for some systems whose lines are more or less stable. The following is a list of the companies and institutions now having calculating tables:

- Alabama Power Co.
- General Electric Co.
- Georgia Institute of Technology
- Hydro-Electric Power Commission of Ontario
- New England Power Co.
- Public Service Co. of New Jersey
- Turners Falls Pwr. & Elec. Co.
- Westinghouse Elec. & Mfg. Co.

The New Jersey, New England and Ontario Companies have tables with fixed resistors, the others with adjustable resistors. All the tables are modelled more or less on the original one described in the October, 1916, GENERAL ELECTRIC REVIEW.

As a matter of interest there are reproduced in Figs. 4 and 5, the original table of 1916 as enlarged and rebuilt in 1917, and an improved table built for a power company in 1918.

It may be readily appreciated that the labor of solving short-circuit problems is greatly reduced by the latest table, and that its conveniences have materially added to the speed and accuracy of the work connected with such problems.

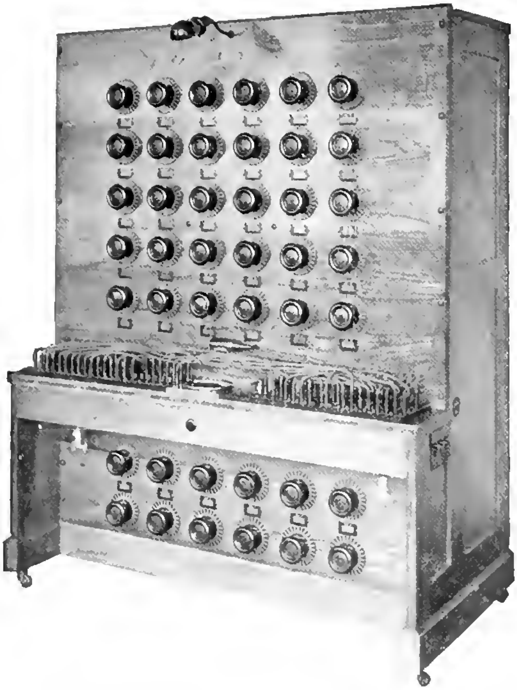


Fig. 5. Improved Calculating Table Built for a Power Company, 1918

The Production and Measurement of High Vacua

PART III

METHODS FOR THE PRODUCTION OF LOW PRESSURES (Cont'd)

By Dr. Saul Dushman

Research Laboratory, General Electric Company

The first installment of this series discussed the bearing which the fundamental principle of the kinetic theory of gases has upon the production and measurement of high vacua. The second installment discussed the fundamental theory of vacuum pumps and described the construction and operation of the mechanical types of pump. The present section of the article deals with Gaede's diffusion pump, Langmuir's condensation pump, and others of the mercury vapor type. An appendix furnishes remarks relative to the care and operation of exhaust equipment.—Editor.

MERCURY VAPOR PUMPS*

The fact that a reduction in pressure can be obtained by a blast of steam or air has been known and applied in the industry for a long time. In steam aspirators or ejectors such as are used for producing the low pressure required in the condenser of a steam turbine, "the high velocity of the jet of steam causes, according to hydrodynamical principles, a lowering of pressure, so that the air to be exhausted is sucked directly into the jet." An analysis of the action of the aspirator shows, according to Langmuir, that in its action two separate processes are involved.

"1. The process by which the air is drawn into the jet.

"2. The action of the jet in carrying the admixed air along into the condensing chamber.

"The aspirators cease operating at low pressures because of the failure of the first of these processes. If air at low pressure could be made to enter the jet, and if gas escaping from the jet could be prevented from passing back into the vessel to be exhausted, then it should be possible to construct a jet pump which would operate even at the lowest pressures."

This problem has been solved in two different ways by Gaede and Langmuir. In the pumps devised by each of these, a blast of mercury carries along the gas to be exhausted into the condenser (process 2). In order to introduce gas into the blast of mercury, Gaede has used diffusion through a narrow opening. On the other hand, Langmuir has made use of the fact that the mercury atoms on colliding with the gas molecules must impart to the latter a portion of the momentum which they possess in virtue of their high average kinetic energy, while the mercury atoms themselves are removed rapidly from the stream of mixed gases by condensation on the cooled walls.

Gaede's Diffusion Pump

The action of Gaede's "diffusion" pump can best be illustrated by referring to Fig. 19. A blast of steam is blown through the tube AB, in which is fixed a porous diaphragm C. The vessel to be exhausted is attached at E.

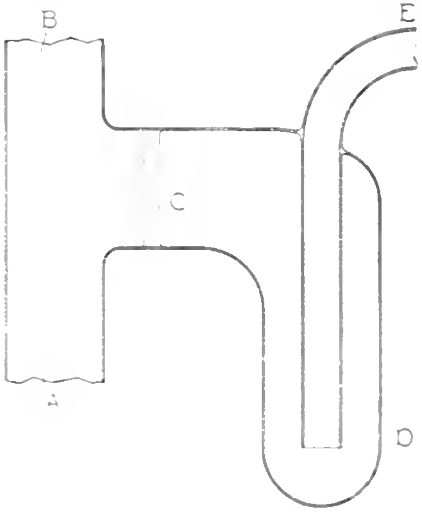


Fig. 19. Diagram Illustrating Principle of Diffusion Pump

Water vapor diffuses through the capillaries in the diaphragm into the trap D where it is condensed by some refrigerating agent, while air diffuses through the diaphragm in the opposite direction into the tube A B from where it is drawn away

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* The [illegible] remarks [illegible] based [illegible] I. Langmuir [illegible] Phys. [illegible] Form [illegible] High Vacua [illegible] GENERAL ELECTRIC REVIEW, 1916, p. 1060 [illegible] Franklin Inst. [illegible] 1916; Phys. Rev. 8, 48 (1916) [illegible]

rapidly by the blast of steam. The result is that the pressure in E decreases and finally reaches a very low value.

A study of the phenomena of diffusion of gas through mercury vapor in narrow tubes led Gaede to the conclusion that at sufficiently low pressures, where the mean free path L of the air molecules in mercury vapor is comparable with the diameter d of the tube, the volume of air, V, diffusing through a tube of length l, per unit time, is given by relation of the form:

$$V = k\pi d^3/l$$

where k is a constant for any given gas. In other words, the speed of exhaust is independent of the actual pressure of the gas in the vessel to be exhausted, and the relative decrease in the pressure per unit time therefore remains constant as the pressure in the system is decreased.

The actual construction of the diffusion pump is shown in Fig. 20. The porous diaphragm is replaced by a steel cylinder C with a narrow slit S whose width can be altered by means of the set screws H. The cylinder is set in the mercury trough G, which forms a seal between the low and high pressure parts. The mercury at A is heated and the stream of vapor passes over the slit in the steel cylinder in the directions indicated by the arrows. The air or other gas from the system to be exhausted (connected at F) diffuses into this mercury stream at S, and then passes out through E into the forepump which is connected at V. Any mercury vapor passing out through S is condensed on the glass in the immediate neighborhood, by means of the water cooling jacket K_1 K_2. The opening V connects with the fore-pump or other source of rough vacuum and is used for exhausting the system until the pressure gets low enough for the operation of the diffusion pump to become effective. As soon as this stage is reached the mercury in the trap automatically closes this opening and the exhaust there continues by means of the diffusion pump.

According to Gaede's theory the maximum speed of the pump is attained when the width of the slit S is of the same order of magnitude as the mean free path of the gas molecules in the slit and when the vapor pressure of the mercury is only slightly in excess of the pressure in the fore-vacuum (at V). Consequently the temperature of the mercury vapor has to be maintained at a fairly constant value. For this purpose a thermometer, T, is placed inside the tube B.

The effect of varying the temperature of the vapor (and consequently its pressure) on the speed of exhaust is shown by the data (given by Gaede) in Table IX and the plot of these in Fig. 21. These results were obtained with a slit width of 0.012 cm. The maximum speed of 80 cm.^{3} per sec. was attained at a temperature of the mercury vapor of 99° C. At this temperature the pressure of the mercury vapor is 0.27 mm., while the mean free path for air in mercury at this pressure according to Gaede's calculation is about 0.023 cm.

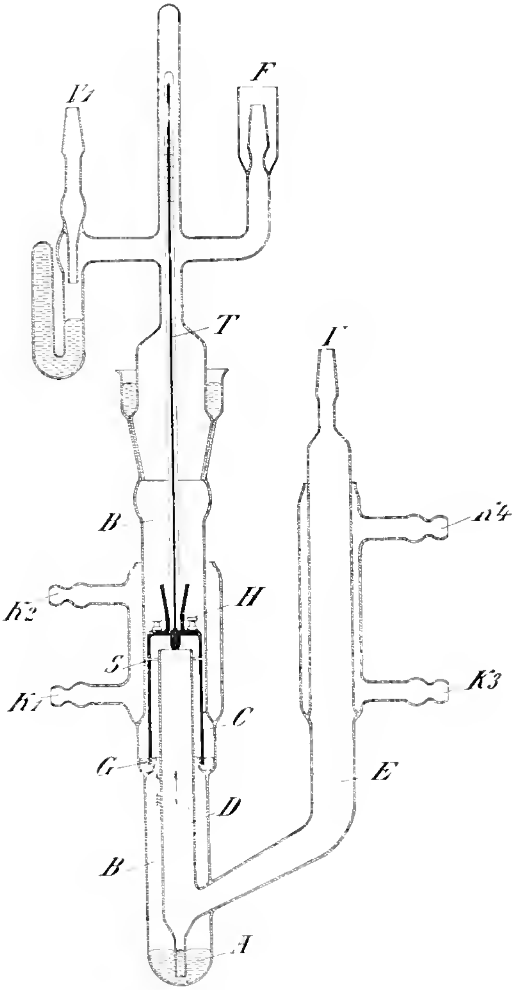

Fig. 20. Gaede Diffusion Pump

Table X (t = 106°) and Table XI (t = 110°) show the effect of varying the width of the slit. The noteworthy fact is that the speed of the pump remains constant as the pressure in the exhausted system is decreased, a result which Gaede previously deduced from theoretical consideration, as mentioned above.

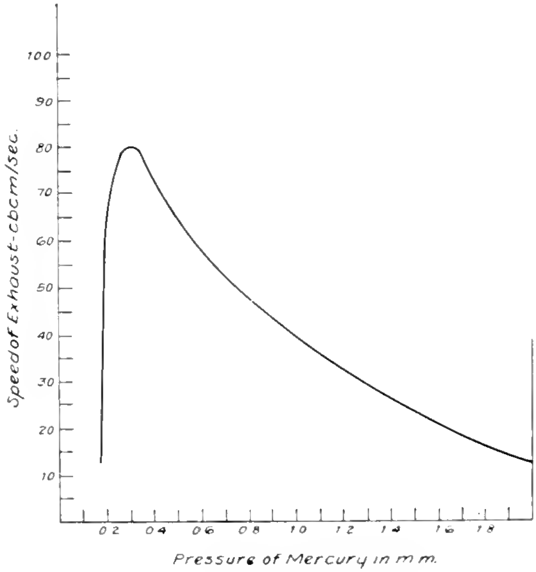

Fig. 21. Effect of Mercury Vapor Pressure on Speed of Diffusion Pump

TABLE IX

T	P (mm.)	S	T	P	S
90° C.	0.165	13.4	118.5	0.72	51
94	0.20	60	127.5	1.10	38
97	0.24	70	134	1.51	23
99	0.27	80	139	1.84	15
113	0.55	62	143.5	2.2	11

The great advantage of the diffusion pump over all the previous types of pump consists therefore in the fact that there is theoretically no limit to the degree of vacuum which can be attained by its operation. In the case of the Gaede rotary pump and all mechanical pumps the speed of exhaust decreases with decrease in pressure. In the case of the Gaede molecular pump the minimum pressure attainable depends upon the pressure in the fore-vacuum as the ratio of the pressures is constant for the pump. There is thus with all these pumps a fixed lower limit to the lowest pressure attainable in the exhaust system. While there is no such limitation with the diffusion pump, it does have the double disadvantage of low exhaust speed and the necessity of carefully regulating the temperature of the mercury vapor.

TABLE X

WIDTH OF SLIT =0.025 CM.	
p	*S*
0.025 mm.	77
0.003	72
0.0025	67
0.0008	72
0.0002	73
0.00006	70

TABLE XI

WIDTH OF SLIT =0.004 CM.	
p	*S*
0.07 mm.	52
0.028	48
0.006	40
0.0015	38
0.0004	41
0.00007	40

Langmuir's Condensation Pump

Both these disadvantages are removed in the type of mercury vapor pump designed by Langmuir, while the advantages of the diffusion pump are retained. In constructing and operating a pump of this type it occurred to Langmuir that "the limitation of speed could be removed if some other way could be found to bring the gas to be exhausted into the stream of mercury vapor."[22] As stated in the introductory section, Langmuir comes to the conclusion that the ejector pump must become inoperative at low pressure, since at these pressures, "according to the kinetic theory of gases, the molecules in a jet of gas, passing out into a high vacuum must spread laterally, so that there would be no tendency for a gas at low pressures to be *drawn* into such a blast."

Furthermore, under these conditions, the mercury atoms condense on the walls of the inner tube near the inlet and owing to the latent heat of evaporation raise the temperature of the walls so that condensation ceases, and the mercury atoms are merely reflected from the walls in *all* directions. Consequently there is just as much tendency for the mercury to diffuse back towards the exhaust system as away from it, and the air molecules are thus prevented from entering into the mercury blast at the nozzle.

These considerations and the results of his previous investigations on the mechanism of condensation of gas molecules on solid surfaces led Langmuir to the conclusion that the mercury atoms could readily be prevented from diffusing back in the direction from which the gas molecules are diffusing by simply cooling the walls of the tube near the mercury vapor outlet. Under these conditions the mercury atoms ought to be rapidly condensed as they strike the walls. At the same time the gas molecules diffusing in from the system to be exhausted would collide with the high

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[22] I. Langmuir, loc. cit.

speed mercury atoms at the jet and thus acquire a velocity component from the latter which would remove them rapidly from the spare around the jet opening. The whole action of the pump constructed on the basis of this reasoning thus rests on the fundamental principle that the mercury vapor is rapidly condensed as it leaves the jet and the temperature is maintained so low that the mercury does not re-evaporate to any measureable extent. Langmuir has therefore suggested that pumps based on this principle should be designated as "*Condensation*" Pumps.

The best type of glass condensation pump as constructed by Langmuir is shown in Fig. 22.

"In order that the pump may function properly it is essential that the end of the nozzle L shall be located below the level at which the water stands in the condenser J. In other words, the overflow tube K must be placed at a somewhat higher level than the lower end of the nozzle as is indicated in the figure. The other dimensions of the pump are of relative unimportance. The distance between L and D must be sufficiently great so that no perceptible quantity of gas can diffuse back against the blast of mercury vapor, and so that a large enough condensing area is furnished.

"The pump may be made in any suitable size. Some have been constructed in which the tube B and the nozzle L were one and a quarter inches in diameter while in the other pumps this tube was only one quarter of an inch in diameter and the length of the whole pump was only about four inches. The larger the pump the greater is the speed of exhaustion that may be obtained.

"In the operation of the pump the mercury boiler A is heated by either gas or electric heating so that the mercury evaporates at a moderate rate. A thermometer placed in contact with the tube B, under the heat insulation, usually reads between 100 and 120 degrees C. when the pump is operating satisfactorily. Under these conditions the mercury in the boiler A evaporates quietly from its surface. No bubbles are formed so there is never any tendency to bumping.

"Unlike Gaede's diffusion pump, there is nothing critical about the adjustment of the temperature. With an electrically heated pump in which the nozzle L was $\frac{7}{8}$ in. in diameter, the pump began to operate satisfactorily when the heating unit delivered 220 watts. The speed of exhaustion remains practically unchanged when the heating current is increased even to a point where about 550 watts is applied.

"The back pressure against which the pump will operate depends, however, upon the amount and velocity of the mercury vapor escaping from the nozzle. Thus in the case above cited, with 220 watts, the pump would not operate with a back pressure exceeding about 50 bars, whereas with 550 watts back pressures as high as 800 bars did not affect the operation of the pump."

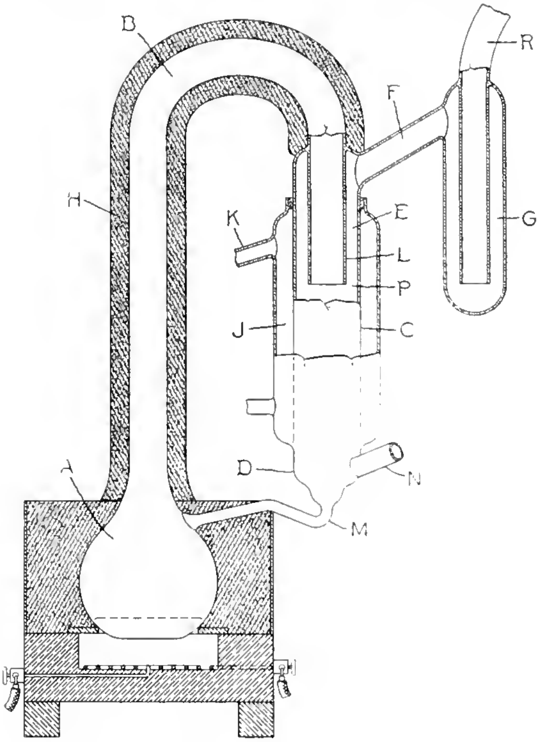

Fig. 22. Langmuir Condensation Pump, Glass Form

Condensation Pumps Built of Metal

For most practical purposes a glass pump has many disadvantages. Langmuir has therefore applied the same principles to the construction of a metal pump.

One such type of pump which has proved relatively simple in construction and efficient in operation is shown diagrammatically in Fig. 23. "A metal cylinder A is provided with two openings, B and C, of which B is connected to the backing pump and C is connected to the vessel to be exhausted. Inside of the cylinder is a funnel-shaped tube F which rests on the bottom of the cylinder A. Suspended from the top of the cylinder is a cup E inverted over the upper end of F. A water jacket, J, surrounds the walls of the cylinder A from the level of B to a point somewhat above the lower edge of the cup E.

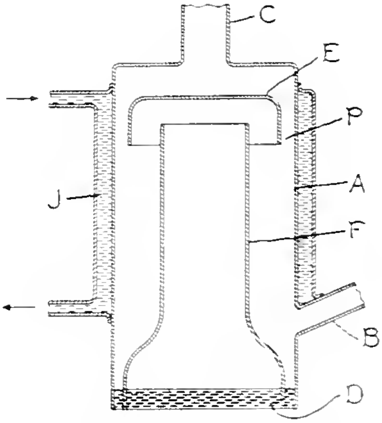

Fig. 23. Diagram of Construction of Condensation Pump Metal Form

"Mercury is placed in the cylinder as indicated at D. By applying heat to the bottom of the cylinder the mercury is caused to evaporate. The vapor passes up through F and is deflected by E and is thus directed downward and outward against the water-cooled walls of A. The gas entering at C passes down between A and E and at P meets the mercury vapor blast and is thus forced down along the walls of A and out of the tube B. The mercury which condenses on the walls of A falls down along the lower part of the funnel F and returns again to D through small openings provided where the funnel rests upon the bottom of the cylinder. A more detailed drawing of the pump as actually constructed is shown in Fig. 24."

A pump in which the funnel F is 3 cm. in diameter and the cylinder A is 7 cm. in diameter gives a speed of exhaustion for air of about 3000 4000 cm.^{3} per second. It operates best against an exhaust pressure of 10 bars or less and requires about 300 watts energy consumption in the heater circuit.

Degree of Vacuum Obtainable

"The condensation pump resembles Gaede's diffusion pump in that there is no definite lower limit (other than zero) below which the pressure cannot be reduced. This is readily seen from its method of operation. A lower limit could only be caused by diffusion of gas from the exhaust side (X in Fig. 3) back against the blast of mercury vapor passing down from L. The mean free path of the atoms in this blast is of the order of magnitude of a millimeter or less and the blast is moving downward with a velocity at least as great as the average molecular velocity (100 meters per second for mercury).[23]

"The chance of a molecule of gas moving a distance about 4.6 times the mean free path without collision is only one in a hundred. To move twice this distance the chance is only 1 in 100^2, etc. If the mean free path were one millimeter the chance of a molecule moving a distance of 4.6 cm. against the blast without collision would be 1 in 10^{20}. In other words, an entirely negligible chance."

Actual observations with the ionisation gauge (described in a subsequent section) in this laboratory, have shown that it is possible with the Langmuir condensation pump to obtain pressures which are of the order of 10^{-4} bar or less. The limiting factor which ordinarily makes it possible to obtain pressures as low as this, is the continuous liberation of gas from the glass walls or metal parts, so that it becomes extremely difficult to obtain

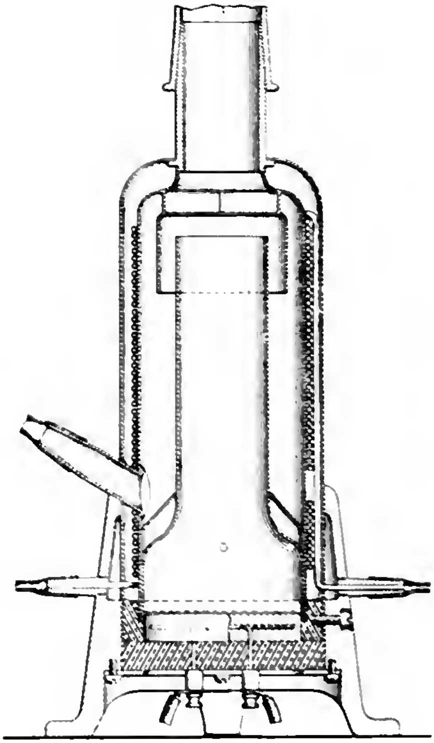

Fig. 24. Langmuir Condensation Pump, Metal Form

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[23] This argument when we consider that no appreciable number of atoms pass up into the space E.

vacua in excess of the above order of magnitude. The necessary precautions in using the pump are discussed at greater length in Appendix I.

Other Forms of Mercury Vapor Pumps

Other forms of mercury vapor pumps have been described by H. B. Williams[24], Chas. T. Knipp[25], and L. T. Jones and N. O. Russell.[26] The construction used by the latter is shown in Fig. 25. The advantage of this form is that it "permits using the pump as a mercury still at the same time that it is being used for exhaustion purposes. Two barometer columns introduce the mercury into the arc, the arc being started by blowing in one neck of the Woulff bottle. As shown at B the mercury vapor is driven through the nozzle N, and condenses in the chamber surrounded by the water-jacket, J. The condensed clean mercury is then drawn off at O." With a current of 10–15 amps., a speed of exhaust of 400 cm.^{3} per sec. was obtained.

A simple construction for a condensation pump has also been described by W. C. Baker.[27] In this form as well as Knipp's the main object of the design is to simplify the glass blowing.

J. E. Shrader and R. G. Sherwood[28] have used a modified form of Langmuir condensation pump made of pyrex. Full details with all necessary dimensions are given in the original paper. The speed of the pump was measured for different amounts of energy input into the mercury heater and was found to be a maximum at about 400–500 watts input. With the speed of exhaustion purposely cut down by a special constriction, the maximum speed observed was around 225 cm.^{3} per sec. and pressures as low as 2×10^{-8} mm. *Hg* were obtained after care had been taken to heat up all the glass parts to a temperature of 500° C. for a long time.

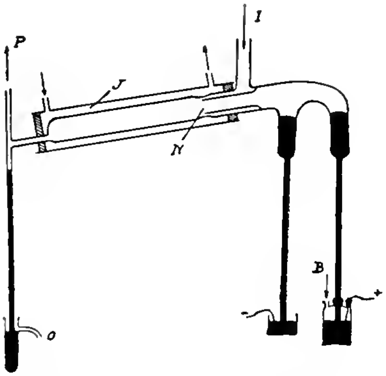

Fig. 25. Condensation Pump, Arc Type

An interesting form of mercury vapor pump is that devised by W. W. Crawford[29] and shown in Figs. 26 and 27. "The mercury vapor generated in the boiler B at a pressure of 10 mm. of mercury or more, escapes through the narrow throat T (Fig. 26), ahead of the point of entrainment. The vapor expands in the diverging nozzle N, and the issuing jet passes through the tube E, which it fills, and condenses in D, mostly, where it is found at the upper end. A slight amount of vapor escapes into the chamber A and condenses there. The condensed vapor drains back through the tubes *a* and *b*, to the boiler." The vessel to be exhausted is connected at *c*, while D connects with the rough pump. The speed of the pump in series with 10 cm. of tubing, 19 cm. in diameter was observed to be around 1300 cm.^{3} per sec. at a boiler pressure of 10 mm. of *Hq*.

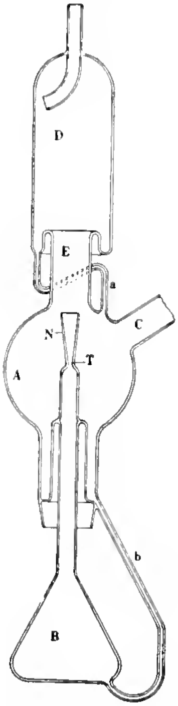

Fig. 26. Crawford's Form of Condensation Pump, Vertical Type

A two-stage mercury vapor pump to work against a primary vacuum of 2 cm. given by a water aspirator, has been described by C. A. Kraus.[30] It consists essentially of two Langmuir condensation pumps in series. The pump is very rapid and is capable of exhausting 1500 cm.^{3} to less than 10^{-4} mm. in 10 min.

H. F. Stimson has also constructed a two-stage pump along the same principles[31], which is illustrated in Fig. 28. "The operation of the pump is as follows: Cooling water entering at tube A flows up through the water jacket B above the lower end of nozzle F, up through the water jacket C above nozzle G, and out tube D. Mercury vapor from the boiler enter-

[24] Phys. Rev. *7*, 583 (1916).
[25] Phys. Rev. *9*, 311 (1917), and *12*, 492 (1918).
[26] Phys. Rev. *10*, 301 (1916).
[27] Phys. Rev. *10*, 642 (1916).
[28] Phys. Rev. *12*, 70 (1918).
[29] Phys. Rev. *10*, 557 (1917).
[30] J. Am. Chem. Sec. *39*, 2183 (1917).
[31] J. Washington Acad. Sciences *7*, 477 (1917).

ing through tubes E flows through the nozzles F and G, is liquified in the condensation chambers H and I, falls into the tubes K, and returns to the boiler through tube L. Gas from the vessel to be exhausted enters at M, flows past nozzle F, is compressed by the jet of mercury vapor in the condensation chamber H, and flows up through N to the intermediate pump. From here it flows past the nozzle G and is compressed through O into the chamber I to a pressure measured by the attached manometer, then out by tube P to the water aspirator."

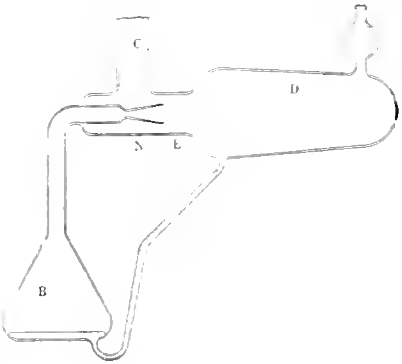

Fig. 27. Crawford's Form of Condensation Pump, Horizontal Type

The speed of the pump as defined by Gaede's equation was observed to be about 250 cm.^{3} per sec.[32]

General Remarks Regarding Exhaust Procedure

As has been pointed out in a previous section, the vacuum actually attained by the use of any pump is dependent, first, on the type of pump used, and second, on the rate at which gases are given off from the walls of the vessel to be exhausted and metal parts inside it. In the case of the Gaede molecular pump, as mentioned above, the degree of vacuum attainable (P_1) is dependent upon the exhaust pressure (P_2) produced by the rough pump. As the value of the ratio P_2/P_1 is about 50,000, it is evident that even with a rough pump pressure of one bar, the pressure attainable with this pump is less than 10^{-4} bar. In the case of the mercury vapor pumps there is theoretically no lower limit pressure, and the only limitation is therefore that due to the second cause mentioned above.

The gases occluded on the walls of the glass vessels consist for the most part of water vapor and carbon dioxide gas along with slight amounts of carbon monoxide and other gases which are not condensible at the temperature of liquid air. Metal parts usually contain carbon monoxide and hydrogen gases. In order to eliminate these gases it is essential to heat the glass walls and metal parts to as high a temperature as practicable. The longer the duration of the heating and the higher the temperature, the lower the pressure of residual gases.

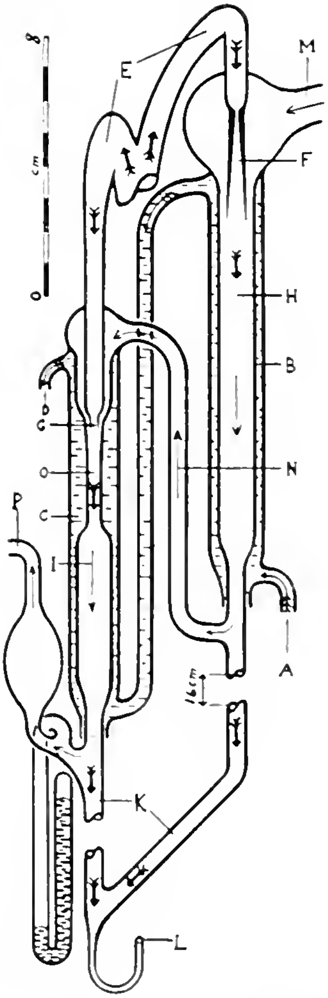

Fig. 28 Stimson's Form of Condensation Pump

A usual procedure is to heat the glass vessels in an oven, during exhaust, for an hour or longer. For lead glass, the temperature in the oven should not exceed 360° C.,

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[32] M. Volmer (Ber. 52, B, 804, 1919), has also constructed a similar form of two-stage condensation pump, which is described briefly in an abstract in J. Chem. Soc. 116, ii, 225 (1919). The original article containing an illustration of the construction is not available to the writer.

in the case of lime glass, the temperature may be raised to 400° C., and for vessels made of pyrex, the oven temperature may be increased to 500° C. The oven may be either heated by gas flames, or more conveniently by electrically heated grids, as the latter method permits of a more uniform distribution of temperature inside the oven and also is more convenient for regulation.

Where a very high degree of vacuum is desirable it is possible to heat the glass to temperatures higher than those mentioned above, by reducing the pressure of air in the oven itself, so that the glass walls will not collapse because of external pressure. For this purpose Dr. Langmuir devised the form of oven shown in Fig. 29.*

It consists of a metal chamber *7*, which is open at the bottom but rests upon a base plate *8*, with which it makes an air-tight joint. The chamber is provided with a heating coil wound on the inside and separated from the walls by heat-insulating lining. The leads for this heating coil are shown at *11*. Uprights *9* are provided for the purpose of allowing the oven to be raised or lowered. As the chamber *7* is to be exhausted it is necessary to make the joint between it and the base plate *8* air-tight. This may be accomplished by means of a rubber gasket, and in order to prevent injury to this by the heat, the chamber and the base plate are cooled by water, which flows as indicated by the arrows through the tubes 23, 24, 25 and 27. Openings are provided in the base plate for the connection between the vessel to be exhausted and the pump, and also for exhausting the chamber itself. A rough pump is, of course, all that is necessary in the latter case.

With this type of oven it is possible to heat the glass about 100° C. higher than in an ordinary oven, so that the residual water vapor and other condensible gases are removed more completely.

In the case of metal parts the elimination of gases is a more difficult matter. Where these parts are so constructed that current can be passed through them (wires or filaments) they ought to be heated to as high a temperature as the metal will stand without injury. In the case of hot cathode devices the anodes can be heated to incandescent temperatures by electronic bombardment.† Heating the metal parts in a vacuum furnace before putting them in the glass vessel also assists materially in the subsequent exhaust on the pump. Special care should be taken to remove all traces of grease and oil from machine-made parts, by washing in acetone and alcohol and drying thoroughly before assembling in the glass vessel.

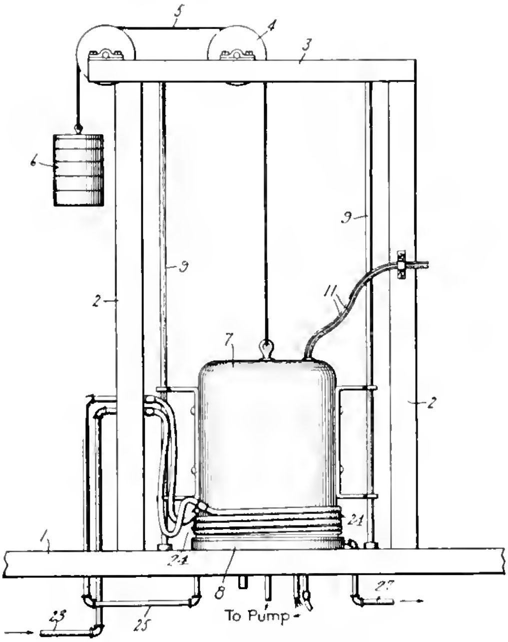

Fig. 29. Vacuum Furnace for High Temperature Exhaust

In order to eliminate mercury vapor and condensible gases emitted from the grease used on the ground glass joint between the pump and the vessel to be exhausted, it is necessary to interpose some form of refrigerating chamber in which these vapors are condensed, as shown at *G* in Fig. 22. (See also Appendix I.)

The most efficient refrigerating agent is, of course, liquid air, which is now available in a large number of laboratories. Failing this, a suspension of solid carbon dioxide in acetone or ether may be used. In the latter case it is well to insert a tube containing P_2O_5 between the oil pump and the fine pump to take care of water-vapor. Observations in this laboratory have shown that in using a condensation pump it is possible to obtain practically as low pressures with solid CO_2 and P_2O_5 as with liquid air, but the interval of time required to attain this low pressure is ordinarily much longer with the former.

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* I. Langmuir, U. S. Pat., 994,010, May 30, 1911.

† For illustrations of this the reader may refer to the following publications:

I. Langmuir, Phys. Rev. *2*, 450, 1913.
S. Dushman, Phys. Rev. *4*, 121, 1914.

The temperature produced by liquid air evaporating freely into the atmosphere is about −190° C. (93° K.), but varies from a lower value for fresh liquid air to a higher value as the nitrogen boils away and leaves the oxygen behind. With solid carbon dioxide a temperature of −78° C. is obtained. Table XII shows the vapor pressures of a number of different gases at these low temperatures. In the case of methane, ethane, ethylene and carbon dioxide the pressures given have been extrapolated from the values in the standard tables for higher temperatures, by plotting the value of *log P* against 1/T, where T is the absolute temperature. The values plotted in this manner are found to lie on a straight line, thus making the extrapolation an easy matter.

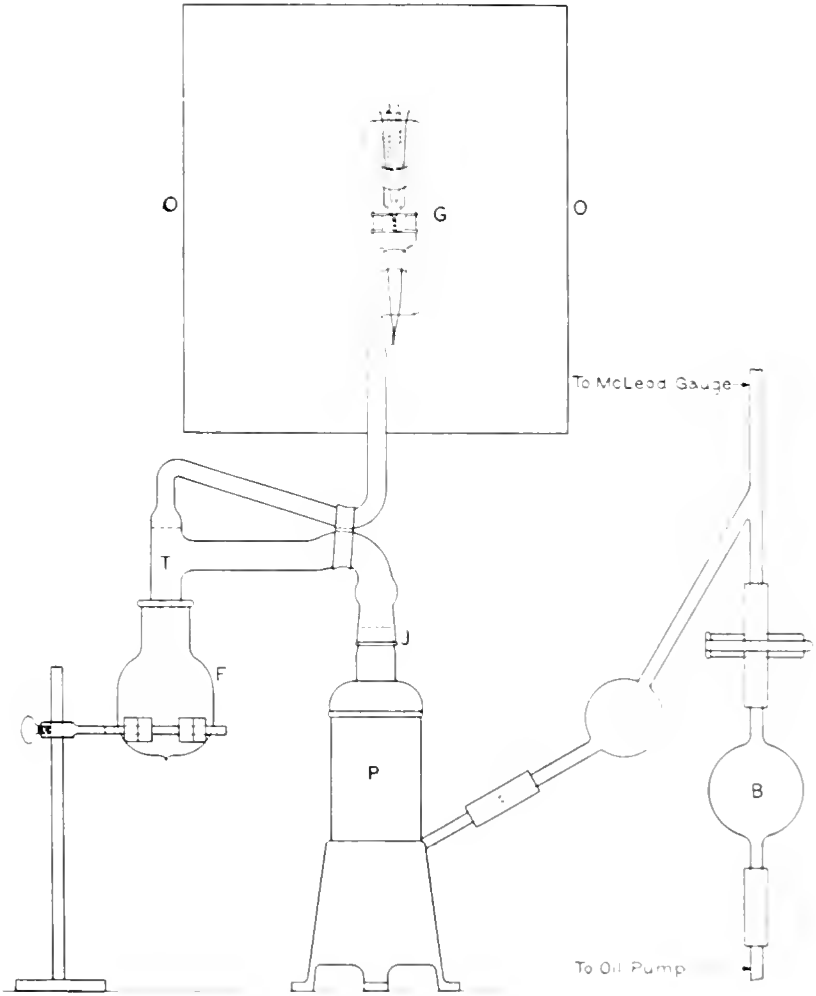

Fig. 30. Arrangement of Exhaust System

Table XIII gives the vapor pressures of carbon dioxide, ice and mercury. In all cases the data for the lower temperatures have been extrapolated in the same manner as those given in the previous table.

As is evident from these data, ice and mercury have no appreciable vapor pressure at −190° C., while carbon dioxide has a vapor pressure between 0.001 and 0.0001 bar at this temperature. Under these conditions any of the latter gas if condensed in the liquid air trap would produce a constant pressure of residual gas of at least 10^{-4} bar. Under the same conditions ethylene and ethane would produce pressures that might exceed 10 bars. However, these gases are not met with in ordinary exhaust operations. The other gases are non-condensible at the temperature of liquid air, and are therefore removed by the pump.

It is also evident that at the temperature of evaporating solid CO_2 ($-78°$ C.) the vapor pressure of mercury is negligibly small, but that of ice is quite high, hence the necessity for using P_2O_5 in order to take care of this. It is also advisable in all cases of exhaust operations not to use the refrigerating agent during the initial stages of heating, so that the bulk of condensible gases will be removed by the pump. Otherwise the vapors may be condensed in the trap and maintain a constant pressure of residual gases in the system for a very long time.

TABLE XII

Temperature Degrees Centig.	Absolute Temperature	Pressure in mm. Hg.
	Oxygen (O_2)	
−182.9	90.2	760
−211.2	61.9	7.75
	Nitrogen (N_2)	
−195.8	77.3	760
−210.5	62.6	86
	Carbon Monoxide (CO)	
−190	83	863
−200	73	249
	Methane (CH_4)	
−185.8	87.3	79.8
−201.5	71.6	50.2
	Argon (A)	
−194.2	78.9	300
−186.2	86.9	760
	Ethylene (C_2H_4)	
−175.7	97	0.76
−188	85	.076
−197	76	.0076
−205	68	.00076
	Ethane (C_2H_6)	
−150	123	7.6
−180	93	.076
−190	83	.0076
−198	75	.00076

Temperatures below $-190°$ C. may be obtained by working with liquid air under reduced pressure. As is evident from Table XII, it is possible in this manner to obtain a temperature as low as $-200°$ C. At this temperature the vapor pressure of solid CO_2 is less than 10^{-5} bar, and it is therefore possible under these conditions to obtain extremely low pressures of residual gases.

Either liquid air or solid CO_2 prevents the diffusion of vapors emitted by grease around the joint, as these vapors are all condensible at these temperatures.

Determinations in this laboratory of the vapor pressures of vacuum pump oils have shown that these range around one bar at room temperature, decrease to 0.1 bar at 0° C., and are negligibly small at $-78°$ C. Stopcock grease and similar compounds possess even lower vapor pressures.

Further details regarding the actual operation and care of typical exhaust systems are given in Appendix I.

TABLE XIII

Temperature Degrees Centig.	Absolute Temperature	Pressure in Bars
	Carbon Dioxide (CO_2)	
−148	125	100
−168	105	1
−182	91	0.01
−193	80	0.0001
	Ice (H O)	
−20	253	1045
−30	243	380
−40	233	127
−50	223	39
−60	213	9.6
−75	198	1.0
−89	184	0.1
−100	173	.01
−110	163	.001
	Mercury (Hg)	
+30	303	3.7
+20	293	1.6
+10	283	0.65
0	273	.25
−10	263	.087
−20	253	.029
−40	233	.0023
−78	195	4.3×10^{-5}
−180	93	2.3×10^{-24}

APPENDIX I

Fig. 30 shows diagrammatically an arrangement of the Langmuir condensation pump and accessory connections which is convenient for high vacuum exhaust operation, while Fig. 31 is a photograph of a set-up such as is used for exhausting Coolidge X-ray tubes of the standard types. The connections to the McLeod gauge and oil-pumps are to be made with as large tubing as practicable; ordinarily about half-inch tubing may be used. For the sake of the illustration an ionization type of gauge is shown connected to the condensation pump; and the oven is indicated diagrammatically. As previously mentioned, the tubing in this case ought to be as wide as possible.

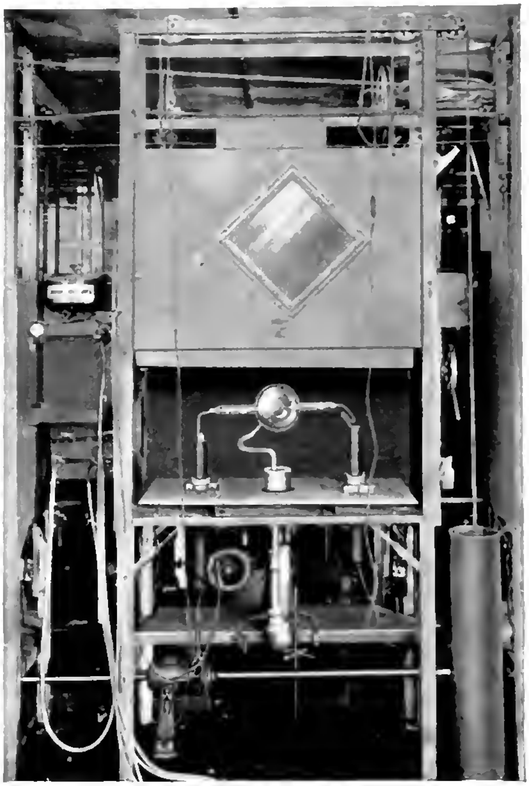

Fig. 31. Photograph of Set-up for Exhausting Coolidge X-ray Tubes

Care of the Condensation Pump: According to the instructions, 626 grams of absolutely clean mercury should be poured into the pump Under normal conditions, with 300 watts input into the heater and a flow of 1000 cm.^{3} per minute through the cooling coils, only the lower portion of the pumps should run warm. If for any reason the flow of water ceases and the grease around the joint is melted, the pump should be removed, the mercury emptied out, and the pump cleaned with gasolene as directed in the instructions. Very little mercury should condense in the glass grinding above the pump. If, however, the grinding rapidly becomes covered inside with mercury and feels warm, it is an indication that the pump is not exhausting and a cleaning is required.

Some observations carried out in this laboratory on the variation in exhaust pressure with energy input into the heater are of interest in this connection. The following table gives the watts used and the corresponding minimum pressure obtained as measured by an ionization type of gauge. The oil pump pressure was 0.0146 mm. of Hg.

Watts in Heater	Minimum Pressure in Bars
130	0.27
150	0.07
170	0.04
180	0.023
200	0.013
220	0.007
240	0.0025
280	0.002
300	0.002

Care of Rubber Tubing: All rubber tubing for use in vacuum systems should be cleaned well inside before use. This is best accomplished by washing with a warm 10 per cent solution of caustic soda, then with water and alcohol, and finally drying thoroughly by blowing air through it, or exhausting with a rough pump. The rubber tubing between the condensation pump and glass tube leading to the mercury trap should be as short as possible. Heavy vaseline or grinding grease[*] should be used to make the junctions air-tight, and after the tubing is in place a little castor oil should be dripped over the joints, and over the rubber tube itself.

Mercury Trap: This is essential in order to prevent mercury from getting into the oil pumps, where it would gradually disintegrate the bearings. A very good scheme which has been used successfully in this laboratory is to make this trap quite large (about 1 liter volume) and fill it with broken pieces of glass tubing, thus increasing the surface for the condensation of any mercury vapor that

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[*] A good stopcock grease may be made by heating approximately equal parts of pure rubber and vaseline. The rubber should be cut into very fine pieces and the heating continued until the mixture has about the consistency of heavy molasses.

diffuses out through the rough side opening of the condensation pump.

Detection of Leaks: A small Tesla coil, one end of which is grounded, is a useful accessory device in all exhaust operations. The high tension terminal of the coil is encased in rubber tubing and provided with a wooden handle so that it can be touched to any part of the glass system. A pin-hole leak will show up by the direct passage of a spark to this point, while at all points there will be a uniform glow if the pressure is over a few bars and there will be no glow at all when the pressure is one bar or less.

Seal Off Procedure: Constrictions in glass vessels at points where they are to be sealed off after exhaust should not be too thick walled, otherwise a large body of glass will have to be heated during the seal-off, causing the liberation of a great deal of gas. Furthermore, the constriction should be torched till it is almost melting and the pump allowed to exhaust the gas thus liberated for about two minutes, after which the sealing off should be performed as rapidly as possible without heating the glass any more than absolutely necessary.

The importance of these precautions may be judged from the following observations: An ionization gauge, having a volume of about 100 cm.^{3}, was exhausted till the residual gas pressure was less than 0.001 bar. On sealing this off without observing the precautions mentioned, the pressure in the sealed off tube was 0.25 bar, whereas by torching the constriction first and sealing off afterwards, it was possible to obtain a residual gas pressure in the sealed off gauge of less than 0.01 bar.

(*To be continued*)

Five Thousand Horse Power Electrically Operated Pumping Plant

By E. Bachman and W. J. Delehanty

San Francisco Office, General Electric Company

The centrifugal pumping plant described in this article is of particular interest in that it is probably the largest of its type in the world and is electrically operated. The authors explain the purpose of the installation, describe the construction of the building (which is especially heavy), the pumping and electrical equipment, the power supply and its protection and control, and the lighting system employed.—Editor.

During the development of the Sutter Basin Reclamation Project, a large pumping station was erected at Knight's Landing, California, to drain the vast area of land which is protected by levees. The district lies between the Sacramento and Feather Rivers, and is commonly known as "Sutter Basin." The area comprises approximately 68,000 acres.

The plant is probably the largest centrifugal pumping plant in the United States, if not in the world, has a total capacity of 676,000,000 gallons of water per day, and requires 5000 horse power for its operation. The plant operates approximately 30 to 60 days during the normal year, during which period it may be run partly or as a whole, depending upon the amount of water to be handled. The larger part of this will be rain water with a certain amount of seepage through the levees.

On account of some of the adjacent lands not being protected by levees, the Reclamation Board took every precaution to limit the liability of failure of the pumping equipment.

The plant is located at the extreme southern end of the district, on the Sacramento slough, about 1½ miles above its confluence with the Sacramento River, approximately 22 miles from Sacramento city, via the Sacramento River.

Fig. 1 shows the general layout of the plant as finally constructed. It will be noted that a timber piling bulkhead is built at the outer and inner toe of the levee at the nearest point to the river proper, thus forming a suction forebay. The pumping plant is located with its long side parallel to the canal at this point, the pumps taking their suction from the canal and discharging through the levee into the Sutter Basin by-pass.

The building is of extremely heavy construction, being designed so that the total weight of the building and machinery will overcome the tendency of the structure to float at high water. The building is 99 ft. 6 in. long and 25 ft. 6 in. wide, inside measurements, standing 36 ft. 6 in. from the main floor level to the roof. It is supported on reinforced piles spaced approximately on 5-ft. centers longitudinally and 4 ft. centers crosswise of the building. Built upon this is the floor which is 4 ft. thick over the entire area. The walls are 4 ft. 6 in. at the floor line, tapering to 30 in. at the high-water elevation, and from that point tapering off to 15 in. at the roof-line. In addition to the extremely heavy walls, there are six buttresses on the north and south walls and two on the east and west walls. The lower portion of the building is entirely without openings, the windows and doors being above the high-water level.

Running at the high-water level through the entire length of the building is a mezzanine platform, built of reinforced concrete, access to the main-floor level being obtained by steel stairs. At the east end of the building, at the same level, is a switch gallery, the switchboard being placed on the main floor immediately below. An operating platform runs along the south wall just underneath the mezzanine floor, constructed entirely of structural iron and checkered floor plating so that it may be easily removed to give access to machinery. The roof of the building is a flat reinforced concrete slab supported on 20-in. I-beams, the roof being finished with an impervious coat of asphalt and gravel. The building is well lighted, having three large steel frame windows approximately 12 by 14 ft. on both the north and south walls and two windows in the east and west walls, one of these windows being removable to admit the machinery into the building.

For the handling of machinery there is installed a 15-ton crane, having a motor-driven hoist, with the bridge and trolley hand operated. The motor is a 110-volt 3-phase 60-cycle variable-speed induction motor, capable of raising 15 tons at the rate of 20 ft. per minute.

A reinforced concrete platform is built alongside the east wall of the building to

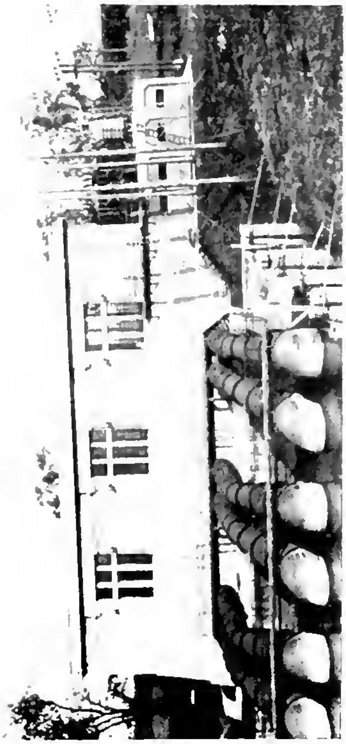

Fig. 1. Suction Forebay Side of the Electrically Operated Pumping Station, Knights Landing, Calif.

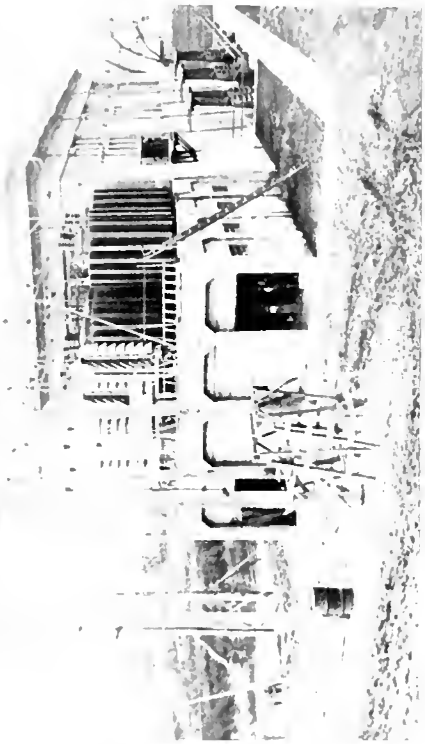

Fig. 2. End View of the Station Showing Outdoor Step-down Transformers and Lightning Arresters

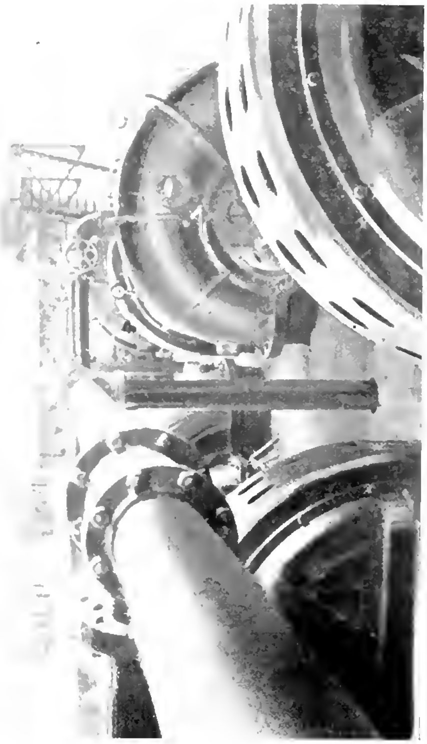

Fig. 3. A Partial View of the Main Motor-driven Pumps, Six in Number, Each Having a Capacity of 175 Second Feet of Water

Fig. 4. A Close-up View of the Oxide-film Lightning Arrester, Located on the Concrete Platform as Shown in Fig. 2

support step-down transformers as shown in Fig. 2. The floor of this structure is just above the high-water line and is supported by concrete columns, in turn resting on reinforced concrete piles.

The pumping plant consists of six 50-in. pumps, direct connected to induction motors, each pump having a capacity of 175 second feet of water when pumping against the maximum head of approximately 29 ft., the lower limit of head being approximately 10 ft. The static head varies from approximately 2 to 25 ft., with approximately 4-ft. discharge friction. The pumps are of the double-suction type, similar to the pumps installed in other large reclamation projects in this section. The large size of these pumps can be seen by reference to Fig. 3, which is an interior view of the pumping house.

The pumps are direct connected to General Electric squirrel-cage induction motors, operating at 248 r.p.m. through flexible leather link couplings. The motors are rated at 800 h.p., at 40 deg. temperature rise, with 25 per cent overload guaranteed for two hours. The pumps are so designed that the horse power over the entire range of pumping from the lowest to the highest head varies only from 800 h.p. under minimum head to 825 h.p. at the maximum operating head.

For priming purposes there is installed two 12 by 12-in. duplex motor-driven vacuum pumps, having suctions connected to the top portion of the casings of all the centrifugal pumps. When priming the pumps, the gate valve in the discharge line is closed and, after priming, the pump is started. After reaching full speed the gate valve is opened.

The suction pipes are approximately 60 ft. long, running directly out through the south wall of the building, a distance of 32 ft., and then dropping down with easy bends into the suction forebay, the diameter at the pumps being 50 in. and tapering to a diameter of 96 in. at the lower end. These suction pipes are of 3/8-in. plate steel construction, the lower end of the pipes resting on a grillage work of structural I-beams provided with proper grizzlies to prevent foreign matter entering the pumps.

In the discharge pipes just outside of the building are placed motor-operated gate valves. These valves are controlled by General Electric direct-current motors. They are capable of opening and closing safely in two minutes under the conditions of usual operation, and each motor with its valve is equipped with limit switches and an indicator showing the amount of gate opening. This indicator is visible from the switchboard, where the control of all valves is centralized.

The Power Company's 60,000-volt lines run to the step-down transformers immediately outside of the building. From the trans-

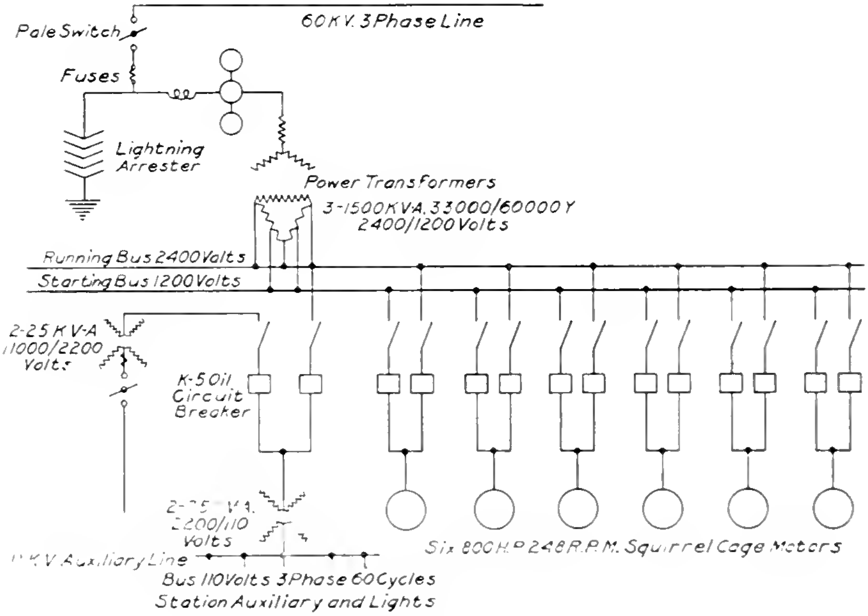

Fig. 5. One-line Diagram of the Power Connections in the Pumping Station

formers, five leads run through the building walls to busses forming one 2200-volt and one 1100-volt circuit, from thence through disconnecting switches to the starting and running switches and thence to the motors. The starting and running switches for the motors of the main circuit are 300-ampere, 2300-volt, triple-pole, single-throw, hand-operated, remote-control, oil-break switches, with overload and undervoltage protection. The switches are installed in groups of two, mechanically interlocked. The starting switches are connected to the 1100-volt bus and all switches are operated from the main switchboard on the lower floor of the pump house.

Incoming power is taken from the Pacific Gas & Electric Company's 60,000 Y-volt, 3-phase, 60-cycle line through a General Electric automatic, outdoor type, oil circuit breaker. This circuit is then run to three Y-delta connected, 1500-kv-a. 60,000-1100 2200-volt self-cooled, outdoor type transformers, and thence to the station switchboard.

An outdoor type oxide film lightning arrester, as shown in Fig. 4, has recently been installed to further insure the station against shut-down. This arrester has been in service a sufficient length of time to demonstrate the advisability of placing an arrester at this point.

For operation of small motors, lights, and other station auxiliaries there are installed two 25-kv-a., 2200 to 110-volt distribution transformers. From these transformers a 10-kv-a. motor-generator set is used to charge a 56-cell, 112-volt chloride accumulator type storage battery which is used to operate the valve motors, emergency lighting service, and supply tripping current for the outdoor oil circuit breaker. The storage battery is used to operate the valve motors in order to provide safety in case the main power supply should fail.

The switchboard consists of eight panels of blue Vermont marble mounted on pipe frame work. All vacuum gauges, pressure gauges, voltmeters, ammeters, power-factor indicators, etc., are finished alike, and are all mounted on the switchboard proper. With this arrangement it is only necessary for the operator to remain at the switchboard, making an occasional inspection of the bearings at the pumps while operating.

The lights on the mezzanine floor, on the valve-motor platform, and the switch gallery are equipped with Holophane steel reflectors and 150-watt Mazda lamps. The bracket fixtures along the north wall are equipped with 26-in. Mazda economy diffusers, suspended from ornamental iron brackets by links; each fixture is equipped with five 100-watt Mazda lamps. The main entrance fixtures near the door are equipped with 100-watt Mazda lamps. The lighting circuits are all controlled from the lighting panel, which is installed near the main switchboard. The direct-current circuits are equipped with a three-point switch at the main entrance with the corresponding switch on the lighting panel. This permits the lighting of the station from either end, thereby making it unnecessary for the operator to grope in the dark in case of power failure.

The building and concrete discharge pipes were constructed by the Sound Construction & Engineering Company, and the pumping plant contract was let to Charles C. Moore & Co., who sub-let the electrical machinery to the General Electric Company.

Power Control and Stability of Electric Generating Stations

PART I

By Charles P. Steinmetz

Chief Consulting Engineer, General Electric Company

About a decade ago our larger central stations had grown to such size as made necessary the adoption of reactors to limit the enormous amount of power which might accidentally be concentrated at a fault in the system's lines and thus prevent its destructiveness. This revision in the scheme of operation has given rise to a new set of conditions with respect to maintaining the stability of connected synchronous machinery. For the purpose of furnishing a complete mathematical analysis of the subject, Dr. Steinmetz presented at the last annual convention of the A.I.E.E. a paper of which the following is a reprint of the first half. The remainder will appear in our September issue.—Editor.

POWER LIMITATION

With the increasing use of electric power, the size of electric generating systems has steadily increased from the small electric lighting stations of the early days to the huge metropolitan systems having several hundred thousand kilowatts capacity in steam turbine alternators.

The problem of close inherent regulation of the generators has ceased, since no possible sudden change of load—less than short circuit—is sufficient appreciably to affect the voltage of these big systems. The reverse problem however has become serious, that of limiting the power which can accidentally be concentrated at any point of the system, and of limiting its destructiveness.

With the increasing size and extent of systems, they were divided into a number of generating stations, more economically to cover the territory, as under present conditions there seemed to be no material gain in going much over hundred thousand kilowatts in one station. Thus two or more main generating stations are generally used, together with a number of smaller secondary generating stations to stabilize the power at the end of long feeders, in outlying centers of distribution, etc.

Economy and reliability of operation demand parallel operation of the entire system, and synchronous operation of all the generating stations thus is the universal custom.

In the former 250-volt direct-current generating systems, from which most of the large metropolitan systems have developed, subdivision into a number of generating stations limited the power which could be developed at any point and thereby its destructiveness, by the resistance of the feeders and mains. In the present three-phase systems, interconnected by and distributing through underground cables at 6600 to 22,000 volts, the impedance of these cables is entirely insufficient to limit the power concentration possible at any point of the system, and special means of limiting the possible power concentration in these systems thus became necessary. This problem became aggravated by the inherent characteristics of the high-speed steam-turbine alternators which have completely superseded the former low-speed engine-driven machines.

In the belt-driven 60-cycle alternators of former days, the output was from 15 to 30 kw. per machine pole, in the 25-cycle low-speed engine-driven multipolar alternators such as were installed in the first Metropolitan Railway Station of New York City, etc., the output was about 100 to 125 kw. per machine pole, while in the modern high-speed steam turbine alternator values of 15,000 to 20,000 kw. per machine pole have become necessary. This means enormously larger magnetic fluxes and correspondingly larger armature reactions per pole. But with increasing output per pole, the effective or equivalent reactance of armature reaction (which is not instantanous, but requires several seconds to develop) increases at a faster rate than the true or self-inductive reactance of the armature (which latter is instantaneous, and thus is the only reactance which limits the momentary short-circuit current of the machine). Thus, while in the early high-frequency alternators the ratio of effective reactance of armature reaction to true self-inductive armature reactance was less than 0.5 to 1, it has risen in the large low-frequency turbo-alternators to values of 20 to 1, and more. That is, while in the early high-frequency turbo-alternators the momentary short-circuit current was very little larger than the permanent short-circuit current, in large low-frequency turbo-alternators the momentary short-circuit current may be 20 or more times the permanent short-circuit current. Thus in a high-power system of several hundred thousand kilowatts connected steam-turbine generator capacity, without power-limiting devices, the momentary short-circuit current may represent several million kilovolt-amperes, with corresponding electrical, thermal, and magnetic stresses. It is not the question of whether a circuit breaker can be designed to open such power safely, but it is the fact that such a circuit breaker would in size and cost be economically impracticable, when considering that the hundreds of feeder cables and interconnecting cables of such systems would require several hundreds of such circuit breakers

The practice of giving the circuit breakers a considerable time limit, so that they open only after the momentary short-circuit current has greatly decreased, greatly relieves the stress on them, but at the expense of the system which is exposed to the full momentary short-circuit stresses, usually resulting in a shut down. The use of group circuit breakers in series to the circuit breakers in the individual feeders (and usually of larger interrupting capacity than the latter) reduces the number of high-power circuit breakers required and increases the reliability, and thus is extensively used, but by itself does not solve the problem as the still large number of group circuit breakers places an economic limit on their interrupting capacity, and the required time limit of their operation leaves the system exposed to the full destructive effect of the momentary short circuit.

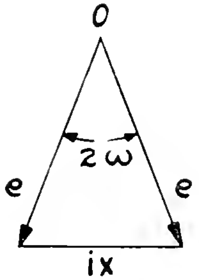

Fig. 1

Thus power-limiting devices, in some form or another, have become necessary and are universally used in all modern high-power systems.

Such devices comprise:

(1) *Power-limiting Generator Reactors.* Besides designing the generator for the highest possible internal self-inductive reactance, which can be given to it without serious sacrifice of its other characteristics, reactors are inserted into the leads between the generator and the busbars, so as to limit the power which the generator can feed into the busbars in case of short circuit at or near the busbars and to limit the power which the busbars can feed back into the generator in case of accident to the generator.

Such power-limiting generator reactors are used wherever the internal self-inductive reactance cannot be made sufficiently high (10 to 15 per cent). The latter is frequently the case with 60-cycle machines.

Internal reactance of the generator, wherever it can be secured without material sacrifice of other characteristics, has the advantage of saving the space and cost of the external reactance, but it is not quite as good in protective value since, in case of an accident in the generator, its internal reactance is more or less eliminated and thus does not protect against the busbars feeding back into the generator.

The amount of generator power-limiting reactance necessarily is limited to that value which does not materially increase the total (or synchronous) reactance of the generator. Thus, with many generators running in parallel on the system, even with the power limitation of the individual generators, the total power which may be developed in case of a short circuit on or near the busbars becomes excessive. The economic limit of generator power, which may be concentrated on one busbar, probably is between 50,000 and 100,000 kw. Beyond this value it becomes necessary to cut, or divide the busbars, and since parallel operation is necessary, this may be done by:

(2) *Power-limiting Busbar Reactors.* These are reactors that are inserted into the busbars to limit the power which can flow along the busbars from one side to the other side of the reactor, without interfering with the flow of such current along the busbars as may be required for synchronous operation, etc., under the variations of load.

For economical operation, the busbars are naturally arranged so as to require the minimum average flow of power along them. That is, the feeders which carry power from the busbars to the load intermingle with the leads which bring power from the generators to the busbars. The power flowing along the busbars thus is the difference between the incoming and the outflowing power. Theoretically, with a ring bus, cut into sections by power-limiting reactors, the maximum power which may have to flow over any busbar reactor is one quarter that of the smallest alternator connected to the section adjoining the reactor; and may rise to twice as much if the busbar sections are not connected into a closed ring but into an open chain.

The transfer of power from one busbar section to another over the dividing reactance does not mean a drop of voltage, but with the same voltage on two busbar sections, the transfer of power occurs by a phase displacement between the voltages of the two sections. That is, if the load on one busbar section increases beyond the output of the generators connected to it, or decreases below it, power begins to flow over the busbar reactors connecting it with the adjoining sections. The voltages of the adjoining sections however are kept constant by the control of the alternator field excitation at the same value *e*, and the reactance voltage *ix* of the current *i* passing over the busbar reactance *x* thus forms an equilateral triangle with the two voltages *e* of the adjoining busbar section (See Fig. 1). That is, *ix* is approximately in quadrature with the section voltages *e*; and as *ix*, as reactance voltage, is in quadrature with the current *i*, the current *i* is (approximately) in phase with the generator voltages *e*, that is, it is an energy current. The phase angle 2ω between the two voltages *e* of the two adjoining busbar sections then is given by,

$$\sin \omega = \frac{ix}{2e}$$

As the synchronizing power between the adjoining generator sections is a maximum for $2\omega = 90$ deg., and decreases beyond this, no danger of breaking out of synchronism exists, as long as 2ω is materially less than 90 deg. Thus with a phase angle between the generator section voltages *e*, of $2\omega = 30$ deg., that is, fairly small phase displacement,

$$\frac{ix}{2e} = \sin 15^\circ = 0.26,$$

or

$$\frac{ix}{e} = 0.52$$

As theoretically *i* may be limited to one quarter of the full-load current, i_0, of the smallest generator on the section,

$$\frac{i_0 x}{e} = 2.08$$

that is, the maximum theoretically permissible busbar reactance, at a maximum of 30 deg. phase displacement between the busbar sections, would be 200 per cent referred to the smallest generator on the section, as far as concerns energy transfer from section to section with negligible phase displacement, 15 deg.

As the power-limiting generator reactances are 10 to 15 per cent, or an average of 12.5 per cent, it is seen that much larger reactances may safely be used in power-limiting busbar reactors than are permissible in power-limiting generator reactors.

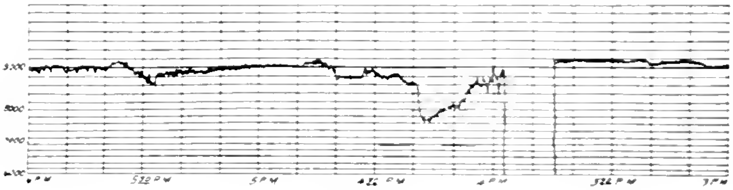

Fig. 2

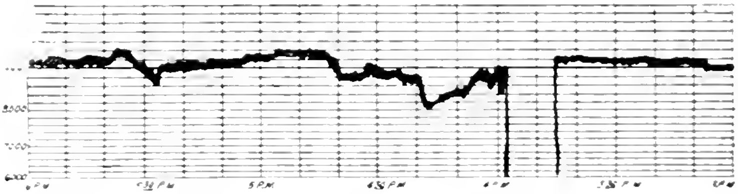

Fig. 3

It is advisable to use as large busbar reactances as possible, to limit to the maximum extent the shock of a short circuit at or near a busbar section, that is, to affect the remainder of the system as little as possible.

Where a number of stations are connected together, operating on the same system, that is, tied together by interconnecting cables into one bus, preferably a ring bus, it is advisable as far as possible to locate the power-limiting busbar reactors in the connections between the stations, that is, tie the stations together over power-limiting reactors. In this case it is advisable to install one half of each of the busbar reactors at each end of the interconnecting cable, since the probability of short circuits in the interconnecting cables is far greater than the probability of short circuits at the busbars, and the division of the reactor into one half at each end of the cable limits the effect of a short circuit in this cable on the generating stations connected together by it.

(3) *Feeder Reactors.* Even with generator power-limiting reactors and busbar dividing reactors, the effect of a short circuit at or near the busbars is very severe, at least on that section of the system operated from this busbar, and will probably shut down this section. However, short circuits on the busbars are very much less frequent than short circuits in cables. The installation of proper feeder power-limiting reactors, by preventing short circuits on feeders from directly affecting the busbars, even when these short circuits occur very near the busbars, thus eliminates most of the severe short circuit shocks from the generator sections, and is therefore economically very desirable. While the reactance of the feeder reactor may be only a small percentage of the feeder rating, it usually is very much larger than the combined reactance of the generators feeding into the sections, and a short circuit beyond even a small (in percentage) feeder reactor will thus result in a very much smaller short-circuit current than would occur without the feeder reactor, and thereby the shock will be greatly reduced. Furthermore, without the feeder reactor, a short circuit in a cable near the busbars means practically zero voltage at the busbars, that is, the dropping out of synchronous apparatus. With a short circuit beyond a feeder reactor, however, considerable voltage is retained at the busbars on the affected generating station, so that synchronous apparatus is not affected, that is, the short circuit passes without material effect on the system, especially if the circuit breakers are set with short time limit which is permissible due to the greatly reduced current which they have to open.

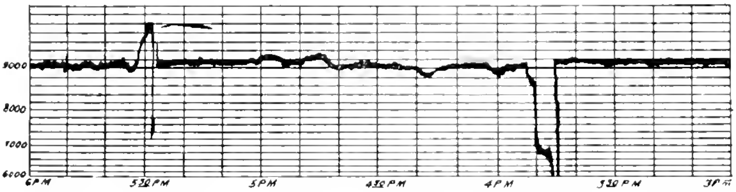

Fig 4

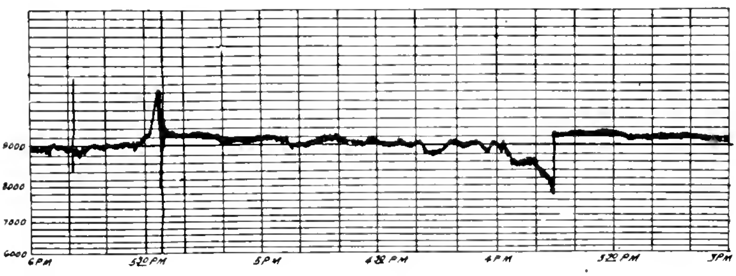

Fig. 5

By the proper use of power-limiting reactors in generator leads, busbars, and feeders it has become possible to operate the modern huge power systems with a high degree of safety and to give the possibility or unlimited extension of the system, that is, a power system of several million kilowatts of connected generator capacity will be just as safe as regards the limitation of the possible destructiveness of short circuits and other accidents as a system of less than hundred thousand kilowatts generator capacity.

When thus sectionalizing the system in installing reactors between the generators, stations, or station sections, these reactors are very low in absolute value of reactance (of the magnitude of an ohm), and thus permit ample current to flow over them for all requirements of the shifting load without giving appreciable voltage drop or phase displacement between the sections. But, relative to the station capacity, these reactances must be fairly high to fulfill their function in power limitation. Thus a reactor of 1.75 ohms reactance, connecting a 9000-volt station section of 72,000-kw. generator capacity, passes a maximum of 45,000 kw. of energy, at the limits of synchronizing power, that is, materially less than the rated generator capacity.

The question then arises, what effect this necessary sectionalizing of the system by reactors has on the synchronizing power of the system and thus on the stability of operation, the more so as in case of accidents or disturbances a local and temporary drop of voltage may occur and a corresponding decrease of synchronizing power.

As illustration is given in Figs. 2 to 5, the voltage record during a trouble on September

18, 1919, in the Commonwealth Edison Company in Chicago. Fig. 6 gives the diagram of the station connections. The system consisted of four sections, *A*, *B*, *C*, and *D*, interconnected in chain connection, from *A to C* and from *C to B* by power-limiting

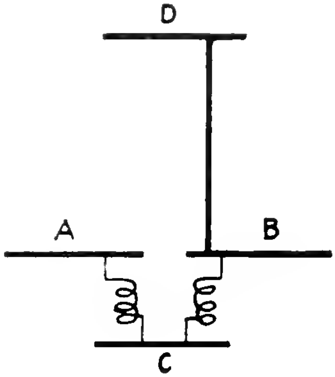

Fig. 6

reactors of 1.75 ohms per phase; from *B* to *D* by six underground cables of 0.31 ohms joint resistance and 0.074 ohms reactance per phase. The busbar voltage was 9000, and the load almost entirely 25-cycle synchronous converters. The connected generator capacity during the trouble was 237,000 kw., nearly full load. A dead short circuit close to the busbars of section *B* dropped out the converters on sections *B* and *D*, and some conveters on sections *A* and *C*; the circuit breakers in the substation opened promptly and cut off the substations, and the short circuit was opened in a very few seconds, so

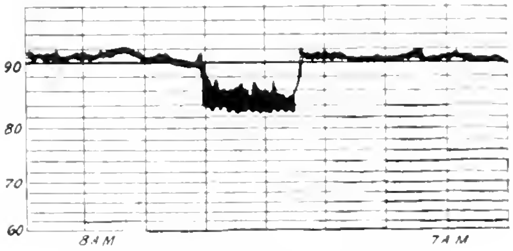

Fig. 8

that the system was clear again in three to four seconds and the voltage should have come back. But it did not come back, it stayed at zero in both stations *B* and *D* (Figs. 2 and 3*), and showed a permanent great drop in station *C* (Fig. 4), and a lesser drop in station *A* (Fig. 5). Interesting also is the wattmeter record of the power exchange between stations over the tie cables between *B* and *D*. (Fig. 7): while usually considerable, practically no power or current exchange occurred, during the trouble. An excessive current however flowed over the power-limiting reactor between *B* and *C*. This reactor was opened after seven minutes, thus cutting off stations *A* and *C* from stations *B* and *D*. As the result of this operation, the voltage

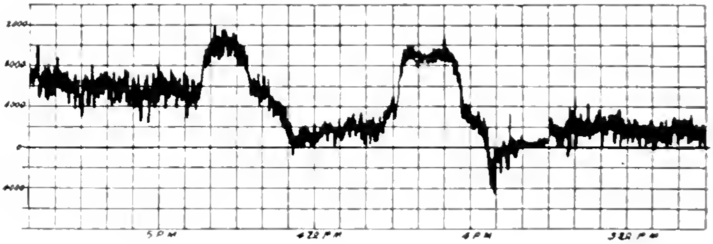

Fig. 7

recovered in *A* and *B*, but still stayed at zero in *B* and *D*, without any apparent reason, until seven minutes later (or after about a quarter of an hour of zero voltage) just as suddenly full voltage reappeared again in both stations *B* and *D*, without any apparent reason.

What happened in this case, as the investigation showed, was that under short circuit the stations *B* and *D* momentarily dropped to zero voltage and lost their synchronizing power. The steam turbines speeded up, cut off steam by closing their emergency valves, but were put back on the steam governors;

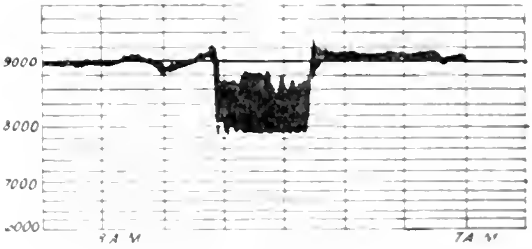

Fig. 9

their speeds however were already too far apart to pull each other into step promptly, and while the unaffected stations *A* and *C* stayed in step with each other, the stations *B* and *D* not only broke out of synchronism with each other and with *A* and *C*, but the individual machines in *B* and *D* broke out of synchronism with each other. The stations *B* and *D*

---

* While the charts do not read below 6000 volts, the station voltmeter showed that there was no appreciable voltage during the entire period

and the individual machines in these stations then kept drifting past each other indefinitely, unable to pull into step until some of the machines happened to drift into phase with each other, caught in synchronism and thereby established some voltage, and then quickly pulled all the other machines into step, and the voltage then came back suddenly.

Figs. 8 to 11 show the voltage records of the same four stations during a trouble on May 19, 1919, and Fig. 12 the wattmeter record of the tie cables between *B* and *D*. The station arrangement was the same, the connected generator capacity 250,000 kw., about ⅔ load.

In this case, a generator short circuited in *A* (Fig. 11), pulling the voltage down to practically zero, but was cut off by the circuit breakers and the system cleared in less than two seconds, so that the voltmeter record of station *A* shows only a momentary drop to zero voltage. Nevertheless, a voltage disturbance resulted in all four stations, lasting for over a quarter of an hour, that is, the voltage greatly dropped, and wildly fluctuated; most at the source of the trouble, station *A*, least at the remote end, in station *D*; and the voltage remained low and fluctuating for no apparent reason, for 18 minutes, and then suddenly recovered and steadied down, without any apparent reason also. An excessive current passed during the disturbance between stations *D* and *B* as shown by the wattmeter record going off the scale, and an excessive current between stations *B* and *C* as shown by the heating of the reactor. In this case, the stations did not break out of step with each other, but stayed in synchronism. In appearance these records look very much like hunting, or surging of the stations against each other, and thus are rather disquieting to the station operation. It is questionable, however, whether it is a real hunting.

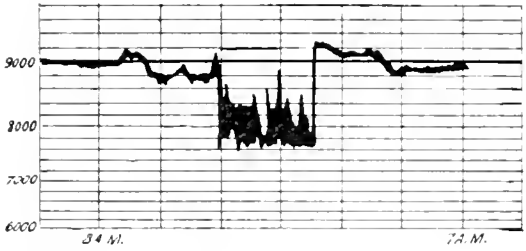

Fig. 10

The matter of the synchronizing power of these big stations and in general of all phenomena of synchronous operation, as affected by the impedance between the machines, thus is of fundamental importance for the safe operation of our modern large power systems.

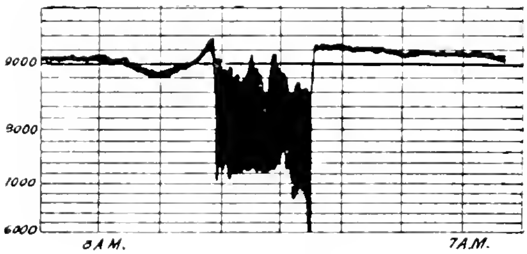

Fig. 11

PARALLEL OPERATION OF SYNCHRONOUS MACHINES

A: Steady Strain

Let two alternators or groups of alternators, such as stations or station sections, of the same terminal voltage, be connected with each other through a reactance, or more general through an impedance, and in synchronism with each other.

We may assume the alternators to be of equal voltage, since a voltage difference merely superimposes on the synchronizing or energy current flowing between the alternators a reactive magnetizing current, without materially changing the energy relations, and the equations thus are of the same general characteristics, merely a little more complicated.

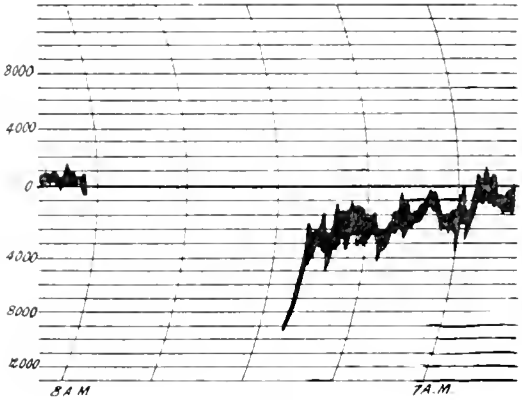

Fig. 12

If the loads on the two alternators equal the power output of the respective machines, no power flows over the impedance between them. If, however, the load on the one alternator is greater than on the other by the same amount less than its output, power must flow over the impedance. The load on the alternators varies with the changing conditions in the system; the relative output of the alternators or groups of alternators however is fixed by the speed governors of their prime movers and can be varied only in steps, by shutting down a machine or starting an additional machine. Thus the output of each generating section cannot always equal the load on it, and an exchange of power must occur between the generating sections, that is, power must flow over the impedance between the generating sections.

Let:

P = the power flowing from the underloaded to the overloaded alternator, over a circuit of impedance z and let:

2ω = the phase displacement between the two alternators, caused by the flow of power.

The e.m.fs. of the two alternators then may be represented by:

$$\left.\begin{aligned} e_1 &= e_0\ cos\ (\phi - \omega) \\ e_2 &= e_0\ cos\ (\phi + \omega) \end{aligned}\right\} \qquad (1)$$

where e_0 = maximum value of e.m.f.

and $\phi = 2\pi f t$.

The resultant e.m.f. acting in the circuit between the two alternators, then is:

$$\begin{aligned} e &= e_1 - e_2 \\ &= e_0\ \ cos\ (\phi - \omega) - cos\ (\phi + \omega) \qquad (2) \\ &= 2e_0\ sin\ \omega\ sin\ \phi \end{aligned}$$

that is, in quadrature with the average voltage of the two alternators.

The interchange current between the two alternators then is:

$$\begin{aligned} i &= \frac{e}{z} \\ &= \frac{2e_0}{z}\ sin\ \omega\ sin\ (\phi - \alpha) \end{aligned} \qquad (3)$$

where:

$z = \sqrt{r^2 + x^2}$

r = resistance

x = reactance

of the circuit between the two alternators, including their internal resistances and reactances.

The phase angle α is given by:

$$tan\ \alpha = \frac{x}{r}$$

The effective value of the current i is then given by:

$$I = \frac{\sqrt{2}\,e_0}{x}\ sin\ \omega$$

or, if

E = effective value of generator e.m.f.

$e_0 = E\sqrt{2}$, and

$$I = \frac{2E}{z}\ sin\ \omega \qquad (4)$$

The power consumed in the resistance r of the circuit is:

$$\begin{aligned} P' &= I^2 r \\ &= \frac{4E^2 r}{z^2}\ sin^2\ \omega \\ &= \frac{4E^2}{z}\ sin^2\ \omega\ cos\ \alpha \qquad (5) \end{aligned}$$

The power of the first alternator then is:

$$\begin{aligned} p_1 &= e_1 i \\ &= \frac{2e_0^2}{z}\ sin\ \omega\ sin\ (\phi - \alpha)\ cos\ (\phi - \omega) \qquad (6) \end{aligned}$$

The power of the second alternator:

$$P_2 = -\frac{2\,e_0^2}{z}\ sin\ \omega\ sin\ (\phi - \alpha)\ cos\ (\phi + \omega) \qquad (7)$$

The sum of the power of the two alternators then is:

$$\begin{aligned} p' &= p_1 + p_2 \\ &= \frac{2\,e_0^2}{z^2}\ sin\ \omega\ sin\ (\phi - \alpha)\ [cos\ (\phi - \omega) - \\ &\qquad\qquad cos\ (\phi + \omega)] \\ &= \frac{4\,e_0}{z}\ sin^2\ \omega\ sin\ \phi\ sin\ (\phi - \alpha) \\ &= \frac{2\,e_0^2}{z}\ sin^2\ \omega\ [cos\ \phi - cos\ (2\,\phi - \alpha)] \end{aligned}$$

and its average value thus is:

$$\begin{aligned} av.\ p' &= \frac{2\,e_0^2}{z}\ sin^2\ \omega\ cos\ \alpha \\ &= \frac{4\,E^2}{z}\ sin^2\ \omega\ cos\ \alpha \\ &= P' \end{aligned}$$

that is, the sum of the powers of the two alternators is the power consumed in the resistance of the circuit between them, as is obvious.

The difference of the powers of the two alternators is:

$$\begin{aligned} 2\,p &= p_1 - p_2 \\ &= \frac{2\,e_0}{z}\ sin\ \omega\ sin\ (\phi - \alpha)\ [cos\ (\phi - \omega) + \\ &\qquad\qquad cos\ (\phi + \omega)] \\ &= \frac{4\,e_0^2}{z}\ sin\ \omega\ cos\ \omega\ cos\ \phi\ sin\ (\phi - \alpha) \end{aligned}$$

$$2\,p = -\frac{e_0^2}{z} \sin 2\,\omega\,[\sin \alpha - \sin (2\,\phi - \alpha)] \quad (8)$$

and its average value thus is:

$$\text{av. } 2\,p = \frac{e_0^2}{z} \sin 2\,\omega \sin \alpha$$

$$= \frac{2\,E^2}{z} \sin 2\,\omega \sin \alpha$$

$$= 2\,P \quad (9)$$

that is, the power transfer between the two alternators (or generating stations or sections of generating stations) is:

$$P = \frac{E^2}{z} \sin 2\,\omega \sin \alpha \quad (10)$$

and the leading alternator, e_2, delivers power to the lagging alternator, e_1.

The power P thus is zero for $\omega = 0$, increases, reaches a maximum of

$$P'_m = \frac{E^2}{z} \sin \alpha \quad (11)$$

for $\omega = 45$ deg., or 90 deg. phase displacement between the alternators, and then decreases again to zero at $\omega = 90$ deg., or phase opposition of the alternators.

Beyond $\omega = 90$ deg., the synchronizing power P_m becomes negative, with the same values, that is, the alternators synchronize at the next pole.

The synchronizing power P is zero for $\alpha = 0$, that is, if the circuit between the alternators contains no reactance but only resistance, and is a maximum when the resistance is negligible compared with the reactance, that is $\alpha = 90$ deg.:

$$P''_m = \frac{E^2}{x} \sin 2\,\omega \quad (12)$$

Substituting in (10):

$$\sin \alpha = \frac{x}{z},$$

gives:

$$P = \frac{E^2 x}{z^2} \sin 2\,\omega \quad (13)$$

that is, with a given impedance z, and thus given synchronizing current between the alternators, the synchronizing power P is directly proportional to the reactance x of the circuit between the alternators.

The maximum synchronizing power between the alternators thus occurs at phase angle $\omega = 45$ deg., that is, 90 deg. phase displacement, and negligible resistance, and is:

$$P_m = \frac{E^2}{x} \quad (14)$$

at current (effective):

$$I_m = \frac{E\sqrt{2}}{x} \quad (15)$$

and resultant e.m.f.:

$$E_m = E\sqrt{2} \quad (16)$$

In this case, the phase angle 2ω between the alternators or station sections is constant during operation, but varies with change of load between the station sections, and can be kept very small by properly apportioning the number of generators in operation in each section to the respective load on this section.

B: Oscillation

Consider again two alternators or groups of alternators, such as stations or station sections which are running in synchronism with each other, that is, have the same frequency, f, but are connected together while out of phase with each other by angle 2ω, or thrown out of phase by some sudden change of load, momentary short circuit, etc. As well known, the alternators then oscillate against each other with (practically) constant frequency of oscillation pf and gradually decreasing amplitude of oscillation, and finally steady down in phase with each other, or at the constant phase angle ω^0 determined by the condition of steady power transfer between the alternators.

Since under normal conditions of operation the steady phase angle ω^0 must be small, we may assume that the oscillation occurs symmeterically around the position of the alternators in phase with each other, that is, the one alternator has the phase $\phi - \omega$ when the other has the phase $\phi + \omega$.

The same equations then pertain as in the foregoing section *Steady Strain*, that is:

The e.m.fs. of the two alternators are:

$$e_1 = e_0 \cos (\phi - \omega)$$

$$e^2 = e_0 \cos (\phi + \omega) \quad (1)$$

The e.m.f. acting in the circuit between the two alternators:

$$e = 2\,e_0 \sin \omega \sin \phi$$

with effective value:

$$E^0 = 2\,E \sin \omega \quad (17)$$

The current flowing between the two alternators:

$$i = \frac{2\,e_0}{z} \sin \omega\,(\sin \phi - \alpha) \quad (3)$$

with effective value:

$$I = \frac{2\,E}{z} \sin \omega \quad (4)$$

where z is the impedance of the circuit between the two alternators or groups of alternators, including their internal impedance. The power transferred between the alternators is:

$$p = \frac{E^2}{z} sin\ 2\ \omega\ [sin\ (2\ \phi - \alpha) - sin\ \alpha] \qquad (8)$$

The first term of equation (8) is of double frequency, $2f$. It thus does not represent energy transfer between the alternators, but merely represents the energy storage and return, twice per cycle, occurring in any inductive circuit. It thus is of no further interest, and it is:

Power transfer between the alternators:

$$P = \frac{E^2}{z}\ sin\ 2\ \omega\ sin\ \alpha \qquad (10)$$

$$= \frac{E^2 x}{z^2}\ sin\ 2\ \omega \qquad (12)$$

In this case, however, the phase angle ω of the e.m.f. is not constant, but pulsates at the approximately constant frequency of the beat and decreasing amplitude.

Let:

$$\omega_0 = \omega_{00} \epsilon^{-a} \qquad (18)$$

be the maximum value of the phase angle during each oscillation, (decreasing from its initial maximum value ω_{00} by the expotential of time ϵ^{-at}).

We may then represent the gradually decreasing amplitude of the phase angle ω by:

$$\begin{aligned} \omega &= \omega_0\ sin\ p\phi \\ &= \omega_{00} \epsilon^{-at}\ sin\ p\phi \end{aligned} \qquad (19)$$

where:

pf = frequency of the beat, or the (complete) periodic variation of the phase angle ω.

In reality, the equations (3), (4), (8), and (10) of section ***A*** are not strictly correct for the conditions under investigation in section ***B***, since in the derivation of these equations in section ***A***, ω was assumed as constant. In the case of section ***B***, oscillation of the alternators, ω varies periodically, is a function of ϕ and thus additional terms appear in these equations. Since however the frequency of variation of ω is very low compared with the frequency of f, that is, p equals a small quantity, these additional terms are small; and the foregoing equations thus are correct with sufficient approximation, especially in the present case, where we are essentially interested in the magnitude of the power relations.

Substituting (19) into (10) gives as the periodically varying power transfer or synchronizing power:

$$P = \frac{E^2}{z}\ sin\ \alpha\ sin\ 2\ (\omega_0\ sin\ p\phi) \qquad (20)$$

where ω_0 is the maximum amplitude of this oscillation.

The average value of P during the half cycle of oscillation may be represented by:

$$\begin{aligned} P_0 &= \text{av. } P \\ &= \frac{E^2}{z}\ sin\ \alpha\ \frac{1 - cos\ 2\omega_0}{2\omega_0} \end{aligned} \qquad (21)$$

and as the duration t_0 of one half cycle of oscillation (during which the power transfer remains in the same direction) is given by half a cycle of $p\phi$, that is:

$$p\phi = 2\pi pft_0 = \pi$$

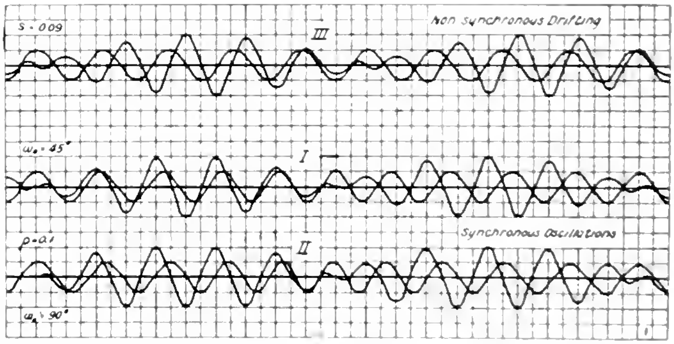

Fig 13

it is:

$$t_0 = \frac{1}{2pf} \qquad (22)$$

and the *energy transfer* between the two machines or groups of machines, during each half cycle of oscillation, is thus given by:

$$\begin{aligned} W &= t_0 P_0 \\ &= \frac{E^2}{4pf\omega_0 z}\ sin\ \alpha\ (1 - cos\ 2\omega_0) \end{aligned} \qquad (23)$$

This is a maximum for $\omega_0 = 90$ deg. $= \frac{\pi}{2}$, and then is:

$$W_m = \frac{E^2}{\pi pfz}\ sin\ \alpha \qquad (24)$$

W_m thus is the maximum energy which can be absorbed by the machine or group of machines, without being thrown out of synchronism. In other words, if a sudden demand greater than W_m is made on the machine, or if more energy than W_m is given by the steam supply to the machine or group of machines, after the load has been thrown off and before the steam has been cut off, the machine is thrown out of synchronism; otherwise it remains in synchronism and after an oscillation settles down again in phase.

As seen from the equations, during each complete cycle of oscillation of frequency pf, the current twice rises and falls, thus reaching two maxima, and the power P twice reverses, so that the energy W flows one way during half the cycle, and in opposite direction during the other half cycle of oscillation. The frequency of the rise and fall of the current thus is $2\ pf$.

Curves I and II in Fig. 13 show the current i and the voltage e_1 of the oscillation for the (exaggerated) value $p=0.1$, and for $\omega_0=45$ deg. and $\omega_0=90$ deg.

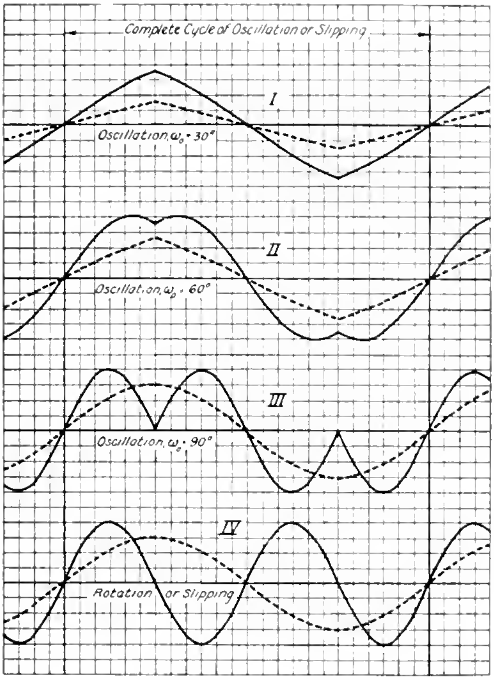

Fig. 14

It is interesting to note from equation (20) that the power transfer P reverses twice per cycle of oscillation (for $p\phi=0$ and 180 deg.). If $\omega_0=45$ deg. or less, that is, 90 deg. or less maximum phase displacement during the oscillation, then the power P has two maxima, at the maximum phase displacement midways between the reversal of power, as seen in Curve I of Fig. 14. If however ω_0 is greater than 45 deg., that is, more than 90 deg. phase displacement, then the power transfer decreases again at maximum phase displacement, midways between the reversals of power, and the power transfer has four maxima separated by two reversals and two minima, as seen by Curve II of Fig. 14, and finally at $\omega_0=90$ deg. (Curve III in Fig. 14), the power reaches four maxima and four zero values during each cycle of oscillation but reverses only twice. That is, at the moment when the two alternators are in phase, the power transfer is zero, the power reverses, and the current is zero, and in phase with the voltage. With increasing phase displacement, power and current increase; the power reaches a maximum at 90 deg. phase displacement between the machines, where the current is 45 deg. out of phase with the voltage. With further increase of phase displacement during the swing of oscillation, the power decreases again to zero at 180 deg. phase displacement or phase opposition; but the current continues to increase and reaches a maximum at phase opposition, with the phase angle between voltage and current steadily increasing, to 90 deg. or zero power, in phase opposition. Then, without reversal of the flow of power, the phase angle between voltage and current again decreases, the current decreases, but the power increases again in the same direction as before, to the second maximum in the same half cycle, at 90 deg. phase displacement, and then the power decreases again to the reversal. This is well illustrated in Figs. 13 and 14.

C: Slipping

Consider now the case that two alternators, or groups of alternators such as station sections, are connected together while different from each other in frequency by $2s$, that is, one alternator has the frequency $(1-s)f$, the other the frequency $(1+s)f$, and the alternators thus are slipping past each other with the frequency $2sf$.

We may again assume the alternators as of equal voltage, since a voltage difference merely superposes on the synchronizing energy current a reactive magnetizing current, without materially changing the energy relations.

The e.m.fs. of the two alternators then may be represented by:

$$\begin{aligned} e_1 &= e_0 \cos\ (1-s)\phi \\ e_2 &= e_0 \cos\ (1+s)\phi \end{aligned} \qquad (25)$$

The resultant voltage in the circuit between the two alternators then is:

$$\begin{aligned} e &= e_1 - e_2 \\ &= e_0\,[\cos\ (1-s)\ \phi - \cos\ (1+s)\phi] \\ &= 2\,e_0 \sin s\,\phi \sin \phi \\ &= 2\,E\sqrt{2} \sin s\,\phi \sin \phi \end{aligned} \qquad (26)$$

and its effective value:

$$E^0 = 2\,E\,sin\,s\,\phi \tag{27}$$

where E = effective value of generator e.m.f.

Assume now that s is a small quantity (just as we assumed in section B, that p is a small quantity), that is, that the two alternators have nearly the same frequency. The change of sin $s\phi$ then is slow compared with that of sin ϕ, and for all phenomena of frequency f, sin $s\,\phi$ may be assumed as constant, and the reactance of the circuit may be assumed as the same, $x = 2\,\pi\,f\,L$, for both component e.m.fs., e_1 and e_2, that is, for both frequencies $(1-s)\,f$ and $(1+s)\,f$.

The interchange current between the alternators then is:

$$i = \frac{2\,e_0}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha)$$

$$= \frac{2\,E\sqrt{2}}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha) \tag{28}$$

hence, the effective value.

$$I = \frac{2\,E}{z}\,sin\,s\,\phi \tag{29}$$

where:

$$z = \sqrt{r^2+x^2}$$

$$\tan\,\alpha = \frac{x}{r}$$

With regard to the e.m.f. of one of the alternators, for instance, e_1, this current always lags. Its lag is 90 deg. when the current is a maximum. With the decrease of current, the lag decreases from 90 deg. in the one, and increases in the next beat, and approaches in-phase respectively in-opposition, when the current is a minimum. The power-factor thus varies from zero at maximum current, to unity at zero current, and its average thus is low. Fig. 13 shows as Curve III the relation of e_1 to i for the exaggerated value $s = 0.09$.

The power of the one alternator then is given by:

$$P_1 = e_1 i$$

$$= \frac{2\,e_0^2}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha)\,cos\,(1-s)\,\phi$$

$$= \frac{4\,E^2}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha)\,cos\,(1-s)\phi \tag{30}$$

that of the other alternator:

$$p_2 = e_2 i$$

$$= -\frac{4\,E^2}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha)\,cos\,(1+s)\phi \tag{31}$$

and the power transfer between the two alternators then is given by

$$2\,p = p_1 - p_2$$

$$= \frac{8\,E^2}{z}\,sin\,s\,\phi\,sin\,(\phi-\alpha)\,cos\,s\,\phi\,cos\,\phi$$

$$= \frac{2\,E^2}{z}\,sin\,2\,s\,\phi\,[sin\,(2\,\phi-\alpha) - sin\,\alpha] \tag{32}$$

The first term, with sin $(2\,\phi-\alpha)$, again is a double frequency term representing the periodic storage and return of the energy during the half cycle of voltage, thus does not represent any power transfer and the power transfer between the alternators is thus given by:

$$P = \frac{E^2}{z}\,sin\,2\,s\,\phi\,sin\,\alpha \tag{33}$$

Usually it is approximately: $\alpha = 90$ deg., that is, the reactance is large compared with the resistance, and equation (33) then becomes:

$$P = \frac{E^2}{z}\,sin\,2\,s\phi \tag{34}$$

During each cycle of the frequency sf, of the slip from synchronism or average frequency, the amplitude of the current i thus twice becomes zero and in phase, and twice reaches a maximum, when the alternators are in opposition, and the power P four times reaches a maximum and four times becomes zero and reverses, twice when the current comes into phase with the e.m.f. but the current becomes zero, and twice when the current is a maximum but in quadrature with the e.m.f., and the power thus becomes zero. The power transfer between the alternators thus reverses four times per complete cycle of slip, sf, that is, is of the frequency $2sf$, with two positive and two negative maxima.

The average value of the power is:

$$\frac{2}{\pi}P = \frac{2\,E^2}{\pi\,z}\,sin\,\alpha \tag{35}$$

and as the duration of one quarter cycle of slip is $t_0 = \frac{1}{4sf}$, the *energy transfer* between the two machines, during a quarter cycle of slip, thus is:

$$W = \frac{1}{4\,sf}\,\frac{2}{\pi}P$$

$$= \frac{E^2}{2\,\pi\,sfz}\,sin\,\alpha \tag{36}$$

The difference between the slipping of alternators past each other out of synchronism and the oscillation of alternators against each other at synchronism is thus that in the slipping the power fluctuation and the reversal of the energy is of twice the frequency of the current fluctuation, while in the oscillation of the alternators against each other at synchronism, the power fluctuation or reversal of energy flow is of the same frequency as the current fluctuation

If two alternators are connected together while out of synchronism, and slowly slip past each other, during each half cycle of slip, or beat, while the two machines e.m.fs. pass from in-phase, to in-opposition, to in-phase again, a periodic energy transfer takes place. During one quarter cycle of slip (that is, while one alternator e.m.f. slips behind, the other pulls ahead of the mean frequency by one quarter cycle, and the two alternators, e.m.fs., thus slip against each other by one half cycle) the alternators are partly in phase with each other, and the slower machine receives energy from the faster machine. The two machines are thereby brought nearer to each other in speed, pulled towards synchronism. During the next quarter cycle of slip, however, the two alternators are partly in opposition, and the faster machine receives energy from the slower one. The faster machine then speeds up, the slower machine slows down, and the two machines pull apart again, by the same amount by which they pulled together in the preceding quarter cycle of slip (if their e.m.f. is constant). Thus the two machines can pull into step only if the energy transferred during one quarter cycle of slip, W, is larger than the energy required to speed up the momentum that is, kinetic energy M of the machine to full synchronism.

Due to the energy transfer W between the machines, resulting in an alternate speeding up and slowing down, the slip s is not constant but pulsates periodically between the minimum value $s-s_1$, at the end of the quarter cycle during which the machines pull together and the beginning of the quarter cycle during which the machines pull apart, and a maximum value $s+s_1$, at the end of the quarter cycle during which the machines pull apart and the beginning at the quarter cycle during which the machines pull together; where s_1 is the amplitude of the pulsation of slip. As the energy required to accelerate the momentum M of the machine by the speed $2s_1$ is $4s_1M$, it follows:

$$W=4s_1M$$

or:

$$s_1=\frac{W}{4M}$$

$$s_1=\frac{E^2\sin\alpha}{8\pi sfzM} \qquad (37)$$

is the amplitude of the speed fluctuation of the two alternators during the slipping past each other out of synchronism with the slip s.

$s_1=s$ gives as minimum slip $s-s_1=0$, that is, the machines pull into synchronism.

The maximum slip s_1 from which the two machines pull into synchronism with each other is thus given by substituting $s_1=s$ in (37) as:

$$s_0=\frac{E}{2}\sqrt{\frac{\sin\alpha}{2\pi fzM}} \qquad (38)$$

s_0 thus is the *limit of synchronizing power.*

In Fig. 14, four curves of power and of current (effective value) are shown, the former drawn in full and the latter in dotted lines, for oscillation; $\omega_0=30, 60, 90$ deg., and slipping.

As seen, the single maximum power, Curve *I*, with increasing swing of the oscillation, becomes a double maximum with a minimum between the maxima, Curve *II;* the minimum then decreases to zero, Curve *III*, at the limits of synchronizing power; and the power curve then overturns, Curve *IV*, that is, the alternator instead of swinging back into phase again continues to slip and drops into phase again by slipping one cycle, etc., and thereby the power transfer curve doubles its frequency by one of the two lobes of Curve *III* overturning, while the current curve remains the same, of the frequency of the beat or slip.

D: Pulling in Step

When the two machines are out of synchronism with each other by a greater speed difference, $2s$, than that from which the machines can pull each other into synchronism within one quarter cycle of slip, from the equations of the foregoing section *C* it would follow that the machines can never pull each other into synchronism, if the voltage E_0 is constant, but must indefinitely continue to slip past each other coming nearer together during one quarter cycle of slip and dropping apart again by the same amount during the next quarter cycle of slip.

This, however, is under the assumption that the machine e.m.f. E is constant. In reality, however, E is not constant but varies periodically with the same frequency as the current fluctuates. The current in the circuit between the machines and thus the armature reaction in the machine varies in amplitude and in phase difference against the machine voltage, and the machine voltage varies with the amplitude and the phase of the armature reaction.

Consider, as an approximation, the armature reaction as proportional to the quadrature component of the current. The e.m.f. of the machine would then be expressed by an approximate equation of the form:

$$E'=E\quad 1-c\sin s\phi\sin\delta \tag{39}$$

where c is a constant and δ is the phase angle between the current and the e.m.f., and $s\phi$ represents the amplitude of the current pulsation by equation (29), thus $\sin s\,\phi\sin\delta$ represents the quadrature component of the armature current.

It is, however, by (25) and (29):

$$\begin{aligned}\delta&=(\phi-\alpha)-(1-s)\phi-90\text{ deg.}\\&=s\phi-\alpha+90\text{ deg.}\end{aligned}$$

thus:

$$E'=E\quad 1+c\sin s\phi\cos(s\phi-\alpha) \tag{40}$$

Substituting equation (40) into the expression of the power of the alternator equation (33), the equations still remain alternating, that is, there is no resultant synchronizing power, but equal positive and negative values of power alternate.

However, equation (40) assumes that the magnetizing effect of the armature reaction is instantaneous, that is, that the e.m.f. E at any moment is the value corresponding to the armature reaction existing at this moment. This, however, is not the case; the armature reaction is not instantaneous but requires an appreciable time, several seconds, to develop, and the magnetizing or demagnetizing effect of the armature reaction on the voltage therefore materially lags behind the armature reaction.

Let then $\sigma=$ the angle of lag of the voltage change behind the armature reaction which causes it. It is then,

$$E'=E\quad 1+c\sin s\phi\cos(s\phi-\alpha-\sigma) \tag{41}$$

and substituting equation (41) into (33) gives the *power transfer* between the machines:

$$P=\frac{E^2}{z}\sin 2s\phi\sin\alpha\quad\begin{matrix}1+c\sin s\phi\\\cos(s\phi-\alpha-\sigma)\end{matrix}\quad^2$$

or approximately, considering c as a small quantity:

$$P=\frac{E^2}{z}\sin 2s\phi\sin\alpha+\frac{2cE^2}{z}\sin 2s\phi\sin\alpha\\\sin s\phi\cos(s\phi-\alpha-\sigma) \tag{42}$$

The first term:

$$\frac{E^2}{z}\sin 2s\phi\sin\alpha$$

is the slowly alternating energy transfer between the machines, discussed in section C, which causes their speed to fluctuate, but does not permanently bring them nearer to each other, that is, exerts no synchronizing power unless and until during these speed fluctuations they reach complete synchronism and then catch into step.

The second term:

$$\begin{aligned}P_1&=\frac{2cE^2}{z}\sin 2s\phi\sin\alpha\sin s\phi\cos(s\phi-\alpha-\sigma)\\&=\frac{cE^2}{z}\sin 2s\phi\sin\alpha\begin{bmatrix}\sin(\alpha+\sigma)+\\\sin(2s\phi-\alpha-\sigma)\end{bmatrix}\\&=\frac{cE^2}{z}\sin 2s\phi\sin\alpha\sin(\alpha+\sigma)+\frac{cE^2}{2z}\sin\alpha\\&\qquad\Big[\cos(4s\phi-\alpha-\sigma)+\cos(\alpha+\sigma)\Big]\\&=\frac{cE^2}{z}\sin 2s\phi\sin\alpha\sin(\alpha+\sigma)+\frac{cE^2}{2z}\sin\alpha\\&\qquad\cos(4s\phi-\alpha-\sigma)+\frac{cE^2}{2z}\sin\alpha\\&\qquad\cos(\alpha+\sigma)\end{aligned} \tag{43}$$

The first two terms also are slowly alternating, at double and quadruple the frequency of slip, as they contain terms with $2s\phi$ and $4s\phi$ and thus represent no continuous power transfer; the third term, however,

$$P_0=\frac{cE^2}{2z}\sin\alpha\cos(\alpha+\sigma) \tag{44}$$

is constant, that is, represents a continuous synchronizing power.

If $\alpha=90$ deg., that is, the resistance is negligible compared with the reactance,

$$P_0=\frac{cE^2}{2z}\sin\sigma \tag{45}$$

If thus two alternators or station sections are considerably out of synchronism with each other, they continue slipping past each other with large fluctuating currents flowing between them, and the speeds of the machines fluctuate with the fluctuations of the current. These currents do not decrease in amplitude, but remain of practically constant value, but their period of fluctuation gradually becomes slower, that is, the fluctuation gradually becomes slower, while currents slowly pull the machines nearer into synchronism with each other, that is, decrease their frequency difference, until the critical frequency $2s_0$ is reached (where the acceleration during a quarter cycle of slip, $2s_1$, reaches full synchronism). Then the machines suddenly drop into synchronism, but oscillate in phase against each other with an approximately constant frequency of oscillation, but with a current fluctuation which steadily (and usually rapidly) decreases until steady conditions of speed, current, and voltage are reached.

The armature reaction of the alternator is represented by the difference of the synchronous reactance x_0 and the true reactance x_1, that is, by an effective *reactance of armature reaction.*

$x_2 = x_0 - x_1$.

The coefficient c in the synchronizing power, P_0 in equation (44), is that fraction of the reactance of the armature reaction x_2 which appears during the short time of the current fluctuation. Thus c is larger, the slower the fluctuation, that is, the less s. In other words, c increases with decreasing slip, that is, increasing approach to synchronism.

Inversely, since σ is a maximum and practically 90 degrees for large values of s, where the voltage fluctuation lags practically 90 deg. behind the fluctuation of the armature reaction, and decreases with decreasing s, that is, increasing approach to synchronism, $c \sin \sigma$, and thus the synchronizing power, P_0 in equation (44), should be a maximum at some moderate slip s and decrease for larger as well as smaller slips.

Assume that it takes t_0 seconds for the field to build up to correspond to the armature reaction. With the current fluctuating with the frequency $2sf$, and assuming that the magnetizing effect of the armature reaction is sinoidal, it would be:

$$c = \frac{1}{4\,sft_0}$$

and:

$$\sin\sigma = \sqrt{1 - \left(\frac{1}{4\,sft_0}\right)^2}$$

thus:

$$P_0 = \frac{E_0^2}{8\,zsft_0}\sqrt{1 - \left(\frac{1}{4\,sft_0}\right)^2} \qquad (46)$$

However, secondary effects occur and more or less modify the value P_0, such as the effect of secondary currents induced in the field structure by that component of the armature current which is due to the e.m.f. of the other machine, and which gives an induction motor torque tending to pull the machines together into synchronism.

E: Equations

$z = \sqrt{r^2 + x^2}$ = total impedance of circuit between alternators. $\tan\alpha = \frac{x}{r}$.

ω = phase angle between alternator e.m.fs.
pf = frequency of oscillation.
sf = frequency of slipping.

	A: Continuous Power Transfer	*B:* Oscillation in Synchronism	*C* and *D:* Slipping Out of Synchronism
Alternator e.m.fs.:			
	$e_1 = e_0 \cos(\phi - \omega)$	$e_0 \cos(\phi - \omega)$	$e_0 \cos(1 - s)\phi$
	$e_2 = e_0 \cos(\phi + \omega)$	$e_0 \cos(\phi + \omega)$	$e_0 \cos(1 + s)\phi$
Eff:	$E = \frac{e_0}{\sqrt{2}}$	$\frac{e_0}{\sqrt{2}}$	$\frac{e_0}{\sqrt{2}}$
Resultant e.m.fs.:			
	$e = 2e \sin\omega \sin\phi$	$2e \sin\omega \sin\phi$	$2e \sin s\phi \sin\phi$
Eff:	$E^0 = 2E^0 \sin\omega$	$2E^0 \sin\omega$	$2E^0 \sin s\phi$
Resultant Current:			
	$i = \frac{2e_0}{z} \sin\omega \sin(\varphi - \alpha)$	$\frac{2i_0}{z} \sin\omega \sin(\varphi - \alpha)$	$\frac{2e_0}{z} \sin s\varphi \sin(\varphi - \alpha)$
Eff:	$I = \frac{2E}{z} \sin\omega$	$\frac{2E}{z} \sin\omega$	$\frac{2E}{z} \sin s\phi$
Continuous Power Transfer:	$P_0 = \frac{E^2}{z} \sin 2\omega \sin\alpha$		$\frac{cE^2}{z} \sin\alpha \cos(\alpha + \sigma$
Low-frequency Power Fluctuation: $P =$		$\frac{E^0}{z} \sin 2\omega_0 \sin\alpha$	$\frac{E^2}{z} \sin 2s\phi \sin\alpha$
Low-frequency Energy Transfer: $W =$		$\frac{E^2}{z} \sin\alpha \frac{1 - \cos 2\omega_0}{4\,pfw_0}$	$\frac{E^2}{2\pi sfz} \sin\alpha$
Attenuation: $\omega =$		$\omega_0 \sin p\phi$ $= \omega_{00}\epsilon^{-at} \sin p\phi$	
Pulsation of Slip: $s_1 =$			$\frac{E^2 \sin\alpha}{8\pi sfzM}$
Critical Slip: $s_0 =$			$\frac{E}{2}\sqrt{\frac{\sin\alpha}{2\pi fzM}}$
Pulsation of Armature Reaction: $c =$			$\frac{1}{4\,sft_0}$
Lag of Armature Reaction: $\sin\sigma =$			$\sqrt{1 - c^2}$

It is interesting to note that the limit case of W, in section ***B*** for $\omega = \frac{\pi}{2}$, and in section ***C*** for $s = s_0$, must coincide: $W_B = W_C$. This gives:

$$\Big/ \frac{E^2}{z} \sin\alpha \frac{1 - \cos 2\omega_0}{4\,pf\omega_0} \Big/_{\omega_0 = \frac{\pi}{2}} = 2 \Big/ \frac{E^2}{2\pi sfz} \sin\alpha \Big/_{s = s_0}$$

Hence:

$p = s_0$

and, substituting for s_0:

$$p = \frac{E}{2}\sqrt{\frac{\sin\alpha}{2\pi fzM}}$$

is the frequency of oscillation.

(To be Continued)

The Penetration of Iron by Hydrogen

By T. S. Fuller

Research Laboratory, General Electric Company

This article describes the results of tests made to determine the effect of current, treatment of the iron, temperature, electrolyte, and surface coating on the penetration of iron by nascent hydrogen. A new and convenient form of apparatus was developed for the experiment. It was found that the rate of penetration increases with increase in temperature and is greater for iron immersed in one per cent sulphuric acid than for iron electrolyzed as cathode in a similar solution. Copper is impervious to hydrogen at ordinary temperatures. Coating the iron with tin increases the rate of penetration, while coating it with zinc or copper has the opposite effect.—Editor.

Some time ago the writer published the results of some plating experiments on steel springs in which he concluded: "The facts are all in accord with the assumption that the absorption by the steel of atomic or nascent hydrogen liberated at the cathode is the cause of the embrittlement of steel springs in the plating-bath." The results of these experiments, together with those of Charpy and Bonnerot[1], Coulson[2], Merica[3], and others led to the study of the factors which govern the penetration of iron by atomic hydrogen, namely, current, treatment of the iron, temperature, electrolyte and surface coatings.

It is well known that iron at room temperatures is impermeable to gaseous or molecular hydrogen (H_2), but that at higher temperature it becomes more or less permeable. It is not so well known, perhaps, that iron at room temperature is permeable to nascent or atomic hydrogen (H). These problems have been investigated by Charpy and Bonnerot[1]. Their apparatus consisted of a steel tube 0.5 mm. thick, connected to a pump which maintained a constant pressure of 0.2 mm. inside the tube. This tube was placed inside another one of porcelain, which was heated and through which gaseous hydrogen at atmospheric pressure flowed, surrounding the steel tube. The iron was found to be impermeable up to a temperature of 325 deg. C. The following table taken from Charpy and Bonnerot's data shows the amount of gaseous hydrogen expressed in cubic centimeters per hour, collected in the steel tube:

Temperature	cc. of H₂ per hr.
350 deg. C.	1.1
450 deg. C.	3.2
550 deg. C.	8.5
750 deg. C.	30.0
850 deg. C.	42.0

Pressures as high as 26 atmospheres were observed by these writers in an iron container which was made cathode in an acid solution.

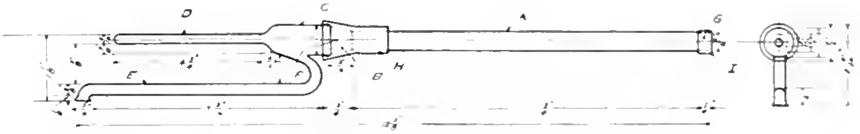

Fig. 1 Diagram showing Construction of Apparatus for Measuring the Rate of Hydrogen Penetration

Apparatus

A very convenient as well as novel form of apparatus has been developed and used for the experiments described in this paper.

It consists of a seamless iron tube plugged at the bottom, and sealed at the top to a glass U tube having one arm closed and calibrated and the other open. After assembling, the apparatus is completely filled with mercury, and when in operation hydrogen penetrates the iron tube, and rising quickly displaces the mercury in the closed and calibrated arm of the U. Fig. 1 is from a drawing showing the construction of one of the units. *A* is a section of seamless iron tubing 12 in. long, and $\frac{11}{16}$ in. outside diameter, with a wall $\frac{1}{16}$ in thick. *B* is a cone-shaped tube of nickel steel having its small end brazed to the iron tube *A*. The large end of *B* makes a vacuum tight seal with the bottom of the

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[1] Trans. Am. Electrochem. Soc., Vol. 32 (1917), p. 247-255.

[2] Compt. Rend. 154, 592-4 (1912), 156, 394-6 (1913).

[3] Trans. Am. Electrochem. Soc., Vol. 32 (1917), p. 237-245.

[4] Met. and Chem. Eng. Vol. 16 (1917), p. 496-503.

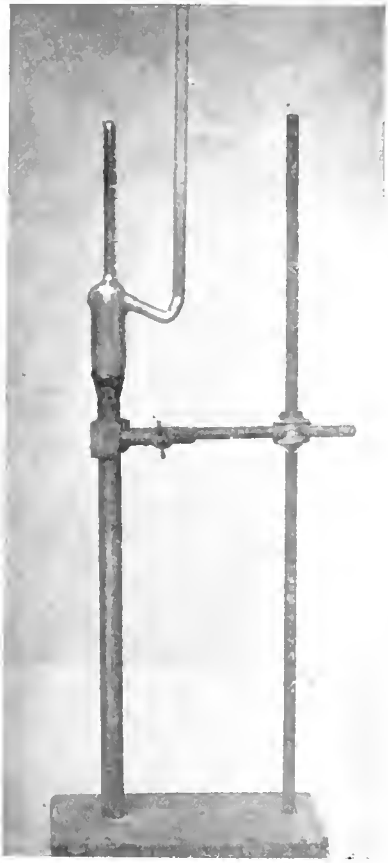

Fig. 2. Apparatus Completely Filled with Mercury

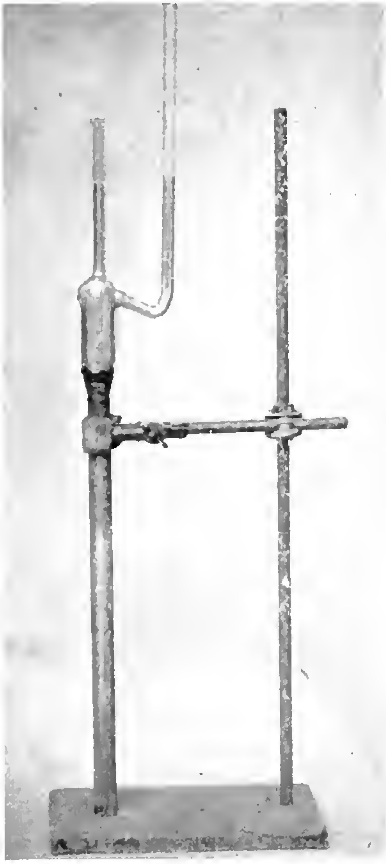

Fig. 3. Apparatus Showing Partial Displacement of Mercury by Hydrogen

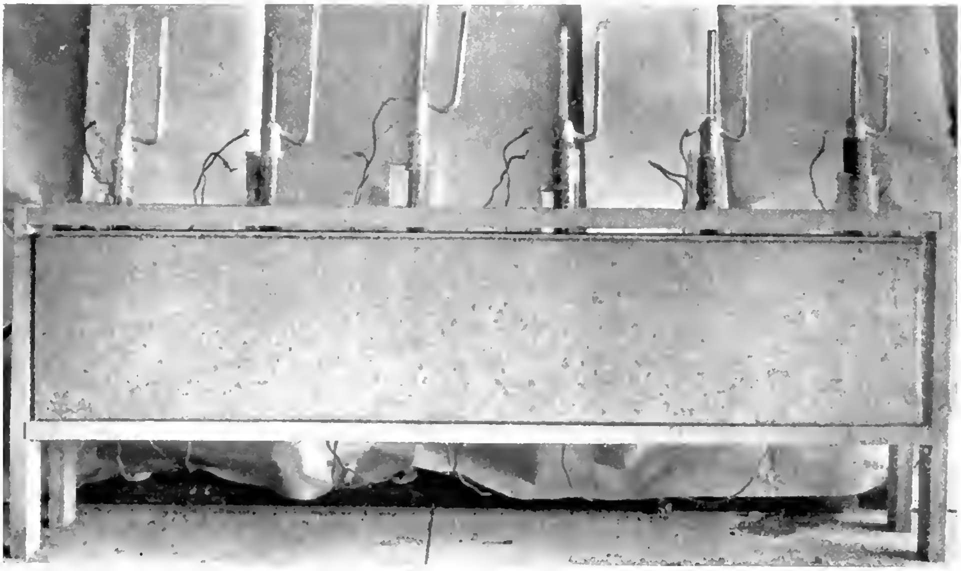

Fig. 4 Arrangement for Measuring Hydrogen Penetration at Different Temperatures

glass tube *C*, which terminates at the top in the U tube *D-E*. *D* is closed at the top and calibrated, and *E* is open. The capacity of *D* is about two cubic centimeters. *F* is a platinum wire which is sealed through the glass and dips into the mercury. *G* is an iron plug which is brazed into the bottom of the iron tube *A*. *H* is a section of rubber tubing which protects the brazed joint between *A* and *B*, as well as *B* itself, from the action of the electrolyte, and *I* is a coating of rubber cement which protects the brazed joint between *A* and *G*. The finished unit is so arranged that the electrolyte comes in contact with only iron and glass. When the unit is complete it is sealed to a vacuum pump and tested for leaks. None have been used which could not be pumped out to a pressure of 0.005 mm. of mercury without showing a leak. After filling with mercury the units are ready for use.

Fig. 2 is a photograph of one of the units completely filled with mercury, and Fig. 3 is a photograph of another unit, the mercury in the measuring tube of which has been partially displaced by the hydrogen which has collected. Fig. 4 shows the scheme for measuring the rate of hydrogen penetration at different temperatures. Six units are immersed in glass tubes, containing the electrolyte, these tubes being in turn immersed in an electrically heated water-bath.

Effect of Current

To determine the relation between current and the rate of hydrogen penetration, four units were made cathode in one per cent sulphuric acid at room temperature, the units being connected in the circuit by means of the platinum wire *F*. Platinum anodes were used. Two of the units were electrolyzed with a current of 0.2 amp. and two with a current of 0.5 amp. The potential across the former cell was 2.5 volts and across the latter 2.8 volts.

Two of the units were electrolyzed a second time.

In every case a current of 0.5 amp. allowed more hydrogen to penetrate the iron than did a current of 0.2 amp., but not 2½ times as much. The velocity of hydrogen penetration is not a straight line function of the current. The rate is influenced by the current; the higher the current, at least for such densities as were used in this experiment, the greater the velocity of penetration.

No Electrical Connections

One of the units was immersed, without electrical connections, in a solution of one per cent sulphuric acid, in other words "pickled." (Table II.)

At the end of 48 hours, hydrogen somewhat in excess of 2 cc. had collected. This rate of penetration is higher than the rate for the units made cathode with currents of 0.2 or 0.5 amperes.

Effect of Repeated Electrolysis

The same unit was made cathode in a one per cent sulphuric acid solution under the same conditions for four successive runs without intervening rest periods. (Table III.)

The velocity of penetration increased with each successive electrolysis.

Effect of Acid "Pickle"

A unit which had been pickled for 48 hours in one per cent sulphuric acid was immediately made cathode in the usual manner. Electrolyte was of one per cent sulphuric acid. (Table IV.)

TABLE I

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
(1) Iron—New	0.2 amp.	19 hr.	20 deg. C.	0.55 cc.
(2) Iron—New	0.5 amp.	19 hr.	20 deg. C.	1.85 cc.
(3) Iron—New	0.2 amp.	24 hr.	20 deg. C.	0.15 cc.
		39 hr.	20 deg. C.	0.90 cc.
		42 hr.	20 deg. C.	1.00 cc.
(4) Iron—New	0.5 amp.	24 hr.	20 deg. C.	0.40 cc.
		39 hr.	20 deg. C.	1.35 cc.
		42 hr.	20 deg. C.	1.50 cc.
(5) Iron—same unit used in (3)	0.2 amp.	24 hr.	20 deg. C.	0.30 cc.
		33 hr.	20 deg. C.	1.00 cc.
		48 hr.	20 deg. C.	2.40 cc.
(6) Iron—same unit used in (4) . .	0.5 amp.	24 hr.	20 deg. C.	0.30 cc.
		33 hr.	20 deg. C.	1.47 cc.
		48 hr.	20 deg. C.	2.40 cc.

TABLE II

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—New	24 hr.	20 deg. C.	0 cc.
	27 hr.	20 deg. C.	0.02 cc.
	33 hr.	20 deg. C.	0.42 cc.
	48 hr.	20 deg. C.	2.00 cc.

TABLE III

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—New. . . .	0.5 amp.	24 hr.	20 deg. C.	0.40 cc.
	0.5 amp.	39 hr.	20 deg. C.	1.35 cc.
	0.5 amp.	42 hr.	20 deg. C.	1.5 cc.
Same unit used above	0.5 amp.	24 hr.	20 deg. C.	0.30 cc.
	0.5 amp.	33 hr.	20 deg. C.	1.47 cc.
	0.5 amp.	48 hr.	20 deg. C.	2.00 cc.
Same unit used above	0.5 amp.	5.75 hr.	20 deg. C.	0.38 cc.
	0.5 amp.	6.25 hr.	20 deg. C.	0.46 cc.
	0.5 amp.	21.5 hr.	20 deg. C.	1.82 cc.
Same unit as above .	0.5 amp.	20 minutes	20 deg. C.	0.08 cc.
	0.5 amp.	7.5 hr.	20 deg. C.	2.10 cc.

TABLE IV

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
"Pickled" 48 hr. in one per cent H_2SO_4.	0.2 amp.	5.25 hr.	20 deg. C.	2.20 cc.
Same unit used above. . . .	0.2 amp.	20 minutes	20 deg. C.	0.20 cc.
	0.2 amp.	7.5 hr.	20 deg. C.	2.10 cc.

The acid "pickle" facilitated the passage of the hydrogen enormously. The same volume of gas penetrated this unit in 5-7 hours as penetrated a new unit in 48 hours under the same conditions.

TABLE V

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—Previously electrolyzed five times, followed by a rest of 72 hours	0.5 amp.	23 hr.	20 deg. C.	0.25 cc.
	0.5 amp.	28.5 hr.	20 deg. C.	0.60 cc.
	0.5 amp.	31.5 hr.	20 deg. C.	0.92 cc.
		48 hr.	20 deg. C.	2.20 cc.

TABLE VI

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—Previously electrolyzed five times, followed by heating in air to 130 deg. C. for 4 hours.	0.2 amp.	24.5 hr.	20 deg. C.	0.03 cc.
	0.2 amp.	47.5 hr.	20. deg C.	0.50 cc.
	0.2 amp.	60 hr.	20 deg. C.	1.28 cc.
	0.2 amp.	67 hr.	20 deg. C.	1.9 cc.

Effect of Rest or Heating

Rest—A unit which had been electrolyzed five times, and whose penetration value was high, was allowed to rest for 72 hours and then made cathode in one per cent sulphuric acid. (Table V.)

Heating—Another unit which had been electrolyzed a like number of times, and whose penetration velocity was therefore high, was heated to 130 deg. C. for four hours in air and made cathode in one per cent sulphuric acid. (Table VI.)

Both of these units, after their respective treatments, behaved like new ones, that is, they showed penetration velocities equal to those of new tubes. The velocity of the latter unit which was electrolyzed with a current of 0.2 amp. was less than the former whose current was 0.5 amp.

If units which have been operating as cathode continuously for several days, and which show a high penetration value; or units which have been pickled for several days in acid, be heated to a temperature of 130 deg. C. for four hours, or be allowed to rest for 72 hours, they will behave like new units; that is, their hydrogen penetration value will have been reduced to that of new units.

Effect of Temperature

A rise in temperature increased the penetration velocity very greatly. A unit was made cathode in one per cent sulphuric acid at a temperature of 90 deg. C. (Table VII.)

The volume of hydrogen which collected in this unit in 3½ hours was equal to the amount collected in a similar tube electrolyzed under similar conditions at room temperature in 48 hours.

Two more units were electrolyzed simultaneously under similar conditions at a temperature of 80 deg. C. The two checked nicely with each other, but the rate of penetration was somewhat slower than the rate of the unit which was electrolyzed at 90 deg. C. The slower penetration was probably due to the difference in temperature. (Table VIII.)

The time required to collect 2 cc. of hydrogen at different temperatures, other conditions being equal follows:

Temperature	Time
20 deg. C.	48 hr.
80 deg. C.	4.75 hr.
90 deg. C.	3.5 hr.

Effect of Various Electrolytes

The rate of penetration varies with different electrolytes. Units were electrolyzed in one per cent solutions of sulphuric acid, potassium sulphate, potassium hydroxide and tap water. The electrolysis in potassium sulphate was done at a temperature of 20 deg. C. and is therefore compared to the behavior of a unit in sulphuric acid at that temperature, while the electrolyses in potassium hydroxide and tap water were done at 85 deg. C. and consequently are compared to the behavior of sulphuric acid at that temperature. (Tables IX, X, XI, and XII.)

The rate of penetration for the unit immersed in potassium sulphate is very slow, being 0.0019 cc. per hour. The rate for the unit in one per cent sulphuric acid is 0.024 cc. per hour, or at this temperature twelve and one half times the rate of the potassium sulphate electrolysis.

Electrolyte of One Per Cent Sulphuric Acid

Under the heading, "The Effect of Temperature," it was pointed out that a unit electrolyzed as cathode in one per cent sulphuric acid with a current of 0.2 amp. required 4.75 hours at a temperature of 80 deg. C. and 3.5 hours at a temperature of 90 deg. C. to collect 2 cc. of hydrogen. If it be assumed that the mean time, or 4.125 hours, would be required to collect 2 cc. of hydrogen at the mean temperature, or 85 deg. C., the relation shown in Table XIII will hold.

The time necessary to collect 2 cc. of hydrogen from an electrolyte of one per cent sodium hydroxide or tap water, other conditions being the same, is 15 times the time required to collect 2 cc. from an electrolyte of one per cent sulphuric acid.

Hot Water and Steam

Hydrogen produced by the reaction between tap water and iron, or steam and iron collected in the iron units at temperatures ranging from 50 deg. C to the boiling point. Tubes without electrical connections were immersed in water at 50 deg. C., 90 deg. C. and in steam. (Tables XIV, XV, and XVI.)

A straight line results from plotting the time required to collect equal volumes of hydrogen from the water-steam system against the corresponding temperatures, measured by the centigrade scale. The velocity of penetration of the hydrogen resulting from the reaction between steam and iron is greater at steam temperature than the penetration of the hydrogen of units made

TABLE VII

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—Had been electrolyzed once followed by a rest of 72 hours.	0.2 amp.	2 hr.	90 deg. C.	0.20 cc.
	0.2 amp.	2 hr. 50 min.	90 deg. C.	0.98 cc.
	0.2 amp.	3 hr. 20 min.	90 deg. C.	1.78 cc.
	0.2 amp.	3 hr. 30 min.	90 deg. C.	2.10 cc.

TABLE VIII

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Previously electrolyzed heated to 130 deg. C. for 4 hours.	0.2 amp.	2 hr.	80 deg. C.	0.10 cc.
	0.2 amp.	3.5 hr.	80 deg. C.	0.80 cc.
	0.2 amp.	4.5 hr.	80 deg. C.	1.69 cc.
		4.75 hr.		2.00 cc.
Previously electrolyzed heated to 130 deg. C. for 4 hours.	0.2 amp.	2 hr.	80 deg. C.	0.10 cc.
	0.2 amp.	3.5 hr.	80 deg. C.	0.60 cc.
	0.2 amp.	4.5 hr.	80 deg. C.	1.65 cc.
	0.2 amp.	4.75 hr.	80 deg. C.	2.00 cc.

TABLE IX
ELECTROLYTE OF ONE PER CENT POTASSIUM SULPHATE

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—New........	0.2 amp.	168 hr.	20 deg. C.	0.2 cc.
		216 hr.	20 deg. C.	0.25 cc.
		264 hr.	20 deg. C.	0.45 cc.
		312 hr.	20 deg. C.	0.58 cc.

TABLE X
ELECTROLYTE OF ONE PER CENT SULPHURIC ACID

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—New........	0.2 amp.	24 hr.	20 deg. C.	0.15 cc.
		39 hr.	20 deg. C.	0.90 cc.
		42 hr.	20 deg. C.	1.00 cc.

TABLE XI
ELECTROLYTE OF ONE PER CENT SODIUM HYDROXIDE

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Iron—New........	0.2 amp.	31.5 hr.	85 deg. C.	0.11 cc.
	0.2 amp.	40 hr.	85 deg. C.	0.37 cc.
	0.2 amp.	49 hr.	85 deg. C.	0.41 cc.
	0.2 amp.	60.5 hr.	85 deg. C.	2.00 cc.

TABLE XII
ELECTROLYTE OF TAP WATER

Description of Unit	Current	Time	Temp.	Volume of Hydrogen collected
Iron—New........	0.2 amp.	21.0 hr.	85 deg. C.	0.05 cc.
	0.2 amp.	30.5 hr.	85 deg. C.	0.85 cc.
	0.2 amp.	43.0 hr.	85 deg. C.	1.51 cc.
	0.2 amp.	61.5 hr.	85 deg. C.	2.00 cc.

cathode in the usual manner in one per cent sulphuric acid at room temperature, and less than the hydrogen of units electrolyzed, in one per cent sulphuric acid at 90 deg. C.

The relative rates follow:

Unit electrolyzed in one per cent sulphuric acid at 90 deg. C.	14
Unit immersed in steam	2.5
Unit electrolyzed in one per cent sulphuric acid at 20 deg. C	1

PENETRATION OF COPPER AND NICKEL STEEL UNITS

Copper Unit

A unit such as is shown in Fig. 1 was made up, having the tube *A* of copper instead of iron. After running as cathode under the usual conditions, namely, one per cent sulphuric acid, 0.2 amp. and 20 deg. C., there was no evidence of gas having collected at the

TABLE XIII

Electrolyte	Time Required to Collect 2 cc. of Gas Under the Same Conditions at 85 deg. C.	Relative Rate of Penetration
1 per cent Sodium Hydroxide Tap Water	60.5 hr.	1.02
	61.5 hr.	1
1 per cent Sulphuric Acid	4.125 hr.	15

TABLE XIV
WATER AT 50 DEG. C.

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—New	3 hr.	50 deg. C.	0.10 cc.
	24 hr.	50 deg. C.	0.19 cc.
	84 hr.	50 deg. C.	0.22 cc.
	112 hr	50 deg. C.	0.40 cc.
	172 hr.	50 deg. C.	0.51 cc.
	180 hr.	50 deg. C.	0.55 cc.
	188 hr.	50 deg. C.	0.60 cc.

TABLE XV
WATER AT 90 DEG. C.

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—New	24 hr.	90 deg. C.	0.30 cc.
	40 hr.	90 deg. C.	0.50 cc.
	48 hr.	90 deg. C.	0.69 cc
	88 hr.	90 deg. C.	1.50 cc.

TABLE XVI
STEAM AT ATMOSPHERIC PRESSURE

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron New	2 hr.	100 deg. C.	0.15 cc.
	3 hr. 10 min.	100 deg. C.	0.20 cc.
	4 hr. 20 min.	100 deg. C.	0.29 cc.
	5 hr. 25 min.	100 deg. C.	0.38 cc.
	6 hr.	100 deg. C.	0.40 cc.
	7 hr. 15 min.	100 deg. C.	0.50 cc.
	7 hr. 50 min.	100 deg. C	0.52 cc.
	9 hr. 10 min.	100 deg. C.	0.57 cc.
	10 hr. 25 min.	100 deg C.	0.60 cc.

end of 384 hours. At this point mercury had amalgamated with the copper to such an extent that the electrolysis had to be discontinued.

Nickel Steel Unit

Another unit was made up having the tube *A* of 3 per cent nickel steel. This was electrolyzed under the usual conditions. (Table XVII.)

The penetration rate was roughly the same as the rate for iron under similar conditions.

Penetration of Iron Units Coated in Different Ways

Four iron units, having the tube *A* of each unit treated with a different coating, were immersed in steam at atmospheric pressure. The coatings were tin (dipped), zinc (galvanized), zinc (sherardized, and copper (dipped).

In this experiment the hydrogen from steam penetrated the tinned iron unit much more rapidly than it did a unit of iron. The passage of the hydrogen was evidently facilitated by the presence of the tin. The rate for the two zinc-coated units was less

TABLE XVII

Description of Unit	Current	Time	Temp.	Volume of Hydrogen Collected
Nickel Steel	0.2 amp.	4 hr.	20 deg. C.	0.04 cc.
	0.2 amp.	23.5 hr.	20 deg. C.	1.00 cc.
	0.2 amp.	29.5 hr.	20 deg. C.	1.20 cc.
	0.2 amp.	54.5 hr.	20 deg. C.	1.80 cc.

TABLE XVIII

TINNED IRON

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—Dipped in molten tin	3.0 hr.	100 deg. C.	0.40 cc.
	8.5 hr.	100 deg. C.	1.12 cc.
	16.0 hr.	100 deg. C.	1.62 cc.
	22.5 hr.	100 deg. C.	2.00 cc.

GALVANIZED IRON

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—Dipped in molten zinc	3.0 hr.	100 deg. C.	0.20 cc.
	20.0 hr.	100 deg. C.	0.72 cc.
	31.5 hr.	100 deg. C.	0.90 cc.
	45.5 hr.	100 deg. C.	1.10 cc.

SHERARDIZED IRON

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—Heated in zinc powder	1.5 hr.	100 deg. C.	0.15 cc.
	13.0 hr.	100 deg. C.	0.40 cc.
	28.0 hr.	100 deg. C.	0.45 cc.
	45.0 hr.	100 deg. C.	0.60 cc.

COPPERED IRON

Description of Unit	Time	Temp.	Volume of Hydrogen Collected
Iron—Dipped in molten copper	40 hr.	100 deg. C.	0 cc.
	44 hr.	100 deg. C.	0.10 cc.
	47 hr.	100 deg. C.	0.14 cc.
	103 hr.	100 deg. C.	0.72 cc.

than for iron. The rate for the coppered unit was very slow, and probably no hydrogen would have penetrated had the coating been thick and uniform. It is likely that the hydrogen went through the iron and not the copper, in small areas where the latter had corroded away.

The comparative rates for iron, and for iron with the various coatings, in steam at atmospheric pressure follow:

Description of Unit	Time Required to Collect 0.60 cc. of Gas	Relative Rate of Penetration
Tinned Iron	4.0 hr.	21.0
Iron	10.5 hr.	8.2
Galvanized Iron	15.5 hr.	5.5
Sherardized Iron	45.0 hr.	1.9
Coppered Iron	86.0 hr.	1

Experiment with Barium Chloride and Potassium Dichromate

Evidence that the hydrogen which collected in the units was produced outside the tube and forced through the metal under pressure, and was not produced by the acid leaking into the tube, and later reacting with the metal, was furnished by two experiments.

(1) An iron unit was immersed, without electrical connections, in one per cent sulphuric acid for 22 hours, during which time 2.4 cc. of hydrogen collected. The unit was then emptied of mercury and 10 cc. of distilled water poured in and shaken so as to come well in contact with the inside surface of the iron tube. This water solution gave a negative test for sulphates with $BaCl_2$, indicating that no sulphuric acid had come in contact with the inside of the tube.

(2) Another unit was immersed, without electrical connections, in a solution of one per cent sulphuric acid to which had been added one per cent of $K_2Cr_2O_7$. No gas collected in this unit after immersion for 96 hours.

The fact that the oxidizing action of the one per cent $K_2Cr_2O_7$ in one per cent sulphuric acid solution prevents the passage of hydrogen through the iron, at least for 96 hours; and that the inside of an iron unit pickled for 22 hours in one per cent sulphuric acid showed a negative test for sulphates, furnish additional evidence that the hydrogen which collects inside the units is formed on the outside and forced through the iron walls, and is not formed on the inside by reaction between the iron, and some sulphuric acid, which has by some seemingly impossible means leaked through to the inside of the tube.

Composition of the Gas

A sample of gas, which was collected in an iron unit electrolyzed as cathode in the usual manner, showed the following analysis:

Oxygen	None
Carbon Monoxide	None
Carbon Dioxide	None
Hydrocarbons	None
Hydrogen Sulphide	None
Hydrogen	94.8 per cent 94.5 per cent

The remaining 5 per cent was an incombustible gas such as N_2.

Another sample of gas, which was collected in an iron unit immersed in steam at atmospheric pressure, consisted largely of hydrogen.

Conclusion

It has been shown that hydrogen penetrates iron at temperatures between 20 deg. C. and 100 deg. C. under a great variety of conditions, all of which influence the rate. The velocity of hydrogen penetration is greater for a unit immersed, without electrical connections, in one per cent sulphuric acid than for units electrolyzed as cathode in a like solution, with such current densities as were tried. The rate for electrolyzed units is influenced by the current; the higher the current, for such densities as were used, the higher the rate, but the relation is not a straight line function. The penetration velocity increases with each successive electrolysis, provided rest periods do not intervene, or with acid "pickling." The effect of rest or moderate heating upon units which have been electrolyzed or pickled is to restore the original resistance of the iron to the passage of hydrogen. Temperature has a marked effect, the rate of penetration increasing with the temperature. The rate at 90 deg. C. for an iron unit made cathode in one per cent sulphuric acid with a current of 0.2 amp. is 11 times its rate under similar conditions at 20 deg. C. The velocities of penetration for units electrolyzed in one per cent solutions of potassium sulphate and sodium hydroxide, and in tap water, are about equal and are 1/12-1/15 the velocity of units electrolyzed in one per cent sulphuric acid.

Hydrogen produced by the reaction between tap water at temperatures from 50 deg. C.-100 deg. C. and iron, or between steam and iron, penetrates the metal at a rate depending directly upon the temperature. The oxide which is one of the products of the reaction forms a coating on the metal, which becomes thicker and thicker, and finally protects the iron from further action. If it were not for this coating of iron oxide, iron pipes carrying hot water or steam would continually give off hydrogen and quickly deteriorate.

The velocity of penetration for 3 per cent nickel steel is the same as that for iron. Hydrogen does not penetrate copper at a temperature of 20 deg. C. The rate for tinned iron is greater than for iron; and for galvanized, sherardized and coppered iron is less. It seems that the passage of hydrogen is facilitated by the presence of tin and retarded by zinc and copper. No evidence of sulphates could be found inside a unit which had been pickled in sulphuric acid and in which 2.4 cc. of hydrogen had collected. No hydrogen penetrated a unit immersed in a solution of one per cent sulphuric acid plus one per cent potassium dichromate in 96 hours. The gas which was collected in one of the units was analyzed and found to contain 95 per cent hydrogen and 5 per cent of an incombustible gas, possibly nitrogen.

The facts will admit of the following explanation of the manner in which hydrogen is forced through iron tubes having walls $\frac{1}{16}$ in. in thickness. Atomic hydrogen (H) which has been liberated by the current, in the case of units which were electrolyzed, or by the reaction between metal and solution in the case of units which were not electrolyzed, penetrates the iron, where gaseous or molecular hydrogen (H_2) is later formed. Iron at room temperatures is impermeable to the latter. The atomic hydrogen continues to penetrate the surface of the metal rapidly and to form molecular hydrogen. The latter can escape only very slowly and as a pressure sufficient to force the gas through the metal is built up. It is a pressure built up in this way which also results in the well known phenomenon of the cracking of hardened steel when "pickled" in acid.

The writer hopes that the experiments which have been described in this paper will help to focus the thought of electro-chemists on these problems, and that as a result a more comprehensive understanding of the mechanism of the passage of hydrogen through iron at temperatures equal to or below the boiling-point of water may be had.

The White Mazda Lamp

By Earl A. Anderson

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Of late years, absence of glare is becoming recognized as one of the essentials of good lighting. A number of schemes have been developed to eliminate glare by manipulating the light after it has left the lamp; for example, variations of semi-indirect and indirect lighting. The latest method in connection with moderate wattage incandescent lamps is the reduction of glare at its source by the use of the lamp described in the following article.—Editor.

Within the past few years many illuminating engineers have been turning their attention more and more strongly toward the elimination of that bugbear of many lighting installations—glare. Although much has been done to minimize this evil in industrial installations, until recently little consideration has been accorded it in residential lighting. The newly developed white Mazda lamp, on account of the softness of its light, has proved especially effective in reducing the glare so often found in lighting units in the home.

Distinctive Features

The outstanding characteristic of this lamp is the diffusion of its light. As shown in Fig. 1, the bulb is made of a special white glass, designed expressly for the purpose of minimizing glare. The large volume of light which the filament emits is diffused to the point where the bulb itself appears luminous. The brightness of the bulb is about 13 candle-power per square inch over the brightest square inch of area which is, of course, far below that of the filament of a Mazda lamp.

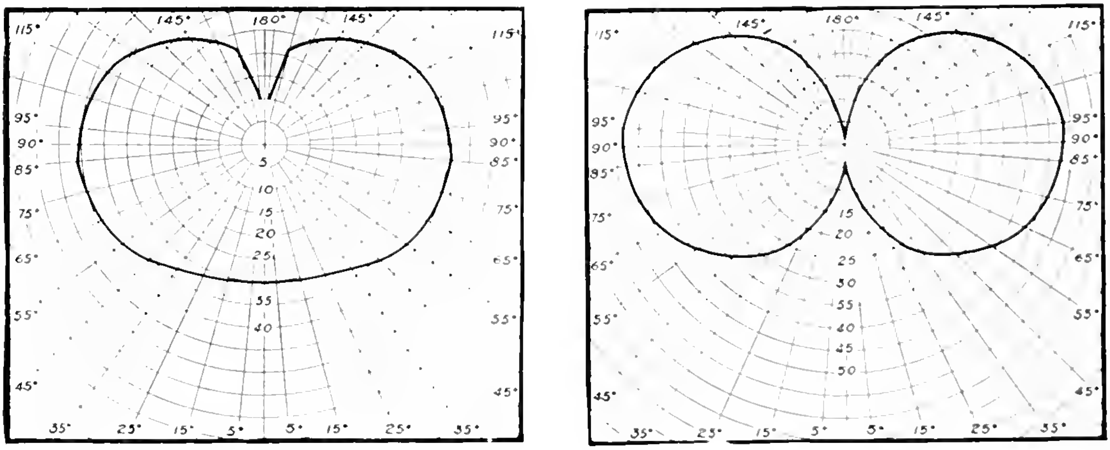
It has been pointed out by many illuminating engineers that glare (which, however defined, is ultimately light that hurts the eye) is to a considerable extent a matter of brightness contrast. The illustration of automobile headlights, which are glaring at night but which are scarcely noticeable during the day, may be recalled. Because of the softness of its light, the white Mazda lamp can be used satisfactorily in locations where other incandescent lamps unless frosted would be objectionably bright. Frosting the bulb has always proved an effective means of reducing the brightness of the incandescent lamp, but the practice has not been widely followed largely because the frosted bulb collects dust and dirt more quickly than a clear bulb and is more difficult to clean. The bulb of the white Mazda lamp is smooth and is as readily cleaned as a clear-glass bulb.

Fig. 1. White Mazda 50-Watt Lamp

The white Mazda lamp is made in the 50-watt size, and, notwithstanding the low brightness of the bulb, has an output of approximately 450 lumens. As shown in Table 1, the efficiency of the lamp is about 9 lumens per watt. Its maximum dimensions are about the same as those of the 40 and 50-watt Mazda B lamps; it is $2\frac{1}{2}$ inches in diameter at the largest point, as compared with $2\frac{3}{8}$ inches for the 40 and 50-watt Mazda B lamps. The lamp is designed for use on standard lighting circuits between 110 and 125 volts, and, in common with all incandescent lamps, operates most effectively at the voltage specified on the lamp by the manufacturer.

An especial feature of the new lamp is its tipless construction. This is produced by an ingenious method of manufacture in which the lamp is exhausted through a tube attached to the stem at the base of the lamp. The absence of the tip results in an appreciable reduction in lamp breakage, and presents a smooth surface.

The 50-watt white Mazda lamp can be burned in any position.



White Mazda

Zone	Lumens	Per Cent Total Clear Lamp
0–60	108	24
0–90	234	52
90–180	216	48
0–180	450	100

Mazda B

Zone	Lumens	Per Cent Total Clear Lamp
0–60	95	21
0–90	236	51
90–180	235	51
0–180	472	100

Fig. 2. Candle-power Distribution Curves of Bare White Mazda Lamp and Bare Mazda B Lamp

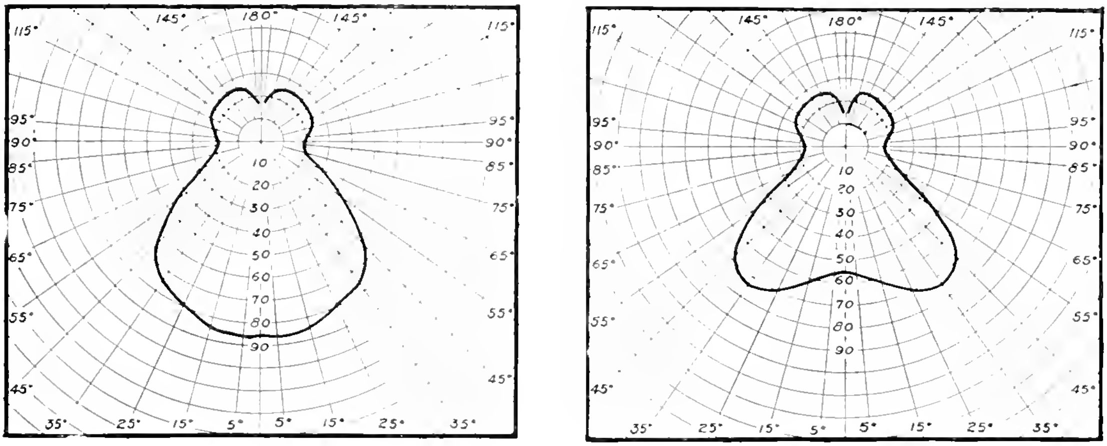
TABLE I

DATA ON THE WHITE MAZDA 50-WATT LAMP

Wattage	Voltage	Approximate Total Lumens	Approximate Lumens Per Watt	Type of Bulb	Bulb Diameter Inches	Maximum Over-all Length, Inches	Base
50	110 to 125	450	9	Pear Shape	$2\frac{1}{2}$	$5\frac{1}{8}$	Med. Screw

Light Distribution

The curves given in Fig. 2 show the distribution of light of the bare white Mazda lamp compared with that of the bare Mazda B lamp. As would be expected, due to the diffusive quality of the bulb of the white lamp, the distribution curve shows a greater candle-power end-on than in the case of the clear Mazda B lamp.



White Mazda

Zone	Lumens	Per Cent Total Clear Lamp
0- 60	207	42
0- 90	277	56
90-180	146	30
0-180	423	86

Mazda B

Zone	Lumens	Per Cent Total Clear Lamp
0- 60	197	41
0- 90	264	55
90-180	143	30
0-180	407	85

Fig. 3. Distribution Curves of White Mazda Lamp and Mazda B Lamp, Both with Bowl-shaped Opal Glass Reflector

In Table II are given the results of tests made to determine the effect of the diffusing bulb upon the output of typical lighting units. Figs. 3 and 4 are examples of distribution curves for two common reflectors. It will be noted that there is but little difference in the absorption of any of the units tested, when equipped respectively with Mazda B and with white Mazda lamps. This is due to the fact that the bare white lamp gives a slightly larger percentage of downward light which compensates for the light lost by cross-reflection between the reflector and the white glass bulb of the lamp.

TABLE II

COMPARATIVE DATA ON LIGHT OUTPUT

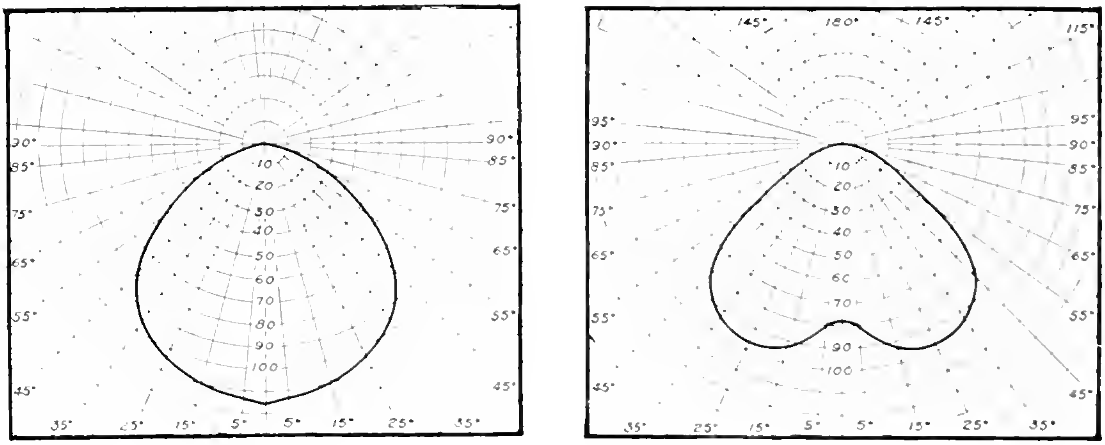
Type of Unit Tested	OUTPUT IN PER CENT OF BARE LAMP OUTPUT	
	Mazda B	White Mazda
Glass Bowl, 6-inch Diameter	85.4	87.6
Glass Bowl, 7-inch Diameter	84.8	86.1
Enclosing Unit	77.5	76.4
Enameled-steel Bowl	60.5	61.3

Field of Application

The white Mazda lamp can be used to advantage in place of the similar sizes of Mazda B lamps in the same reflector equipments. The effect produced by using white lamps in semi-indirect fixtures is particularly pleasing, for distinct shadows of the bowl edge, of the bowl suspension, and of the leads, and all striations on the ceiling are eliminated because of the larger area from which the light comes. For the same reason, the white bulbs are also particularly desirable for portable lamps, where their use will eliminate the formation of grotesque, and frequently annoying, shadows upon the walls or upon the pages of a book. For example, fringe shadows, which are often very disagreeable, are eliminated.

With regard to the service which may be expected from white Mazda lamps, it may be said that experience shows a satisfactory degree of ruggedness for the lighting of homes, offices, hotels and public buildings. Increased usage of these lamps is found in the many pleasing effects obtained by their installation at motion picture and hotel entrances. In many decorative types of fixtures the use of white Mazda lamps has proved very effective in enhancing the artistic appearance. The low brightness of these lamps has resulted in their being used in local lighting units for the inspection of machined interiors and similar places difficult to light with any general lighting system.

The tendency to use the white Mazda lamp without reflecting equipment because of the softness of its light should be discouraged. For most locations the bulb is still too bright to be used alone, and in addition to reducing glare, it is just as important, from the standpoint of effective distribution of the light generated, that a good reflector be used with this as with any other incandescent lamp.



White Mazda

Zone	Lumens	Per Cent Total Clear Lamp
0–60	264	54
0–90	301	61

Mazda B

Zone	Lumens	Per Cent Total Clear Lamp
0–60	252	52
0–90	284	59

Fig. 4. Distribution Curves of White Mazda Lamp and Mazda B Lamp, Both with Bowl shaped Enameled Steel Reflector

The Reward for Efficiency*

By Hon. Edwin O. Edgerton

President, Railroad Commission of the State of California

Mr. Edgerton's belief is that the best of which man is capable is never produced by punishment. Man exerts himself to the utmost only when he sees before him a reward proportionate to his efforts. Maximum efficiency from man and machine is to the best interests of the public, and knowledge by the former that merit will be quickly recognized will serve best to bring about this condition. What is true of the individual worker with respect to reward is also true of the investor, the manufacturer, the public utility, and the public service commission.—Editor.

Introduction

I want to define in my own way the subject which has been given me. I want to broaden it from a mere discussion of definite specific reward and treat it from the standpoint of inducement to do the best that is in each man who is connected with this great industry, and also, finally, I want to suggest inducement to the public utility commissioners to do their best, and on that score I want to say something along the line of what you gentlemen owe these Commissions.

Let us take money. By the way, for some reason that I have not been able to understand—and I have made considerable inquiry on the subject—finance is excluded from public discussion, as an ordinary thing. I looked over your program—and I speak in no sense of criticism—I looked over your program seeking the place where finance would be discussed, and I found nothing. Today, at least in California—and I think it is true over the nation—the greatest single job that we have is to finance these public utility concerns. And why that great subject should not be pulled frankly out into the open so that the most of intellect and ability can be brought to bear, I don't understand.

If I dwell too much on California conditions, it is not in any provincial spirit, it is not in any way feeling that we out here dominate the situation in any degree, but it is first because I know California conditions better, and, next, because of the situation we are in; the problems perhaps are accentuated out here as compared with those of the East.

Now, the job immediately ahead of financing these public utilities is a huge one. In California every time I have made an estimate of the amount of money required in the next few years, I have found that somebody raises that estimate. I started in with $250,000,000 in the next ten years, and I have been raised now to $500,000,000; and I don't know where it is going to end.

The other day in Chicago a very famous banker was on the witness stand before the Public Utility Commission of Illinois, and he made this statement, published largely over the nation, that anybody who invested in public utility stock needed a guardian. I don't admit that the electric public utilities of California are financially sound, basically sound. I affirmatively assert, I insist that it is true, and I say that that statement as a generalization is unsound, and as applied to California is particularly unsound; that sort of statement has the effect of offsetting in some degree at least the efforts that are being made to build up the credits of these companies in order that the investors may have confidence and assurance. And a gentleman of prominence who goes publicly on the witness stand and makes a statement of that kind ought to be careful that by a glittering generality he does not do serious damage, probably not intended by him.

I am one of those who believe that you cannot produce the best that is in men and women by punishment. You cannot whip a man into efficiency. In that belief I am convinced you must proceed by inducement; that every one of us in some degree, in order that he may do the best that is in him, requires that before his eyes there be some reward.

Let us apply that to the fellow who has money to invest. I recognize that we cannot get money out here from the East into California by threat, by argument, by any form of punishment, by any suggestion that because of investment already made they cannot quit; I recognize that the money must come by inducement; and in my judgment it can be induced without paying exorbitant and unreasonable prices for it. We must bid for it, yes; but must we bid for it against speculative securities, against anything anybody is willing to offer, bid for it against the man who offers a chance for large reward? No; I say not. I believe that we have assets in California which, if properly used, will produce the fundamentals of inducement to investors, this

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* An address before the Annual Convention of the N.E.L.A., Pasadena, Cal., May, 1920.

being absolute security of the investment itself, the assurance that the dollar will not become 90 cents or something less, coupled with certainty and regularity of return. And if we have these assets, why not make use of them? Then if money is available on any terms, we will get that money.

Service an Asset

Now, what are these assets? Power houses and transmission lines? Surely. But over and above that we have the assets of a great vital and essential service—a service which the people must have, a service which they cannot get along without. And that is an assurance to an investor that that asset cannot disappear. My judgment is that the public utility financiers and the Railroad Commission have these assets in trust for the people—I think they can make bitter complaint if we do not use them coupled with others, so as to produce the necessary money to do the absolutely essential development that must go forward in this state.

If it is necessary now to persuade investment, to insure regularity and certainty of return, why not face that fact? Why continue to indulge in discussions of technical methods of valuation never settled? Eight years' experience now in the Railroad Commission, with constant discussion of the methods of valuation and proper rate bases and reading of the decisions of courts, puts me in a position to say to you that those questions are no more certainly settled today than they were eight years ago. Now, why not face that as a fact, and why not seek some other method of determining the rate of return the company should get? To face the situation clearly and conscientiously, what methods shall we now pursue?

My judgment is that the thing to do is to start with sound capitalization—an admitted, agreed, established capitalization, and thereafter fix rates based on getting the necessary bond interest, dividends, and fixed charges to support that capitalization. Then in order to meet the contention of the investor that perhaps later a different policy may be adopted, set up a cash reserve out of rates, to be rigidly held for the purpose of insuring bond interest and dividends, so that when you take your securities to the money markets of the country the investor can be shown an actual cash reserve as an insurance policy for his bond interest and dividends. I realize that this suggestion means almost a complete reversal of the attitude of regulating bodies towards this question. But why not? If it is the sound thing to do, why not reverse the attitude?

Degrees of Efficiency

By the way, I make these suggestions in no spirit of finality. If there is one thing I have learned, it is that final opinions are never final. But I do make them for the purpose of starting discussion on this important subject. If those suggestions are not sound, weaknesses may be pointed out, and I for one will welcome such suggestions. I welcome criticism of regulation in California, only providing that the fellow who criticises accords to me the same thing that I accord to him, and that is sincerity of purpose.

Now, there is something else—rewards for efficiency. Are all the electric public utilities at the highest point of efficiency? Well, they are not all here, so we can say they are not. And I think we can conclude that there are different degrees of efficiency among the companies. I believe it is sound to suggest that inducements definitely be held up to the companies to become thoroughly efficient. I think it would pay the public to hold up definite rewards to that end. And incidentally that suggestion has been made quite frequently to our Commission and others. There is a feeling and has been for years that regulation has a tendency to hold the return down to a dead level, that the inefficient company enjoys the same rate of return as the efficient company, no more, no less, and initiative is destroyed. Why work, toil, think, to produce efficiency if the regulating body immediately appropriates the results to reduce rates. A very fair suggestion. But this is to be thought of. Whom must you reward to get efficiency?

Now, if you have taken care of the investor, if you have produced a situation where his investment is safe and intact, his return is regular and sure, must you stimulate him to make him efficient? Well, I would suggest that that is not quite what we are thinking of. Then who is it that we should stimulate by offer of reward? In my judgment, it is the organization of the company itself. Now don't misunderstand me. When I say "organization" I mean from the president to the office boy. I don't believe it produces efficiency merely to hand the management, as such, the reward; in fact, I am inclined to think that that would produce the opposite effect, because all down through the organization would go the feeling that the reward earned by each individual's efforts was going to somebody else, and there is not anything in the American mind that produces more resentment than that situation.

Employees Interested

Rewards for efficiency. Yes, the regulating body, in my judgment—and I think the time has come to consider that seriously—ought to give definite assurance that for increased efficiency and economy, always coupled with good service, a reward should be accorded by the regulating body. But having said that, the job thereafter, in my judgment, is distinctly one of management to make it effective. Management to make it effective must see to it that every member of the organization, no matter how humble, is made to understand thoroughly that his increased efforts towards efficiency and economy will be rewarded. And I speak of reward not only in a money sense, but I speak of recognition of service well performed by men lower in the ranks; I speak of certainty of advancement when opportunity comes; I speak of the absolute elimination of pull or influence in promotion in the organization; I speak of a situation where the management studies personnel, works at the problem, is constantly on the job—first to know what its personnel really is, to know when efficiency and economy are being striven for by the individual in the ranks, and then with absolutely dead certainty to reward that effort on the part of the members of the organization.

Aids Labor Situation

I have had clerks telephone me from the inside of public utility organizations, fearful to give their names to me, complaining that the entire class represented by the speaker over the telephone had been overlooked in the wage increase, and that the wage increase had been given in large part to the organized employees. And in that clerk's heart was the sense that because of that organization, because of the threat held up to the management, additional wages had been accorded and merit had been forgotten.

I think that there is no better way to solve the question often called the labor question—there is no better way to take the body of labor, working people, clerks, away from the demagogue leader of the union than to accord to every individual in an organization rewards for efficiency. It is the best safeguard against the chap who comes about preaching anarchy, preaching this proposition, and it is always his fundamental proposition and he is clever enough to understand it: "You are not getting a square deal." What better safeguard could there be against the agitator than to have in the heart of the fellow he comes to, the knowledge that he *is* getting a square deal? That is better, in my judgment, than all the panaceas that have been suggested; but it requires on the part of the management, work, thought, study, effort.

I remember talking to one of the directors of a company that is generally considered—and I think properly so—one of the most efficient in the United States in the matter of organization. It is generally understood that the employes of that company seldom quit. I began to be interested to know why, and so I talked to one of the directors. Here is the system: He said, "It is the job of the highest officers in our company, it is their principal job to study, to watch, to investigate, to come in contact with all of the employees of the company. A rigid rule is adopted that promotions are made upon merit, that in no instance is an outside man called into the organization unless there is in the organization no one with the special knowledge required at the moment; that men starting with the company have an assurance of a career for life, and that they have the assurance that they will be constantly promoted as opportunity offers." And I said to him: "Well, if this is the job of the principal officers of the company, how do you find time for the ordinary business of the concern?" "Well," he said, "if our organization is efficient, the business takes care of itself. In other words, we sharpen the tool, and we have the confidence thereafter that it will cut."

Commissions Interested

The Railroad Commission—it, too, should be efficient. We are the same kind of animals as you fellows—no different. True, the job is a little different; but in a real sense we are wrapped up in your success, will suffer by your failure. Remember, if the private ownership and operation of public utilities goes down in failure, regulation goes down with it. No matter whether the Commissioners can point the finger of blame to the utility men, if the wreck occurs, regulation has failed.

So you fellows owe a duty to the public utility commissions. You should hold up the reward for efficiency on their part. And the only reward that you have available is affirmatively to make regulation as little necessary as possible; beat the regulating body to it, and you will do the best thing you can do for the regulating body. By the success of your own efforts in satisfying the public will you make the job of the utility commission a job worth having.

It is a cheap and easy thing, and sometimes results in temporary glory, for commissioners to denounce public utilities; but it is a very costly thing for the companies and for the commissioners, because finally a denunciation may go to the point of wreck, and regulation and commissioners go down with the wreck.

And finally, I will say this from the standpoint of California: There is a tremendous job ahead—a job for the electric utilities, a job which involves not only carrying forward the business which naturally accumulates, which normally increases, but the unquestioned job of taking over the work now being done out here by oil. There is not another substitute in sight for oil except hydroelectric energy; and it is a sobering thought to think of the tremendous responsibility this will place upon the electric utility men of this state and the Commission working with them. When you stop to think of a state like California, with agriculture, industry, and the people absolutely dependent upon the ability of electrical men to produce service, the responsibility that you not only ought to take upon your shoulders, but that you will have to take is staggering.

Industry Is a Unit

Now, realizing this fact, I make this suggestion, that it is the wise thing to do to approach this whole problem with an open mind, without any fear whatever of disclosing secrets, withholding information, striving for advantage, this company against the other, to solve the problem in a way that will be sound, considering the whole power situation. I believe the proper position for both the companies and the Commission to take is that it is one great problem, and that it is not sound operation on the part of the companies to allow one company to be seriously injured, because that injures the industry as a whole.

If to produce the service under the conditions that must be accorded the people it is necessary to consider complete unification of all plants, why not discuss it? I say the man who is afraid openly and frankly to discuss that subject is fearful it may succeed. Why doesn't the fellow who believes that there is an inherent fundamental weakness in unification gladly come forward and discuss it with anybody, in the conviction that he can defeat the suggestion?

I only suggest it, because I know it touches the heart of the fellow who has built up a company, who has been with it in fair weather and foul, and has a pride in that company in giving service, and has a pride in its entity. I know that, being a human being, he does not like to merge that company with another. I know that he feels he is giving good service and he is reluctant to consider the unification with other companies that he thinks are below him in the standard of service.

But why not discuss it? If it is the answer, then I say the personal feelings of each of us must go by the board. The great thing to accomplish is the doing of the job, and finally the public will hold us responsible for having the job done. It does not understand all the angles of the problem. The public of California today, if you suddenly said, "Let us put all the companies together under one great organization," might rebel, because it would not understand what that meant; but that does not exclude us from going forward with the discussion to see whether it is sound. My conception finally is that the electric public utility men, with the utility commission, are in responsible charge of doing the job. We must do it efficiently, and then we are entitled to our rewards. If we don't do it, we ought gracefully to take what undoubtedly will result.

IN MEMORIAM

George A. Woolley, Manager of the Denver District of the General Electric Company, died at his summer home in the mountains near Evergreen, Colorado, July 3, 1920. The immediate cause of his death was apoplexy superinduced by a cerebral hemorrhage.

GEORGE A. WOOLLEY

When a young man Mr. Woolley decided to make his home in the West, and in 1890 allied himself with the Edison Electric Company at Denver. He was soon made Manager of the Supply Department and held this position until the formation of the General Electric Company in 1893, when he was made District Manager of the Supply Department. In December, 1913, he was appointed District Manager and retained this position until his death.

On several occasions in early life opportunity to transfer his activities to other lines of business promising quicker and perhaps greater financial reward presented itself, but in each instance was rejected. He had unfailing faith in the ultimate success of the electrical industry and no amount of persuasion could make him forsake his chosen vocation.

Mr. Woolley's later years were saddened by the death of his younger son, Frederic H. Woolley, in October, 1918. Frederic was residing in Schenectady at the time of his death and was employed in the Testing Department of the Company. Mr. Woolley was deeply impressed by the great kindness shown to his son by the officials of the Company and their families during his sickness. Their sincere desire to comfort him as he was leaving Schenectady on the saddest of all his journeys was never forgotten. Many times since he has stated that a corporation is best judged by the personnel of its executives; that a company headed by officers considerate and kind enough to ignore the pressure of business to go to one in trouble, to extend their sympathy and share another's sorrow, cannot be classed as soulless.

The Company has lost an able, loyal and highly esteemed leader, and we in the Denver Office a revered friend and conscientious adviser.

Mr. Woolley was married to Semira Hartzell in Kearney, Nebraska, February 15, 1893. He is survived by his wife and his son, George Allan Woolley, who is at present in the employ of the Great Western Sugar Company.

Mr. Woolley was a member of the Quarter Century Club, Mohawk Club, Denver Motor Club, Denver Athletic Club and the Rotary Club.

B. C. J. Wheatlake.

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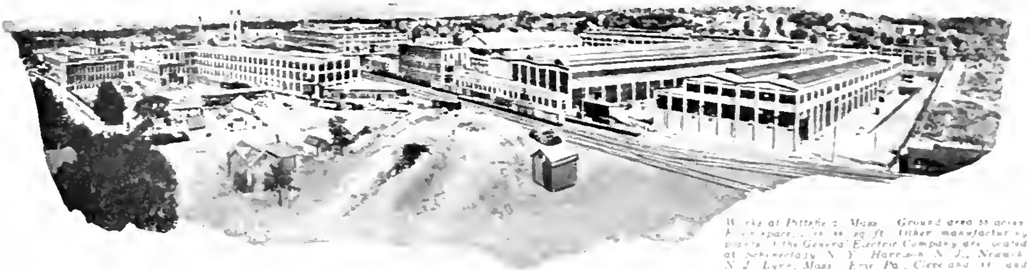

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SEPTEMBER, 1920

More Than Four Years of Electric Operation on the Mountain Divisions of the Chicago, Milwaukee & St. Paul Railway Have Amply Demonstrated the Merits of Electric Traction for Main Line Service. The operating results of this electrification for the year 1919 are published in the article, page 724

GENERAL ELECTRIC REVIEW

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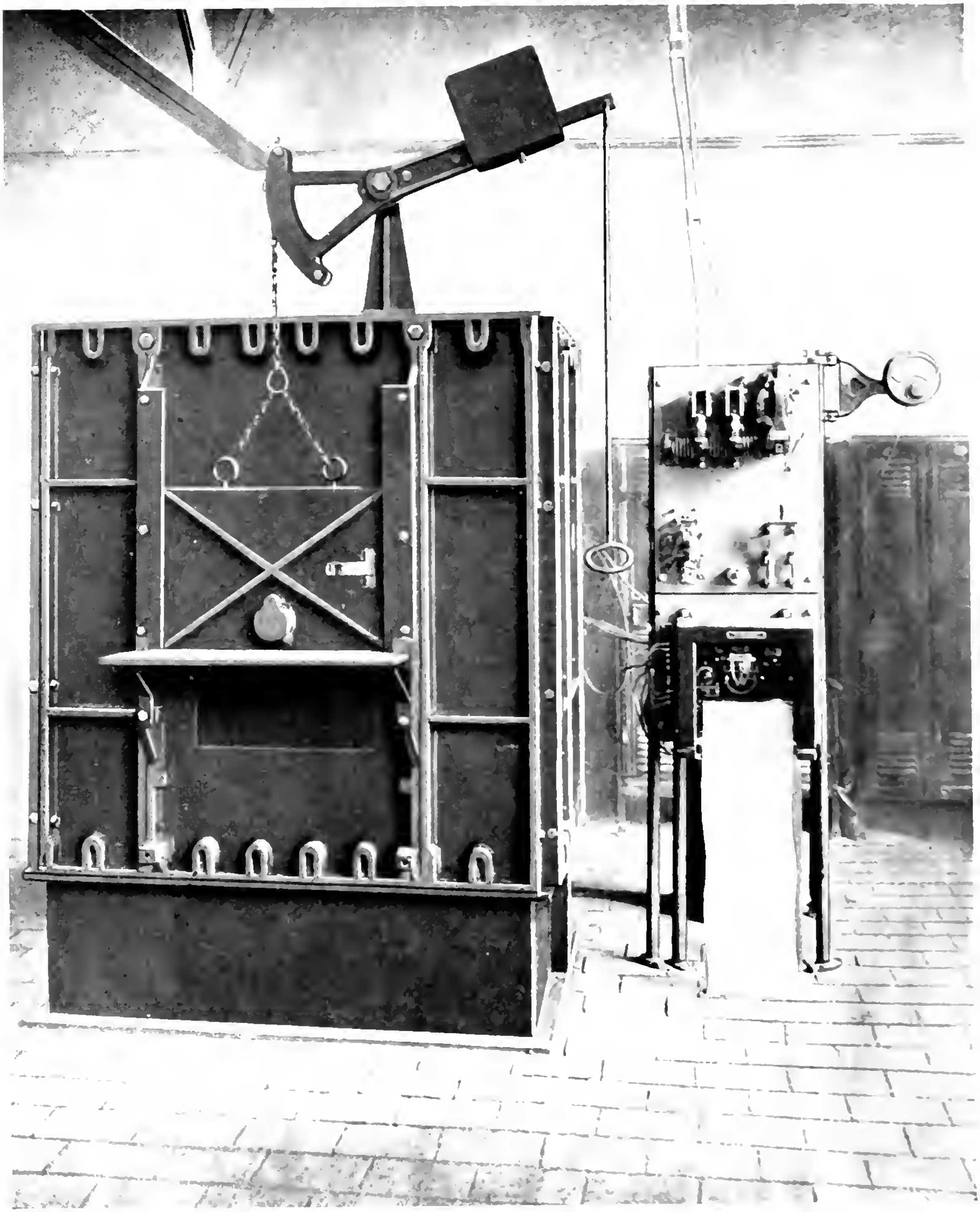

Metallic Resistor Electric Furnace and Automatic Temperature Control Equipment Installed in Building No. 17, Schenectady Works of the General Electric Company. Used for hardening punches, dies and cutters. See article "Relative Thermal Economy of Electric and Fuel Fired Furnaces," page 764

GENERAL ELECTRIC REVIEW

SOME RESULTS OF THE CHICAGO, MILWAUKEE & ST. PAUL ELECTRIFICATION

It is now more than four years since electrical operation was begun on the C. M. & St. P. Rwy., and the performance for the year 1919 therefore covers a period of seasoned operation; in other words, the equipment was neither new nor worn out. The statistics for the year 1919 compiled by Mr. R. Beeuwkes and published in this issue may therefore be taken fairly to represent the results of this electrification and should be carefully analyzed by all engineers and executives interested in railway operation.

The statistics on power consumption of 34.9 kw-hrs. for freight and 39.7 kw-hrs. for passenger service indicate that 40 watthours per ton mile at the high tension bus (commonly used for estimating purposes) is a conservative figure.

It should also be noted that the entire amount of power charged to train haulage (including switching) is apportioned between the passenger and freight service. The segregation of the small amount of energy used by the four 70-ton switchers is unimportant because of the relatively small proportion.

In the table showing power outputs at the high tension bus and at the locomotives the mistake should not be made of assuming that the ratio derived is the efficiency for the substation and overhead distribution. In this case the introduction of the regeneration must be taken into account; otherwise the distribution efficiency for a road using regeneration would appear to be less than it would be without this feature. It will be noted that the greater the amount of regeneration the lower will be the ratio shown in this table. The gross figure before subtracting regenerated energy should, of course, be used to compute actual distribution efficiency.

In selecting substation capacity provision was made for future requirements, which have not yet been reached. That a great reserve capacity is still available is shown by the low average load on the substation. This accounts for the rather high distributing losses. Under the terms of the power contract, however, the losses at light load do not affect the power cost when the 60 per cent load factor is not exceeded.

The data show an interesting record of the experiments made to determine the proper limit setting for the power-limiting and indicating system, and the percentage of time during which the limiting feature was operative for the different settings. In the interest of rapid train movement it was desirable to reduce this figure to as small a value as possible without injuring the load factor. It will be seen that the limit setting of 12,000 kw. must have appreciably slowed down the train schedule, while the 16,000-kw. setting with a somewhat higher average load affected the speed of trains only 2 per cent of the time. Obviously the information constantly at hand with this indicating system is invaluable and the apparatus has undoubtedly paid for its initial cost many times over.

In arriving at the figure for the total unit cost of freight transportation in cents per gross ton mile, items are included to cover the cost of maintenance to the electrical distributing system, two of which (383 and 305) represent principally the cost of substation attendance. The cost of electric power is charged against other accounts under the heading of train power *purchased*. The figures showing the total expense of furnishing energy for train operation are computed both on a basis of trailing tonnage, and total train weight including the locomotives.

Electric Power Consumption on the Rocky Mountain and Missoula Divisions of the C., M. & St. P. Rwy.*

By Reinier Beeuwkes

Electrical Engineer Chicago, Milwaukee & St. Paul Rwy.

The figures presented in this article covering the operation of the electrified divisions of the C., M. & St. Paul Rwy. for the year 1919 should be carefully analyzed by railway executives and engineers. Volumes have been written and published to show the economy and other advantages of electrical operation of main line railways, specially over mountain grades, but no arguments for electrification on paper will carry the weight of conviction of actual performance. If the operation of our main line railways by electric power is ever to be an accomplished thing present experience would seem to indicate that it will be realized by means of high voltage direct current, and this fact gives added significance to the results obtained by the C., M. & St. Paul.—Editor.

Power for the electrical operation of the Chicago, Milwaukee & St. Paul Railway between Harlowton, Montana, and Avery, Idaho, is delivered to the transmission system in the form of 100,000-volt, three-phase, 60-cycle current. The power is supplied under two separate contracts, one for the Rocky Mountain division, extending from Harlowton to Deer Lodge, and the other for the Missoula division, extending from Deer Lodge to Avery.

The power company's 100,000-volt transmission lines are shown in the single line layout of the system, as are also the points of power delivery to the railway company and the latter's 100,000-volt transmission system. The railway transmission line of the Rocky Mountain division extends from Two Dot substation to the Morel substation, a distance of 184 miles, the former point being 12 miles from Harlowton, eastern terminus of the division, and the latter point 17 miles from Deer Lodge, the western terminus. Power is delivered by the power company at the Two Dot, Josephine, Piedmont and Morel substations. The railway transmission line of the Missoula division extends from Gold Creek substation, 18½ miles from Deer Lodge, a distance of 180 miles, to the substation at Avery, the western terminus of the division.

Seven substations on each division are used to convert the 100,000-volt alternating current of the transmission line to the 3000-

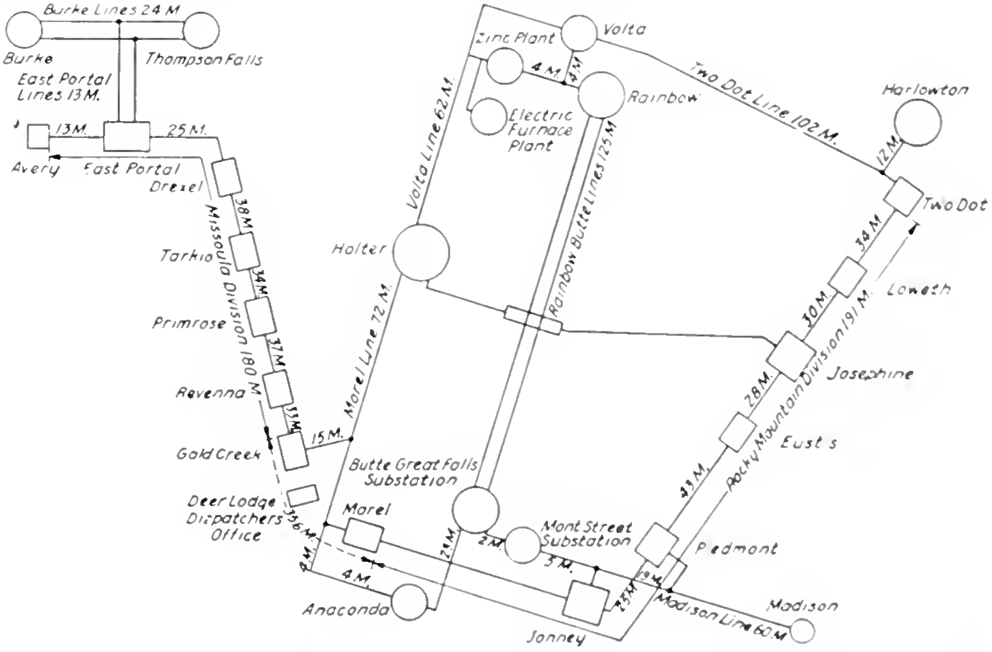

Fig. 1. Transmission Lines of the Montana Power Co. and Substation Layout for the C., M. & St.P. Electrification

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*Paper presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Portland, Ore., July 21-23, 1920.

TABLE I

SUBSTATIONS AND THEIR EQUIPMENT

Substations	Transformers	Motor-Generators
Rocky Mountain Division		
Two Dot	Two 2500 kv-a.	Two 2000 kw.
Loweth	Two 2500 kv-a.	Two 2000 kw.
Josephine	Two 2500 kv-a.	Two 2000 kw.
Eustis	Two 2500 kv-a.	Two 2000 kw.
Piedmont	Three 1900 kv-a.	Three 1500 kw.
Janney	Three 1900 kv-a.	Three 1500 kw.
Morel	Two 2500 kv-a.	Two 2000 kw.
Missoula Division		
Gold Creek	Two 2500 kv-a.	Two 2000 kw.
Ravenna	Two 2500 kv-a.	Two 2500 kw.
Primrose	Two 2500 kv-a.	Two 2000 kw.
Tarkio	Two 2500 kv-a.	Two 2000 kw.
Drexel	Two 2500 kv-a.	Two 2000 kw.
East Portal	Three 2500 kv-a.	Three 2000 kw.
Avery	Three 1900 kv-a.	Three 1500 kw.

volt direct current used for traction purposes. Each motor generator consists of two 1500-volt direct-current generators connected in series and driven by a 2300-volt synchronous motor supplied from the substation high tension busses through a three-phase, 100,000-2300-volt transformer and is guaranteed for a maximum five-minute overload of 200 per cent. The rated capacities of these stations are given in Table 1.

The railway company's high-tension line, arrangement of apparatus in the substations and the general layout of the 3000-volt distribution or trolley system, are shown diagrammatically in Figs. 1 and 3.

The contact wires of the trolley system consist for the main line of two No. 0000 B.&S. grooved trolley wires flexibly supported side by side from a ½-in. steel catenary and tapped at intervals of about every 1000 ft. to a feeder which connects to the adjacent substation busses through switches and automatic circuit breakers. Over passing, industrial and similar tracks only a single No. 0000 copper trolley wire is used. There is an insulated air gap in the trolley in front of each substation separating the trolley system west of the substation from that east of the substation; that is, portions east and west of the substations are fed, respectively, through separate feeder breakers. There is also an insulated air gap at the beginning and end of every passing track, so that by means of a section switch installed in the feeder at the gap the district between any two gaps may be isolated in case of trouble so as to permit operation up to the location of the open switches.

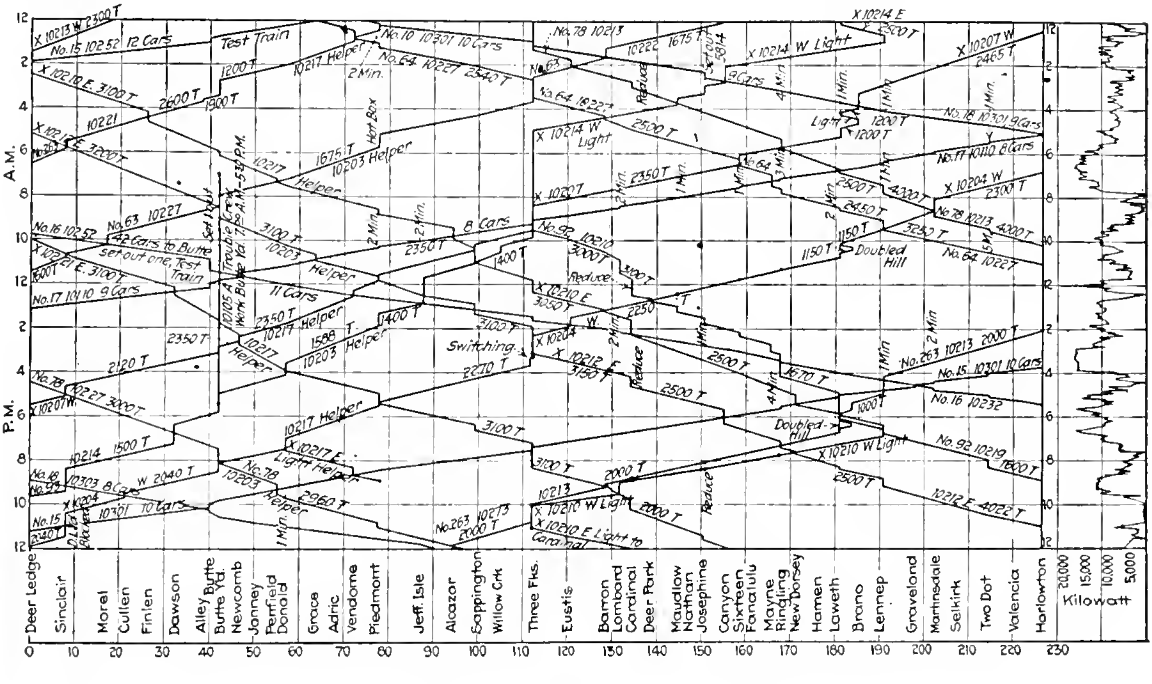


Fig. 2. Graphic Train Sheet and Load Curve for the Rocky Mountain Division, February 19, 1920

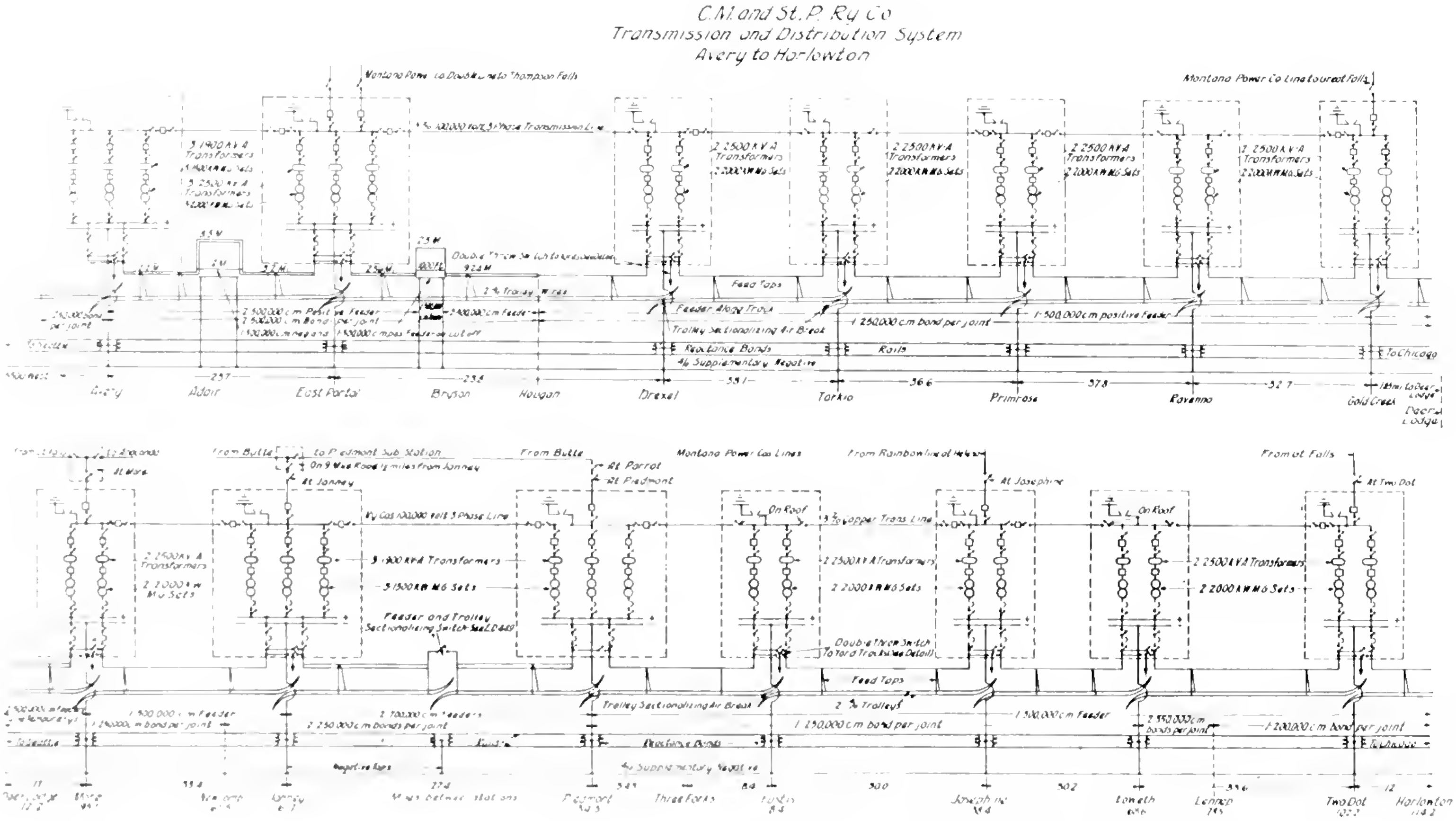
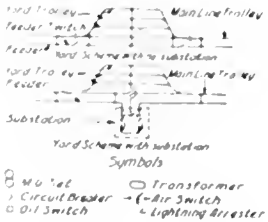


Fig. 3. Diagram of Transmission and Distribution System, Avery to Harlowton



Feeder and trolley sectionalized at all substations and railway stations.
One No. 0000 feeder tap to each trolley every 1000 feet.
Reactance bonds 5000 to 6000 feet apart.
Negative tapped to middle point of every second reactance bond.
Side track rails are bonded in series with the supplementary negative.
One rail bonded with one 250,000 cir. mil bond per joint in yards.
Trolley feed taps are disconnected for a distance of one mile each side of each substation where there is a single feeder and two miles where there is double feeder, except at Ravenna where the tunnel entrance East, and at East Portal where the tunnel entrance West will limit the distance.
Yard switch at substation left open. Yard trolley at substation connected to main lina trolley of east end of yards.
Signal: Two No. 4 B.&S. copper wires carried on trolley poles. Fed both directions from substations, 4400 volts a-c.
Power Limiting: Two No. 8 B.&S. copper wires carried on trolley poles—Morel to Two Dot—1200 volts d-c.

The return circuit consists of the 90-lb. running rails and, in general, of a No. 0000 B.&S. copper supplementary negative wire which is run along the trolley poles and connected to the track at intervals averaging about 8000 ft. through each alternate signal system reactance bond. This supplementary negative, however, is intended more as a safety measure to bridge open rail bonds than to increase the return circuit conductivity. However, on various feeder cutoffs on the mountain grades, where the conductivity of the positive circuit closely approaches that of the return circuit, one of the two feeders on the cutoff is in parallel with the running rails and is provided for the purpose of increasing the return circuit conductivity.

Power Demand Controlled by Train Dispatcher

The terms of the power contracts are similar and each provides for a minimum payment on basis of a 60 per cent load factor. Where the load factor exceeds 60 per cent payment is made on basis of the actual kilowatt-hours consumed, the rate being 5.36 mills per kilowatt-hour. The demand is controlled for each division by means of a so-called power indicating and limiting system,* which on the Rocky Mountain division was put into operation early in the year 1918 and on the Missoula division a few months ago. Briefly, this system is so arranged as to indicate and record at the dispatcher's office at Deer Lodge the total kilowatts or demand being supplied in any instant by the power company to the railway company and to prevent the maximum demand from exceeding a certain amount as determined by the "demand setting made by the dispatcher," this limiting action being secured by lowering of the substation direct-current voltage and therefore of the train speeds.

The effect of this limiting action is clearly indicated on the graphic time-table (Fig. 2) of train movements on the Rocky Mountain division for February 19, 1920, and corresponding load curve traced by tapalog meter of the power indicating and limiting system with the load limit set at 16,000 kw.

The percentage of time when the limiting action will take place, for a given amount of business, will depend on the demand setting and on the possibilities of spacing the trains so that as few as possible will at one time be operating on the heavier grades, the latter matter, except as regards passenger trains and certain time freights, being to a considerable extent in the hands of the train dispatchers. The slowing up of the train speeds of course results in increased train and enginemen's expense and increased time in getting freight over the road, and a proper balance must be struck between this increased expense and the saving in power cost and the limit setting determined upon accordingly. Table II gives an idea of the percentage of time the limiting action takes place with average kilowatt load and settings as indicated, this percentage being based on the number of hours the limiting system was actually in service.

TABLE II

ST. PAUL ELECTRIFICATION, LIMIT SETTING AND AVERAGE KILOWATT-HOUR TAKEN MONTHLY

Month	Limit Setting	Average Monthly Load in Kilowatts	Per Cent Time Limiting Action Takes Place
July, 1918....	12,000	8020	13.0
Aug., 1918....	12,000	7820	15.5
Sept., 1918....	12,000	6675	8.2
May, 1919...	14,000	7840	4.62
Aug., 1919...	14,000	7650	4.12
Sept., 1919....	14,000	8230	9.50
Oct., 1919....	14,000	8420	10.65
Nov., 1919...	14,000	7115	8.24
Feb., 1920...	16,000	8625	2.40
Mar., 1920....	16,000	8680	2.20
April, 1920....	16,000	8620	.90

In arriving at the amounts chargeable for power against the respective classes of train service, the total kilowatt-hours to be paid for—that is, the actual kilowatt-hours, or the actual kilowatt-hours increased, if necessary, to correspond to a minimum 60 per cent load factor—is taken and from it is deducted the kilowatt-hours metered against substation lighting, auxiliary power, signal system supply, etc., amounting to about 1 per cent. The remaining kilowatt-hours is then divided between the different classes of train service, freight, passenger and non-revenue, in proportion to the total net kilowatt-hour readings obtained for these respective services from wattmeters installed in the locomotives. These readings are taken by the engine crew on entering or leaving the engine on the form provided for the purpose, and a record of the power consumption of each train is thus obtained. The readings are referred to as "net" readings, as they represent motored energy less regenerated energy.

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*This system was described in the GENERAL ELECTRIC REVIEW for April, 1920, page 292.

TABLE III

ST. PAUL ELECTRIFICATION—AVERAGE INPUT

Month	ROCKY MOUNTAIN DIVISION			MISSOULA DIVISION		
	Actual Kw-Hrs. System Input for Locomotives	Net Kw-Hrs. Input at Locomotive	Ratio	Actual Kw-Hrs. System Input for Locomotives	Net Kw-Hrs. Input at Locomotives	Ratio
January	6,381,233	4,838,480	75.9	5,540,581	3,753,430	67.6
February	4,610,607	2,921,840	63.3	4,107,960	2,702,710	65.8
March	5,795,859	4,351,126	75.2	5,412,048	3,469,120	64.2
April	5,949,840	3,962,650	66.6	5,429,932	3,574,080	65.8
May	5,803,455	4,146,517	71.4	5,745,397	3,795,770	66.2
June	5,662,650	4,100,810	72.3	5,697,785	3,853,590	67.6
July	5,744,738	3,794,940	66.2	5,318,692	3,505,630	65.8
August	5,648,815	3,755,280	66.5	5,133,008	3,255,820	63.4
September	5,892,430	3,799,830	64.5	5,102,562	3,434,010	67.3
October	6,222,486	3,971,149	63.8	5,389,883	3,654,955	67.8
November	5,095,937	3,425,458	67.2	4,879,130	3,181,456	65.2
December	5,809,976	3,830,870	65.8	4,971,601	3,382,700	67.9
Total	68,618,026	46,898,850	68.3	62,728,579	41,563,271	66.3

The ratio of the total net locomotive wattmeter readings, all services, to the total actual kilowatt-hours input to the system chargeable to locomotives for the various months of 1919 is given in Table III.

As there are no wattmeters installed in the direct-current side of the substations, a ratio for net substation output to system input or to locomotive is not obtainable. There are, however, wattmeters in the circuits of the individual motor-generator sets and Table IV considered in connection with the profile of the line will be of interest in showing the manner in which the energy is distributed among the respective substations, average kilowatts being used for convenience instead of total kilowatt-hours, and the whole of the year 1919 being taken.

Operating Figures for 1919

The figures in Table V show for the year 1919 the net kilowatt-hours per thousand gross ton-miles for freight revenue service and passenger service, respectively, and corresponding cost of these kilowatt-hours at the high tension bus or point of delivery of the power to the railway system. The lesser consumption of energy during the summer months as compared with the winter months will be noted. The figures for the passenger service are approximate, as the ton-mile data are based on the assumption of an average weight per car, no record of the particular cars handled in all the separate trains being available.

The cost of maintaining and operating the transmission lines, substations and trolley system for the year 1919 is given in Table VI

TABLE IV

ST. PAUL ELECTRIFICATION—AVERAGE INPUT OF SUBSTATIONS

ROCKY MOUNTAIN DIVISION			MISSOULA DIVISION		
Substation	Average Annual Kw. Input Net to Motor Generators		Substation	Average Annual Kw. Input Net to Motor Generators	
	* Total	** Per Motor-Generator		* Total	** Per Motor-Generator
Two Dot	895	813	Gold Creek	1150	1128
Loweth	962	783	Ravenna	915	1115
Josephine	1014	1013	Primrose	908	925
Eustis	1022	1016	Tarkio	843	803
Piedmont	1218	617	Drexel	790	778
Janney	1390	559	East Portal	1390	778
Morel	1047	1072	Avery	812	523
System Total	7548	.	System Total	6808	.

* Total kw-hrs. computed on the basis of 8856 hours in the year (four extra days in December being included)
** Computed from total kw-hrs. and total running hours of motor generators.

TABLE V

ST. PAUL ELECTRIFICATION—OPERATING STATISTICS FOR 1919

Net Kw-Hrs. per Thousand Gross Ton-Miles

Month	Thousand Gross Ton-Miles, Trailing	Trailing		Train		Load Factor	Cost of Kw-Hrs. per M. Trailing. Gross Ton-Miles, Cents
		At High Tension Bus	At Locomotive	At High Tension Bus	At Locomotive		
Rocky Mountain Division							
Freight Service:							
January	98,478	47.8	36.3	41.2	31.3	63.7	25.7
February	79,859	43.1	27.3	37.3	23.6	57.7	24.0
March	118,297	39.0	29.3	33.9	25.5	65.3	20.9
April	121,646	38.5	25.6	33.1	22.0	61.1	20.7
May	124,395	36.5	26.1	31.7	22.6	56.0	20.9
June	122,264	36.7	26.2	31.7	22.9	56.4	20.9
July	120,723	36.7	24.3	31.6	20.9	55.4	21.3
August	111,092	40.9	27.2	34.9	23.2	54.6	22.4
September	115,787	39.7	25.6	34.1	22.0	58.8	21.7
October	108,920	45.8	29.2	39.4	25.1	60.0	23.6
November	86,267	44.0	29.6	37.7	25.3	50.9	27.8
January-November	Averages	40.5	27.7	34.8	23.8	57.3	22.5
Rocky Mountain and Missoula Division							
January	87,958	44.3	29.9	38.6	26.1	....	23.8
February	73,481	39.8	26.2	35.2	23.2	....	21.7
March	103,613	40.3	25.8	35.6	22.8	...	21.6
April	109,133	38.5	25.4	34.1	22.4	...	20.2
May	118,331	37.9	25.1	33.5	22.2	....	20.3
June	116,660	37.8	25.6	33.3	22.5	...	20.3
July	106,045	38.1	25.0	33.5	22.0	...	20.4
August	101,017	38.8	24.6	34.3	21.8	...	20.8
September	99,578	38.5	25.9	34.1	22.9	....	20.6
October	100,504	40.0	27.1	35.3	23.9	...	21.4
November	78,459	45.3	29.5	39.2	25.5	...	24.3
January-November	Averages	39.7	26.3	35.0	23.1	....	21.3
Rocky Mountain and Missoula Divisions Combined							
January-November	2,302,507	40.1	27.1	34.9	23.5	....	21.9
January-December	2,476,085	....	....	....	....	....	22.3
Passenger Service:							
January-November	340,480	56.8	38.7	39.7	27.1	....	38.4
January-December	378,080	....	....	....	....	....	38.1

TABLE VI

ST. PAUL ELECTRIFICATION—DISTRIBUTION OF OPERATING COSTS FOR 1919

Account		Total All Services	Per Unit
255.	Power substation buildings	$ 8,487	$ 606.00 per building
257.	Power transmission system	1,773	4.87 per mile
259.	Power distribution system	78,461	179.00 per route-mile
261.	Power line poles and fixtures	24,299	55.50 per route-mile
306.	Power substation apparatus	40,224	2,870.00 per station
383. 395.	Train and yard power produced	102,152	7,300.00 per station
	Total	$255,396	

TABLE VII

UNIT COSTS, INCLUDING COST OF POWER

1.	Cost per thousand gross ton-miles trailing freight as actually distributed in accounts	28.8 cents
2.	Cost per thousand gross ton-miles train freight as actually distributed in accounts	24.9 cents
3.	Cost per thousand gross ton-miles trailing freight on basis distribution in proportion to freight kilowatt-hours	30.2 cents
4.	Cost per thousand gross ton-miles train freight on basis distribution in proportion to freight kilowatt-hours	26.2 cents
5.	Cost per actual kilowatt-hours, delivered to locomotives	1.1 cents

* NOTE.—The items in the table refer to the classification numbers prescribed by the Interstate Commerce Commission for steam railroad accounting. The several groupings are defined as follows:

255. Power Substation Buildings.
This shall include the cost of repairing buildings of power substation * * * used to transform power for the operation of trains and cars, and to furnish power, heat, and light for general purposes: * * *

257. Power Transmission System.
This account shall include the cost of repairing systems for transmitting high-tension power from power houses to the point where transformed for use, including the cost of work-train service and special tools furnished for such work.

259 Power Distribution Systems.
This account shall include the cost of repairing electric distribution systems, whether overhead, surface, or underground, for conveying low-tension power for propelling trains and cars, and for power, heat, light, and general purposes.

261. Power Line Poles and Fixtures.
This account shall include the cost of repairing and replacing electric line poles, cross arms, and insulating pins; brackets and other pole fixtures; and braces and other supports for holding poles in position; also the cost of repairing structures primarily for supporting the overhead electric construction.

306. Power Substation Apparatus.
This account shall include the cost of repairing machinery and other apparatus, including special foundations, for transforming or storing power in power substations used for the operation of trains and cars and for power, heat, and light for general purposes.

Details of Power Substation Apparatus.

Rotary Converters
Storage Batteries
Switchboards
Transformers

383. Yard Switching Power Produced.
This account shall include the cost of the production and distribution of electric power used in operating locomotives and cars in switching service in yards where regular switching service is maintained, and in terminal switching and transfer service.

EMPLOYEES.—The pay of employees engaged in operating electric-power stations and substations, such as engineers, firemen, electricians, dynamo men, oilers, cleaners, and coal passers.

FUEL.—The cost of coal, oil, gas and other fuel, including the cost of labor unloading or stocking fuel.

WATER.—The cost of water used to produce steam or to operate water plants, including pumping, rent of ponds, streams, and pipe lines, also water tests, boiler compounds, and other like supplies and expenses.

OTHER SUPPLIES AND EXPENSES.—The cost of lubricants, such as oil and grease used in lubricating engines, shafting, dynamos, and pumps; cost of waste, carbon brushes, fuses, lamps, and other supplies; also the cost of heating and lighting power plants, and other expenses not elsewhere specified in connection with operation of electric-power plants.

395. Train Power Produced.
This account shall include the cost of producing and distributing electric power for the propulsion of electric locomotives and cars in transportation train service. Otherwise same as account No. 383.

and a final figure thus arrived at showing the approximate total operating costs involved in the delivery of the electric energy to the locomotives is given in Table VII.

Conclusion

The installation being comparatively new it might naturally be assumed without consideration of other facts that the figures for the maintenance are considerably lower than those which will eventually obtain, but it should also be borne in mind that the maintenance and operating costs given will, except for power, remain more or less constant so far as any consideration of their being affected by the business handled is concerned, so that the cost per thousand ton-miles would be correspondingly reduced as business is increased. It is also expected that considerable improvement will be effected in maintenance methods, which would again tend to reduce costs. The figures are therefore given merely to show the results which are at present being obtained

The Production and Measurement of High Vacua

PART IV. MANOMETERS FOR LOW GAS PRESSURES

By Dr. Saul Dushman

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This installment and the next contain a description of different types of manometers used in connection with high-vacuum technique. The present installment deals mainly with the McLeod gauge and different forms of viscosity gauges. The next installment will discuss the Knudsen, Pirani-Hale, and ionization gauges.—Editor.

For the measurement of pressures that lie between one atmosphere and one cm. mercury, a standard form of mercury barometer is generally used. Such a method is obviously very insensitive when it is necessary to measure pressures below this range, and consequently a number of types of manometers have been developed by different investigators for this purpose.

In the simplest type of low-pressure gauge, the difference between the actual pressure and that in an extremely good vacuum is measured by some very sensitive optical method. This is the principle of Rayleigh's manometer. On the other hand, the McLeod gauge represents an interesting application of Boyle's law to very low pressure. By compressing a given volume of the gas whose pressure is to be measured to a very small known volume, the pressure is amplified several thousand-fold and may read directly.

Again, instead of attempting to measure the pressure directly, use may be made of the fact that the amount of heat conducted from a surface varies with the gas pressure. Similarly, the damping effect of gas on a body set in vibration or rotation varies with the pressure. In each case, however, it is necessary to know the law of variation between the observed effect and the pressure.

In the following section are described some of the different types of low-pressure gauges that have been used by different investigators. Only those forms are described in detail which have proved to be most generally useful in the present state of high-vacuum technique; while other forms, which are of more or less historical interest, are mentioned rather briefly.

MERCURY MANOMETERS

Rayleigh's Gauge[1]

The essential parts of this gauge (Fig. 32) are two glass bulbs, one of which communicates with a good vacuum by a tube *C*, and the other with the system in which the pressure is to be measured. Two glass pointers are sealed into the bulbs, and the latter are connected to a T-connection which forms the upper end of a barometric column *A*.

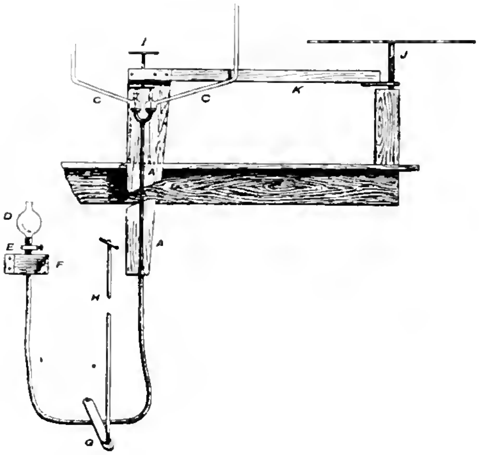

Fig. 32. Rayleigh's Gauge

Mercury can be raised and lowered in the bulbs by means of the reservoir *D* and the level thus brought up so as to be flush with the ends of the pointers. Any difference in pressure on the mercury in the two bulbs is then measured by gradually tilting the framework *AK* and observing the deflection on a mirror which is fastened vertically on top of the bulbs at *I*. According to Rayleigh this gauge can be used to read pressures between 1.5 mm. and 1×10^{-3} mm. of mercury.

A modified form of this gauge was used by K. Scheel and W. Heuse[2] for measuring the vapor pressure of water at temperatures below 0 deg. C., and similar manometers have been constructed by M. Thiesen[3], and E. Hering[4].

More recently, an ingenious modification of Rayleigh's method has been used by C. F.

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[1] Phil. Trans. 196, A. 205 (1901) Zeits. physikal. Chem. *37*, 713 (1901).

[2] Zeits. f. Instrk. *29*, 344-349 (1909) K. Jellinek, Lehrbuch d. physikal. chem. 1, 1, p. 321. Ann. d. Phys. *29*, 723 (1909).

[3] Zeits. f. Instrk. *6*, 89 (1886) and *24*, 276 (1904).

[4] Ann. d. Phys. (4), *21*, 320 (1906).

Mündel[5] for measuring vapor pressures at very low temperatures. A very sensitive optical method for measuring slight differences in level of two mercury surfaces, developed by K. Prytz[6], has been used extensively by different investigators in connection with Rayleigh's method.[7]

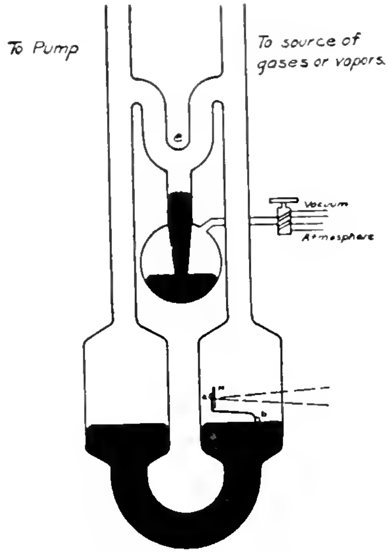

Fig. 33. Optical Lever Manometer

In the *optical lever manometer*, described recently by J. E. Shrader and H. M. Ryder,[8] the same object is attained by a very simple constuction. The following description is quoted from the orignal paper:

"A mercury U-tube manometer (Fig. 33) is formed in the usual manner, except that the surfaces of the mercury are so arranged as to be of relatively large area. Above one of the surfaces, within the tube, is arranged an optical lever as shown in the illustration. This lever is supported by two knife edges, *a-a*, which rest on loops of wire, which in turn are sealed into the glass walls of the tube; a glass bead *b*, fused to the end of the lever arm acts as a float on the mercury surface, and in this way transmits the motion of the mercury surface to the lever arm. A mirror *M* attached at the position shown acts in the usual manner to reflect a beam of light from a lamp to a scale, if the gauge is to be arranged as an indicating instrument. If the gauge is to be used for recording variations in pressure, the scale may be replaced by a photographic device such as is used in oscillographic work.

"The cross connection *e* provides an easy means of evacuating the whole system with one pump located as shown. With this stopcock or mercury cutoff open, a zero reading can be easily obtained, after which this connection may be closed and the gases or vapors introduced for measurement. This system provides also for the measurement of small variations in pressure, with an original pressure of any desired value, this value in no way affecting the absolute sensibility of the gauge."

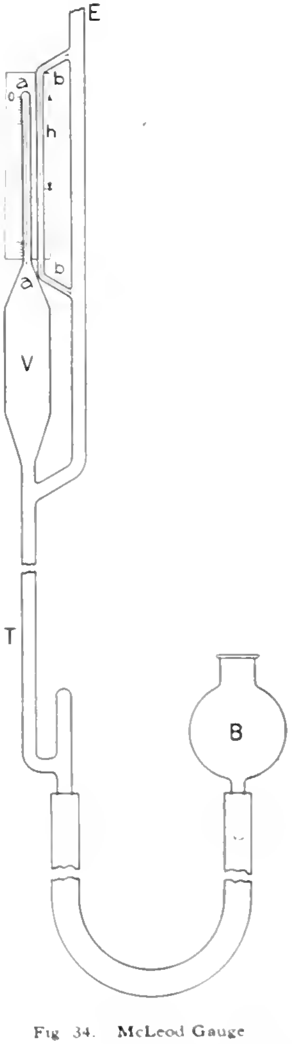

Fig 34. McLeod Gauge

A sensitivity of 10^{-3} mm of mercury is claimed for the gauge, and it certainly ought

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[5] Zeits. f. Physikal. Chem. 85, 435 (1913).

[6] Ann. d. Phys. (4), *16*, 735 (1905).

[7] C. F. Mundel loc. cit., and M. Knudsen, Ann. d. Phys. (4) *33*, 1435 (1910).

[8] Phys. Rev. *13*, 321 (1919).

to prove useful in those cases where the McLeod gauge is inapplicable.

McLeod Gauge

The principle of this gauge consists in compressing a given volume V, of the gas whose pressure P is to be measured, to a much smaller volume v and observing the resultant pressure p which in accordance with Boyle's law is given by the relation

$$p = P\frac{V}{v}$$

The greater the ratio $\frac{V}{v}$, the greater the sensitivity of the gauge.

One of the simplest forms of McLeod gauge is shown in Fig. 34. The bulb V, to which is attached a capillary tube aa, is connected to the low-pressure system at E and also to the barometric column T. In order to avoid errors due to the effect of capillarity, a tube bb of the same diameter as aa is sealed on as a by-path to the larger tube E. To operate the gauge the reservoir B is raised, thus forcing the mercury in the barometric column upward until the gas in V is shut off from the remainder of the system.

As the mercury is raised further, the volume of gas V is compressed until finally the mercury in the capillary bb is level with the upper end of the capillary aa (corresponding to the point O on the scale). The pressure on the gas in the capillary is then evidently equal to that of the mercury column of height h. Now let a denote the volume of the capillary per unit length, and P denote the pressure in the system at E. Then it follows from Boyle's law that

$$P = \frac{a}{V}h^2 \qquad (22)$$

Since a and V are constant for any particular gauge, it follows that the pressure is proportional to the square of the observed value of h. It also follows from this equation that the smaller the ratio a/V the greater the sensitivity of the gauge. Practical considerations, however, make it impossible to use either extremely fine capillaries or very large volumes for V. The following data for a gauge used by the writer are of interest in this connection as an indication of the range of pressures that can ordinarily be measured with a McLeod gauge:

Gauge No. 1

$V = 171$ cm.^{3}, $a = 0.00407$ cm.^{3} per cm. length (diameter of capillary = 0.72 mm.).

Hence, measuring h in cm.,

$$P = \frac{0.0407\,h^2}{171} = 2.38 \times 10^{-4}\,h^2 \text{(mm. of mercury)}$$
$$= \frac{106}{750} \times 2.38 \times 10^{-4}\,h^2 = 0.317\,h^2 \text{ (bar)}$$

That is, for $h = 1$ cm., $P = 0.317$ bar; and for $h = 1$ mm., $P = 0.0032$ bar, so that for a 10-cm. length of capillary aa, the range of pressures that could be measured with this gauge is from 0.003 to 32 bar.

Actually, it is impracticable to make V larger than 500 cm.^{3} and with capillaries smaller than 0.5 mm. the mercury tends to stick badly and the gauge is very sluggish in operation. With $V = 500$, and $a = 2 \times 10^{-3}$ (d = 0.5 mm.), 1 cm. on the capillary would correspond to 4×10^{-5} mm. of mercury, or approximately *0.053 bar*, and 1 mm. to 0.00053 bar. In general, the lower limit of pressure that can be measured with a McLeod gauge is about 0.01 bar.

It is evident that the McLeod gauge does not indicate the pressure of mercury vapor and condensible vapors such as those of oil, water, and ammonia. Even in the case of carbon dioxide the gauge is very inaccurate. In using it to measure very low pressures, such as those produced by a Gaede molecular or Langmuir condensation pump, a liquid air trap should be inserted between the gauge and the remainder of the system.

Regarding the accuracy of the gauge for indicating the pressure of the so-called permanent gases (H_2, He, Ne, Ar, O_2, N_2 and CO) a careful investigation carried out by Scheel and Heuse[9] has shown that if the bulb and tubing are carefully dried (to eliminate the presence of a film of water) the results obtained in the case of air are certainly reliable down to pressures of 0.01 mm. of mercury and are probably just as exact at lower pressures.

Lord Rayleigh[10] found by means of his differential manometer that in the range of pressures 0.001 mm. to 1.5 mm. Boyle's law holds accurately for N_2, H_2, and O_2; and Scheel and Heuse[11] observed the same result with their membrane manometer. A very careful investigation on this point was carried out by W. Gaede [12] in connection with his work on the laws of flow of gases at low pressures. He found that in the case of nitrogen and hydrogen, the McLeod gauge,

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[9] Ber. d. deutsch. Physikal. Ges. *10*, 785 (1908).
[10] Phil. Trans. (A) *196*, 205 (1901).
[11] Ber. d. deutsch. Physikal. Ges. *11*, 10 (1909).
[12] Ann. d. Phys. *41*, 289 (1913).

when care is taken to dry the walls thoroughly, is very accurate down to very low pressures (below 0.0001 mm.), while in the case of oxygen errors are liable to arise because of the formation of an oxide scum on the surface of the mercury which causes the surface to wet the glass in the capillary. However, this scum may be got rid of by heating the capillary carefully and the mercury then becomes quite clean again.

There are certain features about the McLeod gauge that must be carefully observed both in its construction and operation. In sealing off the upper end of the capillary *aa* (Fig. 34), care should be taken to have the capillary bore terminate in as blunt a surface as possible, so as to ensure a fair degree of accuracy in reading the very lowest pressures.

The rubber tubing connecting the reservoir *B* and the tube *T* should be thoroughly cleaned and dried before use to get rid of any loose particles and also to eliminate as much as possible the injurious action of the sulphur present in the rubber. Only the cleanest mercury should be used and all glass parts of the gauge should be dried thoroughly before filling with mercury. A new McLeod gauge will be found to give very erratic results at the beginning until all the condensible vapors adhering to the walls have been removed by gentle heating with simultaneous exhaustion.

For extremely sensitive gauges, where the volume V is large, the mass of mercury to be raised and lowered is so great that the design shown in Fig. 34 becomes impracticable. In these cases, the reservoir *T* may be replaced by a wide bore glass tube with snugly fitting glass plunger. Where a rough vacuum line is available, the top of the reservoir can be closed by a rubber stopper through which passes a two-way stopcock; one way being connected to the rough vacuum, and the other to the atmosphere. The mercury in *T* can then be raised or lowered by opening the stopcock to the atmosphere or to the rough vacuum respectively.[13]

In order to avoid the error which arises when reading the very small volume of the capillary at the upper end, it is often preferable to compress the gas in the capillary *aa* to a *definite volume* and then observe the height h of the mercury in the capillary *bb* above this level. Under these conditions, since

$$P=\frac{v}{V}h$$

it is evident that h is directly proportional to the pressure to be measured. The value of h may then be observed very accurately by means of a cathetometer. This method of using the McLeod gauge is, however, not as sensitive at low pressures as is the preceding method described. Again, in some cases, where the range of pressures to be measured is fairly large, the single capillary *aa* may be replaced by two or more capillaries of gradually increasing bore, the coarser bore being sealed onto the bulb V and the finer are on top of this. The serious objection to this construction, however, is the inaccuracy of the measurements at the junction between the two capillaries.

While the construction shown in Fig. 34 is the usual form of McLeod gauge used in exhaust work, a number of modifications have been suggested which are more convenient in special cases. An interesting construction is that designed by H. J. Reiff[14] and shown in Figs. 35 and 36. The advantages of this form are its compactness and avoidance of the use of rubber tubing which, as Reiff points out, sooner or later causes the mercury to get dirty. The gauge is mounted on a board which can be turned 90 deg. about the axis at *C* (Fig. 36). The system in which the pressure is to be measured is connected at *R* by rubber tubing. In the position shown in Fig. 35, the reservoir *G* and tube V^1 are filled with mercury up to the stopcock *H*. To measure the pressure, the board is turned into a vertical position and *H* opened until the mercury rises in *M* to the desired level. The bulb G^1 prevents any mercury from overflowing into the tube V^2. After the measurement is completed the board is again turned into the position shown in Fig. 35 and the mercury returned into the reservoir *G*.

In the same paper Reiff has also described a further modification of this construction in which the readings are directly proportional to the pressure. Other forms of the McLeod gauge have been described by A. Wohl and M. S. Losantisch,[15] and L. Ubbeholde.[16]

MECHANICAL MANOMETERS

A number of attempts have been made to construct low-pressure manometers indicating the mechanical deformation suffered by

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[13] An excellent description of the construction of such a McLeod gauge, sensitive to pressures as low as 10^{-6} mm., is given by Gaede in the article referred to in footnote (12). He used a capillary tube 0.35 mm. in diameter, while the volume of the bulb was about 1 liter.

[14] Zeits. f. Instkunde, *34*, 97 (1914).

[15] Ber. d. deutsch. chem. Ges. *38*, 4149 (1905).

[16] Zeits. f. Angew. Chem. *19*, 755 (1906).

a surface under pressure. At ordinary pressures this principle has been utilized in the construction of the Bourdon Spiral. Ladenburg and Lehmann,[17] and subsequently M. G. Johnson and D. McIntosh[18], have described a low-pressure gauge consisting of a flat tapered glass tube bent in the form of a spiral. The walls are usually very thin, so that the device may be sensitive to small pressure differences. A glass mirror is attached to the end of the spiral and the latter is sealed into another chamber in which the pressure may be varied. The system whose pressure is to be measured is connected to the spiral. In using the instrument, the pressure outside the spiral is varied until it is equal to that in the spiral, as indicated by the mirror, and the pressure outside is then measured by an ordinary mercury manometer. The device has been used for measuring the pressure of corrosive gases like chlorine and ammonium chloride vapor. A similar type of manometer has also been used very recently by C. G. Jackson for measuring the dissociation pressure of cupric bromide. These gauges are, however, not sensitive to pressures below about 100 bars.[19]

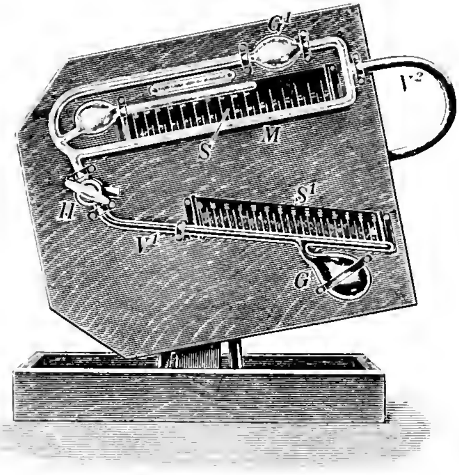

Fig. 35

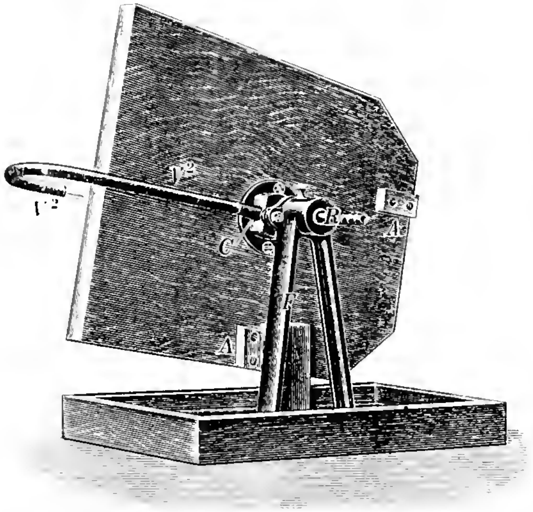

Fig. 36

Short Form of McLeod Gauge

Scheele and Heuse's membrane manometer[20] consists of a very shallow cylindrical glass box separated into two compartments (parallel to the flat sides) by a thin copper membrane. One compartment is connected to the system, while the other is connected directly to a high-vacuum pump. The deformation of the membrane, due to the slight difference in pressure on the two sides, is then measured by noting the number of interference rings produced by the pressure of the membrane against a glass plate.

The instrument was found capable of measuring pressures down to about 0.0001 mm. of mercury, but difficulties were encountered in using it because of the continual gas evolution from the walls of the device.

VISCOSITY MANOMETERS

Theory[21]

If a plane is moving in a given direction with velocity *u* relatively to another plane situated parallel to it at a distance *d*, there is exerted on the latter a dragging action whose magnitude may be calculated from considerations based on the kinetic theory of gases.

At comparatively higher pressures where the mean free path of the gas molecules is considerably smaller than the distance between the plates, the rate of transference of

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[17] Verh. d. deutsch. Phys. Ges. *8*, 20 (1906).

[18] J. Am. Chem. Soc. *31*, 1138 (1909); Zeits. f. Physikal. Chem. *61*, 457 (1908).

[19] For full details regarding this type of manometer, refer to K. Jellinek, Lehrb. d. Physikal. Chem. I, 1, p. 638, also to the references given in footnotes (17) and (18).

[20] Zeits. f. Instrk. *29*, 14 (1909).
Ber. d. deutsch. Phys. Ges. 1909, p. 1.

[21] In this connection the author has quoted to a large extent from his paper on the "Theory and Use of the Molecular Gauge," Phys. Rev. *5*, 212 (1913).

momentum across unit area is given by the equation

$$B=\frac{\eta u}{d} \qquad (23)$$

where η denotes the coefficient of viscosity.[22]

According to the kinetic theory of gases, this coefficient ought to be independent of pressure. The confirmation of this deduction by Clerk Maxwell and others, over a large range of pressures, has been justly regarded as one of the most striking arguments for the validity of the assumptions on which the kinetic theory is based.

It was found, however, by Kundt and Warburg[23] that at very low pressures, where the mean free path of the molecule becomes of the same order of magnitude as the distance between a moving and a stationary surface placed in the gas, there is distinct evidence of a slipping of gas molecules over the planes, so that the apparent viscosity is decreased. As the pressure is lowered the amount of this slip is found to increase and at very low pressures it varies inversely as the pressure.[24]

Denoting the coefficient of slip by δ, it can be shown that the amount of momentum transferred per unit area from the moving surface to that at rest is

$$B=\frac{\eta u}{d+2\delta} \qquad (24)$$

Thus, owing to slip, there is an apparent increase in the thickness of the gas layer between the two surfaces, which amounts to δ for each surface.

As has already been stated, Kundt and Warburg found that at very low pressures δ is inversely proportional to the pressure, and approximately of the same order of magnitude as the mean free path L, of the gas molecules at the corresponding pressures.

More generally, we can write

$$\delta=aL$$

where a is a constant. It is evident that at very low pressures, where d is small compared to L, equation (24) reduces to

$$B=\frac{\eta u}{2aL}$$

Since[25]

$$\frac{\eta}{L}=0.31\,p\sqrt{\frac{8M}{\pi RT}}$$

$$B=\frac{2\times 0.31}{a}\,p.\,u\sqrt{\frac{M}{2\pi RT}} \qquad (25a)$$

That is, with a given gas at constant temperature, the rate of transference of momentum is directly proportional to the velocity of the moving surface and also to the pressure. It follows from this that given the value of a, it would be possible from measurements on the mutual effect of a moving surface and one at rest, to measure the pressure of the gas.

The exact interpretation of a from the kinetic theory point of view has, however, proved to be rather a difficult matter. While the further discussion of this subject must be deferred for another section of this series it may be observed that a relation of the same form as (25a) may also be deduced by considerations similar to those used by Knudsen in connection with his investigations on the laws of molecular flow.[26]

According to the kinetic theory, the mass of gas striking unit area of a surface per unit time is equal to

$$\tfrac{1}{4}\rho\Omega=p\sqrt{\frac{M}{2\pi RT}}$$

where $\rho\Omega=$ density

$=$ average (arithmetical) velocity.

Assuming, as Knudsen does, that *all* the molecules striking a surface are reflected in directions which are absolutely independent of the directions of incidence and that these reflected molecules follow Maxwell's distribution law, it follows that the rate of transference of momentum per unit area from a surface moving with velocity u is

$$B=up\sqrt{\frac{M}{2\pi RT}} \qquad (25b)$$

This relation will, of course, hold true only at such low pressures that the molecules can travel across the space between the two surfaces without suffering collisions with each other.

It will be observed that equations (25a) and (25b) agree in the conclusion that at very low pressures B is proportional to $p\sqrt{M/(RT)}$, so that we can express the relation in the general form

$$B=k\,u\,p\sqrt{\frac{M}{RT}} \qquad (25c)$$

where k is a constant, which may be slightly different for different gases and probably varies also with the nature of the surface.

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[22] See Part I of this series of articles, June, 1920, p. 498. Poynting and Thomson Properties of Matter, pp. 218-220 give an exceptionally clear explanation of the physical significance of η from the point of view of the kinetic theory.

[23] Pogg. Ann. *155*, 340 (1875).

[24] "The diminution of the viscosity at very low pressures is well shown by an incandescent lamp with a broken filament. If this be shaken while the lamp is exhausted it will be a long time before the oscillations die away; if, however, air is admitted into the lamp, through a crack made with a file, the oscillations when started die away almost immediately." Poynting and Thomson, loc. cit.

[25] See equation (9), Part I, p. 498, and equation (4) p. 497.

[26] See Part I of this series of articles June, 1920, pp. 499-501, and Part II, July, 1920.

In applying the relation between the coefficient of slip and the pressure to the construction of a gauge, two different methods have been used. In the first of these, which we may designate for reference as the "decrement" type of gauges, a surface is set in oscillation and the rate of decrease of the amplitude of oscillation is taken as a measure of the pressure. Physically, the damping may be explained as due to the gradual equalization of energy between the moving surface and the molecules of gas striking it.

In the second type of construction, a surface is set in *continuous* rotation and the amount of twist imparted to an adjacent surface is used to measure the pressure. The molecules striking the moving surface acquire a momentum in the direction of motion which they tend in turn to impart to the other surface. If the latter is suspended and free to turn about an axis which is perpendicular to the direction of motion of the rotating surface, it will be twisted around until the force due to the incident molecules is just balanced by the torsion of the suspension. We may, therefore, designate this as the "static" type of viscosity gauge, to emphasize the fact that observations with this method are taken under stationary conditions.

"Decrement" Type of Viscosity of Gauge

A gauge based on this principle was first suggested by W. Sutherland[27] and subsequently a very careful investigation on the same subject was carried out by J. L. Hogg.[28] The construction used by the latter, which was essentially the same as that used by Maxwell and Kundt and Warburg in their determinations of the coefficient of viscosity is shown in Fig. 37. A thin glass disc is suspended by means of a wire between two fixed horizontal plates N. The wire carries a mirror which may be viewed through a plate glass window D by means of a telescope and scale. At the top, the wire is supported by clamps and is connected to a soft iron armature J which is supported by the swivel head K. By turning this armature by means of an external magnet, the center disc can be set in oscillation and the rate of decrease of the amplitude of these oscillations is then observed by means of the telescope pointed at the window D.

Now let T denote the period of oscillation, and S_1 and S_2 two successive amplitudes of oscillation. Solving the differential equation for the rate of damping of the central disc, it can be shown that

$$\frac{S_1}{S_2} = \epsilon^{\frac{aT}{2}} = \epsilon^{\lambda} \tag{26}$$

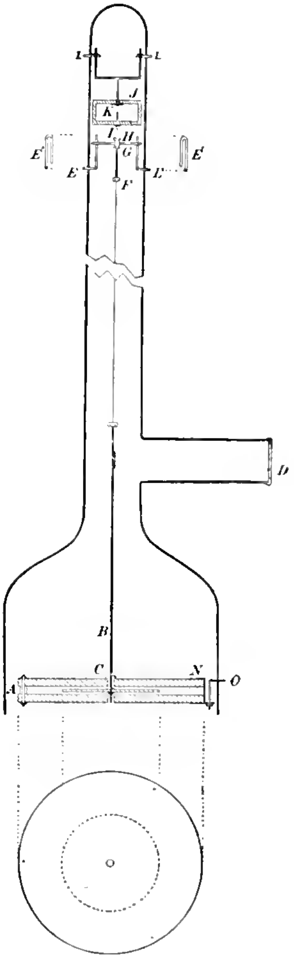

Fig. 37. Decrement Type of Gauge

where λ is defined as the *logarithmic decrement*. That is, the amplitude of oscillation decreases in geometrical progression for successive equal intervals of time. The constant a depends upon the moment of inertia of the vibrating disc and its dimensions.

Thus λ is a measure of the rate of transference of momentum from the vibrating plate to the stationary plates.

At higher pressures, since the viscosity is independent of pressure, the logarithmic

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[27] Phil. Mag. *43*, 83 (1897).

[28] Proc. Am. Acad. *42*, 115 (1906), and *45*, 3 (1909). Contributions from the Jefferson Physical Lab., 1906, No. 4, and 1909, No. 4.

decrement has a constant value which may be denoted by l. Denoting by μ the decrement due to the suspension itself, it was shown by Sutherland that the following relation ought to hold true:

$$\left(\frac{\lambda-\mu}{l-\mu}-1\right)\mathrm{p}=\mathrm{C} \qquad \text{(27a)}$$

where p is the pressure and C is a constant for the particular arrangement used.

The results obtained by Hogg were found to be in satisfactory accord with this equation down to pressures of the order of 0.0004 mm. of mercury in the case of hydrogen.

It is evident from the form of the above equation that the gauge is unsuitable for measuring very low pressures (say below 0.0001 mm.) as the value of λ then becomes comparable with that of μ, thus involving large experimental errors. Furthermore, as mentioned by Hogg, the construction of the gauge and its actual manipulation require extremely great care.

A very recent contribution to the theory of this type of viscosity meter has also been published by P. E. Shaw[29]. He derives an equation of the form

$$p=C\lambda \qquad \text{(27b)}$$

and records measurements of pressures down to 0.35 by 10^{-3} mm. of mercury.

Quartz-Fibre Gauge

This method was originally suggested by I. Langmuir[30] for measuring the residual gas pressure in a sealed off incandescent lamp, and has been used in this laboratory in a number of investigations. It is specially useful in measuring low pressures of chemically active vapors such as those of chlorine, iodine, and mercury which are liable to attack metal parts. A discussion of the theory of the gauge and actual details as to its manipulation have been published by F. Haber and F. Kerschbaum[31].

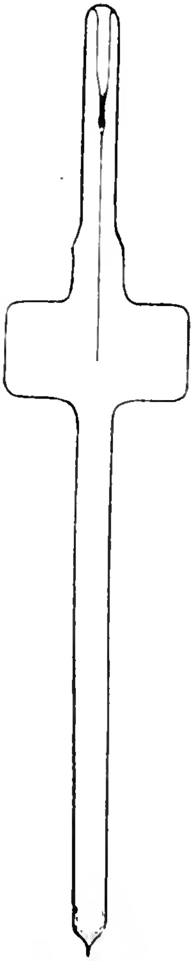

Fig 38 Quartz Fibre Gauge

The construction of the gauge is shown in Fig. 38. It consists of a thin quartz fibre sealed into the top of a glass tube. The fibre is set in oscillation by gently tapping the glass bulb and the rate of decrease of the amplitude of vibration is then observed by means of a telescope and lamp as shown in Fig. 39.

Let t denote the interval of time required for the amplitude to decrease to half value. Then it has been shown by Haber that

$$p\sqrt{\mathrm{M}}=\frac{b}{t}-a \qquad \text{(28)}$$

where p denotes the pressure, M is the molecular weight of the gas, and a and b are constants for the particular quartz fibre. That is, for any gas, the pressure varies linearly with the reciprocal of t.

In the case where the gas to be measured is a mixture of different vapors, the sum of a number of terms $p\sqrt{\mathrm{M}}$ must be taken corresponding to the partial pressure of each constituent.

The constant b in equation (28) is proportional to the diameter of the fibre, that is, the finer the fibre the smaller the pressure at which the amplitude will decay to half value in a given time. On the other hand, a is a function of the elastic properties of the fibre.

It is evident from the form of equation (28) that a b corresponds to the value t_0 at which the amplitude would decrease to half-value in a perfect vacuum. For calibration, it is necessary to obtain only two points, corresponding to the two constants a and b. One of these may be determined by observing the value t_0 in a very good vacuum, while the other point may be obtained by calibrating against a McLeod gauge with some gas of definite composition.

The following data are given by Haber for a quartz fibre 7.0 cm. long and 0.013 cm. in diameter. Air was used for calibration.

Pressure in mm. *Hg*	$p\sqrt{M}$	t (seconds)	b
0.00302	0.01625	74	1.22
0.00494	0.02654	46	1.23
0.00775	0.0417	31	1.30
0.0117	0.0630	22	1.39
0.01880	0.101	12	1.23
0.0260	0.140	10	1.40
$a=0.0003$..			Avg. 1.28

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[29] Proc. Phys. Soc. London, 29, 171 (1917).
[30] J. Am. Chem. Soc. 35, 107 (1913).
[31] Zeit. f. Elektrochem. 20, 296 (1914).

Some measurements with air taken by Mr. Huthsteiner in this laboratory, using a fibre 3.8 cm. long and 0.0045 cm. diameter, are given for comparison.

Pressure in mm. *Hg*	*t* (seconds)
0.00058	105
0.00342	31
0.0080	16
0.0190	6.5

Plotting p against $\frac{1}{t}$ gave a straight line whose equation is $10^3\ p=\frac{131}{t}-0.655$. For air, $M=28.96$. Hence, for this particular fibre,

$$p\sqrt{M}=\frac{0.705}{t}-0.00353$$

Since $t_o=200$ in this case, it is evident that this fibre could not be used for measuring pressures below 0.0001 mm. of air It also follows from the form of the above relation that the heavier the gas the lower the range of pressures over which the gauge may be used.

The optical arrangement suggested by Haber (Fig. 39) may be varied in practice by fastening a scale to the back of the gauge and placing the lamp in such a position that the light beam passes practically parallel to this scale. The scale and tip of the quartz fibre are then sighted by means of a cathetometer.

While Haber used tubes which are more or less flattened on two sides, ordinary cylindrically walled tubes are more convenient and almost as satisfactory. As observed by Haber, care should be taken to tap the glass in such a manner that the fibre vibrates in the plane at right angles to the line of sight from the cathetometer. With a little experience, this can readily be accomplished. In view of the simplicity of construction and relative ease of manipulation, the quartz fibre gauge ought to find a useful field of application in low pressure technique, where the pressures to be measured are not below about 0.05 bar.

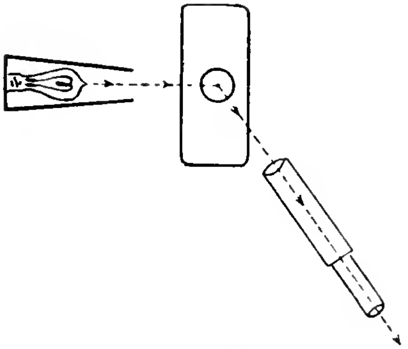

Fig. 39. Optical Arrangement for Quartz Fibre Gauge

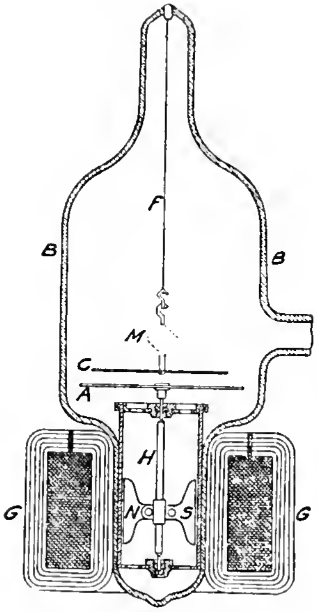

Fig. 40. Molecular Gauge

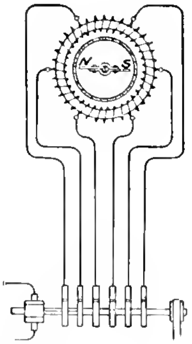

Fig. 41. Rotating Commutator Connection for Molecular Gauge

Static Types of Viscosity Gauge

The molecular gauge suggested by I. Langmuir[32] represents a direct application of equation (25c).

The construction and results obtained with a gauge built on this principle were described by the writer[33] as follows:

"It consists of a glass bulb *B* (Fig. 39) in which are contained a rotating disc *A* and,

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[32] Phys. Rev. *1*, 337 (1913).

[33] Phys. Rev. *5*, 212 (1915).

suspended above it, another disc C. The disc A is made of thin aluminum and is attached to a steel or tungsten shaft H mounted on jewel bearings and carrying a magnetic needle NS. Where the gauge is to be used for measuring the pressure of corrosive gases like chlorine, the shaft and disc may be made of platinum. The disc C is of very thin mica, about 0.0025 cm. thick and 3 cm. in diameter. A small mirror M, about 0.5 cm. square is attached to the mica disc by a framework of thin aluminum. This framework carries a hook with square notch which fits into another hook similarly shaped, so that there is no tendency for one hook to turn on the other. The upper hook is attached to a quartz fibre about 2 by 10^{-3} cm. diameter and 15 cm. long.

"The lower disc can be rotated by means of a rotating magnetic field produced outside the bulb. This field is most conveniently obtained by a Gramme ring, GG, supplied at six points with current from a commutating device rotated by a motor (Fig. 40). In this way the speed of the motor determines absolutely the speed of the disc, and the speed of the latter may thus be varied from a few revolutions per minute up to 10,000 or more."

By applying equation (25c) it can be shown that the angle of torque (α) on the upper disc is given by the equation

$$\alpha=\left(\frac{kt^2 r^4}{2\pi k}\right) p\,\omega\sqrt{\frac{M}{RT}} \qquad (29)$$

where t = natural period of oscillation of mica disc,

k = moment of inertia of disc,

r = radius of rotating disc,

and ω = angular velocity of rotating disc.

Hence, for any one gauge, the torque on the upper disc is proportional to the product of the speed of rotation of the aluminum disc and the quantity $p\sqrt{M/(RT)}$. The sensitivity of the gauge can thus be increased by increasing the speed of rotation; also by illuminating the mirror and using a similar arrangement to that used for galvanometers, it is possible to use the gauge to measure pressures of the order 10^{-3} to 10^{-4} bar.

The gauge actually used for measuring very low pressures showed a deflection of 1100 mm. per bar of air, at 1000 r.p.m., with the scale 50 cm. from the mirror. Up to a pressure at which the mean free path of the gas molecules becomes comparable with the distance between the two discs, the deflections, at constant speed of rotation, were found to be proportional to the pressure as observed by a McLeod gauge.

At extremely low pressures (below 5×10^{-4} bar) the indications of the gauge were found to be inaccurate because of two sources of error. First, the rotation of the magnetic field produced by the Gramme ring tends to induce eddy currents in the metal frame work used to hold the mirror; and second, there is a tendency for the upper disc to start swinging especially at very high speeds of rotation of the aluminum disc. As the damping at low pressures is very feeble, it is very difficult to stop this oscillation when once started.

Working independently of Langmuir, and about the same time A. Timiriazeff[34] also suggested the application of equation (25) to the construction of a low-pressure gauge. As he was primarily interested in determining the laws of slip for different gases his actual design is not suitable for a very sensitive gauge. Instead of using a rotating disc with a stationary disc situated symmetrically above it, Timiriazeff used a rotating cylinder with a stationary cylinder placed symmetrically inside it and suspended by a phosphor bronze wire.

(To be Continued)

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[34] Ann. d. Physik, *40*, 971 (1913).

The Cooper Hewitt Mercury Vapor Lamp

PART I. THEORY AND OPERATION

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This article is the first of a series of three on the theory and uses of the Cooper Hewitt Mercury Vapor Lamps. The second article, which will appear in the October issue, will illustrate the advantages of these lamps for industrial illumination. The third article will be descriptive of the Cooper Hewitt Quartz Lamp and its characteristics.—Editor.

GENERAL PRINCIPLES OF THE MERCURY ARC

The Cooper Hewitt lamp consists of a tube of glass or of quartz containing mercury, mercury vapor and wires sealed into the ends of the tube to conduct electricity to and from the current carrying vapor. In the manufacturing process all foreign gases are removed and the tube closed vacuum tight. In operation there is a direct current arc from the cathode electrode of mercury to an anode electrode of iron or of tungsten (Fig. 1).

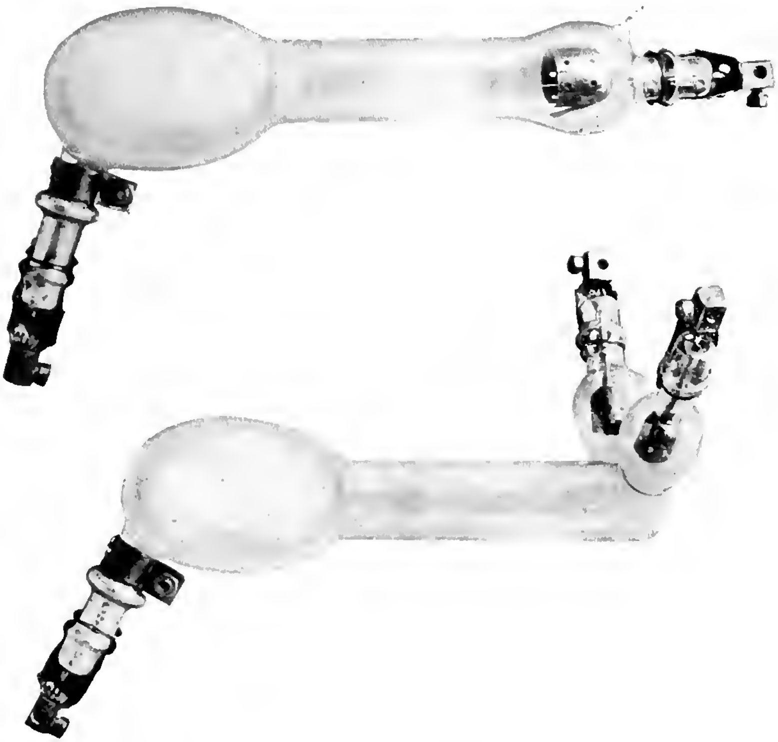


Fig. 1. Upper—Direct-current Cooper Hewitt Lamp
Lower—Alternating-current Cooper Hewitt Lamp

The wattage of a lamp of a given size is limited by the heat resisting quality of the glass used. Two types of lamps have therefore been developed, one of glass to operate at relatively low temperatures, and one of fused quartz to operate at relatively high temperatures. The normal volt-ampere characteristic of a lamp is determined primarily as a very complex function of the mercury vapor pressure and density and of the length and cross section of the tube. With the tube dimensions fixed the vapor pressure is determined largely by the minimum temperature within the tube, while the vapor density varies according to the heat distribution, being in general a minimum along the central axis of the tube. In standard industrial units the normal volt-amperage is then finally determined through the tube temperature by a condensing chamber in the form of a bulb on the cathode end of the lamp tube. A condition of complete equilibrium is reached when the light and heat radiated and conducted from the tube equals the electrical energy input. The effect on the tube voltage and current of the temperature rise during starting is shown in Fig. 2, where they are plotted as functions of time. In the actual design of a lamp these several variables are so balanced as to give at once that critical vapor density at which the light-giving efficiency is

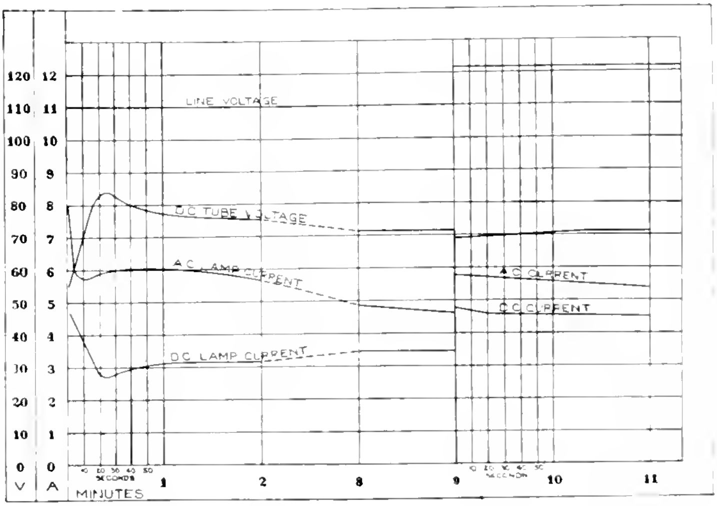


Fig. 2. Volt-ampere Starting Characteristic of Standard Lamps

greatest and a volt-ampere characteristic allowing maximum current regulation with a minimum sacrifice of wattage for that purpose.

Modern theory gives a strikingly graphic picture of the electrical condition in the arc column of the Cooper Hewitt lamp. According to it the tube is filled, during operation, with mercury molecules, mercury ions, and electrons. The ions are molecules which have gained or lost one or more electrons or unit negative charges of electricity, thereby being left charged either negatively or positively as the case may be. These molecules, ions, and electrons move with various characteristic velocities and in individual directions determined by their collisions with their fellows according to the well known kinetic molecular theory of gases. This commotion characteristic of all gas molecules is further complicated by the fact that a constant difference of potential of about one and one third volts per inch of arc length is maintained on the electrodes located in the ends of the tube, and that because of the heat of the cathode and the impact of the electrons, ions and molecules on each other and on the electrodes more electrons and ions are produced than are usually needed to carry the current. The effect of the electromotive force on this gas column is to produce an arc current which may be described as a continuous drift of electrons from the cathode to the anode and a relatively much slower movement of positive ions towards the cathode. The excess of ions and electrons produces the effect of a partial short circuit with a continuous tendency to become a more complete short circuit. The result is a periodic increase of current and fall of potential of a frequency determined by the capacitative and inductive reactance of the arc column and of the supply circuit.

For transient variations of the current this inverse variation of voltage is characteristic of the mercury arc, a cathode phenomenon apparently, for the whole range of practical current values and arc temperatures. It is most pronounced for low currents, but decreases rapidly with increase of normal cur-

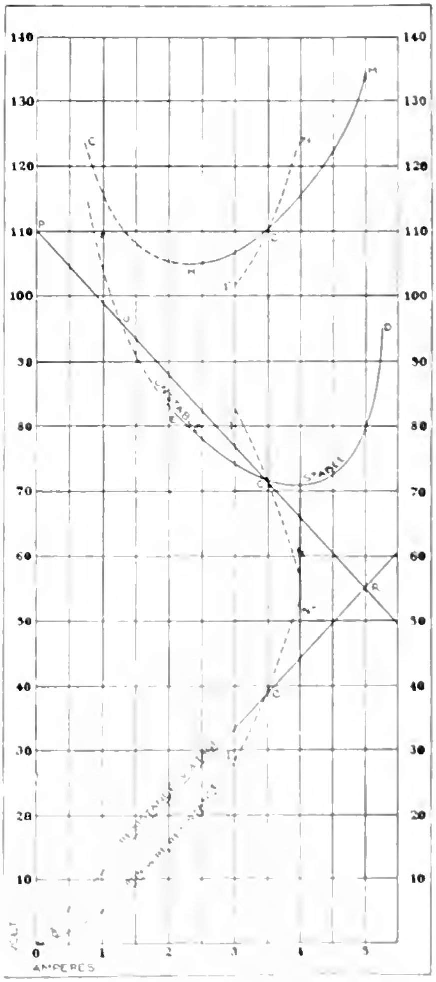


Fig. 3. Volt-ampere "Stationary" Characteristics Regulation

rent. For slow changes of the current this same volt-ampere relationship is characteristic up to a certain critical current value. With further increase of current from this point the tube voltage passes through a minimum and then rises rapidly as shown in Fig. 3. For maximum light efficiency, the Cooper Hewitt lamp is operated at the point of minimum tube voltage, where, if unrestricted, the arc current will fluctuate over a wide range on constant voltage. In order to operate this unstable and essentially constant current device on supposedly constant voltage power lines two forms of regulation are necessary. The current is steadied by an inductance coil, connected in series with the arc and as directly as possible to the cathode so as to oppose every transient action of the current by an instantaneous induced reaction. The falling voltage characteristic of the arc as well as the voltage variations of the line are compensated by an ohmic resistance in series with the inductance coil and the arc as shown in the wiring diagram, Fig. 4. This resistance is so chosen that, for normal operation, with any increase of current the decrease in arc voltage will be less than the increase in resistance potential. In Fig. 3, curve

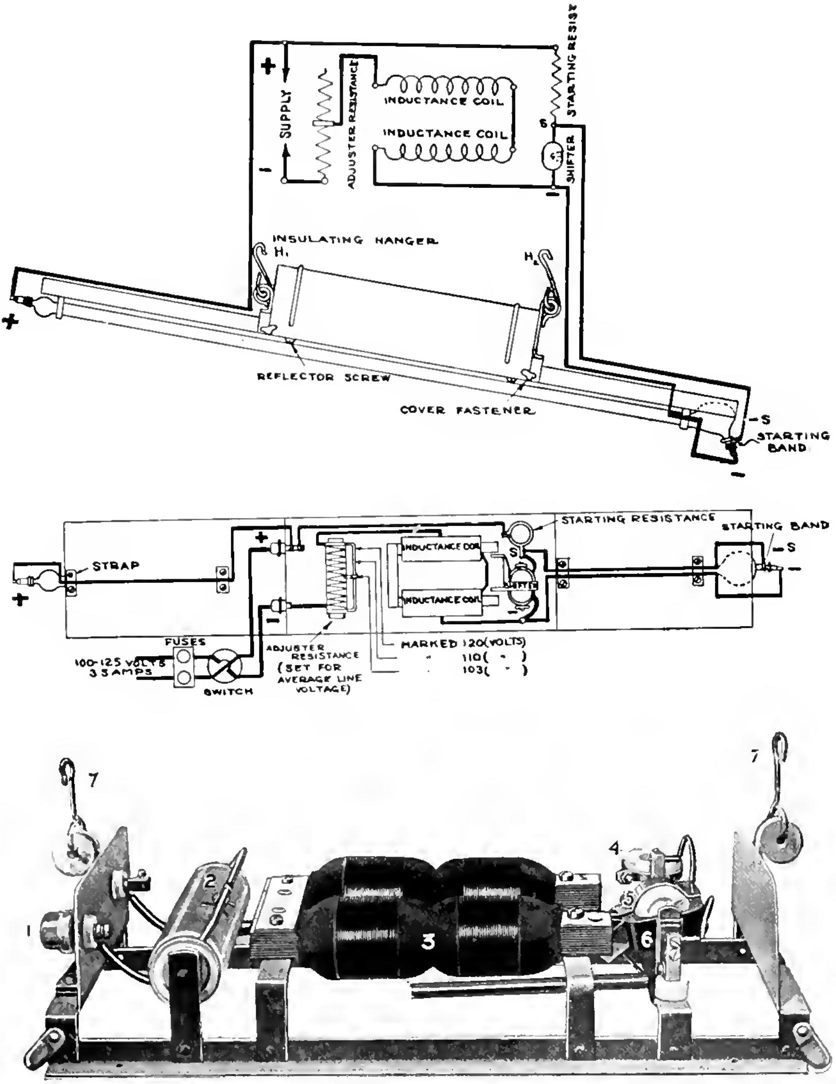


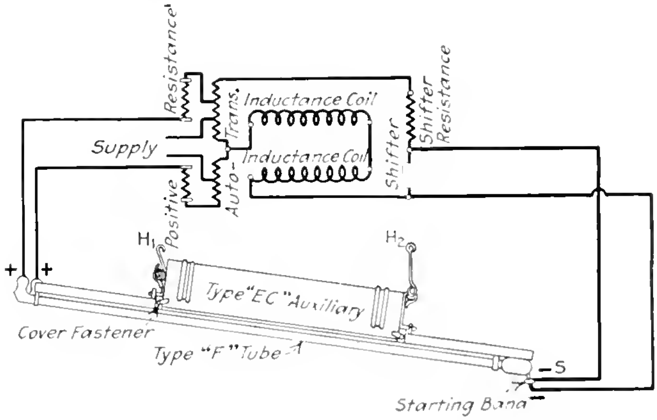
Fig. 4. Wiring Diagrams and the Detail of Direct-current Lamp Auxiliary

$D\ O\ E\ U\ F$ is the volt-ampere characteristic of a Cooper Hewitt arc showing inherent stability above and instability below four amperes. Line $P\ U\ O\ R$ represents the line voltage minus the resistance voltage for various currents, or in other words, the voltage available at any time for arc operation. Point U is, therefore, one of arc instability since any current increase is accelerated by the resulting excess arc voltage. On the other hand, point O is one of stability, a current decrease being opposed by an excess of arc voltage and an increase being limited by the available arc voltage. In this case the regulating series resistance is eleven ohms.

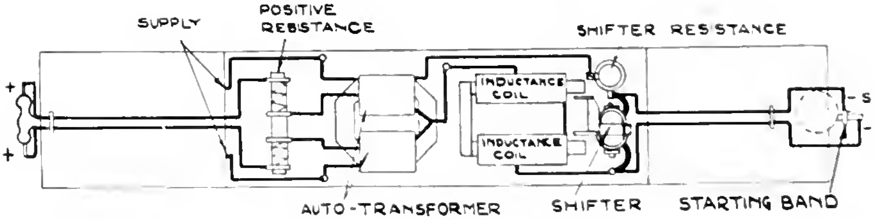
Curve $C\ H\ O''\ M$, the volt-ampere characteristic curve of the whole lighting unit, is the continuous sum of the resistance potentials $B\ O''\ R$ and the arc potentials. Point H therefore represents the minimum maintenance current and voltage of the outfit for the amount of regulation used. The regulation, which is defined as the per cent fluctuation of normal voltage producing a current change from one half ampere below to one half ampere above normal current, is in this case 8 per cent. In the Cooper Hewitt industrial units the series resistance is adjustable to provide for operation on various and on varying voltages.

Starting the Arc

To start the Cooper Hewitt lamp it is only necessary to start and maintain the formation of electrons in a so-called "hot spot" on the surface of the mercury cathode. Collisions with mercury molecules immediately result in the formation of more electrons and ions than are needed to form a current, with the results detailed above. The temperature of this spot, several thousand degrees at least, may be accounted for by the very small cross section of the spot and the fact that some eighteen watts of energy are converted into heat in this small area of liquid



WIRING DIAGRAM EC AUXILIARY



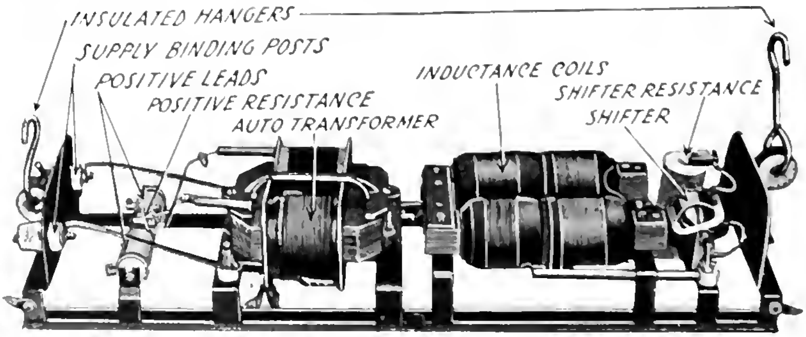


Fig. 5. Wiring Diagrams and the Detail of Alternating-current Lamp Auxiliary

vapor inter-surface, the cathode drop in potential being about 5.3 volts. There is a difference of opinion as to whether ionization at the cathode results from the direct emission of electrons from mercury vapor heated far above its boiling point or whether it results from the impact of positive ions upon hot molecules. In either case the condition is easily produced by bringing the mercury cathode into contact with the anode and then breaking the circuit thus formed, as with the ordinary carbon arc. This tilting method is now used to start the relatively small Cooper Hewitt quartz mercury lamps. An alternative automatic starting method standard for the glass lamps consists in short circuiting a small current through the arc regulating inductance in series with the arc. This current is broken by a mercury switch or "shifter" magnetically operated by the inductance coil itself. The resulting induced high potential is sufficient to start a localized cathode discharge and the arc is formed. A metallic coating placed on the outside of the cathode end of the tube opposite the mercury cathode and connected to the positive side of the supply circuit serves to increase the electrostatic capacity of the cathode and hence to give a greater current density to the induced high potential discharge when it is localized to form an arc. See Fig. 4 for the arrangement of the circuits.

The effectiveness of the "shifter" or mercury switch as a quick acting cut-out switch is worthy of note. It is itself a small glass chamber evacuated except for mercury and mercury vapor and is supplied with leading-in wires for electrical connection. It is made in the same manner as the regular lamps and is itself essentially a small mercury vapor arc. It is so mounted as to be easily rotated by an armature actuated by the magnetic field of the inductance coils. Its operation, in detail, is therefore as follows: At the moment the lamp is connected to its source of electric supply a current is short circuited past the lamp tube, through the arc regulating inductance coils and resistance, through an additional shifter or starting resistance and through the shifter itself (see Fig. 4). The lightly mounted shifter rotates, the mercury pool connecting the two leading-in wires is widely separated, and at the moment of separation an induced electromotive force reaching a very high peak voltage appears on the terminals of the shifter and therefore on the terminals of the arc tube. This voltage is sufficient to start the arc as outlined before, but it will not form an arc in the shifter since the total resistance of the shifter circuit is such as to keep the shifter starting current well below a minimum arc maintenance value. Since the inductance coils used have relatively low self inductance the high induced voltages obtained result from the extremely rapid current decrease when the circuit is broken in the shifter. The effectiveness of this mercury-vacuum switch for this purpose as compared with oil immersed or quick acting circuit breakers is accounted for by the uniquely rapid rate of deionization of cold mercury vapor and the heat dissipating property of volatile contact points. These considerations afford an explanation of the observed fact that the colder the "shifter" the more effective is its operation.

Exhausting the Tubes

In the manufacture of Cooper Hewitt lamps two features are of special interest, the method of evacuation and the treating of the metal anodes. When ready for evacuation the tube containing about twice its final amount of mercury is hung vertically in an upright gas furnace or hot air oven and connected by a tube at the upper end near the anode through a mercury trap to an ordinary vacuum. As the tube heats up to the boiling point of mercury the relatively heavy mercury vapor rises in it, displacing the remaining traces of foreign gases and water vapor. This process is continued until, with the mercury in the tubes boiling vigorously and with the glass walls of the tube nearly at their melting temperature, the tube is acting as a highly efficient mercury diffusion pump to produce its own high vacuum with reference to all volatile substances other than the mercury itself. When this process has resulted in the distillation from the tube of a measured amount of mercury the process is stopped and the bulb sealed off at the tube. Thereafter the "vacuum" of the tube is determined by the vapor pressure of mercury at any given tube temperature.

To free the metal electrodes from occluded gases they are heated to a white hot temperature during the pumping process. This treating is done by operating the lamp on an alternating current at some 4000 to 6000 volts.

The heat of the cathode hot spot is highly localized so that in a glass Cooper Hewitt lamp the arc column temperature varies from some 500 deg. C. in the center to about 125 deg. C. at the surface of the tube. Therefore the vapor pressure seldom rises to over one millimeter. There is a potential drop at the anode of about 5.7 volts and the anode is so designed that its temperature is normally about 350 deg C.

The Quartz Lamp

The Cooper Hewitt quartz lamp differs from the glass lamp as follows: The arc temperature is much higher, varying from some 1400 deg. C. in the center to about 450 deg. C. at the surface of the tube. The vapor pressure is therefore an atmosphere and over. The potential drop is about 25 volts per inch. To withstand the higher temperature a tungsten anode is used, which is white hot in normal operation. The quartz burner has no condensing chamber, direct radiation and the construction of the mercury filled cathode providing the required cooling. Fig. 6 shows a cross section of a 220-volt quartz burner in operation. The cathode surface is relatively smaller than in the glass lamp to restrict the fluctuations of the cathode spot. The arc stream is further steadied by deflection from the axis of the tube to the horizontal surface of the mercury. When cold the mercury flows down out of the cathode chamber and a slight tilting of the burner permits starting by the contact of the electrodes. The quartz mercury lamp requires the same regulation as the glass lamp, but a smaller per cent of energy is required for the purpose. The quartz arc column appears to be constricted along the center of the tube in contrast with the uniform appearance of the arc in glass.

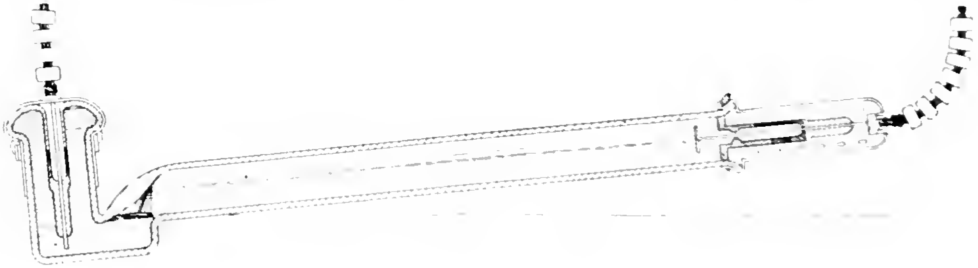


Fig. 6. Cooper Hewitt Quartz Lamp

The Alternating-current Lamp

The Cooper Hewitt alternating-current lamp is a highly specialized form of Cooper Hewitt single-phase constant voltage alternating-current rectifier. As shown in Fig. 1, the construction is identical with that of the direct current lamp except that there are two anode electrodes. The current in the lamp tube is a pulsating direct current of a frequency twice that of the alternating current, as is apparent from the oscillograph curves of Fig. 7. The mercury arc is essentially a unidirectional conductor because its maintenance is dependent upon the existence and peculiar properties of the so-called cathode "hot-spot." This can be formed and maintained at a low voltage, 5.3 volts at ordinary temperatures only on mercury and certain of its alloys, and once formed is itself only maintained by continuous operation; and even with a mercury cathode this discharge of mercury vapor and electrons can only be started by drawing an arc by contact or by a potential of several thousand volts. These peculiarities of the arc are utilized in the Cooper Hewitt lamp as follows: The cathode of the lamp is connected through inductance to the middle point of the secondary of an auto transformer (see Fig. 5), while the anodes are connected to the terminals. Therefore the cathode is continuously negative with respect to one or the other anode during operation. The arc is started by an induced voltage, the mercury electrode becoming the cathode for the reasons indicated above. Thereafter the cathode functions as continuously negative with respect to one or the other anode. Thus the two halves of the transformer secondary and the anodes connected to them function alternately, the arc shifting from one to the other anode with the alternations of the supply current. The series inductance, in addition to steadying the current for transient variations, has the more important function of sustaining the cathode spot and the arc current during the time of zero voltage, or in other words, of causing the current to a given anode during a half cycle to lag its voltage and overlap the current to the other anode to such an extent that the resultant arc current never falls below the minimum maintenance value. Although the potential between the two anodes is obviously always double that between the active anode and the cathode, there is little or no leakage between them. For an alternating current of a given frequency the minimum sustaining inductance is definitely determined and this also fixes the minimum practical power factor of the outfit.

Regulation such as that provided by series resistance in the case of the direct-current lamp could obviously be provided by inductance or choke coils instead of ohmic resistance at a slight gain in efficiency but with the disadvantage of low power factor, viz., 50 per cent. In the Cooper Hewitt alternating-current lamp, ohmic resistance is placed in the anode circuits, Fig. 5, and to secure a maximum of regulating effect on fluctuating voltage a special iron wire resistance unit is used. It is so designed that because of the high temperature co-efficient of resistance of iron the voltage absorbed by the resistance varies more rapidly than the current. The volt-ampere characteristic of a certain iron wire resistance is as indicated by the curve *BO″N″* in contrast with a nearly straight line for an ordinary resistance, Fig. 3; and the effect of using such an iron wire resistance with a direct-current lamp might be as indicated by the dotted lines, *I N*. In actual practice the series inductance provides part of the regulation, absorbing an appreciable amount of the transformer voltage as shown in Fig. 7, *K*, and helping to produce a power factor of 85 per cent.

Fig. 7 shows some of the relationships between voltage, current and time in various parts of a standard alternating current lamp. *A*, the primary voltage, is approximately a sine function as usual, but the current wave form, *B*, is distorted by the reactance and the arc characteristic of the secondary circuit. *D* is the e.m.f. between the arc cathode and the active anode, while *H* is the e.m.f. during the succeeding half cycle when the other anode becomes the active one. *C* is the anode current corresponding to voltage *D*, while *G* is the current in the other anode during the succeeding half cycle. *E* is the voltage drop in the anode resistance units during their current carrying intervals. *I* is the superimposed anode currents, while *J* is the resulting rectified arc current. *L* shows the superimposed arc voltages and their induced overlap which causes the anode currents to overlap as in *I*. Curve K showing the voltage drop in the direct-current reactance coils is of unusual interest. The inductive reactance of the arc circuit and the arc characteristics cause the pulsating arc current to rise more slowly than it decreases. The point of anode current overlap also comes during the time of arc current decrease. The bearing of these facts upon the wave form of the direct-current reactance voltage is evident from *J* and *K*. Thus points of zero voltage correspond to zero time rate of current change, maxima and minima current or to momentarily constant current; while the points of maximum voltage come when the time rate of current change is a maximum. The effect of the overlap discontinuities of the arc current on the corresponding induced voltage maximum is evident. During the period of current overlay, current flows to each anode and there is during that time no potential difference between them, as shown by a prolonged interval of zero voltage on the approximate sine curve of the voltage between the two anodes. The energy represented by this variation from the full sine curve form of the transformer secondary e.m.f. is momentarily absorbed in the common coils of the transformer which are constructed for high self inductance against each other.

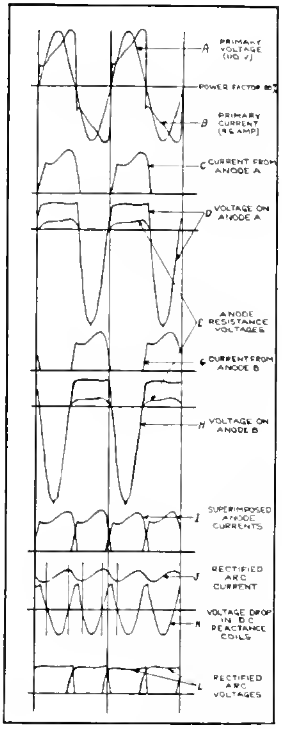


Fig. 7. Oscillograph Record of Alternating-current Lamp Characteristics

As is evident from *B* and *J*, Fig. 7, the tube current fluctuates over a much smaller range than does the usual alternating current. This fact and the lower intrinsic brilliancy account for the success of the lamp for high intensity illumination on alternating currents of frequencies as low as 25 cycles. On the other hand, alternating-current lamps are built for operation on frequencies as high as 133 cycles by modifications in the auto-transformer design.

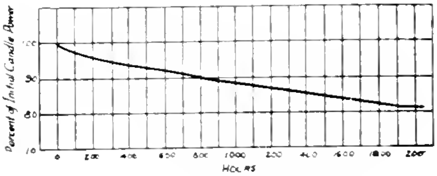


Fig. 8. Candle-power-life Characteristics

While the characteristics of individual lamps vary over a rather wide range, observations for years and on lamps operating under all types of adverse industrial conditions give the basis for a candle-power life of the nature shown in Fig. 8. The regenerative nature of the arc material gives a lamp of theoretically indefinite life, but manufacturing difficulties in the line of impure materials and contamination during the glass-blowing operation seriously complicate the situation. That improved manufacturing methods will produce lamps of even better candle-power life is inevitable.

Luminescence Color Sensations, Visibility and Visual Acuity

The light of the Cooper Hewitt lamp may be thought of as produced by electrical forces acting directly upon the vapor particles in the arc stream. Specifically the phenomenon is thought to be connected with the ionization and deionization of the mercury molecules as outlined above. The result is a relatively cold light since the temperature of the luminescent vapor of a Cooper Hewitt lamp is from 200 deg. C. to 500 deg. C., while that of the filament incandescent lamp is some 2800 deg. C.

The intensity of the light from any artificial source varies for the different wave lengths, being in general greatest for the long wave lengths in the infra-red, as shown on the insert in Fig. 9. These intensities plotted against a wave length scale form a relative spectral

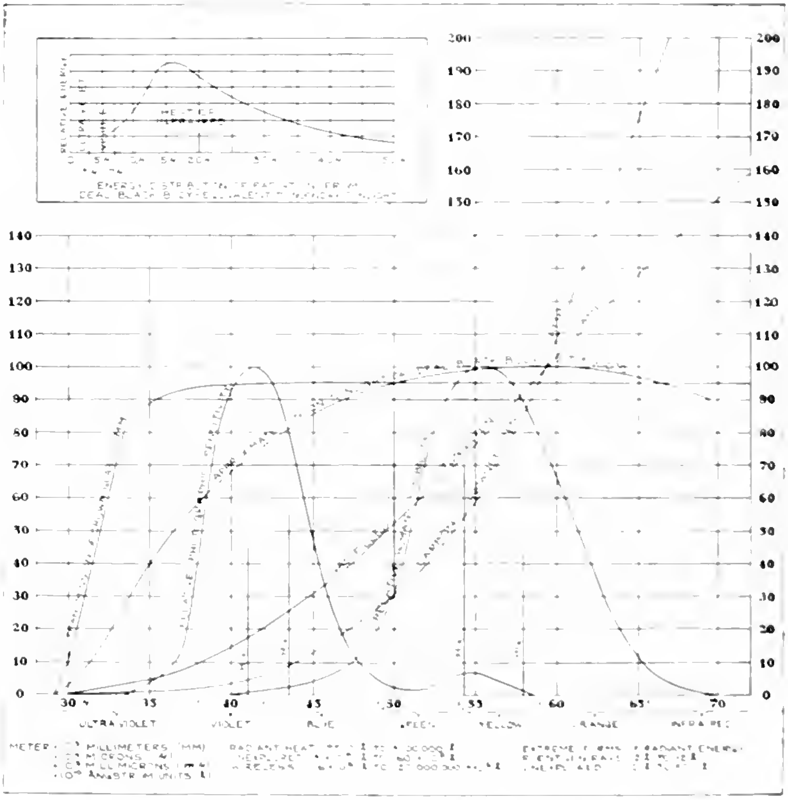


Fig. 9. Energy Distribution in Various Illuminants

distribution curve for any given light source. With increase in the temperature of the source this maximum in the infra-red moves towards the visible part of the spectrum. In so far as this change is not according to Wein's displacement law for a perfect radiator the radiation is said to be selective, favorably so if producing greater visibility.

For the discontinuous spectrum of luminescent light the energy distribution may be located by lines and bands along the wave length scale and the corresponding intensity by their height, as for mercury in Figs. 9 and 10. The spectral distribution of pure luminescence is completely selective and has not as yet been shown to be a function of temperature.

Light of each distinct wave length produces its own characteristic effect of visibility, color, visual acuity, photographic effect and psychologic reaction. All these effects differ in quality and intensity with the nature of the light waves. Some of these complicated relationships may be shown graphically by plotting the relative intensities of these effects against a wave length scale, as in Figs. 9 and 10. These effects also vary with different eyes, photographic plates, and nervous temperaments. The human visibility curve represents the average of a large number of eyes studied by the Bureau of Standards. The photographic sensitivity curve represents approximately the effect of white light on an ordinary photographic plate.

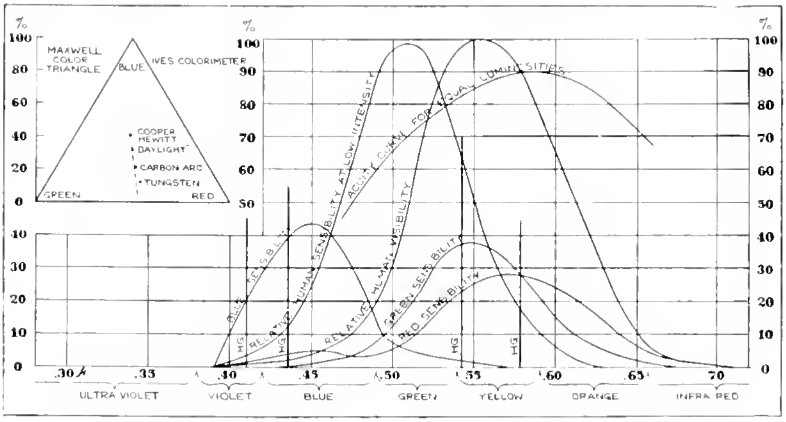


Fig. 10. Color Sensibility Curves

Visible light of any given wave length produces the sensation of a single color—monochromatic light. Light of all wave lengths and uniform intensity utilized in the proportions indicated by the visibility curve produces the sensation of white light. Color or white light produced by any other than these natural means is described as subjective. White light may be produced by the proper mixture of a series of complementary hues, such as orange with blue, yellow with blue-violet, or yellow-green with violet-purple. The whiteness of the Cooper Hewitt light is due to the combination of the nearly complementary hues of the yellow-green lines with the blue and violet lines. The difference between such a subjective white and true white light is only apparent when examining objects of colors other than those making up the former, since colored objects have their color by virtue of the colored light they are able to reflect. One method of studying light considers it as made up of combinations of three primary colors, red, green and blue. Ives has found that on the basis that white light is one third each of red, green and blue the mercury arc light gives the effect of being 29 per cent red, 30 per cent green and 41 per cent blue. Green and red produce the sensation of yellow; therefore the mercury arc light may be said to be 59 per cent yellow and 41 per cent blue, there being an excess of 9 per cent green and 12 per cent of blue light more than needed to produce the sensation of pure white.

Analyzed in terms of hue and saturation the light of the Cooper Hewitt lamp may be described as apparently of dominant hue 0.49 or blue with an admixture of 70 per cent of white light. Other lights analyzed on the same basis are:

	PER CENT	
	White	Hue
Sunlight	100	0
Cooper Hewitt light	70	.490μ
Average clear sky	60	.472
Mazda C	53	.584
Carbon glow lamp 3.8 w.p.c.	25	.592
Neon tube	6	.605

Transparent and solid objects are seen as colored only when they select and absorb from the light illuminating them all but some characteristic color or colors which they either transmit or reflect. Therefore any change in the color of an illuminant by means of colored glass globes or reflectors involves a decrease in luminosity since the color is produced by a process of subtraction from the original light. When the Cooper Hewitt light is produced in a glass tube of true spectral red color the glass absorbs nearly all the light and transmits little or none since there is no objective red in the Cooper Hewitt light. Similarly dull dark red objects may appear nearly black because of maximum absorption and minimum reflection.

As has already been said, the most unique property of the Cooper Hewitt light is that while it produces the sensation of white light the independent investigations of Luckiesh and Bell show that it is essentially a monochromatic light giving a visual acuity some 50 per cent higher than white light. It is of interest to note also that for equal illumination by monochromatic lights of various colors visual acuity is a maximum for yellow light of wave length 58 microns, which is also nearly the color of maximum visibility (Fig. 9). High monochromatic visual acuity and a white light containing a full range of spectral colors are mutually exclusive.

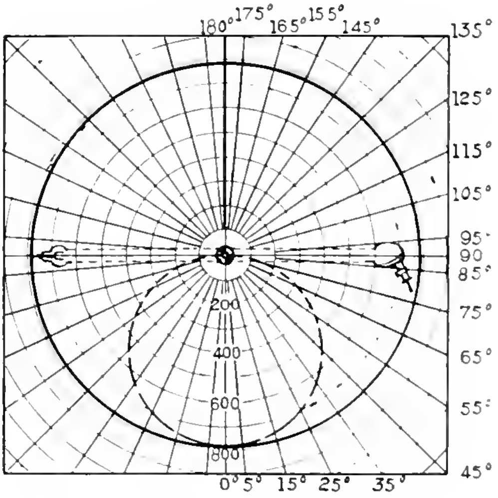


Fig. 11. Candle-power Distribution About a Bare Lamp

While it is claimed by some that subjective white light and colors should not be compared with ordinary white light and the spectral colors, yet there is no basis for defining the difference, which appears to be one of degree only. In fact, according to the most widely accepted theory of color vision, all colors are subjective in the sense that we never actually see the true primary colors which are themselves excited not by narrow ranges of wave lengths of light but in varying degree by wide ranges of light vibrations. Koenig's hue sensation curves for true primary red, green and blue are analogous to the visibility curve for the human eye (Fig. 10). Therefore the yellow Cooper Hewitt light excites moderately the sensations of primary red and green, and feebly the blue, producing the subjective sensation of yellow. The green Cooper Hewitt light excites strongly the primary green, moderately the primary red, and feebly the blue, producing the subjective sensation of green. The blue light excites strongly the primary blue and but slightly the other two, producing a subjective sensation of blue. The human eye apparently integrates these three primary color sensations as white—light visibility. The data for the insert in Fig. 10 were obtained by Ives by methods based on such a three color theory.

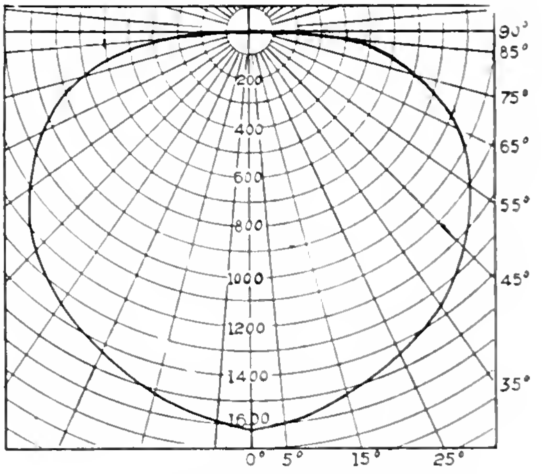


Fig. 12. Representative Light Distribution with a Standard Reflector

Photometery

The physical evaluation of the Cooper Hewitt light has been a perplexing problem for years. Added to the well known difficulties of heterochromatic photometry is the questionable process of comparing a light of discontinuous spectrum with a standard light of continuous spectrum. As yet direct comparisons with and without color corrective screens have failed to give thoroughly consistent results, nor does the flicker photometer seem to solve the problem for all its effectiveness in general heterochromatic photometry. Integrating spheres and hemispheres are limited by the marked effect of a diffuse reflecting surface in increasing the selectivity, by reflection, of a selective light.

Direct comparison with calibrated color filters to reduce the color difference on the comparison field seems as yet to most nearly approximate a physical valuation of use to the illuminating engineer and the candlepower data of Table I were obtained by this method. As the common form of Cooper Hewitt lamp is distinctly a source of finite area, and especially of finite length, the lamp is photometered at such a distance as to reduce this error to less than one per cent while in calculating the mean spherical candlepower the usual spherical reduction factor is used. The approximate distribution curve of a bare lamp, Fig. 11, is characteristic of any line source. A standard reflector widely used for industrial installations is so designed as to give identical distribution curves, in planes both parallel and perpendicular to the tube, of the type shown in Fig. 12. In the layout of an industrial installation these curves and accompanying data are used according to the principles fundamental in all illuminating engineering practice.

TABLE I

Current	Length of luminous tube in inches	Terminal Volts	Amperes	Power Factor	Watts	Mean Spher. C. P. Bare	Lumens per Watt Bare	Universal Reflector M.H. C.P.	Watts per Candle	Lumens per Watt	
Direct	50	110	3.5		385	550	17.9	875	.44	14.2	Photograph Illumination
Direct	2–50	220	3.5		770	940	15.4	1500	.52	12.2	Photograph Illumination
Alternating	50	110 or 220	3.8	85	430	615	17.9	975	.44	14.2	Photograph Illumination
Direct*	67	110	7.		770						Blue Printing
Direct*	67	110	15.		1650						Blue Printing
Direct	3	110	4		440						Quartz Arc
Direct	6	220	3.5		770						Quartz Arc

*Made also for alternating current. Variations in length and shapes of above lamps provide some 25 standard lamp tubes.

Table I is a tabulation of some of the characteristics of standard types of Cooper Hewitt lamps. The larger tubes are used in blue printing machines rather than for lighting, and illumination data are therefore omitted. These straight tubes are modified into specialized forms by variations in length and by bending the standard 50 in. tubes into U and M shapes for photographic enlarging outfits.

The Importance of the Electrical Industry in the Foreign Trade of the United States

By M. A. Oudin

Vice-President International General Electric Company

Ten per cent of the electrical apparatus manufactured in the United States during 1919 was exported, the value of which was ninety million dollars or 50 per cent in excess of the value of these exports for 1918. This high percentage of exports to total production is surprising in face of the exceedingly unfavorable exchange rates and is a true index of the importance of electric power in all countries of the globe. If this electrical apparatus were not absolutely essential to the industrial rehabilitation of European countries it most certainly would not have been purchased in such an unfavorable market. At home this foreign business has served to maintain production in certain lines of electrical apparatus for which domestic demand has temporarily fallen off; and as the manufacture of electrical goods involves the use of many other manufactured products, the exploitation of foreign markets by American electrical manufacturers has greatly increased the business of allied home industries. We should strive to maintain our present advantageous position in foreign trade by improving our knowledge of international business methods.—Editor.

The participation of the electrical industry in the foreign trade of the United States is of very considerable magnitude. Consequently, electrical exports constitute a powerful factor in insuring the prosperity of the industry itself, in preventing the unemployment of labor and in contributing to the maintenance of wages. There are many allied lines of machinery which are essential adjuncts in the use of electrical products and which are exported as a result of that association. The prosperity of such industries is closely bound up with that of the electrical industry. Finally, the ramifications of the electrical industry and its dependence upon other industries are such that its condition of prosperity directly affects through these contacts the welfare of a host of men, women and children in this country.

As to the important part played by the electrical industry in the foreign field, reliable figures indicate that the production of the electrical manufacturing industry in the United States during 1919 was about $900,000,000, of which over $90,000,000 or 10 per cent was exported. This was an increase of 50 per cent over the amount exported in 1918. As great a percentage of electrical products is exported as in any other manufacturing industry in this country, with the exception of typewriters, cash registers, harvesting machinery and a few others.

The accompanying table shows the exports of electrical material from the United States in 1919 compared with 1918.

It is worth while to note the destination of these electrical exports.

Over 40 per cent went to North and South America, Canada, Brazil, Argentina and Cuba being our best customers in the order named.

Over 25 per cent went to the Far East, Japan, China, Australia and India being our principal customers in that part of the world. Europe took about as much as the Far East. Our principal customers in Europe were Great Britain, Norway (which gave the United States over $4,000,000 worth of electrical business, a surprisingly large amount for so small a country), France, Italy and Spain.

This high level of electrical exports during 1919 has been attained in the face of foreign exchange rates, which have become increasingly unfavorable. But the demand for electrical products in Europe especially has been urgent and insistent, so necessary is the utilization of electrical power regarded for its industrial rehabilitation of Europe.

The fact that American electrical manufacturers have been able in general to maintain prices, means that this export business has not been handled at a loss, or in the way of dumping surplus products. It has been developed as a vital and necessary part of their whole business.

How important this foreign business has been in maintaining the production in American factories in lines in which the domestic demand has temporarily fallen off, may be seen from the fact that, while foreign business as a whole was only about 10 per cent of that production, in many instances it became a far greater percentage, offsetting a decline in domestic demand.

For instance, in the case of certain material, such as turbine sets, the foreign demand was about 25 per cent of the total; for street car equipment, it was 60 per cent, and for electric railway locomotives, still higher.

The falling off in domestic demand for these items reflected the financial handicaps of central stations and electric and trunk line railways in the United States, which, because of more or less stationary rates, had to face a rapidly declining net income and in the tight money market found it difficult to finance any considerable purchase of new equipment.

The increased export demand for these items of equipment meant that the manufacturers and their employees were relieved of the necessity of extensive layoffs, or expensive shifting of labor.

Any factor like this, which helps to stabilize demand and consequently production, does a great deal to insure a steady income to the workmen and to prevent the distress and complication attendant upon unemployment.

The export of electrical manufactures aids not only the electrical industry of the United States, but also the manufacturers of allied machinery and materials, the sale of which goes hand in hand with the sale of electrical machinery.

Statistics show that where American-made electrical machinery has successfully entered foreign markets there has been extensively sold allied machines, such as boilers, condensers, pumps, water wheels, hoists, mining machinery, sugar mill machinery, rails and accessories and a host of like material.

The exploitation of foreign markets by large electrical manufacturing companies has done much to open those markets for the products of other American manufacturers. This intensive cultivation is largely responsible for the wide prevalence of American engineering practice in many foreign countries. And this again has reacted favorably upon the exportation of a wide variety of products of American manufacturing industries.

At a recent meeting of the shareholders of the Siemens & Halske Company of Berlin, Kark F. Von Siemens, Chairman of the Company, emphasized the fact that the manufacture of electrical goods belongs to that class of industry which can do nothing with purely raw materials alone but also depends on the articles produced by other industries.

Indeed, it may be said that more than any other industry, electrical manufacturing draws upon the products of the soil and the output of mines and in no less a degree, the manufactured articles of other industries in a finished and semi-finished state.

The accompanying map, while showing the location of plants manufacturing electrical machinery and supplies, indicates only a few of the materials entering into these manufactures and then only the raw materials. It does not indicate the location of other industries which contribute innumerable articles required in the manufacture of electrical machinery and supplies.

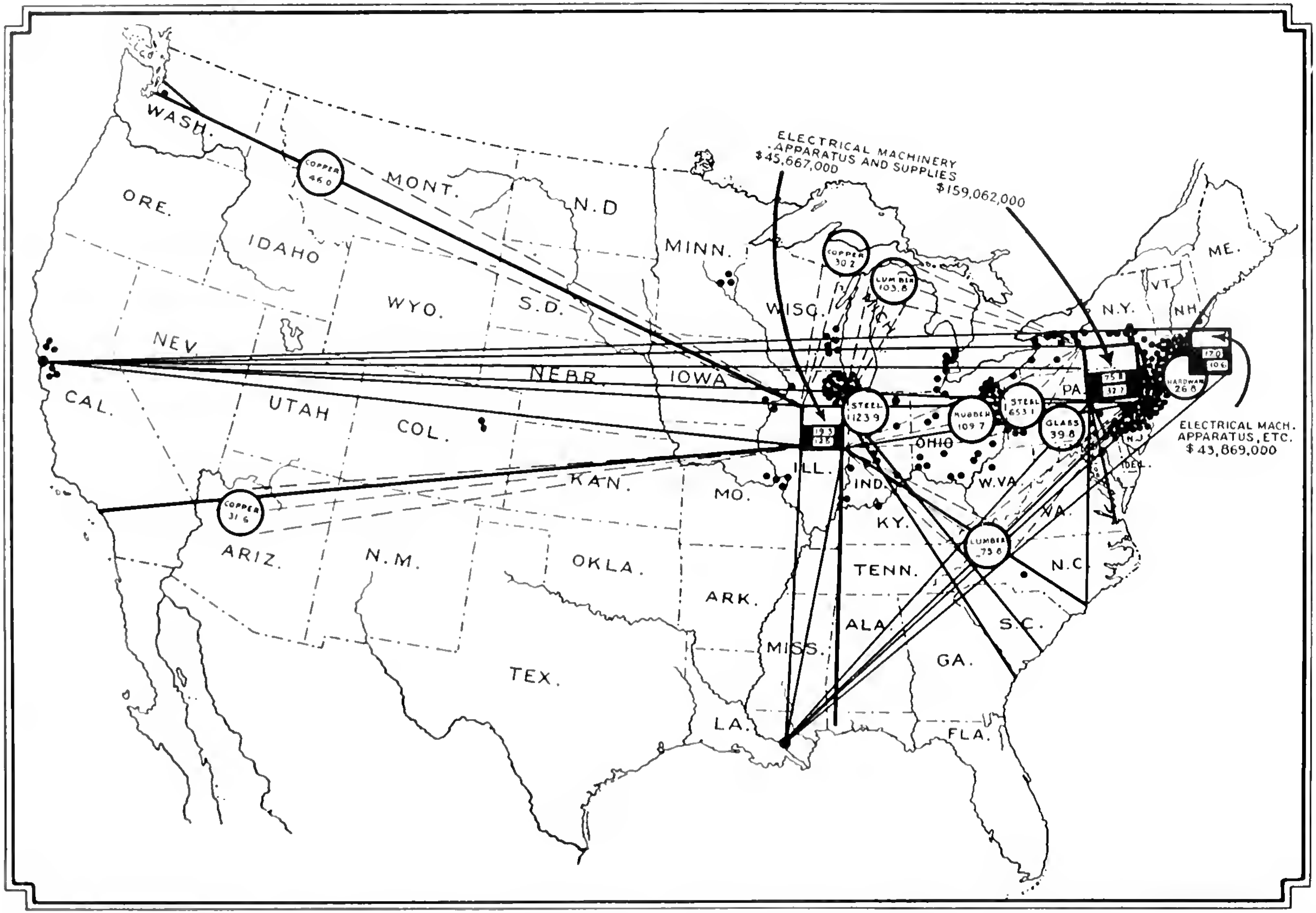
In addition to the raw materials, the source of which is approximately indicated on the map, there are very important items such as

UNITED STATES EXPORTS OF ELECTRICAL MACHINERY AND APPLIANCES (INCLUDING ELECTRIC LOCOMOTIVES)*

1919 and 1918 Compared

	Year 1919	Year 1918	Per Cent Changes
Batteries	$5,998	$3,178	+ 88.6
Carbons	1,392	1,601	− 13.
Dynamos and Generators	5,800	3,363	+ 72.5
Fans . . .	1,421	847	+ 67.8
Heating and Cooking Apparatus	1,580	686	+130.
Insulated Wire and Cables . . .	8,815	5,605	+ 57.4
Interior Wiring Supplies (incl. fixtures)	2,319	1,429	+ 62.3
LAMPS			
Arc	17	14	+ 21.5
Incandescent			
Carbon filament	203	103	+ 97.
Metal filament	4,674	3,369	+ 38.7
Locomotives (Electric)	836	183	+356.
Magnetos, Spark Plugs, etc	3,035	2,750	+ 10.4
Meters and Measuring Instruments	2,891	1,888	+ 53.1
Motors	10,635	8,225	+ 29.5
Rheostats and Controllers	515	289	+ 78.3
Switches and Accessories	3,565	2,195	+ 62.4
Telegraph Apparatus (incl. Wireless)	831	379	+119.2
Telephones	3,783	2,687	+ 40.9
Transformers	3,788	3,529	+ 7.3
All Others	27,827	17,846	+ 56
Total Electrical Machinery, etc	$89,925	$60,166	+ 49.5

(*) Expressed in thousands of dollars.



All values are expressed in millions of dollars. The large squares indicate the chief centers in which the raw material is made ready for consumption.
The value after the name of the material represents the output for the district.
The value in the white portions represent the cost of the principal materials.
The value in the darkened sections show the amount paid in wages.

The large circles indicate the centers of the allied industries.
The heavy solid lines show the paths of the finished product in leaving the United States.
The broken lines show the direction of raw material in moving towards the centers of manufacture.
Each dot represents the location of five establishments.

cotton yarn, cotton cloth and cotton tapes manufactured in the eastern and southern part of the United States.

From the east also there come copper shapes and brass manufactured in endless variety, also such articles as dry goods, textiles and paper products, and for construction purposes almost every kind of machinery and for production purposes machine tools, these coming for the most part from the Middle States. Other articles which lead in the list of domestic commodities, and which are required by the electrical manufacturing industry, in addition to those already mentioned, are the following:

Vulcanized fiber, porcelain materials, steel wire, metal alloys, petroleum wax from the East; aluminum, hardware, coal, coke, pig iron from the Middle West; asbestos, mercury, rutile, turpentine, rosin, oils, pitch from the South; mica and slate from the North, while the West furnishes many of the articles already mentioned and in addition, the raw items of gilsonite, lead and spelter.

This list is sufficiently long to indicate that the electrical industry is of vital importance to every section of the United States. Moreover, the export of electrical goods contributes to the commercial activities of the important seaports of the Atlantic Coast, and of the ports of New Orleans, San Francisco and Seattle. The prosperity of the ports on the Pacific and on the Gulf will be greatly enhanced if our electrical business with Latin America and the Far East continues at its present rate of growth.

With the certainty of the depreciation of European currency continuing for a long time to come and thus the maintenance of a barrier against exports to Europe, more and more does it behoove the American manufacturers to look to those markets which are not affected by unfavorable exchanges. With the inevitable falling off of exports to Europe, new business must be secured from the markets of South America and particularly from those of the Far East. New competition requires new business methods and the demand for electrical material will not be maintained at its present high rate unless there is created a demand for new kinds and new uses of electrical goods.

In the development of electrical projects, also, American interests can do far more than they have done in the past by aiding in the financing of such developments without which many of them will not be undertaken in the near future.

American trade has been given a tremendous impetus during the years of the war and the months which have followed the cessation of hostilities. Whether we shall retain our dominant position and not revert to our restricted and provincial pre-war position will be determined by the answer to this question: Do American merchants, manufacturers and capitalists desire to play the international game?

If this answer be in the affirmative, American enterprise no doubt will overcome the chief handicap to attaining this position which is found in our relative inexperience in the sphere of international politics, finance and commerce.

Power Control and Stability of Electric Generating Stations

PART II

By Charles P. Steinmetz

Chief Consulting Engineer, General Electric Company

The effect of power limitation upon the stable operation of large generating stations is of so great importance that at the recent annual convention of the A.I.E.E. at White Sulphur Springs a session was set apart for its discussion. Also, a session of the coming Edison Convention at New London will be devoted to it. Our August issue contained an editorial and the first half of Dr. Steinmetz's article on the subject. The remaining half appears below.—Editor.

DISCUSSION OF E.M.FS.

The foremost difficulty, and uncertainty in the application of the preceding equations, is found in the selection of the proper values of the machine e.m.f. E. E is not the terminal voltage: by slipping past each other without external impedance, the terminal voltage of the alternators goes down to zero. Neither is E the "nominal induced voltage," as this has no actual existence, but is the voltage which would be induced by the field excitation if the saturation curve of the machine continued as a straight line. It appears to me that E must be considered as the "true induced voltage," or actual induced voltage, that is, the voltage induced by the actual field flux, that is, the field flux due to the resultant field excitation and armature reaction. The armature reaction, however, fluctuates with the current between zero and a maximum, while the actual field flux often may be assumed as practically constant, since the magnetic field cannot follow the relatively rapid fluctuations of armature reaction.

The magnetic effect of the armature reaction is represented electrically in the synchronous reactance x_0. The synchronous reactance thus consists of a true self-inductive reactance x_1, which is instantaneous, and an effective reactance of armature reaction x_2, which requires appreciable time to develop, and does not correspond to any real magnetic flux.

$$x_0 = x_1 + x_2$$

In turbo-alternators, x_2 usually is very much larger than x_1

Electrically, the actual induced e.m.f. thus should be the nominal induced voltage e_0, which corresponds to the field excitation, less the reactance drop of the average current in the effective reactance of armature reaction, x_2.

If I equals the maximum effective value of the fluctuating current, the average current is $\frac{I}{2}$, and the actual induced voltage thus is:

$$E = e_0 - \frac{I x_2}{2}$$

It is, however, in two alternators connected together out of synchronism, through an additional reactance:

$$2E = I(2x_1 + x)$$

where x is the additional reactance through which the alternators of actual induced voltage E and true self-inductive reactance x_1 are connected together, while running out of synchronism with each other.

From these two equations follows:

Maximum (effective) value of the fluctuating interchange current

$$I = \frac{2e_0}{2x_1 + x_2 + x} \qquad (47)$$

and, actual induced voltage,

$$E = e_0 \frac{2x_1 + x}{2x_1 + x_2 + x} \qquad (48)$$

where e_0 equals nominal induced voltage effective value.

If the alternators are connected through an impedance z, z takes the place of x, combining vectorily with x_1 and x_2.

In this calculation, the armature reaction has been assumed as demagnetizing, and the impedance voltage therefore subtracted from the nominal induced voltage. This appears correct, as the interchange current between the alternators out of synchronism with each other is essentially a lagging current, throughout, as illustrated in Fig. 13.

If the two alternators are in synchronism, but out of phase with each other by a maximum phase displacement angle $2\omega_0$, it is:

$$2E \sin \omega_0 = I(2x_1 + x)$$

and again assuming the armature reaction as demagnetizing

$$E = e_0 - \frac{I x_2}{2}$$

thus the maximum (effective) value of the fluctuating exchange current:

$$I = \frac{2\, e_0 \sin \omega_0}{2\, x_1 + x + x_2 \sin \omega_0} \qquad (49)$$

and, actual induced voltage:

$$E = e_0 \frac{2\, x_1 + x}{2\, x_1 + x + x_2 \sin \omega_0} \qquad (50)$$

where e_0 is the nominal induced voltage, effective value.

However, in this case of alternators in synchronism but oscillating against each other, at least for small and moderate values of ω_0 the interchange current I is essentially an energy current with regard to the machine voltage, and the reactive component of this current alternately changes between lag and lead, that is, between demagnetizing and magnetizing. Therefore, the correctness is doubtful of subtracting the impedance voltage from the nominal induced voltage to get the induced voltage, but it would be:

$$E = \sqrt{e_0^2 - i^2 x_2^2}$$

and as i varies between zero and I, the average E would be the mean between

e_0 and $\sqrt{e_0^2 - I^2 x_2^2}$, thus:

combining with the equation:

$$2\, E \sin \omega_0 = I\, (2\, x_1 + x)$$

gives:

$$I = \frac{2\, e_0 (2\, x_1 + x) \sin \omega_0}{(2\, x_1 + x)^2 + x_2^2 \sin^2 \omega_0} \qquad (51)$$

$$E = e_0 \frac{(2\, x_1 + x)^2}{(2\, x_1 + x)^2 + x_2^2 \sin^2 \omega_0} \qquad (52)$$

It is probable that the true value of E lies between those given by equations (50) and (52), but nearer to that of (52).

Substituting these values of equations (48), (50), and (52) into the equations of sections ***A, B,*** and ***C,*** and substituting

$$z = 2\, x_1 + x$$

in these equations, as the impedance of the circuit between the two alternators, gives the equations referred to the nominal induced voltage, e_0, that is, the field excitation.

The nominal induced e.m.f. e_0 is derived by combining the terminal voltage e with iz, where z is the total impedance inside of the terminals, true reactance as well as effective reactance of armature reaction. For non-inductive load—and synchronous machine load may be assumed as approximately non-inductive—this gives:

$$e_0 = \sqrt{e^2 + (ix)^2}$$
$$= e\sqrt{1 + \xi^2} \qquad (53)$$

where ξ is the percentage reactance, and the resistance is neglected as small compared with the reactance.

However, this expression neglects the change of reactance with increase of magnetic saturation, increase of magnetic leakage between field poles, etc., and, therefore, especially in turbo-alternators with their enormous magnetic fields, high saturation and high field leakage, this expression is not very accurate, and reasonably reliable only in the mean range of current and voltage.

In sections ***C*** and ***D,*** the case of two alternators or groups of alternators out of synchronism with each other, the equations of synchronizing power, energy, and critical slip: P, P_0, W, s_0 contain the term:

$$\frac{2\, x_1 + x}{(2\, x_1 + x + x_2)^2}$$

thus are a maximum, if this term is a maximum. This is the case if:

$$x_2 = 2\, x_1 + x$$

or:

$$x = x_2 - 2\, x_1 \qquad (54)$$

that is:

The synchronizing power between alternators out of synchronism with each other is a maximum, and the frequency difference from which they pull each other into synchronism is greatest, if the alternators or groups of alternators are connected together through a reactance which is equal to the effective reactance of armature reaction, less twice the self-inductive reactance of the circuit between the alternators or groups of alternators. With two alternators or groups of alternators connected together without any external reactance, this means if the self-inductive reactance of the alternators or groups of alternators is one-third the synchronous reactance. With turbo-alternators, the self-inductive reactance usually is much less, and with such machines the synchronizing power is increased by the insertion of external reactance.

Substituting above relation into the equations of sections ***C*** and ***D,*** gives as the expression for the case of maximum synchronizing power:

Actual machine e.m.f.:

$$E = \frac{e_0}{2}$$

Resultant e.m.f.:

$$E^0 = e_0 \sin s\, \phi$$

Resultant current:

$$I = \frac{e_0 \sin s \phi}{x_2}$$

Power fluctuation of low frequency:

$$P = \frac{e_0^2 \sin 2\phi \sin \alpha}{4 x_2}$$

Energy transfer of low frequency:

$$W = \frac{e_0^2}{8 \pi s f x_2} \sin \alpha$$

Continuous power transfer:

$$P_0 = \frac{c e_0^2 \sin \alpha \cos (\alpha + \sigma)}{8 x_2}$$

Critical slip:

$$s_0 = \frac{e_0}{4 \sqrt{2 \pi f x_2 M}}$$

FEEDER REACTORS

A: General

Economy in cost and space makes it desirable to use the smallest feeder reactor which is reasonably safe, the more so as the number of feeder reactors required to protect every feeder going out from the generating station is usually much larger than that of the generator and busbar reactors.

Any reactance inserted into the system increases the reactive lagging volt-amperes and therefore, if the load on the system is lagging, lowers the power-factor, the more, the greater the reactance of the feeder reactor. In 25-cycle systems, this is of no moment, as the load usually is almost exclusively synchronous machines, equally operative with leading as with lagging current, so that even with large values of feeder reactors the system operates at unity power-factor. In 60-cycle systems, however, a considerable part of the system usually comprises induction machines and other apparatus which produce lagging current; the power-factor thus is below unity, lagging, and much additional reactance is therefore undesirable. An at least approximate investigation of the relations between the size of the feeder reactance and the disturbance in the generating station caused by a short circuit at the generating end of the feeder is thus desirable.

The function of a feeder reactor is threefold:

(1) It reduces the short-circuit current on the generating station in case of a breakdown of the feeder near the generating station, and thereby reduces the shock on the system.

(2) It permits setting the feeder circuit breakers for a much shorter time of opening, due to the lesser short-circuit current which they have to open, and thereby reduces the time during which the system is exposed to the short-circuit stresses.

(3) It keeps at least partial voltage on the busbars of the generating station during the feeder short circuit, and thereby reduces the liability of the generators, stations, and substations falling out of synchronism with each other.

Without a power-limiting reactor in the feeder, a short circuit in the feeder near the generating station—which is much more liable to occur than a short circuit on the busbars—is practically a short circuit at the busbars. The short-circuit current thus is the maximum which the generators can give, and its momentary or initial value (about eight times the final value, with the usual amount of generator reactors) is so great as to make it necessary to set the circuit breakers for a considerable time limit so as to allow the momentary excess current to die out. During the short circuit, the busbar voltage is zero or practically so, thus there is no synchronizing power between the generators of the affected station section, between this station section and the other station sections, and between the synchronous converters of the substations fed by the affected generating station sections and as due to the time limit of the circuit breakers the short circuit lasts an appreciable time, it is probable that during the short circuit the synchronous machines in the substations, and the generators have drifted out of step with each other so much that at the opening of the short circuit they do not catch into synchronism any more, and a shut down of a considerable part of the system results.

At the moment when a short circuit begins, the alternator field and thus the machine voltage still has full value, and the inductive short-circuit current thus is limited by the true self-inductive reactance only—the external and internal reactance of the generators, and the reactance of the feeder reactor, where such is used. At the moment when the short circuit begins, the busbar voltage drops from its normal previous value, to zero if no feeder reactor is used, or to the reactance voltage of the feeder factor under the momentary short-circuit current, which may be a considerable part of the normal busbar voltage. If then the short circuit could be opened instantly before the alternator field can build down under the demagnetizing action of the inductive short-circuit current, the busbar voltage would recover instantly, to its previous value. If, however, the short circuit lasts any appreciable time, the alternator fields gradually—and rather rapidly—build down; the machine e.m.f. and the short-circuit current decrease (and the busbar voltage, with feeder reactor; without feeder reactor the busbar voltage is zero, as stated). If now the short circuit is opened, the busbar voltage does not instantly recover, but jumps up only to the value corresponding to the then prevailing field flux, and then only gradually—and rather slowly—recovers by the field flux again building up under the effect of the exciter voltage.

In turbo-alternators, the rate at which the machine fields build down under dead short circuit, and at which the busbar voltage decreases which appears at the moment of opening the short circuit, is very high, that is, the field is demagnetized in about half a second, so that with the delayed opening of the circuit breakers the field has practically been demagnetized before the short circuit is opened; but the rate at which the voltage of the machine recovers after the opening of the short circuit is rather slow, from three to five seconds or more (depending on the existing field exciting current and thus on the load previously on the machine).

With a power-limiting feeder reactor, however, of a reactance which though small with regard to the rating of the feeder is considerable compared with the reactance of the generating station (internal and external generator reactances), the rate of demagnetization of the field flux is greatly slowed down, due to the lesser demagnetizing action of the smaller short-circuit current, that is, the time required for the demagnetization of the machine field is of the magnitude of one and one half seconds. It is the larger, the higher the feeder reactance and greater the number of generators connected to the busbars, smaller with lower feeder reactance and fewer generators on the busbars. If then the circuit breakers can be adjusted to open quicker, which appears feasible at the lesser short-circuit current, most of the field flux will still be there at the opening of the short circuit, and the voltage thus would, at the opening of the short circuit, jump back to nearer full value. Considering that even during the short circuit of the feeder cable, considerable voltage remains on the busbars, and that the duration of the short-circuit period is greatly reduced by the permissible quicker opening of the circuit breakers, it appears feasible, with a moderate value of feeder reactor, to limit the voltage drop and its duration in the affected station so that all or at least most of the synchronous apparatus on this station section will remain in step.

B: Armature and Field Transients of Synchronous Machines

(1) If

p = number of poles

n_0 = number of field turns per pole

i_{00} = exciting current at no load

and

Φ_0 = magnetic flux per pole

then $pn_0\Phi_0$ is the total number of interlinkages, and $\frac{pn_0\Phi_0}{i_{00}}$ the flux interlinkages per unit current, that is, the inductance of the field circuit. That is, in standard units:

$$L_0 = \frac{p\,n_0\,\Phi_0}{i_{00}} 10^{-8}\,h \tag{55}$$

is the inductance of the field.

If

e_0 is the voltage of the exciting current

and

i_0 the (permanent) field current,

the resistance of the field circuit is:

$$r_0 = \frac{e_0}{i_0} \tag{56}$$

This is the total resistance, field winding as well as external rheostat, etc., as both have the same action in the field transient. The duration of the field transient then is:

$$t_{00} = \frac{L_0}{r_0} \tag{57}$$

that is:

$$a_0 = \frac{1}{t_{00}} = \text{attenuation constant, and} \tag{58}$$

$$i_1 = I_0 \epsilon^{-a_0 t}$$
$$E = E_0 \epsilon^{-a_0 t} \tag{59}$$

is the field discharge, or the transient by which the field current and thus the field magnetism and the induced voltage decrease on withdrawal of the exciting e.m.f., and

$$i_2 = i_0\,(1 - \epsilon^{-a_0 t})$$
$$E = E_0\,(1 - \epsilon^{-a_0 t}) \tag{60}$$

is the charging transient of the field or the starting current of the field, that is, the transient by which field current and field magnetism and thus the induced voltage rises on the application of the exciting voltage or recover after the demagnetizing action of an excessive lagging current, such as a short circuit.

(2) On inductive load, the armature current of an alternator demagnetizes, and to give the same field flux the field exciting current thus has to be increased to counteract the demagnetizing armature reaction.

In a three-phase alternator:

If

n = number of armature series turns per pole per phase

and

I = armature current per phase (effective), the armature reaction per pole is:

$F = 1.5\sqrt{2}\, nI$ ampere-turns.

and

$n_0 i = 1.5\sqrt{2}\, nI$

thus gives the field current

$$i = 1.5\sqrt{2}\,\frac{n}{n_0}\,I \tag{61}$$

$$= cI$$

where:

$$c = 1.5\sqrt{2}\,\frac{n}{n_0} \tag{62}$$

is the reduction factor from armature to field.

Thus

If i_0 = field exciting current,

and an additional inductive load of I amperes is put on the alternator, to keep the same magnetic flux and thus the same voltage, the field exciting current has to be increased from

i_0 to $i_0 + cI$.

[This does not consider the change of the magnetic flux distribution resulting from the inductive armature current I, such as the increase of leakage flux, corresponding increase of saturation, etc., which requires a somewhat greater increase of field excitation. That is, c is somewhat greater than given by equation (62).]

(3) Let E_0 be the voltage produced by the no-load field excitation i_{00}. An inductive load of current I requires an increase of the field excitation cI. This additional field current cI would produce (assuming a straight-line saturation curve, that is below saturation) a voltage:

$$E_2 = \frac{cI}{i_{00}}\,E_0$$

thus gives an apparent internal reactance of the machine:

$$x_2 = \frac{E_2}{I}$$

or

$$x_2 = \frac{cE_0}{i_{00}} \tag{63}$$

This is the effective or equivalent reactance of armature reaction. It is not a true reactance, and differs from the true self-inductive reactance, that the latter is instantaneous, while the effective reactance of armature reaction x_2 requires some time to develop.

Or, if I_0 equal full load or rated armature current, the effective reactance of armature reaction, given as fraction (or in per cent), is

$$\xi = \frac{x_2 I_0}{E_0} = \frac{cI_0}{i_{00}} \tag{64}$$

that is, the ratio of the field equivalent of the armature current, cI_0, to the no-load field current i_{00}, is the effective reactance of armature reaction, as fraction.

Substituting (62) into (63) gives:

$$x_2 = 1.5\sqrt{2}\, n\,\frac{E_0}{n_0 i_{00}}$$

$$= 1.5\sqrt{2}\, n\,\frac{E_0}{F_0} \tag{65}$$

where F_0 is the no-load field ampere-turns per pole, which give the voltage E_0.

(4) Let E_0 equal the voltage and i_0 equal the field exciting current of an alternator. Let then an inductive load of current I_0 be suddenly thrown on the alternator, for instance by a short circuit beyond a feeder reactance, or on the busbars. If then the reactance (true self-inductive reactance) of the circuit of this inductive load is x_1, the current is:

$$I_0 = \frac{E_0}{x_1} \tag{66}$$

This current I_0 however demagnetizes with the field equivalent cI_0, and the magnetic field flux of the machine, and thus the voltage must therefore decrease. The field flux however cannot change instantly, as in changing it induces a voltage and therefore produces a current in the field circuit, which opposes the change. That is, the field flux begins to decrease at such a rate as to induce in the first moment a voltage in the field winding, increasing the field current by cI_0, the field equivalent of the armature current.

That is, in the moment when the inductive load current I_0 is thrown on the alternator armature, the alternator field current jumps from i_0 to $i_0 + cI_0$.

As, however, the exciting voltage e_0 can maintain only the current i_0 in the field circuit, the momentary excess field current $i_0 + cI_0$ gradually decreases, down to the permanent value i_0, and with it decreases the field flux and the voltage of the machine, from the initial values Φ_0 respectively E_0, to the final values:

$$\Phi_1 = \frac{i_0}{i_0 + cI_0} \Phi_0 = b\Phi_0 \tag{67}$$

and

$$E_1 = \frac{i_0}{i_0 + cI_0} E_0 = bE_0 \tag{68}$$

and with it decreases the current, from the initial value I_0, to

$$I_1 = \frac{i_0}{i_0 + cI_0} I_0 = bI_0 \tag{69}$$

where:

$$b = \frac{i_0}{i_0 + cI_0}. \tag{70}$$

At the first moment the field flux is still Φ_0, the field exciting current however is $i_0 + cI_0$.

Field flux Φ_0 and no-load field exciting current i_{00} give the field inductance L_0. Field Φ_0 and field exciting current $i_0 + cI_0$ thus give an apparent or equivalent or effective field inductance:

$$L = \frac{i_{00}}{i_0 + cI_0} L_0 = b_0 L_0 \tag{71}$$

where:

$$b_0 = \frac{i_{00}}{i_0 + cI_0}. \tag{72}$$

That is, when throwing an inductive load on an alternator, field flux and voltage decrease by the demagnetizing armature reaction, and during the field transient, the mutual inductance of the armature current on the field reduces the field self-inductance from the true self inductance L_0 to an apparent or effective inductance $L = b_0 L_0$.

As the resistance of the field circuit remains the same, the duration of the transient resulting from a sudden inductive load, such as a short circuit, thus is given by:

$$\begin{aligned} t_0 &= \frac{L}{r_0} \\ &= b_0 \frac{L_0}{r_0} \\ &= b_0 t_{00} \end{aligned} \tag{73}$$

and the attenuation constant is:

$$a = \frac{1}{t_0} = \frac{a_0}{b_0} \tag{74}$$

and the equations of the transient thus are:

The armature current, changing from:

$$I_0 = \frac{E_0}{x_1}$$

to:

$$I_1 = bI_0$$

is:

$$I = I_1 + (I_0 - I_1)\epsilon^{-at} \tag{75}$$

or:

$$I = I_0 \left\{ b + (1-b)\epsilon^{-at} \right\} \tag{76}$$

and the voltage then is:

$$E = x_1 I \tag{77}$$

and, if of the reactance x_1, the part x is external, $x_1 - x$ internal in the machine or station, the terminal voltage is:

$$E^0 = xI \tag{78}$$

(5) *Equations and Denotations*

r_0 = resistance of exciting circuit

$= \frac{e_0}{i_0}$ ohms (56)

e_0 = exciter voltage

i_{00} = field current at no load

i_0 = field current at full load

L_0 = true inductance of field exciting circuit

$= \frac{p n_0 \Phi_0}{i_{00}} 10^{-8} h$ (55)

p = number of poles

n_0 = number of field turns per po'e

Φ_0 = magnetic flux per field pole, produced by exciting current i_{00}

t_{00} = duration of field transient

$= \frac{L_0}{r_0}$ (57)

a_0 = attenuation constant of field transient

$= \frac{1}{t_{00}}$ (58)

$E = E_0 \epsilon^{-a_0 t}$

= field discharge transient (59)

$E = E_0 (1 - \epsilon^{-a_0 t})$

= starting transient of field (60)

x_1 = total self-inductive reactance of alternator circuit

x = external part of this reactance

E_0 = machine voltage before closing the circuit on reactance x_1

I_0 = initial (or momentary maximum) value of the current in reactance x (effective value)

$= \frac{E_0}{x_1}$ (66)

I_1 = final (or permanent) value of current

$$= bI_0 \qquad (69)$$

$$b = \frac{i_0}{i_0 + cI_0} \qquad (70)$$

$$c = 1.5\sqrt{2}\frac{n}{n_0}$$

= reduction factor from armature to field circuit

n = number of series armature turns per pole per phase

$$I = I_0[b + (1-b)]\epsilon^{-at} = I_1 + (I_0 - I_1)\epsilon^{-at} \qquad (75)\ (76)$$

= armature transient.

a = equivalent attenuation constant of transient

$$= \frac{1}{t_0} \qquad (74)$$

$$t_0 = b_0 t_{00} \qquad (73)$$

$$b_0 = \frac{i_{00}}{i_0 + cI} \qquad (72)$$

E = total voltage

$$= x_1\, I \qquad (77)$$

E^0 = terminal voltage

$$= xI \qquad (78)$$

(6) From these equations, and the numerical constants of the alternators, it is possible now to calculate the action of a short circuit or similar disturbance on the system, and the effect thereon of the reactance of the feeder reactor, by calculating, and plotting with the time as abscissæ, the transients of induced voltage, current, and terminal voltage resulting from the application of a short circuit. This gives for the moment of the opening of the circuit breaker the values of current, terminal voltage, and induced voltage, and from the latter the value of the terminal voltage immediately after the moment of the opening of the circuit breaker. Calculating then, and plotting, with the latter as initial values, the field transient gives the voltage recovery curve of the system. From the drop of voltage, and its duration, then can be estimated whether any synchronous apparatus such as converters, operated from the affected generating station, are liable to be thrown out of synchronism, and whether by the voltage drop the synchronizing power of the station against other stations tied to it by busbar reactors is sufficiently lowered to fail to keep in step, and whether in this case the duration of the voltage drop is sufficient for the machines or stations to drift far enough apart so that at the voltage recovery they are not able any more to pull each other into step.

C: Numerical Calculations

The constants of some typical steam turbine alternators of large size, three-phase machines of 25 and 60 cycles, are given in Table I.

Considering now as a numerical instance the effect of a feeder short circuit close to the busbars, on a 25-cycle 9000-volt generating station of 60,000 kw. steam turbine alternator capacity, without and with feeder reactors, assuming that the short circuit is opened after one second. Assuming as a fair average:

An equivalent effective reactance of armature reaction of 85 per cent,

A true self-inductive internal reactance of the alternators of 6.8 per cent, and

An external reactance, as power-limiting generator reactor, of 6 per cent.*

Let the duration of the field transient (full-load condition) be

$$t_{00} = 4.51 \text{ sec.}$$

the field attenuation constant thus

$$a_0 = 0.222$$

The field transient then is given by:

$$e = e_1 + (e_0 - e_1)\epsilon^{-a_0 t} \qquad (79)$$

where:

e_0 = voltage of the machine at the moment $t=0$, for instance, initial voltage in the moment when a short circuit has been opened.

e_1 = machine voltage corresponding to the exciter voltage impressed upon the machine, that is, final voltage of the machine.

Consider the three cases:

(a) No feeder reactor, thus dead short circuit on the busbars.

(b) A feeder reactor of 0.5 ohms per phase, or 2.9 times the true reactance of the generating station, or 37 per cent.

(c) A feeder reactor of 0.7 ohms per phase, or 4.05 times the true reactance of the generating station, or 52 per cent.

(a) With 12.8 per cent self-inductive reactance, the momentary or initial short-circuit current, as fraction of the rated current of the station, is given by:

$$i_0 = \frac{1}{0.128} = 7.8$$

From the machine constants, it follows:

$$b = 0.172$$

$$b_0 = 0.129$$

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* A reactance of n per cent means n per cent of the value of $\frac{\text{rated voltage}}{\text{rated current}}$.

TABLE I

CONSTANTS OF THREE-PHASE STEAM TURBINE ALTERNATORS

	25 Cycles					60 Cycles				
Rating, kw.	12,000	11,000	20,000	30,000	35,000	12,500	14,000	20,000	20,000	30,000
Speed, r.p.m.	750	750	750	1500	1500	1800	720	720	1200	1800
Mech. momentum, mega joules $3M$	150	200	233	262	204	97	220	258	310	190
No. of poles, p	4	4	4	2	2	4	10	10	6	4
Volts, terminal	9000	9000	9000	9000	9000	12,000	12,000	12,000	12,000	12,000
Amperes, full load	770	900	1280	1925	2250	*750	†900	*1200	*1200	‡1600
Synchronous reactance, x_0, per cent	89	85	129	108	147	120	74	125	73	130
Internal true reactance, x_{11}, per cent	5.4	4.6	6.8	9.0	11.4	12	9	9	13	15
Eff. react. of armat. reaction, x_2, per cent	83.6	80.4	122.2	99	135.6	108	65	116	60	115
External reactance, x_{12} per cent	6	6	4.13	6.25	...	...	...	..	. .	...
Regulation, non-ind. load, per cent	21	22	29	24	28	31	12	16	15	25
FIELD										
No. of turns per pole n_0	95	96	78	198	243	150	39	36	84	95
Amp., no load, i_{00}	250	307	328	226	185	122	385	348	286	235
Amp., full non-ind. load, i_0	333	388	522	335	320	190	463	517	367	368
Exciter voltage, e_0	125	125	125	250	250	125	125	125	230	230
Flux per pole, ml, Φ_0	111	135	137.5	276	252	71.5	68	68	95.5	117.5
ARMATURE										
No. series turns per pole per phase, n	12	10	10	12	12	10	4	4	5	6
$c = 1.5\sqrt{2}\frac{n}{n_0}$	0.268	0.221	0.271	0.129	0.105	0.141	0.217	0.236	0.126	0.134
$L_0 = \frac{p n_0 \Phi_0}{i_{00}} 10^{-8}$ (henrys)	1.69	1.69	1.30	4.84	6.62	3.53	0.662	0.703	1.80	1.90
No Load										
$r_0 = \frac{e_0}{i_{00}} =$ (ohms)	0.5	0.408	0.385	1.11	1.35	1.02	0.325	0.36	0.806	0.98
$t_{00} = \frac{L_0}{r_0} =$ (seconds)	3.38	4.14	3.38	4.35	4.91	3.45	2.04	1.96	2.23	1.94
$a_0 = \frac{1}{t_0}$	0.296	0.241	0.296	0.229	0.204	0.29	0.49	0.51	0.448	0.515
Full Load										
$r_0 = \frac{e_0}{i_0} =$ (ohms)	0.375	0.322	0.24	0.747	0.781	0.66	0.27	0.242	0.628	0.625
$t_{00} = \frac{L_0}{r_0} =$ (seconds)	4.51	5.25	5.42	6.48	8.47	5.35	2.45	2.91	2.92	3.05
$a_0 = \frac{1}{t_{00}}$	0.222	0.191	0.185	0.154	0.118	0.187	0.408	0.344	0.342	0.328
Short Circuit after Full Load										
Initial current, $I_0 = \frac{E_0}{x_1}$	6700	8450	11,700	12,700	15,200	6200	10,000	13,300	9200	10,600
$b = \frac{i_0}{i_0 + cI_0}$	0.156	0.172	0.141	0.170	0.167	0.180	0.176	0.142	0.240	0.206
Final current, $I_1 = bI_0$	1050	1450	1650	2160	2530	1120	1760	1880	2200	2180
$b_0 = \frac{i_{00}}{i_0 + cI_0}$	0.117	0.137	0.089	0.114	0.0965	0.115	0.146	0.095	0.187	0.137
$L = b_0 L_0 =$ (henrys)	0.198	0.232	0.116	0.551	0.638	0.405	0.097	0.067	0.337	0.260
$t_0 = \frac{L}{r_0} =$ (seconds)	0.527	0.72	0.482	0.737	0.816	0.615	0.358	0.276	0.547	0.418
$a = \frac{1}{t_0}$	1.90	1.40	2.08	1.35	1.23	1.63	2.77	3.63	1.83	2.39

* At 80 per cent power-factor. † At 75 per cent power-factor. ‡ At 90 per cent power-factor.

Thus, final short-circuit current, as fraction of rated current:

$$i_1 = b i_0 = 1.34$$

and, duration of the short-circuit transient:

$$t_0 = b_0 t_{00} = 0.582 \text{ sec.}$$

Thus, attenuation constant:

$$a = \frac{1}{t_0} = 1.72$$

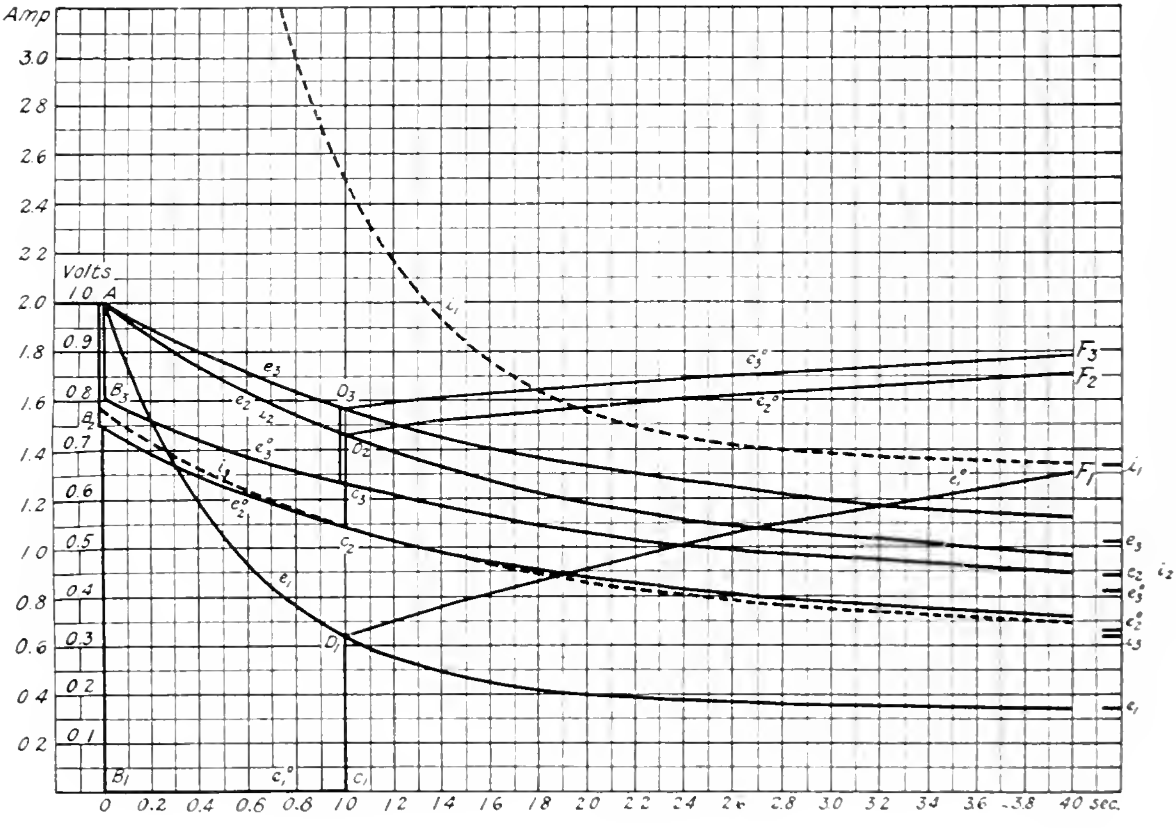

Fig. 15

and, equation of the short-circuit current transient:

$$i = i_1 + (i_0 - i_1)\,\epsilon^{-at}$$
$$= 1.34 + 6.46\,\epsilon^{-1.72t} \qquad (80)$$

This current is plotted in Fig. 15, in dotted line, "i_1."

Proportional hereto is the induced generator voltage, and thus is given, as fraction of the induced voltage immediately before the short circuit, by the transient:

$$e = b + (1 - b)\,\epsilon^{-at}$$
$$= 0.172 + 0.828\,\epsilon^{-1.72t} \qquad (81)$$

Plotted as curve "e_1" in Fig. 15.

The terminal voltage is zero during the short circuit; at one second, with the opening of the short circuit, the terminal voltage jumps back to the same fraction of the terminal voltage before the short circuit, to which the induced voltage has dropped, that is, to the point D_1 of curve "e_1," 32.2 per cent of the previous terminal voltage.*

From this point, of 32.2 per cent voltage at one second, the voltage now gradually recovers on the field transient, equation (73) for

$$e_1 = 1,\ e_0 = 0.322,\ a_0 = 0.222, \text{ thus:}$$
$$e^0 = 1 - 0.678\,\epsilon^{-0.222t}$$

During the short circuit, the terminal voltage thus traverses the values of $A\ B_1\ C_1\ D_1\ F_1$ in Fig. 15. As seen, the voltage recovery is very slow, and it is not probable that any synchronous apparatus will remain in step.

The short-circuit current after one second—which the circuit breaker has to open—is 2.5 times the rated current, or 150,000 kv-a.

(b) With 12.8 per cent self-inductive generator reactance, and 37 per cent feeder

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* Assuming that the conditions of the external load have not materially changed or have no material effect, which latter may be assumed approximately, since the short-circuit currents are very large compared with the normal-load currents.

reactance, the total reactance is 49 per cent, the initial short-circuit current thus:

$$i_0 = \frac{1}{0.498} = 2.01$$

In this case, it is:

$$b = 0.446$$

$$b_0 = 0.335$$

Thus, final short-circuit current:

$$i_1 = bi_0 = 0.894.$$

Duration of short-circuit transient:

$$t_0 = b_0 t_{00} = 1.51 \text{ sec.}$$

Attenuation constant:

$$a = \frac{1}{t_0} = 0.662$$

Short-circuit current transient:

$$i = 0.894 + 1.107\ \epsilon^{-0.662t}$$

Induced voltage:

$$e = 0.446 + 0.554\ \epsilon^{-0.662t}$$

The terminal voltage during the short circuit now is not zero, but is the same fraction of the induced voltage, as the reactance of the feeder reactor is to the total self-inductive reactance:

$$\frac{x}{x + x_1} = \frac{37}{37 + 12.8} = 0.744$$

Thus, the terminal voltage during the short circuit is:

$$e^0 = 0.744\ e = 0.332 + 412\ \epsilon^{-0.662t}$$

The transients of short-circuit current, induced voltage, and terminal voltage are shown in Fig. 15 by the curves "i_2," "e_2" and "e_2^0."

As seen, at the moment of short circuit, the terminal voltage makes a sudden drop to curve "e_2^0," to 0.744 of the previous value, then follows the curve "e_2^0" for one second; then on opening the short circuit suddenly jumps, from 0.543 on "e_2^0" to 0.732 on "e_2," and then gradually recovers on the field transient given by the equation:

$$e^0 = 1 - 0.268\ \epsilon^{-0.222t}$$

The terminal voltage thus traverses the broken curve $AB_2C_2D_2F_2$.

As seen, while the voltage recovery after the short circuit is slow, the terminal voltage even during the short circuit remains above half value.

The current after one second, when opening the short circuit, is only 1.46 times full-load current.

(c) In the same manner the curves are calculated for the 52 per cent feeder reactor, giving:

$$i_0 = 1.55$$

$$b = 0.511$$

$$b_0 = 0.383$$

$$i_1 = 0.79$$

$$t_0 = 1.73 \text{ sec.}$$

$$a = 0.578$$

$$i = 0.79 + 0.76\ \epsilon^{-0.578t}$$

$$e = 0.511 + 0.489\ \epsilon^{-0.578t}$$

$$\frac{x}{x + x_1} = 0.802$$

$$e^0 = 0.41 + 0.392\ \epsilon^{-0.578t}$$

and the recovery transient:

$$e^0 = 1 - 0.215\ \epsilon^{-0.222t}$$

The values are shown in Fig. 15 as "i_3," "e_3," "e_3^0," giving for the terminal voltage the broken curve $AB_3C_3D_3F_3$.

The short-circuit current when the circuit breaker opens, after one second, is only 9 per cent above full-load current.

Table II gives the numerical values of voltage and current, at the beginning of short circuit, after one second and final, as fractions of rated voltage and current.

The question then arises of the bearing of these voltage curves, Fig. 15, on synchronous operation.

During the period of dead short circuit or zero terminal voltage, B_1C_1, there is no synchronizing power. There is no load on the generators beyond the i^2r and the load losses which are moderate even at the initial high momentary short-circuit current and rapidly decrease with the decreasing short-circuit current. Thus the alternators speed up, until the governor shuts off steam or the emergency governor trips. The former necessarily must take an appreciable time to avoid trouble from steam governor hunting. Thus usually the speeding up will occur until the emergency trips and cuts off steam, about 10 per cent above normal speed. Then slowing down occurs until the machines are again put on their governors. The speeding up, however, occurs at different rates, due to the differences in the momentum of the different machines; the speed of tripping cannot be exactly the same, as absolute reliability rather than exactness of speed is the main requirement of the emergency cut off; and furthermore, some speeding up will continue after the closing of the governor, due to the steam contained between the cut off and the turbine, and in the turbine.* Thus, if during this period the machines do not have sufficient power to keep each other rigidly in step, at the time when the short circuit is cleared and the voltage returns, the machines probably have drifted so far apart that they cannot pull each other in step again but continue slipping out of synchronism, short circuiting each other and keeping zero terminal voltage indefinitely.

Let P equal the load on the machine before the short circuit. With the load taken off, the power P then accelerates the momentum M of the machine, until the steam is cut off. This means:

$$2\,sM = Pt \qquad (82)$$

where s is the increase of speed in fraction, and t the time or more accurately:

$$M[(1+s)^2-1] = Pt \qquad (83)$$

however, (82) is sufficiently accurate for our purposes,
thus:

$$s = \frac{P}{2M}\,t \qquad (84)$$

Substituting the values of P and M from Table I, gives the acceleration curves. In Fig. 16 are given such curves for four 25-cycle machines, the 12,000, 14,000, 30,000, and 35,000-kw., as (1), (2), (3), and (4). As seen, the acceleration is very rapid, from 3.5 to 8.6 per cent per second.

The limits of synchronizing power, that is, the maximum speed difference from which the machines can pull each other into step promptly, is given by equation (38) as:

$$2\,s_0 = E\sqrt{\frac{\sin\alpha}{2\pi f z M}}$$

Choosing the same values as in Fig. 15, that is, per 10,000 kw. rated machine capacity:

$$z = 2x_1 = 2.08 \text{ ohms}$$
$$3\,M = 125\times10^6 \text{ joule}$$
$$f = 25 \text{ cycles}$$
$$\alpha = 90 \text{ deg.}$$
$$E = \frac{9000}{\sqrt{3}} = 5200 \text{ volts}$$

gives:

$$2\,s_0 = 1.4 \text{ per cent.}$$

In the moment however when the short circuit opens, the induced voltage of the machine has dropped from the initial value, due to the demagnetizing effect of the short-circuit current, on the curve e_1 of Fig. 15, and the critical speed $2\,s_0$ has dropped proportional thereto.

In Fig. 16 thus is given in dotted line the curve $2\,s_0$, as (0). As seen, even in a fraction of a second, that is, in a time much shorter than the circuit breaker can open the short circuit, machines of different types have drifted apart by greater speed differences than those at which the machines can pull each other in step again at their reduced synchronizing power.

However, even with identical machines, especially if the speeding continues to the

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* One cubic meter of steam at 14 atmospheres (200 lbs.) retained between the turbine and the steam cut off would speed up a 35,000-kw. steam turbine alternator by more than one per cent, after the cutting off of the steam.

TABLE 11

SHORT CIRCUIT ON 60,000-KW., 25-CYCLE, 9000-VOLT STATION

				RESISTANCE OF FEEDER REACTOR		
				None	0.5 ohms	0.7 ohms
Duration of field transient, seconds			t_{00}	4.51	4.51	4.51
			a_0	0.222	0.222	0.222
Duration of armature transient, seconds			t_0	0.582	1.51	1.73
			a	1.72	0.662	0.578
			b	0.172	0.446	0.511
			b_0	0.129	0.335	0.383
Short circuit current	Initial		i_0	7.8	2.01	1.55
	After 1 sec.		i	2.5	1.46	1.09
	Final		i_1	1.34	0.894	0.79
Induced voltage	Initial		e_0	1.00	1.00	1.00
	After 1 sec.		e	0.322	0.732	0.785
	Final		e_1	0.172	0.446	0.511
Terminal voltage	Initial	Before	e_0	1.00	1.00	1.00
		After	$e_0{}^0$	..	0.744	0.802
	After 1 sec.	Before	e^0	..	0.543	0.63
		After	e	0.322	0.732	0.785
	Final		$e_1{}^0$		0.332	0.41

tripping of the emergency steam valves, inevitable inequalities in the tripping speed and in the time of restoring the machines on steam governor control probably cause greater speed differences than permissible by the synchronizing power. Furthermore, even if the short circuit is opened in a second or less, the induced voltage has dropped so considerably (e_1 in Fig. 15) and the recovery curve ($e_1{}^0$ in Fig. 15) is so slow that the machines cannot immediately take load, and speeding up continues for some time.

Thus, it may be expected that with a dead short circuit at or near the busbars of a high-power steam turbine station, the generators drop out of synchronism and are not able to pull back promptly into synchronism, but begin to drift indefinitely, slipping past each other at zero voltage.

For a machine to remain in synchronism with other machines, with full-load steam supply and the load thrown off by a short circuit, etc., the machine must be able to transfer full load to other machines, within its limits of synchronizing power, that is, with a phase displacement not exceeding 90 deg.

The maximum power transfer between two machines is given by equation (11) as:

$$P = \frac{E^2}{z} \sin \alpha$$

where z is the total impedance between two machines, and α may be assumed as 90 deg. This gives:

$$E = \sqrt{zP} \qquad (85)$$

as the minimum voltage E at which the machine will keep in synchronism at a power difference P between the load and the steam supply.

Substituting thus for P the rating of the machine per phase, and for z twice the self-inductive reactance (external and internal) per phase, gives the minimum voltages of remaining in synchronism, that is, the voltage limit of synchronizing power.

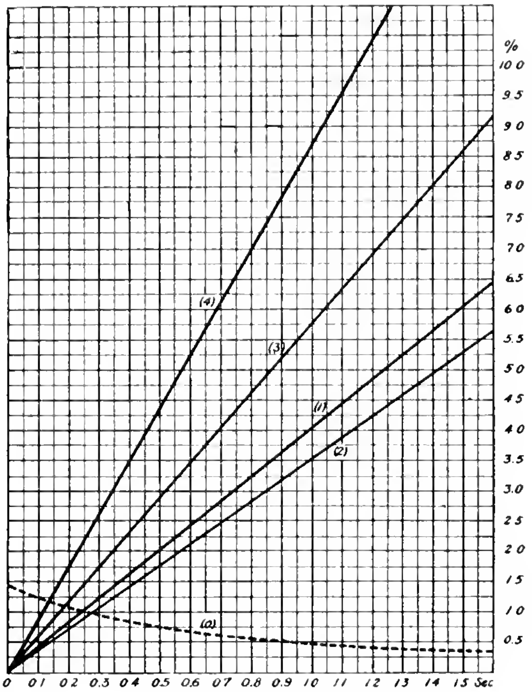

Fig. 16

This gives, for the machines in Table I, the values recorded in Table III.

As seen from Table III, the voltage limit of synchronizing power in most of these

TABLE III

VOLTAGE LIMIT OF SYNCHRONIZING POWER

	25 Cycles					60 Cycles				
Rating, kw.	12,000	14,000	20,000	30,000	35,000	12,500	14,000	20,000	20,000	30,000
Speed, r.p.m.	750	750	750	1500	1500	1800	720	720	1200	1800
Volts per phase, e	5200	5200	5200	5200	5200	6900	6900	6900	6900	6900
Rated current, i	770	900	1280	1925	2250	750	900	1200	1200	1600
$\frac{e}{i}$ = (ohms)	6.76	5.78	4.07	2.71	2.32	9.2	7.67	5.76	5.76	4.32
x_1 = (per cent)	11.4	10.6	10.93	15.25	11.4	12	9	9	13	15
$z = 2\,x_1$ = (ohms)	1.54	1.225	0.89	0.823	0.528	2.21	1.38	1.04	1.495	1.30
P per phase, (watts) 10^6	4.0	4.67	6.67	10.0	11.67	5.17	4.67	6.67	6.67	10.0
$E = \sqrt{Pz}$ = (volts)	2480	2390	2430	2870	2480	3030	2530	2630	3150	3610
E in per cent	47.8	45.0	46.9	55.2	47.8	43.8	36.6	38.0	45.6	52.1

machines is a little below half voltage, and the conclusion thus follows that:

As long as the machines do not drop below half voltage, little danger exists of the machines breaking out of synchronism by the sudden loss of load under short circuit or other accidents, and:

If a feeder reactor limits the voltage drop of the station, due to a feeder short circuit, to 50 per cent or less, the machines in the station remain in synchronism, even when speeding up due to the release of load, when tripping their emergency steam cut offs, etc., and the voltage thus recovers immediately on the opening of the short circuit.

As seen from Fig. 15, this is the case even with the smaller feeder reactor, and under the conditions of this instance the smaller feeder reactor thus should offer complete protection against loss of synchronism of the station as result of feeder short circuit.

Similar relations then exist between generating station and synchronous machine loads, such as converters and synchronous motors.

The synchronous converter probably represents by far the most frequent synchronous machine load. Its internal characteristics are somewhat similar to those of the steam turbine alternator, that is, high effective reactance of armature reaction and low true self-inductive reactance, and it therefore is probable that about the same numerical relations pertain, that is:

Such values of feeder reactors, which are sufficient to guard the generating stations against loss of synchronism, by maintaining the station under feeder short circuits above the voltage limit of synchronizing power, may in general be expected also to guard the synchronous converters in the substations against being thrown out of step, that is, shut down, by the shock on the system due to feeder short circuit.

Relative Thermal Economy of Electric and Fuel-fired Furnaces

By E. F. Collins

Industrial Heating Department, General Electric Company

The pronounced advantages of the electric furnace in providing easy and positive temperature control and uniform heat distribution account for the large number of these furnaces that have been placed in service during the last few years. The extent of these applications is indicated by Mr. Collins' statement that nearly all brass melting furnaces that are being installed are electric furnaces. In many cases the electric furnace was chosen on the basis of performance rather than cost of operation; but today with the higher and still rising costs of fuel even the cost of operation may be decidedly in favor of the electric furnace, as is shown in this article by the data on specific installations. It is not visionary to predict that electricity will ultimately be as widely used for industrial heating as it is now used for industrial power.—Editor.

It is well known that the thermal efficiency of a furnace decreases rapidly with increasing temperature. This decrease is due primarily to the fact that the air required for combustion must be heated to the temperature of the furnace; the heat necessary to raise the air to this temperature being lost in the products of combustion as they escape. A secondary cause is the heat lost from the walls of the furnace, which for convenience is called the radiation.

It is not possible to state with exactness the efficiency which may be realized in a furnace unless all the conditions are known, as there are many factors which may influence the amount of heat lost in the flue gases. For instance, a part of the heat may be recovered by preheating the fuel or incoming air, or by heating water or other materials for incidental uses; or the furnace may in some cases be constructed on the compensating or counterflow principle, when a considerable amount of the heat in the flue gases will be given up to the incoming charge.

These considerations apply in general only to relatively large furnaces or installations, in which cases the plant is carefully designed to utilize the waste heat. In the ordinary furnace, operating under ordinary conditions, with which we are all familiar, none of these considerations apply, and the thermal efficiency can therefore be approximated by calculations, since practically all of the theoretical heat represented in the temperature of the flue gases is lost.

Data showing the theoretical losses in flue gases for various fuels at various temperatures have been submitted by earlier investigators, but it is thought that it might be of interest to complete these data and put them in the

TABLE I

Source of Heat	Per Cent of Air for Perfect Combustion Air at 70 Deg. F.	Calorific Value of Fuel or Power B.T.U.	Temperature of Furnace	B.T.U. Heat Units Supplied	Rate Paid for Fuel or Power	Cost per 100,000 B.T.U.	PER CENT HEAT LOST		HEAT AVAILABLE FOR USEFUL WORK	
							Flue (App.) Gases	Radiation	Per Cent of Supply	Cost per 100,000 B.T.U.
Coke	100	13,000 per lb.	400 deg. F.	100,000	$10.00 per ton	$0.0385	7.5	10	83.3	0.046
	150	13,000 per lb.	400 deg. F.	100,000	10.00 per ton	.0385	10.5	10	80.5	0.048
	100	13,000 per lb.	1600 deg. F.	100,000	10.00 per ton	.0385	32.5	15	57.4	0.067
	150	13,000 per lb.	1600 deg. F.	100,000	10.00 per ton	.0385	48.5	15	43.8	0.088
	100	13,000 per lb.	2300 deg. F.	100,000	10.00 per ton	.0385	47.5	20	42.0	0.092
	150	13,000 per lb.	2300 deg. F.	100,000	10.00 per ton	.0385	71.0	20	23.0	0.167
	100	13,000 per lb.	2800 deg. F.	100,000	10.00 per ton	.0385	57.5	25	31.9	0.121
	150	13,000 per lb.	2800 deg. F.	100,000	10.00 per ton	.0385	87	25	9.7	0.395
Electricity		3415 per kw-hr.	400 deg. F.	100,000	1c. per kw-hr.	.293	0	10	90	0.326
		3415 per kw-hr.	1600 deg. F.	100,000	1c. per kw-hr.	.293	0	15	85	0.345
		3415 per kw-hr.	2300 deg. F.	100,000	1c. per kw-hr.	.293	0	20	80	0.366
		3415 per kw-hr.	2800 deg. F.	100,000	1c. per kw-hr.	.293	0	25	75	0.390
City Gas	100	590 per cu. ft.	400 deg. F.	100,000	$1.00 per M.	.17	15	10	76.5	0.222
	150	590 per cu. ft.	400 deg. F.	100,000	1.00 per M.	.17	17.5	10	74.2	0.229
	100	590 per cu. ft.	1600 deg. F.	100,000	1.00 per M.	.17	44	15	47.6	0.356
	150	590 per cu. ft.	1600 deg. F.	100,000	1.00 per M.	.17	51	15	41.6	0.408
	100	590 per cu. ft.	2300 deg. F.	100,000	1.00 per M.	.17	60	20	32.0	0.530
	150	590 per cu. ft.	2300 deg. F.	100,000	1.00 per M.	.17	70	20	24.0	0.708
	100	590 per cu. ft.	2800 deg. F.	100,000	1.00 per M.	.17	72.5	25	20.6	0.822
	150	590 per cu. ft.	2800 deg. F.	100,000	1.00 per M.	.17	85	25	11.2	1.51
Fuel Oil	100	19,000 per lb.	400 deg. F.	100,000	10c. per gal.	.0748	14	10	77.4	0.097
	150	19,000 per lb.	400 deg. F.	100,000	10c. per gal.	.0748	17.5	10	74.2	0.101
	100	19,000 per lb.	1600 deg. F.	100,000	10c. per gal.	.0748	40	15	51.0	0.147
	150	19,000 per lb.	1600 deg. F.	100,000	10c. per gal.	.0748	55	15	38.2	0.195
	100	19,000 per lb.	2300 deg. F.	100,000	10c. per gal.	.0748	56	20	35.2	0.212
	150	19,000 per lb.	2300 deg. F.	100,000	10c. per gal.	.0748	77.5	20	18.0	0.415
	100	19,000 per lb.	2800 deg. F.	100,000	10c. per gal.	.0748	67.5	25	24.4	0.306
	150	19,000 per lb.	2800 deg. F.	100,000	10c. per gal.	.0748	94	25	4.5	1.66
Anthracite	100	12,000 per lb.	400 deg. F.	100,000	$10.00 per ton	.0425	9	10	81.9	0.052
	150	12,000 per lb.	400 deg. F.	100,600	10.00 per ton	.0425	12.5	10	78.7	0.054
	100	12,000 per lb.	1600 deg. F.	100,000	10.00 per ton	.0425	35	15	55.2	0.077
	150	12,000 per lb.	1600 deg. F.	100,000	10.00 per ton	.0425	50	15	42.5	0.100
	100	12,000 per lb.	2300 deg. F.	100,000	10.00 per ton	.0425	50	20	40.0	0.106
	150	12,000 per lb.	2300 deg. F.	100,000	10.00 per ton	.0425	72.5	20	22.0	0.193
	100	12,000 per lb.	2300 deg. F.	100,000	10.00 per ton	.0425	60	25	30.0	0.141
	150	12,000 per lb.	2800 deg. F.	100,000	10.00 per ton	.0425	87.5	25	9.3	0.456
Bituminous Coal	100	12,550 per lb.	400 deg. F.	100,000	$5.00 per ton	.020	11	10	80.1	0.025
	150	12,550 per lb.	400 deg. F.	100,000	5.00 per ton	.020	15	10	76.5	0.026
	100	12,550 per lb.	1600 deg. F.	100,000	5.00 per ton	.020	38.5	15	52.3	0.038
	150	12,550 per lb.	1600 deg. F.	100,000	5.00 per ton	.020	52.5	15	40.4	0.049
	100	12,550 per lb.	2300 deg. F.	100,000	5.00 per ton	.020	55	20	36.0	0.055
	150	12,550 per lb.	2300 deg. F.	100,000	5.00 per ton	.020	75	20	20.0	0.100
	100	12,550 per lb.	2800 deg. F.	100,000	5.00 per ton	.020	65	25	26.2	0.075
	150	12,550 per lb.	2800 deg. F.	100,000	5.00 per ton	.020	90	25	7.5	0.267
Natural Gas	100	1100 per cu. ft.	400 deg. F.	100,000	30c. per M.	.0273	16.2	10	75.6	0.036
	150	1100 per cu. ft.	400 deg. F.	100,000	30c. per M.	.0273	20	10	72.0	0.038
	100	1100 per cu. ft.	1660 deg. F.	100,000	30c. per M.	.0273	44	15	47.6	0.057
	150	1100 per cu. ft.	1600 deg. F.	100,000	30c. per M.	.0273	59	15	34.8	0.081
	100	1100 perc u. ft.	2300 deg. F.	100,000	30c. per M.	.0273	60	20	32	0.085
	150	1100 per cu. ft.	2300 deg. F.	100,000	30c. per M.	.0273	81	20	15.2	0.179
	100	1100 per cu. ft.	2800 deg. F.	100,000	30c. per M.	.0273	72.5	25	20.6	0.132
	150	1100 per cu. ft.	2800 deg. F.	100,000	30c. per M.	.0273	97.5	25	1.9	1.46

form of tables and charts so as to make this information available for ready reference, and at the same time compare the various fuels with electric heat on the basis of thermal efficiency and the cost per heat unit.

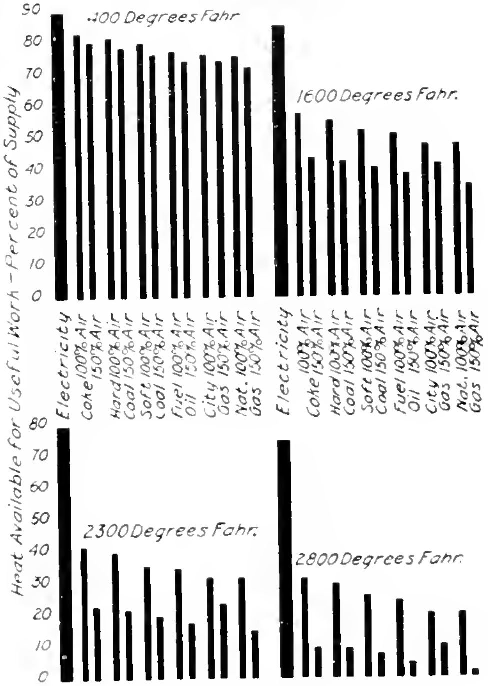

Fig. 1. Curve Showing Heat Available for Useful Work in Various Kinds of Furnaces

The applications of electric heating are being very rapidly extended, and since the cost of combustible fuels tends to increase at a higher rate than the cost of electricity, the point may soon be reached where the comparative cost even on a B.t.u. basis will not be unfavorable to electric heat; as a matter of fact such a comparison even at present prices is not unfavorable at the higher temperatures, as will presently be shown.

Table I has been compiled to show the heat lost and the cost per 100,000 B.t.u. for various fuels including electricity, at temperatures of 400, 1600, 2300, and 2800 deg. F., the temperature usually required for baking, heat treating, forging and melting, respectively. The values of flue losses have been calculated for 100 per cent air, or the theoretical air required for perfect combustion, and also for 150 per cent air, or 50 per cent in excess of combustion requirements, which represents more nearly the usual conditions.

Radiation losses of 10, 15, 20 and 25 per cent respectively have been arbitrarily assumed for the four temperatures mentioned, and the same radiation loss has been assumed for all fuels, so that they are thus compared on the same basis; or it may be assumed that all the fuels are burned in the same furnace.

Average calorific values of the fuels have been assumed, and the costs per ton or per gallon, etc., are in round figures for easy calculation so that any other costs per ton or per gallon may be readily compared.

It should be borne in mind that the heat available for useful work given in the table is the theoretical maximum for the conditions stated, and that perfect combustion is assumed in all cases. The values actually realized in practice will in many cases represent a much lower efficiency than the tables and curves show, except in the case of electricity, which of course, is all converted into heat and only the radiation loss escapes.

The values for the heat available as given in Table I are arranged in the form of a chart in Fig. 1, which shows in a rather striking manner the relative efficiency of the various fuels at the four temperatures chosen. The rapid decrease of efficiency with rising temperature and increased air supply is at once apparent.

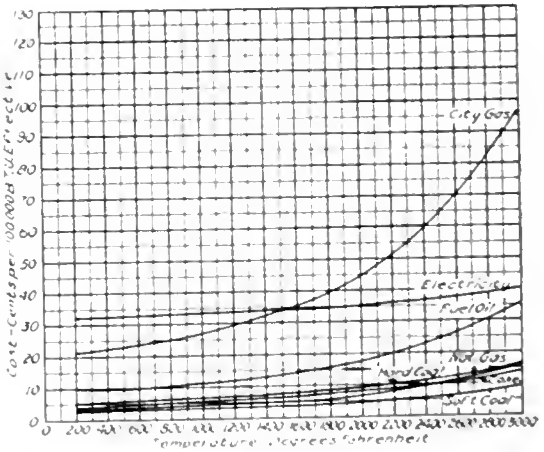

Fig 2. Curve Showing Relative Cost of Fuels at Various Furnace Temperatures 100 Per Cent Air

Fig. 2 shows the relative cost of fuels at various temperatures, with 100 per cent air supply plotted as curves, and Fig. 3 shows the corresponding cost for 150 per cent air supply, the values having been plotted from the last column of Table I. Fig. 1 therefore shows the high thermal efficiency of electricity as compared with combustible fuels, while Figs. 2 and 3 show its comparatively high cost per heat unit.

For fuel costs other than those chosen, curves may be plotted by multiplying the values in the last column of the table by the actual fuel cost. For instance, for oil at 14 cents per gallon, or electricity at 1.25 cents per kilowatt-hour, multiply the values in the last column of the table by 1.4 or 1.25 and plot a new curve.

The foregoing is, of course, on a strictly B.t.u. basis, without regard to the expense of handling or storing fuel, or to the cost of repairs, convenience of manipulation, etc.

It will be attempted to show that even at a higher cost per heat unit electric heat in many cases is actually cheaper, and at the same time it offers an opportunity to increase output and improve the quality of the product, so that the net result is a very considerable reduction in the manufacturing cost. Indeed it is hardly necessary to prove this as a general proposition, because the rapid increase in the use of electric heating equipment is in itself proof that the advantages far outweigh the additional cost of heat units.

Coal and coke are relatively difficult and expensive to store and fire, and natural gas is restricted to a comparatively small area. Further, the supply available at present is such that it is not entirely dependable. Artificial gas is rather expensive, and it is not always available in quantities, so that fuel oil has naturally become the chief source of heat in many of our industries because of the convenience with which it can be stored, handled and distributed, its concentrated fuel value, and its formerly low cost and abundant supply.

Oil has therefore been considered an ideal fuel, and its use has become widespread. However, the very considerable increase in its cost recently and its apparent scarcity have brought about a condition which is very trying to industrial managers, many of whom have become interested in electric heating as a solution of the fuel problem and of many other incidental problems.

It is proposed therefore to show very briefly some of the later applications in which electric heating has met with marked success, and to indicate some of its possibilities.

The advantages of electric heating are, in general, well recognized, but the impression seems to prevail that the cost of operation is excessive. This is perhaps true in a few instances, for example, in a case where the nature of the process permits the recovery of waste heat from the flue gases; but in general it is entirely erroneous, as a few typical examples will show.

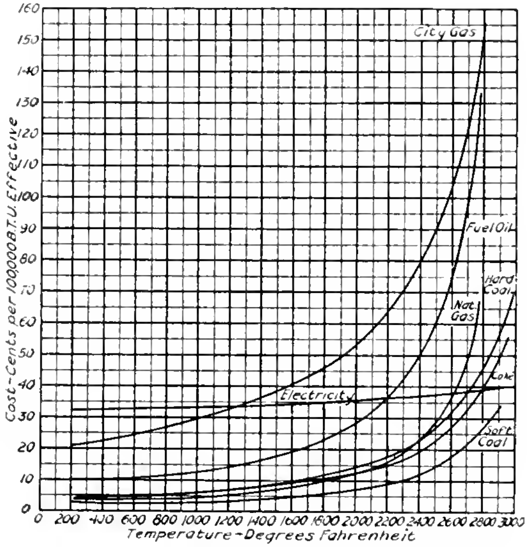

Fig. 3. **Curve Showing Relative Cost of Fuels at Various Furnace Temperatures 150 Per Cent Air**

Electric heating is also being successfully applied over the entire range of temperature, from low temperature ovens for drying and baking to high temperature furnaces for melting and refining, so that equipments are available for practically every application.

Electric ovens for baking japan and enamel are so widely used and their advantages so well known that it is hardly necessary to do more than refer to them here. Their extensive use for enameling automobile bodies and parts and in other work where a superior finish is required is a sufficient argument for their net economy.

Ovens for baking cores are also yielding excellent results from the standpoint of efficiency and net cost, particularly for small cores in which breakage and loss from uneven baking usually is a very considerable item. The uniform distribution and automatic temperature control possible with electric heat considerably shortens the time required for baking and produces perfectly baked cores, so that the losses are reduced to zero.

Several installations have been made in wire mills, all of which have shown a substantial saving. The following data are typical and show the actual cost of baking steel wire to remove grease, and drying it after pickling. These are operations which require no refinement, and it would not be expected that electric heat would have any advantages whatever.

The installation referred to has both electric ovens and coke fired ovens of the same dimensions. Electricity is by far the most expensive fuel on a B.t.u. basis at drying and baking temperatures, as shown in Figs. 2 and 3, while coke is among the cheapest fuels. Therefore a direct comparison in the same plant is interesting.

The normal output of these ovens is considerably less than the maximum capacity, so that "normal" results, or results from observation are given, as well as results which might be expected if they were operated at full capacity.

BAKING AT 525 DEG. F.

	Normal Output	Maximum Output
Electric		
Cost of power per net ton of steel	$5.087	$1.19
Annual charges per net ton	7.839	0.727
Total cost per net ton	$12.926	$1.917
Coke		
Cost of coke per net ton of steel.	$0.921	$0.171
Annual charges per net ton	21.368	1.983
Total cost per net ton	$22.289	$2.154

BAKING AT 330 DEG. F.

Electric		
Cost of power per net ton of steel	$0.787	$0.515
Annual charges per net ton	0.648	0.187
Total cost per net ton	$1.435	$0.702
Coke		
Cost of coke per net ton of steel.	$0.253	$0.146
Annual charges per net ton	1.766	0.510
Total cost per net ton	$2.019	$0.656

These figures show, as might reasonably be expected, that the cost of fuel in the coke fired ovens is practically negligible in comparison with the cost of handling, repairs and other charges. In the electric ovens the cost of power is the principal item.

Perhaps a more familiar example is an ordinary hearth type furnace as used for hardening tools, dies, cutters, etc. Tests were run on an oil furnace and on an electric furnace, both having about the same hearth area and doing the same kind of work at the same temperature.

OIL FURNACE

Inside dimensions	46 in. long, 24 in. wide, 20 in. high
Average temperature held	760 deg. C.
Specific gravity of oil at 60 deg. F.	0.86
Degrees Baume	32.79
Weight, pounds per gallon	7.16
Total time test was run	46 hours
Total weight of oil used	603.5 lbs.
Total gallons of oil used	84 gallons
Weight of steel heated	2670 lbs.
Total time heating steel	31.75 hours
Pounds oil used while heating steel	433
Gallons of oil used while heating steel	60.5
Average gallons per hour heating steel	1.9
Average gallons per 100 lbs. of steel	2.26
Time furnace was empty (holding temperature only)	14.25 hours
Gallons oil used for holding temperature only	23.5 gallons
Average gallons per hour holding temperature only	1.65 gallons
Fuel cost per hour at 14 cents per gallon	23.1 cents

ELECTRIC FURNACE

Inside dimensions	30 in. wide, 36 in. long, 22 in. high
Kw. capacity of furnace	20 kw.
Days run covered by test	19 days
Total working hours	107 hours
Total weight of steel heated	1451 lbs.
Temperature	1450 deg. F.
Average kw-hr. per hour in working hours	8.96 kw-hr.
Average kw-hr. per hour empty (radiation loss only)	8.04 kw-hrs
Fuel cost per hour at 1.25 cents per kw-hr.	10 cents

It may be said that the electric furnace is provided with automatic temperature control and a time switch which throws off the power at the end of the working day and throws it on in the early morning so that the furnace is always ready for use. The furnace and control equipment are shown in Fig. 4.

It is obvious from these data that the fuel used in actually heating steel is almost negligible in either furnace, which of course is well known. The data show that the cost of maintaining temperature in the oil furnace is more than double the cost for the electric furnace.

This may perhaps be surprising to many who base their calculations entirely on the relative cost of B.t.u. It would be still more surprising if the cost of repairs and fixed charges could be included in the comparison. This cost for the electric furnace is practically zero. The figures for this size of oil furnace are not available to the writer, although they are probably available from other sources.

The fact which it is desired to emphasize is that the oil furnace referred to is typical of thousands in regular use for heat treating, which could be heated by electricity for less than half the fuel cost alone, to say nothing of the saving in repairs.

This represents a considerable loss to the individual manufacturer, and in the aggregate it is an enormous economic waste.

An interior view of this type of electric furnace is shown in Fig. 5, which however is a somewhat larger furnace than that shown in Fig. 4.

A large number of these furnaces are in daily operation for such work as annealing, hardening and carbonizing, for which they are particularly well suited. The furnace shown in Fig. 5 is one of a pair which are used for carbonizing. All of these furnaces are equipped with automatic temperature control.

The furnaces referred to are of the metallic resistor type and are suitable for operation to 1000 deg. C. (1800 deg. F.). For higher temperatures, such as are required for forging and melting, some form of arc furnace is required.

There are a very large number of electric brass melting furnaces in operation, most of which have been built in the last few years; in fact, nearly all the furnaces being installed today for melting brass are electric furnaces.

Fig. 5 Interior View of Box Furnace Used for Carbonizing

This is an index of the rate at which electric heating is being adopted, and it seems safe to predict that it will supplant fuel oil to a very considerable extent for many other purposes within the next decade.

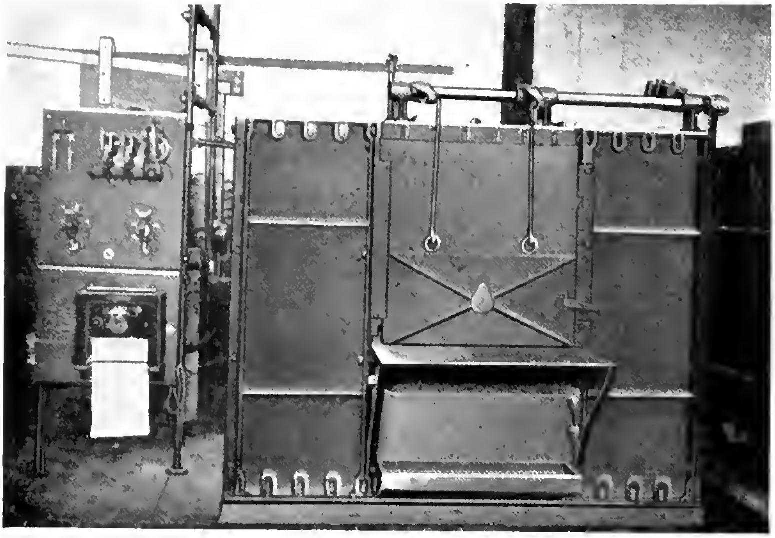

Fig. 4. Box Type Electric Furnace and Control Panel Used for Hardening Punches, Dies and Cutters

Enormous quantities of oil are used in the operations of annealing, heat treating and forging. The furnaces previously referred to are ideal for annealing and heat treating, and operate at maximum economy, and electric forging furnaces will soon be in operation, with corresponding results.

It is unnecessary to dwell upon the many advantages of electric furnaces, such as easy and positive temperature control, and absence of noise, products of combustion and excessive heat, as these features are well known. It is desired rather to emphasize the fact that, contrary to the general impression, the cost of operation is not excessive, but in most cases is not greater and in many cases considerably less than that of fuel-fired furnaces.

The era of electric heating is at hand, and it may well be expected that electricity will ultimately be as widely used for an industrial fuel as it is for industrial power at the present time.

Condenser-resistance Protective Device

By J. L. R. Hayden

General Engineering Laboratory, General Electric Company

The protection of a transmission system from the effects of high-frequency disturbances may be accomplished by the use of a condenser and resistance in series connected from line to ground. With a suitable value of reactance and resistance, the condenser will hold back the low-frequency machine current but will allow high-frequency current to pass freely into the resistance, which in turn will dissipate the energy of the disturbance.—Editor.

In the transmission of electric energy the circuits must be able to operate under normal and abnormal conditions. One of the abnormal conditions which occur in transmission systems of any length are high frequency oscillations created as a result of the readjustment of the stored energy of the circuit when connecting and disconnecting circuits, when lightning strikes a line, or when change of load occurs, etc.

In general these high-frequency disturbances, or more correctly speaking abrupt disturbances, produced by atmospheric lightning and by circuit operation, such as switching, may be divided into three classes:

(1) Impulses: that is, sudden waves of voltage or current, which are not oscillatory.

(2) Oscillations: that is, periodic disturbances which gradually die out, more or less rapidly, depending on the dampening effect of the circuit resistance.

(3) Cumulative oscillations or surges: that is, oscillations which gradually increase in amplitude, until destruction of the circuit occurs, or which are finally limited by increasing energy losses.

To guard against these high frequency disturbances the use of a condenser-resistance is of value, serving to shunt the disturbance and as a high frequency absorber. The operation of the condenser-resistance protective device absorbs the energy of the high frequency disturbances, and thereby keeps them from building up to dangerous voltages.

It consists of a condenser and a resistance in series, shunted across the circuit which is to be protected, from line to ground.

The part which does the protecting is the *resistance;* the condenser is provided merely to keep the low frequency machine current out of the resistance.

If a fairly low noninductive resistance is shunted across a circuit any high frequency disturbance entering the circuit is shunted into the resistance and there rapidly dissipated, so that a building up of the high frequency to higher voltages (such as occur in high voltage power transformers) is made impossible, the disturbance is rapidly absorbed, and effective protection is afforded.

However, such a relatively low resistance—a few hundred ohms—permanently shunted across the high voltage circuit would continuously absorb a very large amount of energy, and would have to be very large, indeed impracticable. For instance, assuming 400 ohms in a 60,000-volt circuit the resistance would continuously consume 150 amperes at 60,000 volts, or 9000 kw., which obviously is out of the question. Therefore a condenser is connected in series with the resistance.

This condenser practically obstructs the low frequency machine current. At high frequency however, the higher the frequency the larger the current through the condenser and if the condenser is large enough and the frequency high enough, the condenser affords no obstruction. Thus the condenser is a means of cutting off the low frequency machine current, without interfering with the high frequency disturbance, and the latter is absorbed by the resistance.

As regards numerical values, the larger the condenser (provided it is not so large as to pass considerable low frequency current) the more high frequency current it will pass, and the greater will be the protection. With a given size of condenser, that value of resistance will obviously be the best which dissipates the energy most rapidly, that is, where the resistance equals the condenser reactance at the danger frequency.

For illustration, to protect a 13,200-volt alternator by condenser resistance: Experience shows the danger frequencies in electrical apparatus, that is, frequencies most liable to build up to high voltages, to be 20 to 100 kilocycles, or an average of 60 kilocycles. Thus a condenser which at 60 kilocycles passes the rated machine current at rated machine voltage should be able to absorb such high frequency as may be anticipated; this gives the capacity reactance, and equal thereto should be chosen the resistance for maximum dissipation.

Typical Installations of Electric Mine Hoisting in South Africa

By E. B. Bell

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The successful operation of electric mine hoists in South Africa and the rapidly increasing number of such installations amply demonstrate the superiority of electric drive for this purpose. The mines are deep, are located thousands of miles from the plants of hoists manufacturers, and the gold content of the ore is comparatively low which factors require high speed, great reliability, and highly efficient operation. In the following article Mr. Bell describes the mines, shafts, hoists, electrical equipment, and control devices of the latest and largest installations of electric mine hoists both of the direct-current motor and the induction motor types.—Editor.

The problem of hoisting from great depths has received very serious consideration from engineers on the Witwatersrand in South Africa.

Since the gold content of the ore raised is comparatively low (from 5 to 13 pennyweights per ton) it has been necessary to study very carefully the questions of efficiency, speed, and reliability.

Until comparatively recent years steam engines were used entirely for this class of service; and it was only after the advent of cheap power, made available by the inauguration of the Victoria Falls & Transvaal Power Company in 1908, that the electrification of hoists began to be seriously considered.

Since 1908 the great advantages to be obtained from electric hoists have been thoroughly appreciated and today South Africa probably leads the world in their use, including among many large installations two practically identical sets, the largest in the world, one of which is in operation at the New Modderfontein Gold Mining Co. and will be described later.

Although over 75 per cent of the electrified mine hoists on the Rand are induction motor driven, due chiefly to the low first cost and simplicity of installation and operation, the Ward Leonard system has been adopted for the larger sizes not only because of the accuracy and simplicity of control but also because of the increased safety and higher efficiency on the heavy duty cycles encountered.

NEW MODDERFONTEIN HOISTING EQUIPMENT

In many respects the hoisting equipment at the circular shaft of the New Modderfontein gold mine will be of interest not only to electrical but also to mining engineers.

The mine, one of the largest in the world, is situated about 25 miles from Johannesburg, Transvaal. For details as to the mine and shaft the author is indebted to a paper presented to the South African Institute of Engineers, by H. Stuart Martin, Consulting Engineer, and for details of the electrical equipment to the Consulting Electrical Engineers of the Central Mining and Investment Corporation.

Mine and Shaft

Since commencing milling operations in 1892 up to the end of 1918, the mine has produced gold to the value of over $66,000,000 from 7,225,480 tons of rock crushed. It has paid in dividends over $21,000,000, the disbursements on this account in 1918 having amounted to $51\frac{7}{8}$ per cent on the capital.

The mine was originally opened up by means of several inclined shafts sunk near the reef outcrop. As mining progressed it became advisable to provide additional means for reaching the deeper levels, consequently an 18-foot diameter vertical circular shaft was sunk to a depth of 2258 feet, at which point it intersects the gold bearing stratum, or reef. This shaft was the first of its kind to be sunk on the Witwatersrand, but of late a number of similar shafts, including some of much greater depth, have been undertaken. The ore delivered by several electrically driven endless rope haulages is collected and stored in two large bins of 1000 tons capacity, each having discharge doors which open onto a level near the bottom of the circular shaft. The rock discharged from bins is conveyed to the surface in steel trucks each of six tons capacity. These travel by gravity to the shaft where their motion is arrested by means of mechanically operated brakes. From this point they are pushed one at a time by air operated appliances onto the cage which raises them to the surface where similar braking and pushing arrangements are installed. As a loaded cage is raised another carrying an empty truck is lowered in the adjacent compartment.

Each cage is kept from swinging in the shaft by means of four guide ropes $1\frac{3}{4}$ in. in diameter, suspended from the head gear, and to prevent the two cages from touching as they pass each other, two division ropes 2 in. in diameter are suspended from a girder at the surface. These guide ropes are held in place by massive cast-iron weights at the bottom of the shaft. The chief advantage claimed for this system is that when raising men the same platforms which carry the wheeled trucks can be used to their fullest capacity, whereas, when skips are employed which dump ore onto grizzly bars it is necessary to disconnect these skips and substitute men cages, an operation necessitating large delays in spite of ingenious mechanical arrangements. It might be interesting to state that even when hoisting at 3500 ft. per min. the absence of vibration in hoist and guide ropes is little less than phenomenal.

The load on the hoisting rope totals 33,300 lb. made up of rock 12,000 lb., cage 15,300 lb., and truck 6000 lb., while the rope fully extended weighs approximately 22,000 lb.

The headgear is of steel 84 ft. high to the center line of the sheaves which are 18 ft. in diameter. Fig. 1 shows a view of the head gear and engine house.

Hoist

The hoist is located in a modern brick and stone engine room approximately 110 ft. back from the shaft and consists of a single built up cylindrical-conical-cylindrical drum carried by a continuous steel shaft 24 in. in diameter coupled at each end to the motor shafts, as shown in Fig. 2. The smaller cylindrical portions of the drum are 15 ft. in diameter and are made of cast-iron, while the large cylindrical and conical portions are made up of two parts each consisting of four cast steel segments securely bolted together, the diameter of the former being 24 ft.

In climbing from the smaller to the larger cylinders, the rope is carried by five complete machine cut grooved spirals, the grooves extending the complete length of the cylindrical portions as well. For adjusting the length of the ropes, two cast steel reels are fitted to the smaller parallel parts of the drum; displacements relative to the main hoist being obtained by means of small hand-operated gear wheels. The total weight of the drum shaft and bearings is approximately 180 tons.

The post brakes, 17 ft. in diameter by 14 in. broad, are built up of mild steel plates and rolled steel channels and are lined with poplar wood. They are both weight loaded and air operated with oil cataract devices, either being sufficient to safely hold the maximum unbalanced load on one rope.

Compressed air for operating these brakes is normally drawn from the main supply, but there is in addition an auxiliary air compressor of 100 cu. ft. per min. capacity driven by a 25-h.p., three-phase, squirrel-cage motor with a 250-cu. ft. receiver, and automatic starting and stopping control apparatus.

The control gear of the hoist is mounted on an elevated platform sufficiently high to enable the driver to obtain a clear view of the drums, ropes and cages as they come to the surface.

Below this platform, which is shown in Figs. 2 and 3, are mounted retarding and overwinding devices consisting of large slowly revolving cams, driven from the main shaft by substantial gear and shafting, which regulate the movement of the driver's lever and consequently the controller, thus preventing the driver from accelerating the winder in either direction beyond a predetermined value and gradually bringing the operating lever back to the neutral position sufficiently early in the event of forgetfulness on his part. There are also stops on an adjacent revolving disk which trip the brake operating mechanism in the event of an overwind.

Electrical Equipment

To the drum shaft are coupled two 2000-h.p., 53.5-r.p.m., 500-volt, direct-current motors with commutating poles, mounted on a steel shaft 22 in. in diameter. The armatures are 10 ft. 10 in. in diameter while the outside diameter of the magnet frames are 15 ft. 5 in. Each motor has 22 main field poles wound for 220 volts excitation. The bearings in addition to being ring oiled are piped for forced lubrication, but experience has proved this to be an unnecessary adjunct.

The motors are connected in series and receive their power from a motor-generator set consisting of two 1650-kw. generators, a 60-kw. exciter, and a 5000-h.p. induction motor. A view of this set is shown in Fig. 4.

Power is supplied to this set by the Victoria Falls and Transvaal Power Co., through the necessary transformers, oil switches, etc., at 2000 volts, 50 cycles. The motor is started by means of a liquid rheostat in the basement below, operated through a handwheel and shaft extended to the ground floor.

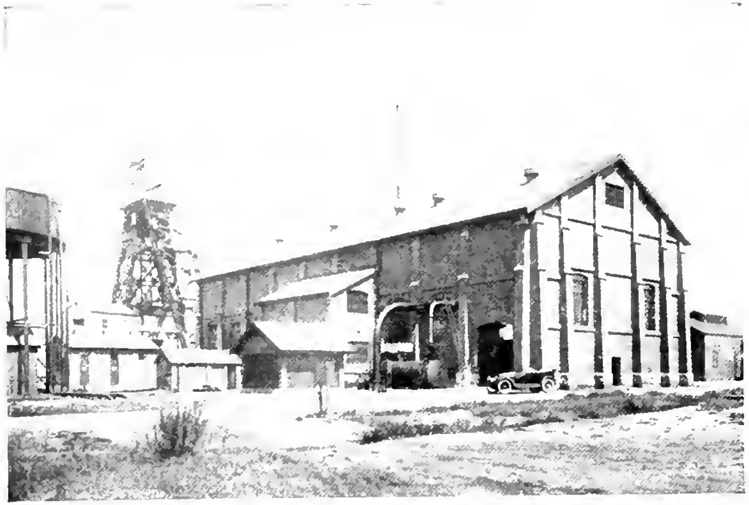

Fig. 1. Headgear and Engine House of the New Modderfontein Gold Mine

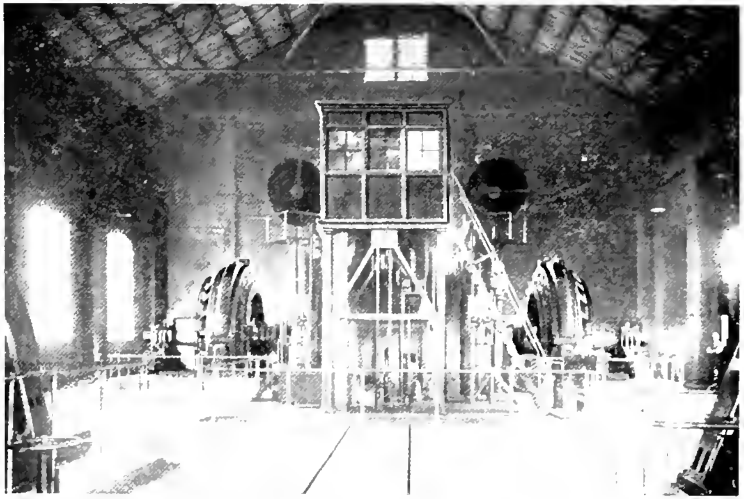

Fig 2. General View of the Electrically Driven Hoist, New Modderfontein Gold Mine

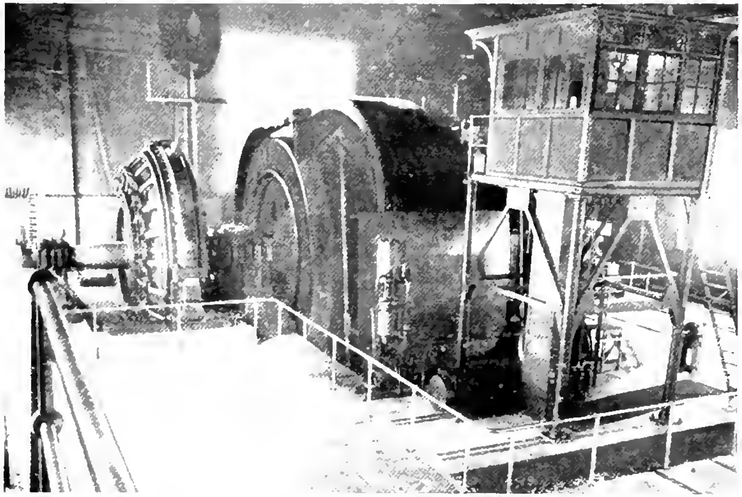

Fig. 3. Another View of the Hoist Shown in Fig. 2 In the foreground is the elevated control platform and in the background is the hoist drum, one brake, and one of the 2000-h p. motors

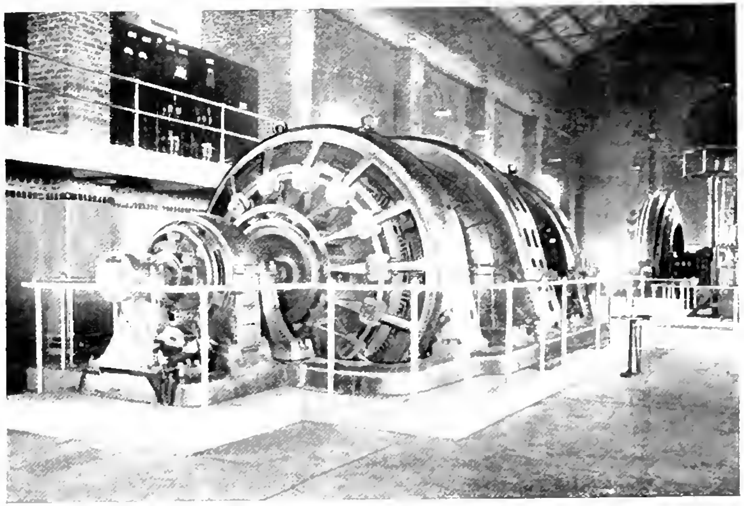

Fig. 4. Three-unit, 5000 h p., 3300-kw. Motor-generator Set with 60-kw. Exciter, that Supplies Power to the Hoist Shown in Fig. 2. At the far end of the room is one of the hoist motors.

As the set approaches synchronous speed the starter is entirely cut out by means of a hand-operated brush-lifting and short-circuiting gear.

The generators are each wound for 500 volts, and in order to successfully commutate the heavy currents at the varying voltages employed are equipped with commutating poles and, in addition, with compensating or pole-faced windings.

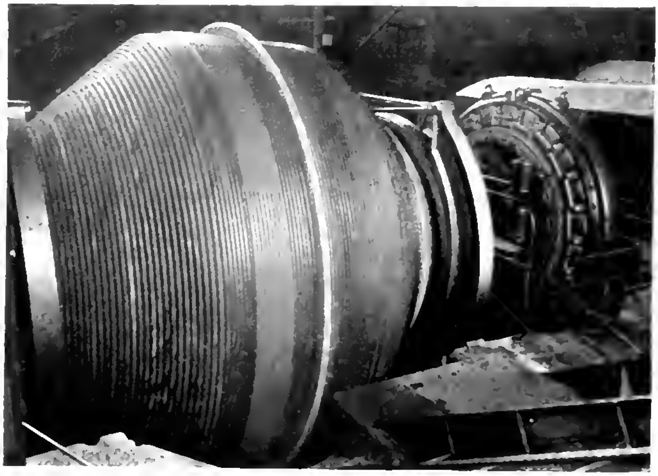

Fig. 5. Drum, One Brake, and One of the Two 2000-h.p. Motors of the Crown Mines' Hoists

The exciter is a standard compound-wound, self-excited machine of 60-kw. capacity at 220 volts feeding directly onto two main busses which supply the motor and generator fields, the brake magnets, and all control devices.

Control and Protective Devices

For controlling the speed and direction of rotation of the hoist motors the well known Ward Leonard system of control is used; or in other words, the control is effected by varying the strength and reversing the polarity of the generator fields.

The motor fields are excited in parallel through equalizing resistors from the 220-volt busses; while in series with each field is a field relay and one of the brake coils, ensuring the application of the brakes and the opening of the main circuit breaker connected between motors and generators in the event of reduction of the motor field strength beyond a predetermined value. In addition a motor field economy resistor is connected in the circuit to permit of long periods at standstill without injurious overheating of the fields and incidentally to reduce the standby losses. The resistor is short circuited by means of a contactor operated from segments on the controller as soon as the driver's lever is moved from the neutral position.

The generators receive their excitation indirectly from the exciter busses. A large resistor, having several tapping points brought out to two rows of studs over which fingers of the controller slide, is connected across these busses. In this manner a large number of different voltage values are obtainable in either direction for field excitation. The generator fields, like those of the motors, are also connected in multiple through equalizing resistors, and together are in series with a weight operated emergency rheostat normally short circuited by a contact arm and clutch, which is solenoid controlled. In the event of the tripping of the main alternating-current oil switch through overload or failure of supply, or through the opening of the main circuit breaker through any cause, the brakes are applied through the operation of brake cut-out relays and the clutch of the emergency rheostat is released, whereby at first an increasing resistance is inserted in the generator fields which are finally disconnected from the supply altogether. It may be interesting to state in this respect that there is located within reach of the driver a small emergency switch which is connected in series with the aforementioned solenoid, the operation of which has already been described.

In general the direct-current breaker will open under any of the following emergency conditions and in turn will operate the brakes and emergency generator field rheostat:

(1) Extreme overload.
(2) Loss of exciter voltage.
(3) Overspeed of motor-generator set.
(4) Loss of motor field excitation.

To prevent the generators from building up when the motors are at rest, a connection commonly known as the "suicide connection" is made. As soon as the controller is thrown into the neutral position, the generator fields are disconnected from the exciter busses and contacts made whereby the fields are thrown across the armatures in such a direction that the residual and generated voltages buck or kill each other.

The calculated duty cycle curves of this hoist are shown in Fig. 6

Unfortunately there are no test figures available as to the operating efficiency of the complete unit, although without doubt exceptionally good results would have been obtained when judged from its excellent operating record.

CROWN MINES' HOIST

The Crown Mines' equipment was ordered and installed a few months prior to that of the New Modderfontein gold mine. As the two mines are in the same group, or in other words, under the same control, it was thought advisable when ordering the latter to duplicate the Crown equipment.

Due to certain inherent differences in the mine and shaft, the mechanical portions differ widely; even so it was still possible to order identical electrical and control equipments, a description of which would be only a repetition of that of the New Modderfontein.

The South Rand shaft of the Crown Mines, situated on the outskirts of Johannesburg, is a six-compartment rectangular shaft 3540 ft. deep.

Double winding drums of the conical-cylindrical type are used, one of which is arranged for clutching at will to the driving shaft, thus making it possible to hoist from several different levels. These drums and one of the 2000-h.p. driving motors are shown in Fig. 5. The diameter of the rope centers at the small end of the drums is 12 ft., and at the larger end, 29 ft. 8 in. The drums are arranged for 25 complete turns on the conical portion, 21 turns on the first layer of the cylindrical portion, and 14 turns on the second.

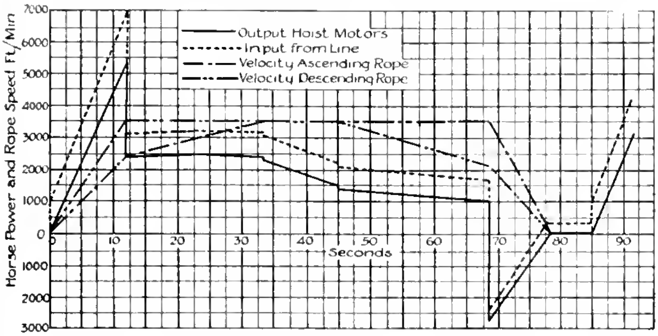

Fig. 7. Calculated Duty Cycle Curves of the Hoist Shown in Fig. 5.

The weight of ore raised per trip is 16,000 lb., that of the skip 8700 lb., and the rope fully extended weighs 22,300 lb. The total weight of the drums is approximately 270,000 lb.

Fig. 7 shows the calculated duty cycle and rope speeds when hoisting rock from a depth of 3540 ft.

An interesting feature relating to both the New Modderfontein and Crown equipments is that due to the loading limits prevailing on the railways in South Africa; the hoist armatures had to be completely built up on site, including core building, winding and shaft pressing.

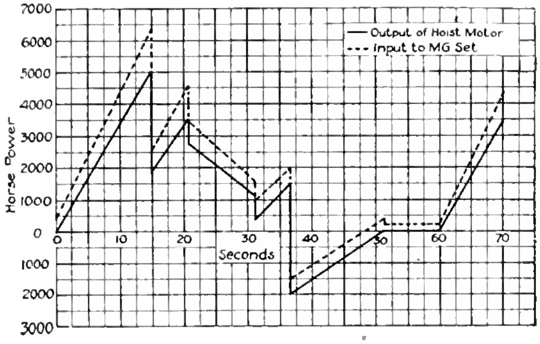

Fig. 6. Calculated Duty Cycle Curves of the Hoist Shown in Fig. 2

That the hoist has given complete satisfaction since its installation in 1917 is fully recognized on the Witwatersrand; and, although approximate, results obtained when hoisting water gave an overall efficiency of 57 per cent calculated from the amount of power consumed at the switchboard and the foot pounds of water raised.

RANDFONTEIN CENTRAL HOISTS

During the latter part of 1919 an order was placed with the South African General Electric Co., Ltd., for two hoisting equipments for the Randfontein Central Gold Mining Co. These will be of interest in that when installed they will constitute, as regards power capacity, the largest hoists in the world; and as such will be briefly described, particularly with respect to the novel features involved.

The mine is about 25 miles west of Johannesburg and the hoists will be installed at two different shafts which are situated about two miles apart. The duty cycles and general characteristics of the two shafts are similar and consequently identical sets will be installed. Fig. 8 shows the calculated duty cycle for balanced hoisting on which the design of the equipments was based.

The load to be hoisted from a depth of 5000 ft. is made up of rock 10,000 lb., skip 7500 lb. and rope fully extended 27,500 lb.

Due to the great depth, conical-cylindrical drums were considered impracticable and therefore double cylindrical drums are to be used. Each drum will be 12 ft. in diameter and 6 ft. wide, necessitating the winding on of four layers of the $1\frac{3}{4}$-in. rope. A drum speed of 106 r.p.m. is to be used, giving a winding speed of approximately 4000 ft. per min.

The electrical and control equipments will be somewhat different from those at the New Modderfontein and Crown Mines. For each hoist there will be two 16-pole, 2500-h.p., 106-r.p.m., 600-volt, direct-current, separately excited motors coupled direct to the drum shaft, one on each side. These will be connected in series with two generators each 2000-kw. capacity, driven by a 5000-h.p. induction motor with liquid starter and brush-raising and short-circuiting gear.

The speed and direction of rotation of the hoist motors will be regulated by means of a master controller governing the action of magnetically operated contactors which will cut resistance into or out of the generator fields. Special reversing contactors will be used for changing the polarity.

The control equipment will provide 15 steps for both forward and reverse direction of motor rotation, all of which will be automatically controlled by adjustable current-limit relays.

The driver can, if he wishes, regulate the speed by hand control for purposes such as shaft inspection where very low speeds are necessary.

In addition to the ordinary mechanical overwind and deceleration devices, similar to those described under the New Modderfontein equipment, two electrical limit switches will be arranged for gearing one to each hoist drum. These will shut off power from the hoist motors and make an emergency application of the brakes in case the skip travels past the landing platform by any predetermined amount.

In each shaft there will also be located switches actuated by the skips themselves to form a further protection against overwind. Re-establishment of the generator field after an emergency shut down will be prevented, by means of an under-voltage contactor relay, until the controller has first been brought to the off position.

To partly relieve the brakes under emergency conditions a device will probably be included, whereby, should the direct-current circuit breaker trip, the armatures of the hoist motors will be short circuited on suitable resistances.

Due to the enormous peak loads which the mine power station would have to carry, a system of relays and interlocks is now being worked out which will prevent the two hoists from being started simultaneously or having their peak loads overlap.

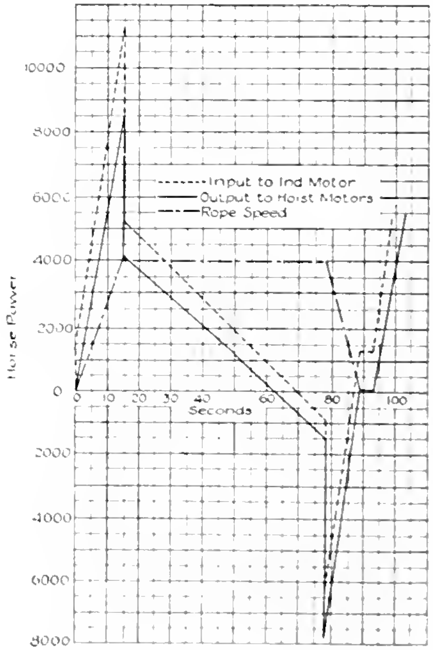

Fig. 8. Calculated Duty Cycle Curves for Balanced Hoisting at the Randfontein Central Gold Mine

For the medium and smaller hoist equipments, induction motor drive with secondary control is specified in most instances, chiefly because of its low initial cost, simplicity of operation, and installation, and the general ruggedness and dependability of the motor.

ROSE DEEP HOIST

The drums which are 10 ft. in diameter by 5 ft. face and are connected to the shaft by means of friction clutches, were formerly driven by a Yates and Thom double-tandem-compound steam engine with Corliss gear; and it was only a short while after the installation of the hoist that it was decided to change over to electric drive. The conversion was accomplished in 1910 by removing the connecting rods and supplying a new disk to the drum shaft equipped with an Oldham coupling. The other half of this coupling is carried by an intermediate shaft upon which is mounted a double helical Citroen gear 8 ft. 4 in. in diameter by 15 in. face. Geared to this by means of a Citroen pinion 18 in. by 15 in. is the 900-h.p., 375-r.p.m., 2000-volt, 50-cycle induction motor.

The mine shaft has a length of 2880 feet and is at an inclination of 37 deg. to the horizontal. The amount of rock hoisted per trip is 8000 lb., while the empty skip weighs 6300 lb., and the $1\frac{3}{8}$-in. rope 2.3 lb. per foot. Primary reversing contactors, mechanically and electrically interlocked, are installed between the line and motor and are operated from the driver's platform by a lever actuating a small master controller.

Speed control is obtained by means of a liquid rheostat in the rotor circuit, which provides for gradual acceleration. Mine hoisting requires rather exacting characteristics in a rheostat of this kind. A high resistance must be provided for starting and low-speed running, and a low minimum resistance is essential for high-speed operation to prevent excessive slip and loss in the rotor circuit.

The rheostat under consideration is provided with two separate sections of electrodes, one consisting of widely spaced pipes and the other of a nest of closely spaced plates. At starting the high resistance section only is connected in circuit, but as the level of the liquid rises and the motor speeds up, with a consequent large decrease in secondary voltage, the low resistance section is cut into the circuit in multiple with the pipes and the motor acceleration is completed. A small motor-driven centrifugal pump forces the electrolyte into the electrode chamber from a storage tank formed by the lower portion of the rheostat, where the electrolyte is cooled by means of coils through which water circulates. The speed and acceleration of the motor is varied by means of a lever situated

TABLE I

MOTOR-DRIVEN MINE HOISTS IN SOUTH AFRICA ABOVE 250 HORSE POWER SUPPLIED BY GENERAL ELECTRIC COMPANY

H.P.	R.P.M.	Voltage	Type Induction or Ward Leonard	Depth in Ft.	Wt. of Ore Raised per Trip	Wt. of Skip and Ore	Rope Speed Ft. mn.	Rope Dia. in In.	Type of Drum	Surface or Underground	Where Installed
275	300	500	Ind.	1500	4000	8000	1200	1	Cyl.	Surface	Falcon Mines, Rhodesia
275	300	2000	Ind.	4500	6000	10000	1440	$\frac{7}{8}$	Cyl.	Under	Knight Central G.M. Co.
320	375	2000	Ind.	6000	24000	37200	750	1	Cyl.	Under	Modderfontein "B" G.M. Co.
350	273	2000	Ind.	4500	8000	14000	1500	1	Cyl.	Under	Witwatersrand Deep G.M.
400	$187\frac{1}{2}$	2100	Ind.	3300	5700	11270	1600	1	Cyl.	Under	Simmer Deep G.M. Co.
400	375	2000	Ind.	3800	12000	20000	1500	1	Cyl.	Under	Government G.M. Areas
400	375	2000	Ind.	3800	12000	20000	1500	1	Cyl.	Under	Government G.M. Areas
450/225	360/180	2100	Ind.	2500	6000	10000	2000	1	Cyl.	Under	Crown Mines, Ltd.
450/225	360/180	2100	Ind.	2500	6000	10000	2000	1	Cyl.	Under	Crown Mines, Ltd.
450	500	500	Ind.	1850	10000	17000	1500	$1\frac{1}{8}$	Cyl.	Under	Cinderella Consd. G.M. Co.
500	375	2000	Ind.	2240	6000	10800	2000	1	Cyl.	Under	Nourse Mines, Ltd.
550	$187\frac{1}{2}$	2100	Ind.	2720	10000	17000	1500	$1\frac{1}{4}$	Cyl.	Surface	Van Ryn G.M. Estates
550	375	2000	Ind.	2800	6000	10800	3000	1	Cyl.	Under	Crown Mines, Ltd.
550	375	2000	Ind.	2800	6000	10800	3000	1	Cyl.	Under	Crown Mines, Ltd.
600	375	2000	Ind.	2500	6000	10800	2000	1	Cyl.	Surface	Bantjes Consd. Mines
835	375	2000	Ind.	2708	8000	13325	2000	$1\frac{1}{4}$	Cyl.	Under	Durban Roodepoort Deep
835	375	2000	Ind.	5000	6000	10000	2000	$1\frac{1}{4}$	Cyl.	Under	Durban Roodepoort Deep
700	55	300	W.L.	3600	5400	13000	2056	$1\frac{3}{8}$	Cyl.	Surface	Cinderella Mine
900	375	300	Ind.	2500	10000	17000	2000	$1\frac{3}{8}$	Cyl.	Surface	Bantjes Consd. Mines
900	375	2000	Ind	2880	8000	14300	2000	$1\frac{3}{8}$	Cyl.	Surface	Rose Deep, Ltd.
*2000 2000	53.5	1000	W.L.	2258	12000	32000	40500	2	Cyl. con. cyl.	Surface	New Modderfontein G.M.
*2000 2000	53.5	1000	W.L.	3540	16000	24700	3500	2	Cyl. con. cyl.	Surface	Crown Mines, Ltd.
*†2500 2500	106	1200	W.L.	5000	10000	17500	4000	$1\frac{3}{4}$	Cyl.	Surface	Randfontein Central G.M.
*†2500 2500	106	1200	W.L.	5000	10000	17500	4000	$1\frac{3}{4}$	Cyl.	Surface	Randfontein Central G.M.

* Motors and generators in series.
† On order.

SUMMARY

	No. of Equipments	H.P.
Induction, above 250 h.p.	19	9990
Ward Leonard, above 250 h.p.	5	14700
Totals. . .	24	24690

on the driver's platform operating a hinged weir in the electrode chamber, and the position of this weir determines the level of the liquid. Due to the limited capacity of the pump, acceleration beyond a predetermined rate is prevented, even should the driver throw his lever suddenly in the fullspeed position. The liberal dimensions of the weir, however, permit practically instantaneous insertion of maximum resistance should he throw his lever suddenly into the off position.

The clutches and post brakes are operated by compressed air. The latter are automatically set, by controlling solenoids wired across a phase of the main supply, should any emergency causing the opening of the main circuit breaker arise.

The installation thus briefly described is typical of induction-motor-driven hoists on the Rand. The majority of these have been operating since their installation under very heavy duty cycles with unqualified satisfaction and exceptionally low maintenance costs.

Opportunities in Office Work

By Anna McCann

Alternating Current Engineering Department, General Electric Company

In these days, when science is making rapid strides, when men are successfully accomplishing what the great thinkers of a century ago conceived as mere dreams, when we look about us and see what has been achieved by man on the land, in the water, and in the air, little do we realize the many details that have had to enter into the processes of these inventions. Do we, for instance, stop to think of the part played by the office force of a great concern?

During the last quarter of a century the business of the General Electric Company has grown extensively, and its office force has kept pace, offering great opportunity in its clerical work. Nowhere is the change in the employee's position better illustrated than in his conquest of office work. Unquestionably, this is the opportune time for the faithful and interested employee.

Of the factors that lead to a successful office career, those to be first considered are of a personal nature. This is a day of exacting requirements and consequently a contemplative employee would do well to complete at least a high school course, so that upon such a foundation a thorough knowledge of office work may be built.

Many, however, who have risen to responsible positions have not had the benefit of a high school training; a large number have had merely an elementary training but possess the natural ability and energy to become successful. By persistent study of English, spelling, and punctuation, and of the duties of an office employee, they acquire a good all-round education.

Another requirement of the employee is trustworthiness. Many persons hold excellent positions for the reason that they are dependable; they are often more valuable to the firm than one more brilliant and clever but less punctual in his duties. They have the welfare of their employer at heart; in other words, they are loyal to his interests. They work not merely for material returns but because they realize that they are filling their niche in the great industrial world.

Still another powerful asset to a successful office career is a pleasing personality. This can best be cultivated by reflecting sincerity and good feeling toward others. The employee should so conduct himself that a favorable impression will be made upon those with whom he comes in contact. A dignified, courteous bearing is sure to win the respect of all.

The efficiency of an office is dependent upon each individual employee. In the successful pursuance of any worthy project, the panacea for troubles is co-operation. For business success, the manager and his subordinates must have at heart the true interests of the firm by which they are employed. The manager who places certain responsibilities upon his subordinates, who is not afraid to intrust them with that portion of the work which they are capable of performing, who will lead but not drive, is the one who will obtain best results. He will recognize those who possess initiative and will be glad to assist in the development of ideas that will make for the success of all concerned.

Again, in the division of labor, the manager of an office should show tact; he should so apportion the work that the brunt of it will not fall on the most willing, but that each individual will be allotted his just share. If, as in other lines of activity, there be one or two who, on account of superior qualifications, are more valuable than the others, the wise manager will do all in his power to have merit recognized in a substantial way followed by words of personal appreciation.

In co-operative relationship the manager and his subordinates will be able to work out several problems that will make for the efficiency of the office. The exchange of constructive criticisms, the keeping abreast of the times by reading helpful business methods, and the consideration of the human element—that the individual is subject to human feelings and shortcomings—are forces which help to promote harmony.

Another factor that must not be lost sight of in considering this subject is the office equipment. With the best possible manager and office force but without proper equipment, no office can be efficiently conducted. Office ventilation and lighting, attractive and suitable office furnishings, convenient arrangement of desks, files, and other equipment, including cleanliness, all tend toward ideal conditions. In bettering the physical conditions of the office, much time may be saved and more work accomplished if the manager and his workers co-operate in the study of conditions and in the planning of improvements. They surely are the ones who know to what extent they are handicapped by unfavorable physical conditions and should, when possible, confer to remedy them.

With the expansion of the Company's business office conditions have not always been ideal, in fact, they are at present not all that could be desired; but, when we look back upon the conditions of twenty-five years ago and compare them with those of today, we must admit that the business methods have been progressive, that the morale of the office force has, in general, been directed toward the Company's interests and that the Company in turn has not failed to show its appreciation of services rendered. That the General Electric Company's office conditions are favorable, for the most part, may be evidenced by the fact that the employee is made to feel that he is a useful cog in this great electrical industry to which every employee owes loyalty.

ERRATA

A number of typographical errors occur in Dr. Tolman's article, "Relativity Theories in Physics," published in the June number of the GENERAL ELECTRIC REVIEW. Of these the most important are:

Equations (1) should read

$$l' = xl \quad t' = xt \quad m' = \frac{m}{x} \quad e' = e \quad S' = S$$

Equations (2) should read

$$v' = v \quad E' = \frac{E}{x} \quad \nu' = \frac{\nu}{x} \quad f' = \frac{f}{x^2}$$

Equation (14) should read

$$\delta \int - \Sigma \frac{E_0}{c} \sqrt{-(dx^2 + dy^2 + dz^2 - c^2dt^2)} = 0$$

Equation (16) should read

$$\delta \int - \Sigma \frac{E_0}{c} \sqrt{g_{11}dx_1^2 + g_{12}dx_1dx_2 + g_{13}dx_1dx_3 + \ldots + g_{44}dx_4^2} = 0$$

or

$$\delta \int - \Sigma \frac{E_0}{c} \sqrt{\sum_1^4 g_{ij}\, dx_i\, dx_j} = 0$$

A New Co-operative Course in Electrical Engineering

By W. H. Timbie

Associate Professor of Electrical Engineering at the Massachusetts Institute of Technology

The co-operative electrical engineering course described in this article is an attempt on the part of the General Electric Company and the Massachusetts Institute of Technology to solve the problem of supplying each year to the manufacturing industry a number of highly trained electrical engineers who can, in a minimum length of time after graduation, take responsible positions in the manufacture of electrical appliances. In this plan the students have the advantage which the Institute offers in the way of theoretical and technical training combined with the enormous resources which the General Electric Company offers for practical experience in the manufacture of electric appliances. Most of the theoretical training is given at Cambridge; the greater part of the practical training is given at Lynn, a distance of about ten miles from Cambridge, in six thirteen-week periods during the last three years of the five-year course.—Editor.

For the past year the General Electric Company in conjunction with Massachusetts Institute of Technology has conducted a co-operative course in Electrical Engineering. The co-operative plan is not new in itself. The decided advantage of making immediate connection between the theory, as studied in school, and practice as it exists in the engineering field, early led to the establishment of co-operative courses abroad. In this country Dr. Herman Schneider years ago inaugurated this type of education at the University of Cincinnati. Similar courses were put in operation at the University of Pittsburgh and other technical schools. The cooperative plan that was started last year between the General Electric Company and the Massachusetts Institute of Technology presents a wide divergence from other plans both as to the educational principles upon which the work is founded and in the working out of the various details of operation.

In the first place, this co-operative course does not take the place of the old and well-established Electrical Engineering Course at the Institute, but is operated in addition to this course and for a specific and collateral object. It is avowedly an effort at intensive training of engineers to meet a specific demand. Perhaps the easiest way to describe just the field that these men are being trained for, is to consider for a moment the various fields in which electrical engineers are needed. We can roughly divide electrical engineers into three rather arbitrary divisions:

First, the consulting engineer, who is usually attached to one or more electrical companies or users of electrical power, to advise them in cases where expert electrical knowledge is needed.

Second, the administrative engineer who may have a large financial responsibility in addition to his duties as electrical engineer. Such a man would be called upon to take the responsibility for the electrical end of any project in the development and utilization of electrical power. In fact, both of these first two types are more closely connected with the development and administration of projects for using electric power than with the manufacture of the machinery involved in such projects, and are in fields which are of themselves of tremendous magnitude, breadth and importance.

In the third division, then, belongs the engineer who is intimately connected with the design and manufacture of electric machinery and accessories. He superintends the design and manufacture of most of the apparatus used by the other two types. His qualifications call for an intimate knowledge of the best manufacturing processes and a thorough training in modern research methods- to which must often be added the ability for creative design. This is the engineer that the General Electric Company and the Massachusetts Institute of Technology are endeavoring to train by means of the cooperative course in electrical engineering.

He is not confined to manufacturing electrical appliances. This is the engineer that will be needed in ever increasing numbers as the country turns more and more to the manufacturing industries in order to sustain itself. The alarming rate at which the natural resources of the country are being depleted has made it imperative that the country at large eventually rely almost entirely upon its manufactures. No longer can we depend upon our exports of raw materials to pay our bills. These raw materials, lumber, ores, and oil, must be manufactured into finished products if the living expenses of the population are to be met. Our water powers must be utilized and new methods of using our oil and coal more efficiently must be devised.

In all this work manufacturing engineers of the highest type are needed, and become the most valuable asset of the country. It is these men who in the last analysis must direct the operation of the nation's industries; for our industries cannot compete with those of other countries unless they are conducted by men who have large vision, intimate knowledge of manufacturing details, and a thorough training in science and scientific methods. Manufacturing must be conducted on a sound financial basis, which means that processes of production must be so managed that the total cost of the finished article will be low enough to compete with the products of foreign factories. For this task the services of an engineer who has a thorough knowledge of manufacturing processes are invaluable and his duties multifarious. He must not only be familiar with the best methods of production, but he must thoroughly understand scientific research, in order that he may take advantage of discoveries and continually better his methods of production. This cannot be stated better than in the words of the Governor of Massachusetts, Calvin Coolidge: "Our prosperity comes from our industry and our industry cannot flourish unless it is directed with the highest intelligence. Far more in the future than in the past will this intelligence call for sound training in science and in its innumerable applications to industry."

The co-operative electrical engineering course covers a period of five years, the first two years being identical with the regular course in electrical engineering at the Institute; the last three years being divided between the instruction in theory at the Institute and training in manufacturing methods at the Lynn Works of the General Electric Company. The co-operative features thus occupy only the last three years, starting in the summer after the sophomore year. The course is supervised by a joint committee of the Institute and the Company. A professor at the Institute is associated with an officer of the company in the duty of supervising the progress of the students while at the Lynn Works.

While at the Works the students are given a fixed payment per week as employees of the Company, which is the same for all departments to which the students are assigned. At the completion of the five year course the students receive the Master of Science degree and the Bachelor of Science degree, their graduation taking place at the regular commencement time at the Institute.

The first class was limited to thirty members. The class which entered July 6th this year consisted of sixty. The size of future classes may be still greater.

The first week in July the members of the entire class who have just completed their sophomore year at the Institute are sent to the General Electric Company's Works at Lynn and placed in various shops. Here they remain for thirteen weeks. At the opening of the fall term at the Institute, one half of the students return to Cambridge and pursue for one term what is practically the regular course in electrical engineering. At the end of this term they have a vacation of two weeks and then go back to the Works of the General Electric Company for further experience. The other group then returns to the Institute for further theoretical instruction. This schedule is carried out for three years, each group spending alternately thirteen weeks at the General Electric Company's plant and eleven weeks at the Institute. The vacation of two weeks given the students at the end of their period at the Institute divides the year into four equal periods of thirteen weeks each. The last period of the fifth year is spent by both groups at the Institute, so that the two groups graduate together at the regular commencement time; yet each group has spent an equal number of weeks in theoretical instruction and practical application.

Perhaps the most striking feature in which this arrangement differs from the former co-operative plans is in the length of the periods. This, however, is perhaps the least important difference. It was endeavored to arrange the details of the course so that they would fit into a system of education which the founders believe is basic. This system combines the rudiments of Spencer's theory of education with the central idea of Josiah Royce's. It is an endeavor to develop all the desirable sides of a student's mind, character, and body, and at the same time inculcate in him the spirit of loyalty to his life work. The course had to be planned so that these several activities would be carried on uninterruptedly throughout the periods which the student spends at the Institute and at the Works. You will note that in the scheme as outlined, the following activities are carried on continuously throughout the course: Instruction is given in theory, classes are conducted in some humanistic study, time is given and facilities provided for collateral reading, and arrangements are made for physical exercise and recreation. The change at the end of each period therefore does not mean so much a change in occupation as a change in emphasis, and the length of the periods thus becomes a rather unimportant detail.

The period of thirteen weeks at the shop and eleven weeks at the Institute followed by a vacation of two weeks was decided upon for the following reasons: It was believed that the period at the Works should be long enough for the student to spend in each department an uninterrupted period of sufficient length to become thoroughly familiar with the men, methods, materials and spirit of that department. In some departments the time required for this is practically three months, and in others it may be as low as one month. The thirteen weeks period will therefore meet the conditions required for those departments in which he must spend the longest time and does not prevent him from dividing his time among two or three departments, in case he is able to master the details in a shorter time. The same is true concerning the length of the period at the Institute. The shortest course at Technology is ten weeks in length, and all longer courses are some multiple of ten weeks. The student is thus able to pursue his studies at the Institute in units of standard length. Furthermore, the fact was not lost sight of that at each change some time was lost by the student in getting started on the new work. Therefore, the periods were made of sufficient length to keep the number of changes as low as practicable. Finally it was hoped that the length of the period had been so chosen that the sojourn at the Works would come as a sort of mental relief and recreation from the term's work at the Institute. In fact it was hoped that toward the end of the term's work the student would begin to look forward to the change as a welcome break in the routine of study, and on the other hand, that the length of the period at the Works would be sufficient to quicken his desire and appetite for further mental concentration and study. The fact is, the thirteen weeks' period has proved that these results have been accomplished. Whether a somewhat shorter or longer period would produce the same results has not been experimented with, because the period of thirteen weeks fits into the Institute calendar in such a way that the periods spent at the Institute are practicably coincident with the regular Institute terms. So much for the length of period.

The real vital difference between this course and other co-operative courses conducted in this country, is the fact that the co-operating company recognizes that for three years these students are placed in its plant for the particular purpose of being educated and trained as electrical engineers of a particularly high grade. There is not the slightest effort or inclination on the part of this Company to use these students for the purpose of getting out greater immediate production. It is clearly understood that these students are in the shops and offices to learn manufacturing methods, and the best relations of labor, mechanism, and materials in high-grade production, and to learn them thoroughly. Because he can best obtain this knowledge by actually doing the work himself, and because the skill which he attains in any process is the only fair indication of his knowledge of that process, the student is put on the company's pay roll and becomes part of its organization. The length of time spent in each department is regulated not by the needs of that department but by the value of the experience to the student. As soon as it is deemed that he has all the knowledge of the details of the department that a manufacturing engineer should have, he is immediately changed to another department. This change is made upon consultation between the foreman of the shop, the officer of the Company, and the professor of the Institute, who are associated in conducting the course.

It is not to be inferred from this statement that the co-operative students do not work as earnestly and as consistently as the other men in the various departments. The co-operative students are graded on the amount and the quality of the work which they do in the various shops, and as strong inducements to do good work are put before them as are put before the regular workmen. The only difference between their work and that of the other employees is that the students' work is so laid out that they receive a maximum amount of experience from each job and they are kept at it just long enough to enable them to become fairly proficient in the necessary operations. In this way the minimum amount of time is spent in learning the details of manufacture in the different shops, testing departments, drafting rooms and engineering offices.

This spirit on the part of the co-operating company is the fundamental contribution which this co-operative scheme offers to engineering education. All the other points of difference between this and other co-operative courses are made possible and have their origin in this spirit of the General Electric Company, which, we believe, is the true co operative spirit. It is the one factor which has allowed us to carry out the plans of the originators and to make such innovations and experiments as we believe will improve the curriculum. I will explain a few of these innovations more in detail later, but I want it clearly understood that it is not these changes and departures from the ordinary curricula which are the important things in this course, but rather the real co-operation which the General Electric Company has offered.

Do not think, however, that this Company has an entirely unselfish motive in this work. The officials of the Company frankly confess that they are pursuing this work because they believe that by this method they can procure the future engineers who will be so badly needed by the Company and by other industrial concerns in the near future. It was because they believe that this is the best way to secure these men that they have entered into this scheme and after one year's trial they report that they are more convinced than ever of the value of co-operative education conducted along these lines.

Perhaps the spirit in which the work is being done is most clearly manifested in the attitude which the officials of the Company are showing in their lectures on manufacturing methods. Once a week one of the superintendents has the students come to his office, and in an informal way talks to them for an hour concerning the details of the work of which he is in charge. This feature was introduced into the course at the suggestion of one of the superintendents and is given entirely upon the superintendent's own time. Some of these men have already prepared six or seven talks on their work, many of them illustrated with lantern slides; some have prepared exhibits of the work in the shops, showing the material in the different stages of manufacture, and arranged in order of the processes. Others have arranged to have the students come to their shops in small groups in order to follow through the manufacture of some typical article so that they may become familiar with the output and the processes before the lecture is given. When we think of the amount of labor and time that is involved for the superintendent who does these things, we can appreciate how the spirit of the originators of the course has permeated the personnel of the Works. It has entered into the attitude of the workmen themselves, who at all times have shown the finest spirit of helpfulness and of real co-operation. Twenty-eight students mingled for a whole year with the other employees of the shops and offices and experienced nothing but extreme courtesy and eagerness on the part of the men to show them all about the work and to demonstrate and explain the details of particular processes. This, it seems to me, shows the degree to which the Company has entered into this scheme as a purely co-operative project.

Of course, you must also appreciate that the students have done their share in co-operating. They have in every case entered into the spirit and work of the shops and offices and have quickly become a part of the company. Particular attention was paid to impressing upon the students the great factor which human engineering plays in their chances for success. They are impressed with the fact that nothing is of more importance than to understand the sterling qualities of the men with whom they are working, to study and learn how to adapt themselves to the personal characteristics and eccentricities of the various foremen under whom they are working—that these things will be of the utmost importance when they are in a position to direct the work of others. Therefore during their sojourn at the shop they get experience not only in electrical engineering but also in human engineering, and each man's progress along this line is followed carefully by those in charge of the course. Do not get the idea from this, however, that the students are in any way coddled. Here is an excellent chance for them to learn to stand on their own feet with all kinds of fellow workmen and all kinds of foremen, and they are compelled to do so. Of course, they make mistakes and occasionally get into trouble, but it is better for them to make these mistakes and get into these few troubles while they are still students under the supervision of the instructing staff of the plant and school rather than later. Each mistake is used as material to impress upon them the value of human engineering. They are thus able to learn valuable lessons without having to suffer too severely from the mistakes.

Great credit belongs to Magnus W. Alexander, whose initiative was a principal force in the origination of the plan, and to C. K. Tripp, Superintendent of Apprentices, of the General Electric Company for the excellent work they have done along these lines. They have worked out highly successful methods for utilizing in the most practical way all the opportunities which the shop work affords for education and training in the human element of the job. To be sure, they have thrown themselves enthusiastically into all activities of the work and have brought to the task experience of twenty years in training executives. But in the development of the human side, I believe they have contributed a particularly valuable feature to the educational program of engineers. This discussion is a little from the point I was trying to bring out, but I believe it shows how the far-sighted policy of the co-operating company allows us to broaden the training in every desirable way.

As the third point of difference from other co-operative courses, should be mentioned the continuity of the theoretical studies and humanistic subjects. All through the course, both while at the Institute and during his sojourn at Lynn, the co-operative student is pursuing the study of electrical engineering theory. At the same time he is taking courses in the study of English. While the main purpose of the latter is to train the engineer in more effective speaking and writing, it also affords opportunities for enlarging his vision and creating new interests. Accordingly when a student goes to the Works he continues the study of electrical engineering just as though he were at the Institute. During this period, however, we have found that he can comfortably cover only about half as much ground as he would in a like period at the Institute. This schedule calls for six hours of study per week and three recitation hours for the two subjects, Electrical Engineering and English. Thus, including the one hour lecture given by the shop superintendent each week, the students spend four hours per week in recitations or lectures. Their schedule at Lynn, therefore, comprises:

48 hours per week in shop or offices
4 hours per week in class room work
6 hours per week in preparation for class room work.

This schedule allows the student to do all his study in three evenings a week and yet get to bed at half-past nine. There is still left for him three week-day evenings, Saturday afternoon, Sunday and Sunday evening for collateral, reading and recreation. At the Institute his schedule calls for a total of forty-eight hours per week in class room and preparation. Thus while he is at the Works the student's weekly schedule is increased from forty-eight hours of classroom and study to fifty-eight hours of a combination of shop work and mental work.

Inasmuch as the material used in the study of English and the method of conducting the English classes is unique, I believe a word concerning this work would be interesting. It is a well known fact that engineering students as a class have an aversion to the study of English for its own sake. So it was felt necessary to arouse an interest in this work before starting it. A plan which was conceived by Professor H. G. Pearson, head of the English and History department at the Institute, was adopted. At the first session, letters from successful graduates of the Institute were read to the class. These letters all brought out the fact that the higher the engineer rises in his profession, the greater is his need to be able to speak well and to write well. Several instances were cited where promising engineering projects were turned down by committees or boards of directors because the engineers back of the schemes were unable to present their side of the case effectively, while a lawyer who knew nothing about the engineering features was able to talk effectively and persuasively. The class was then formed into a committee or a board of conferees and the session, instead of being called a "recitation in English," was called a "meeting of the board." At each of its sittings one of the students presided, and two or three members, acting as a subcommittee, presented a report to the board and advocated its adoption. This report generally consisted of some engineering project. For instance, at a typical session, the class was formed into a committee from a manufacturing company about to build a machine shop of a given size, and requiring a definite amount of energy for lighting, heating and power. Two members of the class, acting as engineers of a company dealing in power plant equipment and supplies, put before the board the advantages of the company owning its own power plant. Two other members of the class representing the local electric power company advocated that the board purchase central station power. After the presentation of each side, the class discussed the matter and finally voted upon the question. The presentation and discussion were made without notes, except for numerical data, etc. At the close of the discussion an instructor in English criticized the session, taking up such points as the work of the presiding officer, showing how he might have avoided some of the difficulties he encountered, and how he might have more easily extricated himself from those he did get into. The effectiveness of the presentation of the subject was taken up from the grammatical, literary, and psychological standpoints, the discussion of the class was commented upon from the point of view of its relevancy, and the vote of the class was criticized as to whether the class had really voted upon the merits of the question. A member of the engineering faculty usually discussed the whole subject from an engineering standpoint, generally as to whether a fair statement of the facts had been made. At the succeeding session of the class, a written report was always handed into the English instructor by the men presenting the projects to the class and by the secretary of the board. During the first period at the Works every man in the class had an opportunity to serve on two subcommittees, to preside over the meetings twice, and act as secretary twice.

During the second period at the Works, the sessions in English took a different tack. On the previous occasion, emphasis had been placed on effective presentation of engineering projects in the interest of some company for which the student was supposed to be working. During this term's work the emphasis was laid upon the effective selling of one's own service or project. The instructor took pains to explain the purpose of this term's work before asking the students to talk or to write. He showed them that each letter and each article that they wrote was written for the purpose of producing a certain effect and everything in the letter or article should add to this effect; that any piece of writing was effective only in so far as it produced the result that was desired. A letter written for the purpose of obtaining the writer a job is effective if it lands the job. A prospectus written for the purpose of selling goods is effective if it sells the goods. In keeping with this idea the instructor put forward as the aim of this term's work, effectiveness in writing. Every bit of writing done that term was to have a definite purpose and be written to produce a certain effect. Such exercises as these were used: Write a description of a dusty room which will make the reader sneeze. Write a letter asking for an appointment that will make the reader really desirous of seeing you.

When the idea and aim of this course was understood, and the purpose of these themes explained, interesting writing competitons arose and work which formerly was looked upon as drudgery became an exciting contest. The class used as a textbook examples of forceful writing contained in a volume of short articles by a well known reporter.

I have dwelt at considerable length upon this first year's work in English because I am convinced of its importance to engineers. We still have two more years with this class in which to continue the work, and plans are being formulated to develop courses which combine industrial psychology and instruction in English in such a way as to appeal to the engineering student and induce him to put sufficient effort into the work to make it effective.

To go back to the differences between this co-operative course and others, I should like to mention as a fourth point the provision which is made for further liberalizing the engineering student's education by means of collateral reading. So important do we consider this side of the engineer's education that his program has been laid out with the definite purpose of giving him an opportunity for reading outside of the prescribed courses. We thoroughly believe in the desirability of creating the habit of general reading on the part of the engineer. This is in line with our conviction that if the men with engineering training can be induced to bring this training to bear on public questions and civic affairs, a great dynamic force for good will be put into public life, a force which has behind it all the power of a highly trained mind.

The fifth point of difference which this course offers is the intense spirit of loyalty which has been inculcated in the members of this course; a loyalty to one another, to the Institute, and to the co-operating company. Several things have contributed to bring about these conditions. First, the closest connection has at all times been maintained between the Institute and the group at the plant of the co-operating company. On three or four days each week a member of the electrical engineering department of the Institute spends a half day at the plant visiting the various shops and offices to which the students are assigned, or to which they are to be assigned. In this way, as well as by the direct contact which is maintained in the two sessions a week in the class room, the student is made conscious of the supervision which the Institute exercises over his work in the shop. Another feature which has not only kept the men closer to the Institute, but has made a closer bond between the members of the two groups of co-operative students, has been the practice of having the group at the Institute visit the Lynn Works on evenings when the officials of the company deliver their lectures on manufacturing methods. During good weather the department of electrical engineering furnished automobiles for the transportation of the men. The members of the group at Lynn were also encouraged to make frequent trips to the Institute and to enter into the student activities there whenever it was possible.

The fact that these students are all taking the same co-operative course at the same institution, and are working for the same co-operating company, and finally are living together under the very pleasantest conditions, quickly develops this three-fold loyalty. It is this loyalty to the Institute and to the Company, founded upon the student's conviction that both the Institute and the Company are planning the work for his highest education and best welfare, that in the last analysis must be depended upon to produce results in the way of conscientious and intelligent effort in delivering an honest day's work in the plant and in doing the full quota of study. Finally the co-operating company relies upon this loyalty to influence some of the men in each class to remain with the company after completing the course.

As the sixth point of difference in conducting this work should be mentioned the fact that throughout the three years the students are kept in the plant of the same co-operating company. Under the right conditions we feel that this has its decided advantages, because once the officials of a company have determined upon a policy, this policy can be maintained and pursued in every department through which the students pass. Of course the company must be of such a size that it has all the departments in which an electrical engineer needs experience. The General Electric Company admirably meets these requirements. It designs and manufactures electrical and mechanical machinery and apparatus of nearly every description and of the widest range of capacities, and many mechanical devices large and small, some of the most intricate design. Thus we are able to offer the student a wide choice in the departments in which he is to get his experience as well as in the particular branch he desires to specialize in. This arrangement has the advantage of offering the student the same diversity of work which a large number of smaller companies might offer him, without the disadvantage of a lack of co-ordination in details and in educational ideals.

The only remaining point of difference I wish to call attention to is the unusual amount of theoretical work in the course and the fact that a Master's degree is awarded by the Institute upon the completion of the five years' work. From the beginning of his freshman year to the end of his postgraduate year, the student pursues one course after another in mathematical physics. In the middle of his sophomore year he starts his work in the principles of electrical engineering and continues it without a break four terms a year for the remaining three and one half years of his course. During the last year the work at the Institute is composed of advanced research and creative design, while at the Works the student is given experience in the research laboratories of the company, or upon important work in the engineering and manufacturing offices. For a successful completion of this course the institute confers the degree of Master of Science. The degree of Bachelor of Science, conferred as of the year preceding the conferring of the Master's degree, is associated with the Master's degree. By this the Institute shows its appreciation of the value of advanced theoretical training combined with practical experience, which has been intelligently planned and carefully supervised.

In conclusion it may be fairly stated that the one year's experience with this course has demonstrated that it represents a workable program in electrical engineering that includes the following three fundamental elements which it has become recognized should be a part of the training of every modern engineer

1. It includes eighteen months practical experience in the industry; experience which is not gained hit-or-miss, but experience which has been carefully planned and thoroughly supervised. Every engineer must sooner or later obtain such experience before he can fill any responsible position.

2. It provides a greater amount of theoretical training than is usually given in a course of electrical engineering. The practical experience, therefore, is not gained at the expense of the theoretical instruction which, above everything else, it is the function of the school to provide.

3. It is enriched with a wealth of humanistic studies and experience in human engineering which it is believed is adequate to enable the young engineer early to take his rightful place among his fellow workers in the industry and among his fellow citizens in social activities.

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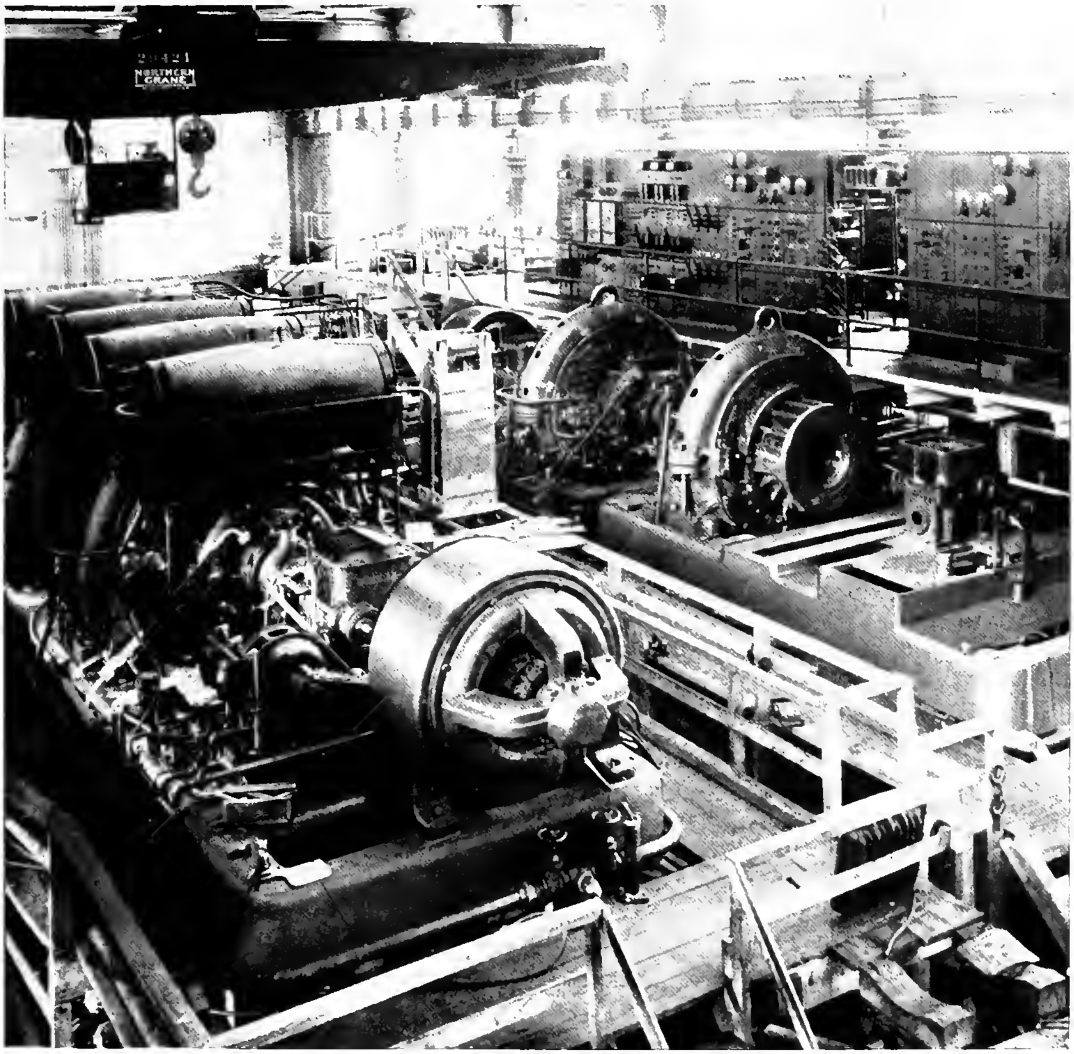

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CHARLES E. PATTERSON

Elected a Vice President of the General Electric Company September 1[illegible], 192[illegible]

GENERAL ELECTRIC REVIEW

THE DEVELOPMENT AND COMMERCIAL APPLICATION OF RADIO COMMUNICATION

To one who does not follow the art of radio communication by a study of its technical literature, information as to its progress comes chiefly from newspaper items and articles of a more or less popular nature. To the engineer, however, such references are often not very satisfactory.

This condition is largely due to the fact that no part of the electrical apparatus employed is operated, or in most cases is even seen, by the person sending or receiving the message. With the telephone, electric light, and most of the applications of electric power a part at least of the apparatus is in plain view, and changes and improvements are quickly noted and interest aroused to learn further of the nature of the changes.

To a person just becoming familiar with this art it would also seem that the amount of time, effort, and expense devoted to research and development work is out of all proportion to the relatively small amount of apparatus built and actually used commercially. Nevertheless while radio communication has been in real practical use for over 15 years, many new developments are usually made even today between the time of the preliminary design of a radio set and manufacture in commercial quantities. This state of affairs is typical of a new art.

The everyday applications of radio are far behind its laboratory accomplishments. One of the principal reasons for this condition is the fact that the various phases of the art have been developed by many widely scattered investigators. To utilize and co-ordinate these many developments and discoveries for the manufacture of practical radio apparatus, a large group of engineers and ample facilities are necessary.

In the January, 1913, issue of this magazine an editorial pointed out the advantages of continuous-amplitude high-frequency alternating currents over the spark system producing groups of damped currents for radio communication and predicted the increasing use of the former. This prediction is being strikingly fulfilled, and it is interesting to note that the articles of this issue on widely different phases of radio deal, as a basis, entirely with the production and utilization of continuous-amplitude high-frequency currents. W. C. W.

CHARLES E. PATTERSON ELECTED A VICE-PRESIDENT OF THE GENERAL ELECTRIC COMPANY

Charles E. Patterson, comptroller of the General Electric Company, was made a vice-president on September 10, 1920.

Mr. Patterson was born in New York City in 1866. He entered Princeton University with the class of '86, but soon after was obliged to leave college on account of his father's death. He secured a position in New York and during his leisure hours continued the college studies.

In 1885 he entered the employ of the New York Central Railroad and for 15 years sacrificed his vacation periods in striving for knowledge and advancement. In 1899 he took up residence in Princeton, N. J.; and by crowding his New York Central work into three and one-half days and many nights, and spending the remaining two and one-half days each week at the University, he completed the interrupted college course and received his degree in 1901.

At this time Mr. Patterson had risen in the ranks of the New York Central to assistant comptroller. On the same day that he received his diploma at Princeton University he was elected comptroller of the American Locomotive Company, which position he held for eight years.

Mr. Patterson has had wide experience in accounting, in fact has been engaged in this line of work for the past 25 years. Even while preparing for and completing the interrupted college course, he was studying higher accountancy and corporation finance. In 1909 he became associated with the General Electric Company to study its organization and methods with a view to introducing a more comprehensive system of accounting and statistics. His untiring efforts and aggressive business qualifications resulted in promotion in 1913 to the position of comptroller, filling the vacancy caused by the death of R. E. Steele.

That Mr. Patterson's advancement to a vice-presidency is well earned is best expressed by the brief statement made by one of the Company's officials when informed of this elevation: "He is a tremendous worker and has earned a just reward. It is not unusual to find him busy at his desk at ten or eleven o'clock at night."

A. E. T.

Transoceanic Radio Communication

By E. F. W. Alexanderson
Chief Engineer, Radio Corporation of America

A certain spirit of romance has been directed in turn toward the initial feats of spanning the oceans by the sailing vessel, steamship, cable, radio, submarine, airplane, and airship. The passing of the romance attached to the earlier of these means has revealed us in possession of another thoroughly practical and established transoceanic type of communication. In the line of succession, radio now stands in midst of its transition stage. Skillful developmental work is hastening the process. The following article briefly reviews the highly successful Alexanderson system of telegraphic and telephonic radio. Each component piece of apparatus is described, its function outlined, and the operation of the whole equipment explained.—Editor.

During the last few years a system of transoceanic radio communication which has been developed by the General Electric Company under the direction of the author has come into use in the United States. This system has been adopted by the Radio Corporation of America which recently absorbed the interests of the American Marconi Company. The system has been adopted for future installations by the British Marconi Company. The object of this article is to describe the principal features of the system.

Historical

The continuous wave system of radio communication which is now exclusively used over long distances was foreshadowed by the early work of Tesla and Fessenden. In order to find means for putting his ideas in practice, Fessenden turned to the General Electric Company with the request for development of an alternator with frequencies from 50,000 to 100,000 cycles, which to that time had been considered impractical. The result of this was the development of a 2-kw., 100,000-cycle alternator.* A number of these 100,000-cycle alternators were built and one of these found its way to the laboratory of Mr. Marconi who took personal interest in this development. In 1915, Mr. Marconi made a visit to Schenectady in order to witness the tests of a 50-kw., 50,000-cycle alternator, and on his invitation this alternator was installed experimentally in the transoceanic radio station of the American Marconi Company in New Brunswick, N. J., which was not then in use. This provided the opportunity not only to test the alternator and other features which have been developed in connection with it, such as the magnetic amplifier and speed regulator, but gave the author the opportunity to demonstrate on a large scale his theory for radiation and improvements of antenna design.

The experimental demonstrations of telegraphy and telephony which were made during 1917 with this installation attracted the attention of the United States Government and scientific commissions that were sent to the United States on account of the war. A circumstance which particularly brought the new system into prominence during the war was the partial failure of the cable system and the urgent demands for transoceanic radio communication that developed in connection with American military operations in France. The 50-kw. alternator set in New Brunswick, though installed in an experimental way, was commandeered for official transoceanic service by the United States Navy in January, 1918, and was operated until it was replaced by the 200-kw. alternator set which is now in use in that station.

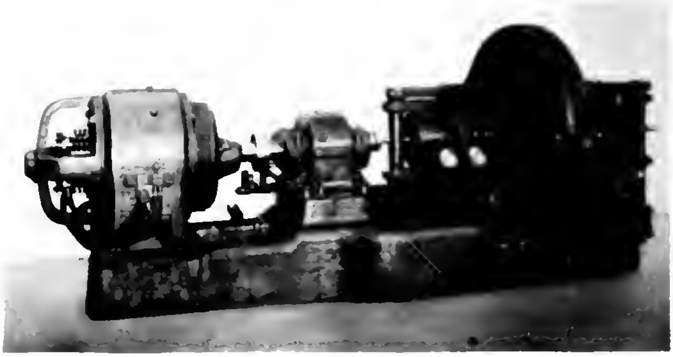

Fig. 1. 50 kw High Frequency Alternator Installed at the New Brunswick Radio Station

Radio Transmitting System

Several types of radio transmitting systems are at present in use with a high degree of success. The descriptive matter in this article will, however, be confined to the system for which the author is responsible, as

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* Alexanderson, General Electric Review, January, 1913

represented by the Naval Radio Station at New Brunswick, N. J.

Generally speaking, any radio transmitting system consists of three essential elements:

1. The generator of radio frequency energy.
2. The modulating system whereby the energy is controlled so as to produce the dots and dashes of the telegraph code or the modulations of the human voice.
3. The antenna or radiating system.

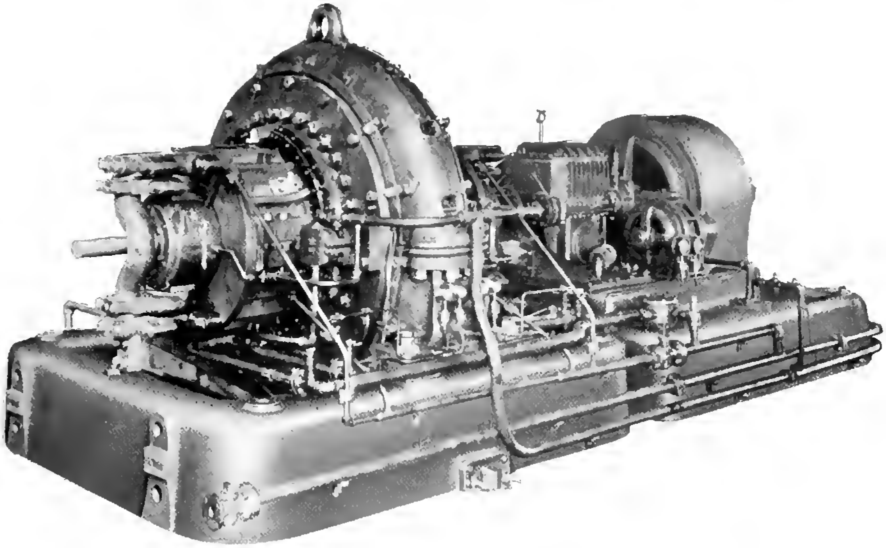


Fig. 2. 200-kw. High Frequency Alternator. Another view of this machine with air-core transformer mounted over the machine is shown on page 814

Generating System

There are four types of generating systems of radio frequency energy in use at the present time.

1. The spark or impulse generator.
2. The Poulsen arc generator.
3. The radio frequency alternator.
4. The vacuum tube oscillator.

The system which will be described is of the type employing a radio frequency alternator. The installation in New Brunswick contains a 50-kilowatt alternator shown in Fig. 1, which was operated for some time for experimental purposes with radio telephone at a wave length of 8000 meters, and later in transatlantic telegraph service at 9300 meters.

A larger equipment, which has been in continuous service, consists of a 200-kilowatt alternator shown in Fig. 2. The poles consist of projections on each face of the disk near the periphery. The slots between these poles are radial with the axis of the disk and are filled with non-magnetic material so as to present a smooth surface and thereby reduce air friction to a minimum. The disk runs between the two laminated armatures which are cooled by water pipes, as shown in the photograph. The armature winding which consists of wire back and forth in straight open slots, is divided in 64 sections, each section generating about 100 volts and carrying 30 amperes. The current generated by these 64 windings is collected in the air-core transformer mounted on the top of the machine (see page 814). This transformer has 64 independent primary windings corresponding to the armature windings. The single secondary winding of the transformer delivers the complete output of the alternator. This collecting transformer is thus to be considered as an integral part of the generating unit; and for all purposes of calculation the characteristics of the generating unit, such as electromotive force and current, are given as delivered from this secondary winding. At full output the alternator delivers 100 amperes at an electromotive force of 2000 volts. It can thus be seen that the alternator is designed for a load resistance of 20 ohms. However, the same machine might be adapted for any other load resistance by selecting a different number of turns in the secondary of the collecting transformer. The reason why this particular machine was designed for a high voltage and low current will be given later in the discussion of the new type of antenna with which it is used.

The 200-kw. alternator when operated at the New Brunswick wave length of 13,600 meters runs at a speed of 2170 r.p.m. It is driven by an induction motor through a gear having a ratio of 2.97:1. When the radio frequency alternator is used as a source of radiation the wave length is determined directly by the rotative speed of the machine. Thus obviously it is important that the rotative speed should be as nearly absolutely constant as it is possible to make it. An important accessory of the alternator set is therefore the speed regulator. The 50-kw. alternator set shown in Fig. 1 is driven by a direct-current motor, whereas the 200-kw. set is driven by an induction motor of the slip-ring type. The 50-kw. set was equipped with a direct-current motor because the problem of speed regulation of that type of motor is somewhat easier. Induction motors were, however, decided upon for the later types because alternating-current power is more easily available in most localities.

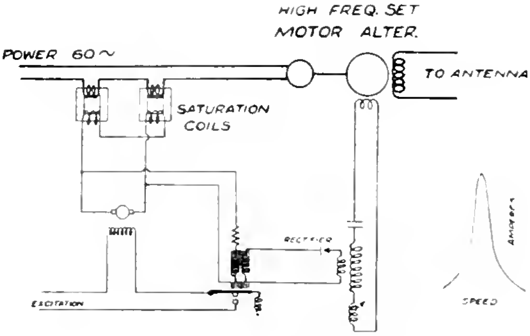


Fig. 3. Diagram of Speed Regulator for High Frequency Alternator

Speed Regulator

The speed regulator consists of a speed-determining element and a power-controlling element. The speed-determining element is a resonant radio frequency circuit fed by one of the 64 alternator windings which is set aside for that purpose. The oscillating energy of this radio frequency circuit is associated by magnetic couplings with a rectifying circuit in which the radio frequency energy is changed into direct current. This rectified current in turn actuates the controlling magnet of a vibrating regulator of the type that is generally used for voltage regulation in power stations. When the driving motor is a direct-current motor it is easy to see how this vibrating regulator may be made to control the speed by regulating the voltage of the power supply to the motor. In order to accomplish the same object with an induction motor some new features have been introduced.

An ordinary induction motor is operated at constant potential. When the motor runs light it draws from the line a magnetizing current which is almost wattless. Thus it operates at a low power factor. When the motor is fully loaded, it draws power at a high power factor, the motor used having a power factor of 90 per cent.

When the New Brunswick station was adjusted for operation, it was found that a wave length was desired which required the induction motor to work at 19 per cent slip. The rheostat in the secondary of the motor could easily be adjusted so that the motor would deliver the desired power with full load at 19 per cent slip. However, inasmuch as the output of the alternator varies continually with the making of dots and dashes of the telegraph code, the motor is alternately loaded and not loaded, therefore, the tendency would be for the motor to speed up during the intervals. If the potential of the power supply to an induction motor is varied the motor torque varies by the square of the voltage. It is easy to show, by the theory of the induction motor, that if a motor consumes power at 90 per cent power factor at full load and the load is reduced to ¼ by the reduction of voltage to ½, the power factor will remain 90 per cent. In fact, it will always consume power at 90 per cent power factor regardless of its load if the voltage

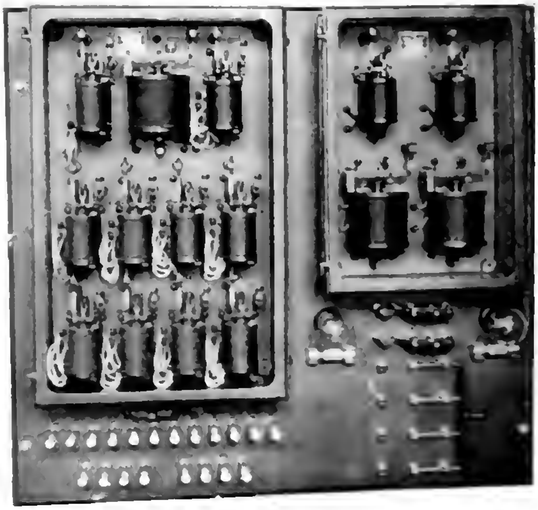


Fig. 4. Vibrator Regulator for High Frequency Alternator

supply is adjusted accordingly, and so long as the secondary resistance remains constant and the speed remains constant.

Thus it may be said that the standard method of operating an induction motor is at constant potential and variable power factor. The method of operating the driving motor of the radio set on the other hand may be characterized as variable potential and constant power factor.

The problem which thus presented itself was to find means for varying the applied voltage in accordance with the action of the speed-determining element, and this has been done in the following way:

Between the motor and the power supply is introduced a choke coil with an iron core, the permeability of which can be varied by saturation. The change in permeability is produced by a direct current which is controlled by a vibrating regulator. When the motor carries full load the iron core is saturated so that the choking effect is practically zero. At fractional load, the choking effect is automatically adjusted by the regulator so that the motor delivers at all times the power required to hold constant speed. The motor itself operates at all times at its maximum efficiency and power factor, but the power factor of the current drawn from the lines varies with the load. Thus when the motor operates at ¼ load, the power factor of the line is 45 per cent, while the power factor of the motor is 90 per cent. The circuits of the regulator are shown in Fig. 3 and the photograph of the vibrator regulator in Fig. 4.

Modulating System

The method of controlling radio frequency energy involves an apparatus which has become known as the "magnetic amplifier." This device is described in a paper by the author in the Proceedings of the Institute of Radio Engineers, January, 1916, and therefore needs to be referred to only briefly. The magnetic amplifier is a device which is physically of the nature of an oil-cooled transformer. The iron core which is made of fine laminations, is designed in such a way that the magnetic permeability of the iron core can be varied by magnetic saturation. By a special combination of tuned circuits, as shown in Fig. 5, it has become possible to separate the controlling current from the radio frequency current so that a comparatively weak current of a few amperes controls as many hundreds of amperes in the antenna.

When the transmitting station is used for telegraphy, the magnetic amplifier is controlled by the telegraph relays which are a part of the wire telegraph system. During the war service the telegraph key was operated in the centralized operating room of the Naval Communication Department in Washington. When the station is used for telephony the controlling current is an amplified telephone current.

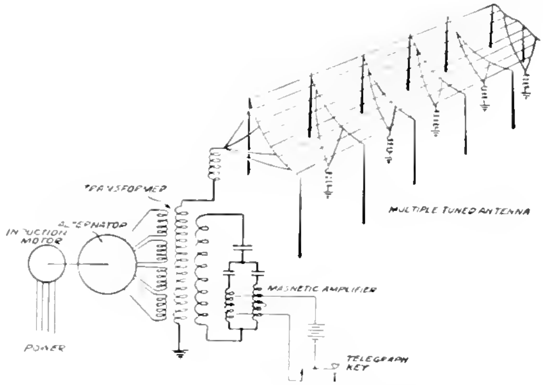


Fig. 5. Diagram Showing Method of Controlling Heavy Antenna Current by Means of a Combination of Tuned Circuits

While the magnetic amplifier has proved to be a very satisfactory and reliable controlling device for ordinary telegraphy, its particular advantages are most prominent in high speed telegraphic transmission and telephonic transmission, on account of its instantaneous magnetic action without any arcing contacts. Fig. 6 shows an oscillogram of radiation at 100 words per minute and a photographic record of reception at the same speed. Fig. 7 shows the telephone modulation of the antenna current when Secretary Daniels was speaking over the telephone line from Washington, controlling the output from the New Brunswick station, thereby transmitting his voice to President Wilson's ship at sea.

The Multiple Antenna

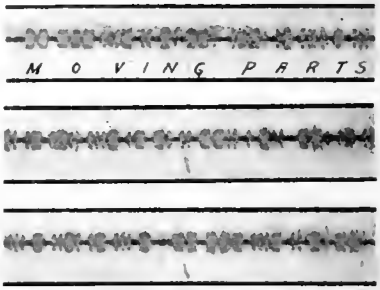
The antenna of the New Brunswick station represents a new departure in the method of radiation. The old antenna structure was originally one of the horizontal Marconi antennæ, 5000 feet (1500 meters) long, 600 feet (180 meters) wide, supported on towers 400 feet (120 meters) high. The original antenna had a resistance of 3.8 ohms.

The antenna as now operated has a resistance of 0.5 ohm, distributed approximately as follows:

	Ohm
Radiation resistance . . .	0.07
Tuning coils and insulation . .	0.10
Ground resistance	0.33
Total multiple resistance	0.5

The reduction in total resistance of the antenna is due to the reduction of the ground resistance. While the old antenna had one tuning coil located in one end, the new antenna has six tuning coils as shown in Figs. 5 and 8.

OSCILLOGRAM OF RADIATED SIGNAL FROM NEW BRUNSWICK



PHOTOGRAPH OF RECEIVED SIGNAL FROM NEW BRUNSWICK AT 100 WORDS PER MINUTE.

Fig. 6. Oscillograph Record of Transmission and Photographic Record of Reception at a Speed of 100 Words Per Minute

Theory of the Multiple Antenna

The improvements in radiation efficiency which have been demonstrated by the use of the multiple antenna can be explained in terms of the Hertzian equation for radiated energy.

$$\text{Watts radiated} = 1600\left(\frac{Ih}{\lambda}\right)^2$$

This equation takes into account only the oscillating current I, the effective height h, and the wave length λ, but not the horizontal dimensions nor the capacity of the antenna. This explanation is accurate and convenient and reduces the radiation efficiency into terms of ground resistance. The improvements of radiation efficiency by multiple tuning are thus indicated by the measured reduction of ground resistance as stated above. In accordance with this explanation the improved efficiency is gained by spreading the antenna over a large ground area and reducing the ground resistance by leading the charging current of the antenna to ground through a multiplicity of tuning coils located far apart. The minimum ground resistance in any one point is of the order of magnitude of 2 ohms, and thus by utilizing several of these ground connections in multiple the total resistance of the antenna can be reduced.

The above explanation is convenient to use in practical calculations, but the author has found radio engineers and scientists not always ready to accept this explanation without further proofs, and quite justly so, because the Hertzian equation is only a condensed mathematical formula in which such essential physical facts as horizontal dimensions and capacity are apparently disregarded. It shall therefore be attempted to present the physical conception of radiation which led the author to the development of the multiple antenna

There are two forms of radiators known and in use at the present time; viz., the electrostatic radiator and the electromagnetic radiator. Of these the electrostatic radiator is used much more extensively. Combination forms of radiators are sometimes used, such as the Marconi directive

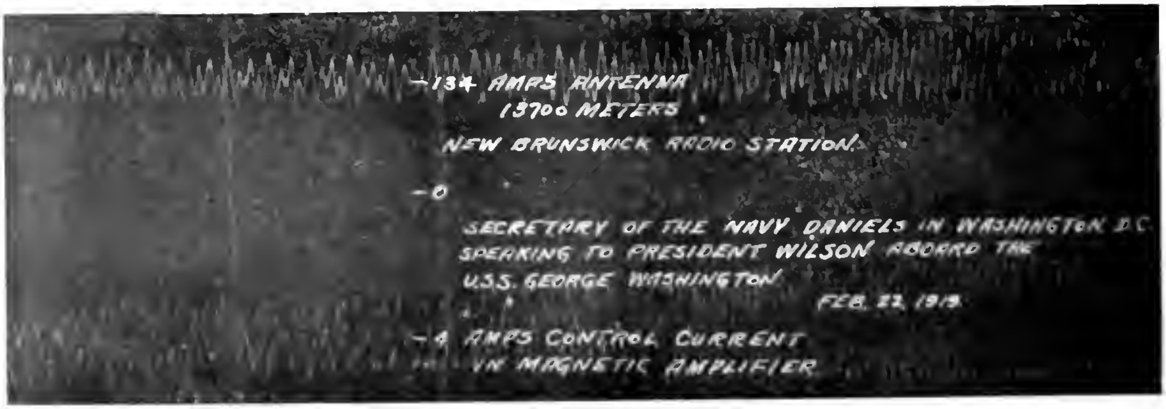


Fig 7 Oscillograph Record of Antenna Current Modulated by Radio Telephone

antenna and Bellini-Tosi antenna. The ordinary antenna with large capacity and moderate height compared with the wave length and large loading coils is almost exclusively an electrostatic radiator. The purely magnetic radiator is the closed magnetic loop. While it is true that in any oscillator circuit the energy alternately appears in electrostatic and electromagnetic form, the electrostatic radiator is characterized by the fact that the energy when appearing in electrostatic form is spread out over a large volume of space, whereas the energy when appearing in electromagnetic form is confined to a tuning coil of small dimensions which does not spread the magnetic lines to any appreciable distance. The magnetic radiator is characterized by the fact that energy when appearing in magnetic form spreads over a large volume of space, whereas the energy in electrostatic form appears in an artificial condenser. The radiation by an electrostatic antenna is produced by the electrostatic lines of force which reach as far away as one-quarter wave length and there produce a secondary electromagnetic field, thus throwing off energy in the form of electromagnetic waves; similarly, radiation takes place from an electromagnetic radiator by the lines of force which reach to a distance of one-quarter wave length and produce an electrostatic field.

In accordance with the author's conception of the electrostatic radiator, it is sufficient to create an electrostatic field which has lines of force reaching into distance. It is conceivable that an insulated plate may be laid directly on the ground, but have such dimensions and such potential charge that it will throw electrostatic lines far into space, and thus will become an effective radiator if charged with a high frequency oscillating potential. The distant effect is obviously proportional to the size of the plate and to the potential applied. The height of the plate over ground and the charging current between plate and ground on the other hand would appear to be immaterial; thus it would appear that the two quantities, height and charging current, which exclusively determine the radiation efficiency in accordance with the Hertzian equation, are non-essential, while the potential and the horizontal dimensions which do not appear in the Hertzian equation are essential. This apparent contradiction can, however, be easily explained. It is only two methods of stating the same fact, but these two statements represent different points of view which are apt to lead to different developments of the technique.

Returning to the large plate laid on the ground: it is evident that the closer the plate is to the ground, the greater is the charging current at a given potential. Furthermore, the larger the plate the greater is the charging current required to maintain the same potential. Thus the horizontal dimensions of the plate are in the Hertzian equation expressed by the charging current. The voltage of the plate is in the Hertzian equation expressed by the height over ground, inasmuch as a greater height corresponds to a lower capacity and consequently to a higher voltage. Thus the height in the Hertzian equation corresponds to the charging voltage in the electrostatic conception of radiation from a low ground plate. So long as we are satisfied that the Hertzian equation is a general and true expression, though it represents a translation into a mathematical language which does not directly correspond to the physical phenomena, we can continue to use the Hertzian equation for the purpose of calculation without losing sight of the phenomena which really take place.

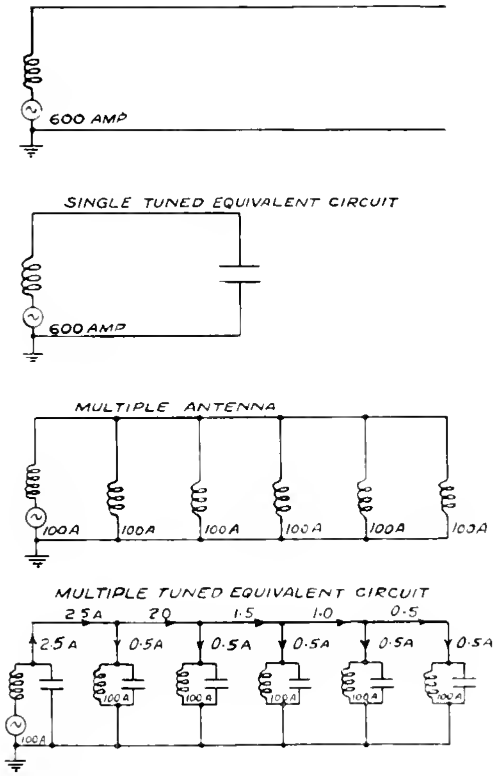


Fig 8. Diagram of Multiple-tuned Antenna Circuit. This circuit has six tuning coils instead of one as in older antennæ

The process of reasoning which led to the development of the multiple antenna was briefly:

The tendency in long distance communication has been towards longer wave length. The Hertzian equation indicates only one way of adapting the antenna to longer waves and that is by increasing the height. This has been carried to the extreme by building towers approaching the height of the Eiffel tower. The practical limit for height of tower has thus been reached and the economical limit much exceeded. If we look at the antenna as an electrostatic radiator, the question presents itself: Why go so high in the air? The only object of so doing is to throw lines of force to great distance. Why not accomplish the same result by mounting the antenna wires at a moderate height, say 100 meters, but covering sufficient ground area for the purpose? The Hertzian equation confirms the correctness of this reasoning, inasmuch as two unit charges at a height of 100 meters will produce a radiation equal to one unit charge at a height of 200 meters. The cost of mounting an aerial capable of taking two unit charges at a height of 100 meters is very much lower than the cost of mounting an aerial for one unit charge at 200 meters. But if we are aiming at a strength of signals corresponding not to one unit charge but to ten units of charge, we have the privilege of extending the antenna indefinitely in horizontal dimensions, whereas further increase of height would be impossible. The antenna in New Brunswick on which this theory has been demonstrated is 1.6 kilometers (one mile) long and the new antennae which have been designed for future and more powerful stations are 6.4 kilometers (four miles long).

The reason why the ground resistance of the original antenna at New Brunswick was as high as 3.8 ohms was the fact that charging currents passing between the aerial and ground at a point one mile away from the station had to be carried over one mile of ground and back again through a mile of antenna wires.

Multiple tuning consists in connecting inductances between the antenna and ground in various places. The current in the inductance lags 90 deg. behind the antenna potential, whereas the electrostatic charging current leads by 90 deg. These two currents which are equal and of opposite phase thus neutralize each other and it is possible to maintain a high antenna potential without carrying high charging currents from the transmitting set to the various distant points of the antenna. In accordance with the electrostatic theory of radiation given above it is only necessary to maintain the antenna potential because it is only the lines of force which reach a distance of a quarter wave length that produce radiation. Thus by using the expedient of neutralizing the electrostatic charging current under the antenna by corresponding inductance currents the energy losses are avoided, which are otherwise incident to carrying currents long distances through the antenna wires and back again through the ground. The only current that it is thus necessary to distribute through the antenna wires is the energy current, which is about one half of one per cent of the charging current. This is the reason for the measured reduction of energy consumption of the New Brunswick antenna at the ratio of 3.8:0.5 ohms at the same average charging potential and the same radiation. The distribution of currents on this multiple tuned antenna at New Brunswick is shown in Fig. 8.

What actually takes place is: The tuning coil to which the alternator is connected transforms the energy of the alternator into a power supply at a potential of 60,000 volts, and each of the oscillating circuits draws energy from this power supply at that voltage. Thus the energy current consumed by each oscillating circuit is only 0.5 ampere. It can thus be seen that while the total oscillating current of the antenna is 600 amperes, the energy current which flows horizontally from the power source to the multiple oscillating circuits is only a total of 2.5 amperes. In other words, the energy which is delivered by the first tuning coil in the form of 100 amperes at 1800 volts is transformed by the first oscillating circuit and distributed as in a transmission line from which 0.5 ampere at 60,000 volts is drawn in five places. The analogy between the multiple antenna and a high tension power distribution system is thus apparent.

This point of view is a departure from the conventional theory of radiation; but it must be remembered that there was a time in the development of electric power technique when the introduction of the high tension multiple distribution system was a radical departure.

When an antenna is built which is four miles long, it may be considered as four antennæ, such as a New Brunswick antenna connected in multiple. The ground resistance will then be reduced again to one quarter of the multiple tuned resistance of the New Brunswick antenna. Calculations of the radiation efficiency of such large multiple antennæ indicate that it will be practical in the future to construct radiators with a radiation efficiency of as much as 50 per cent or more, instead of the radiation efficiency of a few per cent that has been common up to the present time.

Directive Radiation

The multiple antenna as described in its simplest form is adjusted so that the radiation from each of the individual oscillators is in phase. If, however, the antenna dimensions are so chosen that the phase displacement of the travelling wave between the different radiators becomes an essential factor, it is possible to obtain directive radiation. The radiated wave will then not be a simple circular wave, but an interference pattern which may be treated like the corresponding phenomena in light and sound waves. Furthermore, the phase displacement of the oscillations of the individual radiators may be regulated by tuning. Thus a variety of interference patterns may be created and analysis of these possibilities shows that an efficient unidirectional radiation by such methods should be possible.

Methods for unidirectional radiation have been established through the well-known work of Bellini and Tosi. Through the courtesy of Mr. Bouthillon, of the French post office, results of tests made in France have been placed at the disposal of the author which show conclusively directive radiation by the Bellini and Tosi antenna.

With the dimensions of antenna used up to the present time efficient directive radiation has not been practical. It has, however, been proved by various tests that the system of a central power source and a distribution system of energy to a large number of multiple radiators place means at our disposal for constructing radiators of dimensions of one wave length or more. The New Brunswick antenna (1500 meters or 5000 feet long) has a minimum wave length of 8000 meters as a single antenna, whereas it can be operated as a multiple antenna at 2000 meters wave length. A detailed analysis of the possibilities of multiple radiation would fall outside of the scope of this article, but the author is in position to predict with confidence that directive radiation on a large scale will not only prove practical but will be the most effective method of radiation.

To add directive radiation to the proposed program for increasing the capacity of radio traffic would perhaps be premature until it has been demonstrated on a large scale. However, it deserves mention in order to show that new principles which may be utilized for still greater expansion of the radio technique have not yet been exhausted.

The Receiving System

The principal problems of the present day reception of radio signals are the avoidance of disturbances due to atmospheric conditions and other radio stations. The solution to both of these problems appears to lie in the development of unidirectional reception. The old type of static receiving antenna receives signals and atmospheric disturbances equally from all directions. The magnetic loop antenna has a bidirectional characteristic and is somewhat of an improvement over the static antenna. The investigations undertaken by the author during the war period and after on selective reception have led to a type of receiver which was adopted by the United States Navy for transoceanic reception and has become known as the "barrage receiver," because it was developed to meet certain military requirements in France.

The Barrage Receiver

The barrage receiver is fundamentally a unidirectional receiver. The principle of unidirectional reception was first developed by Bellini and Tosi. While the unidirectional Bellini-Tosi receiver has been used as a direction finder, it has, to the knowledge of the author, not been used to any extent for reception of long distance signals. The Bellini-Tosi receiver is based on the principle of receiving the signal through two antennæ of different characteristics and neutralizes the signals received from one direction by a system of balancing.

The principle followed by the author in devising the barrage receiver was:

1. That the antennæ or energy collectors should be aperiodic, because the balance of two tuned circuits is fundamentally very delicate and difficult to adjust for a perfect balance.
2. That the balancing should consist in neutralizing the electromotive forces in the aperiodic antennæ before those electromotive forces have had a chance to create oscillating currents. The phase shifting device should therefore be aperiodic.

3. The two or more antennæ should be of the same character; in other words, it is preferable to balance a magnetic exposure against another magnetic exposure rather than against an electrostatic exposure.

Fig. 9. Barrage Receiving Set Assembled in Carrying Case

The unidirectional Bellini-Tosi receiver works on the principle that the electromagnetic and electrostatic exposures are 90 deg. out of phase. The barrage receiver takes advantage of the geographic phase displacement in the wave as it travels over the surface of the earth. In the first barrage receivers which were installed, the antennæ consist of two insulated wires laid on the ground a distance of two miles (3.2 km.) in each direction from the receiving station. It was originally intended by the author to mount the wires on poles, but the easier procedure of laying the wires on the ground was adopted at the suggestion of Commander A. Hoyt Taylor, and the arrangement has proved entirely satisfactory. The barrage receiving set, photographs of which are shown in Figs. 9 and 10, consists of a standard receiving set, combined with a phase rotator set. Fig. 10 shows the receiving set proper lifted out of the box. This part of the set is arranged so that it can be used as an ordinary receiving set. When used as a barrage receiver, a condenser is used in place of the antenna and the set is coupled to the aperiodic antenna by the phase rotator set. The diagram of the phase rotator set is shown in Fig. 11. Each antenna is connected to ground through an intensity coupler, the secondaries of the intensity couplers being connected to the primary of the phase rotators. Each phase rotator is built on the principle of a split phase induction motor or induction regulator. A single-phase current introduced in the primary is split into a quarter-phase current which produces the equivalent of a rotating magnetic field inductively related to the secondary. By adjusting the position of the secondary coil the electromotive force induced in it may be made to assume any desired phase relation to the primary voltage. The receiving set proper when used with the barrage receiver has all the normal characteristics of a standard receiving set. A signal originating in any direction whatever may be neutralized by adjustment of the intensity couplers and phase rotators. This adjustment is very easy to perform, even by an inexperienced operator, and is perfectly stable after it has been made.

An experimental barrage receiving set was operated for several months of the summer and fall of 1918, about three miles from the New Brunswick, N. J., radio station. Records were kept on the reception of European stations during the operation of the New Brunswick station. As the New Brunswick wave is 13,600 meters and the Carnarvon, Wales, wave is 14,200 meters, the reception of Carnarvon was the hardest test to which the set could be put. It was found that in spite of the overwhelming intensity of the New Brunswick signals on an unbal-

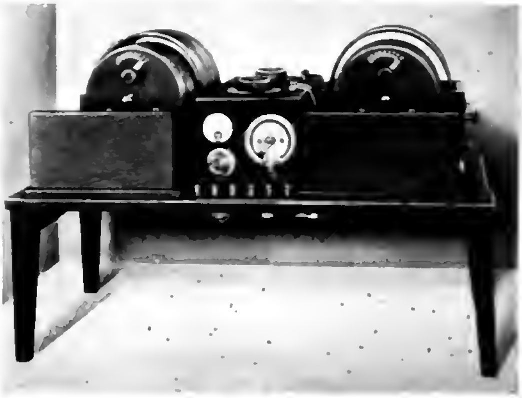


Fig. 10. Barrage Receiving Set Assembled on Operating Bench

anced receiver, the barrage receiver could be adjusted so that the transmitted wave not only did not interfere with the Carnarvon signals, but the New Brunswick signals could be made entirely inaudible. During these tests it was found that the directive characteristics of the barrage receiver was a material help in reduction of inteference by static and strays, as it was found very frequently that solid copy could be obtained by proper directive adjustment, while the signals were practically unreadable with ordinary methods. The improvement in reception of signals by the use of the barrage receiver depends upon the highly directive qualities of this receiving system.

A rather surprising characteristic was discovered by the use of the barrage receiver. It was expected that this receiver could be used to neutralize signals from all directions except the direction close to the signal to be received.

As a matter of fact, it was found that interference originating from the same direction as the signal could be neutralized. This was first discovered in the New Brunswick installation. Signals from San Diego, Calif., right in line with the transmitting station, could be received without great reduction in intensity, while the set was adjusted so as to neutralize the transmitting station. The explanation for this is the fact that the wave front of the nearby station is curved and the radiation diverging, whereas in the case of the far away station the radiation is parallel. The receiving antenna covers a space of four miles (6.4 km.) and in this space there is sufficient divergence of the radiation from the nearby station so that an adjustment can be made whereby the diverging and parallel radiation have different effects upon the receiving set. The phenomenon is comparable to the focussing of a field glass on nearby and distant objects. In this case we have a radio field glass of four miles (6.4 km.) diameter; and for such dimensions, the focussing effect is sufficient even at considerable distances to produce an effective discrimination.

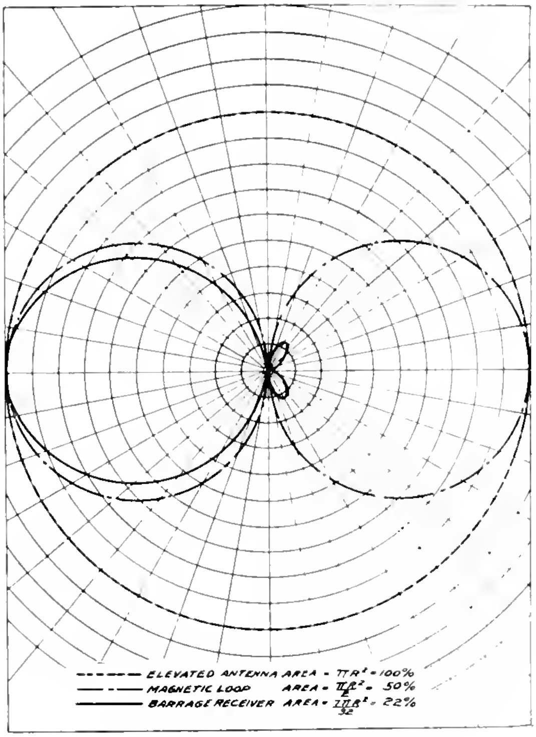


Fig. 12. Diagram Showing the Horizontal Intensity of Various Forms of Antennæ

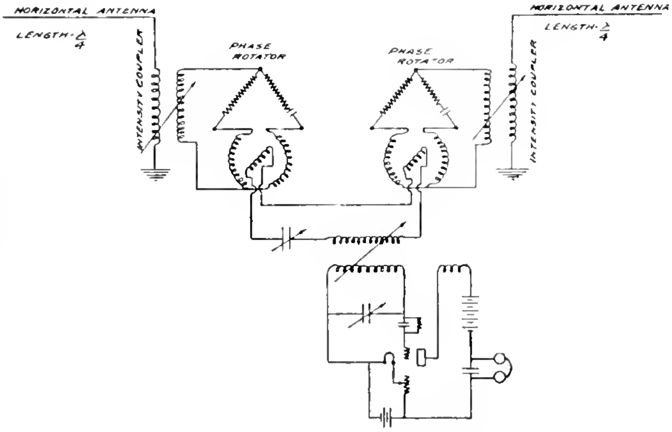


Fig. 11. Wiring Diagram of Phase Rotator Set

While the barrage receiver was worked out primarily to avoid interference in transoceanic communication, it may also be found useful for simultaneous sending receiving from small shore stations or ship stations. In such cases it may be used to neutralize interference from any other ship or shore station. By the use of a double set of phase rotators the barrage receiver may be used to neutralize two stations in different directions simultaneously, and this principle may be carried still further if desired. It is thus hoped that this development will open up new possibilities in dealing with a problem which is perhaps the most important in the immediate future; that is, to meet the demands of radio technique for a rapidly increasing number of systems of communication.

Radiophone Transmitter on the U.S.S. *George Washington*

By John H. Payne

Research Laboratory, General Electric Company

This article and the one following describe the radio equipment installed on the U.S.S. *George Washington* to enable President Wilson to engage in direct telephonic communication with his officials in Washington while on his homeward trip from the Peace Conference in Paris. The makeup of the transmitting apparatus is described below and interesting details of its operation are furnished.—Editor.

During the first part of March, 1919, the Navy Department asked the Research Laboratory of the General Electric Company to install a radio telephone transmitter on the U.S.S. *George Washington*, to work in connection with the New Brunswick station, so that the President would be able to get into telephonic communication with Washington while still on the high seas. It will be remembered that at that time President Wilson was in Paris, attending the Peace Conference.

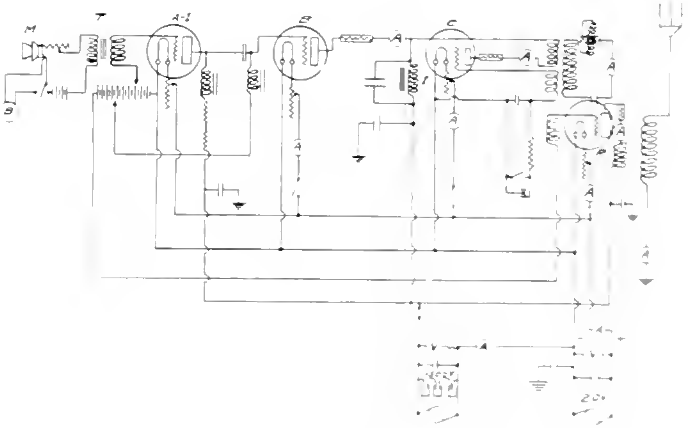


Fig. 1. Connections of the Radiophone Transmitter Installed on the U.S.S. *George Washington*

The General Electric Company had then no finished equipment that would be suitable for such purpose and it was necessary to design and build a special set for this particular work.

It was decided to build a set employing a number of large pliotrons as generators of the high-frequency current required. There was in the Laboratory at that time a panel arranged to hold twelve of these large tubes and to this was added another section containing the necessary modulating apparatus.

These tubes required a source of 1500 to 2000 volts direct current and a separate source of 20 volts direct current. Special motor-generators designed to operate from the ship's mains and to supply these voltages, together with their control and starting panels, were hurriedly put together and the whole apparatus shipped to Hoboken by auto truck. There the apparatus was assembled and installed on the boat, and although the time was so short that it could not be tested until after leaving the dock, it performed remarkably well and gave practically no trouble during the three months it remained abroad.

The connections of the radiophone transmitter are shown in Fig. 1. In this diagram the actual number of tubes used in each stage are not shown; also the details of the control circuit, by which the operator of the transmitter was able to supervise conversations and to connect the set with the receiving apparatus in the receiving room and to the President's suite, are omitted for the sake of simplicity.

The action was as follows: The microphone transmitter *M*, a standard telephone desk set, was used and the currents generated by the voice were stepped up in voltage by the transformer T, and amplified by the pliotron tube A_1. In this set this was a single small tube having a rated output of about 50 watts. The output circuit of this tube was connected at B through a capacity to the grids of two larger tubes of 200-watt capacity each, where the voice currents were still further amplified.

Two similar tubes, C, were connected as oscillators to generate an alternating current of about 170,000 cycles (1800 meters). The high-frequency output (in watts) of these tubes is proportional to the voltage supplied to their plates. The plates of the tubes C and B are connected to the direct-current source through the high impedance I, and therefore any change in the current flowing through the tubes B will cause a voltage to be set up across this impedance and a resulting change in the output of C. In this way the high-frequency output of C is made to correspond with the voice currents supplied by the microphone M.

R is a bank of twelve 200-watt tubes having their grids connected in multiple and coupled inductively to the oscillating circuit of C. The plates of these tubes were also connected in multiple and inductively coupled to the antennæ. The tubes R therefore acted simply as an amplifier for the fluctuating output of C.

With an input to the plate circuits of all the tubes of 1600 volts and between two and three amperes, an antenna current having a steady value of from 30 to 33 amperes was obtained. An oscillogram taken when speaking into the microphone showed that the current in the antenna then fluctuated from 3 to 35 or more amperes. The wave length was at all times maintained at 1800 meters.

After the installation of the set was completed on April 12th, a great many interesting tests were made before the President boarded the ship almost three months later.

On April 14th, we talked to the U.S.S. *Frederick*, at that time about 150 miles ahead of us, and they reported: "Phone loud and strong, easily understood." On April 16th, the log reads: "Before beginning the 3:00 p.m. schedule a broadcast message was sent on the *George Washington's* spark transmitter at 600 meters and at 952 meters asking all ships to listen for our radiophone on 1800 meters and report how they received us and giving their position." About a dozen ships sent in reports. The ship farthest away that reported was about 320 miles from us. They reported "Phone fine on crystal with Marconi type receiver." The U.S.S. *President Grant*, about 150 miles from us, reported hearing our radiophone 75 feet from the head phones using a four stage amplifier.

Fig. 2 is a chart showing the names and positions of the ships which reported that they had received on the test. This was one of the first tests of this sort and from then on we often entertained the operators of other ships by phonograph concerts transmitted via our radiophone. The log of the Navy receiving station at Otter Cliffs, Maine, shows that at one time, when we were 1000 miles away, the music of one of these concerts came in so loud that the sailors there danced to the tunes we played.

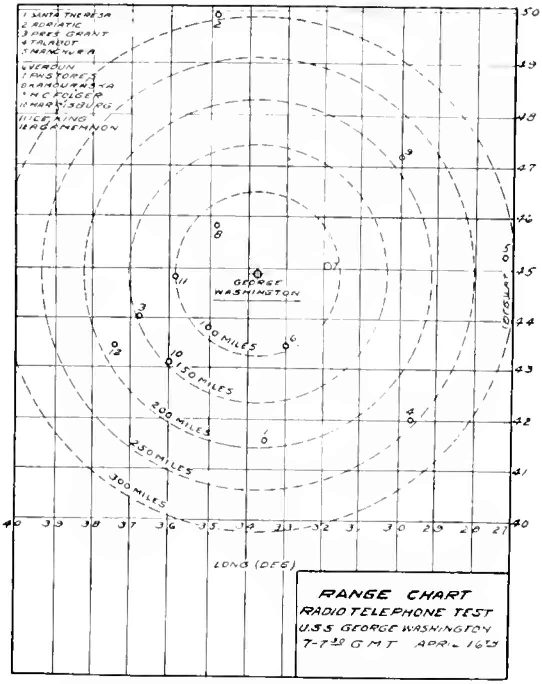


Fig. 2. Chart Showing the Names and Positions of Ships which Reported Hearing Radiophone Messages from the *George Washington*

On April 17th, when we were 2184 miles from Ambrose Light, Otter Cliffs reported hearing our tests but that the speech at that time was not clear.

Up to this time the full output of the set had never been obtained because of some trouble with the power circuit supplying our motor-generator sets. In Brest this trouble was remedied and thereafter all our tests were made at about full output.

On April 27th, we began our first return trip, Secretary of War Baker and several thousand soldiers being on board. The static most of the time was very bad and we did not get into touch with Otter Cliffs until May 4th, when they reported: "Your telegraph signals excellent; speech at first half of schedule loud but not clear and on the last half very loud and clear." We had made an adjustment in the middle of the schedule when we had discovered that the quality of the speech was poor. Four hours later they reported that they were copying our speech on a typewriter. Later in the day a number of commercial messages were transmitted by the radiophone set. The first one read as follows:

"From U.S.S. *George Washington* via Otter Cliffs, Maine, to Perkins Street, New York City. 'Expect to see you Monday night. Love. (Signed) Ted. 3:30 p.m.'" As far as the writer is aware this was the first actual paid commercial message ever transmitted by radiophone from ship to shore. Later that day Secretary Baker spoke a few sentences over the phone which were received at Otter Cliffs.

On the following day the set was used to transmit to New Brunswick, where the speech was automatically relayed over the wires to Washington. Several persons talked over the phone on the ship to people in Washington, Secretary of War Baker talking for some time with Assistant Secretary of Navy Roosevelt, and making arrangements to meet some relatives in New York upon his arrival there.

On the occasion of one of the concerts which we gave on this trip the radiomen on the U.S.S. *Pastores*, then 600 miles distant, connected the loud speaking telephone on the bridge of the ship with the receiver and tuned in the *George Washington's* wave. One of the radio men, telling the writer of the incident, said that some of the officers and men were so surprised at the loudness and clearness of the music and voices that they at first refused to believe that the sounds were actually coming from the *George Washington*, and it was only with difficulty that they were convinced that the radio men were not up to some trickery.

On May 10th the *George Washington* again started for France and on this trip numerous tests were made. We were in communication with New Brunswick until we were some 800 miles away, when the interference and static became so heavy that we gave up and all tests were discontinued until our arrival at Brest.

While lying in Brest harbor we tested out the set and representatives from Admiral Sims' office in London listened for us there. We received the following report: "Your schedule received, signal strength ten, modulation good . . . ." London is about 300 miles from Brest and "strength ten" seems very loud.

While we were in Brest the NC-4, enroute from Portugal to England, passed over and circled the ship. An effort was made to talk with her by the radiophone. The operator of the NC-4 in conversation with the writer later said that he heard our signals but that they were so loud with the amplifier that he was using as to be uncomfortable and scarcely understandable. If more time had been available it is probable that good communication could have been established with the NC-4 before she landed in England.

On June 29th, we started on our return trip, President Wilson and party being aboard. When we had approached to within 1300 miles from Ambrose Light we picked up a message from Otter Cliffs to New Brunswick saying: "For information, can hear *George Washington's* wireless telephone fine; can copy solid but at present Glace Bay causing interference."

On July 4th an effort was made to transmit the President's speech to the troops by radiophone. A telephone microphone was concealed on the stand where he was scheduled to speak, but due to a misunderstanding the President spoke on a lower deck some 20 feet from the microphone. All ships had been notified to listen for the President's speech, but only an occasional word could be heard. This was very much to be regretted, as the atmospheric conditions were splendid at the time. The writer read the President's speech in the phone a few hours afterward. Colonel Carr, Department Signal Officer of the Southwestern Department of the Signal Corps, has since told the writer that he heard portions of the speech on a small antenna in San Antonio, Texas. This distance was roughly 3000 miles and almost entirely over land.

On July 5th and 6th, the static conditions were so bad that we had difficulty in getting into good communication with either New Brunswick or Otter Cliffs, but on the 7th we got several messages through, though it was not at all satisfactory. The ship was then only about 375 miles from Ambrose Light.

Later in the day the conditions grew worse and it was not until the following morning that really satisfactory two-way communication was obtained and the President was able to send a message over the radiophone to Secretary Roosevelt in Washington.

Duplex Radiophone Receiver on U.S.S. *George Washington*

By Harold H. Beverage

Radio Engineering Department, General Electric Company

In arranging for duplex or two-way communication between the *George Washington* and land stations, one of the major difficulties encountered was the prevention of each receiver from being affected by the powerful interference of its own transmitter. This problem as applying to the land station at New Brunswick was solved by separating the transmitting and receiving stations a distance of four miles. The solution employed on the *George Washington* was of necessity totally different. A description of the schemes used, with particular reference to receiving, is given in the following article. Extracts from the ship's log are included to show the successful performance of the equipment.—Editor.

Introduction

On February 22, 1919, Secretary of Navy Daniels, sitting at his desk in Washington, picked up his telephone and spoke a few words of greeting to President Wilson, then 800 miles at sea on the U.S.S. *George Washington*.

Secretary Daniels' voice was carried over the regular toll line from Washington to the Naval Radio Station at New Brunswick, N. J., where the voice currents were amplified to such an extent as to modulate the output of an Alexanderson alternator. This modulated energy was radiated from the New Brunswick antenna and was picked up on the *George Washington*.

Previous to this demonstration, the operators on the *George Washington* had heard New Brunswick's radiophone while the ship was lying at anchor in Brest Harbor, France.

The results of these tests were so encouraging that the Navy Department decided to install a powerful radiophone on the *George Washington*, to enable the ship to talk back to the shore. The General Electric Company was asked to furnish the radiophone equipment, both transmitting and receiving.

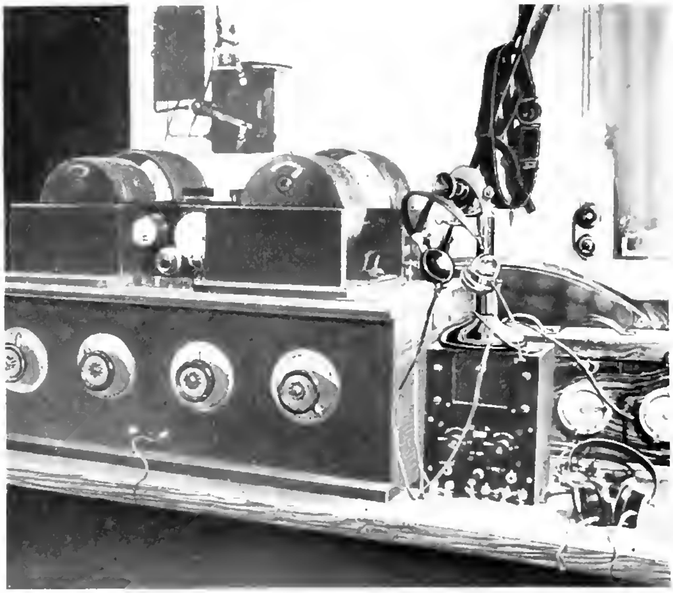


Fig. 1. Receiving Set and Telephone Communication Station of the U.S.S. *George Washington's* Radio Telephone Pliotron Equipment

Requirements for Two-way Radiophone Conversation

In order to make a two-way conversation possible over a radiophone, it is necessary either to shut off the transmitting set when receiving, or to so arrange the receiving apparatus that it will be unaffected by the powerful interference from the local transmitter.

On small radiophone sets the first method is often used, the transmitter being started and stopped by a convenient push button located on the microphone support. More or less confusion is likely to result from this method of control, as it is impossible for the party talking to hear the other party until he releases the push button, thereby shutting off his transmitter. This method of operation is not readily adapted to remote control over a long-distance toll line.

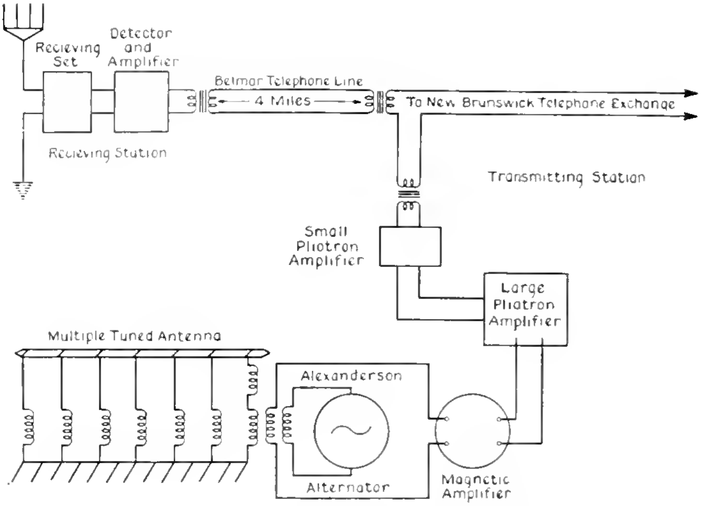


Fig. 2. Connection Used for Duplex Operation at New Brunswick Station

On high-power radiophones, particularly where an alternator is used to supply the radio frequency energy, the push button method of control is impractical, if not impossible in many cases. For these reasons, the second or duplex method for two-way conversation was chosen for both New Brunswick and the *George Washington*.

Duplex Arrangements at New Brunswick

At New Brunswick, Mr. Burke Bradbury made arrangements for duplex operation by setting up the receiving apparatus at a point about four miles from the radio station, and sending the amplified received currents back to the radio station over an existing telephone line connecting New Brunswick with the Marconi receiving station at Belar.

Fig. 2 shows the connections used for duplex operation at New Brunswick. It will be noted that the received currents are introduced in series with the toll line leading from New Brunswick, enabling the party talking from Washington or any other point to hear the incoming radiophone speech over the same wires which transmit his own speech to New Brunswick, as in an ordinary land wire connection. It is also evident that, with this connection, the speech and signals picked up by the receiving apparatus at New Brunswick will modulate the alternator output and be re-radiated again at New Brunswick's wave length. Anyone listening on New Brunswick's wave length would, therefore, hear both sides of the conversation. This explains a point which puzzled many amateur operators, who reported that they heard the *George Washington* radiophone on 8000 or 13,600 meters, whereas the wave length of the radiophone on the *George Washington* was 1800 meters. The wave lengths of 8000 and 13,600 meters were both used at New Brunswick for radiophone tests at various times. The writer often heard short wave spark signals while listening to the New Brunswick radiophone on the *George Washington*, the signals being picked up by the receiving apparatus at New Brunswick and being re-radiated in the manner described.

Duplex Arrangements on U.S.S. *George Washington*

The solution for duplex operation on the *George Washington* was necessarily different than for New Brunswick, as the receiving and transmitting apparatus could not be located at different points as at New Brunswick. The problem which presented itself, therefore, was to provide receiving apparatus sensitive enough to respond loudly to received currents of a few millionths of an ampere on 8000 meters, and yet be practically unresponsive to a radiation of thirty or more amperes at 1800 meters, radiating on an antenna stretched from the same masts as the receiving antenna.

As a solution for this problem, Mr. E. F. W. Alexanderson, Chief Engineer of the Radio Engineering Department, suggested the circuit shown in Fig. 3. This circuit was first tried out in Schenectady, using the same antenna for both receiving and sending. It was found possible to receive signals from Europe on long wave lengths and at the same time radiate ten amperes at 1000 meters on the same antenna, using either an Alexanderson alternator or a pliotron oscillator as the source of energy.

On the *George Washington*, however, separate receiving and transmitting antennæ were used, arranged as shown in Fig. 4.

Fig. 3 shows the connections used in the duplex receiver on the *George Washington*.

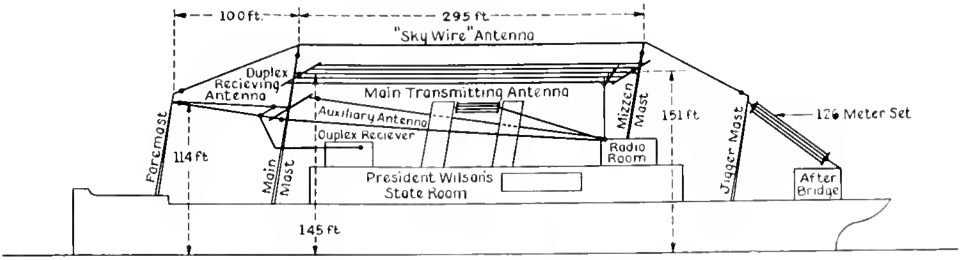


Fig. 4. Arrangement of the Separate Receiving and Transmitting Antennae on the U.S.S. *George Washington*

The current from the receiving antenna divides through two parallel branches; C_1 being one branch, and FC_2L_1, the second branch. The "frequency trap" F is tuned to the transmitting wave length of 1800 meters, and offers an impedance of about 250,000 ohms at 1800 meters, but a very low impedance to long wave lengths. The condenser C_1 has a capacity of 0.006 microfarads, and offers an impedance of about 160 ohms at 1800 meters. As the primary L_1 of the receiving set is in series with the frequency trap, the interference from the local transmitter is reduced in the ratio of the impedances of the two branches to 1800 meters, or 160/250,000, so that the interference is reduced to 0.6 of one per cent of the interference that would be experienced without the filter circuit. The remaining interference is so small that it is easily taken care of by tuning alone.

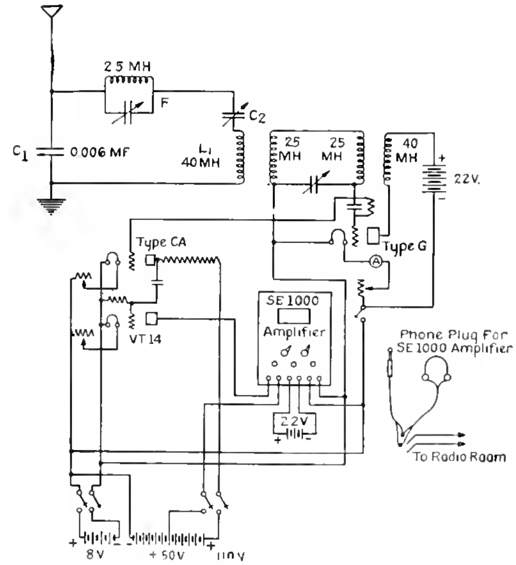


Fig. 3. Connections Used for the Duplex Receiver on the U.S.S. *George Washington*

The variable condenser C_2 tunes the primary of the receiving set to the long wave length which it is desired to receive. The inductance of the frequency trap F enters into the tuning of the primary circuit, and therefore the frequency trap offers practically no impedance to the long waves. The branch FC_2L_1 offers only a few ohms effective resistance to the long wave length to which it is tuned, while the branch C_1 offers a comparatively high impedance, about 1200 ohms for 13,600 meters. It is, therefore, possible to receive the long waves at practically full intensity, and yet render the receiver very insensitive to the effects of the powerful radiation from the local transmitter.

The remainder of the apparatus is the same as is used for receiving telegraph signals, excepting that it is adjusted to receive a wider band of frequencies than a telegraph receiver, in order to receive all components of the telephone wave necessary for clear speech. If the receiver is too sharply tuned, the quality of the telephone speech on long waves is very poor, because only one frequency is received strongly and other frequencies are suppressed. For long wave telephony, it is very essential to tune the receiver in such a manner that it is capable of receiving a band of frequencies within about 1000 cycles on either side of the carrier wave. On short wave lengths, 1000 cycles is a very small per cent of the carrier frequency and an ordinary sharply tuned telegraph receiver will receive telephone speech clearly. On wave lengths above 10,000 meters

1000 cycles is several per cent of the carrier frequency, and the average telegraph receiver is tuned too sharply to receive all of the frequencies necessary for clear speech, the speech sounding muffled and being very difficult to understand. With broad tuning, however, the long wave length speech may be received clearly with good quality.

The adjustment of the duplex feature of this receiver is very simple. First, the receiving set is tuned to the wave length it is desired to receive. Then, the frequency trap F is adjusted until the interference and noise produced by the local transmitter disappear and the distant signals are heard clearly. The frequency trap adjustment is very sharp, and in the case of the *George Washington* the radiation from the transmitter was so powerful that the detector bulb was rendered inoperative until the frequency trap condenser was within a very few degrees of the correct position.

Some idea of the effectiveness of the duplex feature of the receiving set may be gained from the following demonstrations: When the pliotron transmitter on the ship was in operation, radiating about 30 amp. on the main antenna at 1800 meters, the receiving antenna was sufficiently exposed to light a 40-watt lamp to full brilliancy when the lamp was placed in series with the receiving antenna. The intensity of the interfering current reaching the receiving set secondary was so small, however, that no interference whatever was experienced above 6000 meters when the pliotron transmitter was being used for continuous wave telegraphy with 30 amp. radiation. When the pliotron transmitter was modulated by voice or buzzer, the modulation could be heard weakly on 13,600 meters, and a little stronger on 8000 meters. The interference from the modulation was never strong enough to interfere with telegraph reception from New Brunswick on either 13,600 meters or 8000 meters, even in Brest Harbor, but it was strong enough to interfere slightly with the New Brunswick radiophone when the ship was several hundred miles away from New Brunswick, as the radiophone intensity was very much less than the intensity when New Brunswick was telegraphing. The interference or "side tone," however, was not loud enough or clear enough to understand; and it was necessary for intercommunication purposes to introduce an artificial side tone enabling the transmitter operator to speak to the receiving operator for changes in control, etc. For duplex telephony the side tone is not only unobjectionable, but is more or less desirable, as it more nearly approximates the conditions in the ordinary land wire telephone.

It was noted that in very wet weather the side tone was appreciably stronger than in dry weather, probably due to leakage currents between the transmitting and receiving antennæ over the wet insulators. However, duplex operation was satisfactory in very wet weather, with a few exceptions. On one or two occasions, it was found that wet halyards swinging against the receiving antenna produced more or less inductive disturbance when the transmitter was working. During rough weather, when the ship was rolling and pitching badly, it was sometimes quite difficult to keep the receiver quiet when the transmitter was in operation. Loud inductive disturbances, synchronous with the rolling or pitching of the ship, were observed several times. In each case, the source of disturbance was found to be an antenna lead-in grounding somewhere on a metal stay or some other grounded metal object. As there were about twelve antennæ on the ship, it was sometimes difficult to locate the source of disturbance immediately. It was found necessary to insulate each antenna lead-in carefully in such a manner that it could not swing against a grounded object when the ship was rolling and pitching in a storm.

Extracts from Log

Mr. John Payne and the writer made two trips to France on the *George Washington*. On the first trip, the ship sailed from Hoboken on April 11th. Due to the short time available for installing the radiophone, the ship was out of range before arrangements were completed for duplex operation and no duplex conversations were tried.

During this trip, the New Brunswick radiophone was operated at a wave length of 13,600 meters with an average antenna current of 120 amps. The New Brunswick radiophone was operated on definite schedules during the day and evening, and was received consistently up to about 1200 miles, with the exception of a few schedules when the ship was in the gulf stream, and heavy static interfered with reception. The speech was partially understood up to 2500 miles when the static conditions were favorable, and was heard but not understood at still greater distances.

On the return trip from Brest, the New Brunswick radiophone was heard, but not understood, as soon as the ship left Brest Harbor. At a distance of 2000 miles from New Brunswick, complete sentences and orchestra selections were recognized on the ship. The orchestra music was obtained by placing a telephone near the orchestra at the New Brunswick Opera House, and also at the Hotel Klein. At a distance of 1200 miles practically all of New Brunswick's speech was understandable under normal static conditions.

Due to very unfavorable static conditions, duplex conversations were not satisfactory until the ship was about 200 miles from New York, on the morning of May 5th. After establishing satisfactory duplex conversation with the engineers at New Brunswick and Navy officials in Washington, Secretary of War Baker on the *George Washington* held a conversation with Assistant Secretary of Navy Roosevelt in Washington. Secretary Baker remarked that "the connection was as good as over an ordinary toll line."

The *George Washington* sailed from Hoboken again on May 10th. The first duplex conversations were held while a heavy sea was running and in a driving rain, and considerable difficulty was experienced from inductive disturbances caused by the lead-in on unused antennæ swinging against grounded objects. Later, fairly satisfactory conversations were held with New Brunswick up to a distance of about 400 miles from New York. At that distance, very bad static was experienced which made the reception unsatisfactory on both ends, particularly on the *George Washington*. After the ship was about 800 miles out the static conditions on the ship end were much improved, so that New Brunswick was easily understood again. New Brunswick could hear the *George Washington* at this distance, but could not understand the speech well enough to work duplex satisfactorily.

While the *George Washington* was lying at anchor in Brest Harbor, some radiophone tests were made at New Brunswick, using a wave length of 8000 meters. During these tests, the average antenna current at New Brunswick was about 50 amp., as compared with an antenna current of 120 amp. at 13,600 meters. At night, the 8000-meter wave length radiophone was received much clearer and stronger than the 13,600-meter wave length, but very little was understood due to interference and static. However, it was possible to recognize selections sung at New Brunswick. On one occasion, Mr. W. W. Brown's voice was clearly recognized singing "America." Sometimes, at night, the 8000-meter wave with 50 amp. average antenna current was received by heterodyne note as strong or stronger than the 13,600-meter telegraph wave with an antenna current of 350 amp. In the daytime, the conditions were reversed, and the 13,600-meter wave length was received much stronger than the 8000-meter wave length. In fact, it was often impossible even to pick up the 8000-meter wave length in Brest Harbor in the daytime, although at night the same radiation was very strong.

The *George Washington* sailed from Brest again on June 29th with President Wilson and party aboard. When the ship was 2400 miles from New York, New Brunswick began to make tests comparing the 8000-meter and the 13,600-meter wave lengths with 50 and 120 amp. average antenna current respectively. The first test was run at night, and the 8000-meter radiophone was understood fairly well at this distance of 2400 miles, while the 13,600-meter wave length could not be understood due to static, although the radiation in amperes was over twice as great. The next test was made on the following day, with daylight. The distance between New Brunswick and the *George Washington* was about 2000 miles. Both wave lengths were received about the same on this occasion. From this point on the 8000-meter wave length was received better than the 13,600-meter wave length, day or night. From a distance of 1600 miles until the ship docked, the 8000-meter radiophone was understandable at most schedules excepting when there was interference from Glace Bay.

The first duplex conversation on this trip was held on July 7th, when the *George Washington* was about 375 miles from New York. The first conversation was not very satisfactory, due to static and interference at New Brunswick. Later in the day, fairly satisfactory duplex conversations were held between New Brunswick and the *George Washington*, but it was necessary to repeat some of the sentences several times before they could be understood. It was decided that the conditions were not quite favorable enough for President Wilson to talk, and it was hoped that the static conditions would improve later in the day. The static conditions became worse, however, so the presidential conversation was deferred until the following day. On the following morning, satisfactory communication was established, and the President was able to send a message over the radiophone to Assistant Secretary Roosevelt via radiophone to New Brunswick and thence to Washington over the toll line.

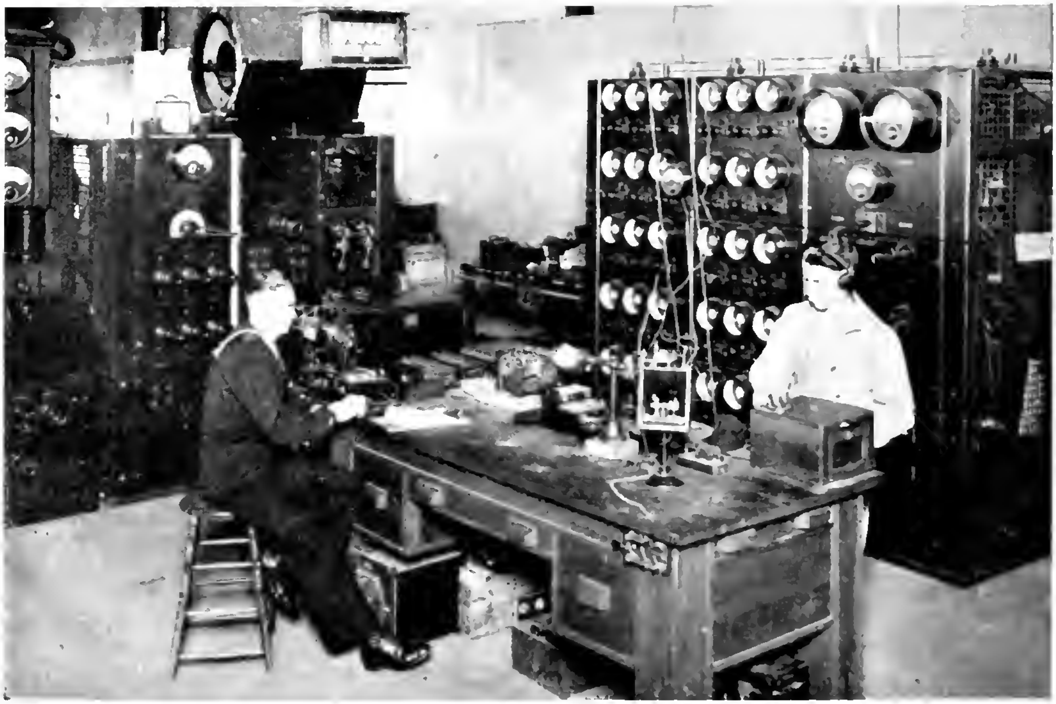
Conclusion

On all trips, New Brunswick was received well up to about 300 or 400 miles. Between 300 and 500 miles from New York, the reception of New Brunswick radiophone was generally comparatively poor on every trip, due to very strong static. Beyond 600 miles from New York, the reception on the *George Washington* was generally good again on all trips. The static conditions seemed to be most unfavorable on the western edge of the Gulf Stream, and all signals appeared to be comparatively weak there.

During all of these tests, the New Brunswick radiophone was received with the detector oscillating at zero beat. Non-oscillating detector reception was also tried, using a multistage radio frequency amplifier. Good reception was obtained, but it was found more practical for duplex operation to use the oscillating detector, as it was not as subject to interference from the transmitter as the radio frequency amplifier system, due to the fact that the radio frequency amplifier tended to amplify the high-frequency harmonics from the transmitter to a great extent.

The duplex reception with the zero beat method of reception with oscillating detector was very satisfactory. Under normal conditions, the static produced a much louder sound than the side tone from the local transmitter, so that the distance that it was possible to receive New Brunswick's radiophone successfully was limited by the static rather than the side tone from the local radiophone transmitter. The master oscillator method of generating the radio frequency energy used by Mr. Payne on the *George Washington* radiophone produces a wave which is remarkably free from harmonics.

When the pliotron set was being used for continuous wave or buzzer modulation telegraphy, sending commercial messages to Otter Cliffs, Maine, it was found possible to stand watch on New Brunswick without the slightest interference from the pliotron transmitter. This feature may be found useful in the future on large ships with heavy traffic, as it enables them to send and receive simultaneously. With this type of duplex, it is possible to work down to within about twice the wave length of the transmitter when the transmitter is being used for continuous wave telegraphy.



Relaying Messages from Washington Through the New Brunswick Radio Station

The Alexanderson System for Radio Communication

By Elmer E. Bucher

Commercial Department, Radio Corporation of America

The attainment of a system of radio communication free from the objectionable features and limitations of the arc and spark gap types has been realized in the Alexanderson system. It has introduced into the realm of radio the same degree of certainty of expectations and reliability of results, in generation, control, and distribution, as has for a long time been characteristic of operations in the field of commercial light and power. The generator, although necessarily of special construction, is designed in conformity with established electric, magnetic, and mechanical laws. Its speed is held constant within one-tenth of one per cent by an especially developed speed regulator. The output of the station, which fluctuates with the message being sent, is controlled by an ingenious and extremely sensitive non-arcing device called a magnetic amplifier. The multiple tuning of the antenna permits of radiating the energy at a vastly improved efficiency. The following article thoroughly describes the complete system in great detail and in a manner that is easily understood.—Editor.

General

Radio engineers early foresaw that the ultimate generator of oscillations for radiotelegraphy and telephony would be one of a type providing more efficient and reliable operation than the systems utilizing the "arc" and "spark." In fact the literature of the past makes frequent references to the desirability of an oscillation generator constructed along the lines of an ordinary power-house alternator; but because such alternators were required to provide frequencies a thousand times or more in excess of those used in power engineering, new problems of designs were encountered which were declared by many to be well-nigh insurmountable. For a time the development of the art seemed to follow the line of least resistance, and it resulted in the evolution of several systems utilizing the "arc," the "spark gap," and the type of radio frequency alternator which generates at a comparatively low frequency, the necessary increase of frequency being obtained either by groups of mono-inductive transformers external to the alternator, or by tuned "reflector" circuits associated with the alternator. None of these systems, however, can be said to have satisfied fully the exacting requirements of commercial operation.

An oscillation generator suitable for commercial radio service over great distances should possess the following qualifications:

(1) It should generate a steady stream of oscillations of constant amplitude.

(2) It should generate a so-called "pure" wave; that is, a fundamental wave in which the radiation incurred by superimposed harmonics is negligible.

(3) It should provide a performance as reliable as the ordinary power dynamo.

(4) It should operate economically and efficiently.

(5) It should permit manufacture of units in any desired power.

(6) The design of the whole system should be such as to permit telegraphic signalling at very high speeds.

The above specifications are met fully and fairly in the Alexanderson system.

As is well known, the design of radio frequency alternators has occupied the attention of Mr. Ernst F. W. Alexanderson of the General Electric Company (U. S. A.), and his staff for a number of years, and the pioneer work of these men in that branch of radio research is now a matter of common knowledge. Starting with the development of several experimental types of alternators, they have steadily progressed toward the designs of more powerful machines which are now available for commercial use. Standardized alternator sets for transmission at wave lengths between 6000 and 10,000 meters and between 10,500 and 25,000 meters are now in production. This description is devoted principally to the discussion of a 200-kilowatt set, although sets of other powers are now under construction.

The typical Alexanderson high-power station may be said to represent a radical departure from current ideas regarding radio design. In fact, at first glance, it seems to possess little in common with the apparatus of other systems. These features will presently be described in greater detail.

The Radio Corporation, after an extensive test of the Alexanderson system at its high power station at New Brunswick, N. J., has acquired the rights to the Alexanderson system, and it will be employed at all its stations devoted to long-distance signalling. A 200-kilowatt alternator set was installed at New Brunswick in September, 1918, and from that time it has provided continuous and most satisfactory service in continent-to-continent communication. Normal transmission is at present conducted at the wave length of 13,600 meters, with antenna current of 400 amperes corresponding to an alternator output of approximately 80 kilowatts. With this fractional value of the available output of the alternator, transoceanic communication has been maintained with European stations throughout the twenty-four hours of the day. The alternator is capable of supplying 600 amperes to the New Brunswick antenna, but its full output of 200 kilowatts is not at present utilized, due to the lack of adequate power supply at that point. The alternator, as installed at the New Brunswick station, is shown in Fig. 1.

With this brief disclosure of progress to date, there will follow an explanation of the basic principles of the Alexanderson system and the fundamental circuits of a typical station. This may be accepted as indicative of a standard 200-kilowatt installation, although largely based upon the apparatus at the New Brunswick station.

Standard Equipment

A high power radio station of the Alexanderson type contains three important developments:

(1) An ALTERNATOR—which generates currents *directly* at the frequencies which are required for the radio circuits with which it is associated. The frequency of these currents is solely dependent upon the number of field poles on the machine, and upon the speed at which the rotating member is driven. This is in distinct contrast to certain other systems in which the radio frequency currents are obtained *indirectly* by means of "reflector circuits" or frequency raising transformers electrically associated with the alternator.

(2) A MAGNETIC AMPLIFIER—which provides a non-arcing control of the alternator output for radio telegraphy, and is equally applicable to radio telephony.

(3) A MULTIPLE TUNED ANTENNA—a development which has markedly reduced the wasteful resistance of the flat-top antenna, and has therefore increased the transmitter overall efficiency many fold.

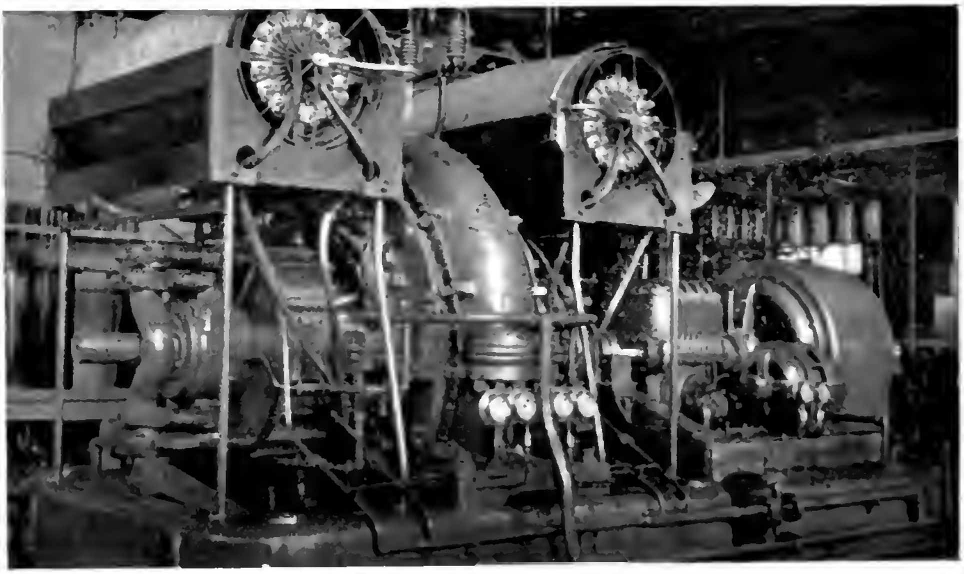


Fig. 1. 200-kw Alexanderson Radio Frequency Alternator Installed at the Radio Corporation's Transoceanic Station, New Brunswick, N. J.

Alternator Development

To date the development in radio frequency alternators has included the following types:

(1) 2-kw., 100,000-cycle alternators.
(2) 50-kw., 50,000-cycle alternators.
(3) 200-kw., 25,000-cycle alternators.

The characteristics of several alternators of other power outputs have been investigated from time to time. A standard 25-kw. and a 5-kw. alternator are now under construction and will be shortly put into commercial production.

With the object of providing a distinct range of frequencies, both the 25-kw. and the 200-kw. alternators are manufactured with armatures and rotors with different numbers of poles; also with gears of different ratio for different driving motor speeds. Thus the 25-kw. machine can be assembled for any wave length from 6,000 to 10,000 meters, and the 200-kw. machine for any wave length from 10,500 to 25,000 meters. Frequencies lower than these for which the machine has been assembled can be obtained by running the alternator at a reduced speed.

The standard drive for the 200-kw. Alexanderson alternator is two-phase, 60-cycles, 2300-volt alternating current. By the use of suitable transformers, the voltage of the power supply can readily be transformed to the value for which the motor was designed. Special driving motors and control equipment can be supplied for other frequencies.

The Alternator

The Alexanderson alternator is an *inductor type* of generator with a solid steel rotor having several hundred slots milled radially on each side of the rim. The slots are filled in with non-magnetic material, with the object of reducing wind friction to a minimum. The fillers are brazed into the disk in order that they may withstand the centrifugal strain of rotation. The rotor is designed for maximum mechanical strength by providing it with a thin rim and a much thicker hub. With this construction the strain on the material due to centrifugal force is the same from the shaft to the outer rim.

The *rotor* of the 200-kw. alternator (with half of the field frame removed) is shown in Fig. 2. This also shows the collars of the thrust bearings and a partial sectional view of the main bearing housings.

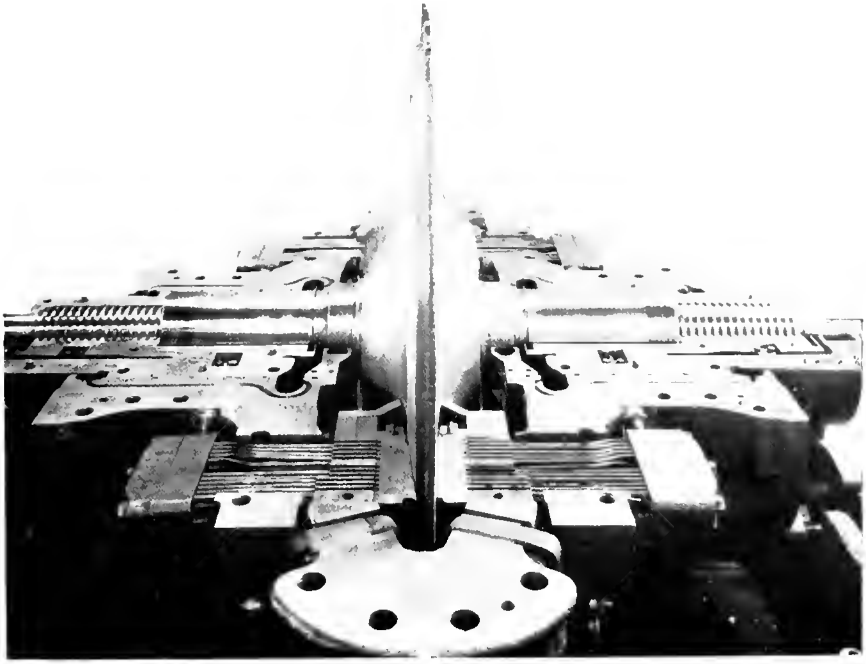


Fig. 2. 200-kw. Alexanderson Alternator, with Top Half Removed

An assembled 200-kw. alternator with its driving motor is shown on page 814, Fig. 1. The alternator is driven by a 600-h.p. induction motor of the wound-rotor type, which is operated from a 60-cycle, 2300-volt, quarter-phase source of supply. The motor is connected to the alternator through a double helical gear (with a speed step-up ratio of 1:2.97), which operates in a container partially filled with oil.

The *main bearings* and the *thrust bearings* of the alternator are oil-lubricated by force feed at pressures varying from 5 to 15 pounds according to the demand on the bearing. During the periods of stopping and starting, and in possible emergencies, oil is supplied by a special *motor-driven pump* mounted on the alternator base. When the alternator is working under normal operating conditions, a *separate pump* geared to the main driving shaft feeds the bearings, and the *motor-driven pump* is automatically cut out of service. The *oil-supply tank* is located in the base of the alternator, to which the oil returns after being pumped through the bearings. The oil gauge on the main feed pipe is fitted with a *signalling circuit* to call the attention of the operator in case the oil supply fails. The main bearings of the alternator, which are self-aligning, are also *water-cooled* by a series of copper pipes which run through the bearings near to the friction surface. The armatures of the alternator are also water-cooled from the same pumping source by a series of parallel copper tubes cemented in the frame alongside the laminations.

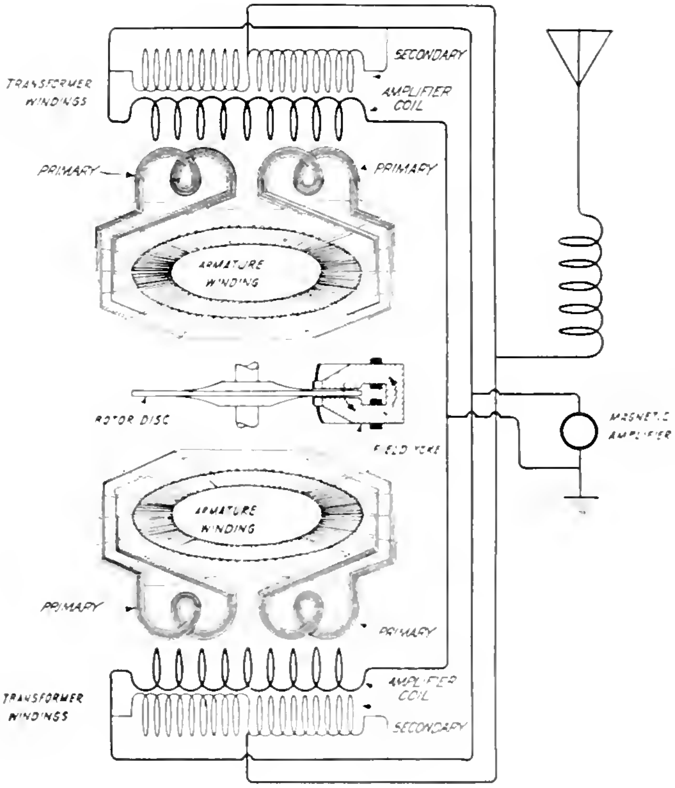


Fig. 3. Schematic Diagram of Alexanderson Radio Frequency Alternator Circuits

In order to avoid large losses through magnetic leakage, the air gap between the rotor and the stator frame is maintained at a spacing of 1 millimeter. It is important that the rotor be kept accurately centered, for otherwise the armature coils on one side of the rotor will become overloaded. This is accomplished by the use of specially designed *thrust bearings* which are inter-connected by a set of *equalizing levers* with an adjustable controlling leaf between them. These prevent the possibility of binding between the thrusts, due to expansion of the shaft from heating, and they also take up automatically all slack in the bearings as they become worn. Any tendency towards a change in the air gap is thus counteracted by the action of the levers. The equalizers are, in part, the heavy vertical column shown at the end of the alternator in Fig. 1 on page 814 Should the air gap on either side tend to get smaller, the pull of the field on that side would cause an excessive strain on the thrust at that end and cause heating. This, however, is prevented by the leverage system, which automatically corrects this and holds the rotor in a central position at all times.

In regard to some of the electrical features of the alternator it will be noted from Fig. 3 that the *armature* and *field coils* are stationary, the requisite flux variations for the generation of radio frequency currents being obtained from the slots cut in the rotor. The diagram points out the fundamental construction of the alternator and the general mode of winding the armature. The rotor disk revolves between the two faces of the field yokes. The direct current supplied to the field coils produces a magnetic field flux which passes between the field yoke faces and through the rotor as shown by the arrows.

The armature coils, which are placed in slots cut in the two faces of the field frames, are shown in the sketch as tipped away from the rotor, although in the actual machine the spacing between the rotor and the frame is but 1 millimeter. Two distinct armature windings are thus provided, one on each side of the rotor. There is but one conductor in each slot and two of these slots make a complete loop, and comprise a *pole* in the armature windings. One slot in the rotor is therefore provided for each loop in the winding. The armature windings on each side of the rotor are divided into thirty-two independent sections, the circuits of which are completed through *transformer primary coils* as shown in Fig. 3. Each primary consists of two turns with sixteen separate wires in each turn. There is no direct connection between the individual armature sections, but through the two-turn primaries they combine to act upon the secondary coils of the transformers. It is obvious that with this division of armature circuits the potential on any armature coil (or on the corresponding transformer primary) is very low, and as such, it permits a grounded or open-circuit armature coil to be cut out of the circuit and the operation of the alternator to be continued with but a slight decrease in its output—an obvious advantage.

A detailed view of a portion of the alternator armature windings is given in Fig. 4, and of the preliminary stages of assembly in Fig. 5.

Fig. 4. Detail View of Section of Armature, Alexanderson 200-kw. Radio Frequency Alternator

Fig. 6 shows the laminated armature, which is wound with 0.037 millimeter steel ribbon.

The completed rotor and its shaft appears in Fig. 7

Alternator-Antenna Transformer

It is to be noted that a transformer is provided for the armature coils on either side of the rotor. There are therefore two transformers, and they each contain the three coils P_1, S_5, S_1, and P_2, S_5, S_2, shown in the fundamental station diagram, Fig. 14. The primary of each transformer contains two turns of sixteen wires each, as mentioned above. The *intermediate coils* S_5 have twelve turns on each transformer. The two intermediate coils are connected in parallel, and are shunted by the magnetic amplifier. The coils S_5 are also connected in series with the secondary proper, and the antenna system.

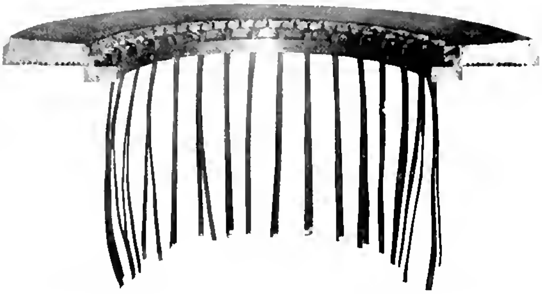


Fig. 5. A Section of the 200-kw. Alternator Armature

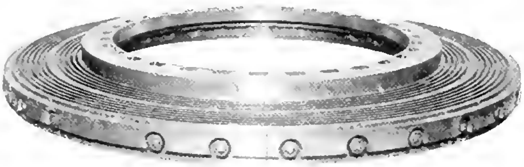


Fig. 6. Completed Armature Ready for Sawing Into Two Sections

The *secondary coils*, which consist of seventy-four turns on each transformer, are wound so that their high potential ends are at the center in order to provide a uniform potential gradient. The two secondaries are connected in parallel and their final terminals are in series with the antenna circuit. More in detail, the low potential terminals of the intermediate coils are connected to the ground, the other terminals of the intermediate coils are connected to the low potential terminals of the secondary coils, and the high potential terminals of the secondary coils to the antenna loading coil. The intermediate coils S_5 are placed between the primary and secondary of each transformer in order to obtain a close coupling with the alternator. One unit of the high frequency transformer is shown in Fig. 8.

The voltage at the terminals of the secondary winding of the transformer when the alternator is operated at normal speed is about 2000. The normal output current is 100 amperes. It is thus seen that the alternator is designed for a load resistance of 20 ohms.

Speed Regulator

Since the antenna circuit is directly associated with the alternator circuit, any change in the rotative speed of this machine would throw the alternator circuit out of resonance with the antenna circuit; consequently it is easily seen that the speed variation of a radio frequency alternator for substantially constant output must be held within very close limits. The variable load imposed by telegraphic signalling has a tendency to cause a variation of speed that must be compensated for by some device which operates more critically than any of the mechanical and electrical methods of speed control devised for ordinary power use. The characteristics of any satisfactory governor must be such that a small variation of speed will effect a maximum change in power input to the device under control. To accomplish this, some mechanism must come into such a critical state at the speed to be maintained that a low percentage of change in speed causes a high percentage of change in itself.

Fig. 7. Typical Rotor Construction of Alexanderson Alternators

It can be shown that a change in speed of one-quarter of one per cent from that necessary to maintain resonance will reduce the antenna current in a station utilizing the wave length of New Brunswick—13,600 meters—to one half its full value. This clearly infers that the speed variation must be much less than one fourth of one per cent to maintain a constant output at the alternator. As a matter of fact, a regulation within *one tenth of one per cent* is obtained by the Alexanderson speed regulator.

The necessity for close speed regulation becomes equally important when considered from the standpoint of the receiving station. With a modern receiving apparatus of low decrement, a very slight change in the wave length of the incoming signal will materially decrease the received current. A change of wave length or frequency is likewise detrimental when reception is obtained by the heterodyne or beat principle, for should the speed of the alternator vary markedly while signalling, the beat note may vary to the degree that will render it objectionable for ear reception. A variation, for instance, of 50 cycles in the alternator will cause the beat note at the receiver to vary by 50 cycles, which is the equivalent of a speed variation of 0.23 per cent at the wave length of 13,600 meters.

A solution of the problem of speed regulation with a-c. motor drive was found by Mr. Alexanderson in the use of a *resonance circuit*, which is tuned to a frequency slightly above the frequency to be maintained at the alternator. This circuit is supplied with current from one of the armature coils on the alternator. The current in this circuit increases with the alternator speed and, through the agency of a *rectifier*, a d-c. component operates on a *voltage regulator* connected in the circuit of the dynamo which supplies the saturation current for a set of *variable impedances* in the two phases of the motor supply circuit. The function of the regulator is to prevent, within established limits, either an

Fig 8 One Unit of the High Frequency Transformer

increase or decrease of alternator speed. Additional compensation for the load imposed when signalling is provided by a *relay* which also operates through the d-c. control circuits to vary the line impedances mentioned above. A detailed diagram of the speed control system is shown in Fig. 32, and the theory of operation is disclosed in greater detail on pages 833 to 836.

The panel board of the voltage regulator system is shown on page 796, Fig. 4.

Multiple Tuned Antenna

This may be said to establish a radical departure from the types of antennæ formerly used for high-power radio transmission. The immediate object of the multiple antenna is to reduce the wasteful resistance of the long, low, flat-top aerials formerly used and to permit the length of such aerials to be increased indefinitely for the use of greater powers. In the case of the New Brunswick antenna, its resistance as a flat-top aerial—3.7 ohms—was reduced by multiple tuning to 0.5 ohm. The radiation qualities of the flat top are not impaired by multiple tuning, as a series of tests have shown that with an equal number of amperes in either type, the *same signal audibility* is obtained at a receiving station, but there is an enormous saving of power in the case of the multiple antenna, as will be presently pointed out.

As shown in the station diagram, Fig. 11, the multiple antenna has, instead of the single ground wire usually employed, a number of ground leads which are brought down from the flat top at equally spaced intervals, and connected to earth through appropriate tuning coils.

The capacitive reactance of the flat top is thus neutralized by inductive reactance at six points to earth, instead of but one point as in the ordinary system. The inductive reactance in each down lead is therefore made six times the capacitive reactance at a given frequency. The multiple antenna is thus the equivalent of *six independent radiators*, all in parallel and resonant to the same wave length. Their joint wasteful resistance obviously is much less than that of an antenna with a single ground, and herein lies the saving of power which the Alexanderson antenna brings about.

The relative power inputs required by both types of antennæ for the same value of antenna current will be seen from the following illustration: To maintain 600 amperes in the multiple-tuned antenna at New Brunswick, at a resistance of $\frac{1}{2}$ ohm, the power required is $600^2 \times 0.5$, or *180 kw.* To maintain the same antenna current in a flat-top antenna with resistance of 3.7 ohms requires $600^2 \times 3.7$, or *1330 kw.* The economy of power secured in the case of the multiple-tuned antenna is an important consideration from the standpoint of the cost of daily operation.

Prior to the advent of the Alexanderson antenna, theory and practice pointed to the desirability of a very high antenna structure for long distance communication at high powers, but as is well known, the cost of erecting an antenna increases very rapidly with the effective height. The multiple-tuned antenna, however, permits the use of a less expensive antenna structure, and gives the same signal audibility at a given receiving station as a high antenna of the old type *with less power.* The example given above demonstrates quite conclusively that the multiple antenna will provide the same antenna current as the flat-top type antenna, but only one seventh of the power. The multiple-tuned antenna is treated more comprehensively on pages 823 to 833.

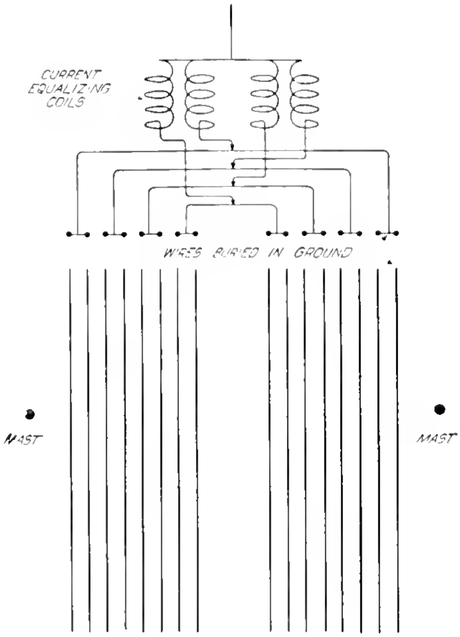


Fig. 9. Schematic Diagram of Earth-wire System at the New Brunswick Station

Earth System

The earth-wire system at the New Brunswick station is a combination of a *buried metallic* and a *capacitive ground.* Sixteen parallel copper *conductors* are laid underneath the antenna and buried one foot in the ground.

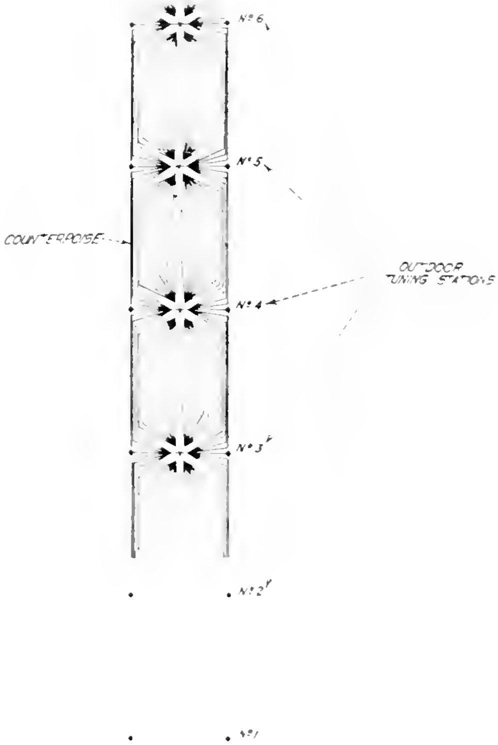


Fig. 10. Plan View of Counterpoise at New Brunswick Station

They extend the entire length of the antenna and are spaced between towers somewhat as shown in Fig. 9. A network of wires and zinc plates are also buried in the ground around the station. At each of the five tuning points outside the station, connection is made from the antenna flat top to the sixteen underground wires.

In order to secure equal distribution of current through the buried ground conductors, *equalizing coils* are inserted between the tap on the down lead coil and the earth wires at each of the five tuning points outside the station, as shown in detail in Fig. 9. The function of the equalizing coils is to increase the impedance of the wires near the center and hence force current in the outside wires. Since the coils are wound in opposite directions they add no appreciable inductive reactance to the tuning circuits. In one instance, the use of these coils reduced the multiple resistance of the antenna system from 0.9 to 0.7 ohm.

A still better distribution of the earth currents at New Brunswick was obtained by using a capacitive ground commonly known as a *counterpoise,* which is erected underneath the antenna and a few feet above the earth. A plan view of the counterpoise is shown in Fig. 10. The capacitive ground may be considered as a combination of a tuned and a forced oscillation circuit, and it has the effect of drawing the current from the ground circuit more uniformly than with wires lying on the ground or buried beneath the surface. In practice the total current in the down lead may be distributed between the capacitive ground and the wire ground in any desired ratio. The effect of adding this unit to the system at New Brunswick was to decrease the multiple antenna resistance from 0.7 to 0.5 ohm. The capacitive ground may be divided into separate units for each tuning down lead or the units may be connected together as shown. A schematic diagram of the connections between the flat top and the capacitive and earth-wire grounds is shown in Fig. 11. The equivalent circuit is given at the right of the drawing. The construction of the *outdoor inductances* for multiple tuning is shown in Fig. 12.

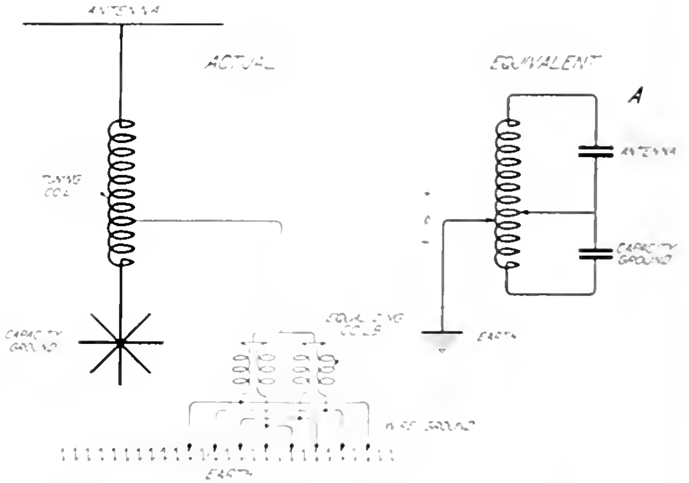


Fig. 11. Schematic Diagram of Antenna to Earth Connections of the Multiple-tuned Antenna

Magnetic Amplifier

Telegraphic control of the large antenna currents involved in high-power radio transmitters has ever presented a difficult problem. Particularly has this been true when signalling at high speeds. Rapid signalling obviously requires some device that will not cause destructive arcs and will provide the desired modulation of antenna power without taking upon itself the burden of carrying the full power of the system, during the intervals between signalling.

The *magnetic amplifier* is a device which meets these exacting requirements, for it provides a non-arcing control with a minimum current in the key circuit, and it takes within itself only a small proportion of the total alternator output. A photograph of the amplifier, removed from its container, is shown in Fig. 13.

The magnetic amplifier in general may be described as a *variable impedance* which is connected in shunt with the external circuit of the radio frequency alternator. Its function is to *reduce the voltage* of the alternator and to *detune* the antenna system when the sending key proper is open, and to perform the opposite functions when it is closed. Thus when the sending key is open the amplifier short circuits the alternator and detunes the antenna system, thereby reducing the antenna current to a negligible figure. When it is closed the output of the alternator is fed to the antenna system.

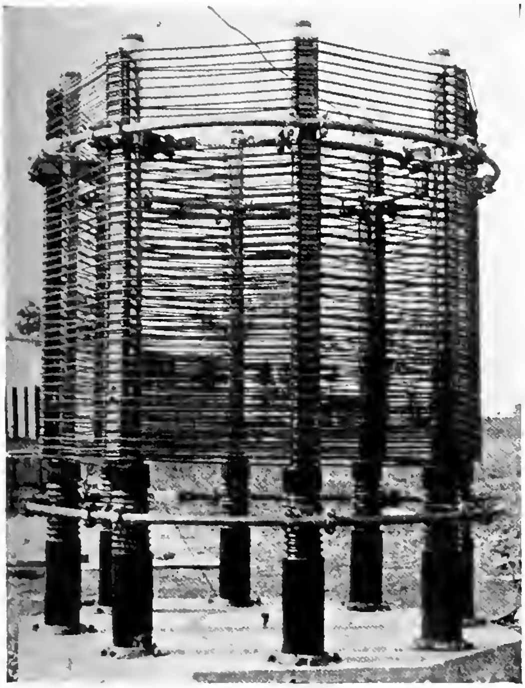


Fig. 12. Tuning Inductance for Multiple-tuned Antenna

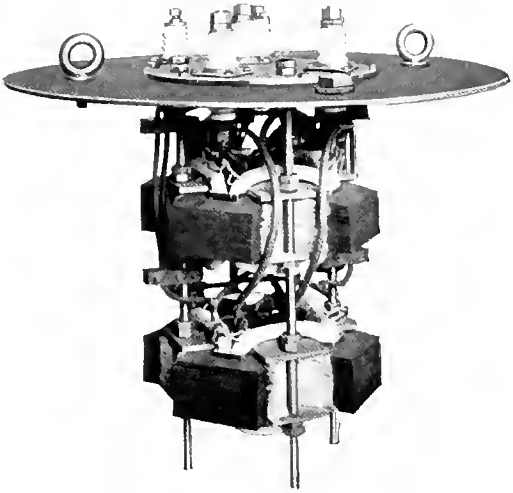


Fig. 13. Magnetic Amplifier Removed from Containing Case

A general idea of the operation of the amplifier can be obtained from the fundamental circuit, Fig. 14, where it will be noted that the radio frequency coils A and a control coil B are mounted on a common iron structure, and are so disposed that the effect of the control coil upon the radio frequency coils is obtained solely through the agency of flux variations within the core. The impedance of the amplifier is dependent upon the degree to which the iron core is saturated by the control winding. The saturation in turn varies as the current is fed into the control circuit. When the control circuit is closed the alternator is short circuited; when it is open, the alternator assumes normal voltage and its output flows into the antenna system.

The magnetic amplifier has been employed in experimental telegraphic signalling at speeds above *500 words* per minute, at which rates it functions without lag. It is equally applicable as a *modulator* of antenna power in *radio telephony*, in which case the control current of the amplifier is modulated at speech frequencies by a bank of pliotron (vacuum valve) amplifiers, which in turn are controlled by an ordinary speech microphone.

The characteristics of the amplifier are treated in greater detail on pages 836 to 838.

Fundamental Station Circuit

The fundamental *circuits of a typical Alexanderson alternator station* are shown in Fig. 14. Beginning at the left of the drawing, it is to be noted that a source of two-phase, 60-cycle alternating current drives an *induction motor M*, having a wound rotor, the circuits of which include a liquid rheostat R_3. The motor is connected to the *radio frequency alternator* through a helical step-up gear.

The alternator armature coils are indicated at A_3, A_4, the field coils at F_1, and the rotor at A_2. There are two sets of armature coils, one on each side of the rotor, which as already mentioned, are divided into 32 sections on each side. The windings on each side connect to the primaries of two transformers shown at P_1, P_2. The primary of each transformer (see Fig. 3) contains two complete turns of 16 wires in each turn, which carry the current developed in the 32 sections of the armature coils on each side of the rotor. As can be seen from the diagram, there is no direct electrical connection between the armature circuits leading to the transformer primary, but the individual primary circuits are disposed so that their magnetic fields at any instant are in the same direction, that is, their fields combine to operate on the secondaries S_1, S_2. In addition to the primary and secondary coils, the two transformers have intermediate coils S_5 which are connected in parallel and shunted by the magnetic amplifier coils A. The coils S_5 are connected in series with the antenna system, and are also closely coupled to the primary and secondary.

The *multiple-tuned antenna*, shown in the upper part of Fig. 14, is a long, low, horizontal aerial of the Marconi type, from which are brought down leads to earth, which include the tuning inductances L_1, L_2, L_3, L_4, L_5, L_6. For any given wave length the *joint inductive reactance* of the down lead circuits L_1 . . . L_6 is made *equal to the capacitive reactance of the entire flat top* at the operating frequency or wave length. The multiple antenna is therefore the equivalent of *six independent radiating systems* resonant to the same wave length, and for all practical purposes, the oscillating currents in them flow in phase.

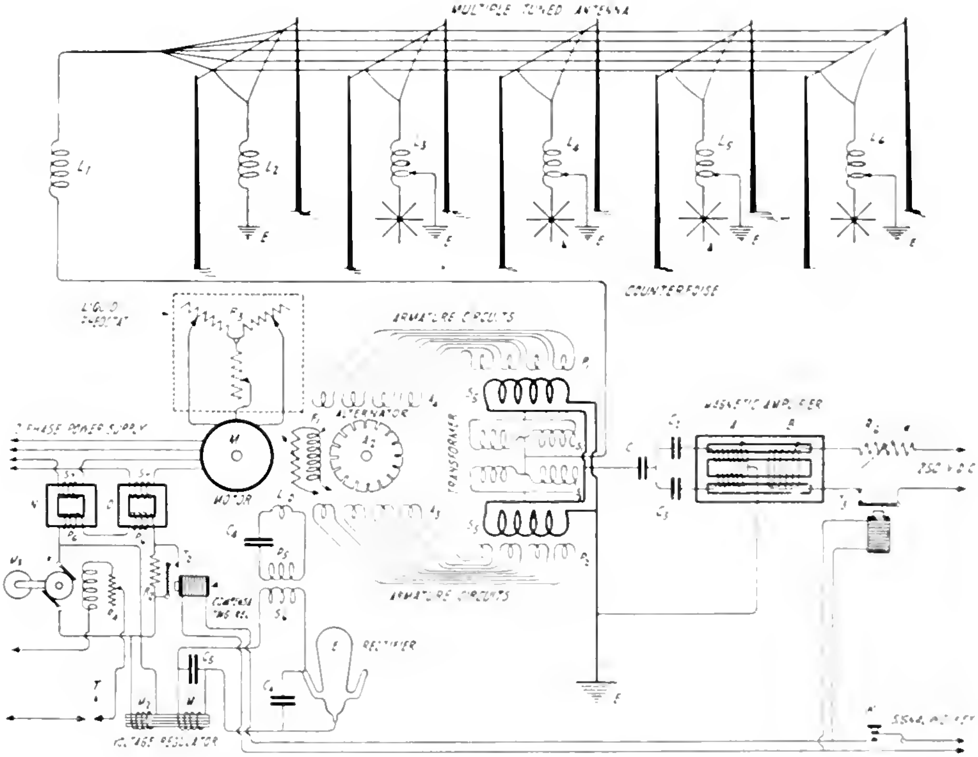


Fig. 14. Fundamental Station Diagram of 200-kw. Alexanderson Alternator Set
Radio Corporation's Transoceanic Station, New Brunswick, N. J.

The magnetic amplifier, shown to the right of the diagram, comprises the parallel-connected *impedance coils* A, which are connected in series with the *condenser* C_1 and the transformer *amplifier* coils S_5. B is the *control* coil, wound to include both branches of the windings A, which is fed with direct current, regulated by the rheostat R_6. When the control circuit is closed the impedance of the amplifier coils A becomes a minimum; when it is open the impedance is a maximum. In the former case the alternator is placed on short circuit and the antenna is detuned; in the latter case the alternator assumes normal voltage and its output flows into the antenna system. In practice the capacity of C_1 is selected to neutralize the inductance of windings A for some value of current in the control coil.

The circuits of the *speed regulator* appear in the lower left hand part of the drawing. Note is to be made first of the variable impedances N and O in the motor supply line with their d-c. control coils P_6 and the variable impedance coils S_7.

The extremely close speed regulation essential to alternator operation is obtained from the *resonance circuit* L_{10}, C_4, P_5, the coil L_{10} being one of the alternator armature coils. This circuit is made resonant to a frequency slightly above the normal frequency at which the alternator is to be operated and the current developed therein acts inductively on the circuit S_6, E, M_1 (E being a rectifier). The latter rectifies the radio frequency current and sends a d-c. component through M_1, which acts with an increase of speed to decrease the voltage held by the *voltage regulator* M_2, T_1 on the generator K_1. This increases the impedance of the coils S_7 and therefore tends to reduce the speed of the driving motor. As the speed now falls the current in the resonant circuit falls off and likewise that in the coil M_1. This permits the voltage held by the voltage regulator to increase, and therefore acts to reduce the motor supply line impedance and thus increase the speed. A given *mean voltage* is thus maintained in the control circuit by generator K_1, which depends upon the magnitude of the control current in M_1. This keeps the speed variation within exceedingly close limits.

Antenna Support

A standard tower for high-power stations is shown in Fig. 15. This is of the self-supporting type erected on a suitable concrete base. The antenna wires are suspended from the steel cross arm at the top. This method of antenna suspension lends itself admirably to the long narrow antenna which has been found most suitable for the Alexanderson system.

The antenna layout for a two-alternator unit high-power station using these towers is shown in Fig. 16 where two antenna wings of any desired length extend in opposite directions from the station house which is located at the center. With this construction the wings may be tuned to different wave lengths and each energized by a single alternator, thus permitting simultaneous transmission at two different wave lengths; or the two alternators may be joined in parallel to energize both wings at some selected wave length.

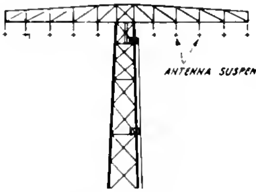


Fig. 15. Section Standard Tower to Support Alexanderson Multiple-tuned Antenna

PERFORMANCE AND OPERATION OF THE ALEXANDERSON SYSTEM

Multiple Tuned Antenna

The antennæ commonly used at high-power radio stations may be broadly classified into two types, viz., the long horizontal aerials which are suspended on comparatively low towers, and the vertical, fan or umbrella aerials which are generally supported at great heights. The flat-top antenna was adopted for long distance transmission because it was believed to have marked directional properties and would therefore provide maximum radiation in the direction desired and lesser degrees of signal intensity in all other directions.

Experiment has indicated, however, that this directional effect disappears at distances beyond 300 miles or so from the transmitter and thus the benefits of directional radiation are realized only in a limited area. *Beyond this* the flat-top antenna has been found to have comparatively high resistance. This may be said to be due to the long path through which part of the ground current has to pass to the far end of the antenna, which is a path of relatively high resistance. This resistance cannot be materially decreased by laying wires in the ground, for because of the inductive impedance of such long wires (at radio frequencies) a large percentage of the ground current will still pass through the earth. It is therefore evident that if the length of the ground path in a radiating system could be reduced, a considerable saving of power would be effected.

At any given wave length the radiation from an antenna has been found to be proportional to the square of the effective height and the square of the antennæ current. The exact relation is $W = \frac{1600\ h^2 i^2}{\lambda^2}$. This points to the desirability of a high antenna, but since the cost of building such a radiating system increases very rapidly with its height, the factor of economy requires that the money expended on a station be apportioned between the cost of the antenna, power apparatus, and maintenance in order to arrive at the lowest total cost for transmission over a given distance. It is obvious that if, by any means, the wasteful resistance of the long, low, flat-top antenna, that is, conductive losses, leakage through insulation, etc., could be reduced, and if its radiation properties still could be maintained, then assuming equal power inputs into the two systems, a station using a long, low and relatively cheap antenna could produce the same signal strength as that from a high and costly antenna.

The multiple-tuned antenna devised by Mr. Alexanderson brings about a marked decrease in the ground resistance of a flat-top aerial. His antenna can be compared to a station using a number of small antenna connected in parallel, the height of each of which is great compared with their horizontal dimensions. It follows from simple electrical principles that several antennæ in parallel will possess a lower joint resistance than a long antenna of the same radiating capacity. The result may be obtained from the Marconi flat antenna by bringing down leads from the flat top, at regular intervals, to the ground through appropriate tuning inductances. With this construction it will be seen that the antenna charging current has a much shorter path through the down leads than it had with the former design.

The improved efficiency of the multiple-tuned antenna has been amply demonstrated at the New Brunswick station where the resistance of the Marconi flat top has been reduced from 3.7 ohms to 0.5 ohm with the consequent saving of power pointed out on page 819.

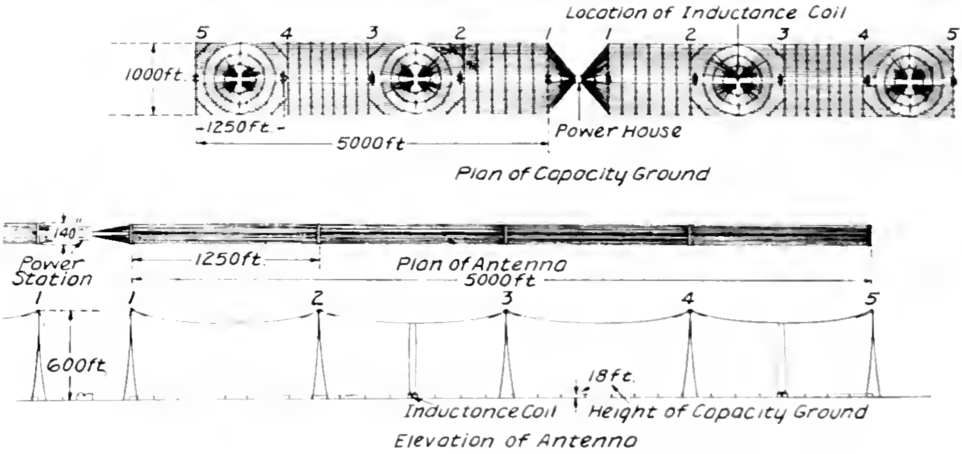


Fig. 16 Antenna Construction and Counterpoise for Typical 200-kw. Alternator Installation

Comparison of Radiating Qualities

The curves of Fig. 17 show the results of a series of experiments conducted between New Brunswick, N. J., and Schenectady, N. Y., with the object of comparing the relative signal audibilities ampere for ampere in the old *antenna with a single ground* and the Alexanderson *antenna with multiple grounds.* The results show quite conclusively that with the same current in a flat-top antenna and in a multiple-tuned antenna, substantially equal audibilities are obtained at the receiving station. However, the power required by the plain antenna for a given number of amperes is very much in excess of that fed to the multiple-tuned antenna for the same total current. Thus as the curve shows, to put a total of 70 amperes in the branches of the multiple-tuned antenna with six grounds, requires but 3 kw., whereas with the flat-top antenna and a single ground, 18½ kw. are required. This is, of course, a very small proportion of the total output available at New Brunswick. The values shown in the curve should not be taken as indicative of those used in daily operation.

Theoretical Comparisons

The points of distinction between the two types of antennæ may become evident from the following comparative analysis. Thus the *flat-top* antenna with single ground is shown in Fig. 18. The equivalent circuit resolved into lumped or concentrated values of inductance and capacitance is shown in Fig. 19. The schematic circuit of the Alexanderson antenna is that of Fig. 20 where L_1, L_2, L_3, L_4, L_5, L_6, are current paths between the flat-top and the earth. The inductance of each down lead is made six times the capacitive reactance of the flat top at the frequency of operation selected. The capacitive reactance of the flat top is thus neutralized at six places. The circuit is therefore the equivalent of *six independent radiators* operating in parallel.

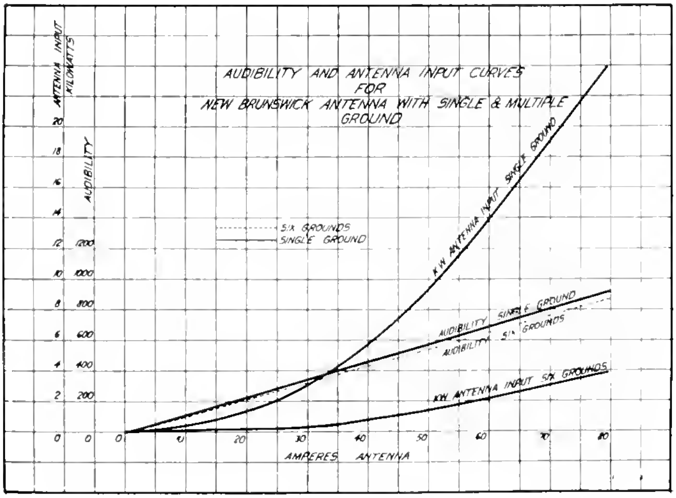
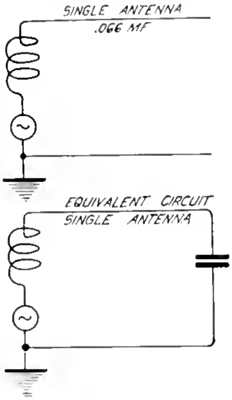


Fig. 17. Curves Showing Comparative Signal Audibilities Obtained from Alexanderson Multiple-tuned Antenna and the Open-ended Flat-top Antenna

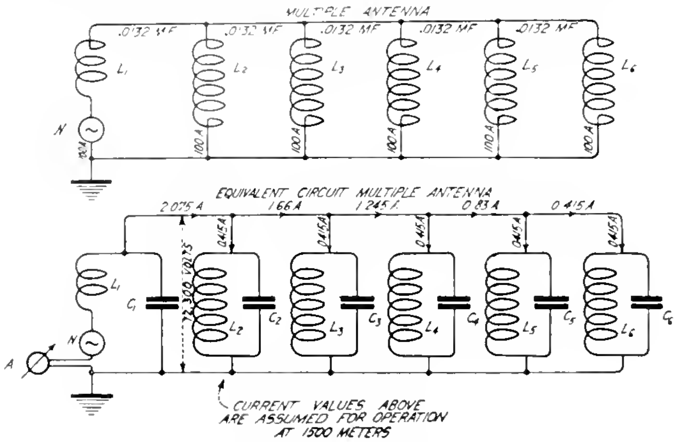
The equivalent circuit of Fig. 20 is that of Fig. 21, which is an artificial circuit comprising a number of parallel resonance circuits adjusted to the frequency of the alternator N. The branches $L_1\,C_1$, $L_2\,C_2$, $L_3\,C_3$, etc., which are in shunt to one another, are fed by the alternator. When each branch is tuned to the frequency of the alternator it will follow the well known laws for parallel resonance. A large current will flow back and forth between the inductance and the condenser, and the alternator will simply supply power to compensate the resistance losses of the circuits. These large currents are directly due to the high voltages maintained across the inductance and the capacity, when the circuit is tuned for resonance. These voltages may be calculated when the value of inductance or capacitance and the current flowing therein are known.



Figs. 18 and 19. Fundamental and Equivalent Circuits of Flat Top Antenna

If a parallel resonance circuit had no resistance, the conditions for parallel resonance would be strictly the same as for series resonance. These conditions are, however, very closely realized in the parallel circuit. In series resonance the e.m.f. on the condenser is equal and opposite to that of the coil and thus there is a large flow of current between the condenser and coil. There is also a large current flowing between the condenser and the coil in parallel resonance, but viewed from the standpoint of the feed or power supply circuit, the feed current is simply the difference of the currents in the condenser and the coil.

The resistance of a parallel resonance circuit, in radio, is often treated as a negligible quantity. This resistance, however, assumes considerable importance in the multiple antenna as it determines the power taken from the alternator. Thus if the wasteful resistance of each branch in a multiple-tuned antenna of six branches is 2.7 ohms, their joint resistance is 2.7/6=0.45 ohm (assuming equality) and it is this resistance *plus the radiation resistance of the entire antenna* system through which the alternator works.



Figs. 20 and 21. Fundamental and Equivalent Circuits of Alexanderson Multiple-tuned Antenna

It is obvious that the alternator can be connected as in Figs. 22, 23 and 24 with the same effect as shown in Fig. 21. Thus in Fig. 22 the alternator terminals are connected in shunt to the parallel resonance circuits. In Fig. 23 the alternator output is fed to the antenna through the inductive transformer P S. In Fig. 24 an auto-transformer connection is employed.

Multiple Tuning

In order to obtain resonance between the alternator and the several radiators of the multiple antennæ of Figs. 20 to 24, the joint reactance or impedance of the down leads L_1, L_2, L_3, L_4, L_5, L_6, must be chosen to equal the capacitive reactance of the flat top at some particular frequency. Hence with multiple tuning at six points the reactance of each down lead, for a given wave length (or frequency), must be six times the capacitive reactance of the whole antenna.

The method of computing the inductance in the down leads for a given wave length is as follows: We may take as a representative example the capacitance of the New Brunswick flat-top antenna, which is a long low aerial of the Marconi type. Its capacitance as measured is 0.066 mfd. Assume that operation is desired at 15,000 meters.

The oscillation frequency.

$$N = \frac{30,000,000}{15,000} = 20,000 \text{ cycles}$$

The capacitive reactance of 0.066 mfd. at 20,000 cycles

$$= \frac{1}{2\pi NC}$$

$$L = \frac{1}{6,2832 \times 20,000 \times 0.000,000,066}$$

$$= 120.5 \text{ ohms.}$$

The inductance required to neutralize the capacitive reactance is found from the relation

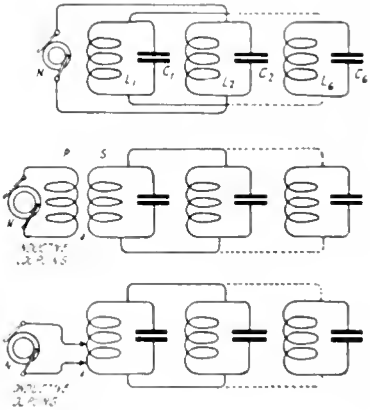
$$L = \frac{X}{2\pi N}$$

$$= \frac{120.5}{6.2832 \times 20,000}$$

$$= 0.000,958 = 0.958 \text{ millihenry}$$

The total inductance of each down lead should then be 6×0.958=5.74 millihenry; and the reactance of each down lead, 6×120.5=723 ohms.

Curves may be prepared to give the values of inductance required to tune the multiple antenna with various numbers of grounds at different wave lengths. If then the line coils be calibrated for different numbers of turns at different frequencies, it is a relatively simple matter to set these inductances to the correct value for any wave length. A series of curves showing the inductance required to operate the New Brunswick antenna at various wave lengths are given in Fig. 25. These are cited merely as illustrative examples.



Figs. 22, 23, and 24. Equivalent Circuits of Alexanderson Multiple tuned Antenna

Feed Ratio

The term "feed ratio," for convenience, has been applied to express the ratio of the total current in the six radiators of the multiple antenna to that flowing in the down lead of the branch to which the alternator is coupled. Assume that equal inductances are inserted in each down lead. With all other conditions equal, the same current will flow in each of the six circuits when supplied with energy at the frequency which produces resonance.

Thus if the ammeter A, when connected in series with the station down lead, Fig. 21, indicates 100 amperes (at resonance), and the same current is obtained in each branch, the total antenna current is 6×100 = 600 amperes.

The feed ratio is then equal to

$$\frac{\text{Total Current}}{\text{Current in the station down lead}}$$

which in this case $= \frac{600}{100} = 6:1.$

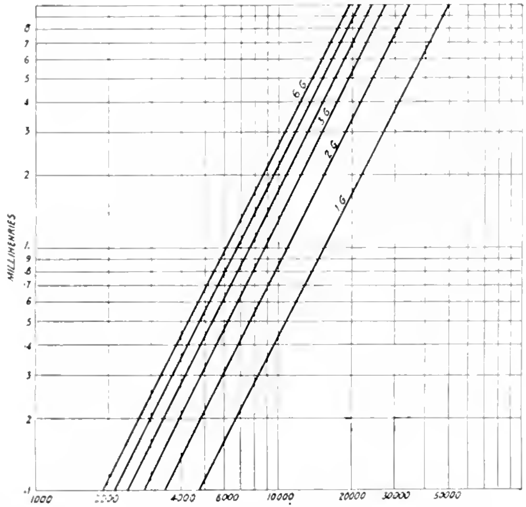


Fig. 25. Graphs Showing Inductance Required to Tune the Multiple-tuned Antenna at New Brunswick to Different Wave Lengths

It is of interest to note that the above feed ratio is only maintained when the inductance in all the down leads is equal. Assume for example, that the inductive reactance in the branch through which the energy is supplied is decreased and the frequency of the alternator is raised for resonance. Assume also that the feed ratio previous to this change is 6:1, the wave length 15,000 meters, the frequency 20,000 cycles, and the inductive reactance at each down lead 723 ohms. If now the wave length is reduced to 14,500 meters, the frequency increases to 20,700 cycles. This represents an increase of 700 cycles, which is 3½% of the original frequency of 20,000. It may be shown that 1% change in frequency requires a 2% change of inductance for resonance. Hence the inductive reactance in the circuit for 20,700 cycles is 100% − 7% or 93% of the value at 20,000 cycles; that is, 93%×723 = 672 ohms.

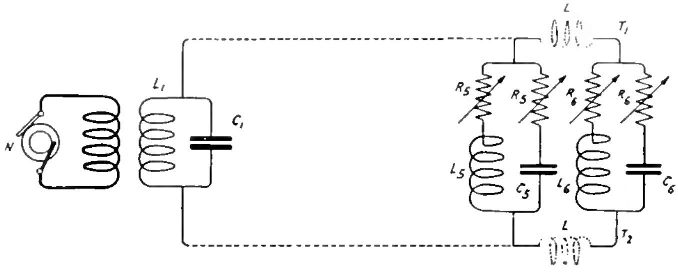


Fig. 26. Equivalent Circuit of Multiple-tuned Antenna for Computation of Phase Difference

Now if the five line coils to earth are left unchanged and since each has an impedance of 723 ohms at 20,000 cycles, or multiple impedance of 723/5 = 144.6 ohms, the impedance at 20,700 cycles obviously is 20,700/20,000×144.6 = 149.6 ohms. The new feed ratio is evidently proportional to the two impedances or 672/149.6 = 4.49:1.

The value of this determination lies in the fact that upon changing the wave length by tuning at the station down lead only, the new feed ratio can be computed, thus enabling the operator to ascertain the correct feed current necessary to maintain a given total value of antenna current.

Phase Difference

After viewing the physical aspects of the antenna layout in Fig. 19 it might appear that a disturbing phase angle would exist between the currents in the radiating circuit embracing the alternator, and those in the radiators placed at increasing distances from the power source. It can be shown, however, that for all practical purposes the currents in all of the down leads are substantially in phase. Thus in Fig. 26, the branch L_6 C_6, since it is a tuned circuit, operates at unity power-factor and therefore may be treated as a non-inductive resistance of a value equal to

$$\frac{L}{C\,R}\left(\text{or } \frac{1}{R\,(2\,\pi\,N^2\,C^2}\right)$$

If (at $\lambda = 15,000$ m.) $C_6 = 0.011$ mfd., $L_6 = 0.00574$ henry and $R_6 = 2.71$ ohms, then the impedance of any single branch to the e.m.f. impressed thereon is equal to

$$\frac{0.00574}{0.000,000,011 \times 2.71} = 192,500$$

ohms approximately.

Since the circuit $L_6\ C_6\ R_6$ is in resonance with the e.m.f. impressed at $T_1\ T_2$, the current in it is also in phase with the impressed e.m.f., which may be considered to operate through a non-inductive resistance of approximately 192,500 ohms.

Let now the inductance of the flat-top between the fifth and sixth branches be represented by L. The value of L is one-fifth of the total flat-top inductance without loading and in the case of the New Brunswick antenna is approximately 0.00013 henry. We then have in the last branch ($L_6\ C_6$) a current which lags behind the current flowing in $L_5\ C_5$ by the angle θ where

$$tan\ \theta = \frac{2\ \pi\ N\ L}{R}$$

$$= \frac{6.2832 \times 20,000 \times 0.00013}{192,500}$$

$$= \frac{1}{11,780} \text{ (which is negligibly small)}$$

The phase difference between the sixth and fifth radiator is thus negligible. The phase difference between the currents in branch $L_1\ C_1$ and branch $L_6\ C_6$ is five times as great, but it is still of negligible importance. The currents in the six radiators are therefore in substantial phase, the effect of the inductance between branches is negligible, and the charging currents which are measured currents in the down leads can be considered to be in phase. Since the length of the antenna is but a fraction of the wave length employed and the phase difference is slight compared with the wave length, no appreciable directive effects will be obtained.

Antenna Voltage

The antenna voltage may be computed when the equivalent capacitance of one section and the current in the station down lead, or the total antenna capacitance and total antenna current are known. This is obtained from the relation,

$$E = \frac{I}{2\ \pi\ N\ C}, \text{ or } E = \frac{I}{X}$$

where X is the capacitive reactance of the antenna at some frequency.

Using the values in the foregoing discussion, assume that I as measured by an ammeter in the station down lead is 100 amperes. Then since the capacity reactance to be neutralized by the down lead is one-sixth of the whole capacity or 0.011 mfd., then

$$E = \frac{100}{6.2832 \times 20,000 \times 0.000,000,011}$$

$$= 72,300 \text{ volts.}$$

A current of 100 amperes performs the same functions in each of the remaining branches, so that the whole antenna is maintained at a voltage of 72,300 volts by six separate currents, all in phase, of 100 amperes each. Since the multiple impedance of the six branches, as shown above, is 120.5 ohms, the total antenna current is $72,300/120.5 = 600$ amperes. This is merely a further proof of the assumption made at the outset.

As previously cited the branches of the multiple antenna follow (except in one respect explained below) the laws of parallel resonance circuits with lumped inductance and capacitance, and the current supplied to any branch by the main or power supply circuit is at any instant the algebraic sum of the currents in the capacity and the inductance. If there were no resistance in the branch antenna it would have infinite impedance to the power supply at resonance and no current would flow in the feed circuit after the initial e.m.f. has been applied. In the actual circuit there must, however, be some resistance and the energy for heating this resistance must be supplied by the alternator, that is, the alternator makes good this loss of energy.

The branch circuit of Fig. 26 at $N = 20,000$ cycles, $C = 0.011$ mfd., $L = 0.00574$ henry and $R = 2.71$ ohms, was shown to have an impedance of approximately 192,500 ohms. The antenna charging voltage at 100 amperes is approximately 72,300 volts. The energy current supplied by the power source to one branch is therefore $72,300/192,500 = 0.375$ ampere. The power supplied to each branch is $72,300 \times 0.375 = 27.1$ kilowatts and to the six branches (assuming equality throughout) $6 \times 27.1 = 162.6$ kilowatts.

The foregoing method of computation while correct for parallel resonance circuits with lumped inductance and capacitance from which feeble radiation takes place, requires some modification when the phenomena of radiation from the multiple antenna is considered. Thus, in the multiple antenna, the radiation resistance, whatever its value, may be said to be common to all six antennæ, whereas, the ground and coil resistances belong to the different antennæ individually. The combined circuit of the multiple antenna can therefore be represented by a radiation resistance common to all antennæ which is in series with a group of six wasteful resistances connected in multiple.

Thus assume now that the radiation resistance of the individual radiators in the multiple antenna (at $\lambda = 15{,}000$ meters) is 0.06 ohm and the ground and coil resistance of each antenna individually, 2.63 ohms. A current of 600 amperes works through 0.06 ohm radiation resistance, while 100 amperes flow through each of the 2.65 ohm resistances. The consumption of power in radiation is $600^2 \times 0.06 = 21.6$ kw., and in each branch $100^2 \times 2.65 = 26.5$ kw., or $6 \times 26.5 = 159$ kw., in the six branches. The total consumption is therefore 180.6 kw.

The point to be brought out is that if the radiation resistance of 0.06 ohms was added to the wasteful resistance in each radiator, and the energy consumption computed therefrom, the result would be too small. Thus assuming that the total resistance of each antenna was taken as $2.65 + 0.06$ or 2.71 ohms, the power in each radiator would be 27.1 kw. and in the six branches, 162 kw., but, as just shown, the correct value, when the radiation resistance is treated properly, is 180.6 kw.

The multiple antenna may be treated in another way. With a total power consumption of 180 kw., the power supplied to each antenna is 30 kw. and the energy current consumed by each oscillating circuit at 72,300 volts is 0.415 ampere. Thus while the total oscillating current is 600 amperes the energy current which flows horizontally from the power source is 2.075 amperes. This distribution is shown by the arrows, Fig. 21. In other words, the energy fed to the system by the first tuning coil in the form of 100 amperes at say 1800 volts is transformed in the first oscillating circuit to 72,300 volts (in the case of the particular problem cited) and distributed as in a transmission line from which 0.415 ampere at 72,300 volts is drawn at five places.

Multiple Resistance

When the inductance in each of the down leads has been adjusted to provide resonance with the alternator and the feed ratio has been determined, the multiple resistance of the Alexanderson antenna can be computed from simple measurements taken within the station house.

The process is as follows: Measure the current in the station down lead at resonance and then measure the open circuit voltage of the alternator (at the transformer secondary). The voltage divided by the current gives the "series" resistance of the antenna from the standpoint of a load on the alternator. This resistance is evidently the combined resistance of the alternator and the "series" resistance of the antenna system. The resistance of the alternator must be obtained from a separate measurement and subtracted from this value to give the "series" or load resistance of the antenna system.

Thus if the open circuit voltage of the alternator transformer is 2000 and the current in the down lead is 100 amperes, the resistance of the alternator plus the "series" antenna resistance is obtained from $R = E/I$ or $R = 2000/100 = 20$ ohms.

Assume that the alternator resistance (from the standpoint of the transformer secondary) as obtained from previous measurements is 2 ohms; then the series antenna resistance (considered as a load on the alternator) is $20 - 2 = 18$ ohms. The multiple resistance of the antenna is then equal to

$$\frac{\text{Series Resistance}}{\text{Square of the Feed Ratio}}$$

which in the problem above $= \frac{18}{6^2} = 0.5$ ohm.

Proof of this formula is given below.

A set of curves showing the comparative values of these two resistances at the New Brunswick station for wave lengths between 2500 and 9000 meters are shown in Fig. 27. Thus at $\lambda = 8600$ meters, the series resistance is 32.5 ohms and the multiple resistance 0.9 ohm. It is the latter value that must be used to compare the multiple tuned antenna with the common antenna with single ground. Curves showing the decrease of multiple resistance at New Brunswick with increase of the number of tuning points are given in Fig. 28. It is to be noted that the data for these curves and also that of Fig. 27 was taken without the capacitive ground and the current equalizers described on page 820.

In making measurements as above the transformer must be regarded in all respects as a part of the alternator, that is, the open circuit voltage of the transformer secondary, and the resistance of the alternator from the standpoint of the transformer secondary must be treated as the voltage and the resistance respectively of the alternator.

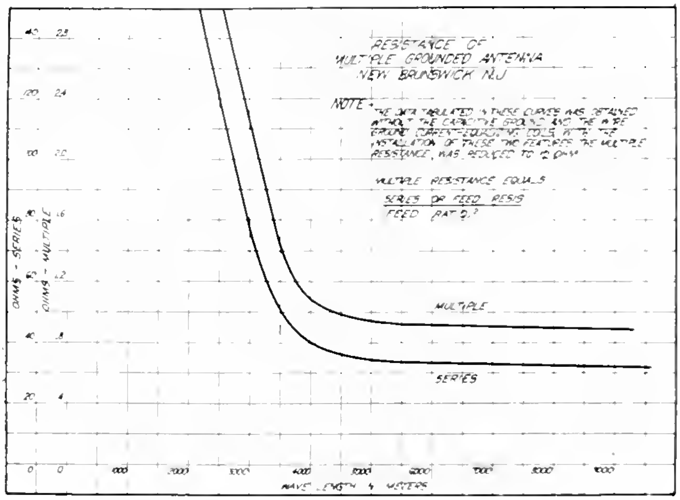


Fig. 27. Comparison of Multiple and "Series" Resistance of Alexanderson Multiple-tuned Antenna

A proof of the formula Multiple Resistance =

$$\frac{\text{Antenna Series Resistance}}{(\text{Feed Ratio})^2}$$

may be had from the following simple analysis. Reference should be made to the equivalent circuit, Fig. 29, which is assumed to be made up of a number of radiating systems in parallel, all tuned to resonance with the alternator X.

Let E = open circuit voltage of transformer secondary.

I = current in the station down lead at resonance.

R_a = the effective alternator resistance from the standpoint of the secondary.

r = the "series" resistance of the external or antenna circuit considered as a load on the alternator.

Then

$$E = I\ (R_a + r)$$

from which

$$r = \frac{E}{I} - R_a$$

(R_a is obtained from a separate measurement).

The power consumed in the "series" or load circuit external to the alternator is then,

$$W = I^2 r.$$

Consider now the resistance of the complete antenna from the standpoint of several radiators in parallel:

Let F = feed ratio.

Then FI = total antenna current in the several radiators.

Also let R_m = multiple resistance of the several radiators in parallel.

Then, the total energy in the several radiators is equal to the product of the multiple antenna resistance and the square of the total antenna current, or,

$$W = (FI)^2\ R_m.$$

This energy obviously is the same as that consumed in the circuit external to the alternator, which as shown before $= I^2 r$.

Hence

$$(F\ I)^2\ R_m = I^2 r$$

from which

$$R_m = \frac{F^2}{r}$$

That is, the antenna multiple resistance is equal to the "series" or "alternator load" resistance divided by the square of the feed ratio. Expressed in terms of all the factors involved

$$R_a = \frac{\frac{E}{I} - R_a}{F^2}$$

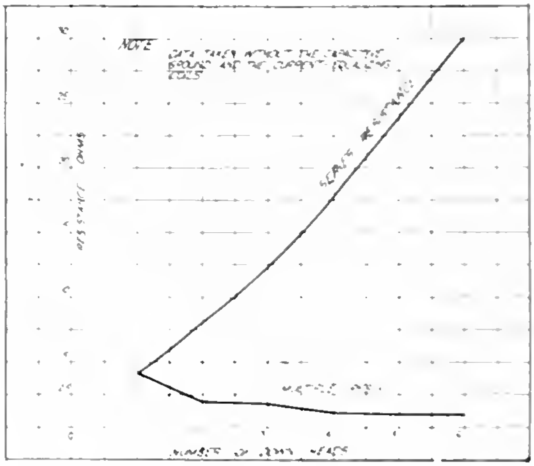


Fig. 28. Graphs Showing "Series" and Multiple Resistance, New Brunswick Antenna with Different Numbers of Down Leads

It is thus possible to compute the multiple resistance of the Alexanderson antenna from a few measurements made within the station with instruments used in ordinary power work.

Accurate measurement of the current in each down lead is essential, prior to making the foregoing measurements, as equal divisions of current, due to physical factors surrounding the station, cannot always be obtained. Only in this way can the true feed ratio be determined.

General

The multiple antenna can, under some conditions, be used to advantage with unequal currents through the down leads although, in general, equality of currents gives the lowest resistance. This is apparent from the fact that with unequal division some of the current has a longer path to travel than with equal division, making that particular branch of higher resistance. This also is obvious from the fact that if a given amount of current is to be passed through parallel conductors their joint resistance will be less if the division of current is in inverse proportion to each path.

Unequal division of current is an advantage under two conditions. First, the "series" or "load" resistance of the antenna can be adapted to the voltage of the alternator, if the alternator voltage cannot be adapted to the antenna resistance. Second, by allowing unequal division of current the wave length of the system can be changed in a much simpler manner than when equal division is maintained. Each change of wave length clearly requires a change in the inductance of all the down leads to maintain equal current division. If the inductance in all down leads is not the same, the current will divide itself in inverse proportion to the inductance of each path.

Further consideration will reveal that for wide changes of wave length it may be advisable to disconnect some of the down leads.

Calibration of Ground Inductances

In order to compute the amount of inductance that is necessary in each down lead at some given wave length, the capacity of the antenna must be measured by the ordinary processes and its capacitive impedance calculated as shown on page 826. This, of course, must be computed for each wave length. The capacitive impedance for any other wave length can be obtained from this value, since impedance is directly proportional to wave length. The inductive impedance of each down lead should then be adjusted, previous to tuning of the alternator, to a value six times the capacitive impedance of the antenna, if six tuning points are used. The inductance of the down leads to the tuning coils can be estimated roughly and the value allowed for when placing the tap on the ground coil.

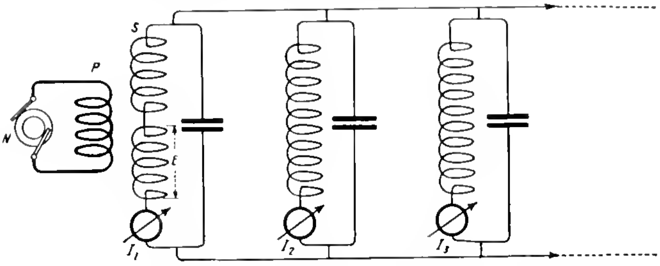


Fig. 29. Fundamental Circuit of Multiple-tuned Antenna for Determining the Distinction Between "Series" and Multiple Antenna Resistance

The inductance of the tuning coils should be computed for different numbers of turns at different wave lengths and plotted in a series of graphs as in Fig. 25. This will simplify the operation of obtaining the correct inductance for any wave length. In case there are no means at hand of calibrating the tuning coils, the required number of turns may be selected by trial. The supposed number of turns required can be estimated roughly and connected in all six down leads, but an allowance must be made in the case of the *station down lead* for the inductance of the alternator (or for the inductance of the secondary coil of the transformer). The speed of the alternator may then be varied until resonance is found. If the number of turns selected tune at too long a wave length too much inductance has been inserted in the down leads, and if it tunes at too short a wave length not enough inductance has been added.

Capacitive and Wire Ground System

A general description of the earthing system at the New Brunswick station has been given on page 820. In the early experiments it was found that when connection was made from the tap on the down lead inductance to the wire ground, the inner wires carried the greater proportion of current, due to the fact that they offered less impedance than the outer wires. A more equal current distribution was obtained by inserting the equalizing coils between the line inductances and the earth wires as shown in detail, Fig. 9. These coils are in inductive relation and are connected to pairs of the buried wires as there shown. The effect was to increase the impedance of the wires nearest the center and therefore to force practically the same amount of current in the outside wires as in the center wires. This lowered the antenna resistance from 0.9 to 0.7 ohm.

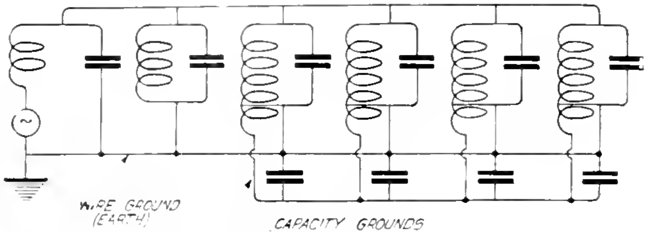


Fig. 30. Equivalent Circuit Multiple-tuned Antenna, New Brunswick Transoceanic Radio Station

A still better distribution of the earth currents was obtained by installing the counterpoise already shown in Fig. 10. As is shown schematically in detail A, Fig. 11, the section of the coil above the ground connection may, for purposes of illustration, be considered as positive with respect to the ground and the section below the point at which the ground is connected may be considered as negative with respect to the ground. The capacitive ground may therefore be considered as a combination of a forced and a tuned oscillation circuit. It has the effect of drawing the current from the ground more uniformly than with the wires lying on the ground or buried beneath the surface. The addition of the counterpoise in the case of the New Brunswick station reduced the antenna resistance from 0.7 to 0.5 ohm.

By suitable tuning, the total current through the down leads may be distributed between the capacitive ground and the wire ground in any desired ratio. If the wire ground is disconnected and the capacitive ground is tuned to take all the antenna current, the capacitive ground then takes on the characteristics of a tuned circuit. In this case the wire ground may be connected to the zero potential point on the coil (which may be found by experiment), under which condition it forms a path to earth for the lightning discharges with no other appreciable effect upon the system. An efficient ratio of current in the wire and capacitive ground is half of the total in each. The capacitive ground may be installed in separate units at each tuning point or may be connected together as a single unit as shown in Fig. 10.

Taking into consideration the counterpoise and buried wire ground, the equivalent circuit becomes that of Fig. 30.

It may be well to point out here that the design and construction of the grounding system for the multiple antenna may undergo considerable modifications in future high-power installations. It is probable that the system can be considerably simplified and yet provide a lower total antenna resistance than that obtained at the New Brunswick station.

Radiation Efficiency

An antenna with a single ground and effective height equal to that of the New Brunswick aerial can be assigned at the wave length of 15,000 meters, a radiation resistance of 0.06 ohm and a total resistance of 2.71 ohms. This is, in fact, about the values that would be obtained in practice. The radiation efficiency is therefore 0.06 2.71 or 2.21%.

As a multiple tuned antenna the resistance of the New Brunswick aerial is slightly under 0.5 ohm, and the radiation efficiency is 0.06 0.5 or 12%. The radiation efficiency of the multiple antenna at this wave length is therefore 12% against 2.21% in the individual antenna.

The radiation efficiency of the multiple antenna is very much higher at the wave length of 8000 meters which has been found the most suitable for radio telephony. Thus the radiation resistance of the New Brunswick antenna at 8000 meters is 0.2 ohm and the multiple resistance 0.6 ohm. The radiation efficiency is 0.2 0.6 or 33%.

It is important to note that the New Brunswick antenna may be operated at the wave length of 2500 meters, although its natural wave length as a flat-top antenna is 8000 meters. Operation at such short wave lengths obviously would not be possible with the antenna in its old form. The multiple resistance of the New Brunswick antenna at 2500 meters is 3 ohms, and the radiation resistance is 2.1 ohms. The radiation efficiency is therefore 2.1 3 or 70%; whereas with a single ground antenna the resistance at the same wave length would be about 5.4 ohms, and the radiation efficiency, 2.1/5.4 or 40%.

A curve showing the computed values of the radiation resistance of the New Brunswick antenna, at various wave lengths, is given in Fig. 31. The multiple resistance as actually measured at the wave lengths of 2500, 8000 and 13,600 meters is pointed out. The radiation efficiency at these three wave lengths should be noted, and also the comparative efficiencies of the common antenna with the single ground and the Alexanderson antenna with multiple grounds, at the wave length of 13,600 meters.

Although the radiation efficiency of all types of antennæ decreases with increases of wave length the smaller absorption obtained at the longer wave lengths offsets this decrease. Efficient wave lengths for transoceanic communication have been found to lie between 10,000 and 20,000 meters.

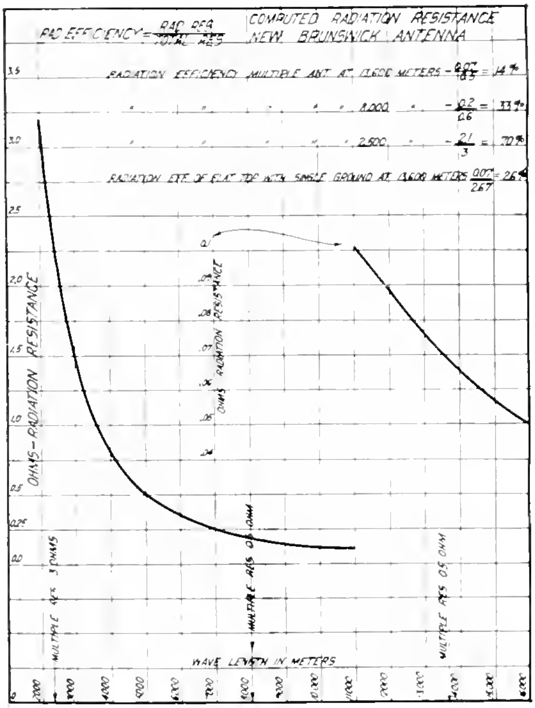


Fig. 31. Computed Radiation Resistance Multiple-tuned Antenna, New Brunswick Transoceanic Radio Station

Alexanderson Speed Regulator

As pointed out on page 818, in order to secure a constant output at the alternator and to prevent a diminution of the received current at the receiving station, the speed variation of the radio frequency alternator, when signalling, must be maintained within one tenth of one per cent. It is evident that the governing mechanism to maintain such constant speeds must come into such a critical state, at the motor speed to be maintained, as to cause a high percentage of change in itself for a low percentage change in speed.

The circuits of the Alexanderson speed regulator have been shown in the fundamental station circuit, Fig. 14. They are shown separately in Fig. 32. L_{10} is an armature coil which supplies a constant voltage at the frequency of the alternator. C_4 and P_5 are a capacity and an inductance which are tuned to a frequency slightly above that at which the alternator is to be worked. The coil S_6 is coupled closely to P_5, but not so closely as to affect appreciably the tuning of the resonant circuit. E is a rectifier (of the G-E Tungar or Mercury Arc type) which is shunted by a condenser C_4 of 0.16 mfd. capacity.

M_1 is an auxiliary control coil of the voltage regulator. The latter through the contacts T_1 acts to control the voltage of a generator K_1. C_5 is a condenser of 1 mfd. shunting the coil M_1. Care is taken that the circuit S_6, C_4, C_5, is considerably off resonance with the frequency of the circuit L_{10}, C_4, P_5, in order that the speed held by the regulator may be changed with the greatest simplicity.

N and O are variable impedances connected in the two phases of the power supply lines. They contain the d-c. control coils P_6 and the variable impedance coils S_7. R_3 is a liquid rheostat connected in the circuits of the rotor.

The generator K_1, which is driven by the motor M_3, is provided with field current from a d-c. source of constant voltage which is varied by the rheostat R_4.

In regard to the functions of the impedances N and O, it may be said, in general, that with zero current in the control coils P_6, their impedance becomes a maximum. If on the other hand the current through P_6 is such as to saturate the cores, their impedance becomes a minimum. Any intermediate value of d-c. control current will vary the a-c. impedance of the coils S_7 accordingly.

It will now be shown how the motor input may be varied inversely as the current fed into the coil M_1 from the resonance circuit brought from a coil in the armature. Since the circuit L_{10}, C_4, P_5 is resonant to a frequency slightly above that of the alternator, it will develop an increased current as the motor M speeds up. This will send a d-c. component through the coil M_1 which assists that flowing in coil M_2; this causes the voltage regulator proper to maintain a lower voltage at generator K_1. This in turn decreases the current through the coils P_6 and therefore increases the impedance in the power supply circuit, tending to decrease the speed of the motor. When the speed falls slightly the rectified component through the coil M_1 decreases, thus causing the voltage regulator to maintain a higher voltage on the generator K_1 and therefore increase the control current through P_6, and thus again decrease the impedance in the power supply circuit. A given mean current is thus maintained through the control coils P_6, the value of which is determined by the value of the current through M_1. The speed of the driving motor is thus held constant.

Theory of the Speed Control Regulator

A series of graphs showing the phenomena involved in the action of the speed regulator are shown in Figs. 33 and 34.

In curve A, Fig. 33, the "motor input" is plotted against "per cent variation of normal speed" with the normal line voltage and frequency and with the resistance R_3 (in the rotor circuit of the motor) properly adjusted to provide the required power. The flat part of the curve to d, indicates the motor input with maximum field on generator K, Fig. 32, which is the result obtained with zero current in the coil M_1 of the voltage regulator. It should be noted that the motor input with the speed less than 99.95%, normal is well above that required to drive the alternator with the sending key closed. The motor will therefore increase its speed up to point [illegible] where the

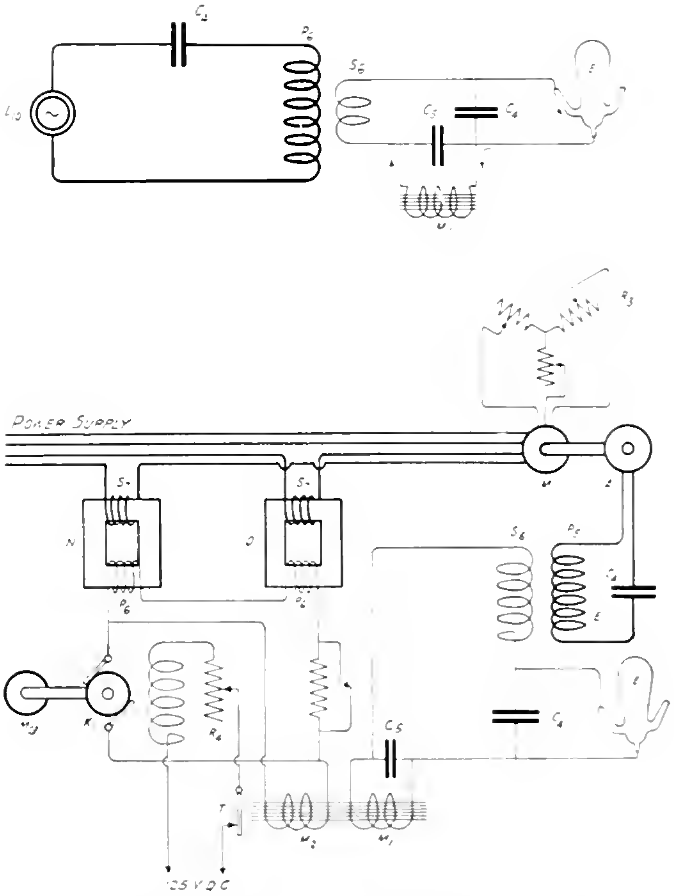


Fig. 32 Fundamental Circuits of Speed Regulator of the Alexanderson Radio Frequency Alternator System

speed regulator takes hold. From here the motor input drops off rapidly because of the increasing current in coil M_1, (of the voltage regulator) until its curve intersects curve B which represents the power required to drive the alternator at point e. Here the motor input and the power required to drive the alternator are equal and the speed will remain constant.

When the key is opened, the power required to drive the alternator drops off to that indicated by the dotted line and the surplus of power supplied to the motor speeds up the alternator until the motor input has dropped off to a value equal to that required to run the alternator light. This condition is represented at the intersection f at 100.05% normal speed.

Point g represents the point at which the speed regulator has decreased the motor input the maximum amount possible, with minimum field on generator K_1; and for any small increase in speed above this point, the input will be the same as at g. Since here the power required to drive the alternator is greater than that supplied to the motor, the motor will slow down until equality is obtained as at point f with the key open, or as at point e with the key closed. With the speed at point f when the key is closed, the speed will decrease to point e, and when the key is opened again, it will increase again to that represented by f. This speed variation being less than 0.1%, no inconvenience is suffered.

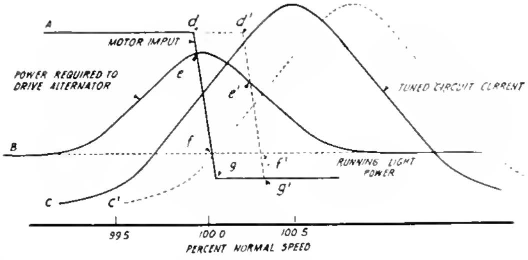


Fig. 33. Graphs Showing Certain Characteristics of the Alexanderson Speed Control System

If, however, the characteristics of the speed regulator are such that it lags in action, the speed may fall below e, before the regulator can effectively increase the power input. This will cause a greater variation of speed than would otherwise obtain. "Hunting" may then take place and result in a speed variation greatly in excess of the allowable variation for constant alternator output.

The speed held by the regulator at a given alternator frequency may be changed to some other value by retuning the circuit L_{10}, C_4 P_5 through variation of its capacity or inductance. This will change curve A, Fig. 33, which will then maintain the same relation to the curve C, thus providing a different speed at which the power required to drive the alternator will equal the motor input. These conditions are represented in dotted lines in Fig. 33, e' and f' representing the speeds held with the key closed and open respectively, and d' the point at which the speed regulator takes hold.

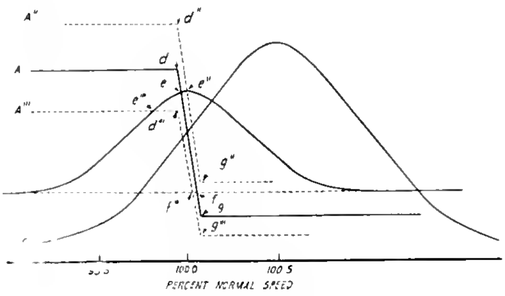


Fig. 34. Graphs Showing Certain Characteristics of the Alexanderson Speed Control System

To obtain proper regulation the speed regulator must be adjusted so the point e will be on the left or lower side of curve B, for on that side of the curve an increase in speed will incur an increase in load (as resonance in the alternator antenna circuit is approached), which automatically will tend to keep the speed down. On the other hand, if the point e lies on the high side of the curve B an increase in speed will decrease the load which will tend to cause still further increase of speed. This is prevented only by the fact that the speed regulator causes the motor input to fall off faster than the load falls off. Because of the fact that better regulation is secured on the low side of the curve, it is called the *stable side*, and the high side the *unstable side*.

If the power supplied to the driving motor is increased, such as by an increase in line voltage or frequency, or by a change in the setting of the motor circuits (such as a decrease in the rotor resistance of an induction motor) the curve for motor input will rise as to A'', Fig. 34. If the power supplied to the motor is decreased the curve of motor input will fall as to A'''.

The motor adjustment must be maintained so that point *g* on the motor input curve will be kept well below the power required to run the machine light (as shown by the dotted lines), and also point *d* must be kept well above the power required to drive the alternator at maximum tune of the antennæ. In case point *g* is not well below the power required to run the machine light a surge in line voltage or frequency might increase it to *g″* where it would be greater and thus cause the alternator to run away when the sending key is left open a short interval. Also if point *d* is not well above the power required to drive the alternator at maximum tune a slump in line voltage or frequency might decrease it to *d‴* and thus cause the machine to slow down to *e‴* when the key is closed, with a consequent falling off in signal strength and a swing in the pitch of the received note.

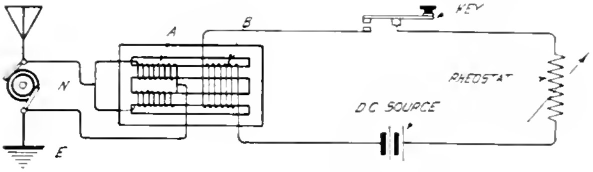


Fig 35. Magnetic Amplifier in Simplified Form

If adjustments are made so that the conditions outlined above are realized, no difficulties are encountered in maintaining a uniform speed at any desired alternator frequency.

Magnetic Amplifier

This device already has been described as a variable impedance connected across the terminals of the radio frequency alternator for the purpose of controlling the power input to the antenna circuit. Its characteristics are such that a relatively small current in an excitation winding is enabled to control many hundreds of amperes in the antenna system. The amplifier performs two functions: When the sending key proper is open the alternator is placed on short circuit and the antenna system detuned. The joint effect of these two phenomena is a reduction in antenna current to 9% of its normal value. When the sending key is closed, the alternator assumes substantially its normal voltage, the antenna system returns to a state of resonance and the alternator output flows into the antenna system.

The great advantage of the amplifier over other methods of modulation is that it gives a non-arcing control of the large currents required in high-power radio transmission and therefore permits rapid telegraph signalling. In fact, the amplifier has been operated experimentally at speeds in excess of 500 words per minute with perfect success.

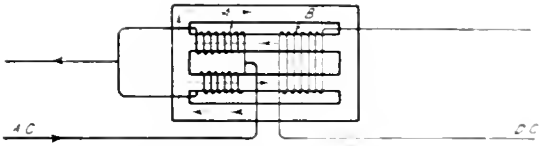


Fig 36 Diagram Showing Inductive Action of Amplifier Windings Upon the Control Winding

An idea of the fundamental actions of the amplifier can be gained from the circuit, Fig. 35, where the two windings designated by *A* and *B* are wound on a common iron core. The windings *A* are connected in parallel and shunted across the radio frequency alternator *N*. The coil *B* is an excitation winding which includes both the positive and the negative branches of the flux produced in the windings *A*, and hence, no voltages are induced in *B* by the radio frequency currents flowing in *A*. This is illustrated by the reference arrows in Fig. 36, which show the direction of flux in the amplifier coil at a particular half-cycle of the impressed current. It is clear that the tendency to induce an e.m.f. in one side of the control coil by one branch of *A* is counteracted by an opposing e.m.f. in the other branch.

It is apparent that should the flux produced in the core by the coil *B* be sufficient to saturate it fully, the impedance of windings

A would become that of a coil without an iron core. On the other hand, with zero current in the winding *B*, the core will be magnetized by the windings *A* and the impedance of *A* will thus become a maximum. In general, in order to obtain large flux variations in the windings *A*, the opposing ampere-turns in *B* must be approximately equal to those in *A*. Utilizing the alternator control circuit of Fig. 35, the problem is to obtain a minimum impedance in the windings *A* when the circuit to the excitation or control winding is closed and thus short circuit the alternator; and to obtain a maximum impedance when the control circuit is open, so that the alternator may assume within reasonable limitations its normal voltage. In this way the necessary variation of the antenna current for telegraphic signalling is secured.

The characteristics of a magnetic amplifier operated in a given instance as in Fig. 35 are shown in the curve *A*, Fig. 37, where antenna amperes are plotted against different currents in the excitation or control coil. The curve *A* shows incomplete modulation of the antenna current, but it should be mentioned that with this circuit it is possible to secure more complete modulation with stronger currents in the control winding.

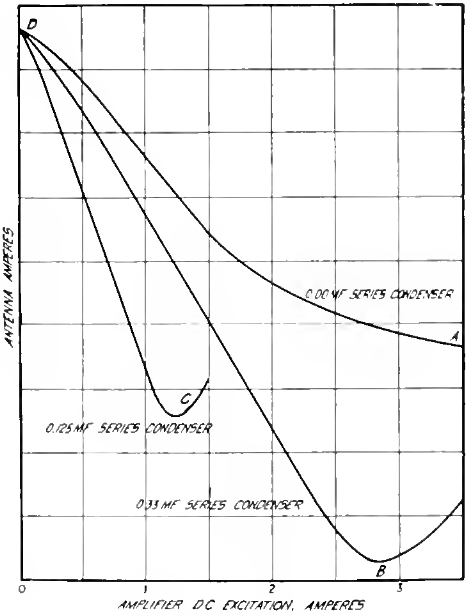


Fig. 37. Control Characteristics of the Magnetic Amplifier

A more sensitive control of the alternator output to the antenna system can be secured by the series condenser C_1 of Fig. 38, for by the use of this condenser a much smaller control current is required to effect a given variation in antenna current. If the capacitance of C_1 is chosen to neutralize the inductance of the windings *A* for some definite value of excitation current in the control coil *B*, the impedance of the circuit C_1, *A*, becomes a minimum. The impedance at any lower excitation is determined by the difference between the inductive reactance of the amplifier coil and the capacitive reactance of the series condenser. However, the smaller this difference the lower will be the amplifier excitation which gives minimum impedance and therefore minimum alternator voltage.

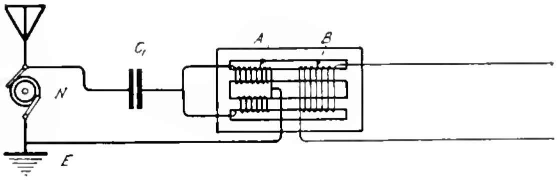


Fig. 38. Magnetic Amplifier with Series Condenser

The increase in sensitiveness obtained from the series condenser is well shown by the curves *B* and *C* of Fig. 37. The curve *A*, as already mentioned, shows the antenna currents for different control currents, without the series condenser C_1. The curve *B* shows the control obtained with a series condenser of 0.33 mfd. and the curve *C* with 0.125 mfd. The curve *B* shows almost complete modulation of the antenna current. Although it is a matter of principal importance in radio telephony it is pointed out here that the curve *B* indicates a linear proportionality between control and antenna currents almost throughout its range. This is an essential requirement for satisfactory speech reproduction in telephony. The excessive control indicated at the right of point *B* with the larger values of control current is a condition easily avoided in practice.

In the final form of the magnetic amplifier, the condensers C_2 and C_3 are inserted in the amplifier windings *A*, as shown in Fig. 39. Their function is as follows: If telegraphic currents were introduced into the control coil *B* with the condenser C_2 and C_3 absent, a short circuit current would flow between the branches of *A* without producing any flux variations to the radio frequency current. This, however, is prevented by choosing values of C_2 and C_3 to have a low reactance to the radio frequency currents and a high reactance to the audio frequency currents. These condensers have no appreciable affect upon the tuning of the amplifier circuit.

In the commercial set the constants of C_1 are selected for the particular frequency at which operation is to take place, and it is therefore only necessary to vary the control current in the coil B until the most complete modulation of the antenna current is obtained. In the event that the alternator is worked at some frequency different from that originally contemplated, a value of C_1 can be found for some definite value of control current in B, at which a minimum impedance in the amplifier coils is obtained.

Theoretical considerations of the circuits involved and actual test show that this drop in alternator impedance reduces the alternator voltage and detunes the antenna system to the extent that no more than 9% of the total normal current flows in the antenna system (when the current in the control winding is zero).

In explanation of the control current of 18 amperes (fed by a 250-volt source) in the case of a 200 kw. installation, it may be said that the same variation of alternator output might be obtained with much smaller values of control current. The larger value is purposely used to permit rapid signalling, that is, it permits the magnetic amplifier to function without lag.

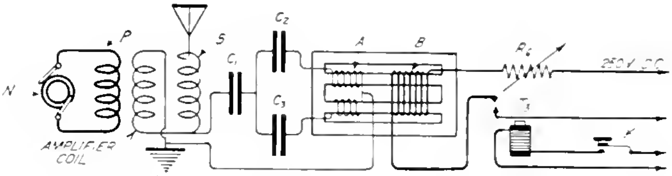


Fig. 39. Magnetic Amplifier with Series and Short-circuiting Condensers

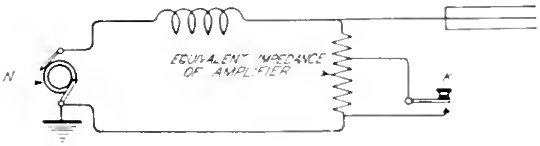


Fig. 40 Equivalent Circuit of Fig. 39

In summary of the foregoing the equivalent circuit of Fig. 39 will be seen to be that of Fig. 40 where the telegraphic key K when closed reduces the impedance of the amplifier and therefore the impedance of the amplifier-alternator circuit. This simultaneously detunes the antenna circuit and reduces the alternator voltage.

Characteristic curves showing the variation of alternator voltage, and change of alternator-amplifier impedance with different values of current in the excitation winding (for the standard 200 kw. set) are presented in Fig. 41. Thus with zero current in the control circuit the alternator open circuit voltage is 2000, and approximately 500 volts with 18 amperes in the control coil. Similarly with zero current in the control coil the alternator impedance is 67 ohms and it drops to 37 ohms with 18 amperes in the control coil.

Radio Telephony

Since the magnetic amplifier provides a linear control of the antenna current and functions with small values of control current, it is applicable as a modulation device in radio telephony. When telephonic currents of suitable amplitude are passed through the control coil B, Fig. 39, similar variations of the antenna current will be obtained, provided the amplifier characteristics are selected to give linear proportionality; otherwise inaccurate speech reproduction will result. It has been amply demonstrated in practice that such characteristics are readily obtained from the amplifier. Thus the curves B and C, Fig. 37, both show the desired linear proportionality between control currents and antenna currents, but the curve B shows the most complete modulation of the antenna input.

The perfection of control provided by the magnetic amplifier has been well demonstrated in a series of tests made on the 50-kw. Alexanderson alternator. With a telephonic control current varying in amplitude by 0.2 ampere, the antenna current was changed from 5.8 to 42.7 kw., a variation of almost 37 kilowatts.

An oscillographic record taken on the 200-kw. set at New Brunswick, N. J., with Secretary Daniels, of the U. S. Navy Department, at Washington, D. C., speaking to President Wilson aboard the U. S. S. *George Washington* at sea is shown on page 798, Fig. 7. The satisfactory operation provided by the amplifier is here again well demonstrated.

When the Alexanderson system is used in radio telephony, the control circuit of the amplifier is placed in the output circuit of a bank of vacuum valve amplifiers. The input circuits of the amplifier bank are controlled by three preceding steps of vacuum tube amplifiers, which in turn are actuated by the microphone.

In a number of experimental tests made with the telephone set at New Brunswick, the voice was projected to European stations. At distances up to 2500 miles very satisfactory results were obtained.

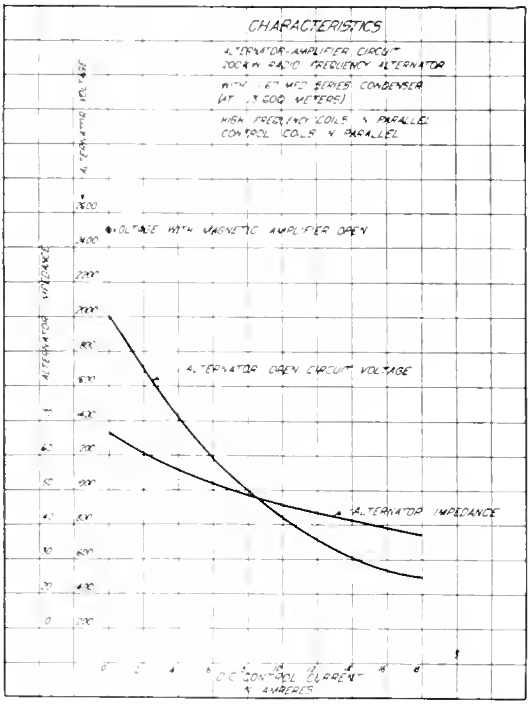


Fig. 41 Characteristic of Alternator-amplifier Circuits, 200-kw. Alexanderson Radio Frequency Alternator

Some Practical Operating Features of Tungsten Filament Electron Tubes

By W. C. White

Research Laboratory, General Electric Company

In describing the operating features of tungsten filament electron tubes, as affecting the limitations and possibilities of these tubes, the author analyzes the subject with respect to the filament, grid, plate or anode, bulb and glass, vacuum conditions, tube circuits and their operation, and power supply. The information contained is of value to all who have to deal with electron tubes, especially to those who are interested in making experimental set-ups or in changing in some way apparatus in which the tubes are a part.—Editor.

General

During the past few years a great deal has been published upon the theory and methods of using electron tubes, or vacuum tubes as they are often called, particularly in the field of radio communication.

In this article it is assumed that the reader has some knowledge about the principles and functions of vacuum tubes. It is written for those who have, or may have, occasion to operate them.

When these tubes are an integral part of a piece of apparatus, the designer has taken into account many of the limitations and possibilities of the tubes, so that some of their characteristics are not observable. However, when the tubes are used in some experimental set-up, or the apparatus of which they are a part is changed or used in some special way, unusual or unlooked for effect often occur. In this article some of these effects will be discussed and some of the more unusual characteristics of the tubes given.

The Filament

Since in most tubes of the kenotron and pliotron type a tungsten filament is the electron emitting cathode, some of the characteristics of a tungsten filament as they apply to these tubes will first be given.

As used in vacuum tubes the useful range of temperature for the filament is 2300 deg. K to 2700 deg. K.* At lower temperatures the electron emission is very low and at higher temperatures the life of the filament very short. In this range of temperature the resistance of the filament is approximately 13 to 16 times as high as at room temperature.

Owing to this changing resistance the relation between voltage and current is not linear. In the operating range given above, a 1 per cent change in current causes approximately a 1¾ per cent corresponding change in voltage, this change in voltage being slightly higher at the higher temperatures and lower at the lower temperatures. In vacuum tube work the two factors we are most interested in are electron emission and life to filament burn-out.

The electron emission varies rapidly with the temperature and in amount follows the curve shown in Fig. 1, where for different temperatures it is plotted as milliamperes emission per watt of energy used to heat the filament. This function is independent of filament length and diameter.

In the operating range a 1 per cent change of filament current makes approximately a 20 per cent change in electron emission. A 1 per cent change in filament voltage makes approximately an 11 per cent change in emission. These changes are slightly less at the higher temperatures and slightly greater at the lower temperatures.

The filaments of vacuum tubes are usually operated at approximately constant current or constant voltage. At constant current the emission increases considerably during life; it may reach double the initial value just before burn out. At constant voltage the emission may drop slightly or remain practically constant during life.

The life of a filament in a vacuum tube cannot be accurately predetermined by calculations based only on its dimensions and operating temperature.

If careful tests on a considerable number of tubes of a particular type have been made and an average life determined then the life of a tube of similar construction but with its filament of a different size, or operating at a different voltage, may be calculated with sufficient accuracy for practical purposes.

Tests on a large number of filaments have shown that on the average a filament burns out when a certain proportion of its mass has

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* These temperatures are expressed in the absolute or Kelvin scale which is degrees centigrade plus 273.

been evaporated. Therefore, for the same emission and temperature a larger diameter filament will have a longer life.

A 3 per cent increase or decrease in filament current will respectively halve or double the life of a filament. This shows the great gain in tube operating cost that may be effected by careful regulation of temperature. The corresponding figure for filament voltage change to halve or double life is approximately 5 per cent.

With a filament operating at constant voltage, the life is approximately three times longer than with operation at constant current. For this reason adjustment and maintenance of filament temperature by voltage is to be preferred. It has usually been the custom to adjust vacuum tube filaments by current readings on an ammeter. This was because in the early manufacture of tubes a more uniform emission was obtained by a current rating. However, modern methods of tungsten tube manufacture insure sufficient uniformity to allow voltage rating.

With operation at constant voltage the current will drop 5 to 10 per cent before burnout occurs. However, as has been pointed out, the emission varies only slightly and therefore the operating features vary but little.

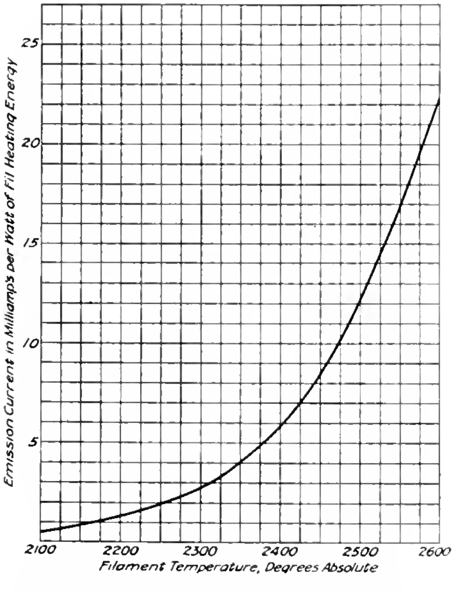

Fig. 1. Curve Showing Milliammeters of Electron Emission Per Watt of Energy Used to Heat the Pliotron Filament

There is a factor which is negligible on receiving and other low power tubes but which is an important factor on high voltage power tubes. This is the effect of the combination of the electron current of the plate circuit with the current in the filament causing a change in filament temperature and therefore a change in electron emission and life.

If the filament is operated from a 110 or 220 volt direct-current source with a series resistance in the circuit, the electron current will add to the filament current and increase its temperature if the negative of the plate voltage source is connected to the negative filament terminal. It will subtract from it if connected to the positive filament terminal. This effect will not be uniform over the entire length of the filament but will be variable being a maximum or minimum at the end of the filament to which the negative terminal of the plate source is connected.

In case the filament is operated from a few cells of storage battery or directly from a low voltage direct-current generator so that little or no series resistance is used, it is immaterial whether the return from the plate circuit is made to the positive or negative terminal of the filament; the heating current in the negative side of the filament is augmented by the same amount wherever the return connection is made.

The series filament resistance is essential to any alteration in the distribution of the flow of plate current through the filament circuit as a safety precaution. In any case the filament regulating resistance should be so connected as to cause the additive currents to flow through it while the differential current flows through the low resistance side of the heating circuit.

This result is always accomplished by connecting the return to the positive side of the filament, regardless of whether the regulating resistance is connected to the positive or to the negative terminal of the filament voltage source. It might also be accomplished by connecting the return between the negative terminal of the filament battery and the regulating resistance in the case where this rheostat is on the negative side of this battery.

When it is remembered that the effective plate current of a tube in the oscillating condition usually has a value between 2 per cent and 7 per cent of the filament current and that, as previously stated, a 3 per cent increase or decrease in filament current halves or doubles the life, the importance of this effect is apparent.

This filament heating effect of the plate current also has another important aspect.

If for any reason a high voltage, high power tube stops oscillating the plate current will usually rise to a value limited only by the filament emission. If the connection, as explained above, is such that the plate and filament currents are additive this abnormally large plate current will increase the temperature and therefore the emission, which in turn increases the plate current, this effect being accumulative, often destroying the filament in a few seconds.

If possible, alternating current should be used for filament excitation with the regulating resistance in the power side of the transformer and the return of the grid and plate circuits made to a center tap of the coil supplying the filament. This connection assures minimum disturbance in the plate and grid circuits from the frequency of the filament source.

The effective plate circuit current in this case divides evenly between the two filament legs. Also the direct-current electron current and the alternating-current filament current add at a 90 deg. displacement to give the combined heating current so the additive effect is much smaller. Take, for instance, a 1 ampere electron current to the plate and a 4 ampere filament current. If the latter were direct current the current at the hottest part of the filament would be 5 amperes, while if it were alternating current it would be only 4.13 amperes and equally distributed.

In operating tungsten filament pliotron tubes the following points should be kept in mind to insure the maximum possible life:

(1) Do not exceed the maximum rated filament current or voltage, and in all cases reduce the filament current to as low a value as possible consistent with satisfactory operation.

(2) In order to make possible the reduction of filament current mentioned, the best adjustment of the set is the one giving the desired result with the lowest value of plate current.

(3) It is poor policy to materially raise the filament temperature to obtain a slight increase of output.

Pliotron tubes are usually designed to operate in a certain position, that is, horizontally or vertically, with a certain side or end up. This preferred mounting position is usually specified for each type of tube. This is necessary because a hot tungsten filament has a tendency to sag very slowly and unless the tube is correctly mounted the filament may be so displaced as to change the electrical characteristics or even cause it to short circuit against the grid.

Severe vibration, particularly rapid sustained vibration, as from a high speed engine, greatly accelerates filament sagging. Under such conditions tubes should be spring suspended.

In a detector or amplifier circuit in which there is a telephone receiver directly in the plate circuit it will be noted that, with all other circuits closed, when the filament is switched on there will be no click in the telephone; when the filament is switched off there will be a decided click. This is accounted for by the fact that when cold there is no emission from the filament so that the current through the telephone rises slowly with the filament temperature. However, when the filament current is turned off the voltage drop along the filament changes to zero instantly before the filament has started to cool. This sudden disappearance of voltage drop along the filament changes its average voltage with respect to the grid, which of course, in turn causes a change in plate current and this produces the click in the telephone.

Assume a filament taking 20 volts to operate at normal temperature; suppose also that the plate voltage is low, about 50 volts, and the grid is connected to the negative end of the filament. The grid is therefore negative to the entire filament length with the exception of the extreme negative end. Under these conditions of an effective negative grid the plate current is greatly reduced. Now if the filament current is suddenly switched off the entire grid and filament are at the same potential so that there will be a sudden increase of plate current. This is demonstrated in a long filament tube operated as described, with the filament above rated temperature (so that emission will continue for a longer time after current is switched off and a current indicating instrument in the plate circuit. If the grid connection is changed to the positive end of the filament the plate current will make a sudden decrease on opening the filament circuit.

Occasionally while the filament is cold unusually severe vibration or mechanical shock may loosen a filament weld or break a lead or soldered connection in the base or stem of the tube, the resulting contact resistance being so high that no current flows at the low voltage of the filament supply. Occasionally in such cases a temporary emergency repair can be effected by connecting the filament in circuit from a 110 or 220-volt direct-current source with sufficient resistance to bring the current to about rated value and also including an inductance such as a transformer coil or field winding. If, then, the filament terminals are short circuited and the circuit suddenly opened at this point, the voltage set up by the inductive effect will often cause a slight welding together of the loose contact surfaces.

The Grid

In the construction of a transmitting tube and its base, the grid and filament elements are insulated from one another sufficiently for all normal conditions of operation. However, in experimental work unusual conditions may arise which will set up voltages between the grid and filament as high as ten times that normally present. It is impractical to build a tube to take care of this very abnormal voltage which only rarely occurs due to incorrect adjustment.

A spark gap should therefore be provided between the grid and filament terminals at or near the base of the tube. This gap should be set at $\frac{1}{32}$ in. to $\frac{1}{4}$ in. depending on the voltage employed and the number and type of tubes used. This precaution should be taken on any tube or group of tubes delivering over 50 watts of alternating-current energy or operating at a plate potential above 2000 volts.

In experimental or temporary wiring, great care should be taken not to confuse the wires leading to the plate and grid. A high positive potential applied to the grid which is close to the filament and of relatively small mass may overheat or even melt it.

Occasionally when a receiving or low power type of tube has been operated over a considerable period of time, a slight conducting deposit will form over the glass of the seal, giving an electrical leakage path between the grid and filament terminals. This will greatly impair the operation of the tube as an amplifier or detector. This condition can be removed by connecting the grid terminal and one filament terminal across a $\frac{1}{16}$ in. to $\frac{1}{8}$ in. spark gap of an induction coil. The thin conducting film will be disrupted in a few seconds by the high tension discharge.

Plate or Anode

Tubes are usually designed and constructed to give a safe continuous dissipation of a certain amount of energy. It is desirable that tubes should be able to operate for a long period of time with rated voltage on the filament, and with the plate and the grid at zero voltage. In the small transmitting tubes this is possible, but in the higher power high voltage tubes this involves too expensive a construction and fuses or circuit breakers are used in the plate circuit. However, any tube in order to be conservatively rated should be capable of dissipating continuously from the anode an amount of electron bombardment energy equal to the output. In other words, unless the conditions of operation are unusually favorable as regards protective devices and attendance, an efficiency of over 50 per cent between plate voltage source and output should not be relied upon.

The three metals used mostly as anode material are nickel, molybdenum and tungsten.

By good design and careful exhaust treatment, nickel can be operated at a just visible red heat, but operated in this way the tube has a very small factor of safety against overload due to a variety of causes.

Molybdenum is the most common anode material for pliotrons. With ordinary exhaust methods it will safely dissipate 10 times more energy per unit area than nickel. The melting point of molybdenum is about 2535 deg. C., while that of nickel is only about 1450 deg. C. Molybdenum as an anode can run continuously at a good red heat. This high melting point, together with the favorable mechanical properties of molybdenum, makes it almost an ideal anode metal.

Tungsten with its higher melting point and low rate of evaporation will dissipate safely even more energy than molybdenum, but its mechanical properties offer many difficulties.

It is altogether probable that, as vacuum tube engineering develops, one basis of the power rating of a tube will be a factor based on the material, area and form of the anode; that is, each metal will have a certain allowable energy dissipation in watts per square inch of exposed area. At the present time molybdenum anodes are usually designed for a total heat dissipation (filament watts and electron bombardment watts) of 30 to 50 watts per square inch of exposed area. These are conservative figures.

Bulb and Glass

In power tubes the glass bulb runs at a temperature of the order of 100 deg. C. or even more. In order to avoid strains in the glass which are liable to cause cracks, care should be taken to prevent liquids or cold metallic bodies from coming into contact with the hot bulb. Care should be taken also not to scratch the glass as it is possible thus to start a crack which may ruin the tube.

In the small types of power tubes all the lead-in wires are usually carried in through a common stem and seal. If this is the case, the plate voltage which may be used is limited by electrolysis in this seal. Hot glass is a conductor of electricity, and the conduction is accompanied by electrolysis, that is, the metallic elements in the glass appear at the negative pole and the negative ions (usually a gas in this case) at the positive pole.

This electrolysis ruins the seal, making it leak air and sometimes even cracking it. An early indication of this electrolysis which appears long before leakage occurs is a blackening of the grid leads in the glass of the seal just beyond the point of entrance of the lead into the glass from the vacuum side. This action takes place at the grid terminals as these are the most negative when the tube is oscillating. The black layer is, in most cases, lead deposited out from the glass. As stated, this is not a danger signal but merely an indication that electrolytic action has started. Therefore if small tubes of this type are operated considerably above their rated plate voltage the life is liable to be terminated by leakage of air due to electrolysis rather than filament burnout.

Vacuum Conditions

Glass contains gases and vapors which are liberated by heating in a vacuum. During the exhaust treatment of tube manufacture this process is carried on to as high a temperature as the glass will stand.

During operation of the tube it may be possible to so overload it, without proper ventilation around the bulb, that gas is liberated from the glass in sufficient quantities to affect its operation. Pliotron transmitting tubes are designed and rated to carry their normal load without artificial cooling, natural ventilation only being required. However, in the case of overload, or operation in a small, entirely enclosed space, or in very hot surroundings, an artificial cooling of the bulb by a current of air is beneficial in maintaining the vacuum.

In some of the larger types of transmitting tubes the plate or grid lead is brought out through a separate seal in the bulb, a small lead wire connecting to the electrode. Under ordinary conditions of operation this lead wire will be called upon to carry only a few milliamperes in the case of a grid lead or a fraction of one ampere in the case of a plate lead. However, under certain circuit conditions, one of which will be described later, very high frequency oscillations may occur (10,000,000 cycles per second or greater), in which case the capacity current to the grid or plate may reach 10 amperes or even more. One result of the abnormal current is to overheat portions of the tube that will not carry this very heavy current, such as the small lead wires mentioned. This overheating may cause liberation of gas.

If from some cause the gas pressure in a tube during operation rises to a sufficient value a glow will appear in the bulb as a result of the positive ionization. If this gas pressure is due to gases evolved from the metal or glass the glow will appear blue. If, however, it is due to leakage air it will appear purple or pink.

If air leakage into the tube has increased the pressure sufficiently to prevent a pure electron current, a dark blue or black oxide of tungsten from the filament will appear on the grid or plate. If a still greater air pressure is present the combination of hot tungsten and oxygen will cause the formation of a yellow oxide of tungsten which floats in the tube like a heavy vapor and which deposits on the bulb or electrodes.

Vacuum Tube Circuits and Their Operation

A great deal has been published on this phase of the subject, particularly receiving circuits, and therefore comments in this article will be confined almost entirely to oscillating circuits for supplying high frequency energy.

There is one point, however, in connection with the use of vacuum tubes as amplifiers of very small amounts of energy, such as radio signals, that does not seem to be as widely appreciated as it deserves. This fact is the effect of energy loss in the grid circuit which may arise from a variety of causes.

One of the characteristics of a vacuum tube which gives it such value as an amplifier is that its control can be effected by almost a pure potential effect. In other words, when operating under proper conditions for the amplification of audio frequency currents the grid current and therefore the energy absorbed is exceedingly small; it may even be considered zero for most cases

Still another way of expressing this fact is to say that the input impedance of the tube is very high, several megohms.

In the design of audio frequency amplifiers, using transformers between stages, advantage is taken of this fact and the available energy to be supplied the grid of each tube is stepped up by a high turn ratio to as high a voltage as possible. Therefore in order to realize the full amplification possible it is necessary to adjust the filament and grid voltage on the tube to give a sufficiently high input impedance, and to avoid any leakage resistance path between filament and grid or grid and plate in the circuit or at the terminals. A leakage of the order of one megohm will often considerably reduce amplification.

In the use of a tube as a power oscillator, there are a number of points which often cause trouble.

A type of oscillating circuit commonly used in experimental work is shown in Fig. 2 and some of these points will be taken up in connection with this circuit. If a direct-current ammeter is used to measure the input energy to the tube, it should be placed as shown at A_1, that is, between the source of the direct-current voltage and the by-pass condenser C_2. If placed in some part of the circuit carrying a considerable component of high frequency current it will indicate the average value instead of the effective value, and calculations of input energy based on its indication will be low. If a very high voltage circuit is being used so that a meter in the high side is dangerous, it may be placed in the negative high voltage lead, providing it is placed on the generator side of the by-pass capacity C_2.

It is advisable to use fuses or a circuit breaker in the high voltage circuit. They should be located in the circuit as near the generator as possible. If obtainable, a fuse rated at about double the normal plate current should be used.

In a capacity coupled type of circuit (the type shown in Fig 2) the lead wires from the plate and grid terminals of the tube should be short to the point of connection to C_1L_2 and CL_1 respectively. If these wires are a few feet in length, the tube is very liable to oscillate at a very high frequency that is independent of the constants L_1, L_2, and C, but determined by the inductance of the lead wires mentioned and the capacity between the electrodes inside the tube.

If for certain measurement work, it is quite necessary to keep the generated frequency very constant even though the voltage supply varies somewhat, a great deal can be accomplished in that direction by using a very high value of grid leak resistance R_1. This steadying effect is due to the fact that an increasing supply voltage decreases the impedance of the tube and also increases the output which, if R_1 is high, increases the negative grid voltage, which in turn tends to lower the impedance again towards its initial value.

With a decreasing voltage supply the reverse effects occur.

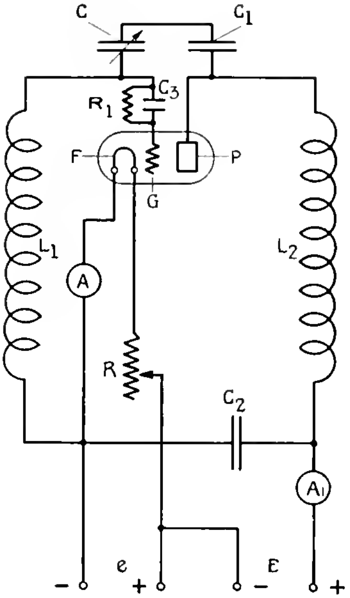

Fig. 2. Common Form of Oscillating Circuit for Experimental Work with Pliotrons

In capacity coupled circuits in general the coupling and oscillating circuit capacity C is connected across the terminals of the plate direct-current supply through the inductances L_1 and L_2. In case of a breakdown of condenser C this direct-current supply would be short circuited. It is therefore advisable to include a second condenser C_1 in series with C. It may be of any capacity, large compared with C_1, and should have a dielectric strength sufficient to insulate for the value of direct-current plate voltage used.

In any type of oscillating circuit employing a high power tube and particularly several in parallel the ultra high frequency oscillations mentioned are liable to occur. One good way of preventing these oscillations is to insert a very small inductance (a few microhenries) in the grid lead of one or more tubes as close to the grid terminal as possible.

In radio telephony the type of circuit most used includes a modulator tube, the function of which is to amplify the energy from the telephone transmitter and thus to cause an audio frequency variation of voltage in the plate circuit of the oscillator tube. Therefore the plate voltages and currents in the oscillator tube at certain parts of their cycle reach a peak value about double the peak value they reach in an oscillator circuit alone. Thus for satisfactory operation, the oscillator tube in such a circuit must have approximately double the emission necessary for a simple oscillator tube. Under these conditions the tube is also delivering double the energy output.

Power Supply

In the use of direct-current generators to supply plate potential to pliotron tubes operated as power oscillators there are several factors which are of importance.

The plate current in a three-element vacuum tube is controlled by the grid voltage. The plate current can be instantly brought to zero by a sufficiently negative grid voltage. For this reason the plate current may be brought to zero far more quickly than is possible by opening a switch of some sort.

This very sudden cessation of current causes high voltages to be built up across any inductances in circuit including the generator armature windings.

On voltages above 500 and power outputs above 50 watts, some sort of protective device to safely limit and discharge this voltage should be used. For this service aluminum cell lightning arresters are very suitable. They should be connected across the generator terminals.

Generators should not be over compounded to any great extent, because a breakdown in the tube or circuit will often cause a current heavier than normal to pass, which will tend to greatly overheat the anode. Over compounding will aggravate this effect.

For radio telegraphy, using beat reception, speed regulation of the driving engine or motor from no load to full load is of more importance than voltage regulation of the generator. This is so because in the generator the voltage decrease with load is due to armature drop, and this occurs instantly and so does not affect the tone of the received note. The drop in generator voltage, due to speed drop, takes place more slowly, however, and is appreciable in varying the tone of the received signal during a telegraphic dash. This effect is increased in small machines and at short wave lengths.

In radio telephony the commutator ripple in the generator may introduce a voltage variation which interferes with the clear reception of speech. This difficulty can, of course, be overcome by a "smoothing out" combination of inductance and capacity which, however, becomes large and expensive when the ripple voltage is high.

Birdseye View of the U. S. Naval Radio Station, Sitka, Alaska

The Production and Measurement of High Vacua

PART V. MANOMETERS FOR LOW GAS PRESSURES (Continued)

By Dr. Saul Dushman
Research Laboratory, General Electric Company

The present installment of this series is a continuation of Part IV and deals with the Knudsen, Pirani-Hale, and ionization gauges. The next installment will treat of physical-chemical methods of producing high-vacua and will appear in our January, 1921, issue.—Editor.

RADIOMETER GAUGES

Crookes' Radiometer

One of the first instruments to be used for detecting low gas pressures was the radiometer devised by Sir William Crookes in 1873. The instrument, which is described in all text-books, consists of a glass bulb in which a small vane or fly is mounted on a vertical axis. The vane has four arms of aluminum wire on which are attached four small plates of thin mica, coated on one side with lamp black. These plates are set so that their planes are parallel to the axis. If a source of light or heat is brought near the bulb, and the rarefaction is just right, the fly rotates, but at very low pressures the rotation practically ceases.

The theory of the device was apparently not very well understood for a long time, and attempts to use it as a gauge for low pressures yielded very unsatisfactory results. Dewar has stated the case for this instrument as follows:

"The radiometer may be used as an efficient instrument of research for the detection of small gas pressures. For quantitative measurements the torsion balance or bifilar suspension must be employed."[1]

Some years ago W. E. Ruder, of this laboratory, developed a method of using the radiometer for the measurement of the residual gas pressure in incandescent lamps. The following account was prepared by him at the request of the writer:

"It was found that when exhausted to the degree required in an incandescent lamp the radiometer could not be made to revolve, even in the brightest sunlight. In order to get a measure of the vacuum, the radiometer vanes were revolved rapidly by shaking the lamp and the time required to come to a complete stop was therefore a measure of the resistance offered to the vanes by the gas, together with the frictional resistance of the bearings. The latter quantity was found to be so small in most cases that a direct comparison of the rates of decay of speed of the vanes gave a satisfactory measure of the degree of evacuation. In this manner a complete set of curves was obtained which showed the change in vacuum in an incandescent lamp during its whole life and under a variety of conditions of exhaust. The chief objections to this method of measuring vacua were the difficulty in calibrating the radiometer and the difference in frictional resistance offered by different radiometers. For *comparative* results, however, the method was entirely satisfactory."

As a result of his investigations of the laws of heat transfer in gases at low pressures, Knudsen arrived at a clear explanation of the radiometer action and furthermore developed, along the same lines, an accurate gauge for the measurement of extremely low pressures.

According to Knudsen, there is a mechanical force exerted between two surfaces maintained at different temperatures in a gas at low pressure. This is due to the fact that the molecules striking the hotter surface rebound with a higher average kinetic energy than those that strike the colder surface. In the case of the radiometer the blackened surfaces absorb heat from the source of light and the molecules rebounding from the vanes are therefore at a higher temperature than those striking the walls of the bulb. Consequently a momentum is imparted to the vanes which tends to make them rotate.[2]

Knudsen Gauge

The principle of the gauge constructed by Knudsen[3] may be explained by referring to Fig. 42. Let us consider two parallel strips A and B placed at a distance apart which is *less* than the mean free path of the molecules. Let A be at the same temperature T as the residual gas, while B is maintained at a higher temperature T_1. On the side away from B, A will be bombarded by molecules having a mean velocity G, corresponding to the temperature T, as given by the equation

$$G = \sqrt{\frac{3\,RT}{M}}$$

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[1] Proc. Royal Soc., A, *79*, 529 (1907).

[2] Two recent papers by G. D. West (Phys. Soc. London, *32*, 166 and 222, 1920) deal rather fully with the theory of the radiometer, especially at medium pressures, and also with the forces acting on heated metal foil surfaces at low pressures.

[3] Ann. Phys., *32*, 809 (1910).

These molecules will of course rebound from A with the same velocity. However, on the side towards B, A will be bombarded by molecules coming from B, and having a higher velocity G_1 corresponding to the temperature T_1. Consequently A will receive momentum at a greater rate on the side towards B, than on the opposite side, and will therefore be repelled from B.

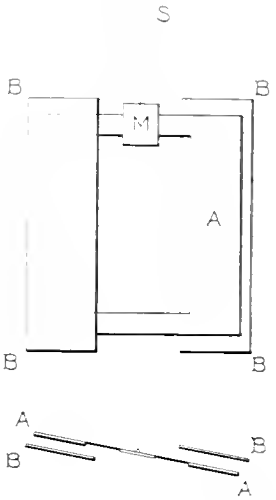

Fig. 42. Elementary Diagram of Knudsen Gauge

From theoretical considerations Knudsen has shown that the force of repulsion K per sq. cm. of the two parallel surfaces, when the distance between them is less than the mean free path, varies with the pressure and the temperatures T and T_1, according to the equation

$$K = \frac{P}{2}\sqrt{\frac{T_1}{T}} - 1 \qquad (30a)$$

For small differences of temperature, and for the purpose of pressure measurements, this equation may be written in the form[4]:

$$P = 4\,K\frac{T}{T_1 - T}\text{ dynes per sq. cm.} \qquad (30b)$$

In order to measure this force of repulsion, Knudsen uses the arrangement shown diagrammatically in Fig. 42. The strip A is replaced by a rectangular vane, cut out in the center and suspended by means of a fibre S. Two strips BB which can be heated are placed symmetrically on opposite sides of this vane, and the force of repulsion is then balanced by the torsion of the fibre. By means of the mirror M, the deflection can then be measured in the same manner as in the case of galvanometers.

For this arrangement, equation (30b) assumes the form:

$$P = \frac{4\pi^2 ID}{rA\,t^2 d}\cdot\frac{T}{T_1 - T}\text{ dynes per sq. cm.} \qquad (30c)$$

where

I = moment of inertia of the moving vane,
r = mean radius of the moving vane,
$2A$ = area of the vane A opposite each strip B,
t = period of vibration of the vane,
D = scale deflection, and
d = scale distance.

Since all these quantities can be measured directly, it follows that the device can be used as an *absolute manometer*, without the necessity of calibrating against any other gauge. It is also evident that the indications of this gauge must be independent of the gas to be measured.

In his first paper on this subject, Knudsen mentions several different forms of construction which may be used in making a gauge on the foregoing principle, but gives very few constructional details. One form which looks very simple is that shown in Fig. 43.

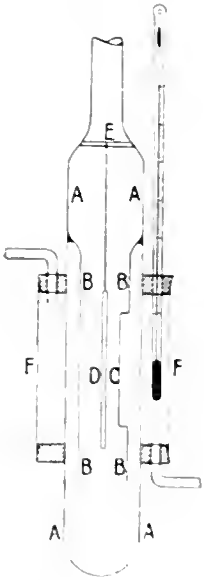

Fig. 43. One Construction of the Knudsen Gauge

AA is a glass tube about 1.4 cm diameter in which is sealed a narrow tube BB. The latter has a rectangular piece cut out at C, 0.14 cm. wide by 2.95 cm in length. A piece of mica D is suspended in front of this opening, by means of a fibre which is fastened at

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[4] A simple derivation of this and the following equation has been given by G. W. Todd, Phil. Mag. 38, 381 (1919).

E. The tube AA can be heated by means of an external water-jacket FF. As the temperature of the water in the latter is raised, the mica plate is repelled by the "hot" molecules traveling through the opening C, and the amount of deflection can be observed by means of a microscope.

Variations of this construction are described by Knudsen in a later paper[5], but very few details are given. E. V. Angerer[6] has described a Knudsen manometer which consists of a silvered mica vane between two electrically heated platinum strips, arranged as shown in Fig. 42. He states that pressures as low as 8×10^{-7} mm. of mercury could be measured with it.

The same type of design has also been used by J. W. Woodrow[7] on the one hand, and by J. E. Shrader and R. G. Sherwood[8] on the other.

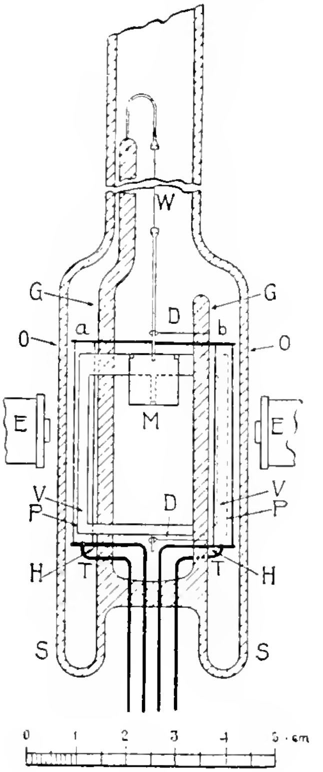

Fig. 44. Woodrow's Modification of the Knudsen Gauge

Woodrow's Modification of Knudsen Gauge

The following description of Woodrow's form of Knudsen gauge is quoted from the original publication:

"Several different gauges were constructed varying in sensitivity so as to be used at different pressures. A typical gauge is shown in Figs. 44 and 45 and the electrical circuits are given in Fig. 46. The glass rods GG served as supports for the metallic parts of the gauge. All the internal electrical connections and adjustments, with the exception of the final leveling, were made before the outer glass walls OO were sealed on at SS. The suspension W was a phosphor-bronze ribbon 50 mm. in length which had been obtained from W. G. Pye & Co. and was listed by them as No. 0000. The movable vane VV consisted of a rectangular frame of aluminum 0.076 mm. in thickness, the dimensions of the outer rectangle being 30 by 36 mm. and the inner 26 by 30 mm. The heating plates PP were platinum strips 4 mm. wide, 40 mm. long and 0.025 mm. thick. The deflections of the movable vane were obtained in the usual way by the reflection of a beam of light from the mirror M. Fig. 45 is a cross-sectional view through the middle of Fig. 44.

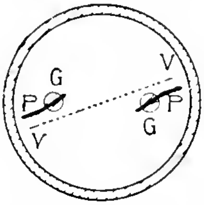

Fig. 45. Cross-sectional View Through the Middle of the Gauge Shown in Fig. 44

"All of the platinum connections were made by electric welding, as that was found much more satisfactory than the use of any kind of solder, especially when heated. After a little practice, it was possible to weld the thin platinum heating vanes to the heavy platinum wire so as to make a perfectly continuous contact throughout its width. The phosphor-bronze suspension was connected at both ends by threading through three small holes drilled into the flattened extremities of the platinum and aluminum wires respectively. The small loops DD were so placed that they supported the movable vane V except when the gauge was leveled for taking readings. This made the gauge readily portable and, by placing in the inverted position when connected to the molecular pump, the danger of the breaking of the suspension by vibration was eliminated. One gauge of medium sensitivity was constructed so as to be sufficiently steady to be used when connected directly to the molecular pump. Large glass tubing was employed in all the connecting portions of the apparatus.

"A small electromagnet, shown at E in Fig 44, was employed in bringing the moving

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[5] Ann. Phys. *44*, 525 (1914).
[6] Ann. Phys. *41*, 1 (1913).
[7] Phys. Rev. *4*, 491 (1914).
[8] Phys. Rev. *12*, 70 (1918).

vane to rest. This was found to be quite necessary in working with the most sensitive gauges, since in a very good vacuum the damping is so small that the vane will not settle down sufficiently for the taking of readings for some time after an accidental disturbance has set it vibrating. It should be noted that the electromagnet must have either an air core or one of good, soft Norway iron, for otherwise the residual magnetism will produce a false zero if the aluminum vane is at all magnetic, as was the case with the samples of metal investigated in this laboratory. Under these conditions it is obvious that the electromagnet should be used only for damping and that the exciting current should be shut off while making observations.

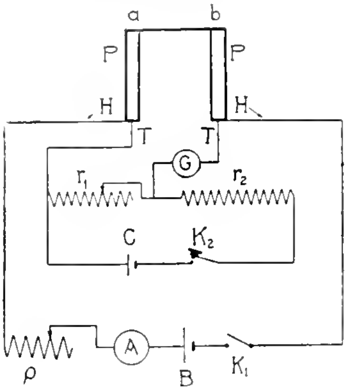

Fig. 46. Electrical Connections of the Gauge Shown in Fig. 44

"Several methods were tried for determining the temperature of the heating strips and that shown in diagram in Fig. 46 was finally settled upon as giving the most satisfactory results. The potentiometer leads TT were connected by electric welding to the very extremities of the platinum heating vanes PP. The heating current was regulated by the variable resistance ρ and its value was read on the ammeter A. The resistance r_2 was kept constant at 10,000 ohms and r_1 varied to obtain a balance of the sensitive galvanometer G. The potentiometer battery C consisted of a carefully calibrated Weston Standard Cell. This arrangement gave an accurate method of measuring the resistance of the platinum strips PP, plus the heavy platinum wire ab, the total cold resistance being 0.47 ohm. This cold resistance was determined by plotting the curve connecting resistance and heating current under a constant low pressure and extrapolating backward to the intersection with the axis of resistance. If the resistance is measured for small currents, the value at zero current, that is the cold resistance, can be determined very accurately. The temperature coefficient of resistance of the platinum, which contained a small amount of iridium, was carefully determined and was found to give a linear relation within the range of temperatures employed. The value of the coefficient was 2.35×10^{-3} ohms per deg. C. With this system one can determine the mean temperature of the heating strips with sufficient accuracy, the error for temperature difference of about 50 deg. C. being less than four per cent."

Woodrow also observes that in order to avoid electrical effects it was necessary to silver-coat the outside of the glass walls which were then grounded. Similarly the moving system was connected through the suspension to that terminal of the heating strips which was grounded.

"With the gauge whose dimensions are given above, the period of a complete oscillation was 10 sec., and the calculated moment of inertia of the moving vane was 0.074 gm. cm.² This gives for the pressure,

$$P = 2.9 \times 10^{-5} \frac{T}{T_1 - T} d \text{ (bars)}$$

$$= 2.2 \times 10^{-8} \frac{T}{T_1 - T} d \text{ (mm. of mercury)}$$

where d is the deflection in mm. on a scale at a distance of one meter from the mirror." Thus with a temperature difference of 100 deg. C., the gauge could be used to read pressures as low as 3×10^{-8} mm. of mercury.

Shrader and Sherwood's Modification of Knudsen Gauge

The construction used by Shrader and Sherwood differs in a few details from that used by Woodrow. In view of the importance of the Knudsen gauge for low pressure measurements, the description of this modification is worth quoting:

"The gauge is shown in Fig. 47. It is enclosed in a hard glass tube two inches in diameter and nine inches long. The heating strip aa is of platinum, 0.018 mm. thick and 7.5 mm. wide with a total length of 18 cm. It is folded at the top forming a cross piece and two parallel sides. The ends are brazed to 20 mil tungsten leading-in wires at the bottom. Fifteen mil tungsten wires b sealed into the glass-rod support serve as a spring support for the platinum strip. This allows accurate adjustment of the strip and sufficient tension is secured to keep the strip taut during heating. One of these wires is carried up the glass-rod support, sealed into it at *c*, leaving a free end *d* to serve for electrical connection of the moving vane to the heating strip. Connection is made by the wire pressing under tension against the tungsten wire *e* to which the suspension of the vane is fastened. Potential leads of fine platinum wires *ff* are welded to the strip about one centimeter from the ends and are brazed to tungsten sealing-in wires.

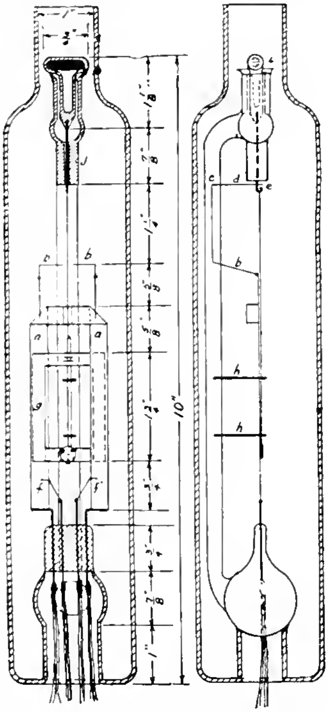

Fig. 47. **Shrader and Sherwood's Modification of the Knudsen Gauge**

"The movable rectangular vane *g* is made of aluminum 0.0076 cm. thick. A standard size adopted is 3.2 cm. by 4 cm. outside dimensions, the width of the vane being 0.5 cm. Because of liability of warping during heat treatment the vane is stiffened by an aluminum wire passing through slits at the top and a hole at the bottom into which the wire is hooked and fastened firmly. For portability, two copper wires *h* are sealed into the glass-rod support while the free end formed loops around the rod, these forming guides for the vane. The mirror is fastened at the bottom of the vane by leaving a small projection of the aluminum at the lower edge and cutting out small tongues from the material of the vane on either side. The mirror is laid in place and the projection and the two tongues are pressed closely over it, holding it securely.

"Silver mirrors were tried, but failed to withstand the heat treatment to which the gauge and system were subjected. Mirrors made by coating microscope cover glass with china decorators' platinum solution, followed by baking at 500 deg., solved this difficulty.

"The distance between the heating strip and the vane is adjusted from outside the case by magnetic control on a piece of soft iron *i* sealed into a glass stem to which the suspension is fastened.

"The suspension is 0.0005-inch tungsten wire. This is fastened to small aluminum hooks around which the wire is wrapped several times after which the hooks are pressed firmly together. This method is not difficult and holds the wire securely. A hook on the end of a tungsten wire sealed into a glass stem, the free end passing through a capillary rod *j* on the glass support, serves to hold the suspension. . . .

"A gauge such as has been described, using a 0.0005-inch tungsten suspension from 6 to 7 cm. long, has such a sensibility that a scale deflection of 1 mm. at a meter's distance with a temperature difference of 150 deg. C. between the heating strip and the movable vane indicates pressures of 1×10^{-8} to 5×10^{-8} mm. Hg. One gauge of other dimensions than those given above would indicate a pressure of 5×10^{-9} mm. Hg. under the same conditions."

The temperature of the heated strips is measured by substantially the same electrical method as that used by Woodrow.[9]

RESISTANCE MANOMETERS

At ordinary pressures the heat conductivity of gases, like the coefficient of viscosity, is independent of the pressure. However, as the pressure is decreased, a point is reached at which the heat conductivity begins to decrease with the pressure in a manner which is quite analogous to the phenomena observed in the case of viscosity measurements. Kundt and Warburg pointed out, as a result of their experiments on the coefficient of slip, that a similar phenomenon was to be expected in the case of heat conductance at low pressures. Subsequent experiments by Sutherland, Smoluchowski and Knudsen have shown that such is actually the case.

These experiments have led to interesting speculations upon the mechanism of the

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[9] L. F. Richardson (Phys. Soc. London, *31*, 270, 1919) has described a form of Knudsen gauge in which he balances the force of repulsion by means of a magnetic field. The instrument seems, however, quite complicated in construction.

A commercial form of Knudsen gauge brought out recently in Germany by H. Rieger is described briefly in *Engineering*, July 30, 1920.

heat transfer in gases between surfaces which are separated by a distance which is comparable with or less than the mean free path of the molecules, and the more detailed discussion of this subject will be taken up in a subsequent connection.

Fig. 48. Hale's Improved Form of Pirani Gauge

The important experimental fact from the present point of view is that at very low pressure the heat conductivity of gases depends upon the pressure. Warburg, Leithauser, and Johansen[10] applied this fact to the construction of a gauge by measuring the change in resistance of a small bolometer strip; while Voege[11] used a small thermocouple attached to a wire heated by a constant alternating current. The temperature of the wire as observed by means of the thermocouple was found to be a function of the pressure. Quite recently, W. Rohn[12] has developed a gauge on the same principle.

Pirani-Hale Gauge

Pirani pointed out that in order to construct a gauge based on the relation between the heat conducted from a wire and the pressure, three different schemes could be used.

1. The voltage on the wire is maintained constant, and the change in current is observed as a function of the pressure.
2. The resistance (and consequently the temperature) of the wire is maintained constant, and the energy input required for this is observed as a function of the pressure.
3. The current is maintained constant, and the change in voltage drop observed as a function of the pressure.

The first scheme was tried using an ordinary 110-volt tantalum-lamp. Better results were, however, obtained when the tantalum wire was clamped tightly to the anchor wires in order to keep constant the heat loss through the supports. With the improved instrument the two other methods were tried, using a Wheatstone bridge arrangement to measure the resistance of the wire, and the third one finally recommended as the most sensitive for use in pressure measurements.

While the principle of Pirani's gauge is thus extremely simple, the sensitiveness actually obtained by him was not very great, the lower limit of accuracy being around 0.1 bar.

An improved form of this gauge was constructed by Hale,[13] which is shown diagrammatically in Fig. 48. The following description is quoted from Hale's paper:

"A piece of pure platinum wire, 0.028 mm. in diameter and 150 mm. long, is mounted upon a glass stem carrying two radial glass supports near the top and three at the bottom. The wire is anchored to these radial supports by means of short pieces of platinum wire 0.052 mm. in diameter. The anchor is fused into the radial supports at one end, and the other end is made fast to the manometer wire either by an arc weld or by a tiny glass bead The leading-in wires at *L*, to which the ends of the manometer wire are welded, are of platinum, 0.31 mm. in diameter. All of the platinum wire employed in making the manometer was drawn from the same lot of larger wire and was assumed to be of uniform purity. The temperature coefficient of the manometer wire was found

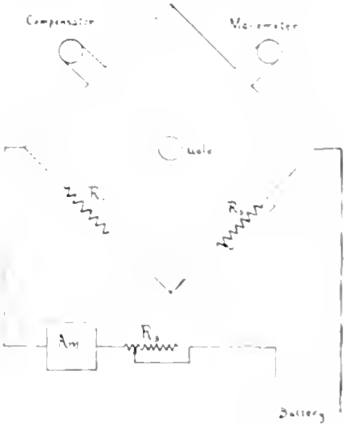

Fig. 49. A Diagram of the Electrical Connections of the Gauge Shown in Fig. 48

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[10] Ann. d. Phys. *24*, 25 (1907).
[11] Phys. Zeits. *7*, 498 (1908).
[12] Zeits. f. Elektrochem. *20*, 539 (1914).
[13] Trans. Am. Electrochem. Soc. *20*, 243 (1911).

to be 0.00376 per cent per degree. The platinum leading-in wires are joined to heavy copper leads (1.1 mm. diameter) by welded joints, and these joints are fused into the stem as in electric lamps. The stem is sealed into a tubular bulb 3.2 cm. in diameter and 11.4 cm. long. This size of bulb is easily obtained, since it is the size regularly used for 50-watt tubular lamps, such as are commonly employed for galvanometer illumination. At *S* is a tube by which the manometer is connected with the system whose pressure is being studied. The upper end of the stem *T* is considerably elongated to permit the complete immersion of the manometer in a constant temperature bath, whose temperature was approximately zero deg. C. This stem tube is made of sufficient length to leave 15 cm. of it above the level of the bath, a provision which we found to be necessary in order to avoid the condensation of atmospheric moisture upon the top of the tube and the leading-in wires during humid weather. For electrical insulation this tube is packed with purified dry asbestos wool."

A diagram of the electrical connections is shown in Fig. 49. A Wheatstone bridge arrangement was used for measuring the resistance changes; and in order to increase the sensitivity of the gauge, an exact duplicate was exhausted as carefully as possible to an extremely low pressure, sealed off, and inserted in one arm of the bridge as a compensator. Both the compensator and manometer were kept immersed in the constant temperature bath. R_1 was a manganin wire resistance of 925.6 ohms, and R_2 a decade plug box containing 10,000 ohms. The strength of the current, as indicated by the milliammeter *Am*, was maintained constant at 9.25×10^{-3} amp. by means of the battery and resistance R_3. This current was sufficient to raise the temperature of the wire in the manometer and compensator to about 125 deg. at the lowest pressures.

In calibrating the gauge against a McLeod gauge care had to be taken to keep mercury vapor out by means of a liquid-air trap inserted between the manometer and the remainder of the system. Fig. 50 shows calibration curves obtained with air and hydrogen at different pressures.

The difference is due to the higher conductivity of hydrogen, so that the indications of the manometer are dependent to a certain extent upon the nature of the gas used. Hale's measurements show that the lower limit of sensitivity for a gauge of this construction is about 0.00001 mm. (i.e. 0.0133 bar).

Recently some further measurements with a Hale gauge have been carried out by Misamichi So.[14]

The construction of gauge used by him differs in a few slight details from that of Hale. It was found that the sensitivity of the gauge is higher, the lower the temperature of the surrounding bath. At zero deg. C., and using a heating current of 0.03 amp. for a platinum wire 0.076 mm. in diameter, the sensitivity as measured by $\frac{dR}{dp}\cdot\frac{1}{R}$ was observed to be 1.38×10^{-3} per 1×10^{-4} mm. of mercury. Furthermore, varying the heat-

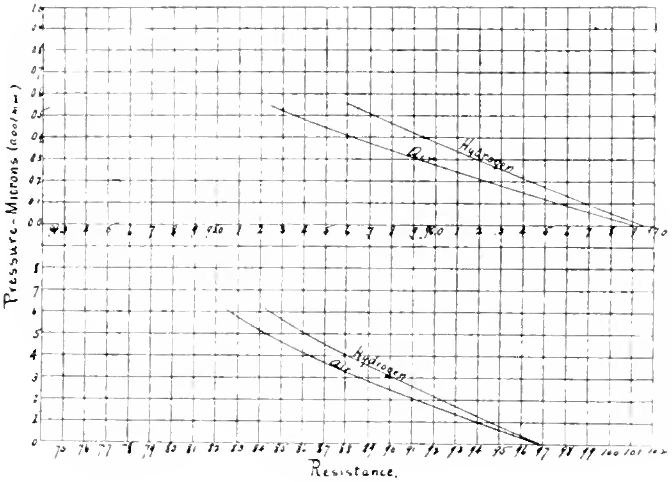

Fig. 50 Calibration Curves of the Gauge Shown in Fig. 48

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[14] Proc. Physico-Mathem. Soc. Japan, 3rd. Ser., *1*, 152 (1919).

ing current from 0.03 to 0.05 amp. was found to produce no change in sensitivity.

A hot-wire manometer based on the same principle has also been described by T. Tschudy.[15]

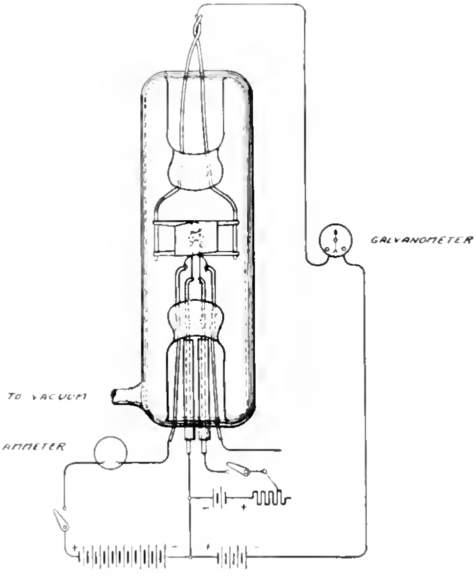

Fig. 51. Ionization Gauge and Connections

IONIZATION GAUGES

An electron stream passing through a gas will ionize the latter when the velocity of the electrons exceeds a certain minimum value. In this process, an electron is knocked out of the neutral atom by the incident electron, with the result that the residual portion of the atom is positively charged. The relation between the velocity u of the electrons and the voltage V required to produce this velocity is given by the equation:

$$\tfrac{1}{2}mu^2 = Ve$$

where

e = charge on electron
m = mass of electron.

So that corresponding to the ionizing velocity there exists for every gas a minimum ionizing potential. These range from one or two volts for the alkali metals to 25 volts for helium

The amount of ionization produced by a given electron current increases with the pressure and while this fact has been used as a qualitative guide for the detection of low gas pressures, it is only recently that attempts have been made to apply this principle to the construction of an actual measuring device.

O. E. Buckley[16] has published a short paper on the results obtained with a manometer of this type in which no details are given as to the actual construction. The gauge consists of three electrodes which are used as cathode (source of electrons), anode, and collector of positive ions respectively. As source of electrons a Wehnelt cathode or incandescent tungsten filament is used. The collector electrode is placed between the anode and cathode, and connected through a galvanometer to the negative terminal of a battery whose positive terminal is connected to the most negative end of the cathode. The anode potentials used range from 100 to 250 volts, while the magnitude of the electron current is varied from 0.2 to 2.0 milliamperes. At a pressure of 10^{-3} mm. the ionization current was observed to be about one-thousandth that of the electron current and proportionately less at lower pressures; so that with an electron current of 2.0 milliamperes, pressures below 10^{-6} mm. could be measured quite easily

According to Buckley "the exact forms of the electrode are not of great importance." However, subsequent experiments by Mr. Found and the writer[17] showed that certain designs are much better than others. A gauge consisting of three hair-pin filaments placed in parallel planes shows erratic effects at low pressures because of charges on the walls. Of the many types of construction tested, that shown in Fig. 51 was found to have the best characteristics for measuring low pressures. This illustration also shows the method of connecting up the electrodes

The gauge consists of two tungsten filaments, each wound in the form of a double spiral and mounted co-axially on a four-lead stem which is sealed into the upper end of a glass tube about 4 cm in diameter and 12 cm. long. The inner spiral is made of 5 turns of 0.125-mm tungsten wire wound on a 2.25-mm. mandrel The outer spiral is made of three turns of 0.125-mm tungsten wire wound on a 3.65-mm mandrel Surrounding the spirals is a molybdenum cylinder about 12 mm in diameter and 12 mm long which is supported on a two-lead stem at the lower end of the tube.

Before using the gauge for any measurements, it is of course absolutely essential that gases occluded in all metal parts and water vapor on the walls should be thoroughly eliminated. This can be accomplished in the manner already described[18]

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[15] Elekt. Zeits. 39, 235 (1918). Electrical World, 73, 137 (1919).

[16] Proc. Nat. Acad. Sciences, 2, 683 (1916).

[17] A brief account of these experiments was published in Phys. Rev. The complete paper on the subject will appear very shortly in the same journal.

[18] See Part II of this series of articles.

The best conditions for the operation of the gauge were found to be as follows:

(a) *For very low pressures (below 1 bar):* 250 volts on the anode, −20 volts on the collector cylinder, and a maximum electron current of 20 milliamperes. Under these conditions, 1×10^{-6} amp. positive ionization current corresponds to 0.0132 bar argon.

(b) *For higher pressures (1 to 50 bars):* 125 volts on the anode, −20 volts on the collector cylinder, and an electron current of 0.5 milliampere. In this case, 1×10^{-6} amp. ionization current corresponds to 0.5 bar argon approximately.

Fig. 52 shows characteristic curves at different electron currents. The greater the electron current used, the lower the upper limit of pressure at which the linear relation is still valid.

It will be observed from these curves that at constant pressure the ionization current is not quite proportional to the electron current. For measuring a considerable range of pressures it is desirable to have this proportionality, since it is then possible to increase the electron current as the pressure is lowered and thus increase the sensitivity of the gauge. The following method of connection has been found to give a linear relationship between ionization and electron current and may therefore be used instead of the arrangement just described. The inner filament is used as collector, the outer filament as cathode and the cylinder as anode. With this connection the ionization current is practically independent of the anode voltage between 125 and 250 volts. The sensitivity is not quite as good as with the first method of connection, 1×10^{-6} amp. positive ionization corresponding to about 0.032 bar argon.

An interesting result which was found on studying the behavior of the gauge with different gases is that at constant pressure and with the same conditions as to anode voltage and electron current, the ionization current increases with the number of electrons in the molecule. Thus the number of electrons in an argon molecule (or atom) is 18, while in a mercury molecule (which is also monatomic) the number of electrons is 80. The ionization currents at constant pressure are found to be in approximately this ratio. Experiments with I_2 and H_2O showed that the ionization currents in these cases, as compared with that for argon at the same pressure (and same electron current) correspond to electronic numbers of 106 and 10 respectively, if that for argon is taken at 18. This generalization is apparently not quite true for H_2, He and Ne, and further investigation is necessary in these cases. For all ordinary cases, however, the calibration for nitrogen (14 electrons per molecule) may be used as a general guide to the value of the pressure.[19]

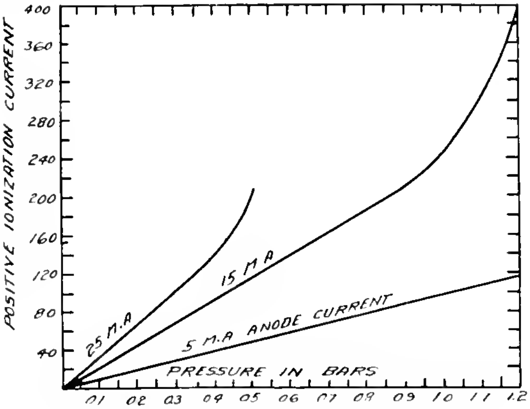

Fig. 52. Characteristic Curves of the Ionization Gauge

The ionization gauge as just described, has been found by the writer to be very useful in investigating the pressure changes in incandescent lamps and hot-cathode devices after sealing off from the pump. The ease of construction and simplicity of manipulation ought to make it a very useful device in high-vacuum technique.

Recently some results with a three-filament ionization gauge have been published by Misamichi So.[20] The ionization currents were, however, measured at constant cathode temperature, and the relation obtained between pressure and ionization current is not linear.

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[19] A preliminary account of this investigation has been published by Mr. Found and the writer in Phys. Rev. The more complete discussion will appear shortly in the same journal.

[20] Phys. Math. Soc. Jap. Proc. I. p. 76 (1919).

A Special Form of Phosphoroscope

By W. S. Andrews

Consulting Engineering Department, General Electric Company

In our March, 1917, issue the author described a form of phosphoroscope which he had developed for the visual observation of the phosphorescent and fluorescent light emitted by various compounds when excited by ultra-violet light. As this device, however, is not well adapted for making photographic spectrographs, he has since developed another form of phosphoroscope that fulfils this purpose admirably. This latter type of instrument is described in the following article.—Editor.

In using the new form of phosphoroscope, designed for spectrographic analysis, a paper ribbon is first prepared by coating it with the phosphorescent material reduced to a powder, a chemically neutral adhesive being employed. When perfectly dry, this coated ribbon is fastened around the periphery of a small flat-faced wheel that is attached to the shaft of an electric motor, Fig. 1. The exciting rays are preferably generated by a high-tension disruptive discharge between two iron terminals that are conveniently concealed and protected within a circular hood. This hood is located close to the periphery of the small flat-faced wheel, as shown in Figs. 1 and 3, and diametrically opposite to it is fixed a screen of sheet metal having a small window cut in it. This opening exposes a portion of the coated ribbon, see Fig. 2. It is evident that when the electric discharge occurs, its rays will excite the adjacent material on the rim of the wheel, and when the motor revolves, the excited portion will be carried around until it is opposite the window. This action being continuous, the phosphorescent light of the material to be photographed will shine continuously through the window; and if the collimator of the spectroscope is pointed into it, the spectrum of the phosphorescence will be seen through the eye piece of the telescope. When the camera attachment is used instead of the telescope, a spectrograph of the phosphorescence may be made in the usual way.

As the electric motor may be operated at a high speed, say 3000 to 4000 r.p.m., the phosphorescent light seen at the window in the screen is practically instantaneous, the time for decay being only about one hundredth of a second. In this way, phosphorescence of very brief period may be seen and photographed; also by varying the speed of the motor, its actual duration may be approximately determined.

Figs. 4, 5, and 6 show the spectrographs of various phosphorescent substances, these being arranged in pairs, with the spectrum of helium interpolated between them to indicate the phosphorescent regions in the spectrum produced by the different substances.

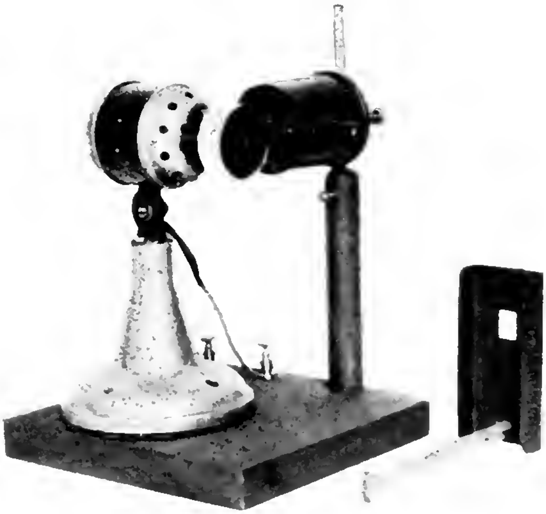

Fig. 1 Phosphoroscope Adapted for Use in Making Spectrographs. Shield Removed Showing Flat-faced Wheel with Phosphorescent Ribbon Attached

Fig. 2. Front View of Phosphoroscope with Shield in Place showing the Observation Window

Attention may be invited to the phosphorescence of calcined chemically pure (?) cadmium phosphate, Fig. 4, which appears snow-white to the unaided eye and which the spectrograph shows to cover the visible spectrum fairly well, being strongest in the yellow, blue, and violet, and weakest in the red and green. Students who have investigated phosphorescent spectra will recognize the striking peculiarity of this one.

In all other cases known to the writer the phosphorescent color of a given substance covers only some specific part of the visible spectrum or, in other words, its color to the unaided eye may appear in some shade or combination of red, yellow, green, or blue. To present a snow-white to the eye, means that all parts of the visible spectrum must be represented as seen in the spectrograph.

It is true that the blue-violet phosphorescence of Balmain's luminous paint (phosphorescent calcium sulphide) usually fades to a whitish color, but at this stage its luminescence is so weak that it can be seen only in perfect darkness after the eye has been rested; whereas, the phosphorescence of the pure cadmium phosphate shows a white light of great purity and considerable intensity. When the exciting light is cut off, the white phosphorescence gradually fades away to a reddish color before it disappears, pointing to the existence of an exceedingly minute amount of manganese in the compound.

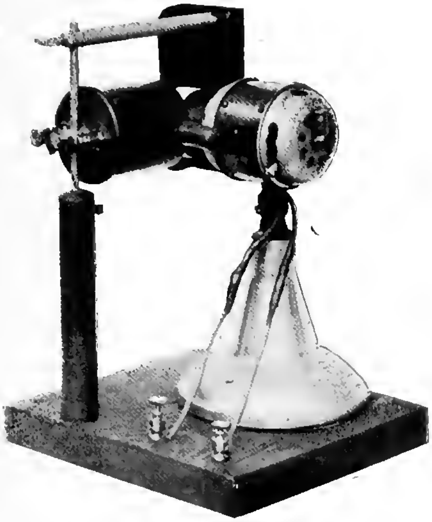

Fig. 3. Rear View of Phosphoroscope

It is well known that a white or nearly white phosphorescence can be obtained by the intimate mechanical mixture of phosphorescent substances that show respectively complementary colors; such for instance, as violet calcium sulphide and yellow zinc sulphide, or a similar effect may be produced by painting sections of a disk with suitable phosphorescent materials and then putting the disk into rapid rotation. The particularly interesting feature of the pure cadmium phosphate preparation, however, is that all the colors of the spectrum are apparently produced in its phosphorescent glow, so that by their combination a pure white light is produced.

Fig. 4

A—Fused C. P. cadmium phosphate; white phosphorescence.
B—Helium. Comparison spectrum.
C—Zinc sulphide; green phosphorescence.

Fig. 5

A—Fused cadmium phosphate plus manganese; orange phosphorescence.
B—Helium. Comparison spectrum.
C—Calcium sulphide, or Balmain's luminous paint; blue-violet phosphorescence.

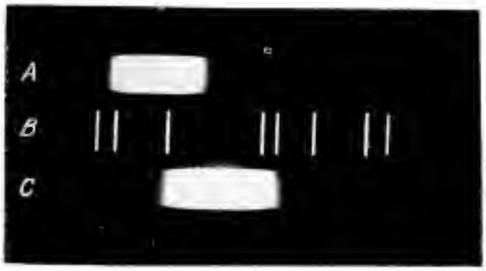

Fig. 6

A—Fused cadmium phosphate plus manganese; red phosphorescence.
B—Helium. Comparison spectrum.
C—Zinc silicate or willemite; green phosphorescence

The Cooper Hewitt Lamp

PART II. DEVELOPMENT AND APPLICATION

By L. J. Buttolph

Engineering Department, Cooper Hewitt Electric Company

This is the second of a series of three articles by the author on the theory and uses of the Cooper Hewitt lamp. Part I, "Theory and Operation," appeared in our September issue. In the following installment the author outlines the development and some of the applications of the lamp from 1901 to the present time. In Part III, the Cooper Hewitt quartz lamp and its characteristics will be described.—Editor.

In April, 1901, at a conversazione of the American Institute of Electrical Engineers, Nicola Tesla and Peter Cooper Hewitt divided the honors in the display of their inventions. The *Electrical World and Engineer* said editorially at that time: "But with all these things in its favor it is still a far cry from even the brilliant exhibits of the other evening to a lamp that will meet the every day requirements of commercial work." The development of a lamp meeting these requirements began with the two types exhibited in 1902 and shown in Fig. 1. *Engineering* of London said, "A lady's lips look purple, so at present no attempt is being made to utilize the light for domestic purposes, as feminine opposition would be too strong." The other problems to be solved were a simple starting device and operation on alternating current.

In 1903 the first industrial installation of two 200-watt lamps was placed in the com-

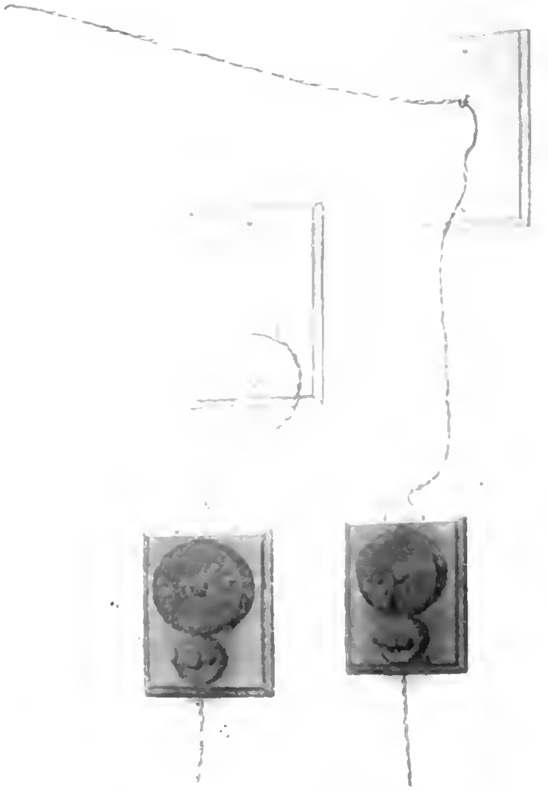

Fig. 1. Original Form of Cooper Hewitt Lamp Which Was First Displayed to the A.I.E.E. in 1901

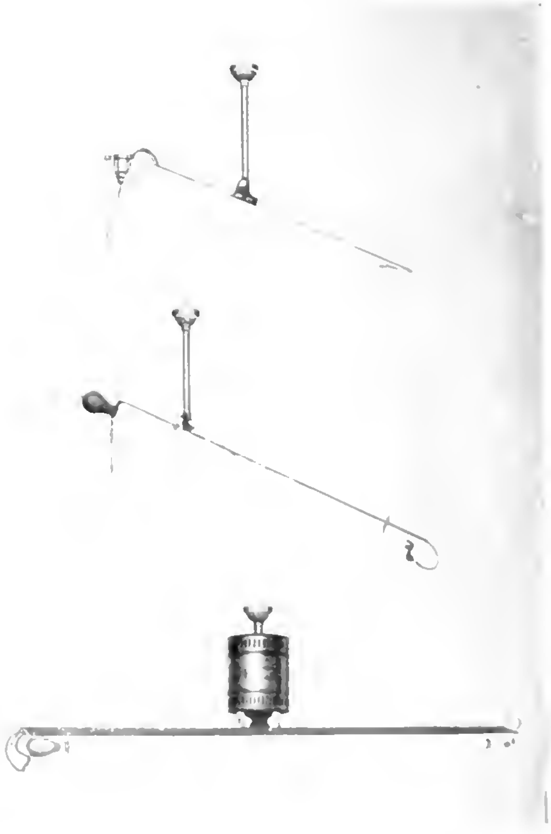

Fig. 2. Progress in the Construction of Cooper Hewitt Lamps from 1902 to 1907

posing room of the New York *Evening Post*. At that time very few features of the lamp had been standardized. Iron, mercury or graphite positive electrodes were variously used, while the condensing chamber was placed at the positive end in some cases and at the negative end in others. The lamps were started either by tilting the tube manually until a thin stream of mercury connected the electrode and then allowing the lamp to resume the normal position when the breaking started the arc, or by an oil immersed switch operating an inductance coil to produce a high voltage kick.

The progress from 1902 to 1907 is illustrated in Fig. 2. During that time the condensing chamber was standardized and iron adopted as a positive electrode material. The starting was made automatic by the development of a magnetic tilting device and of an automatic mercury switch or "shifter" for the high tension method. The latter method consists in short circuiting a small current through inductance in series with the lamp tube. This current is broken by the mercury switch or "shifter" which is magnetically operated by the inductance coil itself. The resulting induced high voltage is sufficient to start a cathode discharge which breaks down the initial high resistance by ionizing the traces of mercury vapor in the tube and thus forming the arc.

The development of a commercial form of alternating current lamp marked the period from 1907 to 1910. As developed then and operated now the alternating current lamp is a single phase Cooper Hewitt rectifier of highly specialized form. In common with all arc lamps it required a current regulating device which consisted of impedance instead of the resistance used in the direct current lamps. The resulting power factor of about 50 per cent was a problem for later solution. In 1910 increasing business forced the Cooper Hewitt Company to seek larger quarters at their present location in Hoboken, and from that

Fig. 3. Orthochromatic Cooper Hewitt Lamp

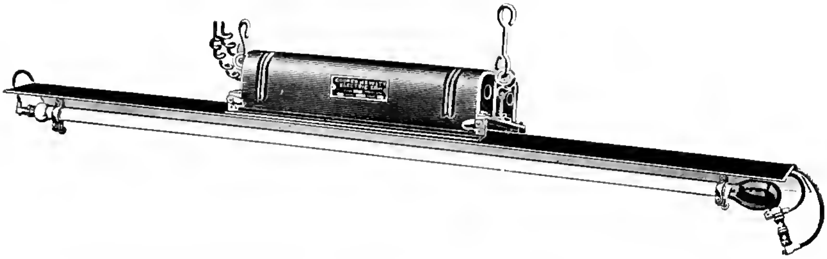

Fig. 4. Direct-current Cooper Hewitt Lamp, 385 Watts, 850 Mean Horizontal Candle-power

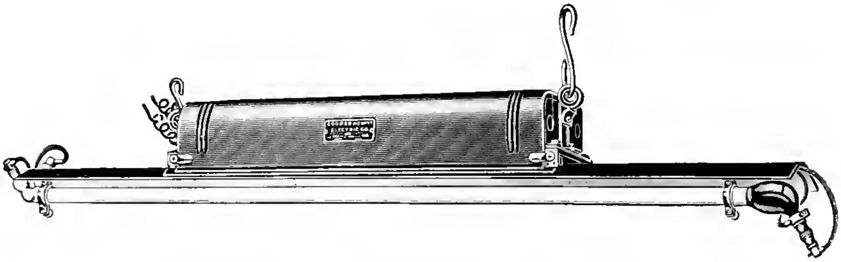

Fig. 5. Alternating-current Cooper Hewitt Lamp, 430 Watts, 950 Mean Horizontal Candle-power

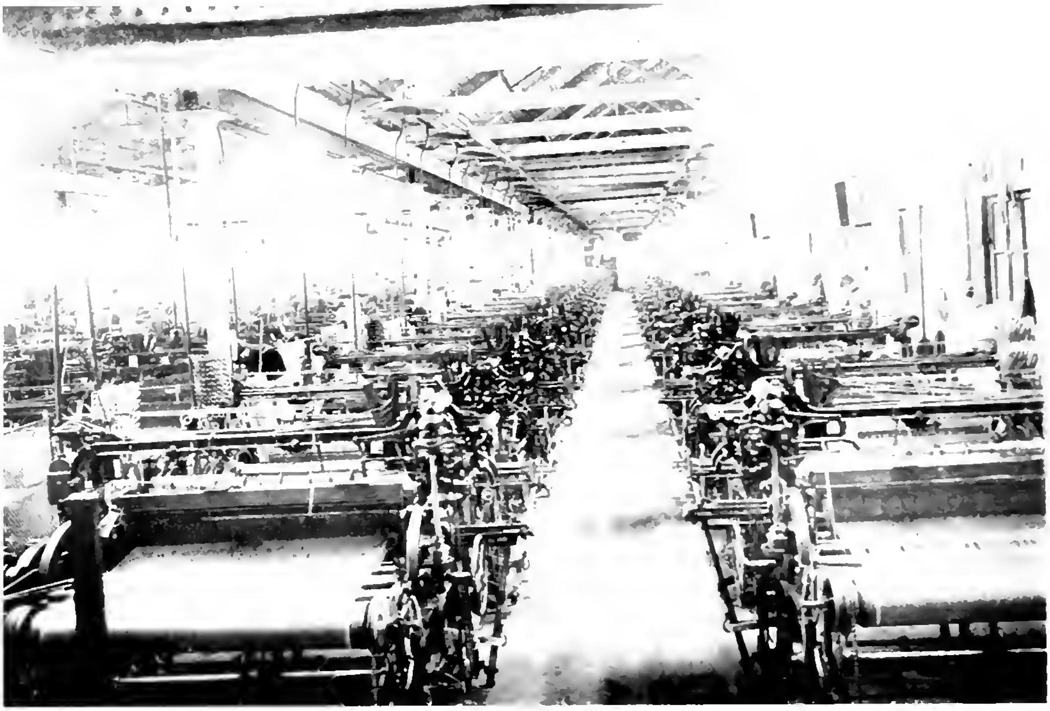

Fig. 6 Installation of Cooper Hewitt Lamps in a Textile Mill

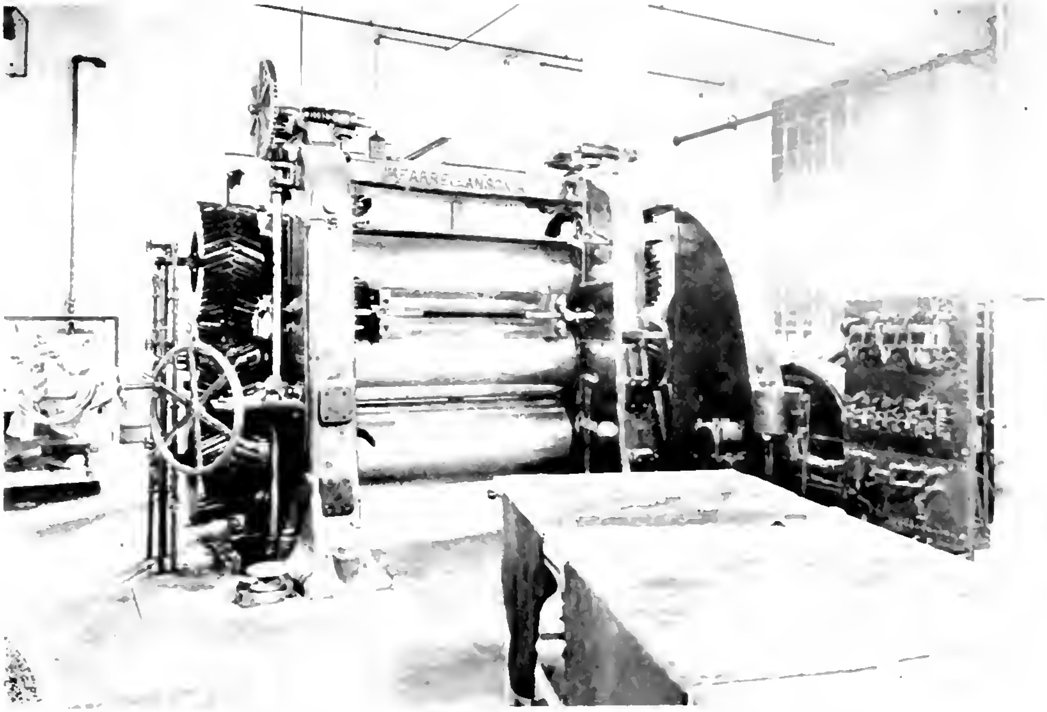

Fig. 7. Cooper Hewitt Lamps Illuminating Machinery Used in the Preparation of Rubber for Shoes

time production was concentrated on standardized outfits for industrial purposes.

A fluorescent reflector for the Cooper Hewitt lamp was put on the market at this time. It altered the quality of the light from the unit by giving off fluorescent light of an orange red color at a sacrifice of a corresponding amount of green and blue.

Among the few radical developments of the succeeding period was a so-called orthochromatic lamp whose arrangement is obvious from Fig. 3. It represented one of the last attempts to change the color of the Cooper Hewitt light. An installation of orthochromatic lamps was placed in the editorial rooms of the New York *World*, with satisfactory results from an æsthetic standpoint. The relatively small demand for the outfit and the fact that it was more novel than efficient led to its discontinuance. From the beginning extensive research has been done here and abroad to change the color of the arc itself by the addition of various substances but the attempts have availed little. At about the time that a solution of the problem began to seem impossible Cooper Hewitt engineers realized that a change in the nature of the color of the light would mean a sacrifice of what was proving to be one of its unique and valuable properties. In certain textile mills careful tests were made to determine the relative ease with which fine textile threads could be seen by direct north daylight and by Cooper Hewitt light. The results were strikingly in favor of the latter, and there was no question as to the relative value of color vision and of visual acuity for general industrial illumination.

During this period the Cooper Hewitt Electric Company also manufactured a quartz mercury arc, similar to the European type but incorporating the Cooper Hewitt idea of controlling the electrical characteristics of the lamp by a condensing chamber, as in the ordinary low pressure type of Cooper Hewitt lamp.

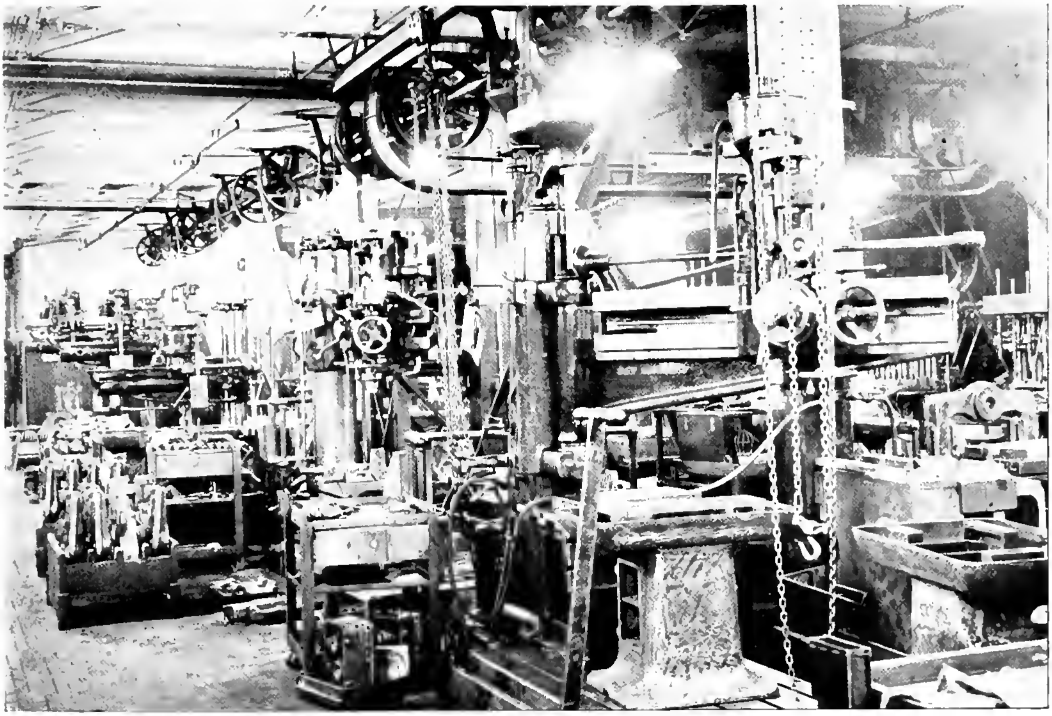

Fig. 8. A Machine Shop Illuminated with Cooper Hewitt Lamps

The first radical change in quartz burner design came with the development of a means of connecting quartz through intermediate steps of glasses of increasing coefficients of expansion to a glass fused directly to a tungsten electrode and forming with it a permanent vacuum tight seal. The result was the greatly simplified quartz burner now manufactured by the Cooper Hewitt Company.

A great many of the old type quartz burners are still in service for industrial illumination. The increasing importance of the mercury arc in quartz as a source of ultra-violet light is opening up a large field for the new type of burners. Among the present uses of these burners may be mentioned water sterilization, the treatment of skin diseases, paint and dye testing, and the acceleration of a great many general photochemical reactions.

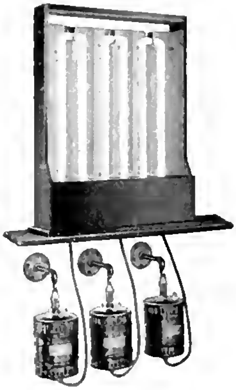
Fig. 9. Triple-tube Cooper Hewitt Outfit for Photographic Work

The shapes and sizes of Cooper Hewitt lamps have only been limited by the imaginations of the designers and by the glass blower's art. Sizes have ranged from a few watts to 3000 watts, while the standard tubes range at present from 200 watts to 1600 watts. A few of the standard outfits are illustrated. The larger tubes, some of them six feet long by three inches in diameter, are principally used in blue printing machines.

The problem of operating the alternating current lamp on a high power factor was finally solved in 1918 by the development of a means of substituting resistance for some of the reactance in the current-regulating impedance of the outfit. This is done by operating hot iron wire resistance units under conditions of high temperature coefficient, such that with change of current the falling voltage characteristic of the tube is counteracted by the rising voltage characteristic of the resistance. By this means the present alternating current outfit is given the high power factor of 85 per cent. In 1919 the development of glass working machinery was begun and with the co-operation of the Edison Lamp Works machines for performing the major tube making operations were placed on factory production in May, 1920.

Now that most of the states are supplementing their sanitary codes with lighting codes, a brief for good industrial illumination is superfluous. The codification of good industrial illumination has, however, been attended by difficulties of the same sort met with in the evaluation of the service of a skilled workman in the terms of physical strength, manual dexterity, mental traits, nervous temperament, etc.—things which do not readily lend themselves to tangible definition and to simple summation. Bearing on the problem is the fact that the early Cooper Hewitt installations did pioneer work in creating the present demand for a diffused general illumination of relatively high intensity and minimum glare and that the system is now established on its merits in spite of much "feminine" opposition. As a result of the slow but cumulative effects of this semi-educational work and of a remarkable record of service in facilitating the intensive production of war materials, the demand for Cooper Hewitt lamps has increased to such an extent that radical steps are being taken to treble production and to develop a unit system of manufacture providing for indefinite expansion.

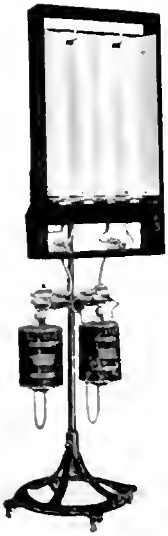
Fig 10. Two tube Cooper Hewitt Outfit for Photographic Work

The Cooper Hewitt idea in industrial illumination is: first, to equal average daylight illumination in point of luminosity, diffusion and apparent color; and second, to surpass daylight for special purposes in point of high visual acuity.

By average daylight illumination is meant that secured by the best practice in modern factory construction. Only such moderate intensities are advocated as have been found to give a maximum production under daylight conditions. Greater intensities than these are recognized as useless and in many cases as a positive menace to the comfort and efficiency of the workman. The good diffusion and monochromatic quality of the Cooper Hewitt light makes it unnecessary to increase the intensity on the working plane beyond a moderate normal to secure good distribution and proper visual acuity. A satisfactory uniform intensity of illumination as measured by any standard illuminometer or foot-candle meter represents quantity only and may be taken as fundamental in all lighting systems but unique in none. The high practical efficiency of the Cooper Hewitt light as rated in terms of quantity only—in terms of total lumens of light flux or in foot-candles of illumination on a working plane—is the result of three things. Its visible radiant energy is largely concentrated in light of those wave lengths to which the eye is most sensitive. Simple reflectors involving little loss by absorption can be used and because of the low intrinsic brilliancy no light is lost through the use of diffusing media, the Cooper Hewitt light being the only high power modern illuminant excepted by many of the state codes from the use of diffusing media. Thus it is, that, for the distribution, diffusion, low intrinsic brilliancy and minimum glare required in the modern industrial installation, the Cooper Hewitt light gives an excellent illumination in foot-candles on the working plane per watt of electrical energy.

Fig. 11. Installation of Cooper Hewitt Lamps in a Motion Picture Studio

Qualities unique in the Cooper Hewitt lamp and not to be directly expressed in foot-candles are the diffusion of its light, a minimum of glare, and high visual acuity. Because the source is in the form of a tube of light one inch in diameter and some 50-in. long, in the standard lamps, the diffusion of light is often literally equal to or better than that secured by daylight illumination while there is the added advantage of a simple control of the diffusion in those cases where shadows are an aid to stereoscopic or perspective vision. As is well known, too perfect diffusion is in such cases a disadvantage. The very slight shadows under machines and tables is the first and obvious result of this high diffusion. The real advantages of it are that a workman can do fine machine work without the glare of local lighting, that his own head and body does not cause confusing shadows, and that all parts of his machine are so well lighted.

Although the light from the Cooper Hewitt lamp is apparently blue white, it is as a matter of fact very largely monochromatic and of a yellow green color. A fundamental limitation of the human eye is its inability to focus in one and the same plane light of different wave lengths or color The result is the formation of multiple superimposed images giving the effect of a single image with a blurred outline; i.e., chromatic aberration.

Fig. 12. Cooper Hewitt Lamp for Photographic Portraiture

Fig. 13. Bank of Cooper Hewitt Lamps for Motion Picture Work

The intrinsic brilliancy of the Cooper Hewitt light is only some 15 foot-candles per square inch so that no diffusing media are needed. To an eye accustomed to the usual working intensity, there is no discomfort in looking directly at and into the luminous source. The construction of the standard reflectors provides sufficient lighting above the source to avoid glare from contrast with a black background. The size and shape of the source and its low brilliancy reduces the glare by reflection from polished surfaces to a degree equaled only by skylight illumination.

This lack of visual acuity in daylight or ordinary white light may be improved strikingly by the use of monochromatic light which results in the formation of a clearly defined image. The coincidence of maximum visibility and maximum acuity in some 60 per cent of the Cooper Hewitt light partially accounts for its marked success in the textile industry, and in machine shops and inspection departments. As a practical matter the fine threads of textiles and the lines on machined metal surfaces can be seen with an increase in detail equal to a

Fig. 14. Illustrating Use of Cooper Hewitt Portrait Outfit

Fig. 16. Long and Short of the Cooper Hewitt Lamp

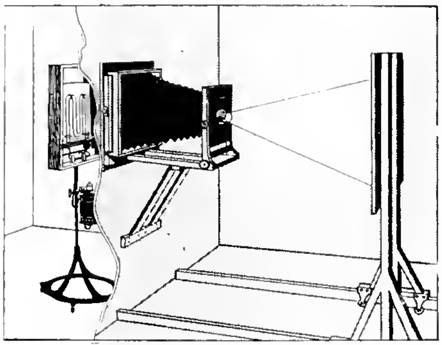

Fig. 15. Cooper Hewitt Lamps Arranged for Photographic Enlarging

Fig. 17. Banks of the Cooper Hewitt Lamp on the Metro Motion Picture Stage

magnification of one and one half to two times under Cooper Hewitt light.

Since the Cooper Hewitt light is entirely lacking in red rays it is obvious that red objects do not seem colored but black or brown under the light, even as dark blue or violet objects look black under incandescent sources. This has proved no handicap in industrial lighting, since colors are matched in the factory by numbers and not by comparison.

Interesting contributions to the psychology of color have come from users of the Cooper Hewitt system. Traces of green hue in the light combined with the well known hue imparted to a face of good color in ordinary light invariably produces a strong reaction against the light. Workmen who are very prejudiced for these reasons are however won over to the light by a subtle but definite personal reaction variously characterized by describing the light as restful, soft, cool, etc. The change is probably because the first reaction is largely mental, the result of a subjective green hue rather than the yellow green light of the so-called green mercury line; while the second reaction is fundamental and in response to the recognized psychological effects of true blue and violet light. Contributory to the latter reaction is also the physiological fact of reduced eye strain under relatively monochromatic light. More striking still is the oft repeated testimony to the greater apparent coolness of a room lighted by Cooper Hewitt lamps than by any other artificial illuminant. While for a given intensity of illumination approximately the same quantity of energy is dissipated in a room regardless of the system of illumination, a smaller proportion is radiant heat in the Cooper Hewitt unit and that heat is of as relatively low intensity as the light. This probably serves to strengthen the subconscious impression of coolness produced by the blue white quality of the light.

Of the numerous special applications of Cooper Hewitt lighting the most interesting is in the motion picture industry. Here the system is competing directly with California sunshine and apparently winning out by virtue of its remarkable actinic power and reliability. Feminine opposition has changed to feminine approbation. New York must have its movie shows regardless of rainy days in California. Other special applications of lesser importance are: general photography, photographic enlarging without condensers, photographic reproduction of drawings, blue printing, and certain photochemical processes not requiring the more intense Cooper Hewitt quartz arc light.

That a properly laid out Cooper Hewitt lighting system can be made to give an illumination equal to or better than daylight is proved by large and successful installations in nearly every basic industry. Night shift production rates equal to and even greater than day rates are the rule. In certain inspection departments and in certain highly specialized industries the light is used continuously in preference to daylight because of its unvarying luminosity and color.

The Cooper Hewitt lamp is unique from a scientific standpoint in combining high efficiency with low intrinsic brilliancy, large total light flux with good diffusion, and maximum monochromatic visual acuity with apparent whiteness. It makes possible the unique idea in industrial lighting of adding to the required luminous intensities those qualities of light which will enable the eyes of the workman to function to best advantage in their essentially artificial work of the continuous observation of details.

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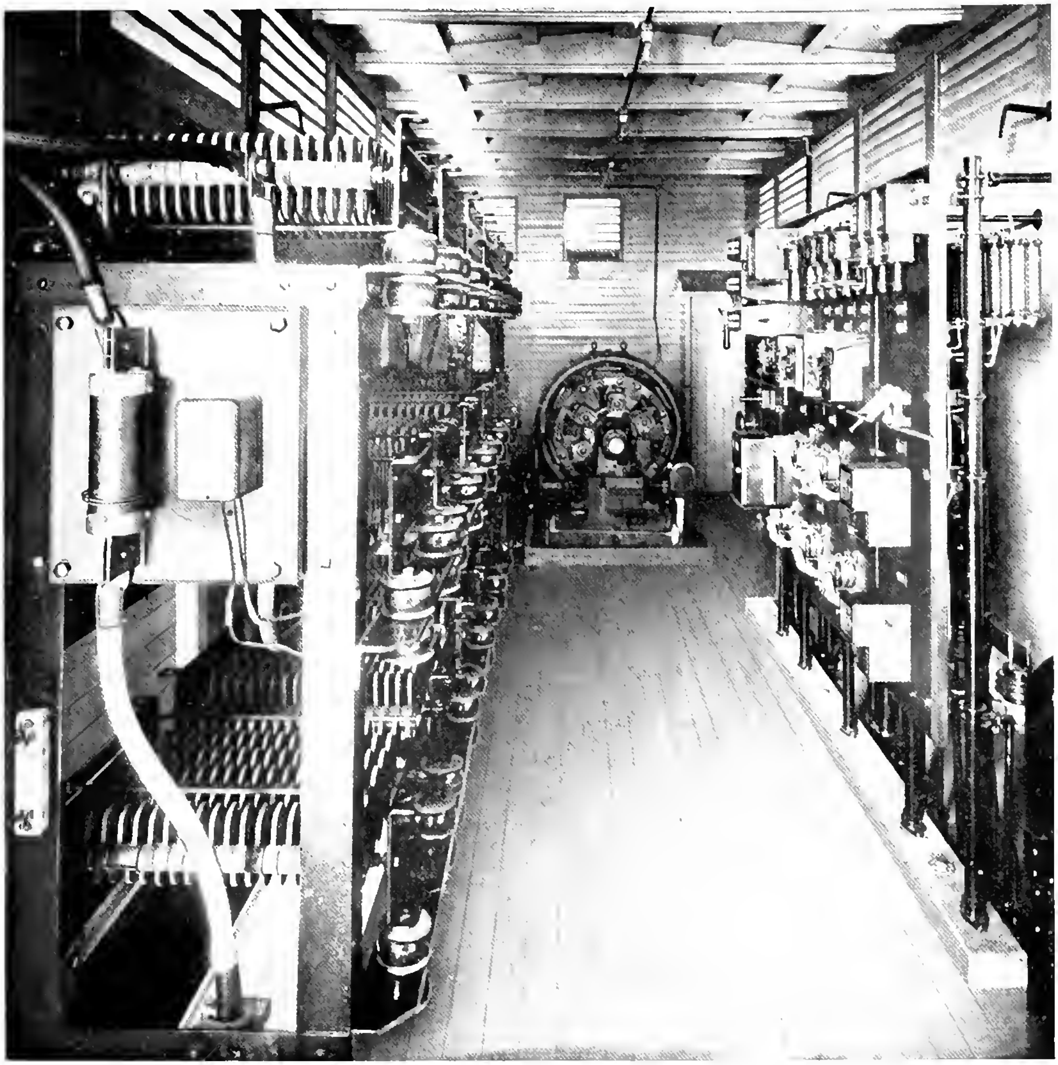

AUTOMATIC RAILWAY SUBSTATION, SACRAMENTO NORTHERN RAILROAD

(See article, page 894)

GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

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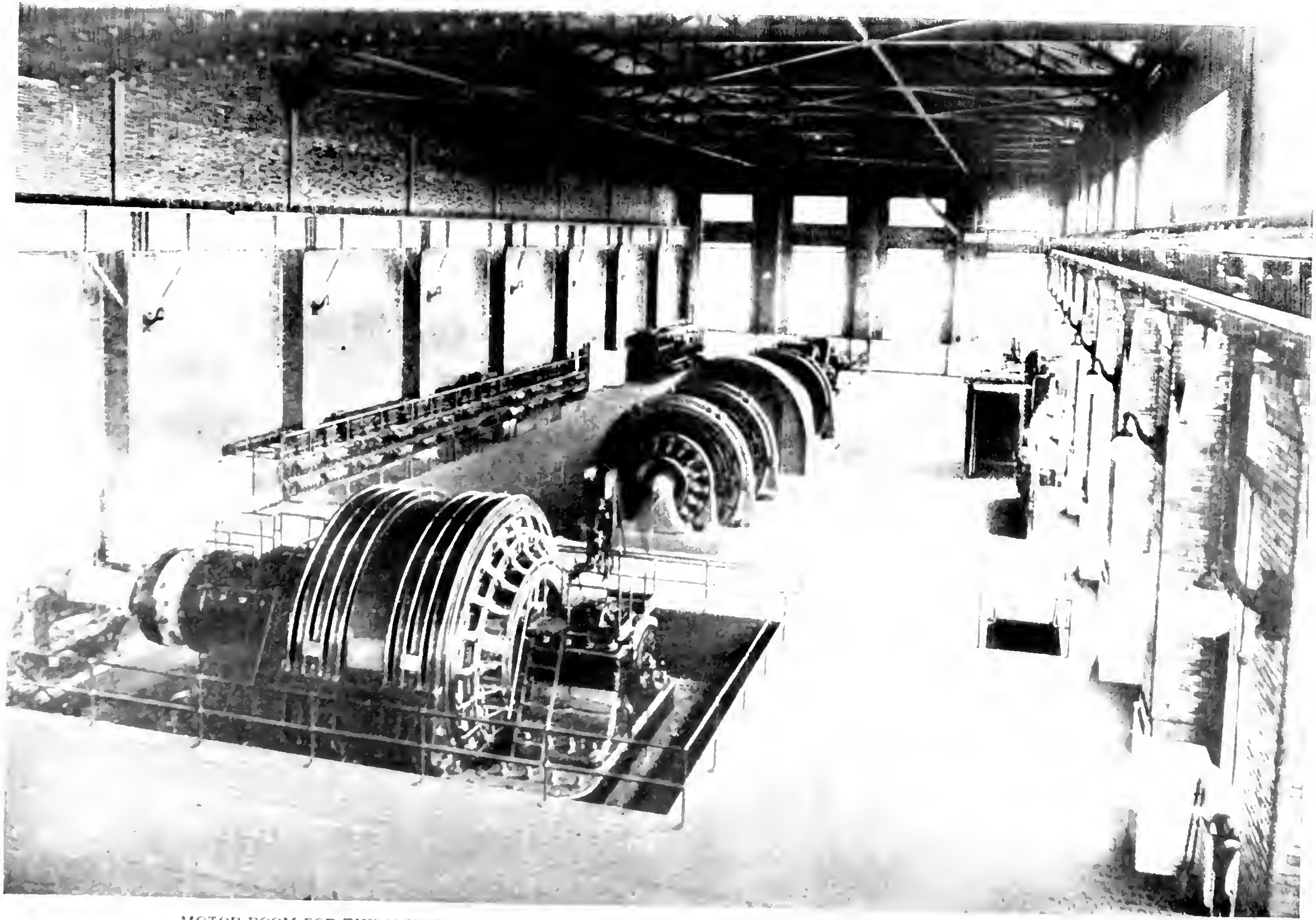

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GENERAL ELECTRIC REVIEW

PHOTO-ELASTICITY FOR THE DETERMINATION OF STRESSES

In recent years, when economy in every possible way has been of such prime importance in engineering, the problem of accurate determination of stresses in construction members and parts of machinery has attained unprecedented prominence. While for simple cases the ordinary engineering methods of stress determination by calculation are sufficient, it is becoming more clearly recognized that these methods have to be used with great care, and that for members of unusual shapes they may give seriously incorrect results.

There are two ways by which trustworthy results may be obtained. The first is the theoretical method, depending on the exact solution of the well-known and accepted equations of elasticity for the particular case in question. The second is the experimental method, using a means by which the required stress distribution can be determined by direct measurement.

Each of these methods introduces difficulties of its own. The first, or the theoretical method, gives good results for those cases which can be solved; but unfortunately it is only in the simplest cases that even an approximate solution is possible. For complex shapes no known mathematical method can solve the equations. For simple members and stress systems the solutions obtainable are embodied in the ordinary methods of stress calculation used in the engineering schools, and as stated, if these methods are extended and applied to more complex shapes in approximate or common sense ways, mistakes will surely be made. Stress distribution in an odd-shaped member is by no means as simple a thing as distribution of magnetic flux or electricity in odd-shaped paths, and greater errors will be made in estimating the former than the latter. We can thus sum up for the theoretical method by saying that it helps us but little except in the simplest cases.

The experimental solution of the problem has until recently been worse off than the theoretical, it having been impractical in even simple cases. However, a unique method has been developed by Dr. E. G. Coker, F. R. S., of University College of London, which gives reliable measurements in difficult cases and which promises to take care of all ordinary cases of plane stress, or stress in two dimensions.

This method offered promise of assistance in certain stress problems, and it was therefore decided by the General Electric Company to institute similar work in their Research Laboratory at Schenectady. A special set of apparatus to fill the requirements of this work was designed with the co-operation of Dr. Coker and manufactured in London and shipped to Schenectady the past summer. Dr. Coker also made a visit to Schenectady to assist in getting the work started.

Some of the problems which have already been studied by this method are stress distribution in curved and notched beams, in tension members of different shapes, stress about elliptical and circular holes, that produced by a rivet in a plate, etc. During the time that the apparatus has been in use at the Laboratory study has been given to the analysis of stress distributions in various types of steam turbine bucket dovetails and tenons with different types of load. A fact which is clearly shown by the method is the importance of avoiding sharp re-entrant angles in design. Many engineers appreciate this fact, but there are also others who do not, as designs in use at the present time bear witness. There are many cases where re-entrant angles are necessary but there are few where a sharp angle cannot be rounded with a curve or fillet which may easily reduce the local stress to one-half.

This method of stress determination and its application are described in a series of five articles which Dr. Coker has prepared for the General Electric Review. The first article appears in this issue.

A. L. Kimball.

Photo Elasticity for Engineers

PART I

By E. G. Coker, D.Sc., F R.S.

Professor of Engineering in the University of London, University College

Written specially for General Electric Review

This is the first of a series of five articles by Professor Coker on the investigation of stresses by means of polarized light transmitted through models of transparent material under stress. Professor Coker has been able to solve with this method many problems of stress that have defied solution by the usual methods of mathematical analysis. This installment includes a brief explanation of the principles involved in this method and then proceeds to show how it is applied in practice.—Editor.

The strength and properties of materials under load play so great a part in constructional work of every kind that it is not too much to say that a study of those branches of science concerned with the distribution of stress in a material are fundamental for engineers who are for the most part engaged in the design and construction of appliances capable of bearing relatively great loads and often subjected to stresses of much complexity.

Moreover, modern needs and scientific discoveries are ever leading to new and more difficult problems in engineering, for which solutions must be found and expressed in the form of definite machines and structures. In most of these problems stress distribution occurs of a somewhat complicated kind since the exigencies of construction necessarily lead to forms and dispositions of material which are not amenable to exact calculation. Although a large number of solutions of stress distribution in elastic bodies have been obtained, and are continually being added to by the labors of mathematicians, yet it seems impossible to keep pace with actual needs by philosophical reasoning alone; and, as is well known, most of the difficulties met with in engineering construction have to be solved by bringing to bear upon them all the theoretical and experimental knowledge available and utilizing this store of accumulated knowledge coupled with practical experience of allied problems to obtain a safe and economical structure or machine for the purpose required. One of the most useful experimental methods of attacking a new engineering problem is to examine the properties exhibited by a model of the proposed form in the same or in a different material, under loads bearing a proper scale relation to those to be borne by the full sized structure. Such methods need no words of commendation here since they are employed extensively in research and have recently, I understand, been useful in demonstrating some of the most interesting phenomena relating to rapidly rotating disks used in turbines.

This series of articles is intended to explain another method of experimental investigation by the use of models which has certain advantages peculiar to itself, and although it is not new in principle its applications have been much neglected in the past.

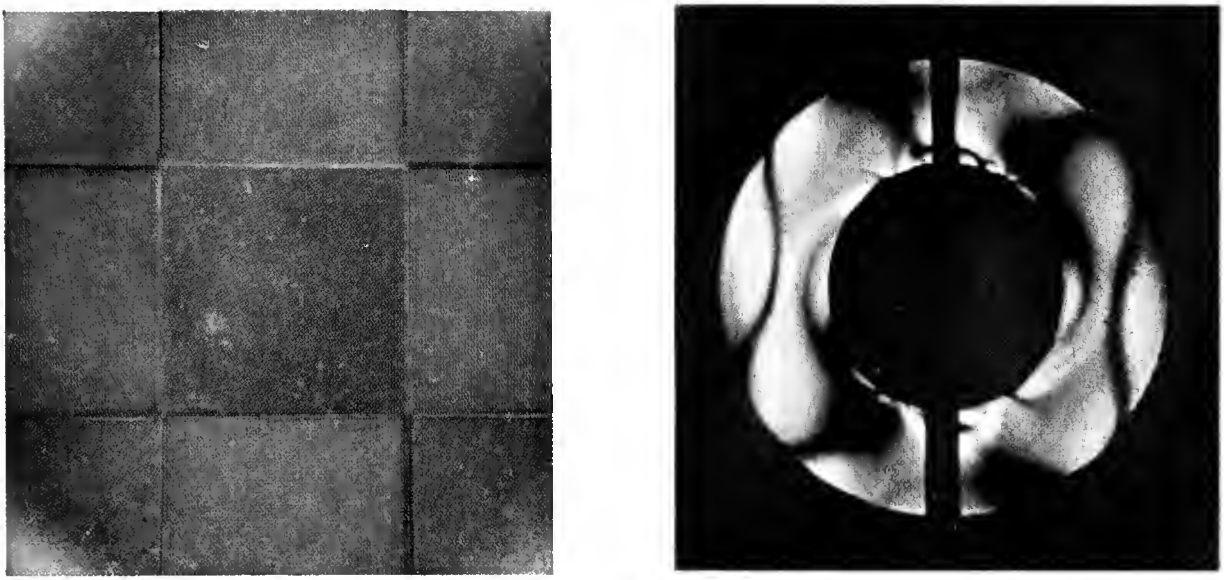
The starting point of all photo-elastic research is due to the discovery of Sir David Brewster, in 1816, that when a piece of glass is loaded and viewed in polarized light under suitable conditions it shows brilliant color effects due to the internal stresses produced in the material. This property is shared by most transparent bodies in more or less degree, and its application to engineering problems was immediately obvious to its discoverer, who suggested that the stress distribution in masonry bridges might be investigated by constructing glass models, subjecting them to suitable loads, and examining the optical effects produced thereby. Little use appears to have been made of this suggestion at the time, and, so far as I have been able to find, no useful contribution to the study of bridges was ever obtained until recently, when Professor Mesnager, the head of the State Laboratory of the Department for Roads and Bridges in Paris, investigated the stresses in a large reinforced concrete bridge in Southern France by aid of a model in glass.

Here and there one finds attempts to utilize this temporary double refraction due to stress to investigate engineering problems, but the difficulties of fashioning glass to the required shapes and the high stresses required to produce optical effects have always stood in the way, and it is only in recent years that new kinds of transparent products have

PHOTO-ELASTICITY FOR ENGINEERS

(*A*) Beam subjected to uniform Bending moment.

(*B*) Simple tension member.



(*C*) Equally stressed tension members arranged crosswise.

(*D*) Circular ring in plane polarized light with black band effect.

Fig. 1. These Color Plates Illustrate the Effects Obtained by the Use of Polarized Light in the Study of Stresses in Material

become available for various commercial purposes which can be utilized for the experimental investigation of engineering problems of stress distribution. We are fortunate in now having at our command many transparent bodies possessing great optical activity under load. For example, a simple tension member of nitro-cellulose exhibited in a plane polarized field, when unstressed, is hardly visible in the dark field produced between crossed Nicol's prisms, but immediately load is applied it shows vivid colors. When a small load is applied, the specimen in the field gradually becomes visible, and shows a white color, which gradually changes to a uniform lemon yellow as the load is increased, and becomes successively orange, red, blue (as Fig. 1B shows), and later a somewhat changed white as the load increases; while if further stress intensity is produced these colors are repeated with some slight modifications to a second, third and even higher order, until the specimen fractures, when it is usually found that there are residual colors owing to the permanent internal stresses produced. If instead of white light a homogeneous light had been employed the phenomena observed would have been different. We should then have found as the load varied that the changes consisted merely of alternations from darkness to brightness, according to the load employed.

From the practical point of view these results are important from the fact that the colors indicate a definite stress intensity which can be observed with ease in the polariscope, and if the stresses are simple tension or compression their intensities are immediately obvious by aid of a color scale like that shown in Table I or by comparison with those observed on a simple tension member. Thus, for example, if a beam of rectangular section, Fig. 1A, is subjected to pure bending it shows color bands parallel to the contours, each of which marks a stress which can be definitely stated by reference to the comparison tension member, since it is found (subject to small corrections for change of thickness) that tension and compression stresses produce exactly the same effects in a polarized field, and it is therefore possible to map out the distribution of stress across the section of the beam and to show that the intensity varies according to the distance from the central longitudinal section, at which place a persistent dark band indicates that there is no stress for an applied bending moment.

TABLE I

Order	Color	Stress
I	Black	0
	Grey	3.5
	White	5.5
	Straw	8
	Orange	10
	Brick Red	10.5
	Purple	11
II	Blue	13
	Yellow	18
	Red	21
	Purple	22

Having indicated the nature of the phenomena observed in the simple cases, it will be useful to form some idea of the physical conditions which obtain, and it will probably be sufficient if we content ourselves with an elementary explanation based on the wave theory of light and to ignore the fact that light is an electro-magnetic phenomenon in which there are electric and magnetic disturbances, mutually at right angles to one another, and also to the path of the ray. We will, in fact, select one of these groups and ignore the other.

An ordinary beam of light, under this simple hypothesis, may be considered as consisting of vibrations in the ether transverse to the direction of the ray, and of all azimuths. If a transparent specimen under load is viewed in such a light, there are no visible effects of stress in the material, and none can be observed unless a more simple type of light vibration is employed. A convenient method of showing the existence of stress is to pick out from this composite beam only those constituents of it which have the same transverse plane of vibration, and this may be accomplished by reflecting the beam from a plate of black glass at a suitable angle, or by passing it through a series of transparent glass plates arranged at a suitable angle; or best of all, through a prism of the form invented by Nicol and composed of two wedges of Iceland spar cemented together with Canada balsam. Any of these arrangements exercise a selective effect, and the emergent ray is found to be more or less uni-directional as regards its transverse vibrations, or, as it is commonly termed, is polarized. Such an arrangement is indicated in Fig. 2, in which a beam of light after passing through a polarizing prism A emerges as a uni-directional ray B, and is afterwards passed through a transparent plate C under load. The effect of the interposition of such a plate depends on the stress imposed thereon, but in general the stressed plate causes the uni-directional beam to break up into two systems of transverse waves, both of which suffer retardation in passing through the stressed plate and are, moreover, found to execute their vibrations in planes at right angles, so that when they emerge from the stressed member they are uni-directional wave systems D and E out of phase with one another and executing the vibrations in planes at right angles. So far as the eye is capable of judging there seems to be no difference in the emergent beam except a diminution in the intensity of the light, and there are no visible color effects; but if these wave systems are passed through a second polarizer F which exercises a selective effect and allows only components of each system to pass through which execute vibrations parallel to its principal plane, there emerge two trains of uni-directional waves in the same plane which are out of phase with each other and therefore give interference effects which, when white light is used, show brilliant color effects on a screen, or if homogeneous light is used show bands of color separated by black fringes wherever the two wave systems are in phase or opposed respectively. The arrangements of two polarizing prisms or their equivalents, termed respectively polarizer and analyzer, have found many applications besides those mentioned here and form a useful combination, for example, in microscopes used by mineralogists.

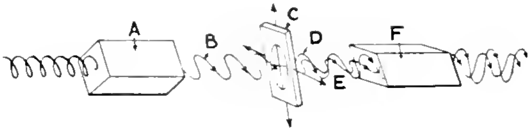


Fig 2

The most usual arrangement of the polarizer and analyzer is to place them in such a position that their principal planes are crossed at right angles so that the uni-directional beam from the polarizer is stopped by the analyzer and little or no light passes through. This arrangement of a dark field is so convenient that it is almost always used in practice, but in this arrangement a peculiarity is observable which is very useful in one branch of photo-elastic work, but is highly inconvenient in another.

When a stressed specimen like the circular chain link shown in Fig. 1D is turned round in the field of view there is in addition to the color effects a system of black bands which continually change their form as the specimen is rotated. They only occur when the specimen is loaded, they change in appearance when the type of load is changed, but they are practically independent of the stress intensity. Their forms are, in fact, dependent on the kind of stress distribution which the loading imposes, and on the disposition of the planes of the crossed polarizer and analyzer. If it were possible to rotate both these latter devices at a sufficiently high velocity and still keep their principal planes crossed, the unaided eye would no longer be able to follow the rapid changes of these black bands, and the effect would appear as a slight darkening of the field of view, but the color effects of the stress would remain stationary. This mechanical method of obliterating the dark fringes, or iso-clinic bands as they are usually termed, is obviously not very convenient, although it has been occasionally resorted to, and a much more convenient arrangement has been devised which permits all the apparatus to remain stationary.

It is found that certain natural substances like mica and selenite in the form of plates have the property of dividing a plane polarized ray into two constituent rays, and that if their axis and thickness are properly adjusted a definite amount of retardation between the two rays is produced. Such plates are in common use and are known as wave plates; thus a half wave plate is one which gives a relative retardation of half a wave length of some definite light vibration. If, therefore, such a plate R_1, Fig. 3, giving a retardation of a quarter of a wave length, is interposed after light has passed through the polarizing prism *P*, we have a system which gives a circularly polarized beam. The effect may be described as analogous so far as a mechanical illustration will afford a parallel, to the effect of two simple harmonic disturbances with a quarter-phase difference, applied to a particle moving in a plane and

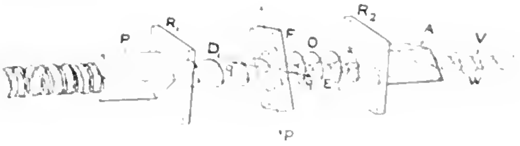


Fig 3

thereby giving a circular motion to the particle. The circularly polarized beam produced by the quarter wave plate corkscrews through the stressed material, and the emergent rays O and E remain circularly polarized, although they have been retarded differently by the stressed specimen; but exactly the same amount of retardation is produced as for plane polarized light. The circular polarization is afterwards annulled by the interposition of a second quarter wave plate R_2, and the analyzer A picks out those constituents parallel to its own principal plane as before and affords the opportunity for interference of the two emerging plane waves V, W as described before.

It is worthy of note that since the wave plates can only act perfectly for one definite wave length, they only fulfill their function exactly for the corresponding homogeneous light, and if used with white light which is heterogeneous they give in general an elliptic form of polarization which does not allow a perfectly black field. This, however, is not found to be of any serious inconvenience for most of the applications in which engineers are interested.

So far we have seen that stress can be made visible in a transparent material by aid of polarized light, and as may be surmised the direction of the stress is picked out by a plane polarized beam, and for convenience of practical work it is convenient to use plane polarized light for measuring stress direction, and to measure its intensity in circularly polarized light. It is therefore necessary to address ourselves to the task of determining the laws which govern the phenomena observed in the polariscope.

It will be convenient here to consider some elementary matters relating to stress distribution in plates for which photo-elastic methods are especially suitable, and for ease of demonstration of some of these the usual method of notation of stresses p will be adopted following Rankine, in which the normal to the plane of the stress considered is denoted by a suffix, and the direction of the stress by a second suffix. Thus a stress p_{rs} indicates that the stress considered acts in a plane perpendicular to r in the direction s.

If we now consider the state of stress produced in an element of any plate, say for example a rectangular element $ABCD$, Fig. 4, with sides parallel to the co-ordinates:

The most general system which can be imposed upon it consists of inclined stresses at angles α and β, as shown, which for equilibrium must have shear components of equal intensity along the meeting edges.

The stress across any other plane AC in the plate will in general be of intensity p inclined at some angle γ to the normal to the plane AC. If for convenience the equilibrium of the wedge ABC be considered, the stress on the plane AB may be replaced by stresses p_{xx} normal to AB and a shear p_{xy} in the plane of AB, while for the face BC the stress system will be p_{yy} and p_{yx} in which for equilibrium $p_{xy} = p_{yx}$. Similarly, the stress intensity p on the face AC inclined at θ can be resolved into a normal stress p_{rr} and a shear stress $x\theta$. Resolving horizontally and vertically we obtain as the conditions for equilibrium that

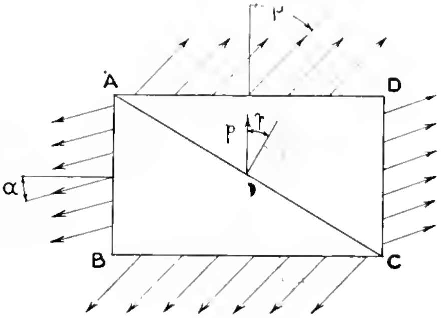


Fig. 4

$$\left.\begin{aligned} p\,cos\,(\theta+\gamma) &= p_{xx}.cos\,\theta + p_{xy}.sin\,\theta \\ p\,sin\,(\theta+\gamma) &= p_{xy}.cos\,\theta + p_{yy}.sin\,\theta \end{aligned}\right\} \qquad \text{(i)}$$

giving

$$\left.\begin{aligned} p^2 &= p_{xx}{}^2.cos^2\theta + p_{yy}{}^2.sin^2\theta + p_{xy}{}^2 + \\ &\quad p_{xy}\,(p_{xx}+p_{yy})\,sin\,2\,\theta \\ tan\,(\theta+\gamma) &= (p_{xy}.cos\,\theta + p_{yy}.sin\theta)\,/ \\ &\quad (p_{xx}\,cos\,\theta + p_{xy}.sin\,\theta) \end{aligned}\right\} \qquad \text{(ii)}$$

for the intensity and direction of the stress on a plane AC inclined at an angle θ.

This stress is wholly normal when $\gamma = 0$ giving the condition

$$tan\,2\,\theta = \frac{2.\,p_{xy}}{p_{xx} - p_{yy}} \qquad \text{(iii)}$$

for which there are two values θ_1 and θ_2 connected by the relation $\theta_2 = \theta_1 + \frac{\pi}{2}$. The stress at a point in a plate under the most general system of plane stress is, therefore, wholly normal on two planes at right angles drawn through the point and defined by equation (iii).

It is moreover easily shown by differentiating the first equation of (ii) with regard to θ and equating to zero to obtain maximum and minimum values of the stress that the criterion is of the form (iii) precisely. Therefore at a point in a plate under plane stress the maximum and minimum stresses are normal to the planes on which they act and these latter planes intersect at right angles. If therefore the magnitudes and directions of the normal stresses at a point in a plate are determined, the stresses on any other plane through the same point can be calculated. These results are important since the principal feature of a photo-elastic investigation is the ease with which the maximum and minimum stresses and their directions can be determined experimentally, and a solution is thereby obtained of the stress distribution in any plate, no matter what its form may be, which is complete and independent.

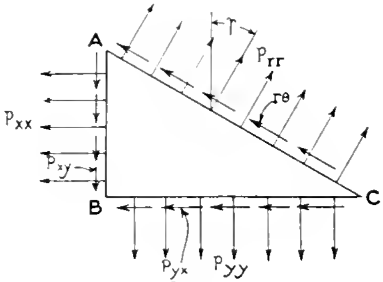


Fig. 5

It is convenient to point out here that the general relations between the stresses on the element are immediately obtainable from Fig. 5 by resolving perpendicularly to and along the plane *AC* and that they are of the form

$$\left.\begin{aligned} p_{rr} &= p_{xx}.\cos^2\theta + p_{yy}.\sin^2\theta + p_{xy}.\sin 2\theta \\ p_{\theta\theta} &= p_{xx}.\sin^2\theta + p_{yy}.\cos^2\theta - p_{xy}.\sin 2\theta \\ p_{r\theta} &= (p_{yy} - p_{xx})\sin\theta.\cos\theta + p_{xy}.\cos 2\theta \end{aligned}\right\} \quad \text{(iv)}$$

where $p_{\theta\theta}$ is derived from p_{xr} by substituting $\left(\frac{\pi}{2}+\theta\right)$ for θ in the first of these equations. This system is equivalent to

$$\left.\begin{aligned} p_{xx} &= p_{rr}.\cos^2\theta + p_{\theta\theta}.\sin^2\theta - p_{r\theta}.\sin 2\theta \\ p_{yy} &= p_{rr}.\sin^2\theta + p_{\theta\theta}.\cos^2\theta + p_{r\theta}.\sin 2\theta \\ p_{xy} &= (p_{rr} - p_{\theta\theta})\sin\theta.\cos\theta + p_{r\theta}.\cos 2\theta \end{aligned}\right\} \quad \text{(v)}$$

as may be shown by direct substitution from (iv) or by direct resolution.

These formulæ also give the useful transformations

$$\left.\begin{aligned} p_{rr} + p_{\theta\theta} &= p_{xx} + p_{yy} \\ p_{rr} - p_{\theta\theta} - 2i.p_{r\theta} &= \epsilon^{21\theta}(p_{xx} - p_{yy} - 2i.p_{xy}) \end{aligned}\right\} \quad \text{(vi)}$$

as may be readily verified.

The Law of Optical Behavior of Transparent Materials Under Stress

The optical properties of glass have been studied with much care and thoroughness and the laws of the particular phenomena presented by stress effect, discovered by Brewster, has been subjected to careful investigation, especially in later times by my colleague, Professor Filon.

It may be taken to be established that a plane polarized ray passing through a stressed plate is divided into two separate rays having planes of vibration in the direction of the principal stresses, and moreover, that the retardations suffered by each are proportional to the principal stresses in these planes so that the relative retardation *R* is proportional to the differences of the principal stresses *P* and *Q* at a point. Further, this relative retardation is dependent upon the thickness of the plate *T* and to the optical character of the material. Hence, the law governing the stress-optical effect is a linear law and is expressible in the form

$$R = C\,(P - Q)\,T$$

where *C* is an optical constant.

Numerous investigations have shown that this fundamental law is approximately fulfilled by very many kinds of glass and until lately it had been assumed to hold for other transparent substances used for investigating stress distribution, although the evidence for assuming its truth was somewhat scanty. Recent investigations on some nitro-celluloses have, however, justified this assumption, and in a later instalment some account will be given of the nature of the evidence on which the law rests.

In this form it is evident that the pictures of stress shown by investigations with the polariscope are not of a simple type, since it is quite possible for a material to be highly stressed at a place and yet exhibit little or no color effect.

Thus, for example, if a rectangular plate is exposed to equal and normal stresses along its boundaries it will show no color effects under any intensity of stress within the range of this optical law, but immediately a difference of stress is established color effects are observed proportional to $(P-Q)$, but so far no means have been described for separating the constituents.

In many problems, however, this is not important since only one stress is present, or if both are present one is so small in value that it may be neglected in all but the most accurate investigation. A particularly interesting group of cases arises at the boundaries of plate models at which there is no direct application of external load. In all such cases a consideration of the equilibrium of an element of the boundary shows that there can be no stress normal to the boundary and that the total stress is tangential to the boundary. The color effect can therefore be utilized to obtain its magnitudes directly. Although it might appear to be the easiest plan to use a color scale for such cases, and compare it with the observed color at a boundary, yet experience shows that this is not the case.

The unassisted eye is not a very perfect instrument for comparing colors, especially under the severe conditions usually imposed by the presence of a number of brilliant bands in the field of view, and moreover there is no certain way of deciding whether the part under inspection is in tension or compression. It is therefore expedient to adopt a uniform method which evades these difficulties, and this is accomplished very perfectly by interposing a member under simple stress in the field of view which will reduce the color at any required point to the condition of no stress corresponding to the dark field between crossed polarizer and analyzer. The principle of the method is indicated in the accompanying photograph, Fig. 1C, in which two equally stressed tension members are shown crossed and the common field of view is then found to be the same as that produced by the crossed polarizer and analyzer alone.

In the majority of cases a simple tension member loaded in any convenient way is used for this purpose, and is applied along the direction of one of the principal stresses to neutralize the color effect. It is clear from the optical law given above that only two cases can arise along a boundary free from external load, and if there is tension the stress can only be neutralized by placing the tension member across the boundary, while if the stress is compressive the tension member must be set along the boundary. An illustration of this is afforded by the case of a circular hole in a wide plate in tension in the direction of the arrows *YY*, Fig. 6. It will be found under these conditions that the boundary of the hole is in compression for an angular distance of about 30 degrees from the center line as the calibration member must be applied tangentially to secure color extinction, but all the rest of the boundary is in tension as is evidenced by the necessity of placing the calibration members athwart the boundary to restore the dark field.

In a few minutes it is easy to verify in this way that the distribution of stress has the form shown in the polar diagram, Fig. 7, in which the maximum stress is a tension, at the point *A*, of approximately three times the average stress applied and this gradually diminishes as the contour is transversed until at the point *B* at an angular distance of about 30 degrees from the central line there is no stress at all as a minute black patch indicates. Thence there is compression which reaches a maximum intensity at the points *C* on the center line, and is approximately of the same value as the average stress applied.

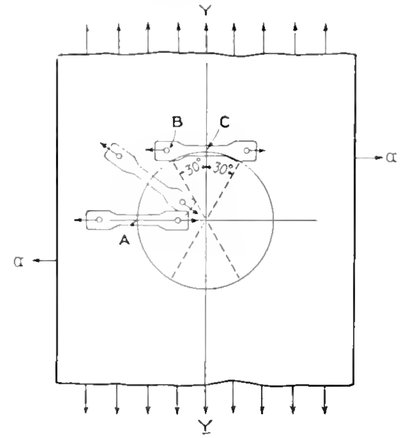


Fig. 6

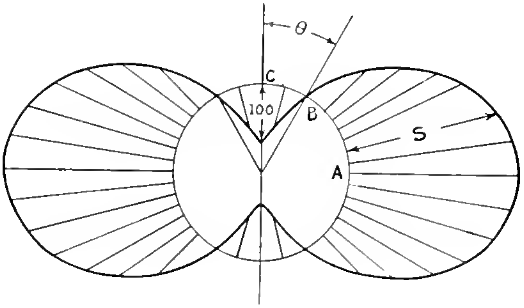


Fig. 7

As a rule, circular holes in engineering practice are subjected to much more complicated stresses owing to loads applied at their boundaries by bolts and the like and such cases require more elaborate investigation involving the separation of the principal stresses, and in general in the body of a plate and away from the unloaded contours there are two principal stresses *P* and *Q*, and these must be determined separately, point by point, before the problem of stress distribution can be considered as solved.

One method of carrying this out is to obtain the values of $(P-Q)$, θ_P and θ_Q at a number of points along a line starting from the contour where the stress can be determined accurately. A process of graphical integration then enables one to separate the stresses in the following manner.

Consider the most general state of equilibrium of an elemental rectangle $ABCD$, Fig. 8, in which the stress components vary continuously from point to point. It is required to express the relations between the variations of stress when we pass from the point A, with coordinates x_1y to a neighboring point C with coordinates $x+dx_1\ y+dy$. On the face AD there is a normal stress p_{xx} and a tangential stress, p_{xy}, and on the corresponding face BC there are stresses $p_{xx}+\frac{d\,p_{xx}}{dx}.dx$, and $p_{xy}+\frac{d\,p_{xy}}{dx}.dx$, with similar stresses on the faces AB and CD as indicated in Fig. 8.

Resolving horizontally and vertically, and neglecting quantities of the second order in comparison with the first, we obtain in the absence of stresses, due to the volume, two equations of the form

$$\left.\begin{aligned}\frac{d.p_{xx}}{dx}+\frac{d.p_{xy}}{dy}&=0\\ \frac{d.p_{xy}}{dx}+\frac{d.p_{yy}}{dy}&=0\end{aligned}\right\}\qquad\text{(vii)}$$

If the plate is not too thick the stresses in these equations may be taken to represent the conditions of equilibrium; provided they are average values across the thickness of the plate. Moreover, along any line the stress p_{xy} at any point is obtained by the relation

$$p_{xy}=\frac{P-Q}{2}.\sin 2\,\theta \qquad\text{(viii)}$$

where $(P-Q)$ is the optical effect there and θ corresponds to the direction of the maximum principal stress.

If, therefore, we know the values of $(P-Q)$ and θ for a sufficient number of points along coordinate lines passing through a point x_1y and terminating at a boundary where the stress distribution can be easily determined, we can infer the stresses p_{xx} and p_{yy} at the point by a process of graphical integration since from equations (vii)

$$\left.\begin{aligned}p_{xx}&=-\int\frac{d.p_{xy}}{dy}.dx+C_1\\ p_{yy}&=-\int\frac{d.p_{xy}}{dx}.dy+C_2\end{aligned}\right\}\qquad\text{(ix)}$$

where the constants C_1 and C_2 represent respectively, the values of p_{xx} and p_{yy} at the boundary.

It has also been shown by Professor Filon* that it is possible to completely determine the stress distribution in a plate if the isoclinic bands are accurately mapped and the stress at a few points is accurately known.

The methods described have the great advantage that the measurements are purely

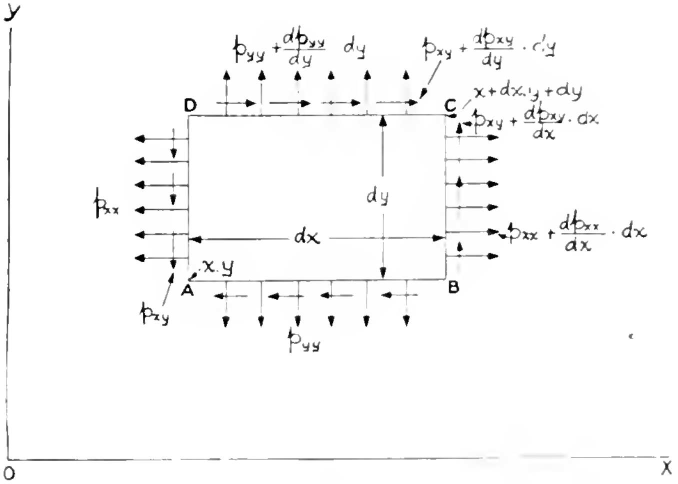


Fig. 8

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* Experimental determination of the distribution of stress and strain in solids, by Professors Filon and Coker, British Association Report, 1914.

optical, but there may be some difficulty in obtaining accurate values of the stresses at a considerable distance from a contour, and an independent measurement is in general preferably based on the lateral strain which a plate experiences when subjected to forces in its own plane. As is well known, simple tension member under a stress p_{xx} in the direction of its length experiences a strain ϵ_{xx} expressed by the relation $p_{xx}=E\ \epsilon_{xx}$, where E is the modulus of direct extension and this is accompanied by lateral strains in the directions of both width and thickness of amounts $-\sigma\epsilon_{.xx}$ where $\sigma=\frac{1}{m}$ is a constant for the material. Similarly a simple shear stress p_{xy} is accompanied by an angular strain ϵ_{xy} expressed by the relation $p_{xy}=\mu\,\epsilon p_{xy}$ where μ is a rigidity modulus which latter is not an independent constant, but has a value expressed in terms of M and E given by the relation

$$\mu=mE\ \ 2(m+1)E \qquad \text{(x)}$$

In an elementary rectangle, therefore, with sides parallel to principal stresses the relations between stress and strain can be written down at once by the relation

$$\left.\begin{aligned} mE\,.\,\epsilon_P &= m\,.\,P-Q\\ mE\ \ \epsilon_Q &= mQ-P\\ -mE\ \ \epsilon_R &= P+Q \end{aligned}\right\} \qquad \text{(xi)}$$

and the last equation of (xi) shows that the sum of the principal stresses can be obtained if the strain ϵ_R is known together with the values of m and E.

As the strain ϵ_R can only be measured across the whole thickness of the plate this method gives the average value of the principal stresses and therefore corresponds exactly with the optical determinations of the difference of the principal stresses at the same point.

An instrument for obtaining measurements of the requisite accuracy should be capable of measuring stress to within 5 pounds per square inch in all cases, and if this is adopted as a criterion of performance the lateral change which an instrument should be able to detect is easily calculated, since frequent measurements have shown that a fair average value of m is 2.5 and $E=3{,}000{,}000$ in lb. and inch units. If, therefore, a plate 0.2 inches thick is taken since $\delta\,(P+Q)=5$ lbs. per square inch we have $\epsilon_R=1\ 150{,}000$ and $T\,.\,\epsilon_R=1\ 750{,}000$ or rather less than one millionth of an inch.

In the lateral extensometer, designed for this purpose, measurements of changes of thickness of the order of one millionth of an inch are obtained by aid of a multiplying lever system actuating a tilting mirror and no difficulty is experienced in measuring these small changes provided the temperature conditions are satisfactory.

The methods described above, therefore, afford a means of determining solely by experimental means the distribution of stress in any plate subjected to loading in its own plane whatever be its form and the type of load applied provided the material obeys the optical law and also that the stresses do not exceed the elastic limit of the material. Under certain conditions, however, these limits can be extended as will be demonstrated later.

(To be continued)

The Advantages of the Modern Electric Locomotive

By A. H. Armstrong

Chairman Electrification Committee, General Electric Company

This article presents the arguments of the electrical engineer for the electrification of main line railroads. The extremely favorable showing made for the electric locomotive is not deduced from electrification on paper; the facts are based on actual operating results on main line operation covering a period of several years. It would seem that about the only favorable comparison that can be made for steam operation is the lower initial cost of equipment; but this factor is very quickly offset by higher maintenance costs, standby losses and lower efficiency generally, smaller hauling capacity, and the fact that almost 20 per cent of the gross ton mileage consists of company coal. This article was one of several papers read at a joint convention of the A.I.E.E. and A.S.M.E., New York City, on the relative advantages of steam and electric locomotives.—Editor.

A comparison of the modern steam and electric locomotive leads immediately to a discussion of the relative fitness of the two types of motive power to meet service conditions. At present railway practice has closely followed steam engine development, but are we not justified in looking at the transportation problem from the broader standpoint of a more powerful and adaptable type of motive power?

Place at the disposal of an experienced train dispatcher a locomotive capable of hauling any train weight that modern or improved draft gear can stand, at any speed permitted by track alignment regardless of ruling grade or climatic conditions, that can be run continuously for a thousand miles with no attention but that of the several operating crews, and witness what he can accomplish in his all-important task of expediting freight movement. It is not merely a question of replacing a Mikado or Mallet by an electric locomotive of equal capacity. The economies thus effected are in many instances not sufficient in themselves to justify a material increase in capital account. The paramount need of our railways today is improved service and this can be brought about by introducing the more powerful, flexible and efficient electric locomotive. Marked changes in present railway practice will undoubtedly follow the adoption of a type of motive power that is free from many of the limitations of the steam engine. As this touches upon the inherent possibilities of steam and electric locomotives, some of the fundamental characteristics of each are but too briefly discussed herewith.

Possibilities of Design

A locomotive is primarily a hauling machine. Its design is defined by recognized limits, such as maximum degree of track curvature, coefficient of adhesion between driving wheels and rail, gross weight and dead weight per axle, tracking qualities at high speed, etc. Furthermore, the locomotive should be simple in construction, reliable and adaptable in operation, and capable of being maintained in condition for a reasonable percentage of its cost (Table I).

Owing to handicap of precedent and prejudice, electricity must take up the railway problem where steam leaves off. In other words, the proof is up to the electrical engineer proposing any marked departure from commonly accepted standards as established by long years of steam engine railroading. Thus while a maximum standing load of 60,000 lbs. per axle has been generally accepted for steam engines, it is well known that an impact of at least 30 per cent in excess of this figure is delivered to rail and bridges due to unbalanced forces at speed. Impact tests taken on electric locomotives of proper design disclose the feasibility of adopting a materially higher limiting weight per axle than 60,000 lbs. without exceeding the destructive effect on track and roadbed now experienced with steam engines. However, owing to the flexibility of electric locomo-

TABLE I

COMMONLY ACCEPTED CONSTANTS

Limiting gross weight per axle	60,000 lbs.
Limiting dead weight per axle	18,000 lbs.
Limiting coefficient adhesion, running	18 per cent
Limiting coefficient adhesion, starting	25 per cent
Ruling gradient	2 per cent
Maximum curvature	10 deg.
Maximum rigid wheel base	18 ft.
Maximum speed on level, passenger	65-70 m.p.h.
Maximum speed on level, freight	25-30 m.p.h.
Maximum draw bar pull	150,000 lbs.

tive design, there is no immediate need of exceeding steam practice in this respect, although this and other reserves may be called upon in the future.

Accepting the Mikado and Mallet as the highest developments of steam road and helper engines for freight service, a general comparison is drawn with an electric locomotive that is entirely practicable to build without in any respect going beyond the experience embodied in locomotives now operating successfully (Table II).

This analysis brings out the fact that to equal the hourly ton mile performance of one electric locomotive it would require three and four engine crews respectively for the Mallet and Mikado types.

The electric locomotive has demonstrated its very great advantages in relieving congestion on single track mountain grade divisions. The number of meeting points on a single track line increases as the square of the number of trains operating at one time, and is proportional to the average speed, so that it will be appreciated what an advance in mountain railroading is opened up by the adoption of the electric locomotive. Furthermore, the electric performance as tabulated above can be obtained with each individual locomotive practically regardless of climatic conditions, efficiency of the crew or time that has elapsed since shopping, and with a demonstrated reliability that has set a new standard in railroading. In view of the facts, it is therefore a modest claim to make that the daily tonnage capacity of single track mountain grade divisions will be increased fully 50 per cent over possible steam engine performance by the adoption of the electric locomotive.

TABLE II

COMPARISON OF STEAM AND ELECTRIC LOCOMOTIVES

	Mikado	Mallet	Electric
Type	2-8-2	2-8-8-2	6-8-8-6
Weight per driving axle	60,000 lbs.	60,000 lbs.	60,000 lbs.
No. driving axles	4	8	12
Total weight on drivers	240,000 lbs.	480,000 lbs.	720,000 lbs.
Total weight locomotive and tender	480,000 lbs.	800,000 lbs.	780,000 lbs.
Trac. efficiency at 18 per cent coefficient	43,200 lbs.	86,400 lbs.	129,600 lbs.
Gross tons 2 per cent grade	940	1,880	2,820
Trailing tons 2 per cent grade	693	1,495	2,430
Speed on two per cent grade	14 m.p.h.	9 m.p.h.	16 m.p.h.
Horse power at driver rims	1,620	2,080	5,570
Indicated horse power at 80 per cent efficiency	2,030	2,600	
Trailing ton miles per hr. on 2 per cent gradient	9,700	13,500	38,800

Regenerative Braking

The hazard of mountain operation is greatest on down grades although the perfection of automatic air brakes has done much to modify its dangers. It is left to electricity, however, to add the completing touch to the safe control of descending trains by supplying regenerative electric braking. Not only are air brakes entirely relieved and held in reserve by this device, but the potential energy in the descending train is actually converted into electricity which is transmitted through the trolley to the aid of the nearest train demanding power. Aside from the power returned from this source (14 per cent of the total on the Chicago, Milwaukee & St. Paul Railway), the chief advantage of electric braking lies in its assurance of greater safety and higher speeds permitted on down grades. The heat now wasted in raising brake shoes and wheel rims often to a red heat is returned to the trolley system and becomes an asset instead of a likely cause of derailment.

Cost of Maintenance

Probably in no one respect does the electric locomotive show greater advantage over the steam engine than in cost of maintenance. Special importance attaches to this item of expense in these days of high labor and material costs. In order to draw a fair comparison, however, there should be added to back shop repairs, all expenses of roundhouse, turntable, ash pit, coal and water stations, in fact the many items contributing to rendering necessary steam engine service as most of these charges are eliminated by the adoption of the electric locomotive. Spare parts can be substituted so quickly that, excepting wrecks, there is no need of the back

TABLE III
ELECTRIC LOCOMOTIVE MAINTENANCE, YEAR 1919

	N. Y. C.	C. M. & St. P.	B. A. & P.
No. locomotives owned	73	45	28
Locomotive weight, tons	118	290	84
Annual mileage	1,946,879	2,321,148	566,977
Repairs per mile	6.39 cents	14.65 cents	6.48 cents

shop for electric locomotives, unless turning tires and painting may be considered heavy repairs. Electric locomotives are now being operated 3000 miles between inspections on at least two electrified railways and the figures of Table III are available.

On the basis of pre-war prices, maintenance costs were approximately 60 per cent of these figures for the year 1919. In contrast, it can be stated that the present cost of maintaining a type 2-8-8-2 Mallet may be taken at 60 cts. per engine mile, without including many miscellaneous charges not shared by the electric locomotive. Possibly more direct comparison may be drawn by expressing maintenance in terms of driver weight. (Table IV.)

Including all engine service charges, the facts available give foundation for the claim that electric locomotives of the largest type can be maintained for 25 to 30 per cent of the upkeep cost of steam engines operating in similar service.

Fuel Saving

Much has been written on the subject of fuel saving effected by steam railway electrification. The estimates of electric engineers have been called extravagant by steam engine advocates, who in turn have been charged with an incomplete knowledge of all the facts available. Fuel economy figured prominently among the several reasons leading up to the replacement of the steam engine on the Chicago, Milwaukee & St. Paul Railway as brought out by a careful analysis of the performance of the steam engines then in service. The results of the many tests are doubly interesting when compared with the daily performance of the present electric locomotives now running over the same tracks and operated in some instances by the same engine crews. Although the steam engines tested may now perhaps be considered obsolete and not within the scope of this discussion of the modern engine, nevertheless

TABLE IV
STEAM AND ELECTRIC REPAIRS

	Steam Mallet	C. M. & St. P. Elec.
Cost repairs per mile	60 cts.	14.65 cts.
Weight on drivers. .	240 tons	225 tons
Cost repairs per 100 tons loco. weight on drivers	25 cts.	6.52 cts.

TABLE V
LOCOMOTIVE DATA
C. M. & St. P. Tests

	Steam	Electric
Type	2-6-2	4-4-4-4-4-4-4
Weight of engine	206,000 lbs.	568,000 lbs.
Weight of tender	154,000 lbs.	
Weight total engine and tender	360,000 lbs.	568,000 lbs.
Weight on drivers	152,000 lbs.	450,000 lbs.
Ratio driver weight to total	42.2 per cent	79.3 per cent
Rigid wheel base	13 ft	10 ft. 6 in.
Diameter drivers	63 in	52 in.
Cylinders	21 in. by 28 in	
Boiler pressure	200 lb.	
Heating surface	2540 sq. ft.	
Grate area	45 sq. ft.	
Water capacity	8000 gal	
Coal	11 tons	

it is not without value to compare the results of steam and electric locomotives operating over such long distances under identical conditions. The following data are therefore submitted as applying to a particular equipment only. No claim is made that these figures are representative of the best modern steam engine performance, although many thousands of steam engines still in operation will show no greater economies than those given in the table. The general data applying to the steam and electric locomotives tests are give in Table V.

TABLE VI
COAL ANALYSIS

Fixed Carbon	Volatile Carbon	Ash	Moisture	B.T.U's
47.99	38.98	8.35	4.68	11,793

Other engines were also tested over other sections of track, but the following particular runs are chosen for illustration as bringing out most strikingly the inherent disadvantages of operating a steam engine over a single track mountain grade division and handicapped by the usual delays attending freight train service under such conditions. The run of 111.1 miles from Harlowton, elevation 4162 ft., to Three Forks, elevation 4066 ft., over the Belt Mountain divide at Loweth, elevation 5879 ft., was made by steam with 871 tons trailing in 26 cars and by electric locomotive hauling 64 cars weighing 2762 tons. In order to picture a direct comparison of the results of the steam and electric runs, all test data are reduced to a common basis of 1000 gross tons moved, this unit of measurement including the locomotive and tender weight. The running speed of the electric train was but slightly higher than the steam and the additional correction in the power demand rate of the former is made proportional to the lower speed. Both runs are therefore shown as made in identical time on the basis of 1000 total gross tons moved in each instance. The fuel furnishing power to the steam train was coal having the analysis shown in Table VI

Electric power was furnished by water and hence no direct coal equivalent is provided by the test result. To afford a common basis of comparison, however, a single assumption seems permissible and a rate of 2½ lbs. of coal per kilowatt hour is taken as representative of fair electric power station practice. Coal burned under the steam engine boiler was determined by weighing at the end of the run and by detailed record of scoops en route. Power input to the electric locomotive was obtained by carefully calibrated recording wattmeters as well as curve-drawing volt and ampere meters. These values of locomotive input were raised to the value of three phase power purchased in the ratio of 68 per cent given by R. Beeuwkes in his A.I.E.E. paper of July 21, 1920, and the kilowatt-hours so obtained reduced to coal equivalent in the ratio of 2½ lbs. coal per kw.-hr.

The picture thus secured affords a most striking illustration of one of the principles upon which advocates for electrification base their claim for fuel economy (Fig. 1). While the electric locomotive demands power only when in motion, the steam engine requires coal at all times during the twenty-four hours, whether doing useful work, standing idle or coasting down grade. In fact so called "standby losses" were such a large percentage of the total coal consumed that a careful record was kept of their several amounts. (See Table VII.)

TABLE VII
FUEL COMPARISON

	Steam		Electric
Doing useful work		23,640 lbs.	8,100 lbs.
Making up fire . .	1,535 lbs.		
Delay at Harlowton	2,270 lbs.		
Held up at Lennep .	394 lbs.		
Held up at Loweth	128 lbs.		
Held up at Dorsay. .	230 lbs.		
Fire, banked 9 hrs. .	1,425 lbs.		
Coasting down grade	3,060 lbs.		
Total standby losses.		9,042 lbs.	
Regenerative braking.			1,430 lbs.
Total net coal. . . .		32,682 lbs.	6,670 lbs.

The run of a more modern steam engine would have effected a material reduction in the 23,640 lbs. of coal burned in doing useful work, but the amount of coal wasted in standby losses (9042 lbs.) might have been duplicated or even possibly increased with larger grate area. As standby losses constitute so large a proportion of the total coal burned (27½ per cent in this instance) it is apparent that enormous economies over the simple engine tested must be realized in the modern superheater and other improvements since introduced to offset in part the high inherent efficiency of the electric locomotive.

To assist in arriving at a truer comparison of modern steam and electric locomotive operation, a further analysis of the above test is made. The commonly used unit, pounds of coal per 1000 ton miles, is at best a very rough and unstable comparison of steam engine runs over different profiles, with variable quality of fuel and operating conditions. For illustration, the data of Table VIII may apply.

Pounds coal per gross 1000 ton miles may thus vary from 650 to 50.5 according to gradient and with no standby losses whatever included. The boiler must be kept hot at all times, however, and fully 33 per cent can safely be added to the figures to indicate the inevitable standby losses inherent to steam engine operation. Except over very long runs with terminals at the same elevation it seems hardly possible therefore to accurately compare engine performance over different profiles by such a variable unit as pounds coal per 1000 ton miles.

A truer understanding of what takes place under the engine boiler may be shown by continuous records of coal burned, tons moved, profile, delays, etc., all reduced to pounds of coal burned per useful horse power hour work done at the driver rims with segregation of the many standby losses. (Table IX.)

Under the same conditions a modern engine would undoubtedly have consumed much less than 9.02 lbs. coal (11,793 B.t.u.) while doing work measured at the driver rim.

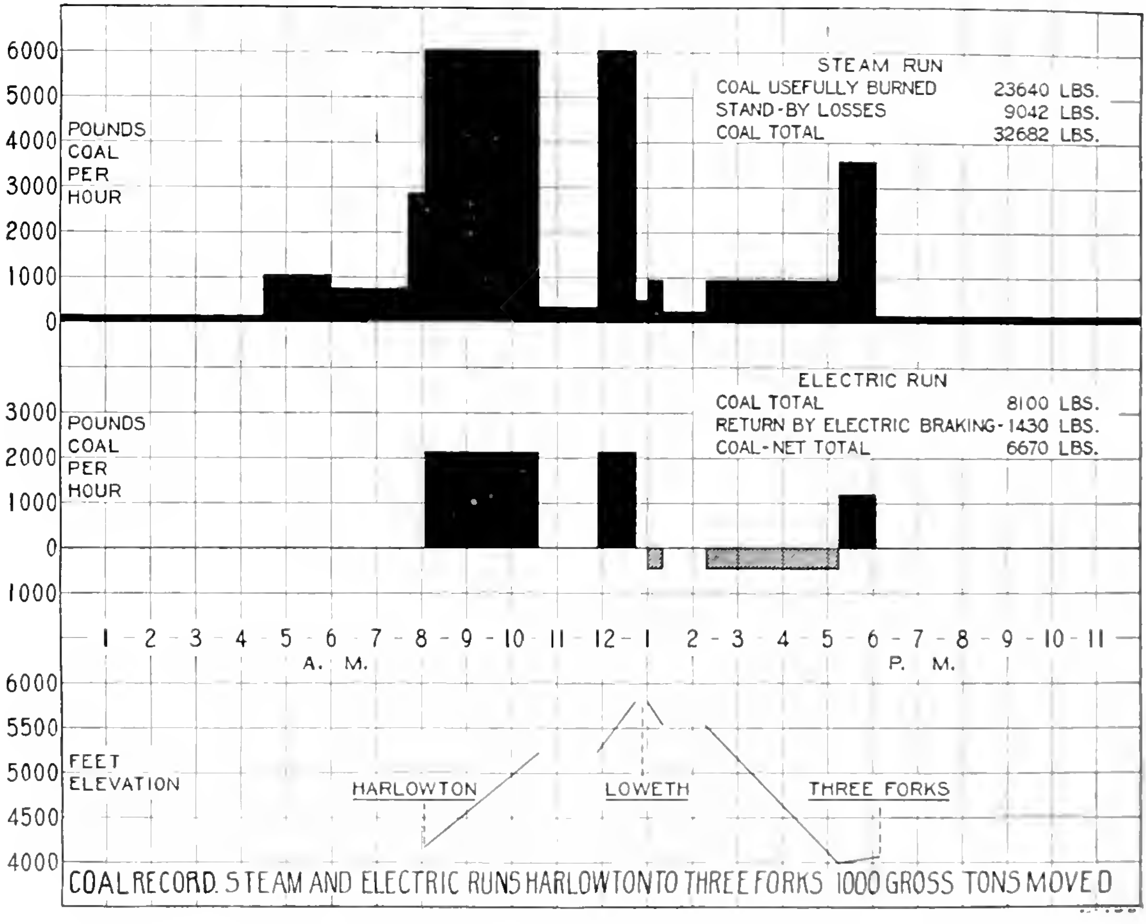

Fig. 1

TABLE VIII
POUNDS COAL PER 1000 TON MILES

	2% Grade	Level Track
Horse power hours at driver rims...	123	18.8
Indicated horse power hours at 80 per cent eff..	154	23.5
Lbs. water per i.h.p. hr..............	20	16
Lbs. water per lb. of coal...	6	8
Lbs. coal per i.h.p. hr.........	3.33	2.0
Lbs. coal per 1000 ton miles....	513	47
Lbs. coal per 1000 T. M. Trailing.....	650	50.5

The addition of superheaters gives greater output and economy, while mechanical stokers add output only and, it is claimed, at some expense in economy over good hand firing. However efficient the power plant on wheels may reasonably be developed without too seriously interfering with the sole purpose of the steam engine, namely, the hauling of trains, it can never approach the fuel economies of modern turbine generating stations. Whatever transmission and conversion losses are interposed between power house and electric locomotive are more than compensated for by the improvement in the load factor resulting from averaging the very fluctuating demands of many individual locomotives.

Every electrical engineer has learned the lesson of the fuel economy resulting from replacing several small and inefficient power stations by one large power house of modern construction. It therefore brings no surprise to his mind that the comparison of steam and electric railway operation discloses such enormous fuel savings in favor of the latter, for as a matter of fact, while our railways carry on a wholesale transportation business of the greatest magnitude, they are nevertheless engaged in burning coal and oil at retail on some 65,000 individual engines. The average output of each engine during the time it is at the call of the transportation department is but a small fraction of its rating. The fuel economy is further effected by the condition of the boiler and climatic conditions. Hence the average performance of many thousands of steam engines must reflect all the many handicaps of construction and service under which they operate.

It would be a simple matter to carry through a series of runs over the electrified zone of the C. M. & St. P. with a modern Mikado equipped with all the up-to-the-minute fuel saving devices and thus provide the necessary data to draw direct comparisons with the electric locomotive. Such tests with modern steam equipment would undoubtedly discredit the above comparison, which is based upon the economies of six years ago and might lead to something approximating the blend of fact and theory given in Table X.

This table is based upon actual electric locomotive performance, Harlowton, to Three Forks, coal taken at $2\frac{1}{2}$ lbs. per kw-hr. at assumed steam power station. Steam engine values are based upon the known working efficiency of a Mikado equipped with superheaters but penalized with the same standby losses actually determined with simple engine tested Harlowton to Three Forks. A test run from Harlowton to Three Forks with a modern Mikado engine hauling 1420 tons may possibly show a lower average fuel rate than 3 lbs. per indicated horse power hour at drivers, and lower standby waste than 9042 lbs. coal, but the average annual performance of many such engines would be most excellent

TABLE IX
ANALYSIS OF STEAM AND ELECTRIC RUNS, HARLOWTON TO THREE FORKS PER 1000 TONS MOVED

	Steam	Electric
Kw-hrs. at driver rims.....................	2038	2038
H.p. hrs. at driver rims............	2625	2625
Coal per h.p. hr. driver rims..........	9.02 lbs.	*3.09 lbs.
Credit regenerative braking...........	.....	.55
Standby losses, $27\frac{1}{2}$ per cent.........	2.47 lbs.	......
Total coal per rim h.p.-hr..............	11.49 lbs.	2.54 lbs.

*Measured at power house and includes locomotive losses and 32 per cent transmission and conversion loss.

if it reached the net figure arrived at, viz., 5.9 lbs. coal per actual horse power hour work performed at drivers. The electric run, however, is being duplicated daily as to relation between kilowatt-hours and ton miles, and it is just this reliability of electric operation that may at times give rise to misunderstanding in the comparison of steam and electric data.

Each individual electric locomotive will reproduce almost exactly the record of all others in similar service, little influenced by either extreme cold or skill of the engineer; while the firemen so-called and still retained has nothing to do with the matter at all. There is no creeping paralysis gradually impairing the efficiency of an electric locomotive until temporary relief is obtained through frequent washing of boiler and roundhouse tinkering, inevitably ending up in the major operations annually performed in the back shop hospital on the steam engine to keep it going. It is for such reasons that the electrical engineer is slow to accept general statements of average service operation based on the results of tests usually made on steam engines in excellent condition and skillfully handled. Then, too, there is insufficient data available as to standby losses, which must finally largely account for the wide discrepancy often noted between the amount of fuel purchased and fuel presumably burned or computed on the basis of test run records.

TABLE X

THEORETICAL COMPARISON, MODERN STEAM AND ELECTRIC LOCOMOTIVES HARLOWTON TO THREE FORKS

	Mikado	Electric
Type..	2-8-2	4-4-4-4-4-4
Weight on drivers	240,000 lbs.	450,000 lbs.
Weight engine and tender	480,000 lbs.	568,000 lbs.
Trac. efficiency 18 per cent coefficient	43,200 lbs.	81,000 lbs.
Trailing tons 1 per cent grade	1,420	2,836
H.p. hrs. at driver rims....	4,360	8,200
Coal per indicated horse power hour.	3	
Coal per driver horse power hr.	3.75	
Standby loss, test result	9,042 lbs.	
Standby loss per h.p.hr.	2.15 lbs.	
Total coal per driver horse power hour	5.90 lbs.	
Coal at power house, kw-hr...		2.5 lbs.
Coal at power house h.p. hr...		1.86 lbs.
Coal at locomotive driver, h.p. hr.		3.09 lbs.
Coal credit due regeneration..		.55 lbs.
Net coal at driver h.p. hr..	5.90 lbs.	2.54 lbs.
Total net coal .	24,800 lbs.	20,900 lbs.
1000 trailing ton miles	157,500 lbs.	314,000 lbs.
Coal per 1000 ton miles..	158 lbs.	66.7 lbs.
Ratio coal burned.. .	2.37 lbs.	1 lb.

It is with some knowledge of all these facts that the broad statement is made that the general adoption of the electric locomotive would probably result in saving fully two-thirds the fuel now burned on present steam engines, and possibly one-half the amount of fuel necessary for steam engines of the most modern construction.

Comparative Cost

The superior operating advantages of the electric locomotive are admitted by many who believe the first cost to be prohibitive, largely due to the trolley construction, copper feeders, substations, transmission lines, etc., which are necessary to complete the electrification picture. It is true that such auxiliaries add an amount that may equal the electric locomotive expense and the task of proving the electric case is not made easier by the fact that steam engine facilities are already installed and may have little or no salvage value to offset new capital charge for electrification.

Comparing the cost of equivalent steam and electric motive power, it is apparent that on the basis of the same unit prices for labor and material, the first cost is approximately the same. While electric locomotives cost possibly 50 per cent more than steam for equal driver weight, the smaller number required to haul equal tonnage may quite offset this handicap, especially with quantity production of electric locomotives of standard design.

The steam engine also demands a formidable array of facilities peculiar to itself, as shown in the following table of expenditures made on 14 railways included in the North Western group from 1907 to 1919. This expense covers fuel and water stations, shops and engine houses, shop machinery, turntables, ash pits, etc.

EXPENDITURES FOR ENGINES AND FACILITIES, NORTHWESTERN GROUP

1907–1919

Engines	Facilities
$68,000,000	$42,200,000

Proper facilities for rendering adequate steam engine service apparently add some 62 per cent to the cost of the latter and no cry of extravagance has ever been raised in this respect.

One of the advantages of electric locomotives rests in the longer engine divisions which they make possible. Two of the four steam engine divisions comprised in 440 miles of the St. Paul were wiped out by electrification and certain sidings and yard tracks were dismantled. To these exclusively steam engine facilities should be added therefore the expense of engine division points not necessary to successful electric railroading. Further credit is due to cover coal cars released. Therefore, considered as a problem of construction only, electrification of a new road may in some instances compare quite favorably with the complete first cost of steam engines and all facilities incident thereto. As the general problem, however, is one of replacing steam engines now running, the economic advantages of electrification are rather individual to the particular railway under consideration. The operating economies effected under favorable conditions have been found sufficient to show an attractive return upon the additional capital charge incurred besides providing the improved service which was the main objective in view in replacing the steam engine.

No discussion of electric railway economies would be complete without comment upon the increased value of real estate brought about by terminal electrification. Not only is neighboring real estate benefited thereby, but the "air rights" over the electrified tracks may become so valuable as to largely pay the cost of the change from steam. With the work but partly finished the Grand Central Terminal District, New York City, is already a remarkable example of the indirect benefits derived from electrification.

Summary

Some of the principal advantages claimed for the electric as compared to the steam locomotive are briefly:

1. No structural limits restricting tractive effort and speed of electric locomotive than can be handled by one operator.
2. Practical elimination of ruling grades by reason of the enormously powerful electric locomotives available.
3. Reduction of down grade dangers by using regenerative electric braking.
4. Very large reduction in cost of locomotive maintenance.
5. Very large saving of fuel, estimated as two-thirds the total now burned on steam engines in operation.
6. Conservation of our natural resources by utilizing water power where available.
7. Material reduction in engine and train crew expense by reason of higher speeds and greater hauling capacity.
8. Increased valuation of terminal real estate following electrification.
9. Increased reliability of operation.
10. Material reduction in operating expense due to elimination of steam engine tenders and most of the Company coal movement, the two together expressed in ton miles approximating nearly 20 per cent of present gross revenue ton mileage.
11. Large reduction in effect of climatic conditions upon train operation.
12. Postponement of immediate necessity for constructing additional tracks on congested divisions.
13. Attractive return on cost of electrification by reason of direct and indirect savings in operation.
14. Far reaching improvements in operation that may revolutionize present methods of steam railroading.

The Electric Reversing Mill Considered from the Standpoint of Tonnage

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This discussion of the operation of the electric reversing steel mills is unique in that it is based on tonnage production. Since the current-limit setting, which is necessary for the protection of the equipment, measures the peak load capacity of the drive and places a limitation on production, a very careful analysis is made of the speed-torque characteristics of the drive as affected by the current setting when rolling the several passes required to break down an ingot. It is shown that an increase in production can be secured with less than the same percentage increase in first cost of equipment. This fact should receive most careful consideration. Originally, this article was presented as a paper before the 1920 Annual Convention of the Association of Iron and Steel Electrical Engineers at New York City.—Editor.

Many articles have been written bearing on the subject of the electrically driven reversing mill but a perusal of them reveals the fact that the matter of tonnage, so important to the steel mill man, has been given almost no place in them. Interesting installations and systems of control, having as their object the protection of the electrical equipment from peak loads, have been described, frequent references have been made to the power consumed in rolling and to its cost, but nowhere has the writer found that we have squarely faced the question of tonnage, the real issue between the steam driven and the electrically driven mill. Can the latter produce, at a reasonable cost, a tonnage equal to or greater than the steam mill? This question we can unqualifiedly answer in the affirmative, as is proved by the records of some of the mills to which reference is made later. From the standpoint of production the electric mill has many advantages over the steam mill, chief among which is the extremely small loss due to delays caused by the drive and because of this an electric mill of the same hourly capacity will exceed the steam mill in monthly or yearly capacity. However, the task of the electric mill is not an easy one and the handicap which the steam mill has over its competitor, due to the lower moment of inertia of its moving parts, must not be treated too lightly.

Obviously the principal factor which affects the hourly capacity of a mill is the time required to roll an ingot without exceeding the capacity of the drive to repeat this cycle indefinitely. Consequently, this article is devoted largely to a discussion of the influence of the control on the rolling time, particularly to the effect of limiting the maximum power delivered to the direct-current motor driving the rolls. As we are concerned only with the reversing mill proper, it is assumed that no unnecessary delays occur in the manipulation of the steel on the live roll tables, in the transfer of the ingots from the soaking pits or in the removal of the finished steel from the mill. If any improvement in these details is possible, no time should be lost in taking the necessary steps whatever the type of drive used for the main rolls. We are therefore assuming that the mill is properly tuned up and that the intervals between passes are the same for all mills, referring briefly later to some of the characteristics of the different types of drives which tend to affect this interval.

The time required to roll an ingot, assuming the interval between passes to be the same, is increased directly by an increase in the time the steel is under the rolls. This in turn is affected by the speed at which the steel enters the rolls, the time required to accelerate to the maximum speed after the steel has entered, the maximum speed attainable, the time the rolls run at this speed during the pass, and the time to retard the mill to a proper delivery speed at the end of the pass. The entering speed is limited largely by the section of the steel, the design of the rolls, the draft, etc., and is independent of the drive. The delivery speed should be as high as is permissible without increasing the interval between passes, and as the time for retardation is extremely short with any drive it may be assumed without appreciable error to be the same for all. This leaves only the time required to accelerate after the steel enters, the maximum speed, and the time of rolling at the maximum speed, as being subject to variations due to the speed-torque characteristic of the drive.

Before entering further into a discussion of the subject, the writer wishes to caution against a very common mistake made by engineers when discussing reversing mill problems. We frequently hear the expression: "The time of reversal." This should not be confounded with the time required to accelerate. If the word "reversal" or the expression "acceleration and retardation" is used, it should be qualified by the limiting speeds between which the reversal or acceleration and retardation takes place, e.g., from 90 r.p.m, forward to 90 r.p.m, reverse. By simply rocking a machine, it may be made to reverse many times a minute; and yet it may be extremely slow in getting up to speed with steel in the rolls.

The reversing mill was first driven electrically abroad where the requirements of the mills are very different from those in America. In general the rolls are larger in diameter, their speeds are higher, and the tonnages are very much smaller than is our practice. Naturally, therefore, we find the motors, generators, and controls designed to meet these conditions rather than those of producing the maximum tonnage from the mills which they drive. A complete description of one of the early German electrically driven reversing mills is given in *Stahl und Eisen*, January 23, 1907, from which the following short description of the system of control is taken:

"The main rolls are driven by three direct-current motors direct connected to the mill and connected electrically in series and supplied from an Ilgner Ward-Leonard flywheel set having two generators designed for 500 volts each, connected in series, making a total of 1000 volts applied to the mill motors. The excitation for the motors and generators is obtained from a small exciter motor-generator, consisting of two direct-current generators driven by an induction motor. One of these generators serves to excite the shunt windings of the generators and main roll motors. The other generator of the exciter set supplies special compound windings provided for strengthening the fields of the roll motors as their loads increase, thereby causing a reduction in their speed and thus relieving the generators of the overloads which would otherwise be occasioned."

In America conditions are very different. Tonnage is usually the all important consideration and a fraction of a second per pass lost because of insufficient capacity in the drive, because of the slowing down of the roll motors due to special windings as described above, or because the motors are prevented by any means from taking the peak loads required to accelerate properly with the piece in the rolls, will cost the operator (through the loss in production) many times the few dollars he will save in the first cost of the equipment.

That reversing mill requirements are severe must be recognized, and the machines used to drive them together with their controls must be designed to meet these conditions with sufficient momentary peak load capacity to take care of the combined acceleration and rolling load of each pass, and with sufficient continuous capacity to roll constantly at the rate necessary to produce the required tonnage. Because of the confusion which now exists due to the different methods of rating the equipments now in use, it is imperative that standard specifications be prepared to cover reversing mill main roll drives. That the need for this is fully appreciated by both the manufacturers and the operators is evidenced by the discussion which followed the reading of the paper, "Standardization of Ratings of Large Rolling Mill Motors," presented by the writer at the 12th Annual Convention of the Association of Iron and Steel Electrical Engineers, held at Baltimore in September, 1918.

There is, of course, a limit to the capacity of any drive; and the characteristics of electrical equipment are such that unless some automatic means is provided for limiting the power of the roll motors a careless operator can abuse the equipment. Current-limit controls have been developed for this purpose, their function being to limit the current taken, and, therefore, the maximum power developed by the roll motors to a value which they and their generator can safely carry at frequent intervals. The current-limit setting for the main roll motors is therefore a real indication of the relative peak load capacities of two equipments designed for the same voltage. This limitation of current taken by the roll motors should not be confused with the control of the induction motor driving the flywheel motor-generator through the slip regulator. As time is required for the current-limiting device to function, the current tends to rise above the value corresponding to the relay setting, but the peak in excess of the setting is of such short duration that it produces little effect on the acceleration of the roll motor. The effect of the setting of the current-limit relay on the tonnage produced in the mill, and the importance of setting it for as high a current as is possible can be very well understood by a brief study of the effect of different current-limit settings upon the time to make the pass.

For the purpose of comparison, we have assumed the mill to be driven by a motor with the current-limit set for three different values (9500, 8500, and 7000 amp.), the potential of the generators supplying the motors being 1200 volts when delivering the currents for which the current-limit relays are adjusted.

and with the motor-generators running at the minimum speed occurring during the normal rolling cycle. Such a generator or generators will develop 1450 to 1500 volts when running at full speed and carrying no load, and care must be taken in computing the horse powers corresponding to any specified current-limit setting that only the voltage delivered by the generators when delivering these currents is used and not the running light voltage, as is frequently done.

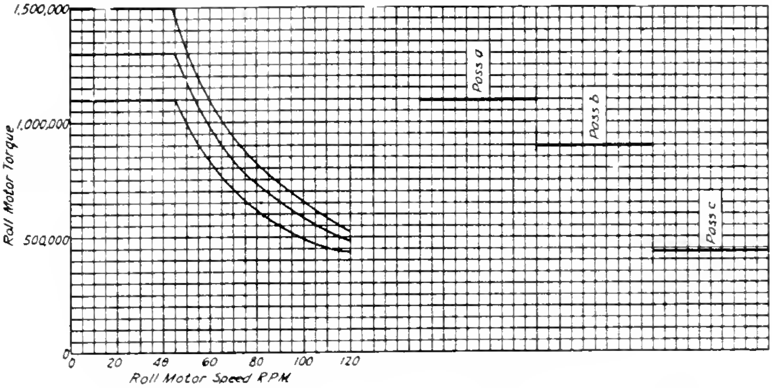

Fig. 1. Speed-torque Curves of a Reversing Mill Motor Corresponding to Three Current-limit Settings, and Torques Required to Roll Three Passes

The curves in Fig. 1 are the approximate speed-torque curves of a typical reversing mill motor corresponding to these three current settings, together with the torques required to roll three of the passes in breaking down an ingot 22 by 24 inches on the butt end and weighing 8100 lb. to an 8 by 8-inch bloom in 15 passes. These passes are the first pass after the ingot has been squared up, referred to later as pass "a"; the middle pass "b"; and the last pass "c."

Now if the mill is to meet its tonnage requirements, it must be able to accelerate rapidly after the steel has entered. Of the motor torque available for acceleration after the steel has entered, we have only that which is in excess of the amount required to roll and this decreases at a much greater rate than the reduction in current-limit setting. This is clearly shown by Fig. 2, from which it will be seen that although the 8500-amp. setting is only 13½ per cent less than the 9500-amp. setting, the torque with the 8500-amp. setting available for accelerating the mill, after the steel has entered, is for pass "a" only one-half of that with the 9500-amp. setting, and for pass "b" is only two-thirds of that with the 9500-amp. setting. This difference becomes still more marked as the current limit is further reduced until we reach the 7000-amp. setting for which there is no torque available for acceleration after the pass "a" has entered, although the 7000-amp. setting is only approximately 27 per cent below the 9500-amp. setting. Also, with the 7000-amp. setting we have available for acceleration after pass "b" enters only one-third of the torque available for the 9500-amp. setting. At this setting the pass "a" cannot be rolled faster than the entering speed, and the speed during pass "b" can increase only slightly above the entering speed. As the current limit is reduced below 7000 amp. it becomes necessary to increase the number of passes

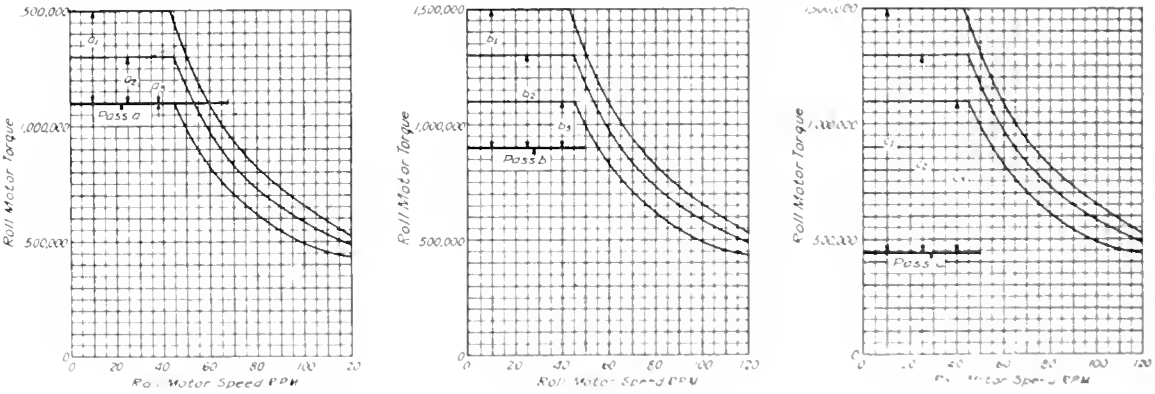

Fig. 2. Speed-torque Curves of Fig. 1 Analyzed with Respect to the Torques Required by the Passes Shown in Fig. 1

and to rearrange the rolling cycle, reducing the drafts of some of the passes and rolling others at the speeds at which the steel enters, the effect of which, on the tonnage output of the mill, is obvious.

On the other hand, it is the peak load as determined by the current-limit setting and not the magnitude of the torque available for acceleration a₁, a₂, a₃, b₁, etc., Fig. 2, which affects the first cost of the equipment, driving the mill, and any saving in first cost conditioned upon a limitation of the current below the value required to roll, with a reasonable margin available for acceleration after the steel enters, is false economy. Furthermore, the first cost is affected by the continuous as well as the momentary peak load capacity. Therefore, the percentage increase in first cost will often be less than the percentage increase in the current-limit setting which this increase in first cost buys. The current-limit setting is, therefore, a matter which should be given very careful consideration in comparing equipments of this type.

The effect of the current-limit setting on the length of time to roll can be determined mathematically by the use of the following formulæ, by subdividing the roll motor torque curve into two parts; the portion corresponding to full motor field and that corresponding to weakened motor field.

The time t required to accelerate from a speed S_0 to S_1 and the distance traveled D by the steel during this time can be determined by the following formula:

When S_0 and S_1 fall within the full motor field portion of the speed-torque curve:

$$t = \frac{0.195\, WR^2\,(S_1 - S_0)}{T_r}$$

$$D = \frac{S_1 + S_0}{2} Lt$$

Where

WR^2 = Weight in pounds times radius of gyration in feet scuared, of the revolving parts of the mill and drive.

T_r = Motor torque minus load torque; a₁, a₂, etc., Fig. 2.

L = Distance traveled in inches for one revolution of rolls.

When S_0 and S_1 fall within the weakened motor field portion of the speed-torque curve:

$$t = \frac{K}{A^2}\left[A\,(S_1 - S_0) + HP_1\, \log_e \frac{HP_1 + AS_0}{HP_1 + AS_1}\right]$$

$$D = \frac{K}{A^3}\left[A^2 \frac{(S^2{}_1 - S^2{}_0)}{2} - HP_1\, A\,(S_1 - S_0) - HP_1{}^2\, \log_e \frac{HP_1 + As_0}{HP_1 + As_1}\right]$$

Where

$K = 0.00223\; WR^2$

$A = -\dfrac{T_1}{87.5}$

HP_1 = Maximum horse power of motor as determined by the current-limit setting.

T_1 = Torque required to roll.

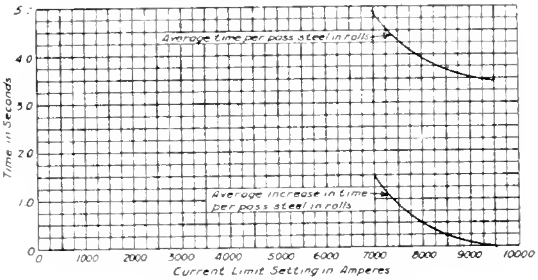

Fig. 3. Curves Showing the Increase in Time Required to Roll Resulting from Lowering the Current Limit

The effect of lowering the current limit on the time required to roll is shown by the curves in Fig. 3, which are based on rolling the 8 by 8-inch bloom from the 22 by 24-inch ingot referred to. This curve has been extended back only to approximately 7000 amp. as it becomes necessary to re-arrange the passes, increasing the number and reducing the drafts, as the current limit is reduced, and thus the time for rolling is further increased with corresponding reductions in tonnage output. The curve shows that lowering the current limit from 9500 amp. to approximately 7000 amp. increases the average time the steel is in the rolls by approximately 1½ seconds per pass, which for a 15-pass cycle means a loss of 22½ seconds per ingot, an amount which will seriously reduce the output

TABLE I

Pass	Approximate Current-limit Setting; Amp.	Maximum Speed During Pass; R.p.m.
a	9500	53
a	8500	42
a	7000	10
b	9500	67.5
b	8500	62
b	7000	52.5
c	9500	124
c	8500	116.5
c	7000	104

of any mill designed for large or moderately large tonnage.

It is recognized that the rate of acceleration, and therefore the time of rolling, is affected by the moment of inertia of the revolving parts, but the variations in modern standard reversing mill drives from the values used in the preparation of the curves in Fig. 3 will produce no material changes in the results shown.

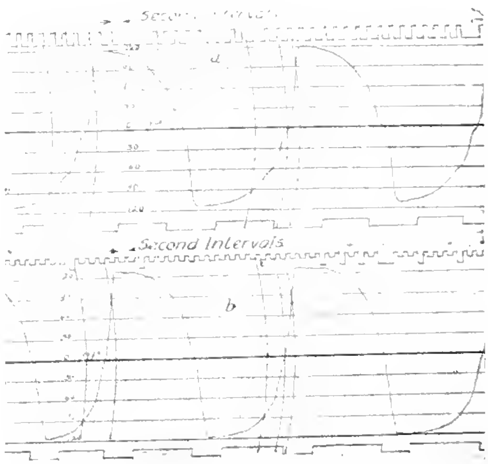

Fig. 4. Speed-time Curves Taken at the Trumbull Mill Before and After Changes Were Made in the Control

It is also interesting to note the effect of the variations in current limit on the maximum speed attained during the pass as given in Table I on preceding page.

Appreciation of the importance of tonnage to American operators led us to adopt the shunt-wound motor for driving reversing mills in preference to the compound-wound motor so generally used throughout Europe, as well as to some extent in America. The machines are designed to commutate large currents, our current limits being set at 9500 amp. and higher for 1200-volt units. The changes in the field flux of the motors and generators have been carefully studied, and the control so designed as to take maximum advantage of the characteristics of each to produce rapid acceleration and retardation without the least interfering with the complete control of the speed of the motors for rolling. Special means are provided for forcing the generator and motor fields to act quickly during acceleration and retardation. The magnet yoke as well as the pole pieces of the generator fields are laminated to reduce to a minimum the eddy currents that tend to reduce the rate of acceleration and retardation. However, in spite of the complexity of the problem involved in the control of these large units, the system of control as finally worked out is readily maintained by the plant electrical department.

It is essential in entering any new field of application to include a larger factor of safety in the design of the equipment involved than is customary in established fields; and after our early reversing mill equipments had been in operation a short time, we appreciated that by certain minor changes in the control we could make a material reduction in the time required to accelerate and retard, and accordingly a complete series of tests were made at the works of the Trumbull Steel Company with this in view. The Trumbull Mill is a 36-inch reversing blooming mill driven by a standard 6250-h.p. (A.I.E.E. rated; 5000-h.p., 35 deg.) 50/120 r.p.m. direct-current reversing mill motor, having a maximum momentary capacity of 17,000 h.p. at 45 r.p.m. and supplied with power from a 5400-kw. (A.I.E.E. rated; 4000-kw., 35 deg.) flywheel motor-generator, consisting of two

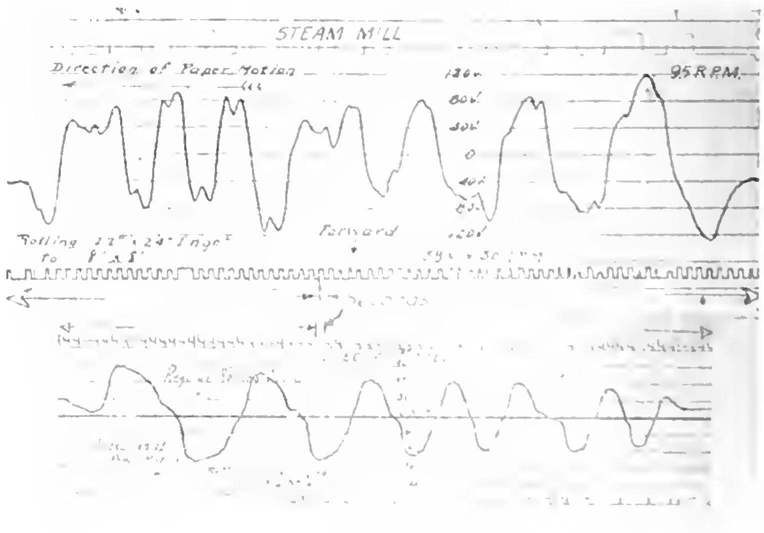

Fig. 5. Typical Speed-time Curves of a Steam Mill and an Electric Mill

2700-kw. A.I.E.E. rated direct-current generators and a 50-ton flywheel, driven by a 3750-h.p. A.I.E.E. rated induction motor. Tests of this nature of necessity require a great deal of time, as one of the factors involved is commutation and intervals of several weeks and often months are required to determine with any degree of certainty the outcome of any change.

Fig. 4 shows curves taken on the Trumbull Mill before and after the changes were made in the control. In order to avoid the introduction of errors due to variations which would unavoidably occur if steel were being rolled because of the irregularities in draft, temperature, etc., these curves were taken without steel in the rolls.

From examination of the curves it will be found that the time required to reverse from 90 revolutions forward to 90 revolutions reverse was reduced from four to three seconds, as a result of the changes which were made in the control. Practically all of this saving was made during the accelerating portion of the cycle, approximately one second being required to retard in either case. This reduction in acceleration time either shortens the time required for the mill to reach a given speed or makes it possible for the rolls to reach a higher speed during the pass, both of which increase the average speed during the pass.

These results compare very favorably with those obtainable with modern steam reversing engines under similar conditions, and any slight advantage which the steam engine may have over the electric motor in the rate of acceleration, as shown in Fig. 4, is more than offset by delays due to slowing down and frequent stalling as the steel enters steam driven mills. This difference between the steam engine and the shunt-wound mill motor is clearly shown by the curves in Fig. 5, which are the speed-time curves for the Trumbull Mill and a modern steam mill. Note that it is approximately one second after the steel enters the steam mill before the engine has regained the speed at which it was running when the steel entered, while with the electric mill there is no drop whatever, as is shown by the Trumbull curve. It is here that the shunt-wound differs from the compound-wound mill motor, the latter dropping in speed as the steel enters although not to as great an extent as the steam engine. These curves are selected to illustrate the speed characteristics of the two types of drives rather than to indicate record speeds.

The developmental work which we carried on at the Trumbull Mill, resulting in increasing the rate of acceleration of the motor beyond the contract obligations, we feel has fully repaid us for the time and expense involved, because of the reduction in rolling time and consequent increase in tonnage made possible by it as evidenced by some of the remarkable records made on this mill. The Trumbull Steel Company has rolled one 22 by 20 by 60-inch ingot weighing 6700 lb. down to a 6¾ by 6¾-inch billet in 11 passes in 57 seconds and has rolled 57 of these ingots, 190 short tons, to the same final section in one hour, taking 13 passes per ingot to bring about the reduction.

The 40-inch blooming mill at the Sparrows Point Works of the Bethlehem Steel Company is driven by a duplicate of the equipment driving the 36-inch Trumbull Mill, except that the changes necessary to bring about the results shown by curve "b," Fig. 4, have not been made, in fact the control is the same as that at the Trumbull Mill when curve "a," Fig. 4, was made. The Bethlehem Steel Company has rolled one 23 by 43-inch ingot weighing 16,500 lb. to a slab 9 by 38 inches in one minute and twenty seconds and to a bloom 8 by 8 inches in two minutes and fifteen seconds, and has rolled 330 tons of 10 by 40-inch slabs in one hour, and 198 tons of 8 by 8-inch blooms in one hour, and during the month of October this mill has rolled 64,000 gross tons of ingots to blooms and slabs.

These curves shown in Fig. 6 were taken on the 40-inch blooming mill at Sparrows Point, curve "a" being taken while rolling slabs 5 by 28-inch from a 28 by 39-inch ingot weighing 18,000 lb. and curve "b" when rolling an 8 by 8-inch bloom from a 26 by 26-inch ingot weighing 9100 lb.

These records made at the Trumbull Plant and at the Sparrows Point Works of the Bethlehem Steel Company exceed those made by any other electrically driven reversing blooming mill and put the electric mill in the class with the steam mill from the standpoint of tonnage. Coupling these records with the advantages of the electric mill over the steam mill from the standpoint of lower power costs, lower maintenance cost, greater flexibility of control, etc., leaves little room for argument in favor of the steam reversing mill, and convinces us that it is now as out of date as the non-reversing steam mill has been for many years.

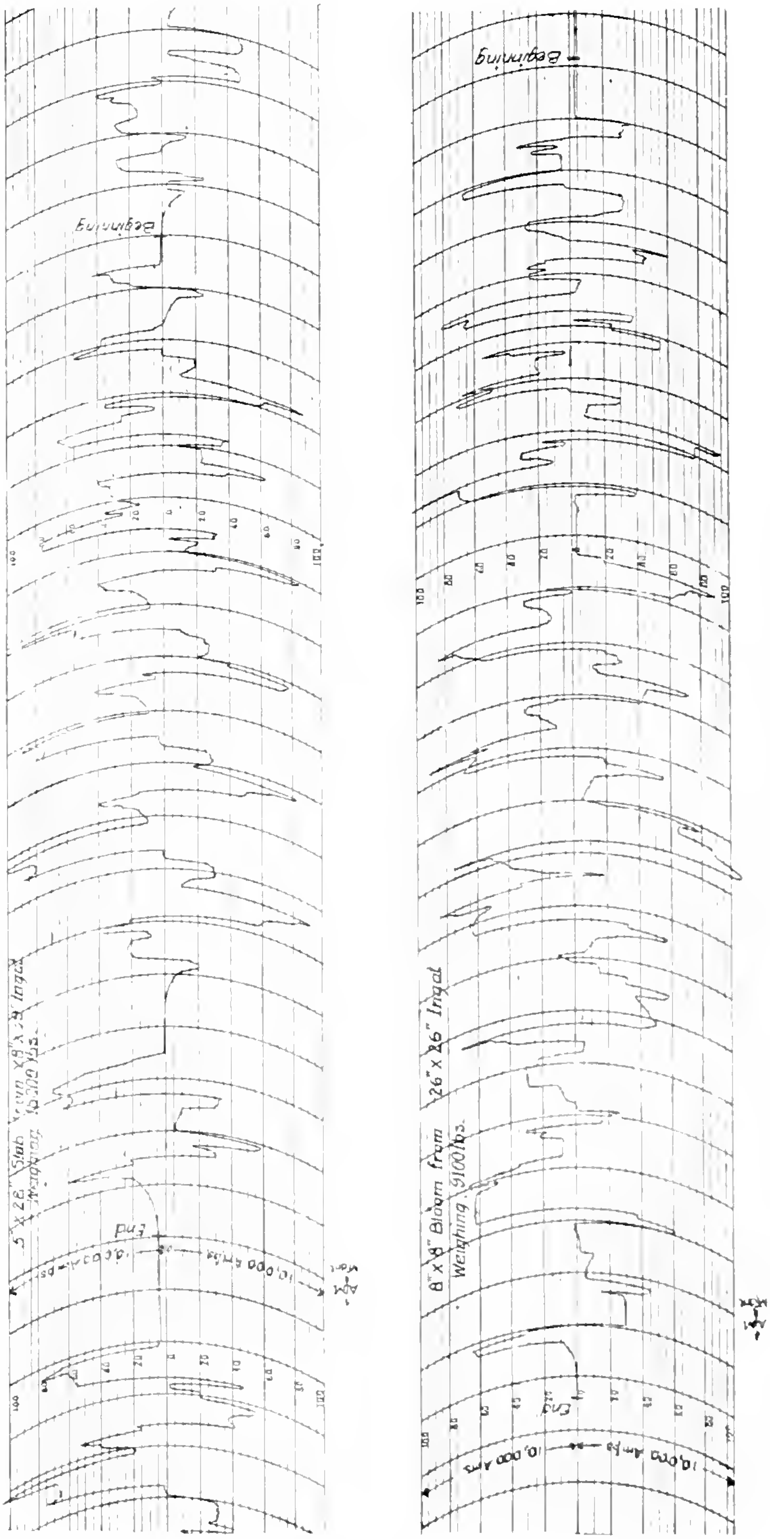

Fig. 6. Speed-time Curves Taken at the Sparrows Point Mill When Rolling Slabs and Blooms as Specified on the Curves

Effect of Ultra-violet Rays on the Eye

Dr. C. R. Kindall, Surgeon of the Bureau of Mines, has issued a report in which it is stated that 30 men were recently viewing the demonstration of a new portable electric arc-welding outfit and a few hours later 17 of the 30 men reported to the doctor for treatment. They were suffering from *traumatic conjunctivitis*. In two cases the pain was very severe and the symptoms were similar to those of iritis. Morphine had to be administered to afford relief from pain. Only two men of the 30 were not affected in some way from this exposure. These two men wore thick-lensed orange-colored glasses. Several of the men wore orange-colored glasses with thin lenses, but the latter were not heavy enough to afford protection against an exposure as long as took place. The distance of the eye from the arc also influences the possibility of injury.

Conjunctivitis is an inflammation of the conjunctiva; the conjunctiva is the mucous membrane covering the inside of the eyelids and part of the eyeball. Traumatic conjunctivitis is caused by foreign bodies in the eye, exposure of the eyes to high winds, dust, smoke, intense light from electric arc lamps, and from electric welding apparatus. In the instance mentioned above, the inflammation was due to the ultra-violet rays. In some cases the effect is so severe that, in addition to conjunctivitis, an inflammation of the skin similar to sunburn is produced.

The symptoms of conjunctivitis caused by intense light or by the ultra-violet rays are abnormal intolerance to light, excessive secretion of tears, intense smarting of the lid, contraction of the pupil, sometimes swelling of the lid, and small ulcers developing on the eyeball or cornea. Unless properly treated by a physician immediately, chronic inflammation of the conjunctiva, cornea, iris, or retina, and possibly blindness, may result.

Under proper treatment most cases get well in a few days. All treatments should be under the direction of a physician. That usually advised is to place ice packs on the patient's eyes three or four times daily. The pack should be left on from 15 minutes to an hour. The eyes should be irrigated with normal salt solution (a teaspoonful to a quart of sterile water) or a saturated solution of boric acid several times daily. If there is a discharge of pus, a few drops of a 25 per cent solution of argyrol or a 5 per cent solution of protargol should be placed in the eyes three to six times daily. The patient should be confined to a darkened room until his condition improves in order to avoid complications. These treatments will reduce the swelling, give the patient comfort, and prevent the development of chronic conjunctivitis. In severe cases it may be necessary to administer morphine to relieve the pain.

All of the eye trouble recounted was caused by neglecting to observe simple and well known precautions. The glare from an intensely bright point of light like the electric arc, even at a distance of 20 or 30 ft., may prove a source of injury to many eyes, although at this distance all injurious ultra-violet rays would be absorbed by the air.

The only safeguard against glare is a dark glass, and a flashed dark ruby glass between two pieces of emerald green glass forms a very good combination. Blue glass should generally be avoided, and orange-colored glasses, unless very dark, will not sufficiently subdue the glare of a strong arc.

At every plant where electric arc-welding outfits are used, there should be an adequate supply of these glasses. There should also be on hand at the plant dispensary or hospital a supply of boric acid, sterilized water, ordinary table salt, argyrol and protargol for immediate use. As previously mentioned, all cases of traumatic conjunctivitis, caused by exposure to bright light or ultra-violet rays, should be treated under the direction of a physician.

For more complete discussion of eye protection from injurious rays see article in GENERAL ELECTRIC REVIEW for December, 1918, entitled "Eye Protection in Iron Welding Operations," by W. S. Andrews.

Addenda to article, "A Special Form of Phosphoroscope," by W. S. Andrews, October issue.

Through error the following paragraph was omitted from the article:

The general features of this phosphoroscope are described in a paper by Dr. Wallace Goold Levison, published in "Annals" N. Y. Acad. Sci. XI, N. 17, pp. 401 to 403, October 13, 1898.

Automatic Substation, Sacramento Northern Railroad*

By W. H. Evans

Electrical Engineer, Sacramento Northern Railroad

The electrical equipment of the portable automatic railroad substation described here is of interest not only to railroad engineers but also to electrical engineers in all branches of the profession as the use of automatic apparatus is becoming of widespread application.—Editor.

Although only the highest type of service can well be tolerated by any public service company, yet there must be certain definite economical relations maintained between the cost of service and the results gained. If the gain in service is not achieved economically the ends will be defeated. If a gain in service may be made with economy, that advantage will be taken. In the case in point, the Sacramento Northern Railroad had been operating its line with substations normally spaced ten miles apart. However, between Sacramento and the first substation north, there were fourteen miles and as the traffic was particularly heavy there the voltage conditions were not the best. The results were slow speed for both freight and passenger trains, and undue heating of motors.

GENERAL FEATURES

To remedy this condition it was decided to install at a point about 5.6 miles north of Sacramento, a portable automatic substation which our figures showed could be installed for something less than $19,000, whereas feeder cable to produce the same voltage regulation would have cost in excess of $40,000.

The portable substation consists briefly of a 300-kw., 600-volt, 60-cycle, 1200-r.p.m., 6-phase synchronous converter, a 240-kv-a., 2344/445-volt, oil-insulated, self-cooled, 3-phase transformer, together with the necessary automatic control equipment. All of this apparatus is installed in a box car constructed in our own shops from an 80,000-lb. capacity, 40-ft. flat car, with the necessary siding and roof added.

Energy is delivered to the railroad's portable substation at 2300 volts, 3-phase, from the power company's 60,000-volt to 2300-volt transformers, which are located on a concrete platform and with the pole-top switches and fuses are enclosed by a high wire fence for protection against trespassers.

Since the substation is automatic, normally the doors are always closed and locked, and in order to provide ventilation, louvers were let into both sides and ends of the car; in addition screened openings are placed in the floor of the car for further ventilation.

METHOD OF OPERATION

It may be of interest to give a short outline of the sequence of operations which takes place in automatically starting up and shutting down.

Starting

With the station shut down, and a train coming into the substation zone on either side, the third rail voltage is gradually lowered until it reaches the value at which the relays in the automatic substation are set to govern starting.

Relay 1 (Fig. 1) is a contact-making voltmeter which is adjustable for any particular trolley voltage desired, in this case 500 volts. In connection with the underload relay 37, which functions to shut down the station, these two relays are the primary control in starting and stopping the station.

Relay 1 closes instantaneously when the voltage drops to 500 volts, short circuiting the coil of relay 2 which is a time-limit circuit-opening relay whose function is to provide a time delay in starting up the equipment as the low voltage conditions appear, because obviously a momentary swing below 500 volts should not be permitted to start up the station; the time setting of relay 2 can be adjusted to suit the particular conditions at any point.

The contacts of relay 2 are normally closed when the station is not running. When relay 1 operates, closing its contacts, relay 2, after a predetermined time, opens its contacts and permits the coil of relay 3 to be energized. Relay 3 then closes its contacts, and control current from the 5-kw. auxiliary-control transformer is admitted to the control circuits of the station. A circuit is then established from the alternating-current control bus through the contacts of relay 27-X, the contacts of relays 3 and 26, operating coil of relay 4, auxiliary switch on circuit breaker and hand-

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* Reprinted with changes from *Journal of Electricity*.

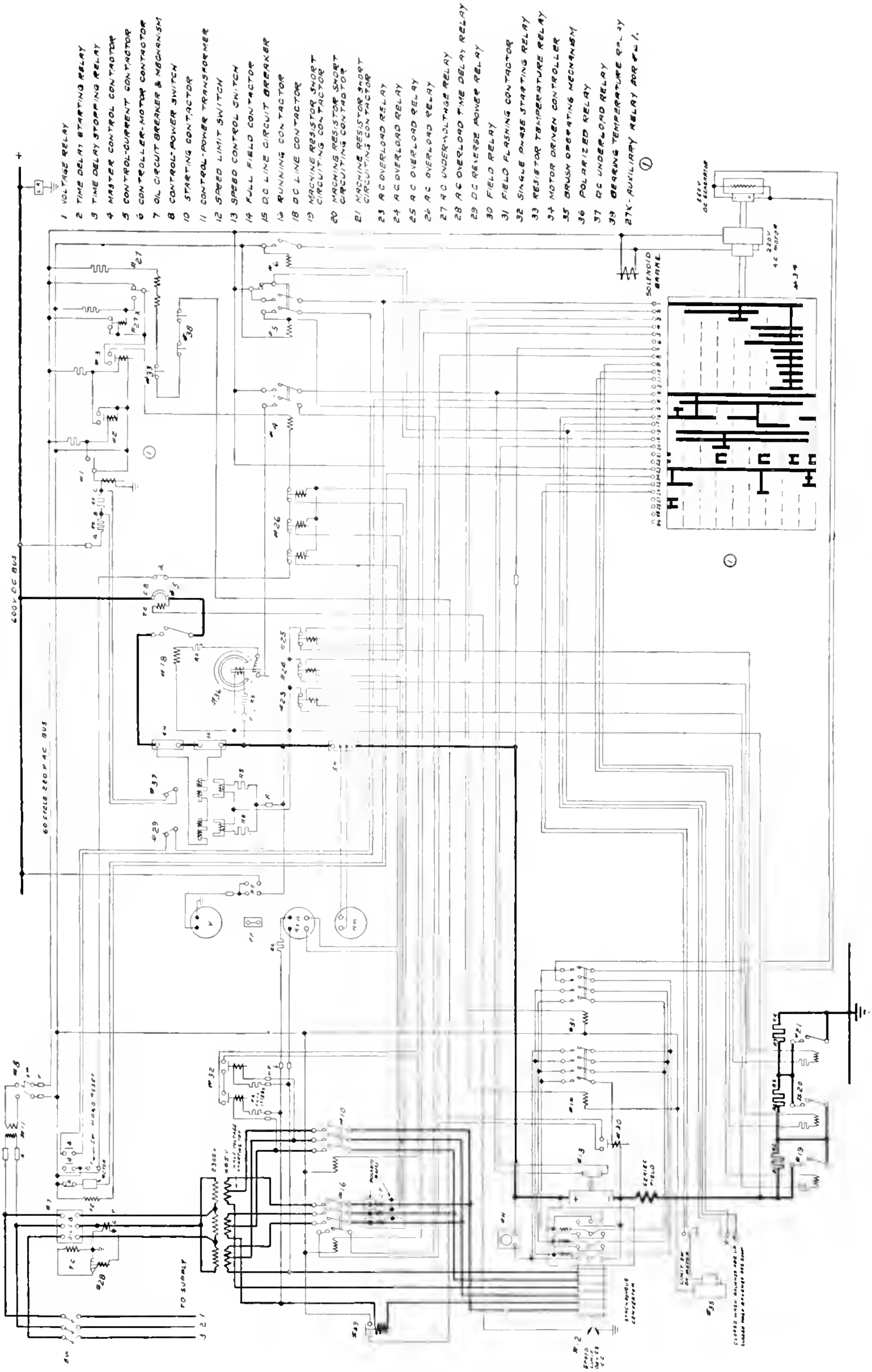


Fig. 1. Schematic Wiring Diagram of Automatic Substation

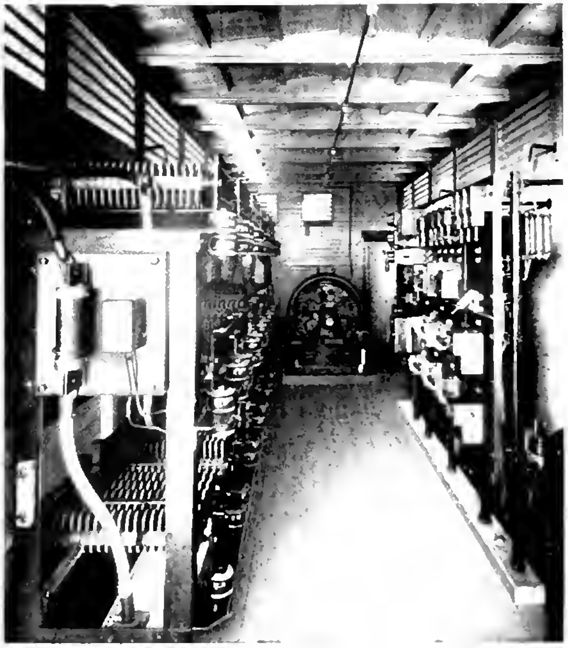


Fig. 2. Converter in Background is Equipped with Flash Barriers and Motor Operated Brush Lifters. Automatic Control Board to the Right and Series Resistances to the Left

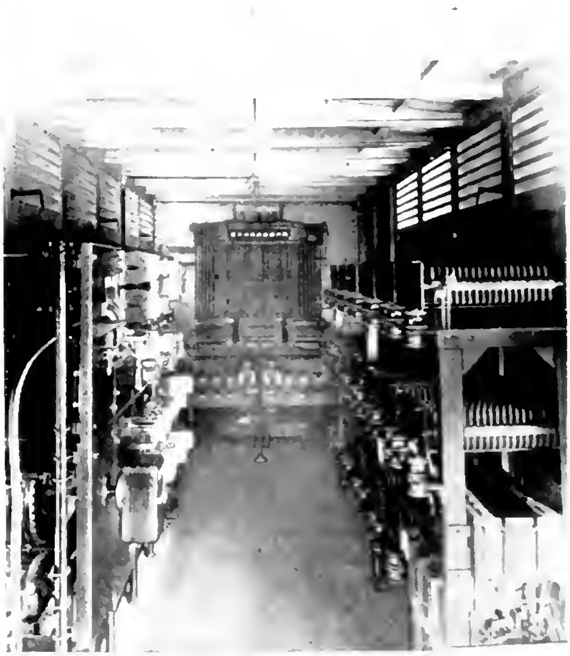


Fig. 3. Transformer End of Car Showing Arrangement of Louvers to Assist Rapid Cooling

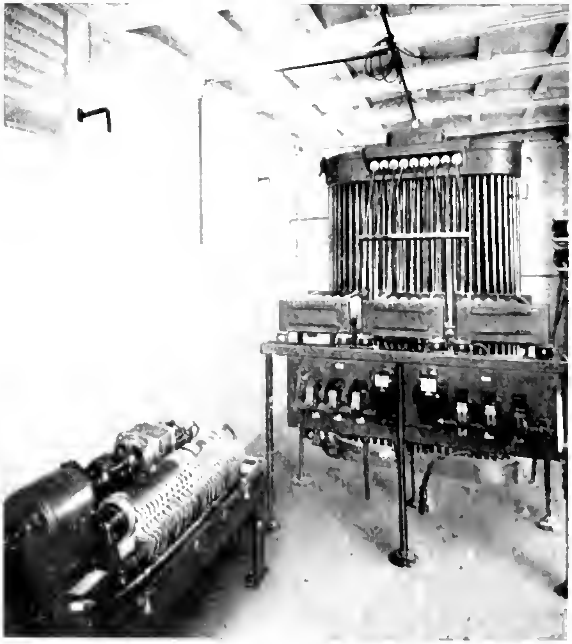


Fig. 4. Starting Grids, Running Contactors and Motor Operated Drum Controller

Fig. 5. Near View of 240 kv-a. Starting Transformer, Motor Operated Oil Breaker and 5 kw. Control Transformer

reset switch on oil-switch motor mechanism back to control bus. The closing of contactor 4 establishes a circuit from the control bus through one of its contacts to segment 13 on the controller, then to segment 16 upper contact of auxiliary switch on brush-raising device, and to the operating coil of contactor 6 and back to the control bus.

Operation of Controller

Contactor 6 closes and starts the motor driving the controller which is very similar to the ordinary type K street-car controller. Through its various contact fingers and segments the controller establishes the necessary sequence of operation of the various switches for starting up and shutting down the station, each succeeding step, however, being checked electrically by means of various relays to insure that the electrical and mechanical conditions have been properly fulfilled.


Fig. 6. The Automatic Railway Substation and Its Outdoor Transformer Installation

Segment 15 on the controller closes the operating coil of contactor 5 which establishes a circuit through one of its contacts to segment 1 on the controller and simultaneously completes a circuit from the same contact to the closing circuit of the oil-switch motor mechanism.

The oil switch now closes, energizing the power transformer, and if the proper alternating-current voltage exists on all three phases of the low tension side relays 32 close. These relays are so connected that no further operation can continue unless the proper phase voltage exists. Segment 14 on the controller then makes contact, completing a circuit through the auxiliary switch on the oil circuit breaker, one of the contacts and the operating coil of 5. This operation thus establishes a holding circuit for contactor 5 as soon as the controller advances beyond segment 15. Segment 2 on the controller then makes contact, completing a circuit through the contacts of the relay 32 and the operating coil of contactor 10.

Start of Converter

The starting contactor 10 now closes, placing reduced voltage from the transformer upon the slip rings of the converter, which starts. If the converter has come up to synchronous speed by the time the first gap in segment 16 is reached, a circuit is established from segment 14 through the contacts of 13 to segment 20 and thence to segment 18 and the operating coil of contactor 6. This holds contactor 6 closed until the gap in segment 16 is passed. However, if the converter has not come up to speed by the time the gap in segment 16 is reached the circuit to the operating coil of contactor 6 is broken and the controller now comes to rest until synchronous speed on the converter is reached, i.e., until the speed control switch 13 has closed its contacts.

Segment 3 makes contact, closing the circuit to the operating coil of field contactor 31. This closes and connects the fields of the converter to the 250-volt exciter on the controller, thus fixing the proper polarity on the converter, and as the converter is brought to the proper polarity, the polarized relay 36 closes its contacts. Segment 3 then breaks contact, opening contactor 31.

Segment 4 makes contact, energizing the operating coil of full-field contactor 14, which closes and places the field of the converter across its own armature for self-excitation. The field contactors 31 and 14 are mechanically interlocked so that 31 must open before 14 can close.

Running Conditions

Segment 2 breaks contact, opening the starting contactor 10 and segment 5 makes contact, energizing the operating coil of running contactor 16 which closes and puts full alternating-current voltage on the slip rings of the converter. At the same time relay 30 closes due to the establishment of full voltage across the armature of the converter.

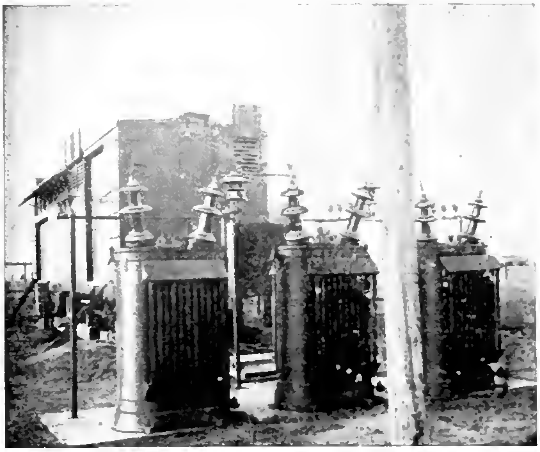


Fig. 7. 60,000 2300-volt Transformers Provided with External Separate Pipes for Natural Cooling of Oil. They are an Unusual Design

Segment 26 makes contact, establishing a circuit through the upper contacts of the limit switch on the brush-raising device and starts the motor of this device, thus lowering the brushes upon the converter. If the brushes reach their lowest position, and the lower contact of the auxiliary switch on the brush-raising device is closed before the controller runs off the second gap in segment 16, a circuit is established from segment 17 through the lower auxiliary switch of the brush-raising device to the operating coil of contactor 6, thus holding 6 closed and permitting the controller to continue to revolve. If the controller runs off segment 16 before the brushes are in their lowest position the operating coil circuit of 6 is opened and the controller stops until the lower auxiliary switch on the brush-raising device closes and completes the circuit from segment 17 described above. These steps insure that the brushes have been properly lowered upon the converter.

Segment 7 makes contact, giving direct-current potential to segments 8, 9, 10 and 11. Segment 8 makes contact, establishing a circuit through the contacts of polarized relay 36, the contacts of relay 30, the electrical interlock on contactor 16 and the operating coil of contactor 18. Contactor 18 now closes, connecting the converter to the bus through all three sections of the load limiting resistance. The converter is then feeding the line through the total series resistance.

Segment 9 makes contact, establishing a circuit through the operating coil of contactor 21 and the contacts of relay 25 and, if the current demand is below the overload setting of relay 25, contactor 21 closes, short circuiting section R-3 to R-4 of the resistor.

Taking Load

Segment 10 makes contact, establishing a circuit through the operating coil of contactor 20 and the contacts of relay 24 and, if the current value is below the setting of relay 24, relay 20 closes, short circuiting the section R-2 to R-3 of the resistor. In a similar manner, segment 11, making contact, closes a circuit through the operating coil of 19 and the contacts of relay 23, thus cutting out the last section of resistance. The machine is now connected directly to the bus and delivering load. During the last several operations mentioned above after contactor 18 closed, the contacts of relay 37 open as the converter picks up load, inserting the section BC of the resistance in series with the contact-making voltmeter 1. Simultaneously the voltage on the bus has been brought up to normal but the contacts of the voltmeter still remain closed due to the resistance BC which has just been inserted.

Segment 17 breaks contact, opening the circuit previously established through the lower contacts of the brush-raising device and the operating coil of contactor 6, the latter opens and the controller comes to rest at the running position, being stopped immediately by its solenoid brake.

Shutting Down

When the load demand decreases and reaches the setting of relay 37, which in this case is adjusted for 100 amperes, the contacts of the latter close, short circuiting section BC of the resistance in the coil of the contact making voltmeter 1, causing the voltmeter to open its contacts. This removes the short circuit from coil of relay 2, closing its contacts instantaneously and short circuiting coil of relay 3 which starts to open its contacts. If the load does not increase long enough for 2 to reset at any time during the setting of the dash-pot on relay 3, the latter's contacts open, interrupting the circuit of contactor 4. Should the load increase before contacts 3 have opened, 37 would open, inserting resistance section BC and causing the voltmeter to make contact. The voltmeter contacts short circuit coil of relay 2. Contacts of relay 2 open after time delay and re-energize 3.

After 3 has opened, contactor 4 opens, interrupting two circuits simultaneously; the first being the alternating-current supply to controller segment 13 and the other direct-current circuit including the operating coil of contactor 18. The holding circuit for contactor 5 through segment 14, the auxiliary switch on the oil circuit breaker and the contacts of 29 are broken and line contactor 18 and control contactor 5 now open.

The opening of contactor 5 interrupts the supply to segment 1 on the controller and establishes a circuit through its electrical interlock to segment 19. Contactors 16 and 14 open, disconnecting the converter from the transformer and discharging its field which in turn drops relay 30 out.

The operating coil of contactor 6 is then energized through the electrical interlock on contactor 5 and segments 19 and 18. The controller motor starts and contactors 19, 20 and 21 open. Segment 24 makes contact, energizing the trip circuit of the oil switch mechanism; also segment 25 makes contact through the lower limit switch on the brush-raising device. The high tension line is now disconnected from the transformer de-energizing relays 32 which open, and the brushes are raised from the commutator. Segments 18 and 19 break contact, and the controller comes to rest at the off position. In the meantime the motor of the brush-raising device continues to operate until reaching the end of its travel when the lower limit switch is opened, breaking the supply to the motor. As the voltage on the converter armature dies down after contactors 14 and 16 are open, relay 30 also opens, and the station is completely shut down.

Protective Features

Direct-current Overload.—Relays 23, 24 and 25 are calibrated at alternating-current loads corresponding to direct-current loads of 900, 1200 and 1500 amperes and upon reaching these successive loads the series resistance of 0.15 ohms, 0.25 ohms and 0.35 ohms are inserted in circuit with the converter, causing a reduction in the trolley voltage supplied to the third rail and consequently reducing the ampere output of the machine.

Alternating-current Overload.—Should trouble develop on the direct current side of the converter inside the connection of the load limiting resistance, relays 26 are energized from the current transformer on the low tension side and will open after a set time and shut down the equipment. Relays 26 are set at a higher value than relays 23, 24 and 25 and are also time-limit opening. This time-limit feature allows momentary swings to occur without shutting down the machine. In our case these relays, 25, 24 and 23, are instantaneous circuit opening and time-limit circuit closing, being adjusted to close at 3 seconds and at 16 seconds after the current has fallen to a certain value for each relay. This time delay permits of the acceleration at a low voltage of heavy trains which when starting up cause the resistance to come in; and when the trains have accelerated and the current demand fallen off, the time setting permits of their receiving full voltage at the end of their accelerated period.

Additional alternating current protection is provided by relay 28 which is energized from a current transformer in the high tension winding and is set considerably higher than the other overload devices. When this relay operates, the coil circuit breaker is tripped open and with it the hand-reset switch, thus completely shutting down the station. The opening of the hand-reset switch interrupts the coil circuit of contactor 4 and simultaneously with it the opening of the auxiliary switch on the oil circuit breaker interrupts the holding circuit of contactor 5. The operation of either of these devices shuts down the equipment. After the oil circuit breaker has been tripped in the above manner and the hand-reset switch opened, the station will not start up again until the hand-reset switch is closed by the inspector. Consequently relays 28 are set very high and are expected to operate only in cases of severe trouble where the attention of an inspector would be necessary.

Low Voltage.—Relay 27 provides the alternating-current low voltage protection. When low voltage occurs, the left hand contacts of 27 are closed, short circuiting the coil of 27-X, opening it and interrupting the supply through the contacts of relay 3 to the coil of contactor 4. Relay 29, in a certain sense, performs the functions of an alternating-current low-voltage relay whenever the converter is running, since, should the alternating-current voltage fall too much, the converter would invert and supply power from the trolley to the alternating-current system. Reverse-current relay 29 would then open, interrupting the holding circuit of contactor 5, shutting down the machine.

Over Speed.—Speed limit device 12 on over speed closes the circuit of the shunt trip of the direct-current circuit breaker. When this opens, the auxiliary switch on the circuit breaker interrupts the supply to the coil of contactor 4 and the equipment shuts down. When this happens it must be hand reset by the inspector.

Under Speed.—The speed control switch 13 is a centrifugal device, the contacts of which remain open until approximate synchronism is reached.

Sequence.—The sequence of events is fixed primarily by the controller but in addition to this there are electrical interlocks on contactors 10 and 16, as well as the holding circuit of contactor 5, all of which are additional safeguards against incorrect sequence.

Polarity.—The 250-volt excitation generator, direct-connected to the motor of the controller, fixes the polarity of the converter, but as an additional precaution the polarized relay 36 must be energized in the proper direction before allowing line-contactor 18 to close.

Temperature.—Should the load-limiting resistance or bearings overheat the thermostats will open, de-energizing relay 27 which, when de-energized, closes the left hand contacts of 27, thus shutting down the equipment. The thermostats over the resistor are self-resetting when the resistor cools off, while those on the bearings of the converter are hand reset and require the attention of the inspector before the converter will again start.

A thermal relay is provided whose rise in temperature is proportional to the heating in the converter winding and in case of a long continued overload which would injure the insulation, this relay operates and shuts down the station. This relay in one of the illustrations is shown mounted on a small panel supported on the resistor grid iron framework.

The thermal element is the fuse-like object connected in one phase of the converter transformer secondary. A small tube containing a volatile liquid connects from the thermal element to the relay on the right—the expansion of the liquid under heat actuating the relay whose contacts, when opened, interrupt the circuit to relay 27 and shut down the station.

Balanced Polyphase Voltage.—This protection is provided on the low tension side of the power transformer by means of the two relays 32 which are connected across different phases. All three phases of the power transformer must be excited to approximately normal voltage, otherwise one or both of these relays will remain open and prevent the starting contactor 10 from closing.

Position of Converter Brushes.—Proper position of these brushes is assured by means of the auxiliary switch on the brush-raising device.

The converter is equipped with flash barriers which completely surround the brush holders and in case of an attempted flash-over between brushes the hot metallic vapors are scooped up from the commutator and dissipated in two sections of wire mesh. The system is subjected to frequent short circuits between the third rail and traffic rail, owing to section-men dropping tamping bars across the conductor rail, and from various other causes, so that flashovers on the commutator of the motor-generator sets have been quite frequent and severe. These flash-overs were usually accompanied by a spill-over to the pedestals of the machines and it has been found necessary to remove the grounds from the machine frames in order to reduce this spilling-over. There has been, during five months' operation of the automatic substation, what was evidently a severe short circuit on the third rail in the immediate vicinity of the substation; the flash barriers no doubt took care of the resulting flash-over at the commutator, some of the flash-screen metal having been vaporized, but the substation cleared itself and when the writer visited the station that day the machine was carrying 50 per cent overload without any evidence of the flash-over having inconvenienced the converter as far as normal operation was concerned. It was evident, however, that a spill-over had taken place to the pedestal of the machine. These spill-overs are believed to be due to the inductive kick occasioned by the sudden extreme variation in current in the third rail, the magnetic effect of which accentuates the short circuit conditions on the machine commutators. In addition to removing the ground from the machine frame an electrolytic lightning arrester has been connected between the positive of the machine and the traffic rail, with the belief that the arrester will take care of any extreme inductive kick occurring across the converter armature, the fields, or the series resistors of the machine.

GENERAL RESULTS OF OPERATION

Our experience so far with the automatic control seems to show that this type of equipment is particularly advantageous for interurban service. The cushion of resistance which is introduced in extremely heavy demands results in much better operation than the manually operated stations, in that improper handling by a motorman of his train, or in case of two or more trains pulling on a station, does not result in opening the station breaker, with the resultant slowing down of trains and probability of again pulling the breaker when the station operator closes his switches. With automatic control, there is no breaker to open. The station simply cuts in the proper resistance which should have been cut in on the train by the motorman if he had handled his train properly. The voltage to the train is thereby cut down and a lower current demand follows; but in the meantime the train continues to accelerate under this reduced current and in a few seconds the amperage falls to a value which allows the resistance contactors to again close, short circuiting the resistors and delivering full voltage to the trains.

This method of operation naturally results in better conditions as regards flashing at commutators of car equipment due to poor handling of trains, as the station resistance automatically takes care of any such defective train operation. For those interurban lines which operate heavy freight trains the automatic control, with the current-limiting resistors and particularly in combination with a 200 per cent overload characteristic in the converter or motor generator set, is particularly fitted for handling this class of service.

IMPROVED OPERATION

In addition to the large saving in operators' wages which the automatic control gives, it also provides a considerable saving in eliminating idle running of a substation with its attendant running-light losses. Substation operators are instructed to cut in or off the line either at defined time intervals or upon certain current and voltage indications upon their station instruments, but we are aware that even under these regulations there is a very considerable amount of idle running. Under automatic control, however, running-light losses are cut to a minimum as the station does not start except upon a predetermined demand for power and then shuts down when this demand no longer exists. The greater the interval between trains, the larger will be the saving of energy obtained through the elimination of running-light losses. The use of automatic control therefore reduces both of the predominant items in the total cost of power, i.e., the energy charge itself and the item of substation wages. Our equipment is adjusted so that approximately three minutes after the demand for power falls below 100 amperes, the station shuts down, this three-minute interval in our case being sufficient to take care of the time consumed by a train in the substation zone, coasting, braking, and stopping. The station delivers current to the line thirty seconds after relay 3 closes, or about thirty-five seconds after the demand for current occurs, there being about a five-seconds delay in the action of the relay 2 to provide against momentary swings bringing the station into action.

TROUBLE EXPERIENCED

This station will be regularly inspected at intervals of about every four or five days, this being done at present by an extra operator who also spends part of his time in line work and affording relief to other station operators. To date the equipment has been remarkably free from trouble, our main difficulty having been loose contacts at terminals of relays which had not been thoroughly tightened up and were shaken loose by the vibration of the car. These only resulted in shutting down the station, and since going over all these contacts thoroughly there has been no further difficulty.

In addition to this unit the railroad has recently ordered another similar equipment to be installed at another point on the system where present substation spacing is also too great and voltage conditions poor. This additional equipment includes a converter with high reluctance poles which is expected to be practically free from all flash-overs incident to shorts on third rail. Curve drawing meters will be provided to give us a record of what is taking place in the station. In addition the relays 23, 24 and 25 will be controlled from direct-current shunts instead of from alternating-current transformers, thus providing an easier means of adjusting the relay settings.

The company has in operation nine manually operated stations, in four of which the apparatus is located in a building, and in the other five in a portable structure similar to the automatic equipment. It is planned to provide all of these nine stations with automatic control and probably take advantage of the portable nature of five of them to shift their relative locations so as to provide better regulation over the system.

This unit was completely installed at a cost of approximately $18,500 including the electrical apparatus, the car in which it is installed, the protection fence, concrete platform for power transformers, and spur track on which the car is mounted. This cost does not include the cost of the 60,000 2300-volt transformers and open-air type switching equipment which the power company provided.

The electrical apparatus used in this automatic substation was designed and manufactured by the General Electric Company of Schenectady, New York.

Automatic Substations for Alternating-current Railway Signal Power Supply

PART I

By H. M. Jacobs

Railway Department, General Electric Company

This article is the first of two which describe the application of automatically controlled equipment to railway alternating-current signal substations for the purpose of maintaining an effectively continuous supply of power to the signals. The maximum interruption which can occur in case the regular power supply fails varies with the type of system employed but at most it is a matter of only a few seconds before the reserve supply is switched into operation. The present article deals with that type of substation in which the reserve power supply is a secondary commercial source, either nearby or distant, and the concluding article will treat of the equipment used in the substation in which a storage battery and converting apparatus constitute the reserve supply.—Editor.

So much publicity has been given to automatic substations for electric railways that one is apt incorrectly to consider all automatic substations, especially for railway service, of this class. An automatic railway substation functions with the direct-current load demand; an automatic substation for alternating-current railway signaling provides against outages due to failure of power supply.

The rapid and efficient handling of railroad traffic depends in a great measure on the dependability of the signaling system. The first step in determining the responsibility for an accident is an investigation of the condition of the signals. It is therefore of extreme importance that the power for operating the signals be as free from interruptions as possible.

Primary or storage batteries furnish the power for signals operating on direct current. The former operate over long periods without renewals; storage batteries of the proper ampere-hour capacity will operate several days without recharging. As long as these batteries are properly maintained there is very little danger of signal failures due to failure of power supply.

The continuity of service in alternating-current signaling depends directly on the continuity of the source of supply. Even a temporary failure is liable to cause serious trouble. When the engineer on the "flyer" sees a signal suddenly go to "danger" without having received a "caution" indication from the preceding signal he does not know the cause. There may be an obstruction, a washout, a broken rail, or a stalled train in the block ahead. It is his duty to stop his train as quickly as possible; and in doing so he causes discomfiture among the passengers and may flatten every wheel on his train. These and many other considerations make it imperative that every precaution be taken to maintain either continuous power or a means for cutting in a reserve source in the shortest possible time. The automatic substation was developed to meet this latter condition and eliminates serious time delays due to hand switching, especially at night when certain attendants are off duty.

There are two general classes of automatic substations: one in which the reserve power is a second commercial source, and the other in which the reserve power is derived from a storage battery through converting power apparatus. The first class is again subdivided according to whether the reserve source is at the same location or at some distance from the preferred source; the principle of operation is the same in either case. Where both sources are at the same location, either one may feed the bus to which the feeders are connected. Where the sources are at different locations, either one may supply a transmission line to which the feeders are connected; in other words, the bus becomes a transmission line.

The second general classification of automatic substations, that in which the reserve power is obtained through apparatus from a storage battery, is likewise subdivided. In one case the apparatus floats continuously on the storage battery, and in the other case the apparatus remains idle until a power failure occurs. In the first case there is no interruption in service when failure occurs, but in the second case there is an interruption for the period of time required for the apparatus to start and switch in. Traffic conditions determine which system is required.

Only the first general classification of automatic substations will be treated in this article.

The ordinary transmission line carries the bulk of the transmitted power throughout its whole length. A transmission line for supplying power to railway signals is different. The power is distributed in approximately equal increments to every signal location, and to every "interlocking" or signal tower controlling power-operated, hand-controlled switches, signals, and signal devices throughout its length. To eliminate interruptions due to prolonged failure of power supply, provision is made for supplying the line from either end. With power available at both ends of a line, prolonged outages due to failure of the main source are eliminated because the line may be connected to the source of supply at the other end. Of course with manually operated substations, the signaling system is "tied up" and all trains are delayed until this connection is made. The greatest delays usually occur at night, and instances are on record where it was necessary to get a man out of bed to switch in the auxiliary source, causing a delay of over half an hour.

If automatic switching equipment is added to the regular equipment of a manually operated substation, the delays due to power failure may be eliminated. This automatic equipment consists of a magnetically operated switch, energized from a potential transformer connected to the local source; a low-voltage relay to connect the switch to the transformer, the relay being energized from a potential transformer connected to the transmission line side of the magnetic switch; indicating lamps; and auxiliary switches mechanically operated from the magnetic switch to seal the switch closed as long as power is available from the local source, and to connect the indicating lamps.

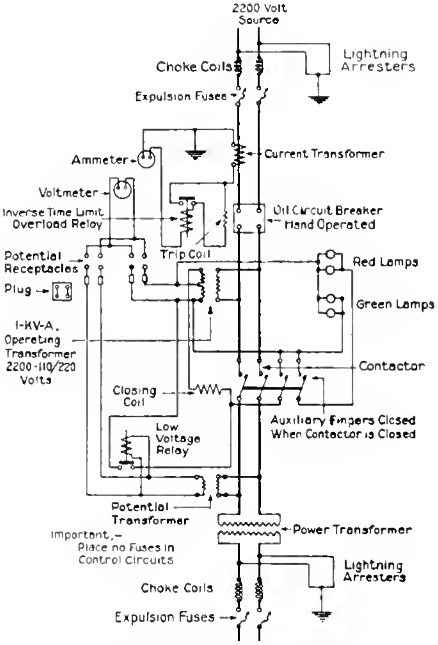


Fig. 1. Wiring Diagram for a Typical Single-circuit, Single-phase Automatic Substation

Fig. 1 is a simple diagram of a complete single-phase automatic substation taking power at 2200 volts and delivering it at a higher voltage. The source and the delivery may be any voltage; it is best from the standpoint of safety and economy to have the control equipment in the low-voltage side. If it is desired to transmit at the same voltage as the source of supply, no power transformer is necessary; if it is desired to transmit at a lower voltage than the source of supply, the transformer is connected ahead of the hand-operated oil circuit breaker.

The principle of operation is as follows: There are two duplicate stations, *A* and *B*, connected to the opposite ends of a transmission line. Assume the power is supplied from station *B*. All the equipment connected to the line side of the magnetically operated contactor switch in station *A* is thus energized from station *B*. The low-voltage relay is energized and contacts are open so that the closing coil of the contactor switch is deenergized. The equipment connected to the supply side of the contactor in station *A* is energized from the local supply. The green lamps are lighted indicating "local power available."

When the power supply at *B* fails, the following action takes place in station *A*: The low-voltage relay is de-energized and the contacts close; this connects the closing coil of the contactor across the 220-volt winding of the operating transformer. The contactor immediately closes and restores energy to the transmission line. The contactor has two auxiliary finger contacts mechanically connected to the moving element, so that when the contactor is closed they make contact. One of these bridges the contacts of the low-voltage relay so that it will not open the circuit to the closing (now holding) coil of the contactor when the relay is energized from the local source through the contactor. The other finger contact closes the circuit to the red lamps. With both green and red lamps illuminated, the indication is "transmission line is being supplied from local source."

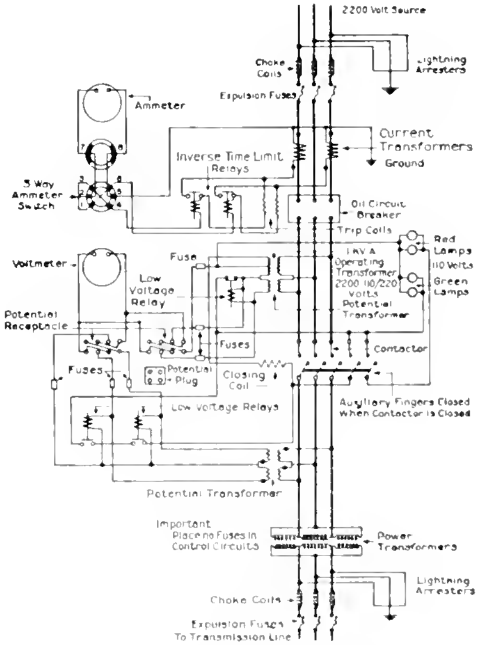


Fig. 2. Wiring Diagram for a Typical Single-circuit, Three-phase Automatic Substation

If it is desired to transfer the load back to station *B*, it is only necessary to open the hand-operated oil circuit breaker. This simulates a failure of power in station *A*, and station *B* will immediately cut in as above described.

Should a short circuit or overload occur on the transmission line, the oil circuit breaker will be tripped out by the action of the inverse time-limit overload relay. This of course will de-energize the line and the other station will be cut in on the short circuit; the oil circuit breaker there will open. The line will then remain dead until the fault is located, the line sectionalizing switches adjacent to the fault opened, and the hand-operated oil circuit breakers closed in both stations. The unaffected portions of the line will then be energized from the adjacent station (see Fig. 10).

A three-phase automatic substation is more complicated. The reserve station must not cut in when only one phase fails, because the two unsynchronized sources would be connected together single-phase. Furthermore, a station must not cut in unless power is available on all three phases. If it should cut in single-phase, only one third of the feeders connected to the transmission line would be energized. To take care of these conditions, two low-voltage relays energized from separate phases are connected to the transmission line side of the contactor; the closing coil circuit is connected to the relay contacts in series, so that both relays must be de-energized before the closing coil of the contactor can be energized. The closing coil circuit is also carried through the contacts of another relay which is energized from a phase other than that from which the closing coil is energized. The contacts on this relay are arranged differently from those on the other two relays in that they are closed only when the relay is energized. Hence, for the closing coil to become energized the latter relay must be energized and the two former de-energized.

The arrangement for shunting the contacts of the two low-voltage relays, and for connecting the red indicating lamps is the same as for a single-phase station. Provision is made for reading current and voltage on all three phases, and two inverse time-limit overload relays provide polyphase protection. Fig. 2 is a complete wiring diagram of a three-phase station.

For the proper functioning of all automatic substations, it is imperative that *no fuses be placed in the control circuits*, especially those including the relays that cause a station or supply source to cut in.

When a transmission line is supplied from one end only, the secondary voltages of the various feeders may be kept fairly uniform by the use of taps on the transformers supplying them. This permits of quite a heavy line drop. However, a transmission line arranged for supply from either end must have a very small line drop and the feeders must not be connected to taps on their individual transformers. To make this requirement clear, assume a line with 10 per cent drop supplied from a source at either end 10 per cent above normal. The feeder adjacent to the preferred source will be connected to a minus 10 per cent tap on the transformer. The last feeder on the line will be connected across the full winding of its supply transformer. The voltage of these two feeders will then be normal. Now suppose the transmission line is supplied from the other end. The voltage on the feeder adjacent thereto is now 10 per cent above normal. The voltage at the other end of the line is then normal, but the signal apparatus, being connected to the minus 10 per cent tap on the transformer, is operating at a voltage 10 per cent below normal. The difference in voltage on the signal apparatus at the ends of the line is therefore 20 per cent, whereas, if the feeders had not been connected to taps on the transformers the dffierence would only have been 10 per cent.

As has already been pointed out, a short-circuit on one section of the line will tie up traffic the length of the line until the faulty section is located and cut out. Naturally the shorter the line the smaller is the zone of disturbance resulting from line trouble. Hence, from the standpoint of lessened liability to disturbance from line troubles, and more uniform voltage on signal apparatus

Fig. 3. Automatic Substation for Alternating-current Railway Signaling, Illinois Central Railroad, Chicago, Ill.

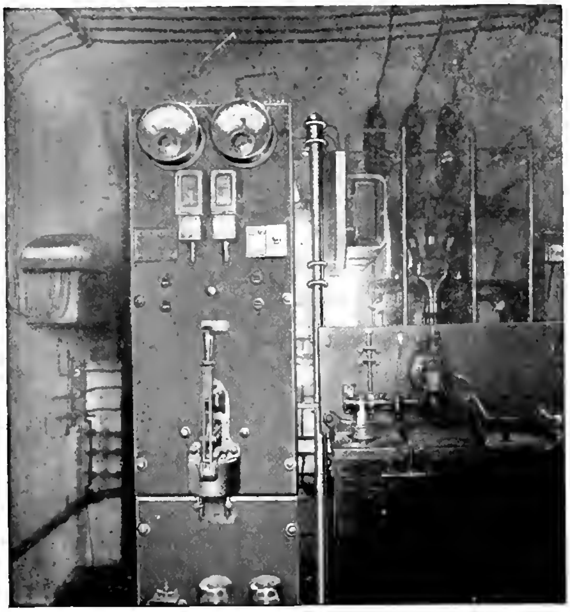


Fig. 4. General Interior View Automatic Substation for Alternating-current Railway Signaling, Illinois Central Railroad, Chicago, Ill.

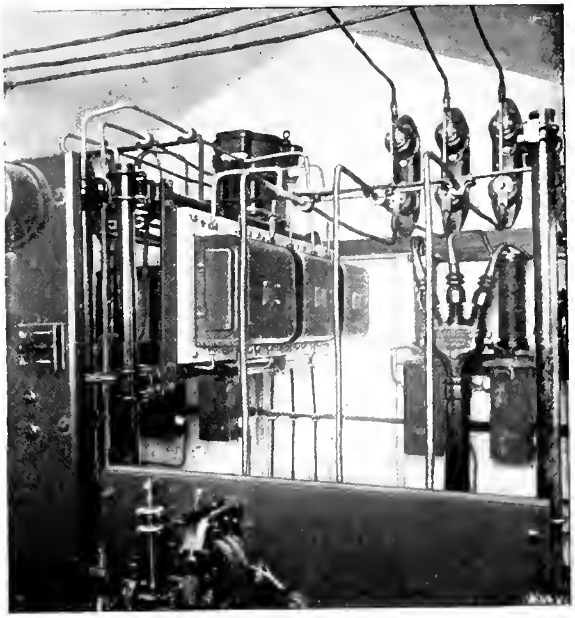
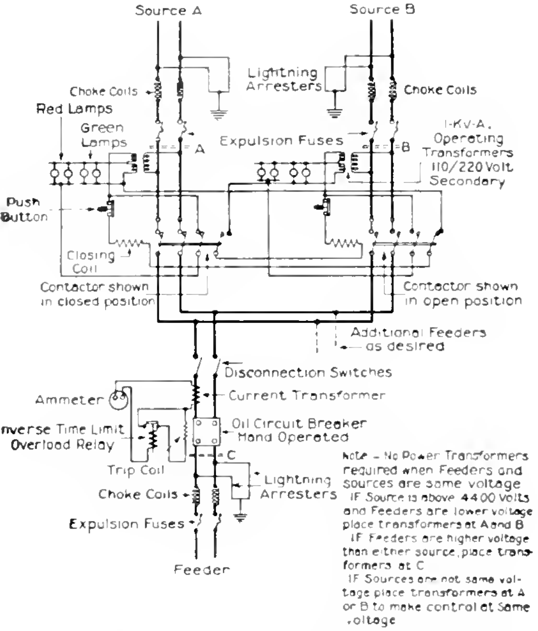


Fig. 5. Interior View Back of Switchboard Automatic Substation for Alternating-current Railway Signaling, Illinois Central Railroad, Chicago, Ill.

due to reduced line drop, a short transmission line between two available sources of power is advisable.

Generally speaking, substations should be approximately 30 miles apart. The distance will depend principally upon the location of reliable sources of commercial power supply and upon the load. Four-track signaling requires more power per block than single or double-track signaling. In some instances it is necessary to transmit 100 miles or more because the power sources at intermediate points are not reliable. With automatic substations installed, power may be taken from some of these more or less unreliable points because, when they fail, another substation picks up the load immediately.



Note – No Power Transformers required when Feeders and sources are same voltage
IF Source is above 4400 Volts and Feeders are lower voltage place transformers at A and B
IF Feeders are higher voltage than either source, place transformers at C
IF Sources are not same voltage place transformers at A or B to make control at same voltage

Fig. 6. Wiring Diagram for Single-phase, Automatic Substation. Two Sources and One or More Feeders in One Station. Push Button Control

This brings up the point of the "intermediate" substation, or what may more properly be termed a "two-circuit" substation. Every substation except those at the extreme ends are two-circuit substations. They feed power when called upon to either or both adjacent sections of the line. The equipment per circuit is essentially the same as for the single-circuit station described. The switchboard panel is wide enough to accommodate the apparatus for both circuits. Only one voltmeter is necessary. Of course the protective equipment for the incoming line is the same as for a single-circuit substation. It is advisable, however, to provide a set of disconnecting switches in each circuit between the switchboard and the incoming line.

The equipment of either single or two-circuit substations occupies comparatively small space. The power transformers and much of the protective and disconnecting equipment may be placed on poles or on a platform outside the building. The remainder of the equipment may be easily placed in an 8 by 10-ft. concrete house as shown in Fig. 3. The interior arrangement of this station is shown in Figs. 4 and 5. The automatic contactor stands at the side of the switchboard. The current and potential transformers are supported on the switchboard framework and wall braces. The operating transformer is on the rear wall near the ceiling. Some of the protective equipment is placed inside the building and is mounted on the rear wall. In this station power is received and transmitted at the same voltage (4400). Since this installation was placed in service a much smaller contactor has been developed for loads up to 30 amperes at 4400 volts. This is approximately 200 kv-a. three-phase; or at 2200 volts three-phase it can carry a 100-kv-a. load. For a three-phase transmission line 50 miles long supplying signal lighting and some small station lighting, 50-kv-a. is considered a good load, so that this new device should meet practically all conditions for 4400 volts and below. It is so small that it can be mounted on a pipe framework back of the switchboard.

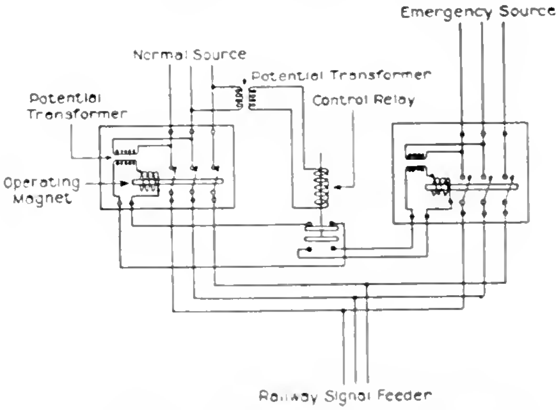


Fig. 7. Partial Wiring Diagram (otherwise same as Fig. 6) for Single-phase Automatic Substation. Two Sources and One or More Feeders in One Station. Relay Control Gives Preference to One Source

It is advisable, though not absolutely necessary, to have a set of disconnecting switches on each incoming and outgoing circuit inside the station, so that the station may be isolated for inspection and repairs without the necessity of going up on the pole or platform to pull the fuses.

Up to this point the discussion has been on the method of keeping a transmission line energized from two sources of supply some distance apart. In some cases energy can be obtained at only one location, or there may be certain territory having congested traffic where it is important to have energy always available. In such cases it is advisable to have a second source of power, if it can be obtained, and a means of quickly changing from one to the other. This can be accomplished by automatic equipment essentially the same as two automatic substations combined into one equipment. The common bus bears the same relation to this as the transmission line did in the arrangement just described. Fig. 6 is the wiring diagram of a simple single-phase equipment. There are no hand-operated oil circuit breakers between the contactors and the expulsion fuses. Normally closed push-button switches for opening the circuit of the holding coils afford a means of opening the contactors when it is desired to change the operation from one source to the other. It is recommended that disconnecting switches be placed between each contactor and bus to afford greater safety to anyone who wishes to inspect or repair a contactor.

It may be that one source is preferable to the other, and that the feeders should be connected to the emergency source only when there is no power available on the preferred. This can be taken care of by one "preferential" relay in place of the two push-button switches. The relay magnet is connected to the preferred source, and when energized the relay serves to connect the contactor on that source; when de-energized it cuts off this contactor and connects the contactor on the emergency source. Fig. 7 shows the wiring for this feature.

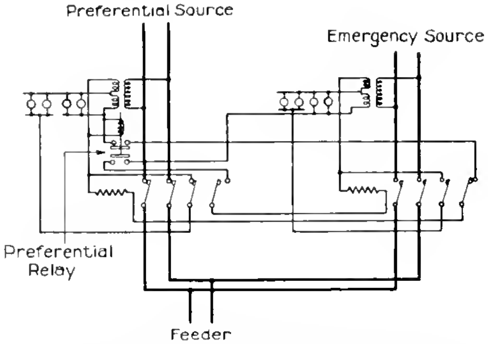


Fig. 9. Wiring Diagram of Simple Automatic Substation Using 4400-volt Contactors, Low-voltage Relay and Potential Transformer

A much simpler form of automatic substation, but working on the same plan as that last described, consists of two contactors recently developed for use as an outdoor

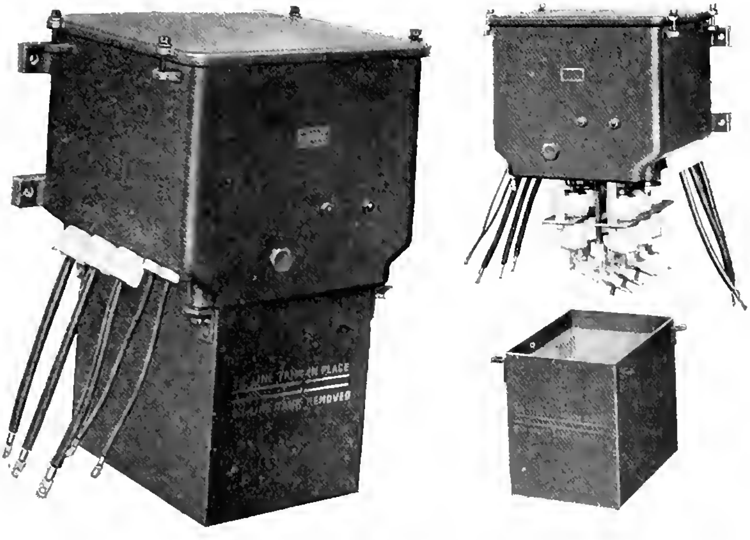


Fig. 8. 4400-volt, 30-amp. Contactor. Holding Coil Takes About 1 to 1¼ Amperes at 110 Volts

remote control switch, together with a control relay and potential transformer. The devices are so small and compact that if the relay and transformer are placed in a waterproof housing the whole equipment may be mounted on one pole out of doors. The external appearance of the contactor and arrangement of the contacts is shown in Fig. 8. This is rated 30 amperes maximum for any voltage up to and including 4400, three-phase. The upper part of the case contains the operating magnet and its potential transformer. Two low-voltage leads are brought out of the case for connection to a control switch. Fig. 9 is a wiring diagram showing how this equipment may be used as an automatic substation. This is simply an automatic change-over equipment; no provision is made for separate control of the sources of supply or feeders and no line protective equipment is included.

To permit of inspection and repairs on a transmission line with minimum interference to traffic, it is the practice to sectionalize the line at many points, usually at each signal location. Two sets of sectionalizing switches are installed at each point, and the transformers which supply the local signal and lighting load are connected to the line between the two sets. To cut out a faulty section of line the one set of sectionalizing switches at each location adjacent to the faulty section is opened. This does not interrupt the service at either sectionalizing point because the local load is connected to the line through the other switch, each portion of the line being fed from a separate station. This arrangement is illustrated by Fig. 10.

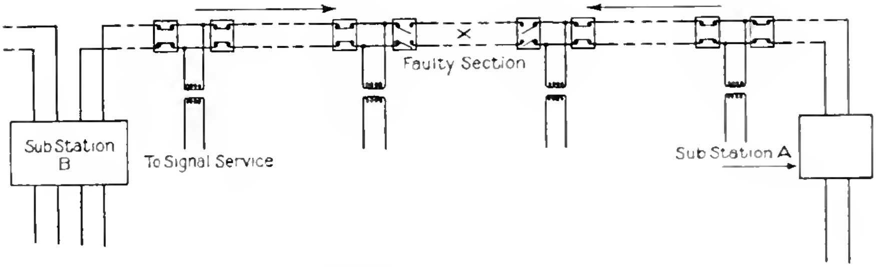


Fig. 10. Simple Diagram Showing Faulty Section of Transmission Line Cut Out and the System Supplied from Adjacent Substations

The sectionalizing switches are of either the oil break or air break type. All live parts of the former are enclosed, and are therefore insulated against accidental contact by the workmen. However, an oil break switch requires considerably more attention than an air break switch. For ordinary service where they are opened infrequently and on moderate loads, and the climate is generally dry, it is recommended that the breakers be inspected and oil tested every six months. If the puncture voltage is below 22,000 volts between 1 inch diameter flat disks 0.1 inch apart, the oil should be replaced by oil that meets the test. If the climate is moist, the inspection and tests should be more frequent.

Air break switches are not ordinarily recommended for opening a circuit under load. However, the normal load of a railway signal transmission line is so small, comparatively speaking, that air break switches having a large breaking distance may be safely used. They must be of rugged construction because they are operated by means of a long rod. The rod should have a weather shield and grounding device.

The Cooper Hewitt Quartz Lamp and Ultra-violet Light

By L. J. Buttolph
Engineering Department, Cooper Hewitt Electric Company

The principles and applications of the glass-enclosed Cooper Hewitt lamp were described in our two preceding issues. This lamp is of low intrinsic brilliancy and finds extensive application in the lighting of industrial plants and for photographic work. The Cooper Hewitt quartz burner, which is described in this article, operates at a much higher temperature, and hence greater intrinsic brilliancy, and its peculiarity is the richness and intensity of its violet and ultra-violet radiations. These ultra-violet rays are screened out by ordinary crown glass, but are transmitted freely by quartz. The quartz lamp is of value in research work, and commercially is of great importance in photo graphic and photo-chemical processes and in the treatment of parasitic and tubercular skin affections. Its therapeutic effects are similar to those of X-rays but are less severe.—Editor.

The increasing importance of the mercury arc in quartz as a source of ultra-violet light has justified a summary of its latest developments and a compilation of some of the related technical data.

Dr. J. C. Pole in "Die Quartz Lamp," 1914; W. A. D. Evans in the Trans. I. E. S., and Dr. E. Weintraub in the General Electric Review, 1914, have detailed the early development of the quartz mercury arc. Bastian, in England, and Heraeus, in Germany, contributed to the development of the first commercial type of quartz burner which was later manufactured in the United States. A burner of this general type was also made by the Cooper Hewitt Electric Co. some years ago. These burners required an elaborate temperature control of the mercury electrodes which was secured in one case by fins of metal and in the other case by a condensing chamber as in the ordinary low pressure type of Cooper Hewitt lamp.

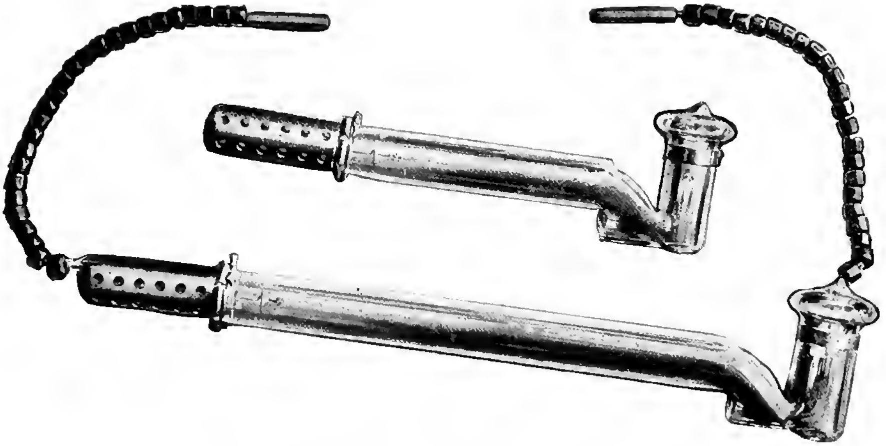


Fig. 1. Cooper Hewitt Quartz Lamp, 110 and 220-volt Direct-current Burners

The first radical change in quartz burner design came with the development of a means of connecting quartz through intermediate steps of glasses of increasing coefficients of expansion to a glass fused directly to a metal lead-in wire and forming with it a permanent vacuum tight seal. The ability of this glass-metal seal to stand high temperature permitted the use of an anode electrode of infusible tungsten instead of mercury. As a result of the use of the new method of sealing-in a greatly simplified quartz burner was developed and is now manufactured by the Cooper Hewitt Electric Co.

The Cooper Hewitt quartz burner is essentially a vacuum arc in a fused quartz chamber. In contrast with the standard glass-enclosed mercury arc the quartz burner operates at temperatures, in certain parts of the arc, which approach the softening temperature of fused quartz, some 1400 C., and at a mercury vapor pressure even above atmospheric pressure. At this pressure and temperature there is added to the discontinuous spectrum of the luminescent mercury vapor a continuous spectrum because of its incandescence. It is this circumstance which accounts for a shift in the relative radiation intensity towards the longer wave lengths with increased energy input. This is in contrast with Wein's displacement law for common incandescent light sources.

As shown in Fig. 3, the quartz mercury arc starts with high current and low voltage when the burner is cold and the vapor pressure low. As the temperature rises the vapor pressure and the voltage follow while the current drops. Normal operation is reached when the heat radiated from the burner equals the electrical energy input and the vapor pressure no longer rises. This point is largely determined by the ventilation of the burner and by the room temperature. For example, with a given maximum burner voltage, determined by the line voltage, the current is increased by cooling the burner. For this reason the Cooper Hewitt laboratory outfit with its open hood and excessive ventilation requires about 4.5 amperes at 180 volts, while the standard illuminating outfit with an enclosing glass globe has a current consumption of approximately 3.5 amperes. As the arc changes from the low to the high pressure condition the luminous arc column becomes concentrated in the center of the tube. There is then some thirty volts drop per inch in the arc as compared with one and one third volts in the mercury arc in glass.

Fig. 4 shows the "stationary" volt ampere characteristics of a quartz mercury vapor arc. The significant feature is the steepness of the curve for voltages above 100. There is a range of some 80 volts over which the current is nearly constant. This condition holds only for temperature equilibrium at the various operating wattages along the curve. The broken lines show approximately what happens when there is a sudden change in the line supply voltage to a quartz arc outfit. Any increase of line voltage makes little change in the burner voltage because of the temperature and vapor pressure lag, shown graphically in the starting characteristic curve. This increase of voltage at first only affects the current through the series resistance and hence through the burner arc. As in starting, with the temperature increase the burner voltage increases, the series resistance voltage decreases, the current decreases and normal operation is resumed at a higher burner voltage but with practically the original current.

The radiation of the Cooper Hewitt mercury vapor arc extends from the extreme infra-red to the region of 1850 Ångstrom units in the ultra-violet. The relative spectral distribution for normal operation is as shown in Figs. 5 and 6 where the principal lines have been shown of lengths proportional to their relative radiant energy.

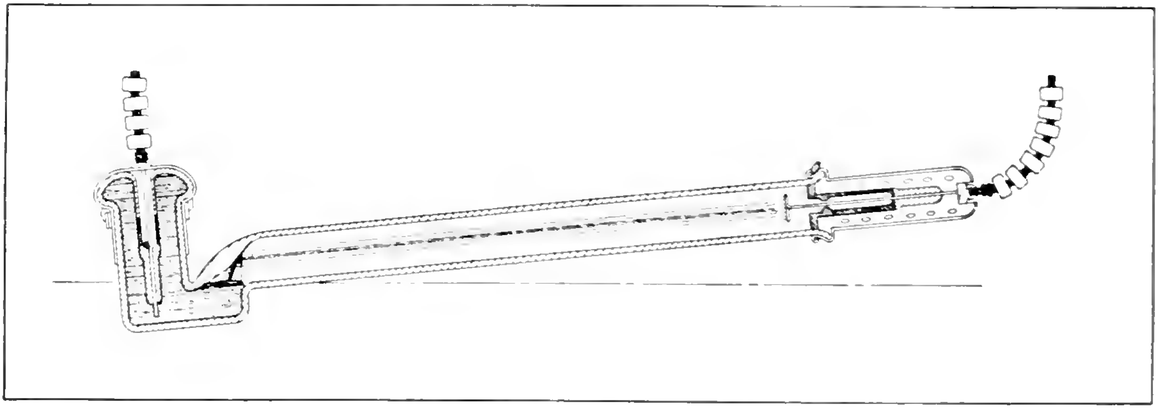


Fig. 2. Sectional Drawing of Cooper Hewitt Quartz Lamp

For convenience in discussion the quartz mercury arc spectrum will be considerd as of two parts, the violet and ultra-violet part extending from 1850 to 4500 and the visible part from 4500 to 7700.

The visible part of the spectrum is of unique value as a source of high intensity monochromatic light for polariscopic, spectroscopic, and interferometer work. The radiation from 4500 to 14,000, one third of all the radiation of wave length less than 14,000, is largely concentrated in a close pair of yellow green lines at 5761 and 5791 and a green line at 5461. In addition to the relatively high radiant intensity of these lines is the significant fact that they lie in a part of the spectrum corresponding to nearly maximum visibility or eye sensibility. These lines are so brilliant that for most purposes they may be separated by refraction through a prism and used directly. Formulæ for filters to isolate any of these lines are readily found in the standard handbooks. For example, a solution of eosin dye in ethyl alcohol will isolate 5764 and 5790 while a double cell filter of neodymium ammonius nitrate and potassium dichromate will isolate 5461 which is one of the finest monochromatic light sources known. Wratten filters have been developed especially for use with the mercury arc and the transmissions of three of these filters are shown on Fig. 5, No. 22E2 isolating 5764-90, No. 77 isolating 5461, and No. 18 isolating 3650. There is also a Wratten filter to isolate 4358, although cobalt blue glass and a solution of quinine sulphate in ethyl alcohol will serve the same purpose.

For very accurate polarimetric readings and measurements of rotary dispersion the quartz mercury arc is unexcelled. The best practice is illustrated in the Hilger polarimeter with a three-field Lippich system to which is added a slit on the polarizer and a direct vision dispersing prism in the analyzer eyepiece. Interchangeable dispersing prisms transmitting green, blue or violet, as the case may be, enable rotary dispersions to be quickly determined.

The Cooper Hewitt low pressure glass-enclosed mercury arc and various forms of Aron's lamp have been used for spectroscopic work, for lens testing and for the study of polarized light. These, however, have fallen short in that they have either a low intrinsic brilliancy or a very small source. The quartz mercury arc provides an intrinsic brilliancy of some fifteen hundred candles per square inch as contrasted with fifteen for the low pressure burner. Furthermore the light source is equivalent to a slit source one-fourth by three inches in the 110-volt burner and six inches in the 220-volt burner.

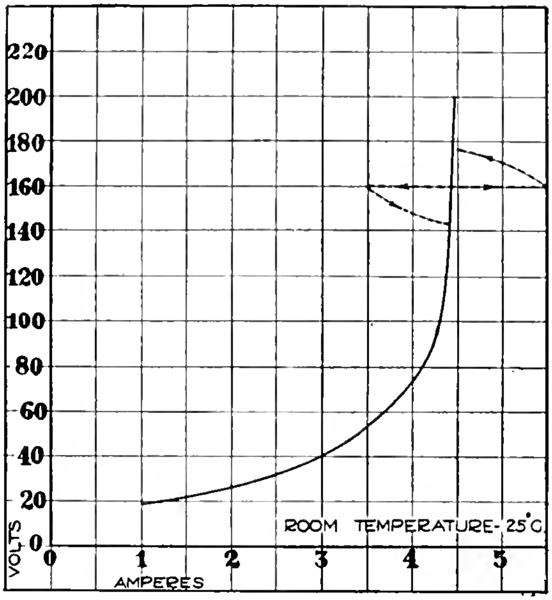


Fig. 4. Volt-ampere Stationary Characteristic of a 220-volt Cooper Hewitt Quartz Lamp

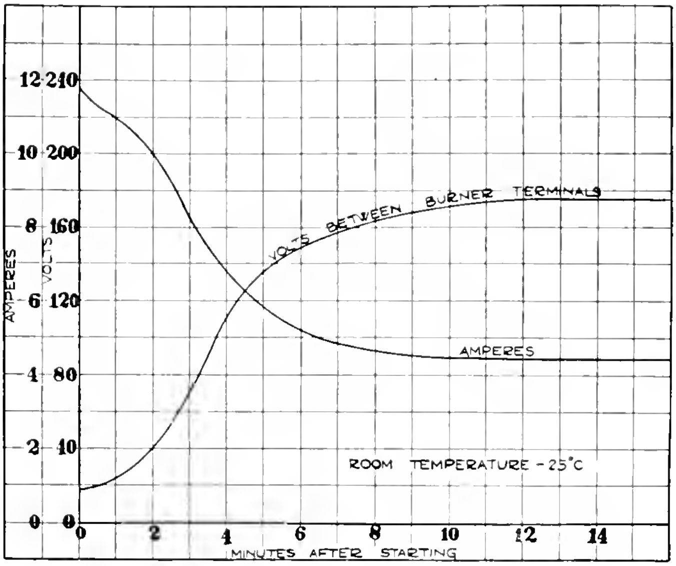


Fig. 3. Volt-ampere Starting Characteristics of a 220-volt Cooper Hewitt Quartz Lamp

The utility of a powerful source of mono-chromatic light for interferometry is increasing with the application of the interferometer to gas analysis and to the testing of solutions.

While designed to operate in a nearly horizontal position, for industrial and routine laboratory work the burner can be removed from its holder, and with the cathode chamber clamped in a laboratory support, may be operated in a vertical position with only a slight change in the electrical characteristics. In general when operated out of the hood a cup-like shield should be placed over and around the ends of the burner to decrease the rate of heat dissipation and to maintain the high vapor pressure characteristic of the burner.

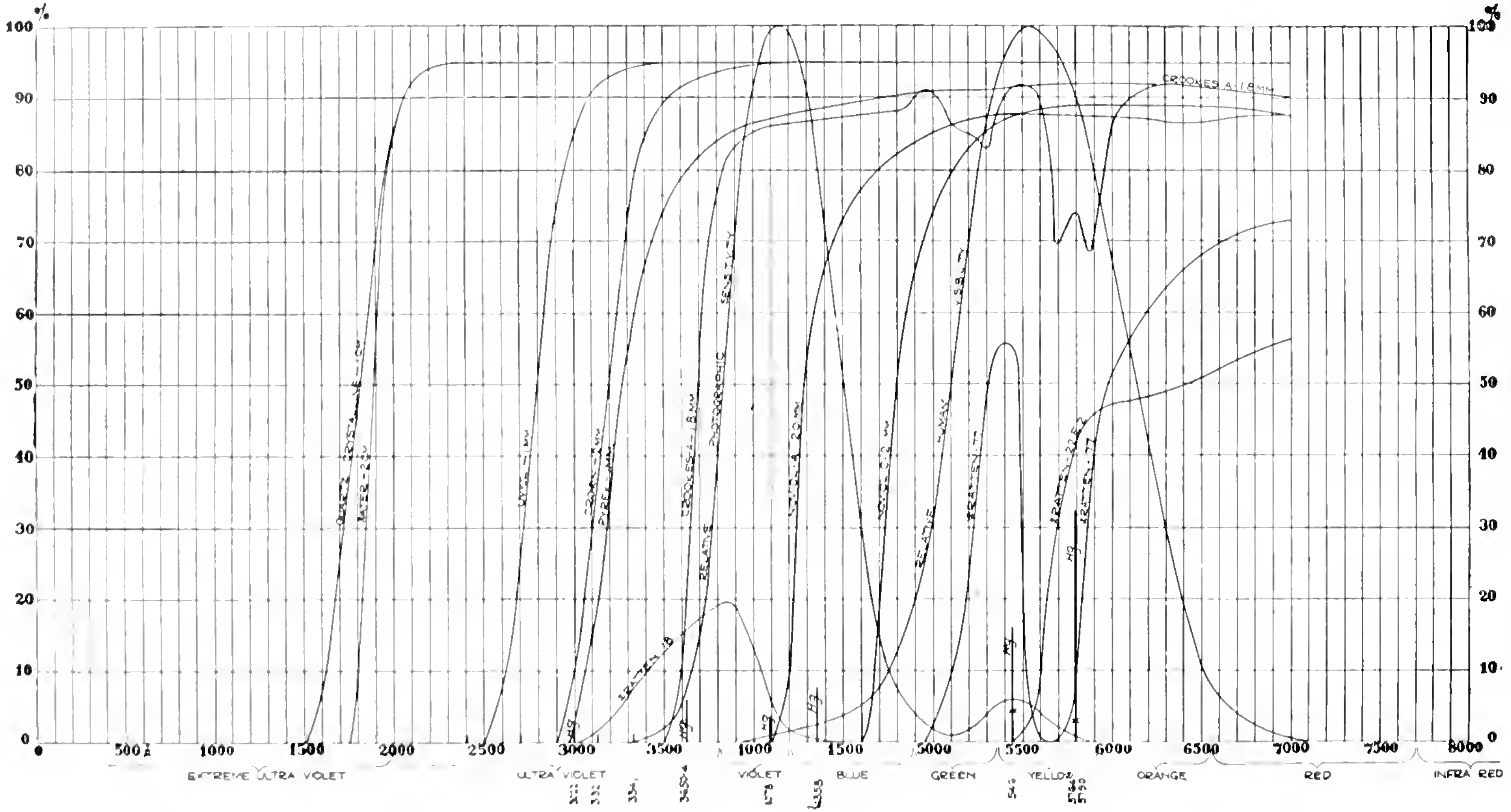


Fig. 5. Energy Distribution and Transmission Curves

1 meter $=10^3$ Millimeters (MM) $=10^6$ Microns (μ) $=10^9$ Millimicrons ($m\mu$) $=10^{10}$ Ångstrom Units (Å)

The Transmissions of Materials and Standard Filters Are for the Thickness Indicated. The Transmission of Fused Quartz Varies Greatly but Lies About Midway Between Crystalline Quartz and Uviol Glass. The Height of the Lines Representing the Mercury Spectrum Show the Relative Spectral Distribution of the Radiant Power in a Quartz Mercury Arc with High Energy Input. X Shows the Relative Spectral Distribution with Low Energy Input

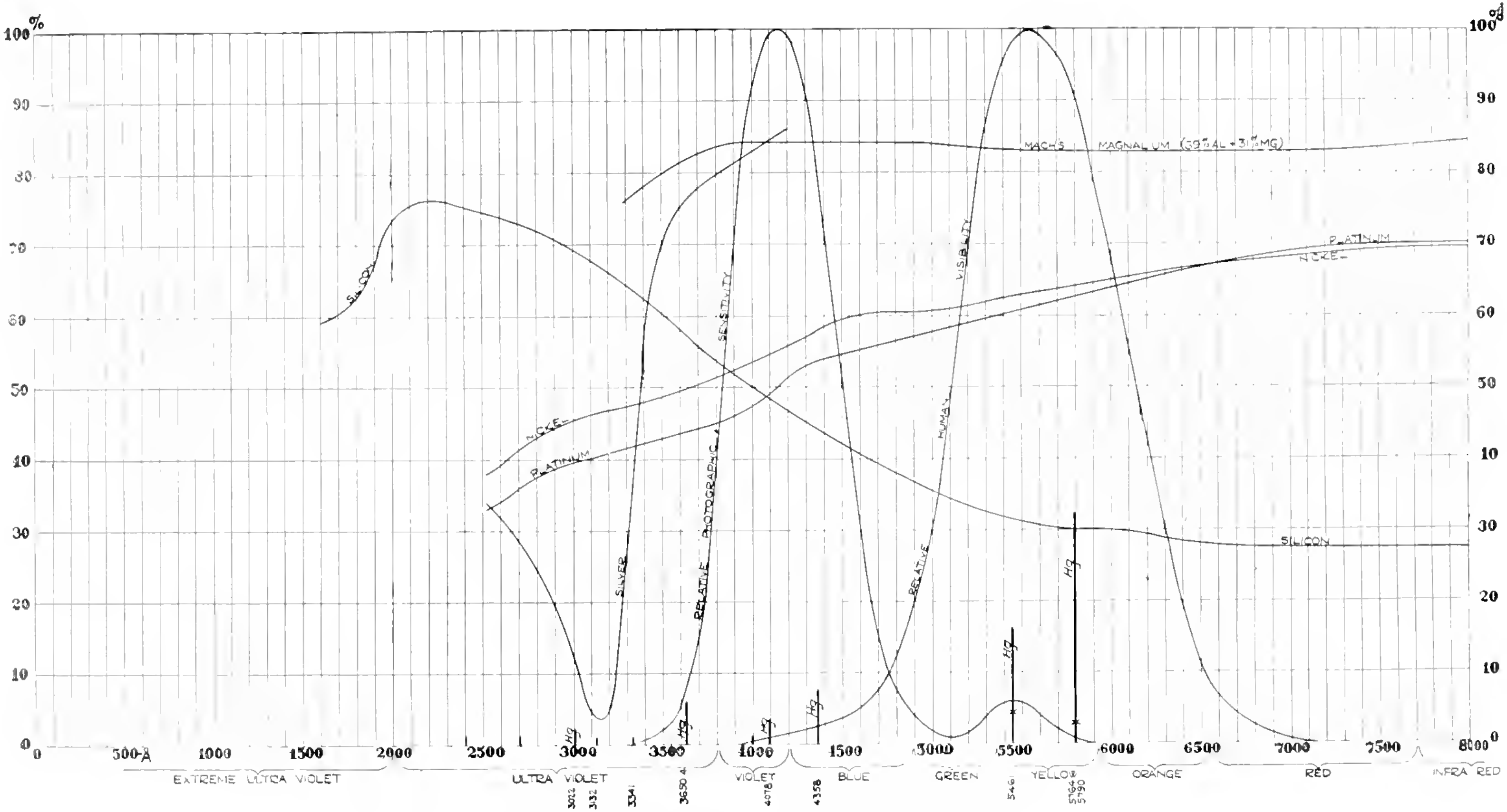


Fig. 6. Energy Distribution and Reflectivity Curves

Extreme Forms of Radiant Energy: Roentgen Rays 2Å to 12Å, Unexplored 12Å to 500Å, Radiant Heat 7700Å to 3,100,000Å, Unexplored 31×10^5Å to 160×10^5Å, Wireless 16×10^6 Å to $120,000,000 \times 10^6$Å

Reflectivities Plotted Are for Normal Incidence on Polished Surfaces. The Relative Visibility and Approximate Photographic Sensitivity Curves Show the Relative Effects on the Average Human Eye and Photographic Plate of a Source Having Constant Radiant Power Throughout the Visible Spectrum

It is vitally important when working with the visible spectrum of a quartz mercury arc that the operator's eyes be protected from the invisible but injurious ultra-violet rays by interposing a sheet of ordinary clear glass.

The intensity of its violet and ultra-violet parts is the most unique quality of the quartz mercury arc spectrum. The radiation of a wave length less than 4500 represents two thirds of the total radiation of wave length less than 14,000 and like the visible radiation is concentrated in a few spectral lines of high intensity. The region from 3000 to 4000 while transmitted by ordinary glass lies largely outside the range of visibility. It is easily detected by a photographic plate and by the fluorescence of such substances as willemite. This part of the ultra-violet seems to have relatively little bacteriological or therapeutic effect. It is however of great importance, photographically and photochemically. Its effects on plant life are very similar to those of intense sunlight and are being studied for possibilities in plant growth control. The photochemical effects while not so striking as in the more extreme spectrum, are nevertheless of extreme importance in the chemistry of plant life, the formation of vegetable dyes, and the fading of synthetic ones.

A pair of especially strong lines occur at 3650-4, one at 3984 and a pair at 4046-78. There is a striking coincidence in the position of these lines near the maximum of photographic sensitivity as well as in the position of line 5461 at the secondary maximum as shown on Figs. 5 and 6. These lines, isolated by cobalt glass filters similar to Wratten No. 18 but of higher transmission, have been used with remarkable success for invisible signalling by means of receivers whose fluorescence transforms the invisible signal light to a visible light in the blue. The light of these lines, isolated from visible light in the same manner as for signaling, is also used for paint testing. Certain paint pigments instantly show their instability by a visible fluorescence undoubtedly accompanying the photochemical reaction, which in time changes the composition and color of the paint.

The region from 2000 to 3000, transmitted by quartz, but not by ordinary glass as indicated in Fig. 8, is unique in the Cooper Hewitt quartz mercury arc. The radiation in this region is very remarkable for its photochemical, therapeutic, and abiotic effects. Its application as a catalyzer in gas reactions, the halogenation of organic substances, the deblooming of oils, the "ageing" of paint materials, and the testing of dyes are a few well known examples. In the latter case it has been found that for practical working conditions, the mercury arc light is eight to ten times as effective as sunlight. The application of the ultra-violet to the sterilization of liquids is limited only by their transmissions. Water sterilization has been a practical process for some time. The limitation of milk sterilization is its opaqueness, but turbulent flow in a thin film offers a solution of the problem. There are immediate possibilities in the application of ultra-violet to qualitative analysis and to factory control of chemical processes. For example, it is now used to control the composition of the tailings in the reduction of zinc ores. It has also been used for the routine analysis of certain unsaturated hydro-carbons by noting the volume of oxygen or of halogen absorbed.

The Finsen light was one of the first attempts to apply ultra-violet to the treatment of disease. It is of value in parasitic and tubercular skin diseases. The physiological effects of ultra-violet are more superficial than those of Roentgen rays and less destructive to the tissues. They are very similar to those of direct sunlight but much more intense. The methods of using a quartz burner for the therapeutic effects of the ultra-violet are similar to those of X-ray practice. They involve placing the burner in a protective hood whose position is universally adjustable and providing the hood with accessory adapters carrying suitable diaphragms and screening devices.

Figs. 5 and 6 need little explanation. Transmissions have been plotted against a wave-length scale for crystalline quartz, water, Uviol glass, crown glass, and certain eye protective glasses designated by their trade names. Three representative filters are shown from the so-called Wratten mercury monochromats. The relative visibility and photographic sensitivity curves have been plotted and the relative luminosity and photographic effect curves for any source of light are then the continuous product of these curves by the relative radiant power of that light source. For sources having continuous spectra these curves are very similar to the dominant form of the visibility and sensitivity curves. For a line spectral source the relative luminosities and photographic effects would then be represented by lines.

A change in the relative spectral distribution of radiant power in the mercury arc spectrum with change of power input has been roughly indicated and shows a shift towards the red end of the spectrum due to a disproportionate increase in the temperature of the quartz tube itself and of the tungsten electrode. For line spectra no simple relationship corresponding to Wein's displacement law has been established.

Fig. 6 shows the reflectivities of a few polished metal surfaces. Mach's magnalium alloy with its peculiarly high reflectivity is impractical because of its non-uniformity. Samples of apparently the same composition and polish differ very widely and, in general, show very much lower values than those indicated. High reflectivity in the region of 2200 and low values in the visible spectrum is the unique property of polished silicon. The quick drop below 2000 and the shape of the curve suggests the possibility of substances having selective reflectivity and little fluorescence in the shorter wave lengths. At present, however, polished nickel remains the most practical reflecting material for the ultra-violet.

A vast amount of interesting research remains to be done on the selective nature of the various ultra-violet reactions. Definite relationships have been noted between certain gas reactions and the selective absorption of the reacting gases for certain portions of the ultra-violet spectrum. It seems probable that for every distinct type of photo-effect whether chemical, abiotic, or therapeutic, there is a curve analogous to the relative visibility and photographic sensitivity curves. More exact data along these lines would be invaluable.

Those planning to do research work should note that to cover the spectrum completely the mercury arc must be supplemented by a tungsten or titanium arc in a vacuum and in quartz which will give a fine-line ultra-violet spectrum of low intensity. Experience has shown that for practical work the high intensity of the mercury arc lines compensates for the gaps in the spectrum although maximum efficiency for certain photo-chemical reactions may make some qualification necessary.

The quartz mercury arc as ordinarily made is essentially a direct-current device and must be supplemented by a rectifier or motor-generator set to adapt it to use on an alternating current. It is however possible to make the quartz burner itself function as a rectifier and an alternating-current quartz arc of this type is under development.

For most experimental and industrial purposes the users devise their own holders and accessory apparatus for use with the burner. As a basis for these special operations the Cooper Hewitt Electric Company manufactures a simple but effective laboratory outfit, shown in Fig. 7. The burner is of new transparent quartz which transmits the ultra-violet light freely. Although quartz glass will stand very high temperatures and sudden changes of temperature it is, like ordinary glass, very fragile and must be handled with care and kept chemically clean of grease and dust. The aluminum reflector and hood serves as a support for the burner and holder as well as a protection to the operator. The auxiliary consists of a reactance coil and adjustable resistance enclosed in a ventilated metal case. The reactance, resistance, and burner are connected in series as shown in the wiring diagram. To operate the burner outside of the outfit it is only necessary to extend the lead wires from the binding posts on the top of the hood to the burner terminals. Directions for the installation and operation of the laboratory outfit are contained in separate instruction books. The one additional precaution to be observed

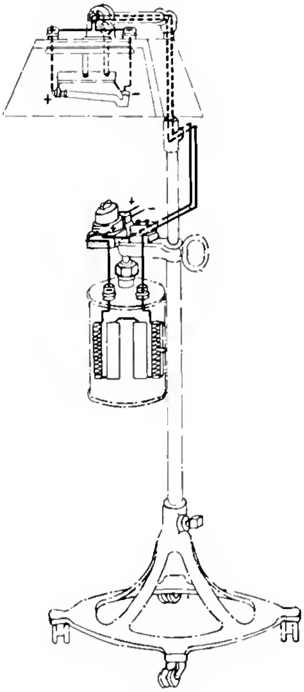


Fig. 7. Laboratory Outfit, Cooper Hewitt Quartz Lamp

in operating a burner outside of the regular outfit is to keep the negative or cathode end lower than the positive end.

The following brief bibliography will, in addition to the standard physico-chemical tables, serve as a guide to the usual methods in ultra-violet research, to some of the original data, and to more extensive bibliography on the subject:

J. C. Pole, "Die Quartz Lampe," 1914.
W. A. D. Evans, Trans. I.E.S. Vol. X, No. 9.
E. C. C. Baly, Spectroscopy.
R. W. Wood, Physical Optics.
S. E. Sheppard, Photo-chemistry.
Theo. Lyman, Spectroscopy of the Extreme Ultra-violet.
M. Luckiesch, Color and Its Applications.
Küch and Retchinsky, Ann. der Phys. (4) 20,563.
Verhoeff and Bell, "Pathological Effects of Radiant Energy on the Eye." Proc. Amer. Academy, Vol. 51.
Bureau of Standards, Bulletin T119, "The Ultra-violet and Visible Transmission of Eye Protective Glasses."
Bureau of Standards, Bulletin S330, "Decrease in Ultra-violet and Total Radiation with Usage of Quartz Mercury Vapor Lamps."
Eastman Kodak Co. "Wratten Light Filters."
Rubens and Hagen, Ann. der Physik. 1352, 1900; 18, 1,1902.
E. O. Hurlburt, Astrophysical Journal 42,205-03 (1915).
Bureau of Standards, Bulletin No. S34, "Spectrum Lines as Light Sources in Polariscopic Measurements."
Bureau of Standards, Bulletin No. T148, "The Ultra-violet and Visible Transmission of Various Colored Glasses."

Fig. 8. Spectrum of Mercury Arc Transmitted Through Crown Glass and Through Quartz

Step-by-step Integration of Curve Areas of Phase Significance

CORRECT AND INCORRECT METHODS

By Chas. L. Clarke

Consulting Engineering Department, General Electric Company

Several ordinate rules are in books for calculating more or less closely, as may be desired, the true area of an irregular plane figure or curve, such as the mean-ordinate, mid-ordinate, trapezoidal, Simpson one third and three eighths, Durand, and Weddle rules, all too well known to require explanation here. Of these the first three mentioned are, in principle, applicable with practically equal accuracy, if rightly used, when conditions of a problem require the area to be determined, or integrated, separately step-by-step between the successive evenly-spaced ordinates. When, however, the step-by-step areas of the total area of a curve thus integrated have a phase relation to another curve or curves, these elementary areas should be taken as concentrated, or located, at points midway between their respective bounding ordinates, that is, at the mid-ordinate of the mid-ordinate rule, and not at one of the bounding ordinates, which are the only ordinates of the mean-ordinate rule and of its substantial equivalent the trapezoidal rule. The necessity for observing this precaution as to assumed position of the elementary areas, when of phase significance, is pointed out and illustrated by examples in the following article.—Editor.

Introduction

The purpose of this article is to direct attention to errors that are bound to occur if the *mean-ordinate* rule, instead of the *mid-ordinate* rule, is used in progressively integrating uniform step-by-step areas going to make up the whole area of a curve, when such integration bears a phase significance to other related curves.

For the purpose of demonstrating the incorrectness of using the mean-ordinate rule in such a case, and the practical accuracy of results obtained by applying the mid-ordinate rule, a convenient example is afforded in the step-by-step approximation method of calculating the phase angle between equivalent sine waves of impressed voltage and exciting current,* in a transformer primary, and therefrom determining the angle of hysteretic lead of current phase (hysteretic angle of advance), or phase position ahead of the 90-degree lag behind the voltage that the current would have were there no consumption of energy by hysteresis, and thus no power required from the circuit to supply this energy. The phase relation between the equivalent waves is determined from the known hysteresis loop for the iron used in the core, and the known effective value and wave shape of the primary impressed voltage.

To demonstrate the nature of the error and how to avoid it, we shall first consider a case in which the impressed voltage is assumed to be a distorted wave composed, for example, of a definitely related fundamental and triple harmonic; and although in practice the wave shape and value of the exciting current have to be determined, we shall here pre-assume this current, and that it also is composed of a definitely related fundamental and triple harmonic.

Then since the maximum instantaneous values of current and magnetic density must be in phase, and the latter has a definitely known mathematical relation to the voltage, we are able correctly to calculate the phase angle between the equivalent sine waves of voltage and current, and thus find the true angle of hysteretic lead, and can also determine the corresponding hysteresis loop for the core iron, although in an actual case the loop must be known beforehand.

Next, beginning with the same voltage wave and hysteresis loop, we shall calculate from these the exciting current and angle of hysteretic lead by the step-by-step method, introducing, however, the error before referred to in handling the method, and thus obtaining an incorrect result. The reason for the error and the manner to avoid it will then be dealt with.

Finally, by way of demonstration, the current and angle of hysteretic lead will be recalculated by the step-by-step method handle in the correct manner, whereby a result for the angle is obtained practically agreeing with the true angle derived in the first instance by precise mathematical means.

MATHEMATICAL SOLUTION

For the sake of brevity in this mathematical solution, only the results and the major steps in obtaining them are given.

Voltage

Assume, for example, an impressed voltage e having a triple harmonic of one fifth the amplitude e_m of the fundamental and in phase therewith.

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* A sine wave of voltage or current that has the same effective value and frequency as a wave of other form is the "equivalent sine wave" of the latter, and is capable of the same effect. Waves of voltage and current of different form in a circuit have no definite phase relation, but their equivalent sine waves may have a fixed phase relation which must be such that the waves together represent the same average power as the actual waves.

In this article the "exciting current" does not include that component of the primary exciting current that may be called for by eddy currents set up in the transformer structure, but is limited to that part of the primary current required to produce the magnetic cycle in the core, composed of the magnetizing current and hysteresis current.

The equation for instantaneous values is

$$e=e_m\left(\sin\alpha-\frac{1}{5}\sin 3\alpha\right) \qquad (1)$$

The relative instantaneous values e_r are given by

$$e_r=g\left(\sin\alpha-\frac{1}{5}\sin 3\alpha\right) \qquad (2)$$

in which g is a constant of any convenient value greater than zero and less than infinity; which means that the wave shape of relative values may be plotted to any desired scale.

The values of e_r corresponding to the time angle α for each five degrees of a half-cycle between zero values of voltage are given in column (2) of Table I.*

Squaring (1), multiplying through by $d\alpha$ and integrating between the limits zero and π, we obtain

$$\text{average } e^2=E^2=e^2{}_m\left(\frac{13}{25}\right)$$

from which

$$e_m=1.3868\,E \qquad (3)$$

and from (1) and (3)

$$e=1.3868\,E\left(\sin\alpha-\frac{1}{5}\sin 3\alpha\right) \qquad (4)$$

in which E is the effective value of the actual voltage wave, which must also be the effective value of the *equivalent sine wave.*

The values of e corresponding to α for each five degrees of the half-cycle are given in column (3) of Table I.

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* All the calculations in this article have been carried out to more decimal places than are given in numerical coefficients in the equations, or written in the tables.

TABLE I

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Degrees α	e_r	e	B	i	f	p
0	$0.0000\ g$	$0.0000\ E$	$-1.0000\ B_{max.}$	$-1.5865\ I$	$-1.5865\ In\ l$	$0.0000\ IE$
5	$0.0354\ g$	$0.0419\ E$				
10	$0.0736\ g$	$0.1021\ E$	$-0.9933\ B_{max.}$	$-1.5231\ I$	$-1.5231\ In\ l$	$-0.1556\ IE$
15	$0.1174\ g$	$0.1628\ E$				
20	$0.1688\ g$	$0.2341\ E$	$-0.9711\ B_{max.}$	$-1.3320\ I$	$-1.3320\ In\ l$	$-0.3118\ IE$
25	$0.2294\ g$	$0.3182\ E$				
30	$0.3000\ g$	$0.4160\ E$	$-0.9279\ B_{max.}$	$-1.0312\ I$	$-1.0312\ In\ l$	$-0.4290\ IE$
35	$0.3804\ g$	$0.5275\ E$				
40	$0.4696\ g$	$0.6512\ E$	$-0.8565\ B_{max.}$	$-0.6608\ I$	$-0.6608\ In\ l$	$-0.4303\ IE$
45	$0.5657\ g$	$0.7845\ E$				
50	$0.6660\ g$	$0.9236\ E$	$-0.7506\ B_{max.}$	$-0.2731\ I$	$-0.2731\ In\ l$	$-0.2522\ IE$
55	$0.7674\ g$	$1.0642\ E$				
60	$0.8660\ g$	$1.2010\ E$	$-0.6071\ B_{max.}$	$+0.0798\ I$	$+0.0798\ In\ l$	$+0.0959\ IE$
65	$0.9581\ g$	$1.3286\ E$				
70	$1.0397\ g$	$1.4418\ E$	$-0.4283\ B_{max.}$	$+0.3584\ I$	$+0.3584\ In\ l$	$+0.5167\ IE$
75	$1.1073\ g$	$1.5356\ E$				
80	$1.1580\ g$	$1.6059\ E$	$-0.2218\ B_{max.}$	$+0.5146\ I$	$+0.5446\ In\ l$	$+0.8746\ IE$
85	$1.1894\ g$	$1.6494\ E$				
90	$1.2000\ g$	$1.6641\ E$	$0.0000\ B_{max.}$	$+0.6451\ I$	$+0.6451\ In\ l$	$+1.0736\ IE$
95	$1.1894\ g$	$1.6494\ E$				
100	$1.1580\ g$	$1.6059\ E$	$+0.2218\ B_{max.}$	$+0.6878\ I$	$+0.6878\ In\ l$	$+1.1045\ IE$
105	$1.1073\ g$	$1.5356\ E$				
110	$1.0397\ g$	$1.4418\ E$	$+0.4283\ B_{max.}$	$+0.7123\ I$	$+0.7123\ In\ l$	$+1.0269\ IE$
115	$0.9581\ g$	$1.3286\ E$				
120	$0.8660\ g$	$1.2010\ E$	$+0.6071\ B_{max}$	$+0.7582\ I$	$+0.7582\ In\ l$	$+0.9106\ IE$
125	$0.7674\ g$	$1.0642\ E$				
130	$0.6660\ g$	$0.9236\ E$	$+0.7506\ B_{max.}$	$+0.8531\ I$	$+0.8531\ In\ l$	$+0.7879\ IE$
135	$0.5657\ g$	$0.7845\ E$				
140	$0.4696\ g$	$0.6512\ E$	$+0.8565\ B_{max.}$	$+1.0035\ I$	$+1.0035\ In\ l$	$+0.6534\ IE$
145	$0.3804\ g$	$0.5275\ E$				
150	$0.3000\ g$	$0.4160\ E$	$+0.9279\ B_{max}$	$+1.1925\ I$	$+1.1925\ In\ l$	$+0.4961\ IE$
155	$0.2294\ g$	$0.3182\ E$				
160	$0.1688\ g$	$0.2341\ E$	$+0.9711\ B_{max.}$	$+1.3836\ I$	$+1.3836\ In\ l$	$+0.3239\ IE$
165	$0.1174\ g$	$0.1628\ E$				
170	$0.0736\ g$	$0.1021\ E$	$+0.9933\ B_{max}$	$+1.5299\ I$	$+1.5299\ In\ l$	$+0.1562\ IE$
175	$0.0354\ g$	$0.0419\ E$				
180	$0.0000\ g$	$0.0000\ E$	$+1.0000\ B_{max.}$	$+1.5865\ I$	$+1.5865\ In\ l$	$0.0000\ IE$

True av. $e=0.8240\ E$ True av. $i=0.8971\ I$ True eff. $i=I$ True av. $p=P=0.3579\ IE$

Similarly, from equation (2),

$$\text{average } e^2_r = g^2\left(\frac{13}{25}\right)$$

from which

$$\text{effective } e_r = 0.7211\ g \qquad (5)$$

Magnetism

The equation for the wave of magnetic density, in terms of maximum density, may readily be obtained by reference to the general solution in the appendix to this article.

Comparing the specific equation (1), for impressed voltage, with the general equation (18), it is obvious for the purpose of the example under consideration that in the general equation $C_1 = e_m$; $C_3 = -\frac{e_m}{5}$; and β_1, β_3, ... β_n and C_4, C_5, ... C_n are each zero.

We may, therefore, pass to equation (23) and by substitution therein at once write

$$B = -\frac{B_{max.}}{e_m - \dfrac{e_m}{15}}\left(e_m \cos\alpha - \frac{e_m}{15}\cos 3\alpha\right)$$

as the equation for the wave of magnetic density in the specific case, which reduces to

$$B = 1.0714\ B_{max.}\left(\frac{1}{15}\cos 3\ \alpha - \cos\ \alpha\right) \qquad (6)$$

where B is the instantaneous magnetic density and $B_{max.}$ is the maximum density in the magnetic cycle.

The wave shape of magnetism is shown in Fig. 1.

From the last equation the instantaneous values of magnetic density are obtained independently of any direct consideration of the voltage, upon the basis of any assumed value for the maximum density.

The values of B corresponding to α for each ten degrees of a half-cycle are given in column (4) of Table I.

Exciting Current

Preassume a current having, for example, a triple harmonic of one-fourth the amplitude i_m of the fundamental and lagging 90 degrees behind the latter, and write the equation for instantaneous values

$$i = i_m\left[\sin\beta - \frac{1}{4}\sin\left(3\ \beta - 90^\circ\right)\right]$$

or

$$i = i_m\left(\sin\ \beta + \frac{1}{4}\cos 3\ \beta\right) \qquad (7)$$

Squaring (7), multiplying through by $d\beta$ and integrating between the limits zero and π, we obtain

$$\text{average } i^2 = I^2 = i^2_m\left(\frac{17}{32}\right)$$

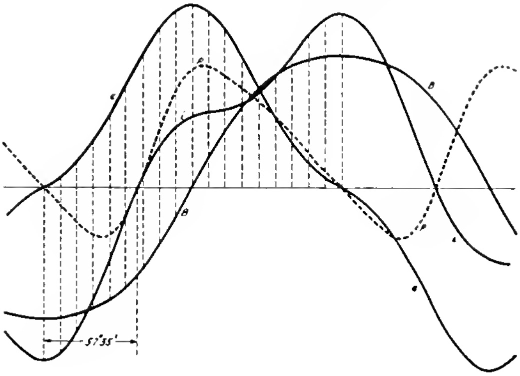

Fig. 1

from which

$$i_m = 1.3720\ I \qquad (8)$$

and from (7) and (8)

$$i = 1.3720\ I\left(\sin\ \beta + \frac{1}{4}\cos 3\ \beta\right) \qquad (9)$$

in which I is the effective value of the current wave.

We have now to establish the time relation of (9) for current to (4) for voltage, and so modify the former equation that the variable time angle therein is also α. The first step is to find the angle included between maximum current and zero value of the fundamental component of the wave.

Differentiating (9) and placing the differential coefficient of i with respect to β equal to zero:

$$\frac{di}{d\beta} = 1.3720\ I\left(\cos\ \beta - \frac{3}{4}\sin 3\ \beta\right) = 0$$

from which we have maximum current when

$$\cos\ \beta = \frac{3}{4}\sin 3\ \beta.$$

This relation is found by trial and approximation to be satisfied for the angle

$$\beta = 110^\circ\ 39'^*$$

that is, the maximum exciting current is 110° 39′ behind zero value of the fundamental.

And since, from physical considerations, maximum magnetism must occur at the same instant as maximum current, the former is also 110° 39′ behind zero value of the fundamental of the current wave. But from (4) and (6) the

---

* By closer approximation, $\beta = 110^\circ\ 39'\ 1.6''$.

corresponding positive maximum magnetism is 180 degrees behind zero value of the fundamental of the voltage wave; hence zero value of the current fundamental lags $180° - 110° 39' = 69° 21'$ behind zero value of the voltage fundamental, from which follows the relation

$$\beta = \alpha - 69° 21'$$

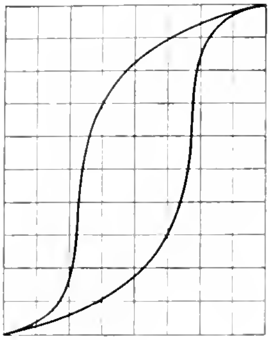

Fig. 2

and we may rewrite (9) in the form

$$i = 1.3720\, I$$

$$\left[\sin(\alpha - 69° 21') + \frac{1}{4}\cos 3(\alpha - 69° 21')\right] \quad (10)$$

as the equation for current referred to the same time angle as is the impressed voltage in equation (4). The wave shape of the current is shown in Fig. 1.

The effective value I of the actual exciting current wave, in (10), must also be the effective value of the *equivalent sine wave.*

When i is zero, from (10) we have by trial and approximation $\alpha = 57°\ 35'$*, that is, zero current is $57°\ 35'$ behind zero voltage.

The values of i corresponding to α for each ten degrees of a half-cycle are given in column (5) of Table I.

Hysteresis Loop

From (10) and the well-known equation

$$f = \frac{ni}{l} \quad (11)$$

in which f is the magnetizing force, ni the ampere-turns of magnetomotive force, and l the length of the magnetic circuit, we may write

$$f = \frac{1.3720\, n\, I}{l}$$

$$\left[\sin(\alpha - 69° 21') + \frac{1}{4}\cos 3(\alpha - 69° 21'\right] \quad (12)$$

The values of f corresponding to α for each ten degrees of a half-cycle are given in column (6) of Table I.

From the simultaneous values of B and f in columns (4) and (6) of Table I, the hysteresis loop is plotted in Fig. 2. In calculating the angle of hysteretic lead of phase in practice, however, the hysteresis loop is, as previously stated, known beforehand.

Power

Multiplying (4) and (10) together, we have for the instantaneous power or rate of energy delivered to the primary for supplying the energy consumed by hysteresis:

$$ie = p = 1.9026\, IE \Big[\sin\alpha \sin(\alpha - 69° 21') + \frac{1}{4}\sin\alpha\cos 3(\alpha - 69° 21') - \frac{1}{5}\sin 3\alpha \sin(\alpha - 69° 21') - \frac{1}{20}\sin 3\alpha\cos 3(\alpha - 69° 21')\Big] \quad (13)$$

The values of p corresponding to α for each ten degrees of a half-cycle are given in column (7) of Table I. The wave shape of power is shown in Fig. 1.

Expanding (13), multiplying through by $d\alpha$, and omitting terms having sine and cosine products, since they become zero when integrated between the limits zero and π, results in the equation

$$p\, d\alpha = 1.9026\, IE \left(\cos 69° 21' \sin^2\alpha\, d\alpha + \frac{1}{20}\sin 28° 3' \sin^2 3\alpha\, d\alpha\right)$$

which, integrated between the limits of zero and π, finally gives

$$\text{average } p = P = 0.3579\, IE \quad (14)$$

Equivalent Sine Waves and Their Phase Angle

Equivalent sine waves of voltage and exciting current, that is, sine waves of the same effective values E and I as the foregoing actual waves, will also represent the same average power P as the actual waves, when

$$P = IE \cos\theta \quad (15)$$

in which θ is the phase difference between the sine waves, or the *equivalent phase angle,* as indicated in Fig. 3; hence from (14) and (15)

$$\cos\theta = 0.3579$$

and

$$\theta = 69° 2'†$$

Since the maximum value of a sine wave is $\sqrt{2}$ times the effective value, we may write, as the equation for instantaneous values of the *equivalent sine wave of voltage,*

$$e_{sin} = \sqrt{2}\, E \sin\alpha$$

---

* More exactly, 57° 34′ 42.4″.

† More exactly, $\theta = 69°\ 1'\ 52.3''$.

and for instantaneous values of the *equivalent sine wave of current*

$$i_{sin} = \sqrt{2}\, I \, sin\, (\alpha - \theta).$$

Multiplying the two last equations together and remembering that $\theta = 69° \; 2'$ we have, as the equation for instantaneous values of *equivalent wave of power*

$$i_{sin}\, e_{sin} = P_{equiv.} = 2\, IE \, sin\, a \, sin(\alpha - 69° \; 2')$$

the wave form of which is shown in Fig. 3.

The effective hysteresis (energy) component of the equivalent sine wave of exciting current, in phase with the equivalent sine wave of impressed voltage, is

$$I \, cos\, \theta = 0.3579\, I$$

and the effective magnetizing (reactive wattless) component, in quadrature with the voltage, is

$$I \, sin\, \theta = 0.9338\, I.$$

Angle of Hysteretic Lead of Phase

Since the lag of the equivalent sine wave of exciting current behind the corresponding sine wave of voltage would be 90 degrees, as indicated by the dotted wave in Fig. 3, were there no hysteresis and thus no power required to supply the energy consumed thereby, the effect of hysteresis has advanced the equivalent sine wave of current by an amount represented by the *angle of hysteretic lead*

$$\begin{aligned}\eta° &= 90° - 69° \; 2' \\ &= 20° \; 58'\end{aligned}$$

STEP-BY-STEP SOLUTION

Erroneous Method

Assume that a transformer is operating under an impressed voltage of known wave shape and effective value, and that the hysteresis loop corresponding to the maximum magnetic density in the core is also known, the problem being to determine the angle of hysteretic lead. Let these factors be the same as heretofore.

First. On a diagram of the voltage wave, nowadays based on an oscillogram record, divide the time of one half-cycle between zero values of voltage into a suitable number of equal parts, in the present example eighteen, and write the corresponding time degrees α in column (1) of Table II.*

Second. With any suitable scale measure the lengths of the corresponding ordinates to the wave, which will represent the relative instantaneous values e_r of the voltage—although in the present case we find these values directly by equation (2)—and write them in column (2).

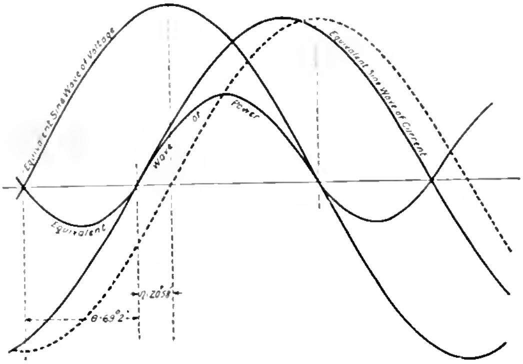

Fig. 3

Third. Enter the squares e_r^2 of the relative values in column (3), the square root of the average value of which will be the relative effective value, or

$$\text{effective } e_r = 0.7211\, g$$

Fourth. As the relative effective voltage *eff.* e_r bears the same ratio to the actual effective voltage E as relative instantaneous values e_r bear to corresponding instantaneous values e, we have

$$e = \frac{e_r \, E}{0.7211\, g}$$

from which the values of e in column (4) are obtained.

Fifth. Remembering that under the conditions of the problem the impressed voltage e and counter induced voltage e_i are substantially equal, although of opposite sign, it will be seen from equation (16), Appendix, that the magnetic density B for a given time angle α is proportional to the integration or summation of e, that is, proportional to the area of the voltage wave up to the same angle, plus an integration constant. The proportional and interrelative integration values of e, that is Σe, up to the respective angles in column (1), are obtained by progressive addition of the values in column (4), as given in column (5).

Sixth. The integration constant is determined from the condition (see Fig. 1) that B at zero degrees must be negative, and equal and opposite to B at 180 degrees. Therefore,

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* The number of divisions best to employ is largely determined by the shape of the wave, and in general should be such that the corresponding ordinates meet the wave as near the maximum, minimum and inflection points as is feasible. Naturally, the greater the number of divisions the more accurate the final result, and the less the importance of the ordinates touching the wave as near to the points mentioned.

TABLE II

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Deg α	e_r	e_r^2	$\frac{e_r E}{0.7211 g}$ e	Σe	$\Sigma e - 7.4078E$ B_r	$\frac{B_r B_{max.}}{7.4078 E}$ B	Time Angle of B α_B	From Hysteresis Cycle f	fl/n i	i^2	$ie =$ p
0	0.0000 g	0.0000 g^2	0.0000 E	0.0000 E	−7.4078 E	−1.0000 $B_{max.}$	0°	−1.5865 In/l	−1.5865 I	2.5171 I^2	0.0000 IE
10	0.0736 g	0.0054 g^2	0.1021 E	0.1021 E	−7.3056 E	−0.9862 $B_{max.}$	14° 9′	−1.4628 In/l	−1.4628 I	2.1282 I^2	−0.1490 IE
20	0.1688 g	0.0285 g^2	0.2341 E	0.3362 E	−7.0715 E	−0.9546 $B_{max.}$	24° 31′	−1.2077 In/l	−1.2077 I	1.4586 I^2	−0.2827 IE
30	0.3000 g	0.0900 g^2	0.4160 E	0.7523 E	−6.6555 E	−0.8984 $B_{max.}$	34° 40′	−0.8640 In/l	−0.8640 I	0.7465 I^2	−0.3594 IE
40	0.4696 g	0.2205 g^2	0.6512 E	1.4035 E	−6.0043 E	−0.8105 $B_{max.}$	44° 46′	−0.4748 In/l	−0.4748 I	0.2254 I^2	−0.3092 IE
50	0.6660 g	0.4436 g^2	0.9236 E	2.3271 E	−5.0807 E	−0.6859 $B_{max.}$	54° 50′	0.0953 In/l	−0.0953 I	0.0091 I^2	−0.0880 IE
60	0.8660 g	0.7500 g^2	1.2010 E	3.5281 E	−3.8797 E	−0.5237 $B_{max.}$	64° 53′	+0.2268 In/l	+0.2268 I	0.0514 I^2	+0.2724 IE
70	1.0397 g	1.0810 g^2	1.4418 E	4.9698 E	−2.4379 E	−0.3291 $B_{max.}$	74° 56′	+0.4619 In/l	+0.4619 I	0.2134 I^2	+0.6660 IE
80	1.1580 g	1.3410 g^2	1.6059 E	6.5757 E	−0.8321 E	−0.1123 $B_{max.}$	84° 59′	+0.6041 In/l	+0.6041 I	0.3649 I^2	+0.9701 IE
90	1.2000 g	1.4400 g^2	1.6641 E	8.2398 E	+0.8321 E	+0.1123 $B_{max.}$	95° 1′	+0.6714 In/l	+0.6714 I	0.4508 I^2	+1.1173 IE
100	1.1580 g	1.3410 g^2	1.6059 E	9.8457 E	+2.4379 E	+0.3291 $B_{max.}$	105° 4′	+0.6998 In/l	+0.6998 I	0.4897 I^2	+1.1238 IE
110	1.0397 g	1.0810 g^2	1.4418 E	11.2875 E	+3.8797 E	+0.5237 $B_{max.}$	115° 7′	+0.7310 In/l	+0.7310 I	0.5343 I^2	+1.0539 IE
120	0.8660 g	0.7500 g^2	1.2010 E	12.4885 E	+5.0807 E	+0.6859 $B_{max.}$	125° 10′	+0.8002 In/l	+0.8002 I	0.6403 I^2	+0.9610 IE
130	0.6660 g	0.4436 g^2	0.9236 E	13.4121 E	+6.0043 E	+0.8105 $B_{max.}$	135° 14′	+0.9254 In/l	+0.9254 I	0.8563 I^2	+0.8547 IE
140	0.4696 g	0.2205 g^2	0.6512 E	14.0633 E	+6.6555 E	+0.8984 $B_{max.}$	145° 20′	+1.1016 In/l	+1.1016 I	1.2131 I^2	+0.7172 IE
150	0.3000 g	0.0900 g^2	0.4160 E	14.4793 E	+7.0715 E	+0.9546 $B_{max.}$	155° 29′	+1.2999 In/l	+1.2999 I	1.6897 I^2	+0.5408 IE
160	0.1688 g	0.0285 g^2	0.2341 E	14.7134 E	+7.3056 E	+0.9862 $B_{max.}$	165° 51′	+1.4777 In/l	+1.4777 I	2.1835 I^2	+0.3459 IE
170	0.0736 g	0.0054 g^2	0.1021 E	14.8155 E	+7.4078 E	+1.0000 $B_{max.}$	180°	+1.5865 In/l	+1.5865 I	2.5171 I^2	+0.1620 IE
180	0.0000 g	0.0000 g^2	0.0000 E	14.8155 E	+7.4078 E	+1.0000 $B_{max.}$					
		$\Sigma = 9.3600\,g^2$		$\frac{1}{2}\Sigma = 7.4078\,E$				Arithmetical	$\Sigma = 16.2775\,I$	$\Sigma = 18.2895\,I^2$	$\Sigma = 7.5968\,IE$

$$\text{Average } e_r^2 = \frac{9.3600\,g^2}{18} = 0.5200\,g^2 \qquad \text{Average } e = \frac{14.8155\,E}{18} = 0.8231\,E \qquad \text{Average } i = \frac{16.2775\,I}{18} = 0.9043\,I$$

$$\text{Average } i^2 = \frac{18.2895\,I^2}{18} = 1.0161\,I^2 \qquad \text{Average } p = P = \frac{7.5968\,IE}{18} = 0.4220\,IE$$

$$\text{Effective } e_r = \sqrt{0.5200\,g^2} = 0.7211\,g \qquad \text{Effective } i = I' = \sqrt{1.0161\,I^2} = 1.0080\,I$$

the constant must have such a value that if added to the first and last values of Σe in column (5) the sums will be equal, the former minus and the latter plus, which obviously obtains when the constant is equal to the negative one half total Σe, or $-7.4078\,E$. Thus by adding $-7.4078\,E$ to the interrelative values in column (5) the interrelative instantaneous values B_r of magnetic density are found, as given in column (6).

Seventh. Since the maximum relative density is 7.4078 E for any given maximum actual density $B_{max.}$, the actual instantaneous densities B corresponding to the relative densities B_r are expressed by

$$B = \frac{B_r\, B_{max.}}{7.4078\, E}$$

by which are obtained the values entered in column (7).

Comparing the values of B in column (7) of Table II, obtained by this step-by-step method, with the values in column (4) of Table I derived by exact mathematical means, we notice a considerable difference between them, and the suspicion should arise that something is wrong with the method up to this point. Since there would arise no occasion, however, for this error to present itself in handling the step-by-step method in practice, let us proceed.

Eighth. The next step is to ascertain the magnetizing forces f corresponding to the densities in column (7) of Table II. In practice the values would be obtained directly from the hysteresis loop for the maximum density, as found by test on a sample of the iron used in the transformer core, and at once entered in column (9). Since in the present example, however, f bears an assumed mathematical relation to B, by substituting in equation (6) the values of the latter from column (7), we obtain by trial and approximation the corresponding values of the time angle α_B, as given, to the nearest minute, in column (8). Here again is evidence of error, since the angles in column (8) do not correspond in value to those in column (1), as they obviously should, but widely differ therefrom.

Finally, by substituting for α in equation (12) the values of α_B in column (8) the magnetizing forces in column (9) are obtained, which in the hysteresis loop of Fig. 2 correspond to the values of B in column (7).

Ninth. From equation (11)

$$i = \frac{fl}{n}$$

thus from the values of f in column (9) we may at once write the corresponding values of the exciting current in column (10).

Tenth. Enter the values of i^2 in column (11), and find the average value, the square root of which is the effective current I', or

$$I' = 1.0080\ I$$

Correctly, I' should obviously equal I.

Eleventh. Multiplying the values of impressed voltage in column (4) by the corresponding values of exciting current in column (10), we obtain the related instantaneous values of power, $ie = p$, as entered in column (12), from which the average power required to supply the energy consumed by hysteresis is

$$P = 0.4220\ IE$$

which by reference to (14) for the correct average power is seen to be 17.9 per cent too large.

Twelfth. But to determine the hysteretic lead we are here concerned with the effective value of current I' calculated by the step-by-step method, and not with the true effective value I. Therefore from the last two equations we have

$$P = 0.4187\ I'E$$
$$= I'E \cos\theta$$

from which

$$\theta = 65°\ 15'$$

that is, the equivalent sine wave of current lags 65° 15′ behind the equivalent sine wave of voltage.

And we have for the angle of hysteretic lead

$$\eta° = 90° - 65°\ 15'$$
$$= 24°\ 45'$$

whereas the correct angle, we already know, is 20° 58′. Thus the step-by-step method, as thus far incorrectly handled, has resulted in an angle of hysteretic lead 18 per cent too large. Had the half-cycle been divided into less than eighteen parts the error would have been larger, and *vice versa*, smaller.

The hysteresis current is

$$I' \cos\theta = 0.4187\ I'$$
$$= 0.4187 \times 1.0080\ I$$
$$= 0.4220\ I$$

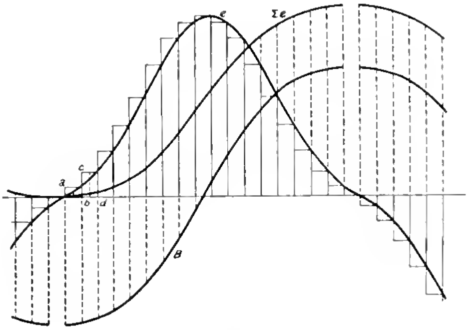

Fig. 4

whereas the correct value is 0.3579 I, and is thus 18 per cent too large.

The magnetizing current is

$$I' \sin\theta = 0.9082\ I'$$
$$= 0.9082 \times 1.0080\ I$$
$$= 0.9154\ I$$

whereas the correct value is 0.9338 I, and is thus 2 per cent too small.

Thirteenth. The underlying cause of the errors before noted will be made apparent by consideration of Fig. 4, in which e is the voltage wave plotted from column (4) of Table II; Σe is the step-by-step integration or summation curve of e from column (5); and B is the wave of magnetism from column (7).

Σe for any angle α should, as before observed, be proportional to the area of the voltage wave from zero deg., thus zero voltage, up to the angle α. But when, for example, α is 10 deg., we have taken the area from zero to 10 deg. as proportional to the value of e at 10 deg., indicated by the rectangle a, b; and when α is 20 deg., the area from 10 to 20 deg. has been taken as proportional to the value of e at 20 deg., indicated by the rectangle c, d; and we have added together the two rectangles for the total proportional area Σe between zero and 20 deg., and so on.

This procedure is wrong. For the area of the voltage wave from zero to 10 deg. is proportional to the value of the dotted *mid-ordinate*, or value of e at 5 deg. (subject to such small error as may be due to curvilinear deviation of the wave from a straight line joining the points on the wave corresponding to the angular limits under consideration); the area from 10 to 20 deg. is

TABLE III

(1) Deg. α	(2) e_r	(3) e_r^2	(4) $\frac{e_r E}{0.7211\,g} = e$	(5) Σe	(6) $\Sigma e - 7.4198E = B_r$	(7) $\frac{B_r B_{max}}{7.4198\,E} = B$	(8) Time Angle of B α_B	(9) From Hysteresis Cycle f	(10) $fl/n = i$	(11) i^2	(12) $ie = p$
0				$0.0000\ E$	$-7.4198\ E$	$-1.0000\ B_{max}$	0°	$-1.5865\ In/l$	$-1.5865\ I$	$2.5171\ I^2$	$0.0000\ IE$
5	$0.0354\ g$	$0.0013\ g^2$	$0.0491\ E$								
10				$0.0491\ E$	$-7.3707\ E$	$-0.9934\ B_{max}$	9° 56′	$-1.5240\ In/l$	$-1.5240\ I$	$2.3225\ I^2$	$-0.1556\ IE$
15	$0.1174\ g$	$0.0138\ g^2$	$0.1628\ E$								
20				$0.2119\ E$	$-7.2079\ E$	$-0.9714\ B_{max}$	19° 53′	$-1.3349\ In/l$	$-1.3349\ I$	$1.7819\ I^2$	$-0.3125\ IE$
25	$0.2294\ g$	$0.0526\ g^2$	$0.3182\ E$								
30				$0.5300\ E$	$-6.8897\ E$	$-0.9286\ B_{max}$	29° 53′	$-1.0405\ In/l$	$-1.0405\ I$	$1.0825\ I^2$	$-0.4329\ IE$
35	$0.3804\ g$	$0.1447\ g^2$	$0.5275\ E$								
40				$1.0576\ E$	$-6.3622\ E$	$-0.8575\ B_{max}$	39° 53′	$-0.6653\ In/l$	$-0.6653\ I$	$0.4427\ I^2$	$-0.4333\ IE$
45	$0.5657\ g$	$0.3200\ g^2$	$0.7845\ E$								
50				$1.8420\ E$	$-5.5778\ E$	$-0.7517\ B_{max}$	49° 54′	$-0.2769\ In/l$	$-0.2769\ I$	$0.0767\ I^2$	$-0.2557\ IE$
55	$0.7674\ g$	$0.5889\ g^2$	$1.0642\ E$								
60				$2.9062\ E$	$-4.5136\ E$	$-0.6083\ B_{max}$	59° 56′	$+0.0777\ In/l$	$+0.0777\ I$	$0.0060\ I^2$	$+0.0933\ IE$
65	$0.9581\ g$	$0.9179\ g^2$	$1.3286\ E$								
70				$4.2348\ E$	$-3.1850\ E$	$-0.4293\ B_{max}$	69° 57′	$+0.3572\ In/l$	$+0.3572\ I$	$0.1276\ I^2$	$+0.5150\ IE$
75	$1.1073\ g$	$1.2262\ g^2$	$1.5356\ E$								
80				$5.7704\ E$	$-1.6494\ E$	$-0.2223\ B_{max}$	79° 59′	$+0.5444\ In/l$	$+0.5444\ I$	$0.2963\ I^2$	$+0.8742\ IE$
85	$1.1894\ g$	$1.4146\ g^2$	$1.6494\ E$								
90				$7.4198\ E$	$0.0000\ E$	$0.0000\ B_{max}$	90°	$+0.6451\ In/l$	$+0.6451\ I$	$0.4162\ I^2$	$+1.0736\ IE$
95	$1.1894\ g$	$1.4146\ g^2$	$1.6494\ E$								
100				$9.0692\ E$	$+1.6494\ E$	$+0.2223\ B_{max}$	100° 1′	$+0.6878\ In/l$	$+0.6878\ I$	$0.4731\ I^2$	$+1.1045\ IE$
105	$1.1073\ g$	$1.2262\ g^2$	$1.5356\ E$								
110				$10.6048\ E$	$+3.1850\ E$	$+0.4293\ B_{max}$	110° 3′	$+0.7124\ In/l$	$+0.7124\ I$	$0.5075\ I^2$	$+1.0271\ IE$
115	$0.9581\ g$	$0.9179\ g^2$	$1.3286\ E$								
120				$11.9334\ E$	$+4.5136\ E$	$+0.6083\ B_{max}$	120° 4′	$+0.7587\ In/l$	$+0.7587\ I$	$0.5756\ I^2$	$+0.9111\ IE$
125	$0.7674\ g$	$0.5889\ g^2$	$1.0642\ E$								
130				$12.9976\ E$	$+5.5778\ E$	$+0.7517\ B_{max}$	130° 6′	$+0.8543\ In/l$	$+0.8543\ I$	$0.7299\ I^2$	$+0.7891\ IE$
135	$0.5657\ g$	$0.3200\ g^2$	$0.7845\ E$								
140				$13.7820\ E$	$+6.3622\ E$	$+0.8575\ B_{max}$	140° 7′	$+1.0055\ In/l$	$+1.0055\ I$	$1.0110\ I^2$	$+0.6548\ IE$
145	$0.3804\ g$	$0.1147\ g^2$	$0.5275\ E$								
150				$14.3095\ E$	$+6.8897\ E$	$+0.9286\ B_{max}$	150° 7′	$+1.1948\ In/l$	$+1.1948\ I$	$1.4275\ I^2$	$+0.4971\ IE$
155	$0.2294\ g$	$0.0526\ g^2$	$0.3182\ E$								
160				$14.6277\ E$	$+7.2079\ E$	$+0.9714\ B_{max}$	160° 7′	$+1.3856\ In/l$	$+1.3856\ I$	$1.9200\ I^2$	$+0.3244\ IE$
165	$0.1174\ g$	$0.0138\ g^2$	$0.1628\ E$								
170				$14.7905\ E$	$+7.3707\ E$	$+0.9934\ B_{max}$	170° 4′	$+1.5306\ In/l$	$+1.5306\ I$	$2.3427\ I^2$	$+0.1563\ IE$
175	$0.0354\ g$	$0.0013\ g^2$	$0.0191\ E$								
180				$14.8396\ E$	$+7.4198\ E$	$+1.0000\ B_{max}$	180°	$+1.5865\ In/l$			
		$\Sigma = 9.3600\ g^2$		$\frac{1}{2}\Sigma = 7.4198\ E$				Arithmetical	$\Sigma = 16.1821\ I$	$\Sigma = 18.0568\ I^2$	$\Sigma = 6.4305\ IE$

$$\text{Average } e_r^2 = \frac{9.3600\ g^2}{18} = 0.5200\ g^2$$

$$\text{Effective } e_r = \sqrt{0.5200\ g^2} = 0.7211\ g$$

$$\text{Average } e = \frac{14.8396\ E}{18} = 0.8244\ E$$

$$\text{Average } i = \frac{16.1821\ I}{18} = 0.8990\ I$$

$$\text{Average } i^2 = \frac{18.0568\ I^2}{18} = 1.0032\ I^2$$

$$\text{Effective } i = I' = \sqrt{1.0032\ I^2} = 1.0016\ I$$

$$\text{Average } p = P = \frac{6.4305\ IE}{18} = 0.3572\ IE$$

likewise proportional to the dotted mid-ordinate at 15 deg. and so on.

Inspection of Fig. 4 demonstrates that by this step-by-step method the rectangles expressing the proportional areas of the voltage wave for successive steps have been given a leading shift, in respect to their true position in angular relation to the voltage wave, amounting to half a step or 5 deg. Moreover, instead of occupying the eighteen steps into which a half-cycle is divided, they are condensed into seventeen steps, thus leaving the eighteenth step open, and producing discontinuity in the summation curve Σe and in the magnetism wave B; also the zero point of the latter has erroneously been advanced half a step.

All the errors noted in the preceding step-by-step method have followed from the manner of summing up the area of the voltage wave.

Correct Method

Let us put the correct method (by taking the *mid-ordinates* of the voltage wave steps, as proportional to the areas of the corresponding steps of the wave) to practical test, using the same data to start with, as before.

First. Referring to Table III, write in column (1) the angles of the eighteen steps in a half-cycle, 10 deg. apart, between which interpolate the mid-angles, to correspond with the mid-ordinates of the voltage wave steps, indicated by the dotted lines in Fig. 5.

Second. In column (2) write the relative values e_r of the voltage for the mid-angles, as found in practice by scaling the mid-ordinates on a diagram of the wave—determined in the present case, however, by equation (2). Then find the values given in columns (3), (4), and (5), in the same manner as before for Table II, writing the values of Σe in column (5) of Table III, however, opposite the corresponding angles for 10 deg. steps up to which, on the voltage wave, they represent a value proportional to the area of the wave up to the same angle.

Third. Continue in the same way as before for Table II, to complete the remaining columns (6) to (12) of Table III, noting that the values of the angle α_B (to the nearest minute) in column (8) closely agree with the corresponding angles in column (1).

Fourth. From column (11) we have

$$I' = 1.0016\ I$$

and from column (12)

$$P = 0.3572\ IE$$

hence

$$P = 0.3567\ I'E$$
$$= I'E \cos\theta$$

from which

$$\theta = 69°\ 6'\ 12''$$

that is, the equivalent sine wave of current lags 69° 6′ 12″ behind the equivalent sine wave of voltage.

And we have for the *angle of hysteresis lead*

$$\eta° = 90° - 69°\ 6'\ 12''$$
$$= 20°\ 53'\ 48''$$

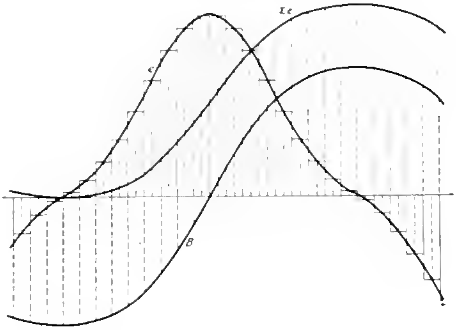

Fig. 5

which by this correct method of handling the step-by-step method is only ⅓ per cent too small, whereas by the incorrect method the result was 18 per cent too large.

The hysteresis current is

$$I' \cos\theta = 0.3567\ I'$$
$$= 0.3567 \times 1.0016\ I$$
$$= 0.3573\ I$$

a result that is practically the same as the correct value, 0.3579 *I*.

The magnetizing current is

$$I' \sin\theta = 0.9342\ I'$$
$$= 0.9342 \times 1.0016\ I$$
$$= 0.9357\ I$$

which is only $^1/_5$ per cent larger than the correct value, 0.9338 *I*.

A still closer determination of the angle of hysteretic lead may be assured, and the more conveniently in practice the more irregular the shape of the voltage wave, by measuring the areas included between the successive voltage steps with a planimeter, having any scale reading, and entering such measurements in column (2) of Table III, opposite the corresponding mid-angles in column (1), and proceeding with the calculations for the rest of the table after the manner already shown. For example, the area between zero and 10 deg. in the present case, assumed to be accurately determined with a planimeter, would be 0.0359 *g*, which enter in the table opposite the mid-angle 5 deg., and so on. We have determined the hysteresis angle for the present example on this plan with only an insignificant error in the result, but deem it unimportant to give here a table of the work.

FORM FACTOR

Mathematical Solution

The form factor of a wave of voltage, or current, is ordinarily taken as the ratio of effective value to the algebraic mean or average value for a half-cycle between zero values of the wave.*

To find the form factor of the voltage wave, multiply (4) through by $d\alpha$ and obtain

$$e\,d\alpha = 1.3868\,E\left[\sin\alpha\,d\alpha - \frac{1}{5}\sin 3\alpha\,d\alpha\right]$$

whence, since e is zero, when α is zero or π,

$$\text{Av.}\,e = \frac{1.3868\,E}{\pi}\left[\int_0^\pi \sin\alpha\,d\alpha - \frac{1}{5}\int_0^\pi \sin 3\alpha\,d\alpha\right]$$
$$= 0.8240\ E$$

Hence the form factor γ_e of the voltage wave is

$$\gamma_e = \frac{E}{0.8240\ E}$$
$$= 1.2136$$

To find the form factor of the current wave, multiply (10) through by $d\alpha$ and obtain

$$\text{Av.}\,i\,d\alpha = 1.3720\ I$$
$$\left[\sin(\alpha - 69°\ 21')d\alpha + \frac{1}{4}\cos 3\ (\alpha - 69°\ 21')d\alpha\right]$$

which, as in the integration of the above differential equation of voltage, must also be integrated between the limits, π distance apart, that represent the angles where the current wave crosses the time axis, that is, where i is zero, therefore between the limits 57° 35′ and 237° 35′.

We then have

$$\text{Av.}\,i = \frac{1.3720\ I}{\pi}$$
$$\left[\int_{57°\,35'}^{237°\,35'} \sin\ (\alpha - 69°\ 21')\ d\alpha + \frac{1}{4}\int_{57°\,35'}^{237°\,35'} \cos 3\ (\alpha - 69°\ 21')d\alpha\right]$$
$$= 0.8971\ I.$$

And the form factor γ_i of the current wave is

$$\gamma_i = \frac{I}{0.8971\ I}$$
$$= 1.1147.$$

Steinmetz, however, considers that the definition of form factor as the ratio of effective value to average value is undesirable because it results in 1.1107 as the form factor for a sine wave, which being always taken as the standard wave of reference, should, in his opinion, be assumed to have unity form factor. And to this end he has in effect adopted the rule that the form factor is equal to $2\sqrt{2}/\pi = 0.9003$ times the ratio of effective value to average value or, stated in another way, the form factor is the ratio of the average value of a sine wave, having the same effective value, as the actual wave, to the average value of the actual wave. It is at once obvious from the last definition, that the form factor is unity, when the actual wave is a sine wave.

According to the Steinmetz definition we have, as the form factor of the voltage wave in the present example,

$$\gamma_e = \frac{0.9003\ E}{0.8240\ E}$$
$$= 1.0926,$$

and of the current wave,

$$\gamma_i = \frac{0.9003\ I}{0.8971\ I}$$
$$= 1.0035$$

Step-by-step Solution

Considering the form factor as represented by the ratio of effective value to average value, we have from column (4) of Table III, average $e = 0.8244\ E$; hence the form factor of the voltage wave is

$$\gamma_e = \frac{E}{0.8244\ E}$$
$$= 1.2130,$$

which is only very slightly smaller than the correct form factor.

From column (10) of the table, neglecting signs, average $i = 0.8990\ I$; hence the form factor of the current wave is

$$\gamma_i = \frac{I}{0.8990\ I}$$
$$= 1.1123,$$

which is only 0.2 per cent smaller than the correct form factor.

The Steinmetz form factor of the voltage wave is

$$\gamma_e = \frac{0.9003\ E}{0.8244\ E}$$
$$= 1.0921$$

and of the current wave is

$$\gamma_i = \frac{0.9003\ I}{0.8990\ I}$$
$$= 1.0015.$$

CONCLUSION

This article has dealt with calculations by the step-by-step method applied to a particular case involving determination of phase relation and some other characteristics of certain interrelated periodic curves, and has differentiated the correct from the incorrect method for that case.

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* A.I.E.E. Standardization Rule, No. 16

The obvious and useful conclusion therefrom, applicable to all cases involving the interrelation as well as other characteristics of periodic curves, is that the step-by-step mid-ordinate, and not the mean-ordinate, rule should be used in progressively integrating the area of a curve, when such integration is of phase or angular significance in the problem.

APPENDIX

General Equation for the Magnetism Wave in Terms of Maximum Magnetic Density

The equation for the wave of magnetic density may be derived from that for the impressed voltage wave, if the resistance of the primary circuit is relatively so low that the voltage drop due to the exciting current is a negligible percentage of the total voltage (which will be the case in well-designed transformers), and therefrom the latter is substantially equal to the counter induced voltage, but of opposite sign.

Write the well-known equation for induced voltage

$$e_i = -\frac{d\phi_n}{10^8\, dt}$$

in which ϕ_n is the number of magnetic linkages between the primary windings and the lines of force, the minus sign indicating the opposition of this voltage to the impressed voltage producing the current and magnetism by which the induced voltage is generated. From this equation and the known relation $d\,\alpha = 2\pi f dt$

$$e_i = -\frac{2\pi f d\phi_n}{10^8\, d\,\alpha}$$

or

$$d\phi_n = -\frac{10^8\, e_i\, d\,\alpha}{2\pi f}$$

thus

$$\phi_n = -\frac{10^8}{2\,\pi\, f_\cdot}\int e_i\, d\,\alpha$$

which, obviously, may at once be recast in the form

$$B = -bB_{max.} \textstyle\int e_i\, d\,\alpha \qquad (16)$$

where B is the instantaneous magnetic density corresponding to the time angle α; B_{max} is the maximum density in the magnetic cycle, and b is a constant, to be evaluated.

The general equation for a periodic impressed voltage wave is

$$e = A_1 \sin\,\alpha + A_3 \sin 3\,\alpha + \ldots . + B_1 \cos\,\alpha + B_3 \cos 3\,\alpha + \ldots . \qquad (17)$$

which may be written

$$e = C_1 \sin(a+\beta_1) + C_3 \sin\,(3\,\alpha+\beta_3) + \ldots . + C_n \sin\,(n\,\alpha+\beta_n) \qquad (18)$$

in which the sine and cosine terms of equal frequency, in (17), have been combined.

Since the counter induced voltage e_i is equal to the impressed voltage, but of contrary sign, from (18), we may write

$$e_i = -C_1 \sin\,(\,\alpha+\beta_1) - C_3 \sin\,(3\,\alpha+\beta_3) - \ldots . - C_n \sin\,(n\,\alpha+\beta_n) \qquad (19)$$

From (16) and (19)

$$B = b\, B_{max.} \textstyle\int [C_1 \sin\,(\,\alpha+\beta_1)\, d\,\alpha + C_3 \sin\,(3\,\alpha+\beta_3) d a + \ldots . + C_n \sin\,(n\,\alpha+\beta_n) d\,\alpha],$$

$$= -b\, B_{max.}\left[C_1 \cos\,(\,\alpha+\beta_1) + \frac{C_3}{3}\cos\,(3\,\alpha+\beta_3) + \ldots . + \frac{C_n}{n}\cos\,(n\,\alpha+\beta_n)\right] + C \qquad (20)$$

To find the angle, or angles, for which B is of maximum or minimum value, place the first differential coefficient of B with respect to α equal to zero, or

$$\frac{dB}{d\,\alpha} = b\, B_{max.}\left[C_1 \sin\,(\,\alpha+\beta_1) + C_3 \sin\,(3\,\alpha+\beta_3 + \ldots . + C_n \sin\,(n\,\alpha+\beta_n)\right] = 0,$$

that is, B is either maximum or minimum when

$$C_1 \sin\,(\,\alpha+\beta_1) + C_3 \sin\,(3\,\alpha+\beta_3) + \ldots . + C_n \sin\,(n\,\alpha+\beta_n) = 0 \qquad (21)$$

thus, when

$$a+\beta_1,\ 3\,\alpha+\beta_3, \text{ etc.} = 0, \text{ or } \pi, \text{ or } 2\pi, \text{ or } 3\pi, \text{ etc.}$$

From (18) and (21), and (19) and (21), it follows, that e and e_i are zero, when B is maximum or minimum, as we otherwise know from physical, independently of mathematical, considerations must be the case.

The second differential coefficient of B with respect to α is

$$\frac{d^2B}{d\,\alpha^2} = b\, B_{max.}\left[C_1 \cos\,(\,\alpha+\beta_1) + 3C_3 \cos\,(3\,\alpha+\beta_3) + \ldots . + nC_n \cos\,(n\,\alpha+\beta_n)\right],$$

which reduces to

$$\frac{d^2B}{d\,\alpha^2} = -b\, B_{max.}\,(C_1 + 3C_3 + \ldots . + nC_n),$$

when $\alpha+\beta_1$, $3\,\alpha+\beta_3$, etc. $=\pi$, or 3π, or 5π, etc., and is negative, and therefore B is of maximum value, and (20) then takes the form

$$B_{max.} = -b\, B_{max.}\left[C_1 \cos\,(\,\alpha+\beta_1) + \frac{C_3}{3}\cos(3\,\alpha+\beta_3) + \ldots . + \frac{C_n}{n}\cos\,(n\,\alpha+\beta_n)\right] + C,$$

$$= b\, B_{max.}\left[C_1 + \frac{C_3}{3} + \ldots . + \frac{C_n}{n}\right] + C,$$

which obviously holds, when the integration constant $C=0$, and

$$b\left[C_1 + \frac{C_3}{3} + \ldots . + \frac{C_n}{n}\right] = 1,$$

thus when

$$b = \frac{1}{C_1 + \frac{C_3}{3} + \ldots . + \frac{C_n}{n}}. \qquad (22)$$

Hence, from (20) and (22), and remembering that $C=0$, we may finally write the equation for the wave of magnetic density in terms of the maximum density,

$$B = -\frac{B_{max.}}{C_1 + \frac{C_3}{3} + \ldots . + \frac{C_n}{n}}\left[C_1 \cos\,(\alpha+\beta_1) + \frac{C_3}{3}\cos\,(3\alpha+\beta_3) + \ldots . + \frac{C_n}{n}\cos\,(n\,\alpha+\beta_n)\right] \qquad (23)$$

Similarly, $\frac{d^2B}{d\,\alpha^2}$ is positive, and therefore B is of minimum value, when $\alpha+\beta_1$, $3\,\alpha+\beta_3$, etc. $=0$, or 2π, or 4π, etc., and we then have $B = B_{min.} = -B_{max.}$, vectorially. The minimum scalar value of B is 0, when

$$\alpha+\beta_1,\ 3\,\alpha+\beta_3, \text{ etc.} = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \text{ or } \frac{5\pi}{2}, \text{ etc.}$$

Performance and Life Tests on the Oxide Film Lightning Arrester[1]

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The development of the oxide film lightning arrester was first announced in a series of papers before the A.I.E.E., in June, 1918. These papers were prepared only after extensive laboratory tests and a few installations on commercial circuits had demonstrated the merits of the device. Further laboratory tests and the performance of an increased number of oxide film arresters on transmission lines during the thirty-month interval have proved conclusively that this form of lightning arrester will satisfactorily fulfill the requirements of service. The behavior of the oxide film arrester during these laboratory tests is recorded in this article. The condition of one cell after four years actual service is also illustrated.—Editor.

Since the first papers on the oxide film (O F) lightning arrester were presented a little over two years ago,[2] the arrester has proved to be a worthy piece of apparatus by performance in regular service. Several hundred arresters are now installed on both indoor and outdoor circuits up to 73-kv. rating, and higher voltage units will soon be in service. Figs. 1, 2, and 3 show the typical designs used. In Fig. 3, the three-phase legs and the ground leg are all arranged in one stack, the bottom section being the ground leg. In Fig. 1, the three-phase legs are the upper sections and the ground leg is the lower section. In Fig. 2, the three-phase legs and ground leg are set up parallel to one another. Fig. 4 shows the covered sphere gap used with the outdoor design, which permits of an indoor setting. Due to the small leakage current of these arresters (about 0.010 amperes), it is not necessary to use horn gaps to aid in breaking the arc, and it is therefore possible to use the covered sphere gap which has previously been described.[3] Fig. 5 shows the testing device used and its method of operation, about which more will be said later.

The efficiency of a lightning arrester is governed by four factors; namely, sensitiveness, discharge capacity, reseal, and life.

Sensitiveness

As most electrical apparatus is tested at twice normal voltage, an arrester should be able to begin discharging at about this voltage. This means a horn or sphere gap should not be set for over double voltage for best results. To care for steep wave impulses the time lag of the arrester should be a minimum.

Fig. 1. Oxide Film Lightning Arrester for Indoor Service on Three phase Circuits, 15,000-25,000 Volts

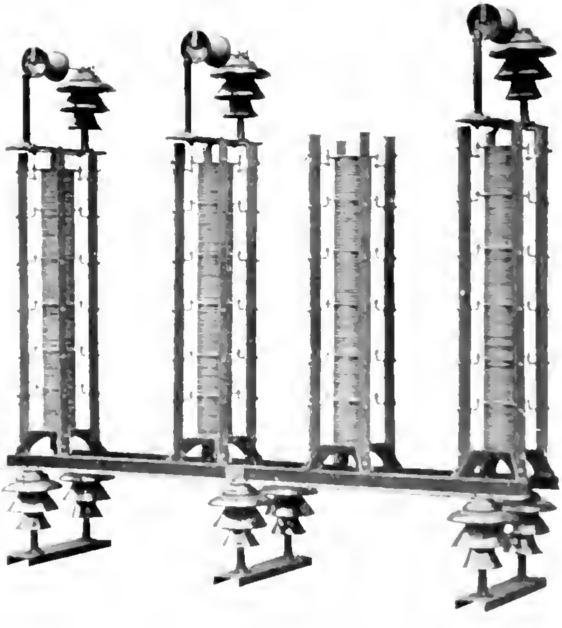

Fig. 2. Oxide Film Lightning Arrester for Indoor Service on Three-phase Circuits, 37,000 50,000 Volts

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[1] Read before A.I.E.E., Chicago, Nov. 12, 1920.

[2] "The O F Lightning Arrester," General Electric Review, 1918; Vol. XXXVII, Transactions A.I.E.E., 1918.

[3] "The Effect of Transient Voltages on Dielectrics II," by F. W. Peek, Jr., Transactions A.I.E.E., Vol. XXXVIII.

Current Discharge Capacity

To discharge the energy from a surge, the discharge path must be of sufficiently low resistance to prevent the voltage drop being above the insulation strength of the apparatus connected to the line. Again, since a double voltage test is given to apparatus, the discharge capacity of an arrester is usually given at double rated voltage.

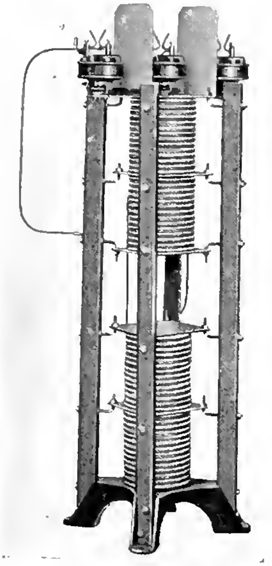


Fig. 3. Oxide Film Lightning Arrester for Indoor Service on Three-phase Circuits, 5,000-7,500 Volts

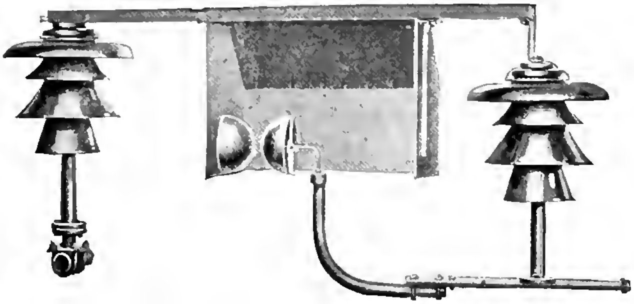


Fig. 4. Covered Hemisphere Gap as Used on Outdoor Type Oxide Film Arrester, 50,000-73,000 Volts. Section of Cover Omitted to Show Gap

Reseal

Reseal is the act of cutting off the discharge path through the arrester when the voltage across the arrester has returned to normal. The quicker this can be accomplished the better it will be, for if an arrester has sufficient discharge capacity, the dynamic or line frequency current that follows will not only be apt to destroy the arrester but may also cause bad disturbances on the line.

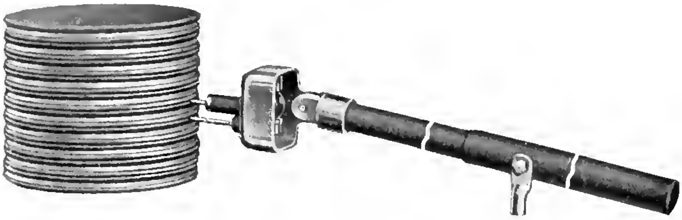


Fig. 5. Oxide Film Cell Testing Device in Position for Testing

Reseal should also permit an arrester to be ready immediately for another discharge, for with a lightning storm over a large area of transmission lines it is fair to assume that impulses and surges can occur extremely close together; that is, at least a second apart, and sometimes several per second.

Life

It is difficult to exactly define what the life of a satisfactory arrester should be, but a good arrester should easily withstand the average surge or impulse. Arcing grounds are the most dangerous type of discharges and as they vary greatly in severity, depending upon the system and just where they occur, it is difficult to state how long an arrester should care for one.

TESTS

The following results of tests show how the O F arrester fulfils the requirements outlined above. A single cell was used in all these tests in order to obtain as powerful discharges through the cell as possible with the power available.

The first set of tests was made with a circuit as shown in Fig. 6. The usual surge circuit was used, which superimposes the 25,000-volt, 2300-cycle surge on the dynamic 300-volt, 47-cycles circuit. Fig. 11 shows an oscillogram of the discharges of an O F cell on this circuit. Vibrator 2 shows the dynamic 47-cycle voltage across the arrester with the 25,000-volt, 2300-cycle surge superimposed. The voltage peaks are kept at about double voltage and the cell reseals without permitting any dynamic current to follow; that is, this test shows that *reseal* and *sensitiveness* are satisfactory. Although the discharge through the cell is about 50 amperes,

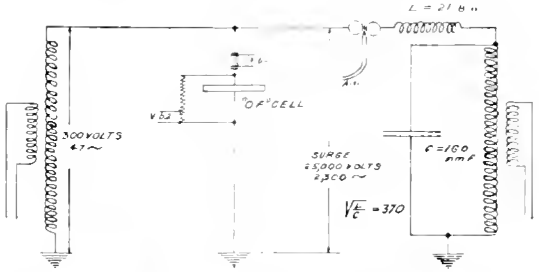


Fig. 6. Circuit Connection Used for Surge Tests

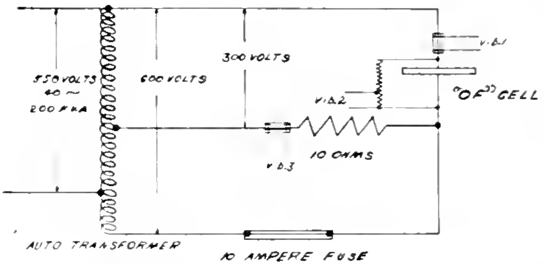


Fig. 7. Circuit Connection Used for Double-voltage Surge Tests

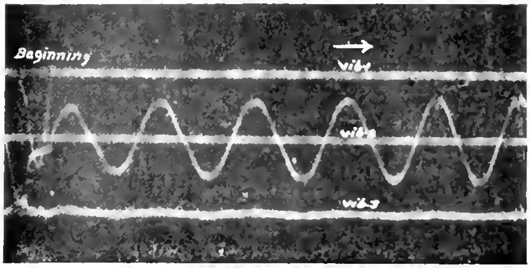


Fig. 8. Oxide Film on Circuit in Fig. 7

Vibrator 1. Current through arrester at 600 volts, 1 mm. = 100 amperes

Vibrator 2. Voltage across arrester, 1 mm. = 22 volts

Vibrator 3. Current through arrester at 300 volts, 1 mm. = 5 amperes

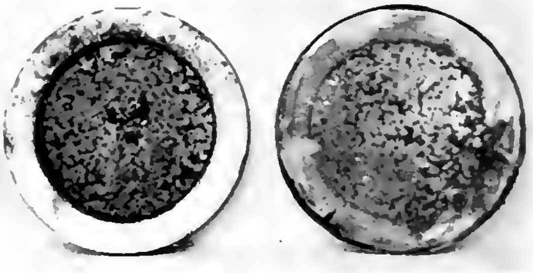


Fig. 9. Inside of Electrodes of Oxide Film Lightning Arrester Cell Returned from 13,000-volt Installation After Four Years of Service

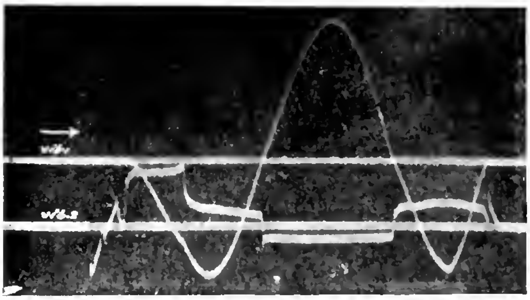


Fig. 10. Oxide Film Cell on a 600-volt, 40-cycle Circuit

Vibrator 1. Current through arrester, 1 mm. = 100 amperes

Vibrator 2. Voltage across arrester, 1 mm. = 22 volts

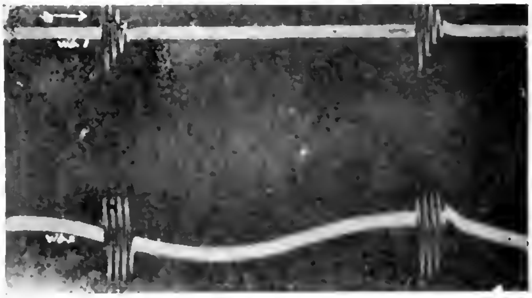


Fig. 11. Oxide Film Cell on Circuit in Fig. 6

Vibrator 1. Current through arrester, 1 mm. = 5 amperes (peak value)

Vibrator 2. Voltage across arrester, 1 mm. = 85 volts (peak value)

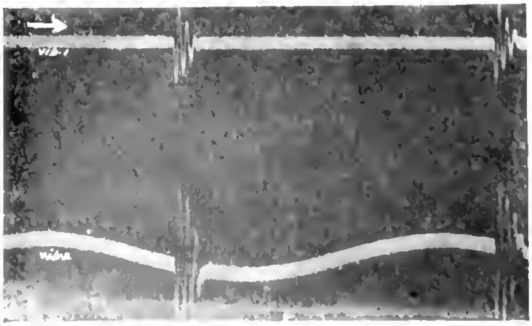


Fig. 12. Arrester X on Circuit in Fig. 6

Vibrator 1. Current through arrester, 1 mm. = 5 amperes (peak value)

Vibrator 2. Voltage across arrester, 1 mm. = 85 volts (peak value)

Fig. 13. Arrester Y on Circuit in Fig. 6

Vibrator 1. Current through arrester, 1 mm. = 5 amperes (peak value)

Vibrator 2. Voltage across arrester, 1 mm. = 85 volts (peak value) since the surge is supplied by a 15-kv-a. transformer, this test is not enough in itself to demonstrate that the discharge capacity is satisfactory.

Fig. 10 shows an oscillogram taken with 600 volts, 40 cycles (double standard voltage) impressed across an O F cell, to show current discharge capacity. The current peaks are 3500, 4200, and 3300 amperes, and the voltage peaks 110, 89 and 154 volts respectively, giving an internal resistance of 0.031, 0.021 and 0.047 ohms respectively. Due to the low resistance of the O F cell and its relative value to the impedance of the circuit, the impressed voltage of 600 was not sustained across the coil when the high current flowed. This *discharge capacity* is extremely high and should be ample under all conditions. The internal resistance of a cell will vary between 0.01 and 0.1 ohm, depending upon the particular path followed by the discharge through the cell.

Fig. 7 gives the connection used for a double voltage surge test with normal voltage immediately following. This is accomplished as shown by bringing out a tap from the transformer at 300 volts (standard voltage) and connecting it through a low resistance to the arrester cell. The resistance is necessary to prevent the lower section of the transformer from becoming short circuited. With this connection, 600 volts is supplied to the arrester until the fuse opens, and the lower half of the transformer then being cut off, 300 volts is continued across the arrester cell. This is about the most severe test that can be given a lightning arrester and only an arrester which has a *low breakdown, good current discharge capacity*, and *good sealing characteristics* will act satisfactorily.

Referring to the oscillogram taken on this circuit, shown in Fig. 8, the switch impressing 600 volts across the cell closed at the extreme left. The cell immediately broke down and discharged 2700 amperes. This current after one-half cycle blew the 10-ampere fuse, thereby cutting off one-half of the transformer, and causing the voltage across the cell to drop to 300 or normal. There was then a sealing current of about 2 amperes for several cycles shown by vibrator 3, which caused the small breaks in the voltage wave. After a few seconds the current through the cell had dropped to normal or a few milliamperes.

To show the relation of protection and current discharge capacity, oscillograms were taken of single O F cells with external resistance in series, on the circuit of Fig. 6. X represents an arrester with a medium internal resistance and a discharge capacity at double voltage of 60 amperes. Y represents an arrester with a higher internal resistance and a discharge capacity of 20 amperes at double voltage. Fig. 12 shows an oscillogram taken with arrester X, and Fig. 13 an oscillogram taken with arrester Y on this circuit. It will be noted that the voltage peaks with X are 1600 and with Y 3650, as against 900 with the standard cell, which was shown in Fig. 11. Moreover, if the frequency were nearer what is obtained in actual service, that is, from 10,000 to 100,000 cycles instead of 2300 cycles which had to be used for oscillographic work, this difference would have been much greater, due to the higher impedance of the transformer at the higher frequencies. Therefore, to give satisfactory protection an arrester must have a good current discharge capacity on double voltage and more than these X and Y arresters show; X and Y also show the bad effect of a poor ground connection.

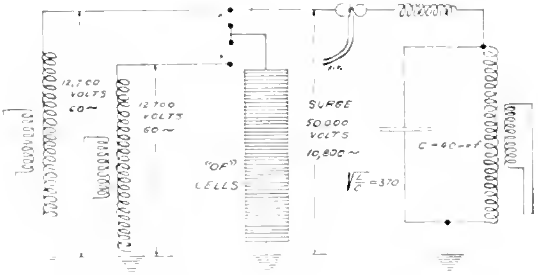


Fig. 14. Circuit Connection Used in Intensive Life Run Tests

Sensitiveness in service is limited by the gap setting, but since no dynamic current follows a surge discharge and the leakage current is only a few milliamperes, this gap setting can be small. The gap settings used in service correspond to line voltage so that breakdown between phases is double voltage and the breakdown to ground is 1.7 times the voltage to ground. Since the covered gap is used for outdoor installations a dry or indoor setting can be used.

The life of a lightning arrester is a very important factor, and one that has to be estimated from both operating and laboratory data. Operating data obtained during the past five years show that little deterioration has occurred in the O F cells. Cells have been returned and tested from typical installations, and little if any change has been found. Fig. 9 is a view of an opened returned cell, and shows the film side of the electrodes and the porcelain spacer. The lead peroxide (PbO_2) filler has been removed. This cell was returned recently from a 13,000-volt arrester installed early in 1916, which has been subjected to much more than average service due to its location and surroundings. The few white spots in the photograph are discharge areas covered with yellow litharge (PbO). This PbO area or plug is what has caused the cell to reseal after the surge has passed through and is reduced from the PbO_2 filler by the heat of the current through the small discharge spot in the film. The larger dark areas are where some of the PbO_2 filler is still adhering to other discharge areas, and the light background is the varnish film. The lead peroxide filler showed no change.

To obtain information on the life of O F arresters several years ahead of outside reports, however, an intensive test has been running during the past few years. Fig. 14 gives the general scheme of circuit used.

In Fig. 14, the surge circuit is shown to the right and consists of the usual inductance, capacitance, and air gap, used to obtain oscillations. The 50,000-volt transformer charges the condensers, which, upon breaking down the air gap set for a little under 50,000 volts cause the surge through the arresters. The transformer to the left supplies the dynamic 60-cycle voltage to all the arresters running on this particular voltage. Ordinarily all the lever switches are down. Fig. 14 shows only one particular voltage, and only one arrester and one set of switches. With this arrangement the arresters are separate from the surge circuit. When it is desired to surge any one particular arrester, the upper lever switch corresponding to this arrester is thrown, thus paralleling the two transformers supplying dynamic voltage. The lower lever switch is then opened and this particular arrester is still on dynamic voltage, but also on the surge circuit, which can now be thrown on. After surging, this arrester is thrown back on the regular dynamic transformer and the next arrester put through a similar operation. This arrangement of transformers and switches permits the regular dynamic voltage to all the arresters to be uninterrupted during surging operations.

O F arresters were placed on 330, 2300 and 12,700 volts respectively at 60 cycles with no series gap, and all arranged as shown in Fig. 14. These arresters have been surged daily, the surge current through the arresters having a maximum peak value of about 50 amperes and dying down to about 20 amperes at the end. This surge, having a surge impedance of 370 ohms, is representative of an actual surge on a line, except that the average actual surge has a higher frequency and may at times be more powerful. It has been found, however, that the lower the frequency of a surge, the more difficult it is for an arrester to seal.

330-volt Circuit, Single O F Cells

These cells take from 5 to 75 milliamperes leakage current and run at a temperature of about 50 deg. C. It took about four years to record a failure with these cells. A failure then occurred by reduction of a sufficient amount of the PbO_2 to cause high internal resistance and hence loss of protection. As the voltage across the cells is, of course, always the same, this group of cells is more permanent than the 2300 and 12,700-volt arresters. With these latter arresters the voltage distribution across the various cells may change. This adds one more variable to the action of arresters consisting of more than one cell.

2300-volt Circuit, Eight O F Cells in Series

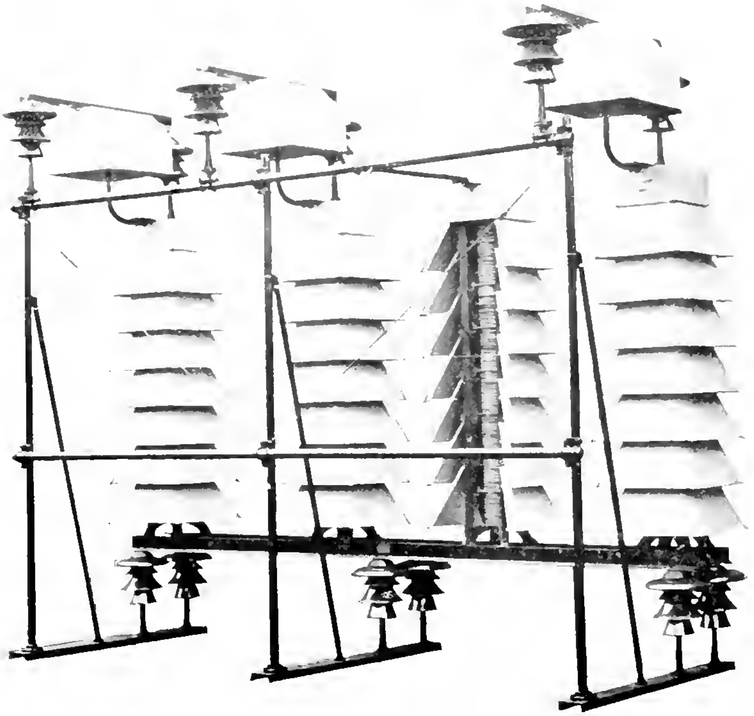
These arresters so far have acted about like the single cells; that is, voltage distribution has remained normal. Voltage distribution is obtained by means of shunting vacuum tubes, which break down or glow at various voltages, across each cell in turn. It is the same idea that is used to test the cells in service as shown in Fig. 5. For service conditions a vacuum tube which will glow at about 1000 volts alternating current is used. As the internal condition of a cell changes, and more particularly the film, the voltage drop when in series with a number of cells may change. Although this is not an infallible method of picking out poor cells in service, it does give a reliable indication in most cases. For voltage distribution tests tubes breaking down between 100 and 2300 volts alternating current are used. For convenience in interpolating these data, a cell having a voltage drop of less than 200 is designated low; from 200 to 400 normal, from 400 to 600 high, and above 600 very high. The results can then be plotted against the respective cells by using a different color for each of these four groups. The units on 2300 volts have shown with one or two exceptions only normal cells on voltage distribution, and the few low or high cells, which have appeared from time to time, have returned again to normal. The leakage current of this group of arresters varies between 1 and 10 milliamperes and the cells run at a temperature of about 40 deg. C. A few units have failed or lost their protection after four years of continuous service.

12,700-volt Circuit, Forty-seven O F Cells in Series

These arresters have been running almost two years with no appreciable deterioration. To obtain the relative effect of dynamic and surge, similar arresters were run with different service characteristics, as follows: (a) dynamic only, (b) dynamic and surge, (c) surge only, and (d) idle. The leakage current is from 5 to 10 milliamperes and about the same through all the arresters. The temperature is about 35 deg. C. at the top of the stack, 45 deg. C. in the middle and 30 deg. C. at the bottom of the stack. Results to date show that (a) and (b) types of arresters give about the same characteristics: that is, the daily surge has no ill effect on the arresters. Both (a) and (b) show a gradual tendency for low voltage cells to appear at the bottom of the stack and higher voltage cells at the top. Here again no change has been found to be absolute; that is, unless a cell is extremely high, it may go from low to high and back again. The low cells at the bottom of a stack may be due to either capacity or temperature, but probably the latter, as all the cells are about normal when first put on circuit. The (c) and (d) types of cells show a general scattering of high and low cells throughout the stack.

This sort of intensive test has been found extremely valuable in determining ahead of time what might occur in service and also for determining the effect of changes. So far as applying to standard arresters in service, it seems fair to assume that if an arrester will stand up say four years under such an intensive test, it will stand up several times four years in actual service. Of course, it is always possible that a more or less direct lightning stroke or a long arcing ground will destroy an arrester, so that this conclusion should apply to normal average service. As yet the factor between test and actual service is not known, but it should be determined when longer service results are available.

The author wishes to express his appreciation to E. E. Burger for his valuable assistance in obtaining the data used in this paper.



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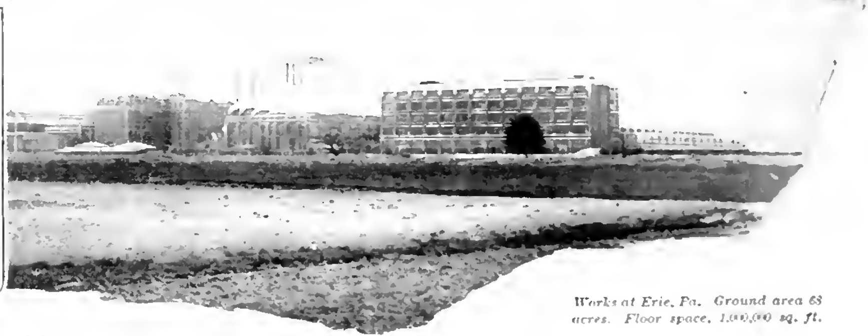

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DECEMBER, 1920

300-TON ELECTRIC SHOVEL IN OPEN-CUT MINING

(See article, page 938)

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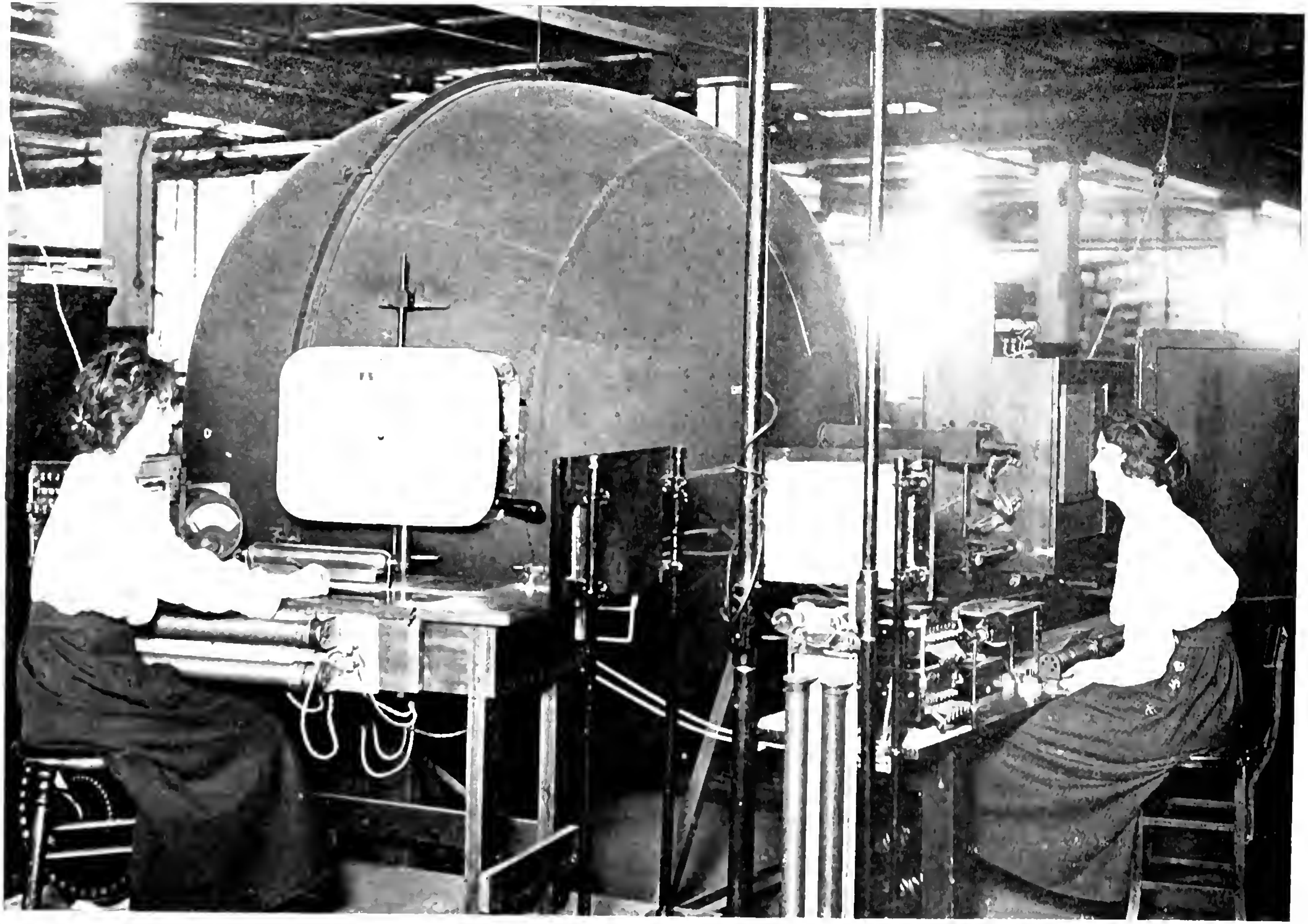


THE INTEGRATING SPHERE PHOTOMETER

See article, "Commercial Photometry," page 954

GENERAL ELECTRIC
REVIEW

THE 300-TON ELECTRIC SHOVEL IN OPEN-CUT QUARRYING

Carl D. Bradley

President and General Manager, Michigan Limestone & Chemical Company

About ten years ago the Michigan Limestone & Chemical Company purchased a tract of several thousand acres extending for several miles along the shore of Lake Huron and containing limestone which the company intended to develop commercially for blast furnaces, chemical plants, etc. The limestone lay close to the water front and delivery to steamers was comparatively easy and economical with proper facilities.

In order to establish a market for its product the company made sales contracts at very low prices which required very careful consideration of all details relating to construction and operation of the plant in order that costs might be kept within the limits prescribed by the selling prices obtainable. Large scale operations were involved and many engineering problems had to be solved. The general problem was to drill, blast, quarry and transport the stone to the mill and there crush, size, wash and convey it to storage, and thence load it into steamers.

Changes were necessarily made in the plant from year to year, and the difficulty of handling the great tonnage was finally overcome by the installation of large crushers, large screens and similar equipment. The loading facilities have developed to a point where steamers of 13,000 gross tons are loaded in six hours, and the management is convinced that theoretically the problem of quarrying the limestone is no different from that of handling and loading it. However, no adequate means of getting large output from open cut quarry operations at low cost had been developed, and therefore attention has lately been forced upon production at the quarry.

Quarrying operations are being conducted against the natural bluff of limestone which is now in excess of one and one-half miles long and more than one hundred feet high, requiring two benches. This bank is too high for the economic and safe operation of the 100-ton steam shovel, and because of this fact and the high costs of labor and material the management has become deeply interested in the application of large digging and transportation units which will permit the quarrying operation to keep pace with the mill and loading system. If a digging machine can be had which will take care of 5000 tons of material in ten hours and operate satisfactorily under this punishment day in and day out, the problem is approaching solution, with a resultant economy in all operations.

For the future the quarry will approximate two miles in length in one face with five large electric shovel units working against it, served by locomotives and cars of comparable capacity. One man will operate the shovel and another the train, and the tonnage per man hour will be multiplied by five over that of present day equipment. With the introduction of the 300-ton electric shovels, quarrying on a large property such as that under consideration is reduced to a scientific basis.

The modern trend in industrial development has been toward increasing the efficiency of the individual, or in other words, the rate of commodity handling per man hour; only by such a test have we the right to measure accomplishment. While the management has been able to satisfactorily increase the rate in crushing limestone, in screening, conveying and loading it, until recently efficiency at the digging end has not kept pace with that of other operations, and it was specifically for the purpose of improving this performance that the 300-ton electric shovel was installed. The results that have been accomplished by the new equipment have been most gratifying, and it is firmly believed that through the proper application of these large electric shovels the quarry operations will be made entirely satisfactory.

The economical reasons that have dictated the employment of these largest electric shovels by the Michigan Limestone & Chemical Company will be better understood by a review of their operations as outlined in an article by Messrs. Fisher and Head, published elsewhere in this issue.

The Electric Shovel in Open-cut Mining

By C. R. Fisher

Electrical Engineer, Michigan Limestone and Chemical Company

and

H. G. Head

General Electric Company, Detroit

Coal deposits with over-burden too shallow to permit shaft mining now constitute the most profitable form of coal mining when large electrically driven stripper shovels are used. The principal contributing factors are the greater depth of cut which the larger shovel can make, the increased bulk of material which its greater radius of action permits it to remove before taking out time to make a forward movement, and the lower labor and power costs. The performance of the large electric shovel in stripping operations has naturally led to its adoption in other branches of mining, and this article describes the construction and operation of the latest type 300-ton electric shovel as applied to open-cut limestone quarrying, where it has every promise of duplicating its success in coal mining.—Editor.

The electric shovel is a new development, the possibilities of which are being recognized more and more by quarrying and mining companies. Heretofore the use of steam as the motive force for mechanically operated shovels has seldom been questioned, but the present high prices of coal, shortage of labor, and general need of economical and increased production are causing progressive companies to scrutinize their operating conditions very closely and to seek every method which will increase the efficiencies of their operating systems.

The development of the large electric shovel has been made possible largely through application in the middle west coal fields and in the iron ranges of Minnesota. Up to a few years ago the 100-ton steam shovel was the largest excavator in general use, but material handling has been greatly improved by the adoption of large electrics.

In coal mining, the usual procedure was for the surveyors to go over all prospective coal mines and buy up mining rights from the owners. Wherever the coal had an over-burden of 25 to 30 feet or more the option was bought, but when the over-burden was 10 to 15 feet, the prospect was considered uncommercial because of insufficient material above the coal vein for safe shaft mining. This meant that there was a large amount of very good coal too close to the surface to be mined. However, with the advent of the large coal strippers, all of this coal land was reclaimed and it is now the most remunerative form of coal mining. The art has developed so rapidly that burdens up to 100 feet in thickness have been removed from coal seams 4 to 5 feet thick. In such cases, the large 300-ton shovel is commonly used, followed by a small friction electric shovel which loads the coal into small dump cars.

The success of these large shovels in stripping has led to their development in other fields, such as excavating and loading ore directly into the dump cars. The success of large shovels for this work is due largely to the great difference in the amount of material available in front of the large shovel without moving ahead. A smaller shovel, say the 100-ton size, would have to move ahead about twenty times to handle the same amount of material. This would necessitate lengthening the loading track eight times, whereas the large shovel would load the same amount of material from one position. Figuring in these delays of the 100-ton shovel, the 300-ton shovel should dig approximately twice as much yardage as the 100-ton shovel per shift.

This article was written primarily to discuss the construction and performance of the model 300 E Marion electric shovel with General Electric automatic control, recently installed in the Michigan Limestone and Chemical Company quarry. In general the shovel is of the large capacity type fitted with an 80-foot boom to give a digging radius of approximately 54 feet at the rail and 99 feet at 40 feet above the rail. The present dipper has a capacity of six cubic yards. Ultimately an eight-yard dipper will probably be substituted. All of the electric equipment except the crowd motor installed on the boom is located in the cab, which is approximately 50 feet long, 22 feet wide, and 15 feet high. The cab and boom revolves as a turntable on a large square platform made up of steel beams and plates and mounted on four trucks for locomotion on eight 130-pound rails

The electrical machinery portion of the equipment consists of one four-unit motor-generator set with direct-connected exciter,

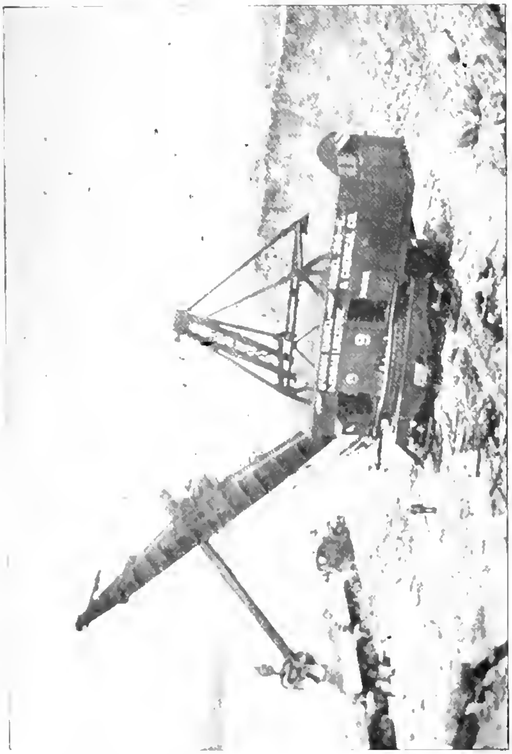


Fig. 1. 300-ton Electrically-operated Shovel Loading Cars

Fig. 2. Taking a 6 Cu. Yard Mouthful of Limestone

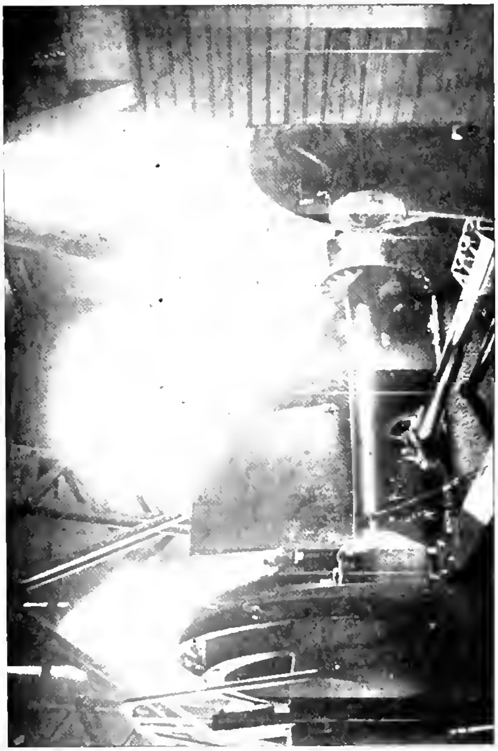


Fig. 3. Interior View Showing Hoist Drum and Gearing

Fig. 4. View of Operator's Stand Showing Master Switches

two hoist motors geared to a common shaft, one swing motor, one crowd motor and one trip motor. The ratings of the units of the generator set are:

Synchronous motor ATI, 6 poles, 435 kv-a., 1200 r.p.m., 2300 volts, 3 phase, 60 cycle.

Hoist generator MPC, 6 poles, 250 kw., 330 volts no load, 250 volts full load, differential compound wound.

Direct connected exciter EC-5, 4 poles, 20 kw., 125 volts, flat compound wound.

Swing generator and crowd generator each MPC, 4 poles, 50 kw., 330 volts no load, 250 volts full load, direct current, differential compound wound.

The ratings of the direct-current motors are:

Two hoist motors each MDS 109, 6 poles, 175/140 h.p., 400/450 r.p.m., 230 volts.

Swing motor MDS 106, 4 poles, 75/55 h.p., 485/550 r.p.m., 230 volts.

Crowd motor MD-106, 4 poles, 70/25 h.p., 500/900 r.p.m., 230 volts.

The hoist, swing and crowd motors are series wound. They are doubly rated, the larger horse power value being the intermittent rating at the lower speed, the smaller horse power value the continuous rating at the higher speed. The trip motor is rated KTE, 8 pole, 50 lb. torque, 900 r.p.m., 220 volt, 3 phase, 60 cycle. This motor is of the high resistance squirrel cage rotor type.

The two hoist motors are connected in parallel and supplied with power by the hoist generator. By a system of gears the hoist motors are used for hoisting the dipper by means of cable and drum, for propelling the entire shovel outfit on its track to new digging positions, or for raising or lowering the boom. The swing motor is supplied with power by the swing generator and is used for revolving the cab and boom on the turntable. The crowd motor is supplied with power by the crowd generator. This motor operates the dipper stick through a system of reduction gears, pinions and racks. The trip motor operates the trip mechanism on the bottom of the dipper by means of cable and drum.

It should be noted that the control of this new electric shovel is radically different from that of the old type which consisted of series motors all operated from one constant potential generator, speed variation being taken care of by a resistance in series with the armature of these series motors, which resistance was short circuited in steps by contactors to produce acceleration. These motors were protected by stalling relays and resistances which automatically kept the current down to a proper value whenever the motor was stalled. It is evident that this type of control meant a heavy energy loss and lack of smooth operation. On the new equipment, the crowd, swing, and hoist motors are each supplied with power from generators of their own and the speed control is entirely through variation of a resistance in the shunt field of each generator similar to the Ward Leonard control on battleship turrets and high duty mine hoists. Due to the inherent protection features of the control, no protection of any kind is necessary as the differential series field of each generator bucks the generator voltage to nearly zero when the motors are stalled at maximum torque. The operation with the new equipment is much smoother than with the old type and does away with the sudden stresses in the hoist cable. These stresses are very objectionable as they shorten the life of the hoist cable very materially.

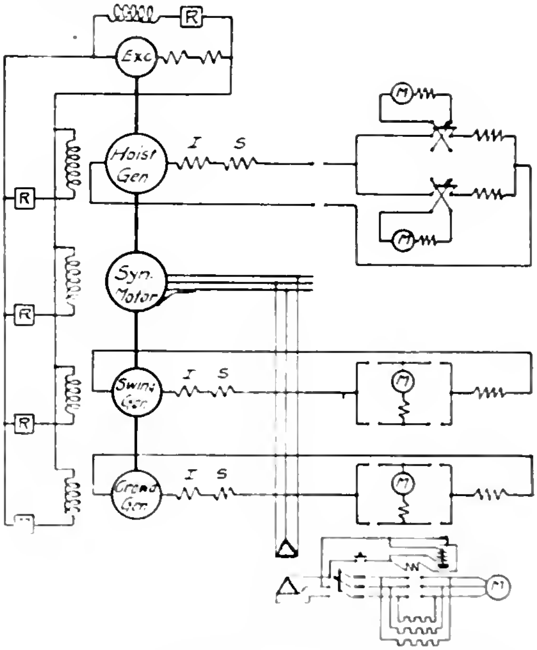


Fig. 5. Diagram of Main Connections Between the Four-unit Motor-generator Set and the Hoist, Swing, and Crowd Motors

The diagram, Fig. 1, shows the main connecting circuits of motor-generator set and motors The direct connected exciter is used to excite the fields of all the generators and the synchronous motor. The resistances in the fields of the hoist generator, swing generator, and crowd generator are varied by means of the three master drum controllers located at the operating station, thus permitting the operator a great range of control over the generator voltages, considerable variation of which must be had during process of operation to give torque as required on the motors. The reversing switches shown with the hoist motors are operated manually by the operator by means of one of two levers located at the operating station. These reversing switches reverse the armatures of the motors with respect to the fields, thereby reversing the rotation of the motors. The rotation of the motors is reversed in this way only when their power is used to move the shovel as a locomotive backward or forward on its track. The swing generator is connected to the swing motor through either of two pairs of contactors depending upon the direction of rotation desired for the swing motor. The crowd generator is connected in a manner similar to that of the swing generator. The trip motor shown at the bottom of the diagram, the air compressor motor, and the lighting circuits are supplied with power from three 7½-kw., 2200/220-volt transformers connected to the incoming line. The trip motor is of high resistance squirrel cage rotor type with permanent resistance connected in the stator circuit. The contactor for this motor and also the time limit relay are energized by means of a push button. When the push button is pressed the contactor closes, short circuiting the permanent resistance in the stator circuit, thereby giving full line voltage and full tripping torque to the motor. The time limit relay prevents the motor being left on full line voltage any longer than is necessary to operate the trip cable. If the push button is held in too long, the time limit relay trips the contactor and releases the trip motor from the full line voltage. When the contactor opens, the permanent resistance is connected in the stator circuit of the trip motor. This resistance allows enough current to flow from the line into the motor to give just sufficient torque to the motor to take up the slack of the tripping cable and maintain a small torque on the drum of the tripping cable at all times except when the motor is operating on full torque to trip the dipper load.

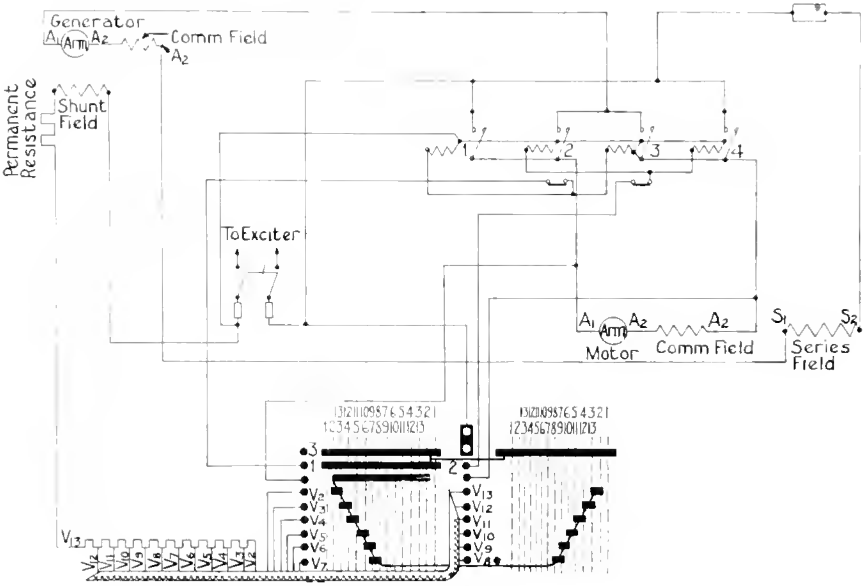


Fig 6. Diagram of Connections for Crowd Motor Control

The common countershaft of the two hoist motors is furnished with a friction band pneumatic brake normally spring set. The crowd and swing motors are furnished with a similar brake. The hoist drum is furnished with two brakes, one similar to the type used with the hoist, crowd and swing motors and another operated directly through a foot lever. The pneumatic brake on the hoist drum is a revolving brake operated by air introduced through the center of the hoist drum shaft. This brake locks the hoist drum to the gear drive of the hoist motor countershaft and is disengaged when the empty dipper is falling and when the hoist motors are used for propelling. This brake is controlled by a solenoid valve from one reverse point on the hoist motor drum controller and from a double pole knife switch. The foot brake is mounted on the hoist drum opposite to the side on which the pneumatic brake is mounted. This brake enables the operator to catch the bucket before it hits the pit on the down drop.

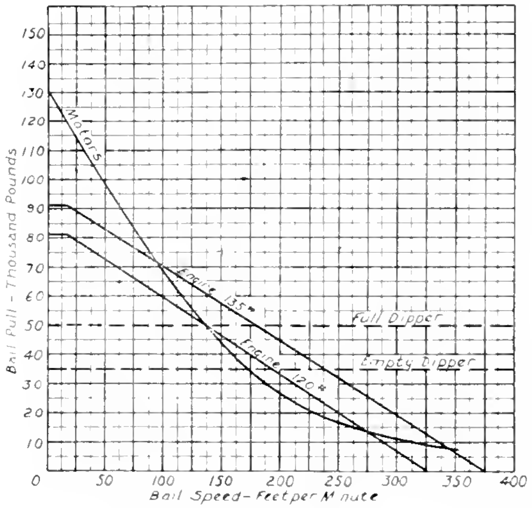


Fig. 7. Curves Comparing the Bail-speed Bail-pull Characteristic of Series Motors with that of a Steam Engine at Two Pressures

The period of maximum regenerative braking is that period of time during which the hoist motors are driven by the hoist cable as series generators when the loaded dipper is allowed to descend while it is swinging from the digging position to the dump car. During the period of regenerative braking, the foot brake of the hoist drum is not used and its pneumatic friction brake is in a locked position.

The pneumatic brakes are all of the same general type consisting of a friction band of wood blocks which are normally set through the action of a powerful spring. The friction band is loosened from the clutch surface by means of an air ram which acts against the tension of the holding spring when air is admitted under pressure by means of a solenoid operated valve energized on the first point of the master controllers.

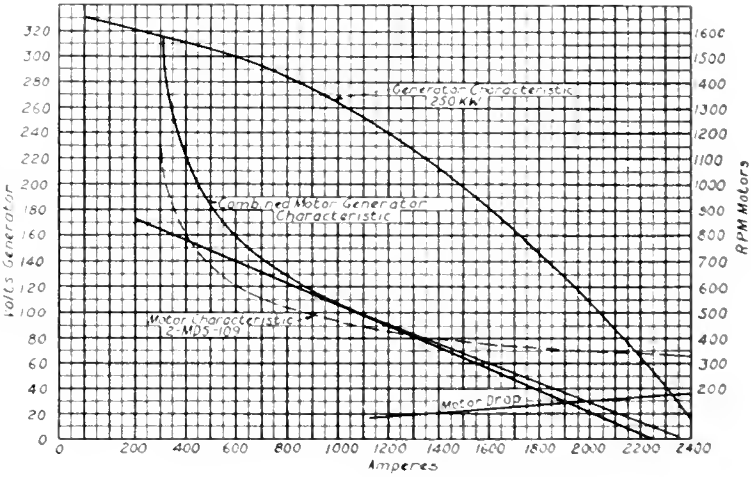


Fig. 8 Characteristic Curves of the Hoist Generator, Motors and Their Combination

The regenerative braking feature of the equipment is a very interesting one. This is accomplished mainly when the dipper is being dropped with load to the dumping position. Thus some of the power consumed in hoisting the dipper is returned to the line, thereby increasing the operating economy. When regenerating, the dipper in its descent exerts torque on the hoist drum through the hoist cable and drives the hoist motors as series generators, their direction of rotation being opposite to that when operating as motors for hoisting. As soon as the hoist motor shaft reverses direction of rotation a switch is closed by means of a small belt from the shaft. This switch closes the small equalizer contactor mounted at the bottom of the hoist generator panel, thus connecting the equalizer circuit and permitting parallel operation as series generators. When these motors are operating as generators the shunt field of the hoist generator has all its resistance cut in, causing a shunt field so weak that the differential series winding is predominant and the hoist generator operates as a series motor, exerting its torque on the shaft of the synchronous motor-generator set. This regeneration occurs only on the first point forward on the hoist controller. As the lever of this controller is moved over to the second, third and fourth positions, the shunt field of the hoist generator is strengthened, the hoist motors stop regenerating, their shafts come to standstill, reverse, and then start up in the reverse direction and the motors begin hoisting. This action occurs once every cycle and for the time of its duration returns to the system approximately the losses of the motor-generator set and the power required to operate the swing motor. This action, together with the energy stored up in the revolving elements in the motor-generator set, keeps the power peaks down to a low figure.

The performance of the swing, hoist and crowd generators and motors is controlled by the three master drum controllers mentioned above. The hoist controller and crowd controller are operated by means of hand levers. The swing controller is operated by two foot pedals, one pedal for one direction of swing and the other pedal for the reverse direction. The controllers operate mainly on the field rheostats of the swing, hoist and crowd generators, but the first point of these controllers operate the shunt contactors of the contactor panels which close and open the main circuits between the swing, hoist and crowd generators, and their respective motors. This point of the controller also energizes the solenoids of the pneumatic brake valves, thereby releasing the particular motors controlled for work. On the lever of the hoist controller is located the push button for operating the control of the trip motor. This tripping feature does away with the services of one man always needed on steam equipments to trip the dipper. Two levers are located at the right hand of the operator. One is used for connecting gears to the hoist motor gears through a clutch to accomplish locomotion of the shovel. The other is used for connecting gears to the hoist motor gears through a clutch for hoisting the boom. The crowd controller and swing controller give reversible operation, but the hoist controller gives one way operation only, although one reverse point on the hoist controller releases the revolving pneumatic brake on the hoist drum.

On the crowd motor, protection is supplied by interlocks which are operated by a limit switch on each end of the dipper stick motion which opens the magnetizing circuit of the contactors whenever the dipper handle is driven too far at either end. This is the only electrical protective feature which is installed, all the other protection being inherent in the design of the equipment.

The shovel proper is supported by four trucks, one at each corner. Each truck is driven by a shaft with bevel gear from the hoisting mechanism. This gives very flexible control of the shovel proper and allows a very quick move up. Each truck is set into a hydraulic cylinder of large dimensions similar to a step bearing. While in operation this cylinder is pumped full of oil and the shovel practically floats, giving automatic alignment and cushioning against shock from digging. Each truck runs on two 130-lb. rail sections put together in short lengths to allow for a small turning radius and carries a load of approximately 85 tons, which is well within the factor of safety for reliable operation.

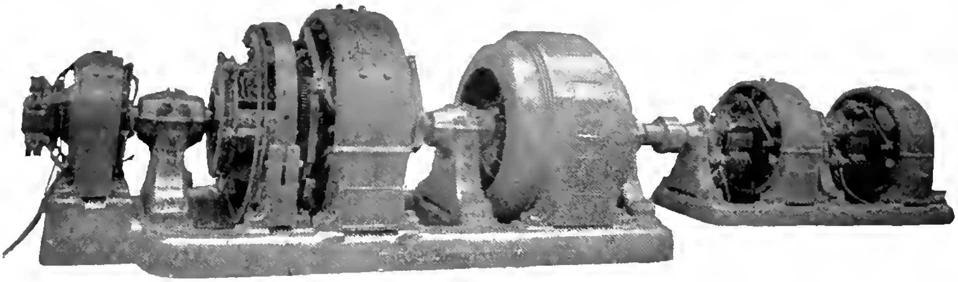


Fig. 9. Four-unit Motor-generator Set, Consisting of a Synchronous Motor, Exciter, and Three Direct-current Generators. The Latter Individually Supply the Operating Motors with Power

The hoist controller is used for propelling after the rotating drum brake is disengaged by opening a double pole knife switch. Reverse motion is secured by knife switches in the field circuits of the hoist motors.

The shovel is served with 2300-volt, 3-phase power from the plant power house at a present distance of approximately 4000 feet. The shovel is grounded by means of a ground wire in the filler of the supply cable. This ground wire is carried back to the generating

COMPARATIVE COST OF OPERATION, TEN-HOUR BASIS

(August 6, 1920)

	First Cost 300 Electric $135,000.00		100 Steam $45,000.00
Interest 8%—440 10-Hr. Shifts	24.55		8.40
Depreciation 7%—440 10-Hr. Shifts	21.87	10%	10.22
Maintenance 5%—440 10-Hr. Shifts	15.61	Actual	16.85
Oil Waste Supplies	2.00		5.00
Coal 70 Bags 80 Lbs. 5600 Lbs. @ $9.20 Ton	0.00		25.80
Electric Power	15.00		
Water Lines and Equipments	0.00		5.00
Labor Engineer	10.00		10.00
Crane Man	0.00		7.00
Oiler	5.00		0.00
Fireman	0.00		5.00
Pitmen (2)	10.00	(4)	20.00
Lighting	1.00		5.00
Operating cost for 10 hours	$105.03		$118.27

Cost per carload 100 ton steam	..100 per cent
10-hour tonnage	.100 per cent
Cost per carload 300 ton Electric	.. 51.5 per cent
10-hour tonnage	..172 per cent

These figures are digging cost—do not include large savings such as track labor, elimination of second cut, etc.

(August 4, 1920)

No. of Train	Cars per Train	Began Loading	Finished Loading	Total Time Loading Min.	Actual Time Loading Min. Sec.	Total Delays Min. Sec.	NATURE OF DELAYS Waiting for Trains Min. Sec.	Cleaning Tracks Min. Sec.	Shovel Min. Sec.	Miscel. Min. Sec.	Average Angle Shovel Swing
0			7:00								
1	6	7:08	7:32	24	25:10	8:00	00:00			*8:00	120
2	6	7:40½	8:04½	24	23:20	8:30	8:00		:30		120
3	6	8:11	8:33½	22½	21:53	6:15	5:45	:30			130
4	6	8:42	9:07½	25½	24:40	7:59	6:30	1:30			120
5	6	9:16	9:41	25	25:04	7:58	5:38		Move up Ties)—2:20		120
6	6	9:47	10:14½	27½	27:00	6:05	6:05				150
7	6	10:20	10:42½	22½	22:49	5:38	4:58	:40			145
8	6	10:54	11:20	26	23:30	12:33	5:33	3:00	Move up —4:00		90
9	6	11:26½	11:49½	23	22:51	6:55	5:55	1:00			110
10	1½	11:57	12:02	5	4:45	8:15	6:15	2:00			
Lunch Hour											
10	4½	1:04½	1:21½	17	18:29	4:30				*4:30	110
11	6	1:30	1:55	25	24:23	8:53	8:53				120
12	6	2:00½	2:27	26½	26:30	5:32	5:32				140
13	6	2:34	3:05	31	31:05	6:29	5:14		Move up Ties —1:15		160
14	6	3:12	3:36	24	24:32	6:32	6:32				150
15	6	3:47½	4:11	23½	23:30	10:01	6:30		Move up —3:31		110
16	6	4:18	4:40	22	22:26	6:35	6:35				100
17	6	5:01	5:23	22	21:42	22:00	22:00				130
18	6	5:29	5:53	24	24:30	5:30	5:00	:30			130

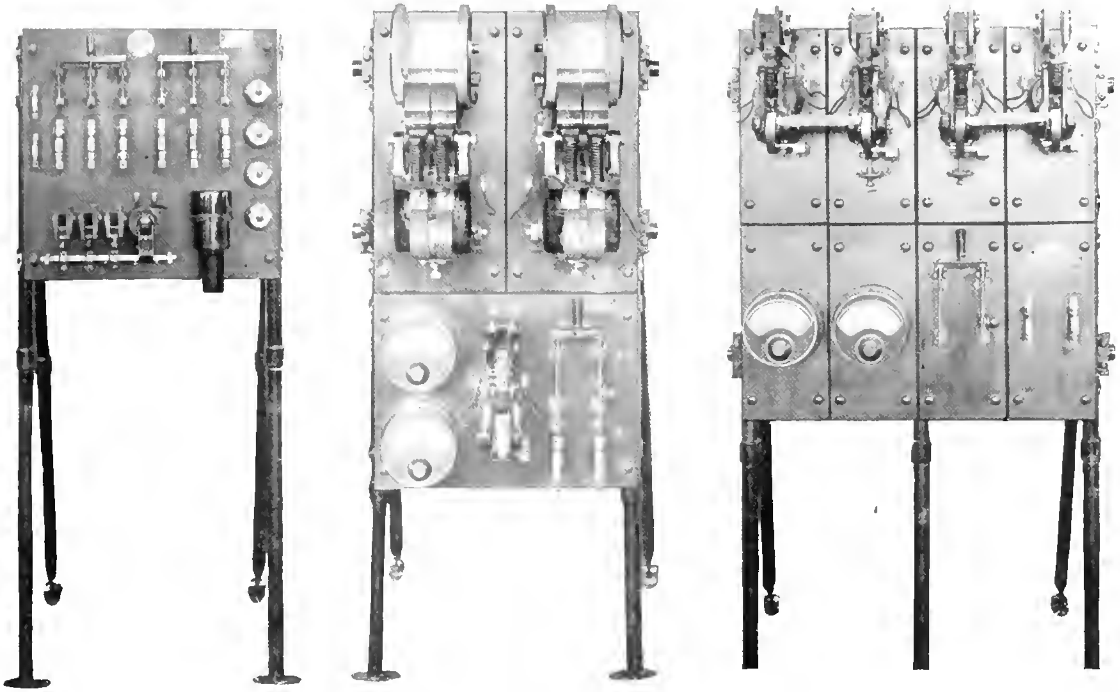
* Inspection, etc.

RECAPITULATION

Stop watch time loading	6 hrs. 57 min.
Delay on inspection	12½ "
Delay on trains (practically all shuttling	1 hr. 55 "
Delay on moving up	11½ "
Delay on ending day at 5:53	7 "
Delay on cleaning tracks	9 "
TOTAL DAY	9 hrs. 32 min.
Unaccounted for (personal errors, false starts, etc	28 "
TOTAL	10 hrs.
Total cars loaded	108
Power consumption	1050 Kw-hrs.
Total digging time	70 per cent

station, where it is effectively grounded. It is evident that the shovel cannot be well grounded locally on account of the nature of the limestone formation. The 3-wire transmission line is carried across the quarry on poles up to a point near the shovel, where it enters into a 3-conductor cable which is wound on a drum attached to the shovel turntable support.

Reference to the diagram, Fig. 2, will show that the series motors give a bail-speed bail-pull characteristic very similar to that of the steam engine. The 120-lb. steam pressure engine curve is the one which should be used in the comparison, as this is the pressure most usually maintained in practice. It will be noted that the full dipper pull is at the same speed for either engine or motors. At lighter loads the dipper speed is slightly lower with motors than with the engine, while at heavy load the dipper speed is much faster with the motors than with the engine. It will also be noted that the motors have much greater stalling pull at very heavy loads, which is a very desirable characteristic, provided it does not exceed the mechanical strength of the shovel.



Figs. 10, 11, and 12. Dipper-trip Panel, Hoist Panel, and Crowd or Swing Panel Used in the Control of the 300-ton Electrically-operated Shovel

The cycle of operation of the 300-ton shovel with an 80-foot boom and 6-yard bucket will average about 55 seconds. This is on the basis of a 180-deg. swing, and loading cars on the same level as the shovel. Loading cars on top of the bank would facilitate this operation, probably cutting it down to 40 to 45 seconds. The working cycle of the small 100-ton shovel with 3½-yard bucket is considerably faster, being from 22 to 27 seconds. This cycle, however, is based on a 100-deg. swing only, as this is the usual arc of operation. With a 3½-yard dipper load swinging an angle of 100 deg. the loading operation of the 100-ton shovel would be very fast if the material were always available in front of the shovel, but due to the small radius of digging a great portion of the time is used in moving ahead and a considerable time in moving the loading track. Also, the loading track is so close to the bank that the small shovels seem to be best served by shuttling trains to them. On the larger shovel the operation can be continuous, as the loading track is entirely clear of the bank. The larger shovel actually operates on an average swing of about 120 deg., which shortens the duty cycle to approximately 45 seconds or better so that it will load one train slightly faster than the smaller shovel, but at a swing of 120 deg., instead of 100 deg. The great gain by the larger shovel is made in the time saved through the necessity of the smaller shovel moving ahead about twenty times and changing the loading track about eight times to handle the same amount of material. This gain is so marked that at the end of 10 hours' operation the larger shovel delivers approximately 50 to 70 per cent tonnage excess over the smaller shovel under unfavorable loading conditions. It is confidently expected that later when loading conditions become more favorable and an 8-yard dipper is substituted for the present 6-yard dipper the larger shovel will double the output of the smaller one. During a season's operation the larger shovel may even show better results than this, as considerable delay is experienced with the smaller shovels due to slides from the bank occasioned by blasting and by storms. The smaller shovels must necessarily operate very close to the bank on account of their small digging radius and they are therefore very much exposed to these bank slides. Besides the loss of time occasioned by the slides, increased repairs must be charged against the smaller shovels due to them. The larger shovel with its 54-foot digging radius at the rail stands well clear of the bank and is in no danger of damage from it.

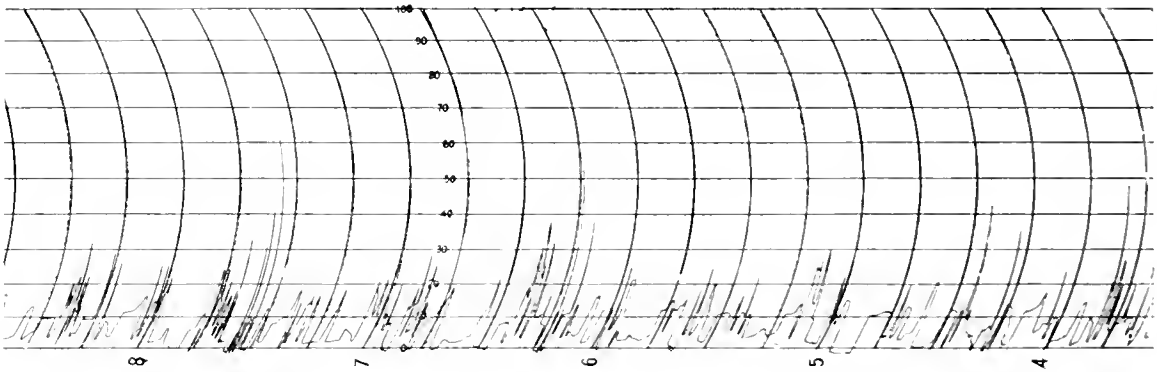


Fig. 13. Crowd Motor Input Current. Full Scale Equals 1000 Amperes. Interval Between Curved Lines 15 Seconds

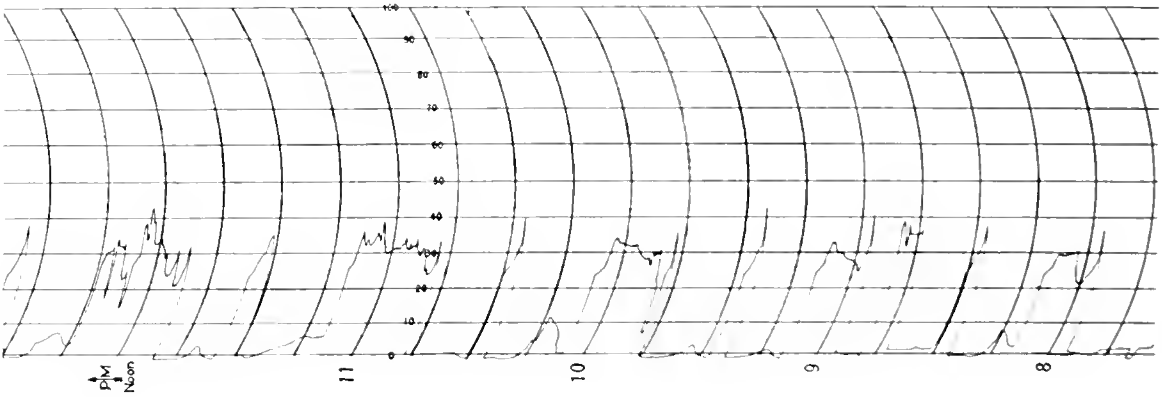


Fig. 14. Hoist Motor Input Current. Full Scale Equals 3000 Amperes. Interval Between Curved Lines 15 Seconds

The operating cost of the electric shovel shows marked advantage over the steam shovel both as regards labor and fuel consumption. While the comparison of costs between a 300-ton electric and a 100-ton steam shovel is manifestly unfair to the electric, nevertheless such comparison shows interesting results. For example, operating crews are as follows:

300-TON ELECTRIC	100-TON STEAM
1 Shovel Runner	1 Shovel Runner
No Craneman	1 Craneman
No Fireman	1 Fireman
2 Pittmen	4 Pittmen
1 Oiler	No Oiler
4 Men Total	7 Men Total

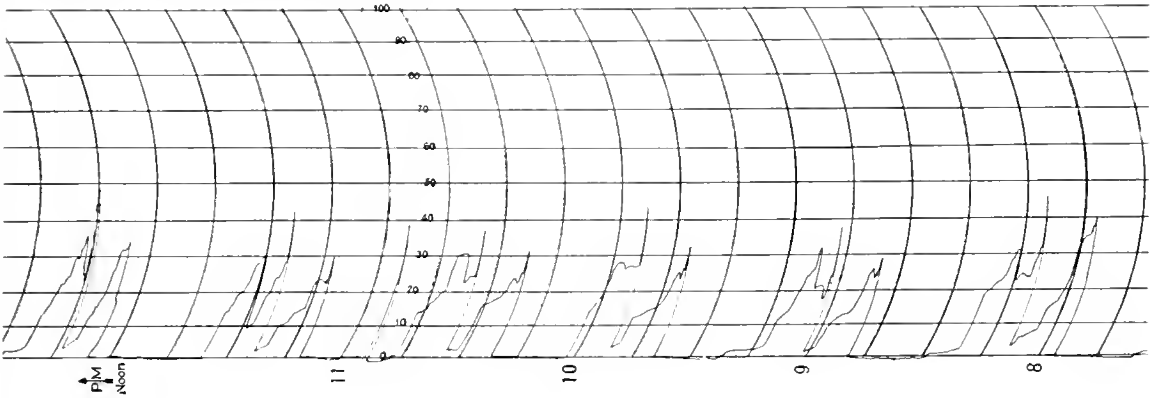


Fig. 15. Swing Motor Input Current. Full Scale Equals 1000 Amperes. Interval Between Curved Lines 15 Seconds

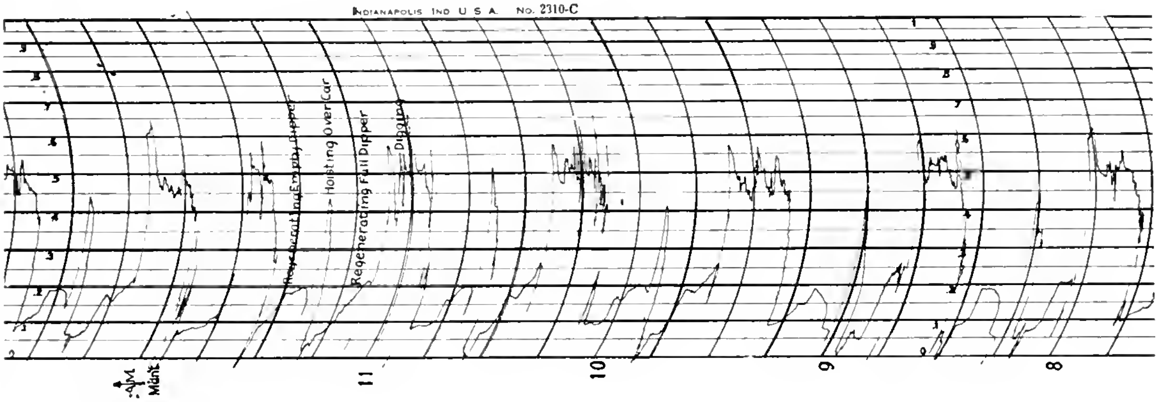


Fig. 16. Kilowatt Input to Shovel. Full Scale Equals 600 Kilowatts. Interval Between Curved Lines 15 Seconds

In addition to these there are men assigned to water line attendance and to coal supply service. This attendance and service is divided among eight steam shovels but would easily add one more man chargeable to each steam shovel.

The electric power for the 300-ton shovel is obtained economically with low fuel consumption, as this power is obtained with less than 5 per cent transmission loss from a highly efficient steam turbine plant. The steam turbines operate condensing with consequent low water rate and the steam they use is derived from boilers designed for high coal economy. The engines on the steam shovels operate non-condensing with full cut-off and their boilers cannot be designed for high coal economy. A pound of coal burned on the power house grates, therefore, is much more effective in power production than when burned under the steam shovel boiler and a great saving in fuel for the same amount of power is the result. Another great source of gain in fuel economy is due to the fact that the electric shovel consumes very little power when not in use, while it is necessary to maintain steam at all times on the steam shovels.

The operating costs of the 300-ton electric and the 100-ton steam shovel were computed by starting with the original investment in each case and charging against each shovel, interest, depreciation, upkeep, labor and fuel cost. Electrical power cost was figured at 1½ cents per kilowatt hour and coal at $9.20 delivered at the shovel. In spite of the heavy handicap of much higher first cost of the large electric as compared to the small steam shovel, the detail figures show the operating cost per shift to be practically the same. As stated above, for fair comparison the same size electric and steam shovels should be compared, so that this result is a striking one. Considered another way, the result shows that every ton dug in 10 hours by the 300-ton electric over the 100-steam shovel is dug at practically no cost, and the cost per ton of all material dug in the 10 hours is correspondingly decreased. For example, if the large shovel digs 50 per cent more material in ten hours than the small shovel, the cost per ton dug is 66⅔ per cent.

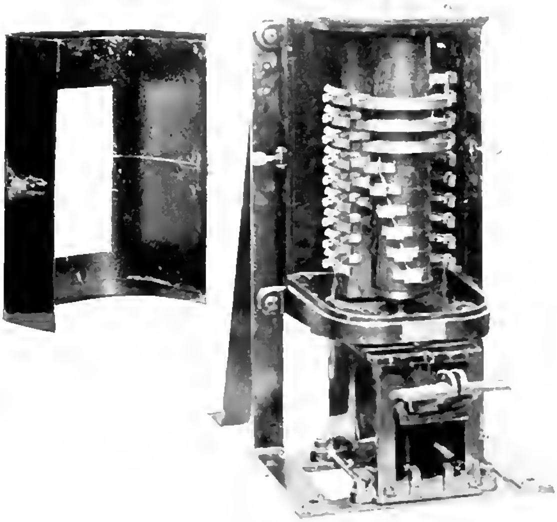


Fig. 17. Foot-operated Master Switch for Controlling the Swing Motor

The elimination of the second cut in the bank was one of the most important considerations in choosing the large shovel in preference to the small one. The consequent saving in track expense will prove a great asset. This is made possible due to the fact that the large shovel can work against banks as high as 100 feet or more, which is inadvisable with a small shovel, as explained in a previous paragraph, on account of danger from bank slides.

Even now more progress is being made in the perfection of the electrical control for shovels, such that future installations will undoubtedly show even better results than at present. The probabilities are that they will also be found advantageous in other applications as operators become more familiar with their characteristics and excellent showing in operation.

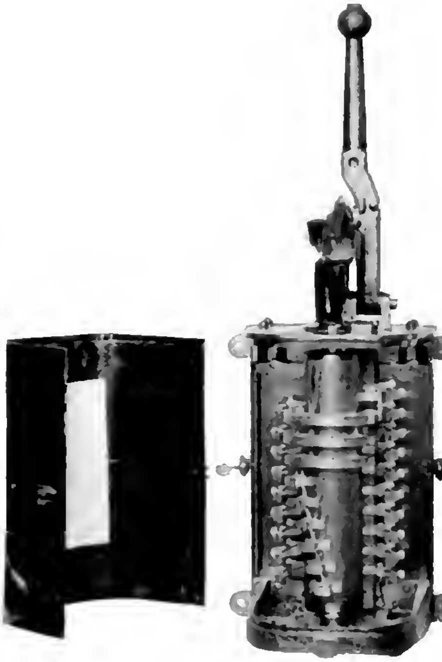


Fig. 18. Hand-operated Master Switch for Controlling the Crowd Motor

Automatic Substation for Alternating-current Railway Signal Power Supply

PART II

By H. M. Jacobs

Railway Department, General Electric Company

The preceding installment of this article described alternating-current railway signal substations in which the source of reserve power is a second commercial service. The present installment describes substations that rely on storage batteries for emergency service and these are of two classes; namely, those substations that demand uninterrupted service, and those that will permit of a short interruption of one or two minutes. With the former class the motor-generator set must float continuously on the storage battery and the control equipment must effect undisturbed operation when commercial power fails. Two motor-generator sets are necessary. In the latter class of substation the converting apparatus stands idle until power goes off, when the control equipment operates to start the motor-generator set in the prescribed time.—Editor.

In the preceding article, railway signal automatic substations for providing against prolonged failure of the signal system due to failure of power supply were divided into two general classifications, and substations in which the reserve power is a second commercial source either at the same station or at some remote point were discussed in detail. This article deals with substations relying on storage batteries as the reserve source. Although there is no reason why this class of automatic substation is not applicable to the supply of power to automatic block signals, every installation that has come to our attention has been at interlocking plants where the movements of trains are under the control of the tower man.

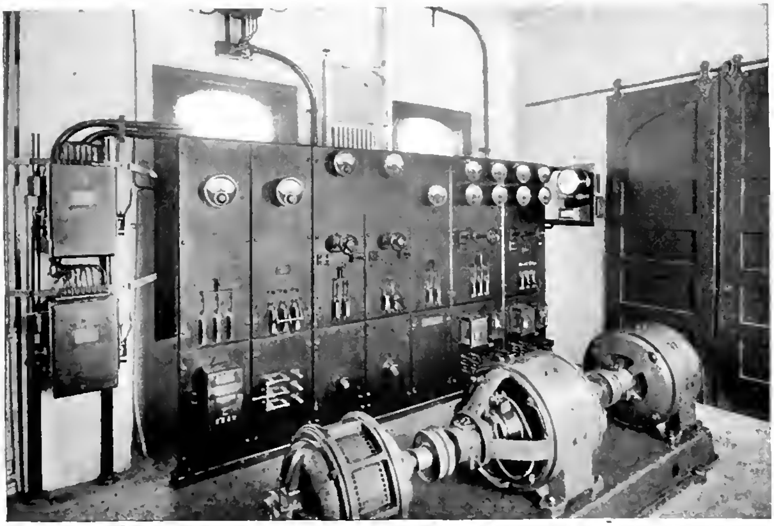


Fig. 1. Power Equipment for Alternating-current Signaling Installation on New York, New Haven & Hartford Railroad, Worcester, Mass.

If traffic conditions are such that even a momentary loss of power would be serious, the converting apparatus must float continuously on the storage battery and the control equipment must be so arranged that the power feeding the signal system is undisturbed when the commercial power fails. If a slight interruption is permissible, say one minute, the converting apparatus may stand idle until the failure occurs; the control equipment must be arranged to start the converting apparatus and connect it to the signal power feeders within the prescribed time.

To meet the first condition requires a motor-generator set consisting of an induction motor, an alternating-current generator to supply power to the signal system, and a direct-current machine which acts as a generator for charging the storage battery or as a motor for driving the set from the battery when the power supply to the alternating-current motor fails. The generator may be either self-excited or excited from a direct-connected unit. A duplicate motor-generator set is necessary. In order to take care of the change in field current of the d-c. machine when changing from the generating to the motoring condition and vice versa, two field rheostats are provided, one for each condition. These rheostats are connected in series, and the one not required is short circuited automatically by the control equipment. A speed regulator is connected permanently to the field rheostat which governs the motoring condition in order to maintain constant frequency on the a-c. machine.

Fig. 1 shows such an equipment installed at Worcester, Mass., on the New York, New Haven & Hartford Railroad. Only one of the motor-generator sets appears in the illustration. As these sets are started by hand-controlled starting compensators, it is necessary to reconnect the motors to the power supply on resumption of power after a failure. This can be taken care of automatically by substituting auto-starters for the hand-control type. With this arrangement the sets will automatically shift from battery operation to induction motor operation. The automatic control employs a low voltage relay energized from the a-c. supply connected to some magnetically operated switches. When power is available, the relay is energized and causes a magnetic switch to short circuit the d-c. motor field rheostat; the d-c. generator field rheostat is adjusted for the desired current for the battery. When power fails, the relay is de-energized; this opens the short circuit of the aforementioned field rheostat and short circuits the other. A speed regulator is connected across the motor field rheostat now cut in circuit, making the direct-current machine motor the set at the same constant speed as before the failure of power, so that the frequency and voltage of the alternating-current generator is not affected.

At many places a slight interruption in service is permissible; at these locations the converting power apparatus may stand idle until the failure occurs. The control equipment must be arranged so as to start the set in the shortest possible time. The equipment required will depend largely on the character of the signaling equipment with which it will be used. Some interlockings use alternating current for all functions, whereas others have alternating-current track circuits and lights but require a storage battery for certain other functions. For an all a-c. plant the battery will be used only for furnishing emergency power to the motor-generator set. The battery may be charged either from a separate motor-generator set, a mercury arc rectifier, or the emergency set running "reversed," that is, the alternating-current generator operating as a synchronous motor and the direct-current motor operating as a generator. Although the control equipment is complicated by using one set for both the emergency power supply and for charging the battery, there is a considerable saving in cost of equipment and floor space.

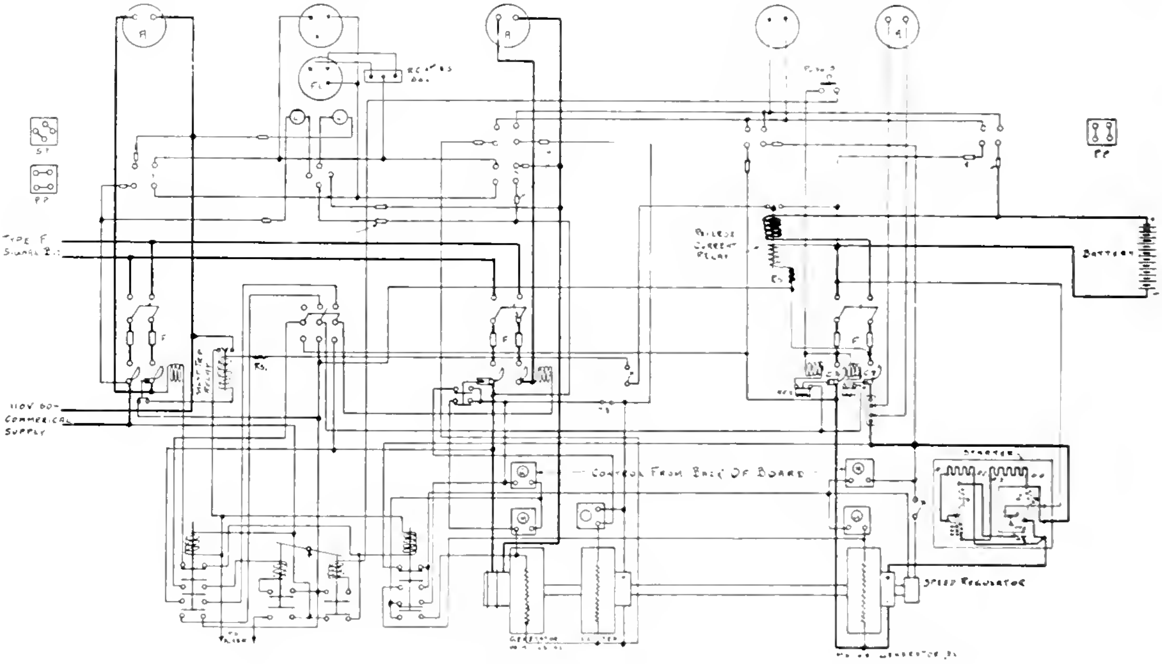


Fig. 2. Wiring Diagram of Automatic Substation Equipment, Boston Switch-Central Falls Signal Tower, New York, New Haven & Hartford Railroad, Pawtucket, R. I.

Two such equipments have been installed on the New York, New Haven & Hartford Railroad, one at Pawtucket, R. I., in 1915, and the other at Stamford, Conn., in 1917. The motor-generator set at the former location is designed to deliver single phase, 60-cycle alternating current at 120 volts, 5 kv-a., 0.7 p-f., with a 3-kv-a. intermittent overload capacity of short duration. The direct-current machine operates as a motor at constant speed with the voltage of the storage battery from 110 down to 80 volts; as a generator it will charge the battery at 50 amperes between 110 and 155 volts.

The control equipment is arranged to fulfill four conditions:

(1) On failure of the commercial power supply when the set is at rest, to disconnect the power supply, start the set from the battery, and connect the a-c. generator to the signal buses at normal voltage and frequency.

(2) On return of power supply, to disconnect the set from the signal bus and the storage battery, and reconnect the power supply to the signal bus.

(3.) On failure of commercial power supply when set is charging the battery, to disconnect the power supply and change the field current of the two units of the set so that the d-c. generator becomes a motor and the synchronous motor becomes an a-c. generator, and connect the latter to the signal bus.

(4.) On return of power supply, to notify the operator so that he can synchronize the a-c. generator with the supply, reconnect the latter, and either continue charging the battery or shut down the set by hand. Automatic synchronizing does not seem of sufficient importance to warrant the added complicated control that would be involved.

Fig. 3. Switchboard, Boston Switch-Central Falls Signal Tower, New York, New Haven & Hartford Railroad, Pawtucket, R. I.

From actual test, the elapsed time to fulfill condition (1) was 13 to 15 seconds. The signals "cleared" in 5 seconds. Hence the total interruption from a traffic standpoint is 20 seconds, or less.

The interruption for fulfilling condition (2) was so short that the semaphore arms on the signals did not drop to the full "stop" position, but merely "bobbed." Conditions (3) and (4) are fulfilled with no interruption since the set is running and energy is not cut off the line at any time.

Fig. 2 is a wiring diagram of this equipment and Figs. 3 and 4 show respectively the

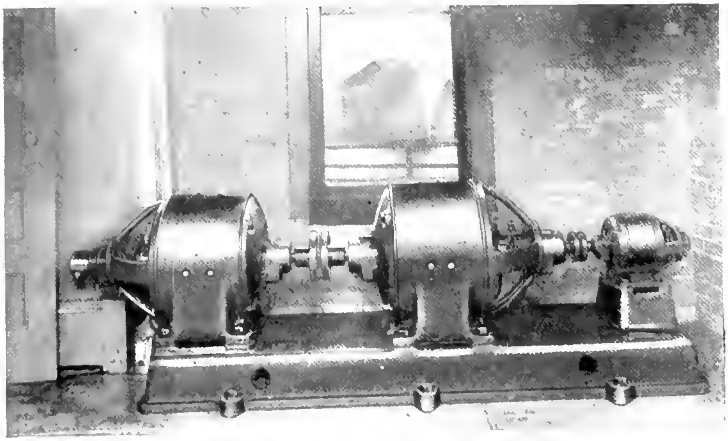


Fig. 4. Motor-generator Set, Boston Switch-Central Falls Signal Tower, New York, New Haven & Hartford Railroad, Pawtucket, R. I.

switchboard and motor-generator set. A complete description of this equipment and its operation appeared in the GENERAL ELECTRIC REVIEW, January, 1916, under the title "Power Equipment for Alternating Current Signaling at Interlocking Plants."

The equipment at the Stamford, Conn., plant is similar but is of larger capacity and provision is made for charging the battery from a 600-volt d-c. source in case of extreme necessity. When the set is operating from the battery, the a-c. machine will deliver 12 kv-a., .53 power-factor continuously and 20 kv-a., .67 power-factor for 30 seconds; when charging the battery the d-c. machine will deliver 85 amperes or less between 115 and 175 volts. By actual test the set started from rest and was connected to the signal bus in 5 seconds—less than half the time required for the smaller outfit at Pawtucket, R. I.

For interlocking plants using alternating current for track circuits and lights, and a 110-volt storage battery for the operating functions, the automatic equipment is very simple. We will describe one of several plants of this nature recently installed on the Philadelphia & Reading Railroad, which is illustrated in Figs. 5 and 6. Fig. 7 is the wiring diagram of the switchboard. Power is supplied to these plants from a three-phase, 60-cycle, 4400-volt aerial transmission line and is stepped down by transformers mounted on the pole structure, to 110 volts. The storage battery is charged in the customary manner from a motor-generator set having a three-phase induction motor started by a self-contained compensator fitted with a low voltage release. Should power fail while charging the battery, an underload circuit breaker will disconnect the generator from the battery, and the compensator will disconnect the motor from the line.

Fig. 5. Switchboard in a Signaling Substation, Philadelphia & Reading Railroad

Fig. 6. Battery Charging Motor-generator Set and Alternating-current Emergency Motor-generator Set in a Signaling Substation, Philadelphia & Reading Railroad

The signal bus, from which all signal circuits are supplied, is normally connected to one phase of the 110-volt power supply by a double pole magnetically controlled contactor switch energized from the source through the "front" or upper contacts of a control relay also energized from the power source. The control relay has two sets of "back" or lower contacts, one set being connected to a d-c. auto starter between storage battery and the motor of the emergency motor-generator set, and the other connected to another double-pole contactor switch energized from the a-c. generator of the emergency motor-generator set to connect the latter to the signal bus. When power fails, the control relay is de-energized and connects the motor to the battery through the auto starter, and the coil of the other contactor switch to the generator. When the set has attained speed and the voltage of the a-c. machine is sufficient to energize the contactor switch to the pick-up value, the latter closes and connects the generator to the signal bus. The generators of all the sets are rated 2 kv-a., 0.6 power-factor, 110 volts, 1800 r.p.m., 60 cycle, single-phase and the motors are 3 h.p., 110 volts, shunt wound direct current. They restore energy to the signal bus in 2 to 3 seconds after power failure.

The switchboard is simple to operate and compactly arranged. The automatic equipment and starter are mounted on the sub-panels and the instruments and hand switches on the upper sections. All the field rheostats are mounted on the back of the switchboard. The alternating-current load on the emergency generator is so constant that after once adjusting the field rheostat for proper voltage, when the set is running at normal speed, no other adjustments are necessary. For this reason this rheostat is not arranged for front of board control. The frequency of the a-c. generator may be varied by adjusting the field rheostat of the d-c. motor. A frequency indicator and voltmeter are mounted on one of the panels.

At some interlockings the switches and signals are operated by compressed air. The air valves are controlled by direct current. The track circuits and lights are sometimes operated by alternating current. Such a plant requires air compressors and battery charging equipment. The control battery is usually 12 to 16 volts. A power failure would tie up such a plant even though the switches and hand-controlled signals could be operated, because the track circuits and lights would be dead. If the air supply is taken from a source not dependent on the commercial power supply, delays due to temporary power failure may be eliminated by installing a larger ampere hour capacity low voltage battery than ordinarily required, and emergency equipment to operate from the battery. Two such plants were installed several years ago at Jamaica, Long Island, N. Y., on the Long Island Railroad. The air is taken from the railroad shops. Only one motor-generator in each plant is used, the motor being a-c. synchronous type, which acts as a generator when running reversed.

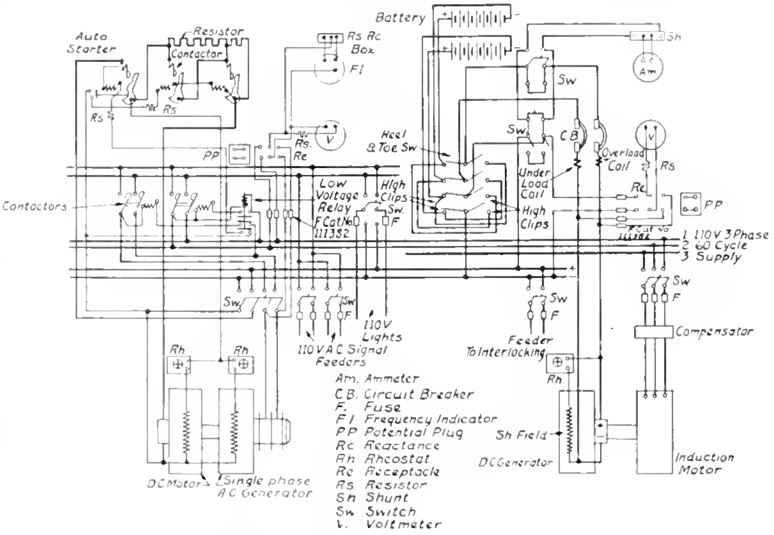


Fig. 7. **Typical Wiring Diagram of Switchboard and Automatic Substation Equipment for Railway Signal Power Supply, Philadelphia & Reading Railroad**

If an inexhaustible air supply cannot be obtained, the reservoir capacity may be made large enough to supply the demand over a long period, and the system can operate without a-c. power until either the air supply or the storage battery becomes exhausted.

Commercial Photometry

PART I

By A. L. Powell and J A. Summers
Edison Lamp Works, General Electric Company

Satisfactory illumination for any given condition is largely dependent on physiological, and to a lesser extent on psychological considerations. Neither of these factors is measurable and the only means we have of gauging the degree of illumination is by the scientific process of photometry. The value of proper illumination is now generally appreciated, and to a corresponding extent have the methods of measuring illumination attained importance. This article is a complete review of the subject of photometry, including descriptions of photometers, their principles, calibration, and use. The correct interruption of a set of readings is necessary in practice and ample explanation is included on this point.—Editor.

SYNOPSIS

Part I

- Introductory
- Elements of a Photometer
- Means of Varying the Light
- Means of Comparing the Light
- The Standard Lamp and Calibration of the Comparison Lamps
- Measuring Horizontal Candle-power of Light Sources
- Measuring Spherical Candle-power or Total Light of Illuminants
- Determination of the Distribution of Light
- Selection of Equipment for Test
- Calculating Results from Test Readings
- Portable Photometers and Their Calibration.

Part II

- Illumination Tests of Interiors
- Brightness Measurements
- Measurement of Reflection Factor
- Illumination Tests on Single Units
- Rough Distribution Determination with Portable Photometer
- Street Illumination Tests
- Projector Tests

Introductory

Distribution curves of lighting devices, or the results of photometric tests, are often misinterpreted. In view of their apparent complexity, they do not receive the attention they justly deserve. Other items, such as appearance and cost, are often given undue weight in making a decision.

If the art of lighting is to advance on firm ground a study of the qualities of equipment to be used is necessary. The fixture manufacturer can well afford to spend some time and money analyzing the properties of the glassware he employs. A purchaser of any large amount of equipment should insist on knowing its performance. This is particularly true where similar units are in competition.

A knowledge of the fundamental principles of photometry is of great assistance in interpreting results of the tests. It is the purpose of this article to point out some of the features often overlooked. The section on Selection of Equipment for Test indicates some of the diversified factors which must be given consideration, and well warrants careful study.

The subject of photometers is treated in greater detail than any other phase of illuminating engineering in text books on lighting. It is therefore unnecessary to discuss minutely the theory of photometry or photometric instruments. On the other hand, there are many phases of light measurements which do not come under the category of laboratory methods, and which only come to the attention of the investigator through actual experience. It is worth while, therefore, to briefly discuss some of these features and to describe the actual procedure necessary to satisfactorily operate the photometric device.

The fundamental quantity which we determine in photometry is the strength or power of luminous flux. Intensity expressed in candle-power is the flux per unit solid angle, while illumination expressed in foot-candles is the flux per unit area.

The eye is very sensitive to light and is the basic instrument, but the unaided eye cannot determine, with any degree of accuracy, the absolute intensity of light or illumination. It can, however, determine the equality of brightness of two illuminated areas provided they are contiguous and not too dissimilar in color.

Elements of a Photometer

The elements of a photometer are: A means of obtaining adjacent fields, a means of varying the intensity of illumination on one or both of the fields, and a standard light source.

Means of Varying the Light

A number of means are used to vary the intensity of illumination on the photometer screen, namely:

The distance of the standard light source of the test lamp from the screen may be varied, the law of inverse squares holding true. Such a method as this is most common.

A revolving sector disc may be interposed between the light and the photometer head, the proportional size of opening determining the amount of light transmitted.

A diaphragm or absorbing media may be interposed. The angle of incident light may be changed by the use of an inclined plate, the intensity being proportional to the cosine of the angle.

The candle-power of the standard may be changed by varying the voltage applied to it.

These methods may be used in conjunction with each other and the typical commercial photometer uses at least two of the possible schemes for obtaining the desired variation. For example, a standard bar photometer is so arranged as to vary the distance and also permit the insertion of a rotating sector disc. A typical portable photometer varies the distance and supplements this with neutral absorbing screens of known transmission, permitting a wide range of measurements with a given standard lamp.

Means of Comparing the Light

The development of the photometric head is interesting from historical standpoints. One of the first schemes was employed by both Lambert and Rumford. An upright rod was so placed in reference to the lamps under test that it cast two shadows on a white background. (Fig. 1A.) When the position of these lamps was so adjusted that the shadows appeared to the eye of equal density, a photometric balance was obtained, and the familiar law of inverse squares applied to calculate the ratio of intensity.

Ritchie employed a triangular shaped prism with the apex toward the observer, one face being illuminated by the standard lamp and the other by the lamp under test. When the balance occurred, the two faces appeared equally bright.

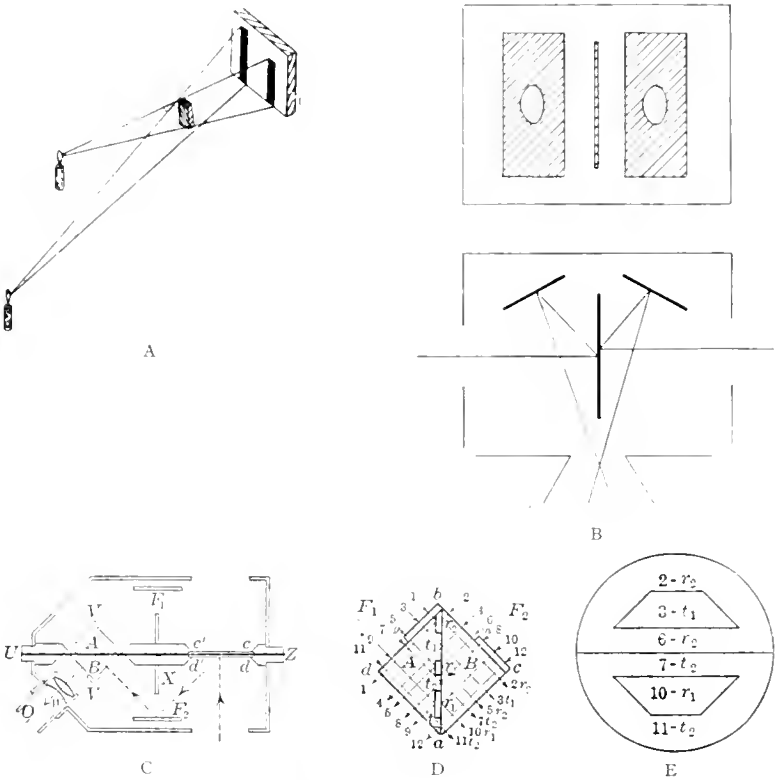


Fig. 1. Historic and Modern Photometer Heads

(A) The Lambert photometer
(B) The Bunsen screen in plan and elevation
(C) Plan of Lummer-Brodhun head
(D) Section of Lummer-Brodhun prisms
(E) Type of field produced by the Lummer-Brodhun prisms

In the Joly-Block, two rectangular prisms of translucent substance, such as paraffin or milk glass, are placed side by side with a very thin opaque diaphragm between them. If one block is then lighted by each of the lamps under test, the front of each block is seen illuminated by the internally diffused light from its respective lamp, and the equality of brightness can be readily observed.

The Bunsen sight box has probably had the widest use of any type of photometer head. Mirrors are arranged so that both sides of a screen can be observed at the same time. (Fig. 1B.) The screen is made of white opaque material, usually paper, with a sharply defined translucent spot, usually made with paraffin, in the center.

The Leeson disc is a modification of the Bunsen screen and is usually made by inserting an opaque sheet, such as tinfoil, with a central opening, sometimes star shaped, between two translucent sheets, such as paraffined paper. The sensitiveness depends upon the density of the translucent sheet. The Bunsen and Leeson screens do not require the use of a telescopic lens and can be read with both eyes. They are particularly advantageous for quick readings, such as are required for sources of rapidly varying intensity.

Two types of Lummer-Brodhun screens are used, namely, the comparison type in which the contrast disappears when a balance is obtained with lights of the same color, and the contrast type in which graded contrast always appears, the balance being judged by the eye.

The Lummer-Brodhun contrast screen is the most satisfactory form for precise work. It is somewhat intricate as will be seen from Fig. 1C, which shows the sight box in plan. The box is mounted on the photometer bar with its axis of rotation U Z perpendicular thereto. The screen proper c, c′, d, d′ is a disc of compressed magnesia which gives a brilliant matt surface upon which the rays from the sources of light to be compared fall normally. This screen is simultaneously viewed from both sides by the help of the mirrors F1, F2, and the right angle prisms, A, B, shown in the plan in Fig. 1D. Prior to cementing together the hypothenuse faces of these prisms, the surface of A is recessed by sand blasting in vertical strips as shown. When the prisms are cemented, the spaces between the strips are transparent, but at the strips there is a total reflection for light entering normal to the free prism faces. Therefore the odd numbered rays (Fig. 1D) received from c, c′ via F1, enter the sight field only through the cemented faces, and the even rays from d, d′ via F2, only by total reflection at the strips. The arrows in the figures show plainly the course of the rays. The result is a field resembling Fig. 1E, each half circle receiving light from one side of the screen and having superposed upon it a trapezoidal area received from the other side of the screen. These areas are slightly darkened by absorption from the glass strips me and gb, so that when everything is in a balance there are two equally shaded areas in a uniform field. The operator can work either by uniformity of field or by equality of contrast of the trapezoids.

When lights of two different colors are to be compared, as for instance red and blue, it is extremely difficult to judge when the intensities are equal. For this work the flicker photometer is used. In this type a screen is illuminated by the two sources of light in rapid alternation. When the speed is adjusted between 10 and 20 alternations per second the illumination appears to flicker until the intensities of the two become equal, or the flash from one bridges over the gap to the flash from the other. It is essential that the speed be regulated to correspond to the degree of accuracy desired. With a low speed the flicker cannot be eliminated, and with too high a speed the photometer loses in sensitiveness.

The Standard Lamp and Calibration of the Comparison Lamp

There are a number of primary flame standards of luminous intensity, or candle-power, based on definite specifications, carefully drawn. The satisfactory operation of any of these is complex and difficult, and they are adapted only to the standardizing laboratory.

Incandescent lamps, carefully standardized by comparison with the primary standards, are now employed universally for all photometry of electric sources. These eliminate variations due to barometric pressure, humidity, air temperature, etc., which render it difficult to reproduce the same light with flame standards.

The incandescent lamp, as a standard of candle-power, was established about 1882 by the Edison Lamp Works and transferred to the Electrical Testing Laboratories. Later the United States Bureau of Standards took charge of the maintenance of the incandescent lamp standards, verifying them by extensive measurements and comparisons with similar determinations in other countries.

Every commercial laboratory should have at least one certified standard incandescent lamp. In the larger laboratories it is customary to have secondary standards which are checked about once a month with the certified standard, and with which the comparison lamps are calibrated each day.

In order that the standard lamp may not change in value, it should not be used more than necessary for this purpose. Care should always be taken not to subject the lamp to abnormally high voltage.

Comparison lamps should be "aged" or burned several hours before they are calibrated. After the initial variation in candle-power of an incandescent lamp takes place, it remains quite constant for a considerable period. The comparison lamp should be set up in a definite position on the photometer, and this position relative to the photometric screen should be marked on the bulb of the lamp with an arrow. For all future work, the same position should be maintained. The candle-power, voltage and current should next be determined, using the standard lamp and the method of procedure discussed under Measuring Horizontal Candle-power of Light Sources. It is obvious that constant candle-power will be obtained by operating the lamp at a constant wattage if there is no blackening of the bulb, since at a constant rate of energy supply there will result a constant light flux. On the other hand, as blackening is likely to take place slowly, it is desirable to check the comparison lamp at reasonably frequent intervals. When the point is reached where appreciable variation is noted between checks, the lamp should be discarded and a new comparison lamp employed.

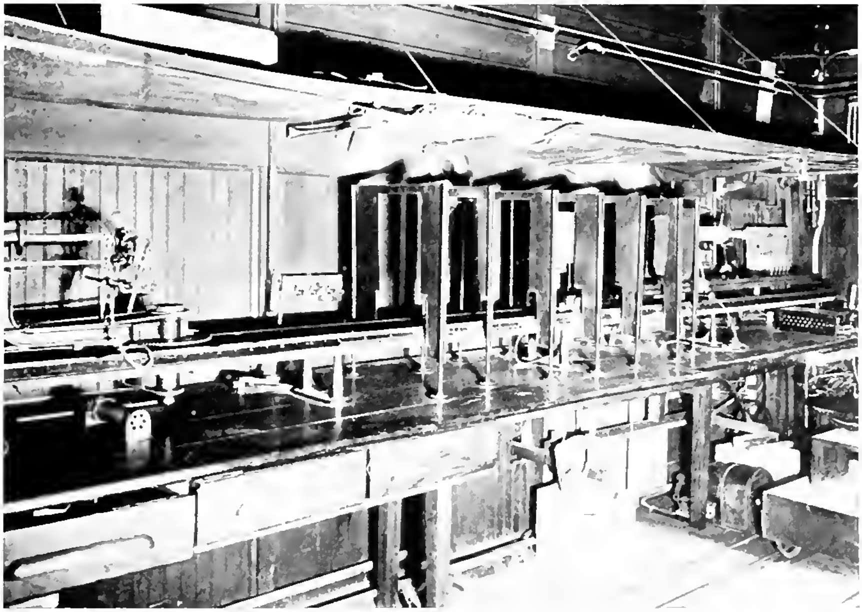


Fig. 2. A Precision Bar Photometer as Used in the Laboratory. (Note the Screens, Means of Rotating the Lamp, Photometer for Maintaining Constant Voltage Movable Head and Graduated Bar or Scale)

Measuring Horizontal Candle-power of Light Sources

The standard bar photometer (Fig. 2) is used for this purpose. It consists in brief of a photometric head of one of the types already described, a socket for holding the lamp under test and a means of rotating it, a comparison lamp and a means of varying the distance from either the test lamp or the comparison lamp or both to the photometer head. This type of instrument is still necessary for precision work and the checking of standard lamps. Its commercial field, however, is rapidly diminishing.

A few years back all ordinary types of incandescent lamps had the same shape of filament and distributed the light in the same general manner. A comparison of them on the basis of the average horizontal candle-power was acceptable. Now, however, with the Mazda B lamps having an extended filament and the Mazda C or gas filled lamps having concentrated filaments of various shapes, the horizontal candle-power of two lamps giving identical total outputs may be quite different. It is therefore wrong to express the efficiency in terms of watts per horizontal candle-power and far more logical to express this factor in lumens per watt. Some means must therefore be provided for measuring the total light emitted by a source in a rapid and convenient manner. This is accomplished by means of the spherical photometer described in the next section.

In the days of the carbon lamp it was necessary to test each lamp for candle-power and efficiency and the bar photometer was used for this purpose. The method of operation was as follows: A boxed-in photometer of a type shown in Fig. 3 was ordinarily employed. The "reader" so-called, because she observes the "spots," was furnished with a resistance connected in series with the lamp under test.

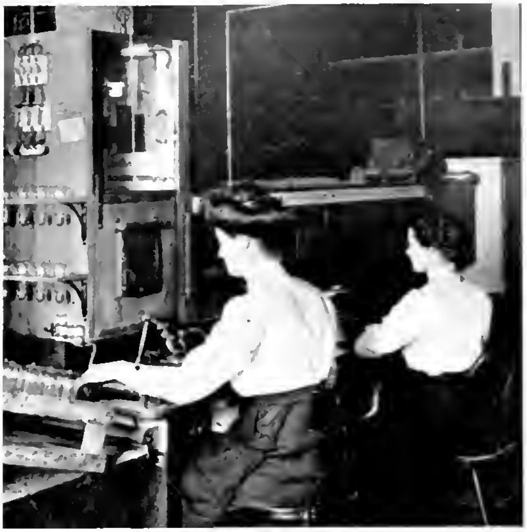


Fig. 3. A Boxed-in Type of Factory Bar Photometer. Two operators are able to photometer a large number of lamps per hour. The working standards will be noted on a rack at the left

The photometer was set up so that it read directly a given candle-power, 16, 20 or 32. The lamp to be tested was put up in the rotating socket, and the voltage applied to it was varied until a balance was obtained. The second operator or "marker" read the voltage and amperage. A glance at a table indicated the efficiency of the lamp. The voltage at which it gave its rated candle-power was marked on the bottom of the bulb and afterwards the lamp was so labeled.

With the diminishing demand for carbon lamps and the fact that Mazda lamps are made of wire so accurately drawn to dimensions and cut to the proper length that it is necessary to photometer only a very small proportion of the total product, this type of photometer is rapidly going out of use.

The bar photometer serves a good purpose in the laboratory or classroom in demonstrating the principles of photometry and making such determinations as the effect of voltage on candle-power and the like. In installing such an instrument, precaution should be taken that surrounding walls do not cast reflections on the photometric screen. Any stray light can be cut off by the use of a suitable number of shields or screens between the lamps and the photometric head.

In calculating the results from the test with this instrument, the standard fundamental and simple formula of

$$\frac{CP_1}{D_1^2}=\frac{CP_2}{D_2^2} \text{ or } \left(CP_2=CP_1\,\frac{D_2^2}{D_1^2}\right)$$

applies, where CP_1 is the candle-power of standard source, D_1 the distance of the standard source to the sight box, D_2 the distance from the test lamp to the screen, CP_2 the candle-power of the test lamp.

Measuring Spherical Candle-power or Total Light of Illuminants

The total light emitted by a source rather than the candle-power in a definite direction is a measure of the energy available for illuminating purposes. It is possible, of course, to analyze the distribution of light as described in the following section, and calculate from this the total flux. Such a method is tedious and unnecessary unless the characteristic of distribution is desired.

The globe photometer or integrating sphere (Fig. 4) gives us a means of determining the total light with one reading and is now widely used. Its theory in brief is as follows: When a source of light is placed inside of a spherical shell having a matt or depolished surface, the light received by any part of the interior surface may be considered in two parts, (a) that coming directly from the lamp and (b) the light received from the remainder of the interior surface of the sphere after one or more reflections. The quantity

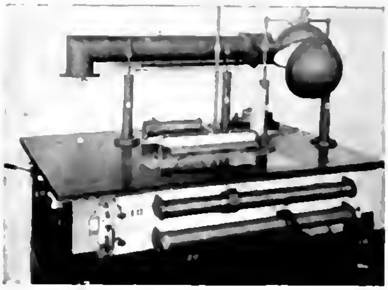


Fig. 4. A Small 12-in. Sphere Photometer for Testing Miniature and Low Wattage Lamps

(a) is that which is measured in the ordinary photometer, which determines the intensity of light emitted in any one direction and is not considered at all in the integrating sphere, for an opaque screen is placed between the lamp to be measured and the opening in which the photometer head is inserted. The quantity (b) is constant all over the surface of the shell and is proportional to the total amount of light emitted by the lamp independent of its position in the shell.

To calibrate the sphere, a lamp of known mean spherical candle-power of the same type and size as being tested is placed within and a reading made in the usual manner with the photometer; in other words, the substitution method is applied.

Where approximate or comparative readings are required and it is not expedient to go to the expense of having a carefully constructed sphere, a box photometer or modified sphere (Fig. 5) is often used. This consists of a large cubical box with the corners cut off approximating a sphere in shape, painted with lithopone (barium sulphate), and operated in the same manner as a standard sphere. Its accuracy is not of as high order, especially for lamps having dissimilar characteristics, but it serves a useful purpose under commercial conditions.

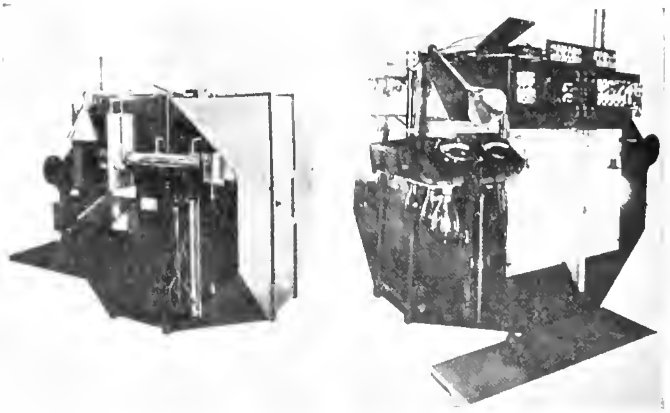


Fig. 5. Front and Rear Views of a Modified Sphere or Boxed Photometer of Suitable Accuracy for Commercial Work

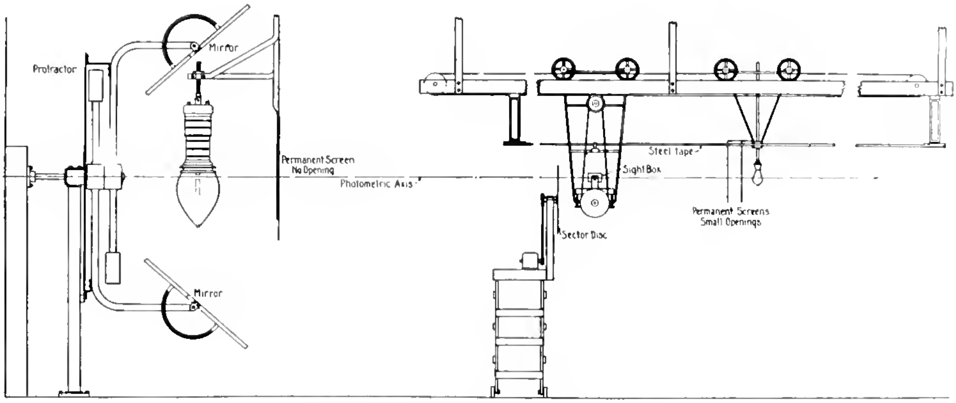


Fig. 6. Sketch of Twin Mirror Constant Radius Distribution Photometer. The component parts are clearly indicated

Determination of Vertical Distribution of Light

There are a number of types of photometers for this purpose which are described in all good text books. One of the simplest to operate and to understand is shown in Fig. 6. This is a twin mirror photometer of constant radius. The direct rays from the lamp are intercepted by a black screen placed in the photometric axis. The light which is measured is reflected by the mirrors and strikes the photometer screen at an acute angle. This necessitates calibrating the apparatus by the substitution method. A source of known candle-power is put in the same position as the test lamp and suitable readings taken.

In the illustration the mirrors are shown in a position not encountered in practice, but this arrangement illustrates the construction. In actual operation each is similarly placed on the opposite side of a vertical line passing through the center of the light source. Thus, if it is desired to determine the candle-power at 10 degrees below the horizontal, the mirrors are placed on the opposite sides of the lamp 10 degrees below the horizontal and so on. In taking the reading at zero degrees or directly beneath the unit, one mirror alone is used, the other being covered with a piece of non-reflecting black felt.

Fig. 7. The Appearance of the Twin Mirrors as Viewed from the Photometer Head When 45 Degrees Above and Below the Horizontal

The mirrors serve to gather the light at any given angle, and reflect it to the photometric screen as shown in Fig. 7. Obviously in theory one mirror could be used instead of two, but two mirrors offer an advantage in arc lamp photometry by reducing fluctuations in intensities due to the unsteadiness and travel of the arc.

In photometering Mazda B (vacuum) lamps, the lamp and its equipment can be rotated and only one mirror used. In photometering Mazda C lamps, rotation is out of the question if accurate results are to be obtained, for the whirling action of the cooling gas affects the candle-power. Two mirrors offer an advantage in overcoming any variation at different horizontal angles.

A rotating sector disc placed in the photometric axis will be noted. This can be used on either side of the sight box and increases the range of the apparatus. The comparison lamp is suspended from a track and manipulated by a steel tape driven by a hand wheel below the sight box. Varying the distance of the comparison lamp from the photometer head enables one to obtain a balance. Any reflected light from the comparison lamp is cut off by the opaque screens with small openings. The sight box remains in the same position or at a constant radius so that the incident angle of the light rays will be the same as when the photometer was calibrated.

To calibrate the photometer by the substitution method, the sight box is set at a definite point, say 10 feet, from the unit being tested. The mirrors are set at a 90 degree angle from the vertical and a secondary standard lamp whose horizontal candle-power is accurately known is inserted in the test socket with its center on the photometric axis. The comparison lamp is now placed at the distance from the photometer screen corresponding to the candle-power of the secondary standard (assuming the scale is graduated according to the inverse square law) and the voltage applied to the comparison lamp adjusted until a balance is obtained. This method takes care of the absorption of the mirrors and other constants of the device.

Having determined the voltage at which to operate the comparison lamp, the lamp and reflector or globe equipment is placed in position so that the center is on the photometric axis. Care is taken to insure that the light center of the lamp is in the proper relative position to the reflector. This is accomplished by raising or lowering the adjustable socket which is part of the equipment. The voltage on both the test and comparison lamp should be carefully watched and held constant. In the case of lamps designed for series burning, the amperage must be held constant. It is generally desirable to see that both amperage and voltage on any lamp remains constant, for a change in either indicates a change in light output.

Having the set-up properly adjusted, the mirrors are revolved around the photometric axis and readings taken at 10 or 15 degree intervals. Three or more settings should be taken at each angle. The number of settings will depend on the constancy of the source. In the case of a fluctuating source, such as an arc lamp, more readings are necessary than with a steady source, such as the incandescent lamp. With a fluctuating source a series of snap readings is preferable to a lesser number of careful settings, otherwise the operator is likely to follow the fluctuations up and down the scale and not obtain a true average.

Selection of Equipment for Test

The purpose of the test has an impotant bearing on the selection of samples. Individual lamps, reflectors and globes vary, and it is therefore necessary to use as much discretion as when testing samples of coal for total heating value. Every engineer knows how necessary it is in this case to obtain a representative sample.

If incandescent lamps are to be tested for efficiency or life performance, it is obviously impossible to test one or two specimens and obtain fair results. Incandescent lamps resemble human beings—some burn out at an early day, others last over the normal life. The average life, however, can be determined by a test on a suitable percentage. The efficiency of individual lamps also varies somewhat. For example, the standard specifications for incandescent electric lamps, prepared by the Bureau of Standards, state that the test quantity shall consist of 5 per cent each lot of lamps inspected of any one type, size and voltage range, and in no case shall be less than 10 lamps.

Individual opalescent enclosing globes and similar accessories differ considerably in density. It is impossible to blow glassware with perfect uniformity. Thickness, and hence density and absorption, will vary. A visual inspection will indicate the general characteristics of the glassware and if only one is to be tested, a quantity should be inspected and the globe selected for test should be of average density. If it is possible to test more than one in addition to the average specimen, the globe which appears particularly dense and one which is very light should be selected to determine the maximum and minimum absorption values.

Porcelain enamel and similar reflectors vary as to quality of reflecting surface, and a similar procedure should be followed in selecting the test unit. A thin coating of enamel, through which the base metal is visible, will have low reflecting power.

In selecting a lamp with which to make a distribution test, particular attention should be paid to its light center length and physical dimensions. If it is impractical to secure a lamp of exactly standard light center length, the position of the socket, with reference to the reflector, should be adjusted so that the standard filament position is attained.

Lamps as ordinarily manufactured vary somewhat in total light output. Tests should always be conducted with the test lamp emitting the proper rated lumens of the clear bare lamp. This is accomplished by placing the test lamp in a sphere without any auxiliary equipment; setting the photometer attached to the sphere at such a value that it reads the mean spherical candle-power corresponding to the total rated lumens of the lamp, adjusting the voltage applied to the lamp under test until a photometric balance is obtained, then operating this lamp during subsequent tests at the voltage thus determined.

In the case of using bowl frosted or bowl enameled lamps, the absorption of the frosting or enameling should first be determined by testing a group of lamps for total output at a given voltage, clear, then frosting or enameling the same lamps and testing them for total output at the same voltage. Having determined the absorption of the frosting or enameling the lamps should be operated at the proper percentage of the clear rated total lumens throughout the test.

The purpose of the test determines, in general, the procedure which should be followed in selecting a sample. If one is endeavoring to find out what a certain equipment will do as put out by the manufacturer, as is the case with the purchaser, the standard arrangement as to socket or length of fixture and regular run of glass, as equipped, should be tested without adjustments.

If it is desired to show from the manufacturer's standpoint what equipment will do under proper conditions, then care must be taken in selecting average glassware and adjusting for standard positions.

If in connection with development work, it is desired to discover what is the best combination of parts, readings can be taken with various lamp positions and with various glassware combinations, eventually determining the best possible distribution with minimum absorption and maximum diffusion, or other desirable qualities.

Calculating Results from Test Readings

Having measured the candle-power or intensity of light from the unit at the various angles in a vertical plane, the readings are plotted on polar co-ordinate paper to any desired scale. It remains to calculate the mean spherical candle-power, the mean hemispherical candle-power, the zonal lumens, the downward lumens and the total lumens.

There are a number of graphical methods devised by Rousseau, Kennelly, Macbeth, Wohlauer and others for determining the mean spherical candlepower and total flux. These are all based on the same fundamental equations.

If we consider a lighting unit as suspended at the center of an imaginary sphere of radius

R (Fig. 8), it is obvious that the light in an angle from 0 to 15 deg. directly beneath the unit will be spread over a comparatively small area while the light striking the sphere at, say, 75 to 90 deg. will be spread over a zone of much greater area. The light flux or lumens embraced by a zone will be equal to the product of the average intensity and the area of the zone. A summation of these products for each zone gives us the total value of the light flux or lumens emitted by the source.

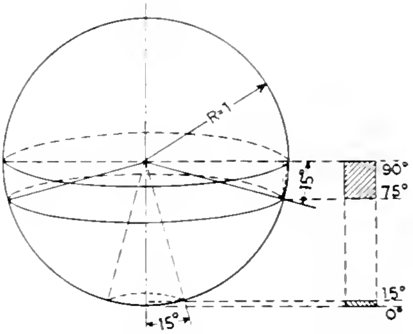


Fig. 8. Diagram Showing Variation in Zonal Areas from Zero to 90 Degrees

It can be shown by spherical trigonometry that the area of the zones of the sphere are to each other as their altitudes; thus the area of any zone of this imaginary sphere of unit radius is equal to

$$2\pi\ (\cos a_1 - \cos a_2)$$

where

$(a_1 - a_2)$ is the angle subtended by the zone in reference, a_1 and a_2 being measured from the vertical.

Substituting in this formula for 10 degree zones, we arrive at the following values:

Angle on Curve	Zone Represented Deg.	Constant
0		0
5	0–10	.095
15	10–20	.284
25	20–30	.463
35	30–40	.628
45	40–50	.774
55	50–60	.897
65	60–70	.993
75	70–80	1.058
85	80–90	1.091

The candle-power readings at the various degrees multiplied by these constants will give respectively the lumens in the zone under consideration. It will be noted that the last constant is but half of the value that would seem logical. This is because it takes into consideration only the flux from 85 to 90 deg. The sum of these individual zonal lumens will give the total downward lumens. The downward (0–90 deg.) divided by 2π (6.283) will give the mean lower hemispherical candle-power.

A similar computation can be applied to the upper hemisphere, obtaining the upward lumens and the mean upper hemispherical candle-power. The downward lumens plus the upward gives the total lumens, which, divided by 4π (12.57), gives mean spherical candle-power. If it is desired to determine the lumens in any particular zone, say from 0 to 60 deg., the sum of the individual zonal lumens should be taken, bearing in mind that the value for the mid-zone angle of 60 deg. covers from 55 to 65 deg., and therefore should be divided by 2 to obtain the flux only from 55 to 60 deg.

The following data should be included in a report of a test to determine the light distribution of a given unit:

Type of fixture.
Trade name and number of manufacturer.
Type of lamp.
Size and kind of bulb, whether clear, bowl frosted, bowl enameled, or all frosted.
Rated volts.
Rated amperes.
Rated watts.
Mean lower or upper hemispherical candle-power.
Watts per mean lower or upper hemispherical candle-power.
Downward or upward lumens per watt.
Mean spherical candle-power.
Watts per mean spherical candle-power.
Total lumens.
Total lumens per watt.
Per cent total lumens of clear bare lamp.
Lumens in various zones.
Dimensions of reflector, diameter and depth.
Light center length of lamp.
Distance from edge of reflector to top of base.
Vertical distribution curve with note as to whether initial, or with depreciation.
Description of equipment.
Total lumens at which lamp is operated during test.
With a constant radius photometer, the distance at which readings were taken.
Test number, date, number of curve and initials of checker or inspector.

A typical distribution curve containing this information is reproduced in Fig. 9.

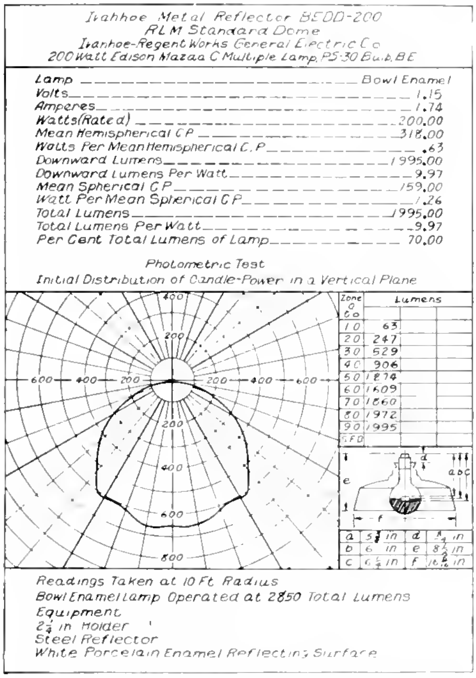
Portable Photometers and Their Calibration

The three portable photometers in most common use in this country are:

Sharp-Millar photometer
Macbeth illuminator
Foot-candle meter

The photometric principle of the first two instruments is practically the same. Both have a Lummer-Brodhun cube mounted in the head, and use a low voltage Mazda lamp as a comparison lamp. In operation the comparison lamp is moved back and forth on the optical axis until a balance is secured in the cube as seen through a telescope. Both have a scale calculated according to the inverse square law and calibrated to read foot-candles direct.

In mechanical construction the instruments are entirely different. The Sharp-Millar photometer (Fig. 10) is a box 5 in. square by 28 in. long. An elbow opposite the photometer head has a 45 deg. mirror at the elbow and a translucent test plate at the end. The lamp is mounted in a carriage on the inside of the box and moves back and forth with a pulley and cord. A slot in the lamp carriage illuminates the scale, so that when a balance is reached the foot-candles may be read directly opposite the slot in the lamp carriage. A resistance is mounted on the box to keep the voltage across the lamp constant. A battery meter set consisting of milliammeter, 6-volt storage battery and resistance, is provided with the photometer. The elbow may be turned in any direction so as to read normal or horizontal illumination. The instrument is quite sensitive and is capable of as great accuracy as is desirable for portable photometric work.



Ivahhoe Metal Reflector BEDD-200
RLM Standard Dome
Ivanhoe-Regent Works General Electric Co
200 Watt Edison Mazda C Multiple Lamp, PS-30 Bulb, BE

Lamp	Bowl Enamel
Volts	1.15
Amperes	1.74
Watts (Rated)	200.00
Mean Hemispherical CP	318.00
Watts Per Mean Hemispherical C.P	.63
Downward Lumens	1995.00
Downward Lumens Per Watt	9.97
Mean Spherical CP	159.00
Watt Per Mean Spherical CP	1.26
Total Lumens	1995.00
Total Lumens Per Watt	9.97
Per Cent Total Lumens of Lamp	70.00

Photometric Test
Initial Distribution of Candle-Power in a Vertical Plane

Zone 0 to	Lumens		
10	63		
20	247		
30	529		
40	906		
50	1274		
60	1609		
70	1860		
80	1972		
90	1995		
SFD			

a	$5\frac{3}{8}$ in	d	$\frac{1}{4}$ in
b	6 in	e	$8\frac{1}{2}$ in
c	$6\frac{1}{4}$ in	f	$16\frac{3}{16}$ in

Readings Taken at 10 Ft Radius
Bowl Enamel Lamp Operated at 2850 Total Lumens
Equipment
$2\frac{1}{4}$ in Holder
Steel Reflector
White Porcelain Enamel Reflecting Surface

Fig. 9. Typical Vertical Distribution Curve Containing Data Essential for Comparison or Repetition of Tests

The range of the foot-candle scale is from 0.4 of a foot-candle to 20 foot-candles, but by means of neutral tinted absorbing screens the range may be increased from 4/1000 of a foot-candle to 2000 foot-candles.

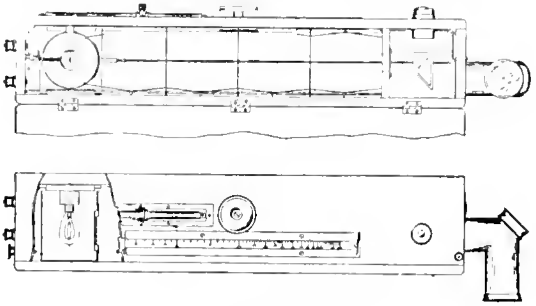


Fig. 10. Front and Top View of the Sharp-Millar Portable Photometer

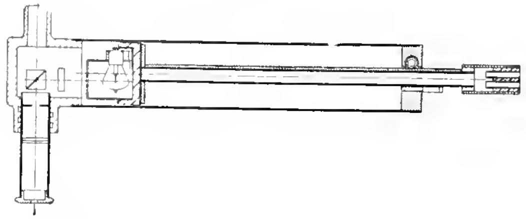


Fig. 11. Sectional View of the Macbeth Photometer

The Macbeth photometer (Fig. 11) consists of a tube 9 in. long by $1\frac{3}{4}$ in. in diameter. Inside of this tube is the carriage which holds the incandescent working standard. The carriage is mounted on a brass rod extending through the end of the tube. A rack and pinion operates the rod and draws the carriage back and forth. On one side of the rod to which the lamp carriage is attached is engraved a direct reading scale calibrated from 1 to 25 foot-candles. An index point is attached to the bottom of the tube. This index point may be changed so as to allow for adjustment if variation in filament position occurs when renewing standard working lamps. At the other end of the tube is the Lummer-Brodhun cube in a rectangular box. The photometric field is observed through a telescope. The opening opposite the telescope is aimed or pointed toward the detached test plate which is placed at the point where it is desired to know the illumination. The test plate made of glass is finished by a special process so as to get the minimum error when viewed at various angles. With a given illumination a perfect plate would be of equal brightness when viewed from all directions. Such a surface has never been secured. The plate used with the Macbeth illuminator shows practically no error up to an angle of 25 deg., and from that point the error is much less than with most other materials that have been tried.

Fig. 12. Exterior of the Foot candle Meter

In order to increase the range of measurements absorbing screens are provided. These screens are made of neutral tinted glass which may be placed on one side or the other of the Lummer-Brodhun cube, thus widely extending the normal range of the instrument. There is no limit to the number of screens which may be used, either neutral or colored, for selective absorption. These screens are easily inserted or removed. With the absorption screens usually supplied the range of the instrument is from 2 100 to 1200 foot-candles. This may be increased by additional screens 3000 times maximum or minimum if desired. The auxiliary apparatus supplied for this instrument is the controller and the reference standard.

The controller is a self-contained unit consisting of a milliammeter, two adjustable resistances, double-pole double-throw switch, the necessary connectors, and two dry batteries. A detachable shoulder strap makes it possible to hang the instrument over the shoulder and conveniently carry it about. Flexible leads connect the controller with the photometer.

The reference standard is in a housing which fits over the tube at the end of the photometer head, and is used for calibrating the photometer. In using this reference standard the photometer may be calibrated at any time, any place, without a dark room, and is a decided convenience because the operator may calibrate the instrument himself and thus eliminate the personal factor which is always present when using the illuminometer standardized by others.

The sensibility and accuracy of this instrument are about the same as the Sharp-Millar.

The foot-candle meter (Figs. 12 and 13) is based on the grease spot or Bunsen photometer principle, which is modified to fit the design and character of this meter. In the case of the Sharp-Millar and the Macbeth photometer the working standard lamp is moved back and forth until the spot in the photometer head is balanced by the external source. In the case of the foot-candle meter a series of spots are lighted from one lamp in a fixed position, which illuminates a box which forms the background of the series of spots. In reading the meter the spot is selected which blends with the background of the scale, this background being illuminated by the external source or room illumination which it is desired to measure.

The screen consists of a piece of clear glass on which are two thicknesses of paper, one of which is punched with a series of round holes and is fairly opaque, and the other is highly translucent. This screen forms one side of the light box, which is so constructed that the screen is illuminated from within to a much higher intensity at the right than at the left. The exposed side of this screen

Fig. 13. Interior of the Foot-candle Meter

is very nearly uniformly lighted, and consequently the round spots appear brighter than the screen surface at the right end and darker at the left. It is evident that the point where the spots change from lighter than the screen surface to darker the illumination on both sides of the screen is approximately the same. When the instrument has once been calibrated the illumination intensity indicated by a foot-candle scale on the screen may be read at a glance.

A three-cell flashlight battery supplies current for the lamp through an adjustable rheostat. A voltmeter across the lamp indicates when the proper voltage is supplied. The entire equipment is built into a small case, 6 by 8 in., weighing only 3 lb. It is not as accurate nor as sensitive as the large photometer, but it has thoroughly demonstrated its value for a light weight non-complicated instrument for general survey work and for measuring the illumination in fields where a large photometer could not be conveniently or practically used.

Calibration

Frequent checking or calibration of photometers is necessary if any degree of accuracy is to be expected. The equipment necessary to do this work is a voltmeter to keep the voltage across the standard lamp constant, a calibrated standard lamp and adjustable resistance, and constant voltage supply. Calibrated standard lamps for this purpose can be secured from the Electrical Testing Laboratories in New York or the Bureau of Standards in Washington.

With a given voltage marked on the standard lamp a certain candle-power is given in a specified direction. The lamp is set up and the exact voltage of the lamp is impressed on it, and maintained constant during the calibration. Place the photometer a measured distance from the lamp and calculate the foot-candle intensity at that point. Set the comparison lamp of your photometer at the calculated foot-candle intensity and vary the resistance on your photometer until a balance is secured. For instance if an 8 c-p. lamp is used set the horn of the photometer two feet from the light source, or filament of the lamp. At two feet from an 8 c-p. lamp according to the inverse square law, we get two foot-candles. Set the comparison lamp of the photometer at two foot-candles, vary the resistance on the photometer until a balance is secured with the calibration lamp. Note the current or voltage on the photometer instrument, and that is the point at which to hold the comparison lamp in the photometer when making the test. Care should be used not to burn the reference standard lamp longer than absolutely necessary, as continued burning will destroy its accuracy.

The only difference in calibrating a photometer with an external test plate, like the Macbeth, is to set the plate in place of the photometer, keeping its face normal to the lamp. In pointing the photometer at the test plate keep within 30 deg. of normal and do not allow any extraneous light to enter the tube.

The Sharp-Millar photometer may also be used with an external test plate by simply removing the cap holding the translucent plate at the end of the horn and calibrating as described above. White blotting paper may conveniently be used as a temporary test plate, although a specially prepared glass plate is more constant and more permanent.

If the calibrating devices that are furnished with the instrument are used they should be checked occasionally against the standard lamp to see that they have not deteriorated.

When calibrating the foot-candle meter it is necessary that the meter lie in a horizontal position while being calibrated. This is true because the needle of the voltmeter contained in the instrument is balanced to read correctly in the horizontal position. When the voltage indication has once been determined, however, the meter may be used in any position.

(To be Continued)

Photo-elasticity for Engineers

PART II

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Written specially for GENERAL ELECTRIC REVIEW

In this article the author first gives the results of some experimental work on the determination of stress in the neighborhood of a circular hole in a tension member, using celluloid models. He also gives the results of some independent determinations of stress in similar steel pieces, and compares the results with those required by theory. A theoretical proof that stress distributions are independent of the elastic constants of the material in many cases is outlined. Further experimental results are given covering the case of elliptical holes in tension members and extending the study to the important matter of cracks and discontinuities. Knowledge of these results is important in many practical cases of design such as boiler plating, steam turbine wheels, and any case where a stressed member contains holes.—EDITOR.

Holes and Cracks

The effect of a hole, or a group of holes, on the distribution of stress in any member or element of a machine under load is of great interest and importance, since in most engineering operations holes are drilled or otherwise shaped for connections like bolts and rivets, or possibly as means of communication between neighboring chambers, for assembling purposes and the like. Whatever their use may be it can be shown that they alter very greatly the stress distribution in their neighborhood, and the combinations in which such discontinuities can occur in practical work are so immense in number that it is only possible to deal with a limited number of simple cases; in fact very few have been solved, as yet, experimentally or by calculation.

The importance of this group of cases, however, warrants us in considering them somewhat early as practical examples of the use of photo-elastic investigation.

In the simplest case of a very wide tension member, having a hole of moderate size drilled centrally, we have already seen that when load is applied the color effects are marked around the boundary of the hole, even when the rest of the plate is under little stress. The effects are symmetrical about the line of pull, and most intense at points distant from the center line, and they gradually decrease in intensity as we approach the axis, until at an angular distance of about 30 degrees from this there is no stress at all. Along that portion of the boundary nearest the center line there is a compression stress which attains its maximum value at the axis, as may be readily verified by aid of the exploration tension member.

Very many holes have been examined optically and as an example of such measurements we may take a hole ¼ in. in diameter in a plate on which the load applied gives a uniform stress of 570 pounds per square inch of cross section well removed from the discontinuity. An exploration of the stresses at different angular points of this boundary shows that the maximum stress reached is 1720 pounds per square inch in tension, and Table I shows that it varies greatly with the angular distance from the axis. Fortunately, we are able to compare these results with calculation, since this example is one of the cases for which an exact solution has been found and it can be shown that the boundary stress follows the law

$$s = p\,(1 - 2\,cos\,2\,\theta)$$

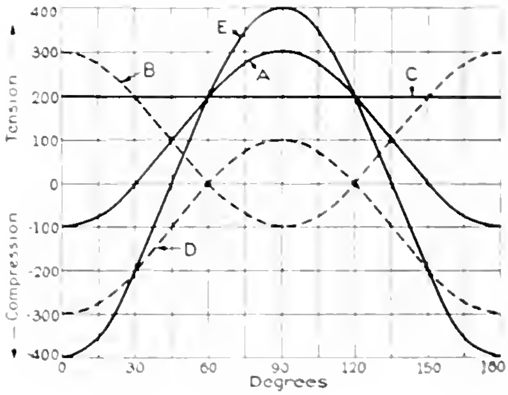


Fig. 1

TABLE I

Angular Distance θ from Axis	0°	15°	30°	45°	60°	75°	90°
Stress in pounds per square inch	540	400	20	+580	+1200	+1530	+1720

This is substantially what is found in this and all like cases. A cylindrical hole, in fact, raises the stress to three times its normal value at the sides of the hole as the linear diagram (Fig. 1, Curve A) shows, and very much increases the stress at places near to this; but this is not, as a rule, realized by practical men, and often a hole is considered as a mere loss in cross section. It is much more than this, however, as an inspection in the polariscope shows. It is, moreover, easy to prove that a new load of the same type may actually decrease the stress at the hole if it is applied at right angles to the former direction. If it has the same general intensity we then get a uniform stress all round the boundary, of twice the mean intensity (Curve C), due to the combined effects of the boundary stresses (Curves A and B), since the effect of the extra load is to eliminate all variations due to angular change. If, on the other hand, a similar load of the opposite sign is imposed (Curve D), in this new direction, the stress is increased to four times the intensity at the edge of the hole at four places (Curve E), two along the axial line in compression and two at the ends of the transverse diameter. Combined stresses of this kind are of frequent occurrence in practice and some of special interest occur in the rotating disks of turbine wheels where they are pierced by holes and it is often found to be necessary to increase the thickness of the metal around these discontinuities in order to avoid fracture.

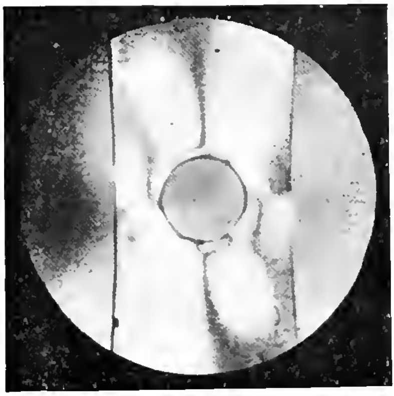


Fig. 2. Stresses Around Circular Hole as Shown by Polarized Light

If now we proceed further to examine the condition of stress away from the boundary of the hole we need to know the directions of the principal stresses since we have no boundary to help us, and it becomes necessary, therefore, to map out the region by the aid of plane polarized light using the crossed polarizer and analyzer. For such a case as the present it is comparatively easy to determine these directions and the process is indicated by the bands observed around a somewhat larger hole and these are found to have the forms of the type shown in the illustration, Fig. 2, thereby fixing the directions of stress in the area around the hole. A number of these bands with the directions of the stress marked on them are shown in Fig. 3, while the stress distribution is indicated in the color photograph of Fig. 4A, and although this diagram gives all the information required it is not in a very convenient form and it is generally preferable to re-cast the information it gives by drawing curves which show more directly the directions of the stress at any point.

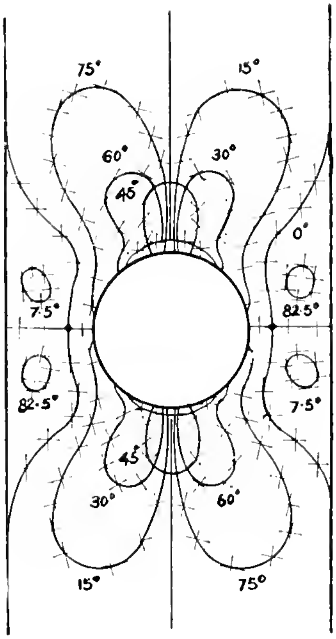


Fig. 3

The simplest way of carrying this out is, in the present instance, to take a cross section at some distance from the discontinuity where the lines of principal stress are parallel and perpendicular to the direction of the pull and then produce these lines in the direction of the hole and guide their directions by the isoclinic lines so that at any point these directions correspond. Proceeding in this way a new map is obtained as shown in

Fig. 5 on which it is usually convenient to project the stress picture formed in circularly polarized light and then proceed to determine the stress difference optically at the points required. If further it is desired to know the magnitudes of each principal stress one of the methods described in the preceding lecture must be applied in order to effect the separation.

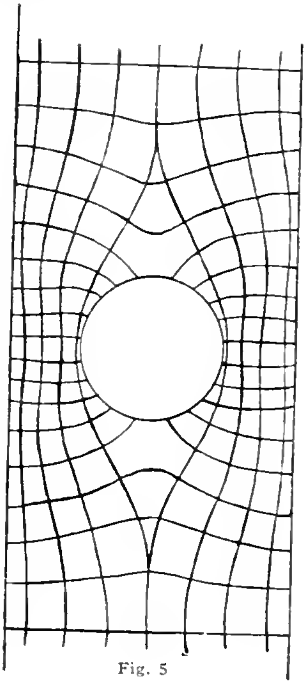


Fig. 5

In a case where a $\frac{1}{4}$-in. hole pierced a plate 1 in. in width this separation was effected by aid of lateral measurements of the strain across the minimum section and it was then found that the values of $(P - Q)$ at various points reckoned from the center of the hole had the following values:

Hole $\frac{1}{4}$ in. in diameter in a plate 1 in. wide

TABLE I

Distance from Center of Hole in Inches	STRESSES IN POUNDS PER SQUARE INCH			
	$p+q$	$p-q$	p	q
—0.50	530	540	535	−5
—0.40	550	580	565	—15
—0.30	650	630	640	+10
—0.20	930	750	840	+90
—0.14	1440	1460	1450	—10
—0.125		1720	1720	
0				
+0.125		1730	1730	
+0.14	1350	1400	1375	—25
+0.20	910	760	835	+75
+0.30	660	660	660	
+0.40	560	580	570	−10
+0.50	500	560	530	—30

which at once gives the separation of the stresses required and also shows that the effect of the pull produces a cross stress at this section which although small is perfectly definite with a maximum value near the boundary of the hole.

It is of interest to compare these results with those obtained by the elastic theory of the effect of a hole in a very wide plate, Fig. 6.

For such a case we obtain the stresses in polar co-ordinates in the form

$$p_{rr}=\frac{p}{2}\left\{\left(1-\frac{a^2}{r^2}\right)+\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\cos 2\theta\right\}$$

$$p_{\theta\theta}=\frac{p}{2}\left\{\left(1+\frac{a^2}{r^2}\right)-\left(1+3\frac{a^4}{r^4}\right)\cos 2\theta\right\}$$

$$p_{r\theta}=\frac{p}{2}\left\{3\frac{a^4}{r^4}-2\frac{a^2}{r^2}-1\right\}\sin 2\theta$$

which become for the cross section measured

$$p_{rr}=\frac{3}{2}p\left(\frac{a^2}{r^2}-\frac{a^4}{r^4}\right)$$

$$p_{\theta\theta}=\frac{p}{2}\left(2+\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)$$

$$p_{r\theta}=0$$

in which the uniform stress p corresponds to an infinite plate, so that for a finite plate some correction is required. As the experimental curve for $p_{\theta\theta}$ is found to closely follow the theoretical value, it is probably sufficiently accurate to assume that it has the same law. If then p_m is the mean average stress at the section through the hole of radius a, where $2\,ca$ is the width of the member, we obtain

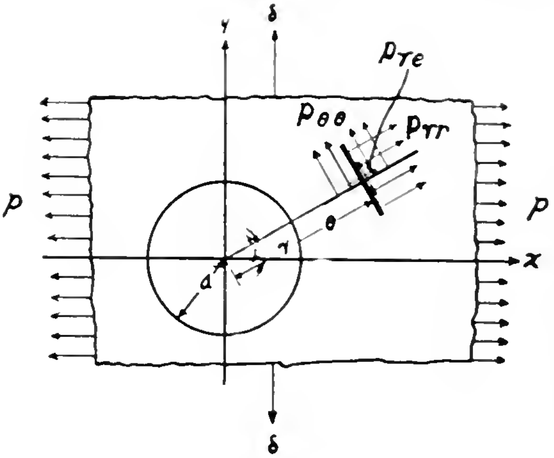
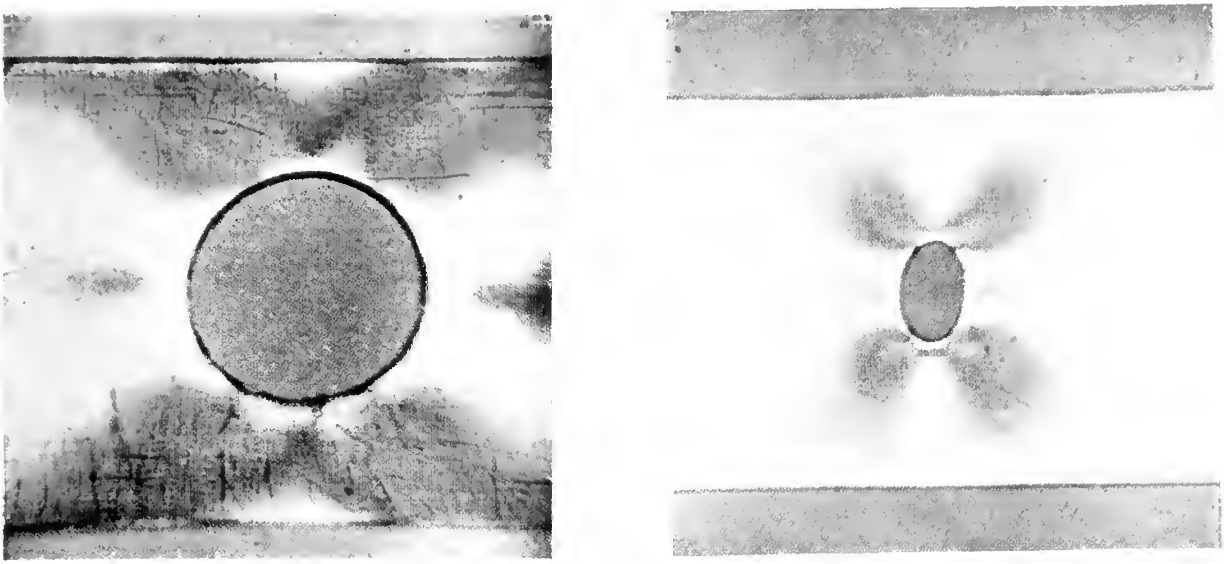


Fig. 6

$$p_m a(c-1)=\int_a^{ca} p_{\theta\theta}\,.\,dr$$



(*A*) Circular hole.

(*B*) Elliptical hole.

(*C*) Slit.

(*D*) Slit with ends bored out to reduce stress.

(*E*) Slit with ends bored with elliptical holes to further reduce the stress.

Fig. 4. Tension Members with Various Shaped Holes in Them Showing Maximum Stress Intensities at Top and Bottom of Holes. Tension is Applied in a Horizontal Direction

giving

$$p = p_m \Big/ \left(1 + \frac{1}{c} + \frac{1}{2c^2} + \frac{1}{2c^3}\right)$$

an equation for the required value appropriate to this case of 570 pounds per square inch. Comparison of the experimental and theoretical results then show almost perfect agreement for the stress across the section, but not so good for the cross stress.

This discrepancy arises from the manner in which the latter value is determined as a difference between the sum and difference of the principal stresses, and as both are in general large values any small errors in their determination become still larger percentages of the cross stress values. Although errors tend to accumulate in this way, there is sufficient agreement to show that the behavior of the cross stress follows the law indicated by theory and that the maximum values of this stress occur at a short distance away from the hole at a radius $r = a\sqrt{2}$ corresponding to $\frac{dp_{rr}}{dr} = 0$ for $\theta = \frac{\pi}{2}$.

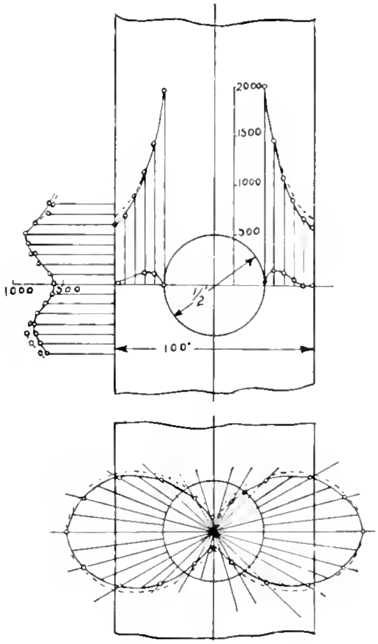


Fig. 7

It is interesting to examine what effect is produced by successive enlargement of the hole in such a plate and it is found that around the boundary of the hole the stress distribution changes gradually with increased size of hole but the maximum stress is still approximately 3 p even when the diameter of the hole is half the width of the plate, Fig. 7. It is noticeable, however, that the zero stress at this boundary tends away from the central line while the stress at the ends of the cross section becomes less than that indicated by the theoretical expression for $p_{\theta\theta}$.

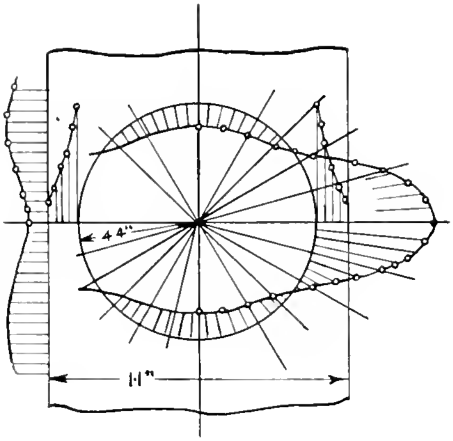


Fig. 8

This latter phenomenon is in fact just perceptible with a ¼-in. hole in a 1-in. plate and becomes more marked with a hole of greater size. Another peculiarity which seems connected with this latter phenomenon is that the stress along the straight edges of the tension member appears to always be less at the intersection with the central cross section than at any other place.

It is quite perceptibly so with a ¼-in. hole and the appearance of the specimen in the polariscope shows that this must be so since the bands of constant stress difference intersect these boundaries at two places away from the central cross section, showing that a minimum stress value lies between. With a ½-in. hole (Fig. 7) in a 1-in. plate the stress at places along the parallel sides about an inch away from the minimum section is actually about 40 per cent greater than that at the ends of the central cross section and as the hole becomes still greater the maximum and minimum values become still more pronounced. In a plate 1.1 in. wide, with a central hole 0.88 in. diameter, Fig. 8, it was found that the maximum stress along the edges rose to three times the value of the minimum and it seemed possible from observations of the color bands shown in Fig. 4A of the stress distribution across this minimum section that the stress at the outer edge might actually change to compression if the hole became sufficiently large.

On trying this with a hole about 5 in. in diameter in a plate about 5.2 in. wide, it was found that the minimum stress did not even in this case become negative but was approximately zero, while the variation across the section was approximately linear. For very large holes, therefore, the maximum stress is approximately double the mean stress across the section.

It seems natural to inquire whether the stress distributions produced by holes in nitro-cellulose are obtained in materials used for constructive purposes, and for one of the cases described here it happened that some data for comparison existed which afforded a completely independent test since the measurements on a steel bar with a central hole had been carried out by one of my Japanese students, Y. Satake, who was not at the time aware of the peculiarities which were afterwards observed in transparent specimens.

He had, in fact, undertaken a survey of the stress condition of a steel bar 1.5 inches broad and 0.488 inches thick, by measuring the lateral contractions observed when a load of 2.8 tons was applied to the ends of this tension member. The measurements afforded values of the sum of the principal stresses at various points when the lateral strains were multipled by the value of E, which latter were obtained by direct measurement and were found to have the mean value 98.3×10^{-6}.

His measurements across the central cross section gave the distribution shown in Table II.

TABLE II

Distance from Center of Hole in Inches	Lateral Strain $\div 10^{-6}$ in Inches	$(P+Q)=mE\epsilon_{zz}$ =98.3 Lateral Strain
0.256	232	22,820
0.266	227	22,310
0.320	205	20,150
0.376	179	17,600
0.476	147	14,450
0.576	114	11,210
0.676	105	10,320
0.710	92	9,040

There were no experimental values on a plate of optical material which corresponded exactly to this case, the nearest available being for a $^3/_8$-in. hole in a 1-in. plate. For comparison purposes, therefore, the linear dimensions of this latter were increased in scale to make the holes agree in size, while the stresses were adjusted in the ratio of their equivalent tensions. These values were then plotted for comparison and they are shown on Fig. 9, in which the upper curves show the value of $(P+Q)$ obtained from the elastic theory with the actual stress distribution curves for the steel members immediately below. This latter curve corresponds very closely therewith except at the ends, while the nitro-cellulose specimen gives slightly lower values and in both cases the stress distribution near the parallel contours have a steeper gradient than theory indicates, although they agree fairly well with each other.

An additional check on the accuracy of the measurements was obtained by integrating the normal stress across the minimum section and comparing it with the pull. For this purpose the cross stress was calculated and deducted from the measured $(P+Q)$ curve for steel to give the stress distribution curve marked P on the diagram, and it was then found that the average error of the measurements was 3.5 per cent in excess, a satisfactory agreement having regard to the difficulty of accurately measuring lateral strains in the steel bar, the largest of which was only two or three ten-thousandths of an inch.

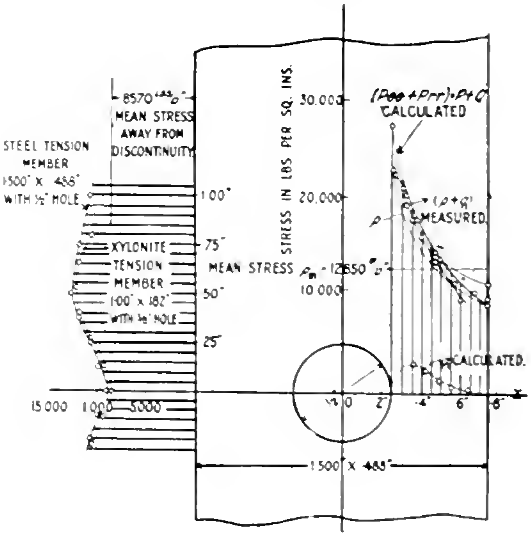


Fig. 9

Additional evidence of the applicability of experiments on nitro-cellulose to steel was afforded by a comparison of the stress distribution along the sides, also shown in Fig. 9, where the agreement was still closer, and would probably have been still more so if the two specimens had been exactly similar. Taken as a whole, this comparison of the stress distribution in two specimens of different materials warrants the conclusion that photo-elastic investigations may be safely used to infer stress distribution in metals within the elastic limits of the material.

This, however, does not complete the evidence, for there are theoretical grounds supporting this conclusion which may be briefly described here.

It has already been shown that the general equations of equilibrium for a plate are expressible in the form

$$\frac{dp_{xx}}{dx}+\frac{dp_{xy}}{dy}=0$$
$$\frac{dp_{xy}}{dx}+\frac{dp_{yy}}{dy}=0 \qquad (1)$$

where the stresses may be taken as mean values throughout the thickness.

If u and v are the average values of the displacements corresponding to a point x,y of the plate the corresponding strains are

$$\epsilon_{xx}=\frac{du}{dx},\quad \epsilon_{yy}=\frac{dv}{dy},\quad \epsilon_{xy}=\frac{du}{dy}+\frac{dv}{dx} \qquad (2)$$

Differentiating the first of the equations (1) with respect to x and the second with respect to y we obtain the stress relation in the form

$$\frac{d^2p_{xx}}{dx^2}=\frac{d^2p_{yy}}{dy^2}=-\frac{d^2p_{xy}}{dxdy} \qquad (3)$$

An identity which is satisfied by a function χ (Airy's Function) if

$$p_{xx}=\frac{d^2\chi}{dy^2},\quad p_{yy}=\frac{d^2\chi}{dx^2},\quad p_{xy}=-\frac{d^2\chi}{dxdy} \qquad (4)$$

In a similar way the strains of equations (2) may be shown to be connected by the relation

$$\frac{d^2\epsilon_{xx}}{dy^2}+\frac{d^2\epsilon_{yy}}{dx^2}-\frac{d^2\epsilon_{xy}}{dxdy}=0 \qquad (5)$$

while the relations between stress and strain are

$$\begin{aligned} mE\epsilon_{xx}&=mp_{xx}-p_{yy}\\ mE\epsilon_{yy}&=mp_{yy}-p_{xx}\\ mE\epsilon_{zz}&=-(p_{xx}+p_{yy})\\ mE\epsilon_{xy}&=2\,(m+1)\,p_{xy}\end{aligned} \qquad (6)$$

If now the stresses in these latter equations be expressed in terms of the function χ by aid of equations (3), (4) and (5), and the values of the strains obtained are substituted in the strain relation (6) we obtain after some reduction the relation

$$\frac{d^4\chi}{dx^4}+\frac{d^4\chi}{dy^4}+2\,\frac{d^4\chi}{dx^2dy^2}=0 \qquad (7)$$

the fundamental equation of plane stress which as will be observed involves no elastic constants. Now since the stresses can all be expressed in terms of χ by equations (4) these latter must also be independent of the elastic constants for any plane stress.

The tacit assumptions underlying this conclusion are the generalized elastic law and a single boundary condition, but Michell has shown that it is still true for bodies with any number of separate boundaries provided the applied forces over each have no resultant. If, however, there is a resultant unbalanced force on a boundary, then elastic constants have to be taken into account and a correction made when applying the results from one material to obtain the stress distribution in another.

This is a subject which offers a very attractive field for further investigation, and until further work is accomplished it is somewhat difficult to form an opinion on the magnitude of the correction to be applied in such cases.

Elliptical Holes and Cracks

The use of elliptical holes in practice is so limited that the stress distribution around discontinuities of this kind would have little interest for engineers if it were not for the information they give on the stress due to cracks. These latter, if straight, may be regarded as cases of an ellipse in which one axis is very small, and it is probable that even if a crack is of irregular shape its ends may still be regarded as limiting cases of an ellipse with a major axis in the directions of these ends.

The stress around elliptical holes in a wide tension member has been examined by Mr. Kimball of the General Electric Company's Research Laboratory, and the writer; Fig. 4B shows the general characteristics of the stress distribution at the boundary of such a hole having a major axis 1.20 inches long perpendicular to the line of pull, and a minor axis 0.8 inches in length in the line of pull. As will be observed, the concentration of stress is very great at the ends of the major axis, and diminishes as the boundary is traversed, and finally becomes a compression with a maximum value at the minor axis. The variation in stress along this boundary in terms of the uniform stress R in the plate away from the hole is shown in Fig. 10, from which it will be observed that the maximum tensional stress is $4R$ and the maximum compression stress is R. These results agree with the theory developed by

Professor Inglis, who has shown for such cases that the maximum stress is $R(1+2a/b)$ where a and b are the principal axes perpendicular to and along the line of pull respectively, and also that this diminishes as the boundary is traversed in the manner shown by the dotted curve of Fig. 10. The agreement between experiment and calculation is in fact very close. In a further case examined with a major axis of 1.25 inches and a minor axis of 0.375 inches, a similar agreement was obtained. The experiments and calculations, therefore, appear to justify us in assuming that when there is an elliptical hole with its minor axis in the line of pull and the minor axis is very small compared with the major axis the tensional stress developed approaches an infinite value according to the law $R(1+2a/b)$. This agrees with observations of the effect of loading a tension member with a very fine slit cut in it across the line of pull as even the smallest load stresses the material beyond its yield point, while the characteristic features of overstress appear and remain after the load is removed. The experiments also show that this intense stress falls off very rapidly as we proceed outwards along the minimum cross section as appears from the measurements, Fig. 11.

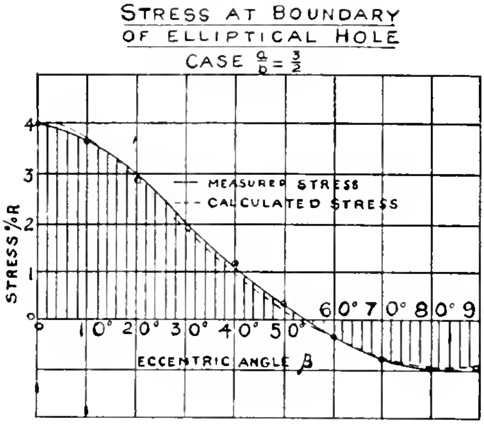


Fig. 10

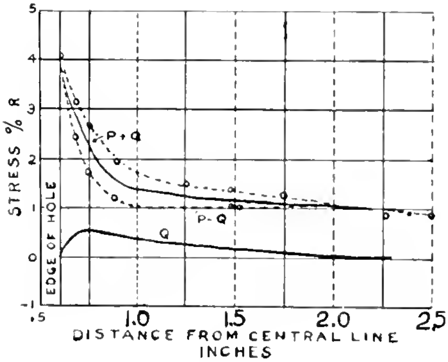


Fig. 11

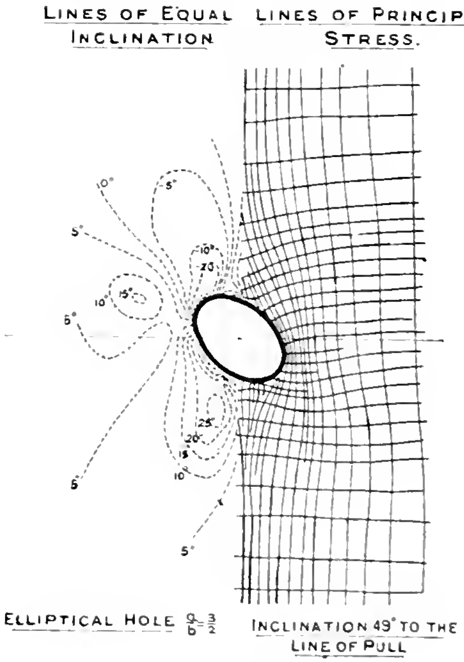


Fig. 12

When an elliptical hole is inclined to the direction of pull the most intense stress is no longer developed at the extremities of the major axis, but at or near a point where a tangent line parallel to the line of pull touches the boundary of the discontinuity. This appears probable from an inspection of the lines of principal stress drawn for a case in which the inclination of the hole is at 49 degrees, Fig. 12, since in this neighborhood the lines of principal stress are most crowded together and when this takes place we find, in general, the most intense stress.

Practical men have long been aware of the extreme concentration of stress produced by cracks and have provided the well known remedy of drilling holes at the ends to stop their extension. This has the effect of reducing the local stress at the end of the crack from a very large but indefinite value to only a few times the average stress in the material; but it seemed possible that this method might sometimes be varied with advantage having regard to the lower stress which is usually found at the minor axis of an elliptical hole. This view is confirmed by some experiments on slits in a wide plate with variously shaped ends. The slits examined are shown grouped together in Fig. 13 and the primary form is a slit half an inch long cut by a drill of $\frac{1}{32}$ inch diameter, the ends being left untouched. When an average stress of 790 lbs. per square inch was applied the stress at the extreme edge of this slit rose to 2900 lbs. per square inch, but fell to 2258 lbs. when the ends were drilled out by a $\frac{1}{8}$-inch drill (Case B). A further reduction took place when this hole was enlarged by drilling two holes tangentially to the center line of the slit (Case C) and the maximum stress again fell to 1670 lbs. at points on the rounded contours. A slight increase to 1700 lbs. per square inch, however, took place when this contour was shaped to an approximately elliptical form (Form D). There seems little to choose between these last two forms, since the last stress was only 30 lbs. more per square inch than for Form C. The distribution of stress for the first case is shown in the colored photograph, Fig. 4C, and as will be observed, it is extremely concentrated around the semicircular end, but when this latter was enlarged by a drill, Fig. 4D, the distribution shows the characteristic features we have already observed with the cases already considered and on further enlargement to an elliptical form as the stress concentration became still less, as Fig. 4E indicates. The experiments, therefore, show that in drilling out the ends of cracks it is an advantage to form the ends with elongated holes of an approximately elliptical form, with the part of greatest radius parallel to the line of greatest stress.

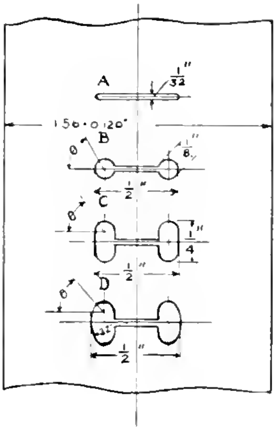


Fig. 13

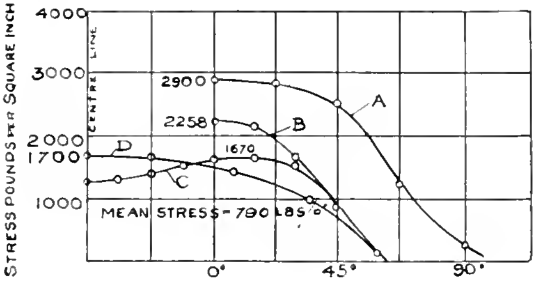


Fig. 14

(To be Continued)

Waste and What It Means in Industry

A far Eastern missionary, on returning to his native land, once remarked that "a Chinaman could live a day on what the average American wastes at a single meal." To the foreigner the American is always an extremist. He admires our ingenuity, our resourcefulness, our productiveness, and our "pep," which is but a synonym for a New World brand of enthusiasm, but he is astonished at our inexcusable extravagance, our shameful waste of foodstuffs, raw materials, and the various by-products of certain commodities.

With all our so-called efficiency experts, we are still a very wasteful nation, and though the lesson of the war, with all its vicissitudes, may have had some beneficial results, the net gain in our favor is negligible. Through the favor of the fates, America has yet to know the actual meaning of the words poverty, hunger and misery, but we must correct and curb this great national shortcoming or pay the penalty at some future date. A policy of national extravagance is not consistent with national prosperity, and the candle burning at both ends soon sears the fingers—sooner sometimes than we might expect.

Let us consider the average employee in the average American industry.

It must be admitted that the success of an industry is just as dependent upon the efficiency and ability of employees as it is upon the directing reins of the management. Brilliant minds might design wonderful ships, but they cannot float off the blue prints into the water; it takes efficient heads and muscles to put together the plates and steel beams that make a seaworthy vessel.

So much for the ability of the American artisans; their calibre is conceded, but how about their honesty to their employer from a standpoint of extravagance in the use of loaned tools, materials, and overhead maintenance? Economy is the first step toward efficiency, and industrial efficiency is the longest and most important step toward national prosperity.

Is the American workman as considerate of the property of the man or company as he would be of the articles were they his own? Hardly. He may not be maliciously destructful or wasteful, but he is often careless and thoughtless. To be a little more explicit, we will consider the average shop. How many times a day is an electric light left burning needlessly? How many hundreds of bulbs are broken in a week by rough handling. How many times is the power turned on without producing anything, with belt or gears speeding in vain? Nature squanders immense quantities of power in each electric storm, but man cannot help that. But he can turn a switch or press a button when light or power is wasting in the shop.

How many thousands of dollars worth of new material is wasted yearly in the average shop or mill through careless handling? It is safe to say that this item alone mounts to the equal of a Liberty Bond issue. It is natural that there should be a certain amount of shrinkage. No concern can hope to consistently operate with a perfect percentage. It is quite proper that production inspectors should be needed to keep the quality of the product at the highest possible standard. But there is plenty of room for improvement in the actuating motive of the employee toward the property and product of the employer. A better spirit of fairness is needed; a feeling of "do unto others as you would have them do unto you" is needed imperatively.

In many respects America is the most progressive country on earth, but we must curb our extravagant methods, or look to our industrial and commercial laurels. Envious eyes from across the seas are watching every opportunity, and you can rest assured that it is only the negligible minimum that goes to waste in those lands where necessity has always taught the lesson of thrift and economy. Play fair with your employer as you expect him to play fair with you, and take the same reasonable care of his property as you would with your own. Thrift is the right way to save, but the "elimination of waste" is his left-handed brother. —*Speed-Up.*

One Hundred Years Since Oersted, Ampère and Arago*

By Dr. Elihu Thomson
General Electric Company, Lynn, Mass.

This account of the epoch-making discoveries in electricity and magnetism by the pioneers, Oersted, Ampère and Arago holds much additional interest from the fact that it is presented by a man who himself has won world renown by his discoveries and inventions in the same branch of science. The work of these pioneers, including Faraday, forms the real foundation of the huge, diversified electrical industry of today.—Editor.

Preamble

It is fitting that in Philadelphia we should celebrate the centenary of the great discoveries in electromagnetism. It was here that Franklin's investigations in electricity were made, culminating in the kite experiment. It was here that he and a few confréres founded the American Philosophical Society, which became a national institution for the spread of that spirit of science and philosophy characteristic of Franklin. It was here not many years ago that under its auspices a very notable commemoration of the centenary of Franklin's work was held. Not far from here in Princeton the pioneer work of Henry in electromagnetism, induction of currents, and oscillations was done nearly a century ago. Not far to the south from here the first Morse telegraph line was established in 1844. In Philadelphia, Robert Hare in the early years of last century did his work with voltaic batteries. Here Bell first exhibited his speaking telephone at the Centennial Exhibition of 1876, calling such witnesses as Sir William Thomson (Lord Kelvin) to hear it speak. Not far from here, in the Laboratory of Edison in Menlo Park, the incandescent lamp was born in 1879. Here again in commemoration of Franklin was established the Franklin Institute, the influence of which has been so marked a factor in science and the mechanic arts everywhere. Under its auspices the first investigation of the electrical properties of the dynamo was made in 1877, and the first Electrical Exhibition held in America in 1884, the Paris Exposition of 1881 being the only forerunner. It is a pleasure to note at this time the possibility of great and increasing lustre to its future in the electrical field has come by a large bequest from one whom the present writer knew well in his old Philadelphia days, Mr. Henry Bartol. I am reminded of the fact that the first meeting of the American Institute of Electrical Engineers was held in Philadelphia. And now, to relate very briefly more intimate but infinitely less important matters, may the writer modestly add that here over fifty-five years ago he built his first electrical machine, voltaic piles, batteries, electromagnets and telegraph, acquiring through them in his early years an insight of the science of electricity as it then existed. It was here that he taught science for ten years in the old Central High School at Broad and Green streets and that during this period in 1875 there was made, incidentally, the first wireless transmission, using induction coil, spark gap, ground and radiating conductor, briefly described in the Franklin Institute Journal of the time, and recently related more in detail by Professor M. B. Snyder, of the school. It was here in Philadelphia that the writer did his first electrical engineering, and definitely chose that professional career which has kept him alive and busy ever since.

There are times when an epoch-making discovery gives rise to a new science or art, or opens up new fields for experimental research. When this has occurred before our time we can at best visualize the antecedent conditions imperfectly. The background of such a discovery as was made in 1819, by Hans Christian Oersted, of Copenhagen, and announced in July, 1820, is scarcely reproducible now. We shall not attempt it. Simple as was the experiment of Oersted, the fundamental character of his results was instantly recognized by his contemporary leaders in science, such as Ampère, Arago and Davy, and served to stimulate them to an intensity of research work which at once brought wonderful additions to human knowledge.

Oersted

Oersted, a Dane, born in 1777, was educated at the University of Copenhagen, and in 1806 occupied the chair of physics there. Though he had already done important work,

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* An address before a meeting of the A. I. E. E., Philadelphia, October 8, 1920.

he was immortalized by his being the first to discover and investigate the effects of a current in a conductor upon a magnetized needle. It was, or at least it may now seem to us, a most simple discovery, the outcome of experiment of equal simplicity. Nevertheless, subsequent events soon proved it to be the foundation stone upon which now rests the great science of electromagnetism. Oersted found that a wire conveying the currents of a voltaic battery, and called by him a "conjunctive wire," affected a freely pivoted magnetic needle in such a manner that the needle tended to set itself at right angles to the wire. The deflection was shown to be definite as to direction, depending on the direction of the current in the wire, the position of the poles of the needle and the relation of positions of the wire and needle. It was recognized, also, that if the magnet was fixed in position and the conjunctive wire free to move, corresponding movements of the wire would take place. This discovery was given out in a brief work in Latin, the title of which was in substance, "Experiments Concerning the Effect of Electric Conflict on the Magnetic Needle."

Oersted had apparently convinced himself long before of there being a necessary connection between electricity and magnetism and had held perhaps more pertinaciously than others to this view. In recognition of the great scientific value of his discovery the prize of the French Institute was awarded to him. This had already been given to Davy for his electro-chemical discoveries, such as that of the separation of the alkali metals, sodium and potassium, from their compounds. Oersted also received the Copley medal of the Royal Society of London and was honored by the distinction of Knighthood. Dying in 1851 at seventy-four, he had lived to see great progress in electromagnetism and to witness some of its early applications, such as the telegraph, to the needs of mankind.

The following translation of Oersted's description appears in Barlow's "Magnetic Attractions," a book published in 1824. After assuming current passing in the conjunctive wire—

"Let the straight part of this wire be placed horizontally above the magnetic needle properly suspended and parallel to it. If necessary, the uniting wire is bent so as to assume a proper position for the experiment. Things being in this state the needle will be moved, and the end of it next the negative side of the battery will go westward.

"If the distance of the uniting wire does not exceed three quarters of an inch from the needle the declination of the needle makes an angle of 45 deg. If the distance is increased the angle diminishes proportionally. The declination likewise varies with the power of the battery.

"The uniting wire may change its place, either towards the east or west, provided it continues parallel to the needle, without any other change of the effect than in respect to its quantity. Hence the effect cannot be ascribed to attraction; for the same pole of the magnetic needle which approaches the uniting wire, while placed on its east side, ought to recede from it when placed on the west side, if these declinations depended on attractions and repulsions. The uniting conductor may consist of several wires or metallic ribbons connected together. The nature of the metal does not alter the effect, but merely the quantity. Wires of platinum, gold, silver, brass, iron, ribbons of lead, and tin, and a mass of mercury were employed with equal success. The conductor does not lose its effect, though interrupted by water, unless the interruption amounts to several inches in length.

"The effect of the uniting wire passes to the needle through glass, metals, wood, resin, stoneware, stones, for it is not taken away by interposing plates of glass, metal or wood. Even glass, metal and wood interposed at once do not destroy, and indeed scarcely diminish, the effect. The disc of the electrophorus, plates of porphyry, a stoneware vessel even filled with water were interposed with the same result. We found the effects unchanged when the needle was included in a brass box filled with water. It is needless to observe that the transmission of effects through all these matters has never before been observed in electricity and galvanism. If the uniting wire be placed under the magnetic needle, all the effects are the same as when it is above the needle, only they are in opposite directions; for the pole of the magnetic needle next to the battery declines to the east.

"That these facts may be more easily retained, we may use this formula: the pole above which the negative electricity enters is turned to the west; under which to the east.

"If the uniting wire be so turned in a horizontal plane as to form a gradually increasing angle with the magnetic meridian, the declination of the needle increases, if the motion of the wire be toward the place of the disturbed needle; but it diminishes if the wire moves further from that place.

"When the uniting wire is situated in the same horizontal plane in which the needle moves, and parallel to it, no declination is produced either to the east or to the west; but an inclination takes place, so that the pole next which the negative electricity enters the wire is depressed when the wire is situated on the west side, and elevated when situated on the east side.

"If the uniting wire be placed perpendicularly to the plane of the magnetic meridian, whether above or below it, the needle remains at rest, unless it be very near the pole; in that case the pole is elevated when the entrance is from the west side of the wire and depressed when from the east side.

"When the uniting wire is placed perpendicularly opposite to the pole of the magnetic needle and the upper extremity of the wire receives the negative electricity, the pole is moved toward the east; but when the wire is opposite to a point between the pole and the middle of the needle the pole is moved towards the west. When the upper end of the wire receives positive electricity the phenomena are reversed.

"If the uniting wire be bent so as to form two legs parallel to each other, it repels or attracts the magnetic poles according to the different conditions of the case. Suppose the wire placed opposite to either pole of the needle, so that the plane of the parallel legs is perpendicular to the magnetic meridian, and let the eastern leg be united with the negative end, the western leg with the positive end of the battery, and in that case the nearest pole will be repelled either to the east or west, according to the position of the plane of the leg. The eastmost leg being united with the positive and westwards with the negative side of the battery, the nearest pole will be attracted. When the plane of the legs is placed perpendicular to the place between the pole and the middle of the needle, the same effects occur, but reversed.

"A brass needle suspended, like a magnetic needle, is not moved by the effect of the uniting wire. Needles of glass and of gumlac remain likewise quiescent."

On first thought it may seem singular that as many as twenty years elapsed after the Galvani and Volta discoveries before such a simple experiment as that of Oersted was tried. The only hint or suggestion of prior observation appears in the statement that about 1802 Romagnasi of Trent (a town in the Austrian Tyrol) had noticed an effect on a compass needle in the neighborhood of a voltaic pile. Evidently, however, the observation made was very imperfect, as it led to no consistent recorded result. In this connection we must consider that the early years of the last century were disturbed by wars stirring the whole of Europe and further that the available voltaic currents must have been relatively weak owing to the small area of battery plates used with a high resistance electrolyte. Strong acid could not be availed of as the zinc elements were not amalgamated, a procedure which was later almost universal. Again, the negative element was usually copper, giving against zinc a low voltage and subject to rapid polarization. There was, therefore, in the years before Oersted, little probability of large currents being available, such as would be needed when a single wire was used for the deflecting agency. This was, of course, before the principle of coiling the conductor to increase its effect was known. Dr. Robert Hare, the inventor of the oxyhydrogen or compound blowpipe, apparently, in 1816 first appreciated the need of increasing the surface of the zinc and copper to obtain, as it was afterward called, "large quantity." The blowpipe in his hands had become the source of heat of highest temperature known to man, and the known heating effects of electric currents naturally led Hare to investigate means of intensifying them. He produced two forms of apparatus which were known as the Hare calorimotor and the Hare deflagrator. In the prior "trough" battery the plates were small, rarely more than four inches square, with only one side active. Hare rolled his zinc and copper sheets into interlaced spirals, spaced apart by wooden separators, so that not only large plates could be used, but both sides of the plates were active. Another form giving a similar result was embodied in the "deflagrator" which was used to deflagrate strips of thin metal in the same manner as the blowing of a modern safety fuse.

In early youth it was the privilege of the writer to see examples of the apparatus of Hare which were preserved at the University of Pennsylvania, then located in Philadelphia, on the west side of Ninth St., between Chestnut and Market streets. Hare had been Professor of Chemistry there during the early years of the past century. The Hare apparatus is mentioned here because of a passage occurring in a work on Heat and Electricity, printed in 1830. Its author, Thomas Thomson, M.D., was very eminent in the science of his time. The passage reads as follows: "The apparatus employed by Oersted, and of the efficacy of which he speaks in high terms, approached very nearly to this last one of Hare." This passage occurs just following a description of the "deflagrator." The statement seems to imply that Oersted early appreciated the value in a voltaic battery of large active surface, or as we should now say "low internal resistance." May it not be that this condition was the secret of his experimental success? Even in Franklin's time it had been observed that electric discharges had some obscure action on the magnetic needle, for sometimes compasses were demagnetized wholly or in part, or even reversed when in proximity to a lightning stroke. Beccaria, the Italian contemporary of Franklin, tried many experiments with magnetized needles and heavy Leyden jar condenser discharges sent through them, but did not succeed in establishing any magnetic effect as due to the discharge. Such effects as he did obtain are readily interpretable at this time as the natural result of a vigorous shaking up, mechanical, or thermal, while the needle was in a magnetic field, such for example as that of the earth. Subsequently to Oersted's discovery, however, condenser discharges sent through a helix or spiral surrounding the needle were found to produce decided magnetic effects thereon.

Ampere

The news of Oersted's discovery reached Paris, as it appears, through Arago, on Sept. 11, 1820, who had witnessed the experiments in Geneva, and on September 18, Andre Marie Ampère presented a paper to the Paris Academy of Sciences, remarkable for its originality and for the variety and accuracy of the experimental results recorded. In it he dealt with the interactions and repulsions of wires conveying currents and the magnetic effects of helices of wire, showing these latter to be possessed of magnetic poles.

The fact that Ampère's paper appeared only a week after Oersted's discovery had become known to him gives to it the unique place in the history of science. It was the production of a mind of the first order working at high pressure. Ampère was born at Lyons in 1775. As a child his precocity was most unusual. His tendency was toward mathematics, though his reading during youth brought to him a wide range of information on many branches of knowledge. The death of his father on the scaffold as a victim of political conditions almost wrecked his young life. Owing later to fortunate environment at a critical time, he gradually recovered, and in 1809, at thirty-four, was made Professor of Analysis at the Paris Polytechnic. The Oersted announcement evidently stirred him deeply and he went immediately to work with wonderful zeal and sagacity, to unravel the mysterious relationship between magnetism and currents, suggested only in part by Oersted's experiment. In his hands the fundamental character of these relationships became plain, and their future possibilities clear. It is recorded that he even suggested at the time the plan of a telegraph of simple form.

As a side light, it appears that Ampère's discovery of the fact that parallel currents in the same direction in wires cause attraction, and when in the opposite direction repulsion, seems to have puzzled some of the philosophers of the time, for it was known of course that similar electricities repel and dissimilar attract. Why should not, therefore, similar currents repel and unlike attract, when in fact the exact opposite was the case? Ingenious, though altogether fallacious, was an explanation first put forward and credited to Oersted. He was apparently driven to imagining that the current in wires did not go straight along the axis, but was conducted in a helical course in them always the same for the same direction of current. This was a pure invention without facts to support it. But upon it he founded a theory of attraction and repulsion of parallel wires involving attraction of unlike and repulsion of like electricities. In reality this theory bore with it its own refutation, as a few test experiments might easily have shown.

In relation to this fanciful theory I find in the old book, before referred to as published in 1830, the following: "This way of accounting for the phenomena of electro-magnetism was first employed by Oersted. It was afterwards used by others, particularly by Dr. Wollaston and M. Ampère, with much felicity." The writer does not vouch for the correctness of these statements. As soon, however, as the effects of currents in establishing magnetic circuits around them was worked out, the true cause of the attractions and repulsions of parallel wires became clear, and the fanciful notion of spiral courses for currents inside a conductor was abandoned. Such a notion has of course no relation to the later theory of Ampère for accounting for magnetism in iron or permanent magnets, in which he assumes each magnetic element to consist of a closed circuit with a current always circulating therein, a theory which to this day has not been displaced, but rather refined and strengthened by its further extension by Ewing and by the electron theory. It was in fact Ampère who referred all magnetism to electricity or electric currents, now interpreted as movement of electrons. The need of Ampère's clarification is perhaps made more evident from the following quotation, if it be a fact: "Oersted originally believed that the negative electricity propelled the north pole of the magnet, but had no effect on the south; while positive electricity propelled the south and had no effect on the north pole." The writer has not verified this statement as expressing the original ideas of Oersted, but if they at any time represented his view they must soon have been dispelled. They would be perhaps a sort of survival of older notions, at least in part, since before the "conjunctive wire" was used fruitless efforts had been made to connect magnetism and electricity while using batteries on open circuit.

Ampère formulated a simple rule known as Ampère's rule, for determining the direction of deflection of a magnet or the direction of development of magnetism by a wire conveying current. It may be stated (bearing in mind that the direction, we assume, positive to negative, is merely a convention) about as follows: Conceive one's self lying or swimming in the current in such a way that the current enters by the feet and leaves by the head as we face the needle. Then the action will be that the north pole of the needle will turn to one's left. The writer must confess that when he first learned this rule it seemed rather clumsy to him, and he was sometimes treated to the ludicrous spectacle of an obese professor trying to twist himself with respect to an immovable wire circuit into curious attitudes so as to lie or swim in the current, and so note the direction of magnetism produced.

Other ways of remembering the relation given by Ampère's rule have been devised, but perhaps none excel in ease and simplicity of application a simple gesture of the hand which has been used by the writer for about fifty years. The hand is held out with the index finger pointed away. If the hand be now given a swing or turn in righthanded direction, still keeping the forefinger directed as at first, such swing, turn, or rotation representing direction of current in a circuit, the north magnetic pole will be directed away as the forefinger points. Reversing the gesture, turning or swinging the hand counter-clockwise makes the north pole take direction toward the wrist or forearm, or what is the same thing the extended forefinger represents the direction of south polarity. As the swing or slight rotation given the hand from the wrist and elbow represents all directions of current, above, below, and to the right or left of the magnetic axle considered, it is easy to select any element of current course matching actual conditions. Moreover, the same gesture (for it is a gesture, not a rule) applies equally to the relations of magnetic field developed around the course of a current, for if current passes in a wire in the direction of the point of the index finger, the magnetic circuit around it will have north polarity directed righthandedly, and lefthandedly or counter-clockwise if the current has opposite direction, as from the tip of the index finger inward toward the wrist. In any case it is only necessary to make the proper gesture, which requires no especial mental effort. This soon becomes a matter of habit, a mistake being practically impossible.

Arago

According to De la Rive, "Traite D'Eléctricité," Vol. 1, it was Arago who was first to show that a wire of copper or other metal acquired, when traversed by a strong current, the property of attracting and retaining around it, under the form of a cylindrical envelope, a quantity of iron filings, the filings falling off immediately when the current ceased to flow, and being reattracted on the restoration of the current. This experiment, prior to all those of Ampère, is the first which established in a striking manner that electric current impresses on conductors when it is transmitted by them properties fully analogous to those of magnets, and not alone to magnetic bodies; in other terms, that it magnetizes them and does not simply render them susceptible of being magnetized. In fact, the iron filings are magnetized by the current as they would be by a magnet, and are in consequence attracted by the wire which transmits the current. This statement is substantially that of the account given by De la Rive, translated. Ampère and Davy are credited with having made the same observation, but if De la Rive is right, it was first made by Arago.

Here then was the first exemplification of the phenomenon of temporary magnetism in iron, so fundamental to the unlimited variety of electromagnets and mechanisms founded thereon; the basic principle of the Morse telegraph and most other signalling or electric recording systems and essential to the greater machinery of electrical engineering, developed for the most part in the latter half of the past century.

Arago went farther and made his conducting wire into a spiral, and then succeeded in magnetizing steel needles placed in the axis thereof. In his pioneer experiments the spiral was wound open around a glass tube as a support, the wire itself being presumably bare.

In Silliman's "Principles of Physics," a well known and much used textbook from its first edition in 1858, and for perhaps thirty years thereafter, in describing the above experiment there is the following statement: "If the helix is wound on a tube of glass, paper or wood, these substances offer no resistance to the passage of the power; but if a tube of copper or other metal were employed, the magnetizing power of the current on the enclosed bar would be destroyed." Such a statement means either that the metal tube short circuited the bare wire of the helix or that currents of extremely brief duration, such as condenser discharges, were concerned. It was indeed soon found that even "if common electricity be made to pass along the spiral conducting wire, the needle is equally converted into a magnet." Common electricity was evidently the frictional or static electricity thus distinguished from the newer or less common voltaic current, later called dynamic electricity. The principle of coiling or increasing the turns in the original rectangular circuits of Oersted and Ampère was soon appreciated, even for the deflection of needles, a hank of insulated wire wound around the hand, or upon a rectangular block of wood and tied by string to preserve its form was used to surround the needle; the prototype of the taped coil of today. It seems to have taken some time to develop the coil consisting of a spool or bobbin wound closely with insulated wire. Schweigger used the rectangular coil of many turns on his "Electric multiplier" the term "multiplier" being extant for at least fifty years as applied to galvanometers with such coils.

The floating battery of De la Rive with its conjunctive wire, or spiral connecting the poles, was an exceedingly neat arrangement for showing the neutral action of currents and magnets, or the effects of wires conveying currents on others more or less parallel thereto. It seems to have been a very early modification of Ampère's apparatus. It avoided the problem of pivots conveying current, mercury cups being usually employed.

Arago's famous disc experiment, involving the discovery that a moving conducting disk of non-magnetic metal, such as copper, possessed an effect in the nature of a drag on a poised magnetic needle near it, was made about 1824. It was found also that if the needle was spun around over a conducting disc or plate, it was rapidly slowed or damped. These experiments were carried on using a great variety of materials, and wide variations in the magnitude of the effects were observed. Precautions were taken to eliminate any effects due to air currents. It was found that discs of the best conducting metal, such as copper, were the most effective. Here we have, then, the prototype of dampers in magnetic fields. Curious hypotheses were advanced to account for the effects, such as the assumption of special forms of magnetism generated by revolution. In reality, had the secret of the action of the Arago disc been found, the generation of currents in a conductor moving in a magnetic field would have been discovered, and Faraday's discovery of that great principle in 1831 would have been anticipated by a number of years.

The full name of Arago was Francois Jean Dominique Arago, and he was a scientist of varied activities. There is no space here to refer to his career, except in the briefest possible way. Born in 1786 at Estagel, near Perpignan, France, he displayed in his early years great aptitude for learning, and at eighteen became secretary to the Observatory of Paris, which brought him into contact with the famous La Place, and he was "collaborateur" with Biot. He served in the determination of the meter as the unit of length, in measuring the ten-millionth of a quadrant of the earth's meridian. This task, involving travel into lands in turmoil, brought great dangers, imprisonment, escape in disguise, capture by the Spanish and prison again. Even after release he remained a long time in quarantine, on account of disease conditions. Given the post of astronomer in the Royal Observatory in Paris by Napoleon, in 1816, he started the famous journal "Annales de Physique et de Chimie." As secretary of the Paris Academy of Science, and Chief of Deputies, his life was a very full one, and its responsibilities not light. He was associated with Fresnel in giving form to the undulatory theory of light, proposing to test the theory by studying retardation in refractive media. In fact his work on polarization of light, invention of the polariscope, and other researches rank scarcely less highly than his work in electro-magnetism, with which we are here chiefly concerned.

Subsequent Discoveries and Application

The later discoveries by Faraday and his brilliant work on electromagnetic rotations, especially his discovery in 1831 of induction of currents by magnetism, refined the early theories and added greatly to the development of electromagnetic science. Somewhat crude as the earlier ideas were, the clarification given them by Faraday, Maxwell, Kelvin and many others had the most profound effect on its future. As a direct outcome of Oersted's observations, mention may be made of the discovery in 1823 by Seebeck of thermoelectric currents in a closed circuit. He used a rectangle in a vertical plane surrounding a pivoted magnetic needle. The base of this closed circuit so arranged was a bar of antimony, while the ends and upper side were of copper. By heating one of the junctions of the antimony bar with the copper, deflection of the needle showed the presence of magnetism in the closed loop around the needle. This was followed by examination of the effects of junctions of different metals and conductors heated to various temperatures, and led to the well known table of thermo electric powers. The Melloni Thermo-pile, so delicate as a heat detector, was the outcome, used by him in his beautiful researches on Diathermany.

Having in the foregoing traced briefly the work of the pioneers in laying the foundation of the science a century ago, it is perhaps unnecessary to remind electricians and engineers of the great scientific advances and the important applications which soon followed. Some of them became familiar studies of the electrical student fifty years ago. This progress has continued and apparently at an increasing rate ever since.

To the consciousness of the writer the period of a hundred years seems continually to dwindle. He is reminded of the fact that his own life's span has covered more than two thirds of a century. Looked at in this way, the Oersted, Ampère and Arago experiments do not seem to have been made, after all, so very long ago. Outside of the forms of electromagnetic telegraph, the years following 1820 saw but few other applications of importance, but there were many examples of electromagnetic apparatus used for instruction in schools. The little book now rare, entitled "Davis' Manual of Magnetism" was and is interesting as a catalogue, with brief descriptions of such apparatus, some of which is doubtless still extant in the older collections. The first edition was published in Boston, in 1842, and the author, Daniel Davis, Jr., called himself "Magnetical Instrument Maker."

How many, or rather how few of us are left of those who as boys experimented with the sulphate of copper battery as their source of current, with flat spirals such as Henry used, or with such apparatus as Oersted, Ampère and Arago used. We find there Henry's electromagnet, De la Rive's floating battery, Faraday's revolving circuits and magnets, Barlow's spur wheel, Page's revolving ring, his revolving magnet and revolving multiplier, and other examples of the simplest types of electric motors with commutator and brushes called "pole changers" and even apparatus with both commutator, revolving brushes, and slip rings, so that both elements of the motor might revolve oppositely. There were bell engines, and reciprocating engines, elementary motors driven by thermoelectric currents, or by batteries revolving, all involving the simple principles of interaction of circuits and magnets permanent or temporary. These and other simple forms of apparatus, besides the so-called devices for static electricity, were the things electrical with which the youngster with an electrical bent became familiar either in his reading, or better, by the fascination of experiment with them. Such equipment characterized the infant years of the science now grown to a giant, with no limit to future growth.

It was natural that the first great practical application of electromagnetic principles should be found in the telegraph.

Attempts had been made as early as 1774 to telegraph by the electricity of frictional machines, which even as late as 1850 was called "machine electricity" or "common electricity from machines." Even in 1816, Ronalds in England was attempting to signal through long circuits by Leyden Jar discharges. After the discovery of the voltaic pile in 1800 there was a better prospect of success, and Sömmering in 1808 proposed a system of 35 wires at the ends of which were gold strips in water, upon which strips gas appeared on the passage of current, which appearance constituted the signal received. There was a wire so arranged for each letter or character transmitted. It was Ampère who, just after Oersted's discovery, proposed to substitute in Sömmering's system deflected needles for the voltameter receivers. Then followed Schilling in Russia, in 1832; Gauss and Weber at Gottingen, in 1833; and finally Cooke and Wheatstone in England, and Steinheil in Munich, in 1837, to whom perhaps more than to any others the development of the needle telegraph for practical work was really due.

The Morse type of telegraph was early distinguished as the electromagnetic telegraph, or one based on the use of electromagnets. Barlow in England seems to have made an early suggestion of the kind, but it was not until 1830, upon the construction of the first powerful electromagnets by Joseph Henry, of Princeton, New Jersey, that such a form became possible. In his first paper on the results of his experiments, Henry proposes to apply them to the telegraph. Samuel F. B. Morse conceived of such a telegraph in 1832, and with the assistance of Vail worked it out practically and publicly exhibited the Morse system working over a circuit of a third of a mile in 1837, but after that it was nearly seven long years before Congress for consideration, when at last a modest grant was made to establish the famous Baltimore-Washington line first put into operation in 1844.

In the subsequent numerous developments of systems of signalling, from the simple call bell to the fire alarm and printing telegraph, the electromagnet holds undisputed sway. In annunciators of many types it is found, as often in relays, in telephone receivers and the like, with polarized cores. It is as indispensable in wireless transmission as in transmission by wires. The extreme sensibility of the telephone receiver, coupled with the wonderful delicacy of the ear, make it most effective for the detection of minute electrical disturbances. With modern thermionic amplifiers the possible extension in range of telephonic transmission by wireless waves seems to be without limit.

It is not necessary here to allude to the great developments in the field of electricity and electromagnetism as exemplified in generation and transmission of electrical energy. They have covered the past half century, but the foundation principles belong to those early years of upward of a century ago. Do we cause movement of iron masses by a current coil? It is the experiment of Oersted. Do we cause movement of coils, one with relation to another, as in our motors? It is the experiment of Ampère. Do we generate currents in a conducting mass in a magnetic field? It is the experiment of the Arago disc. When we measure current or energy by galvanometer, voltmeter, electro-dynamometer, or wattmeter we have the work of Oersted, Ampère, Arago, illustrated. But these early discoveries had a depeer significance still. They showed that electric currents and magnetism are inseparable—inseparable in practice, inseparable in theory.

Moving charges are, as shown by Rowland, the equivalent of currents; and now we are assured that moving charges and currents are moving electrons. Hence moving electrons are magnetic. Like charges or electrons repel each other, but like charges moving in the same general direction attract, for they are the equivalent of parallel currents in the same direction. They repel one another electrostatically and attract one another magnetically. Conversely, oppositely moving charges or electrons should repel, but still not attract, but continue to repel electrostatically. We are now certainly down to the fundamentals. No vacuum, however perfect, lessens or stops the development of the electric field in it, nor prevents the existence of the magnetic field. Space itself is electromagnetic, using the term in its broadest sense. Like electrons moving in the same direction in such space must attract one another and at some speed the static repulsion of the like charges will be balanced by this attraction. The higher the speed, the closer is the approach, until the repulsion balances the attraction. And just here is the key phenomenon of nature. Space, whether empty or full of ether, is fundamentally electromagnetic and perhaps only that. Energy and mass, interchangeable terms and due to relative movements of electrons, is electromagnetic and only that. Matter in all its forms, systems of electrons in motion, is electromagnetic. Alive or dead it is electromagnetic and nothing else. All properties of matter, all forms of energy are electromagnetic and electrostatic. If ether exists it is purely and solely electric and magnetic, without mechanical properites, for such properties depend on motion of electrons. Ether as a medium, then, not being mechanical, can neither be in rest nor in motion; it can only be the theater of electrostatic and magnetic conditions, whatever they may be.

These statements may be very sweeping, but do not the recent notions of the relativity of Einstein carry us even farther? Space is empty, but has a warp in it; it is curved, of four dimensions, (one being time), in which the gravitational field of the sun, or for that matter even the smallest speck of matter or energy, is a local warping. Are electric and magnetic fields but other kinds of warping in this space which though empty is full of electric, magnetic and gravitational fields? Whatever all this may mean, we must remember that scientific theories can never change the facts; they are not creeds, they are means of pointing the way to further additions to our knowledge—to be modified, changed or abandoned according to their usefulness in leading to further knowledge or discovery. The facts of science are its bed rock foundation, unchanged and unchanging. The discovery, then, of the relation between electricity and magnetism was in reality the discovery of a fundamental fact or principle lying at the foundation of the Universe itself, the soul of energy, as of matter; of electric waves from zero periodicity up to the most penetrating rays of the raduim emanations. It is eminently fitting, then, that we celebrate the hundredth anniversary of discoveries, the fruits of which have been of stupendous influence and value, and at the same time carry us to the very foundations of existence.

The coming century will doubtless have its wonders to unfold, but it is fairly safe to predict that they can hardly exceed in fundamental bearing those revealed to us in the past hundred years.

Dr. Elihu Thomson

SCIENTIST, INVENTOR, AND EDUCATOR

By Dugald C. Jackson

Dr. Thomson has been acting president of Massachusetts Institute of Technology since early spring of this year, and the following sketch of his career by a member of the faculty will be read with interest by the many admirers of our eminent scientist.—Editor.

Professor Elihu Thomson: If you speak that name in electrical engineering circles, in any part of the world, it at once brings a word of recognition, for Thomson is one of the fathers of electrical engineering as well as a notable leader and master. Though born in England, Professor Thomson came to the United States with his parents when he was five years old and grew up and was educated in Philadelphia. There he graduated from the Central High School with the degree of A. B. at the age of seventeen, and was immediately appointed Assistant Professor of Chemistry in the same school. Six years later he was made Professor of Chemistry and Mechanics. Here he began his researches in electricity and started on his career as an inventor. Fame has been added to the United States and his name spread in technical and scientific circles for the great range and importance of his achievements in electrical engineering.

Interest in electrical phenomena held him for years before his graduation from the Central High School, but it was during his professorship that he started on his revolutionary series of researches and inventions. Here he invented and constructed the famous arc light dynamo with spherical three-coil armature, which went into commercial use in 1880 and continued a central figure in arc lighting service as long as the arc lamp with carbon electrodes held the field of illumination by large lighting units. Here also he made the researches and discoveries which gave the foundation of his later primary inventions in electrical welding. In 1880 Professor Thomson resigned his post in the Central High School and moved to New Britain, Conn., to become the technical head of a company called the American Electric Company which was established on the foundation of his inventions. Three years later this company was reorganized on a larger scale, moved to Lynn, Mass., and was renamed the Thomson-Houston Electric Company. For many years the company occupied what are now called the West Lynn Works, which were gradually increased in size and importance as the variety and extent of the business grew. After the Thomson-Houston Company became associated with the Edison General Electric Company to make the great company known as the General Electric Company, the River Works were built at Lynn, but the West Lynn Works continue to produce many of the important products which the genius of Professor Thomson has conferred on electrical engineering.

To list all of his inventions would be beyond the scope of this article, for more than six hundred patents have been issued to him by the United States. His inventions in dynamo electric machinery, electric welding, electric watt-hour meters, lightning arresters and magnetic arc extinguishers are fundamental. The arc lamp, the incandescent lamp, the electric motor, the alternator, the alternating current transformer, railway motors, high frequency apparatus, and innumerable other devices of electrical engineering have found improvement at his hands. His touch has ever been of originality and sound scientific conception, so that every part of the art which has passed before him for review has profited from the activity of his illuminating mind.

Broad recognition has come to him at home and abroad. Yale University conferred upon him the honorary degree of Master of Arts in 1890, Tufts College the degree of Doctor of Philosophy in 1894, and Harvard University the degree of Doctor of Science in 1909. He was awarded the Grand Prix at the Paris Exposition in 1889 for his electrical discoveries and inventions, and was decorated by the French Republic as Chevalier et Officier de la Legion D'Honneur. Again at the Paris Exposition of 1900 he was awarded the Grand Prix. At the Saint Louis Exposition of 1904 he was again awarded the Grand Prize for his electrical achievements. He was president of the American Institute of Electrical Engineers in 1889 and in 1910 was made the first recipient of its famous Edison Medal for meritorious achievement in electricity. In 1916 he received the John Fritz Medal of the four national engineering societies, awarded to him for achievements in electrical invention, electrical engineering, industrial developments and scientific research. In 1916 also he was awarded the Hughes Medal of the Royal Society of London. This award carried a money prize which Dr. Thomson donated to a war charity in England. Many lesser medals have also been conferred upon him.

His recognition by scientific and professional societies has been world wide. Having been President of the American Institute of Electrical Engineers in 1889-90, he was United States delegate to the International Electrical Congresses at Chicago in 1893 and St. Louis in 1904, and was President of the Chamber of Delegates and of the Congress at St. Louis. For the three years 1908-11 he was President of the International Electrotechnical Commission which has for its function the important duty of arranging international standardization in electrical engineering, also of providing for the International Electrical Congresses at which units and standards are adopted. Of his numerous scientific and professional societies only his membership in the National Academy of Sciences and honorary membership in the Institution of Electrical Engineers of Great Britain can be mentioned here.

Professor Thomson has been noted for his interest in the careers of younger men, and his assistance and counsel are remembered with affectionate gratefulness by many men who themselves have come to distinguished places in the electrical engineering profession. Men who have had the fortune to serve as his assistants, rejoice in telling of his "many-sidedness" and fertility, for he himself has served them as a University.

—*The Tech Engineering News.*

Studies in Lightning Protection on 4000-volt Circuits*

By D. W. Roper

Commonwealth Edison Company, Chicago

The author presents the results of an investigation of lightning arrester performance in practice extending over a period of five years. The investigation was originally undertaken for the object of reconciling the differences between results obtained in laboratory experiments and actual service, and some of the conclusions previously arrived at were presented in a paper before the A.I.E.E. in June, 1916. The scope of the investigation broadened to a determination of the relative merits of the several types of lightning arresters which were installed on the system under consideration, and the data thus compiled constitute the most valuable contribution ever made to the study of lightning disturbances in primary distribution networks.

Discussions by Dr. C. P. Steinmetz, W. L. R. Hayden and V. E. Goodwin accompany our abstract of the paper.—Editor.

Introduction

The investigations forming the basis of this paper as well as the previous paper[1] on the same subject had as their primary object the determination of the relative merits of the several types of lightning arresters which were installed on the 60-cycle distribution system of the Commonwealth Edison Company in Chicago. The previous investigations had indicated in a general way the several factors which affected lightning arrester performance and also the extreme variability of the distribution and intensity of the lightning storms, from which it appeared that in order to get reasonably accurate results, it would be necessary to accumulate the experience with a large number of arresters over a period of several years.

Description of the System

The system of distribution on which these investigations were made is a four-wire three-phase system, with the neutral grounded only at the substations. The normal potential on the distributing mains is 2080 volts between phase and neutral wires. The distribution pole lines are in the alleys, or along the rear lot lines in the center of the block where alleys are missing. Single-phase transformers are used exclusively and are connected between the phase and neutral wires except in the case of three-transformer three-phase installations in which case the common point of the transformer primaries is not connected to the neutral wire. Secondaries of power transformers are connected in delta. Power and lighting customers are supplied from the same primary mains, but the very large customers are connected to a 12,000-volt system. The feeders are all No. 0 wire and the mains No. 6 A. W. G. About 85 per cent of the feeders and 15 per cent of the mains are underground. About 99 per cent of the transformers are on poles and the rest in manholes or in vaults on customers' premises. At single transformer installations a 2400-volt arrester is connected to the same phase wire as the transformer and a 300-volt arrester to the neutral wire. Where three transformers are installed for a power service there are three 2400-volt arresters, one connected to each of the phase wires; and one 300-volt arrester is connected to the neutral wire. Arresters are installed in this manner on the same pole with all transformers. The lightning arrester ground consists of one-half inch galvanized iron pipe ten feet long, driven into the ground at the base of the transformer pole. Secondary circuits are usually less than one block long and the secondary ground is similar to the lightning arrester ground, but is installed on the next pole. On long secondaries there are at least two such ground connections and in addition the neutral wire on the customer's premises in many recent installations is grounded to the water pipes inside of the building. The distribution system at this time

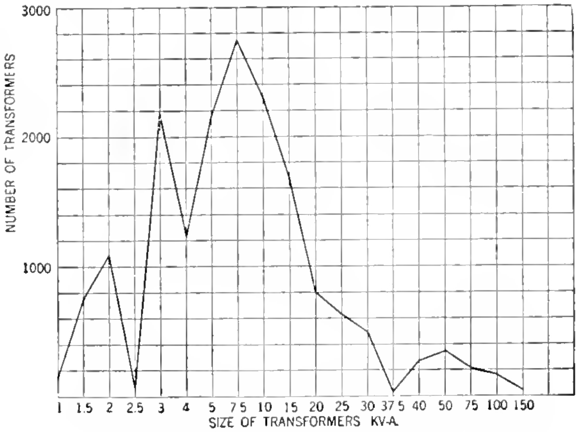

Fig. 1. Diagram Showing the Number of Each Size of Transformer in Service on August 1, 1918

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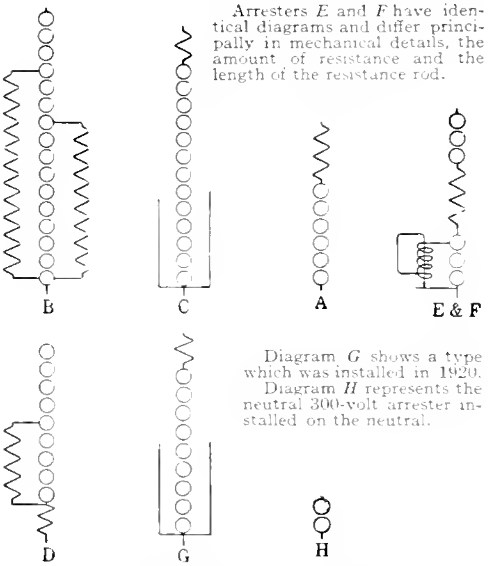
*A comprehensive abstract of paper presented before A.I.E.E. at Chicago, November, 1920.

[1] Trans. A.I.E.E., 1916, Vol. XXXV, p. 655.



Arresters *E* and *F* have identical diagrams and differ principally in mechanical details, the amount of resistance and the length of the resistance rod.

Diagram *G* shows a type which was installed in 1920. Diagram *H* represents the neutral 300-volt arrester installed on the neutral.

Fig. 2. Electrical Diagrams of the Lightning Arresters Used in These Investigations

The gaps are conventional and do not show the actual shape of the gaps on all of the arresters.

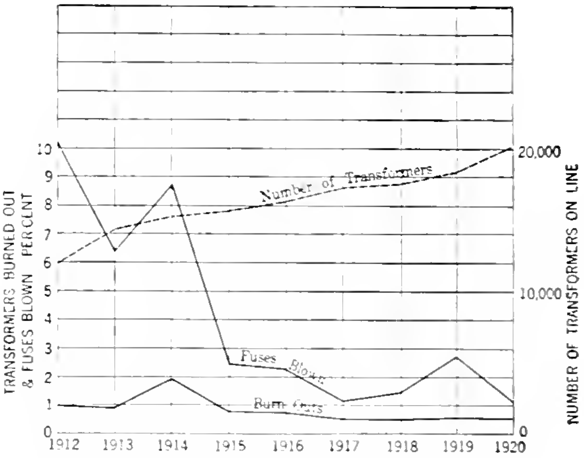


Fig. 3. Graphical Record Showing the Number of Transformers in the Distribution System and the Per Cent of Transformer Troubles Each Year Over a Period of Years

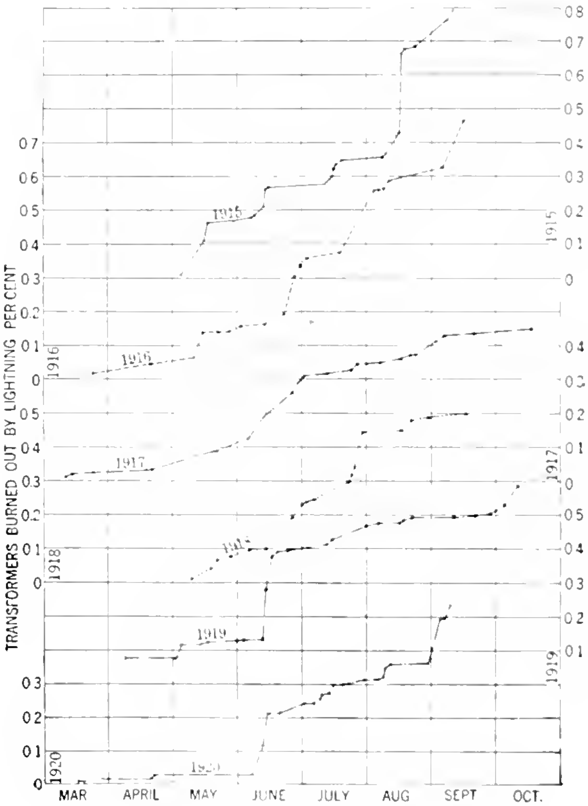


Fig. 5. Diagram Showing the Percentage of Transformers Burned out in Each Storm for the Years 1915-1919 Inclusive

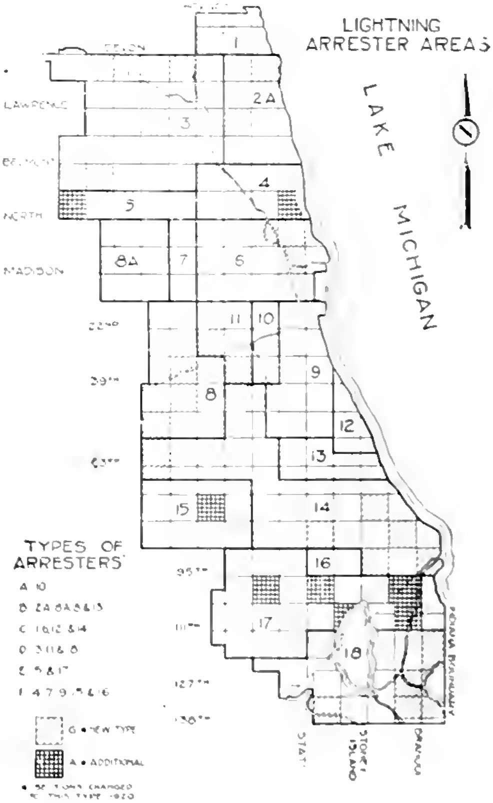


Fig. 5. Outline Map of the City, Showing Section Lines and Lightning Arrester Area Numbers

The lightly shaded areas show the sections in which arrester *G* shown in Fig. 2 was installed in 1920. The heavily shaded portions show the sections in which additional arresters of type 1 were installed in 1920 for the purpose of getting more conclusive information regarding this type.

includes about 100,000 poles, 20,000 transformers with a total capacity of about 270,000 kv-a., 6500 conductor miles of overhead primary line wire, 2200 conductor miles of underground cable and 2500 cable poles. The system serves about 400,000 customers.

In Fig. 1 is shown the number of each size of transformers on the line as of August 1, 1918. This date was selected for the purpose of the calculations, as the number of transformers in service on that date was about the average of the number in the five-year period under investigation. Fig. 2 shows electrical diagrams of all of the lightning arresters used in the investigations. The letters shown on this diagram are consistently used throughout the several tables, diagrams and curves. Fig. 3 shows graphically the number of transformers on the distribution system over a period of years, as well as the percentage of transformer primary fuses blown and transformers burned out by lightning each year. The increase in the percentage of fuses blown during the years 1918 and 1919 was due to causes definitely known to be entirely distinct from lightning, but as some of these fuses were blown during the same day as lightning storms, they were included with fuses blown by lightning because of the impossibility of accurately determining just which fuses were blown by lightning and which by other causes.

In Fig. 4 is shown the percentage of burnouts of transformers for each storm during the five-year period and also for the year 1920, the percentages being plotted cumulatively. From these records it will be noted that it is not unusual to have over one-third of the total trouble in any one year due to lightning occur in one or two days. A composite of these curves for the five-year period is shown in Fig. 6, from which it will be noted that on the average, the lightning is quite uniformly distributed throughout the 4½ months from May 1st to September 15th, and that there is comparatively little trouble outside of this period.

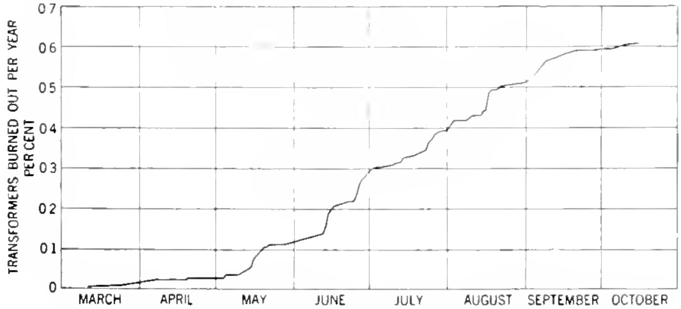


Fig. 6. A Composite Diagram of the Transformer Burn-outs for Years 1915-1919 Inclusive

Fig. 5 is an outline map of the portion of the city covered by the distribution system on August 1, 1918, showing the section lines and the lightning arrester area numbers. These areas will be found to differ from those shown in the previous paper as some changes were made in 1917 for the purpose of trying another type of arrester, a new scheme of protection and incidentally securing a little better distribution of the various types of arresters over the different portions of the city. The shaded areas on this diagram will be referred to later in the paper.

Preliminary Investigations

From the previous paper and subsequent studies it appears that the factors which might affect lightning arrester performance are as follows:

1. The system of distribution and the grounding of the neutral.
2. Primary terminal boards.
3. The shielding effect of trees, buildings or wires of other companies.
4. The resistance of the lightning arrester ground connection.
5. The maker of the transformer.
6. The size of the transformer.
7. The age and previous service record of the transformer.
8. Variation in the distribution and intensity of the lightning.
9. The density of lightning arresters, that is, the number per square mile.
10. The design of the arrester.

In laying out the lightning arrester areas which were given in the previous paper, and which are also shown in Fig. 5 in this paper, it was the intention to arrange the boundaries of the areas and to distribute the several types of lightning arresters over the city so as to eliminate variables 3 to 8 inclusive as given in the above list.

An investigation of the records demonstrated beyond question that the shielding effect of trees or buildings immediately adjacent to the lines considerably reduced the amount of damage on our lines from lightning. This was shown by the following facts:

(a) The percentage of poles in the distribution system shattered by direct strokes is extremely small, being of the order of

1 400 of 1 per cent. This is very much smaller than the corresponding percentage for transmission line poles belonging to the same company in the flat open country in the southeastern portion of the city and is also smaller than experienced in general by companies having transmission lines crossing open country. That there are many direct strokes in every severe lightning storm is shown by the newspaper reports on the day following lightning storms, which record the most severe or unusual cases of damage to trees, church steeples, chimneys, or other portions of buildings and structures.

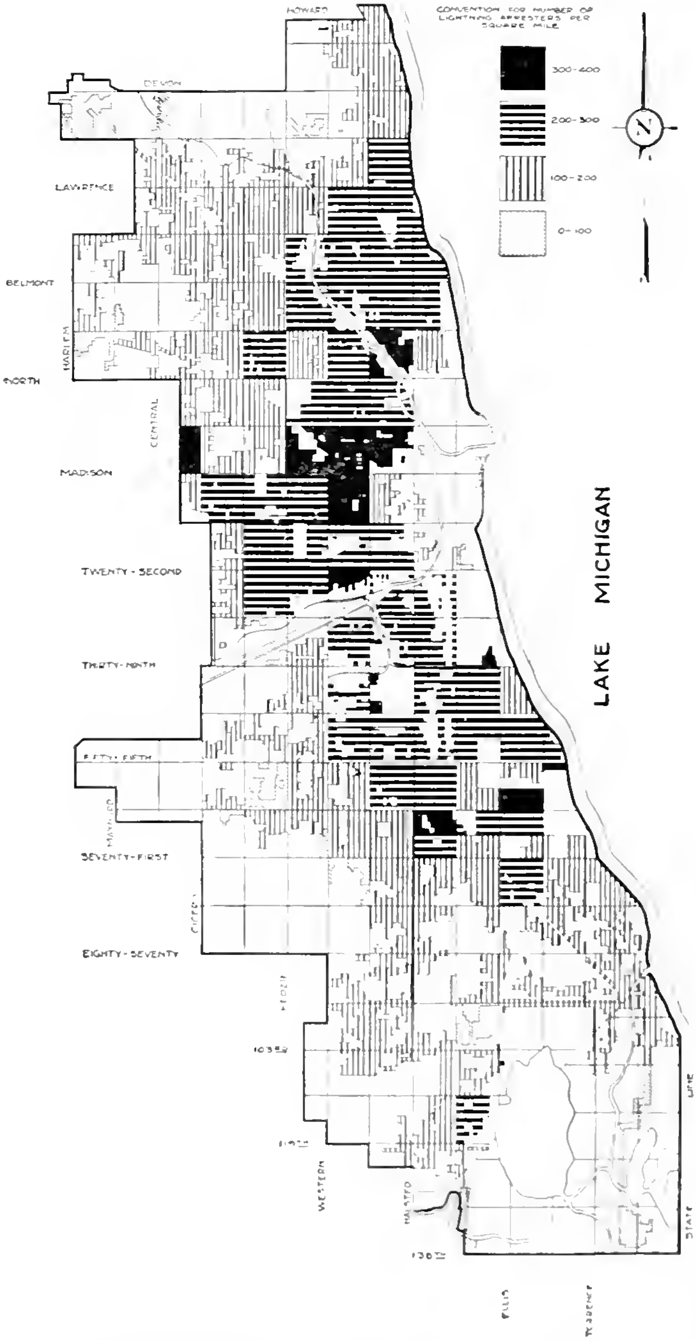


Fig 7. Outline Map of Chicago, Showing Section Lines and Area Actually Covered by Distribution System. Density of shading indicates the density of lightning arresters

(b) An investigation of the conditions surrounding the installation of 97 out of 529 cases covered by these investigations where transformers were burned out by lightning failed to reveal a single case in which the primary wires adjacent to the transformer were over-shadowed by high trees or buildings immediately adjacent.

By "spot checking" selected portions of each of the lightning arrester areas in co-operation with the representatives of the manufacturers, it appeared, although the shielding effect of trees and buildings was considerable, that as far as could be determined without making a detailed survey and record of the conditions in each block throughout the city, no type of arrester was at any serious advantage or disadvantage on this account.

The records and the conditions surrounding the transformer installations were carefully and thoroughly examined to determine the effect of the other points 5, 6 and 7. These investigations included the assembling of the complete history of each transformer that had burned out during the five-year period and the compiling and assembling of all data which might serve to add to the information on the several points. On the completion of the investigation, the representatives of the manufacturers concurred in the decision that none of the arresters appeared to be at any material advantage or disadvantage on account of the first seven variable factors in the above list, and these factors were, therefore, ignored in the further investigation.

There still remains two variables, namely the variability of the lightning, and the density of lightning arresters. In determining the relation between the density of lightning arresters and their performance a method was discovered of eliminating the effect of the lightning as a variable as described at some length later in the paper.

The Effect of Density of Lightning Arresters on Their Performance

A preliminary investigation of the effect of density was made by plotting the density of arresters in each original lightning arrester area against the percentage of burn-outs in that area. The points plotted in this manner were so irregular that they did not permit the drawing of any curve which might be considered as representing the results, but the method appeared to indicate that there was a very marked decrease in the percentage of burn-outs with increase in density which would warrant further investigation along this line. The results also indicated that some further subdivisions of the original lightning arrester areas would be necessary in order to eliminate the lightning as a variable. The manner in which the records were kept enabled this change to be made very readily by using the section (that is, the square mile) as the unit, resulting in an increase in the number of areas from 19 to 192. For each one of these sections there was determined from the records the number of transformers in the section as of August 1, 1918. As there is an arrester on the same pole with each transformer, and comparatively few cases where there were two transformers connected to the same phase wire on the same pole, the number of transformers in each section was taken as the number of arresters. There was also determined for each section the number of transformer burn-outs and primary fuses blown by lightning during the five-year period and the actual area covered by the line. This latter quantity was determined by going over the large scale maps of the distribution system and assuming that a line through the center of the block covered the width of the block. (This width varies in the different portions of the city from about 250 ft. to over 600 ft. and averages approximately 400 ft.) From these figures can be calculated the percentage of burn-outs in any section or group of sections. The data with the sections arranged in the order of density of arresters are shown in Table I.

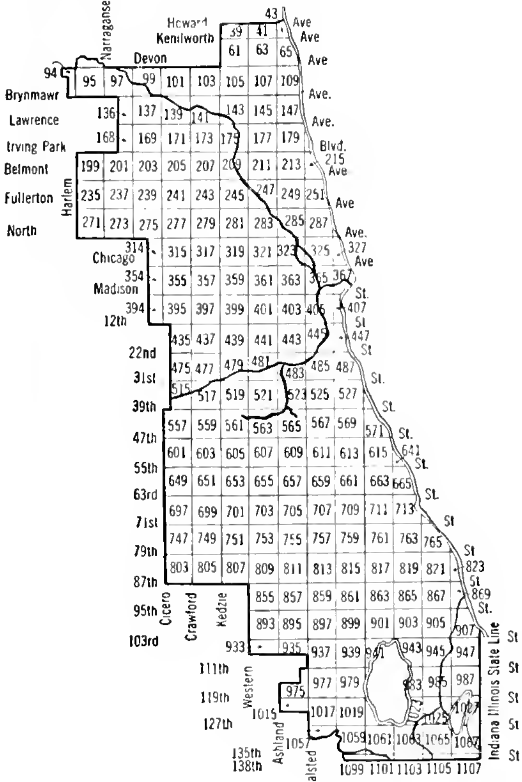


Fig. 8. Outline Map of Chicago Giving the Numbers Assigned to Each of the Sections as Shown in the Third Column of Table I

The data in this table and other data regarding the system are shown graphically in several drawings which give a better idea of the conditions than can be obtained from tables of statistics. In Fig. 7 is shown an outline map of the city on which are shaded the areas actually covered by the lines, the number of arresters per square mile being indicated by the density of the shading. The distribution system extends into 192 sections covering 163.25 square miles within the city, while the area actually covered by the lines, determined in the manner above described is 93.49 square miles. As there were 17,529 transformers on the lines on August 1, 1918, the average density of arresters is thus 187 per square mile.

Fig. 9 shows these data in another manner, from which figure it will be noted that in the larger portion of the area covered by the distribution system, the density of arresters ranges between 100 and 300 per square mile.

TABLE I

DATA FOR DETERMINING THE EFFECT OF DENSITY OF ARRESTERS ON THEIR PERFORMANCE

The types of arresters are indicated in Fig. 2, the area numbers are shown in Fig. 5, the section numbers in Fig. 8. The stars (*) indicate the sections in which the type of arrester was changed in 1917. Figures for the average curve are taken from this table but due allowance for this change was made in plotting the curves for the individual arresters.

Present type of arresters	Area Number	Section number	Number of transformers in section	Number of burn-outs in section	Number of fuses blown in section	Area actually covered by lines	Density of arresters per square mile	Average per cent burn-outs per year	Present type of arresters	Area number	Section number	Number of transformers in section	Number of burn-outs in section	Number of fuses blown in section	Area actually covered by lines	Density of arresters per square mile	Average per cent burn-outs per year	Present type of arresters	Area number	Section number	Number of transformers in section	Number of burn-outs in section	Number of fuses blown in section	Area actually covered by lines	Density of arresters per square mile	Average per cent burn-outs per year
C	6*	325	4	0	0	0.45	9	0.	C	14	811	92	4	11	0.71	130	0.87	F	4	247	120	5	3	0.59	204	0.83
D	18*	987	1	0	0	0.09	11	0.	E	17	895	63	7	14	0.48	131	2.22	D	11*	521	156	5	30	0.76	205	0.64
D	18*	1067	4	0	1	0.13	31	0.	C	14	763	105	4	13	0.80	131	0.76	C	12	615	172	1	7	0.84	207	0.12
D	18*	1107	1	1	0	0.03	33	20.	D	3*	171	124	7	14	0.94	132	1.13	C	6	319	156	6	10	0.76	207	0.77
D	3*	103	3	0	0	0.09	33	0.	C	14	759	101	5	10	0.79	132	0.96	C	14	607	165	4	30	0.79	208	0.48
D	18*	1025	7	0	0	0.18	39	0.	D	3*	241	62	5	8	0.47	132	1.61	C	14	657	203	6	12	0.97	209	0.59
D	3*	99	7	0	4	0.17	41	0.	C	6	405	16	0	1	0.12	133	0.	E	5*	279	201	5	27	0.96	210	0.50
C	1*	61	1	0	0	0.02	50	0.	B	8*	561	109	4	6	0.83	133	0.73	B	8A	354	105	1	3	0.50	210	0.19
D	18*	1059	3	0	2	0.05	60	0.	C	14	813	44	0	9	0.33	133	0.	C	14	867	146	8	21	0.69	212	1.10
D	3*	97	5	0	2	0.08	62	0.	B	8*	603	39	3	19	0.29	134	1.54	F	9	485	119	3	9	0.55	214	0.50
F	15*	751	8	1	2	0.13	62	2.50	E	5*	275	80	2	12	0.59	136	0.50	F	4	245	205	2	10	0.95	215	0.20
D	3*	237	6	0	0	0.09	67	0.	E	17	937	68	3	28	0.50	136	0.88	C	14	761	170	7	19	0.79	216	0.82
E	5*	271	20	2	11	0.30	67	2.	D	3*	169	109	6	11	0.81	136	1.08	B	8	437	216	1	13	0.99	218	0.09
D	18*	1065	19	2	0	0.27	70	2.11	E	17	859	22	1	3	0.16	137	0.91	B	13	659	196	4	14	0.89	221	0.41
F	9	447	5	0	0	0.07	71	0.	B	8A	314	49	1	7	0.38	137	0.35	B	2A	211	218	2	7	0.99	221	4.18
C	14	697	6	1	1	0.08	75	3.33	E	17	977	107	13	21	0.78	137	2.43	C	14	609	84	2	11	0.38	221	0.48
F	15*	725	7	1	4	0.09	78	2.86	F	16	861	36	3	3	0.26	138	1.66	B	8A	355	122	0	4	0.55	221	0.
E	17	899	30	4	9	0.38	79	2.67	C	1	65	88	2	3	0.63	140	0.46	B	2A	177	209	4	11	0.97	221	0.37
C	11	815	15	0	2	0.18	83	0.	B	8A	605	71	3	10	0.49	145	0.86	F	9	525	152	9	17	0.68	224	1.18
F	15*	753	26	3	4	0.31	84	2.31	D	3*	141	76	1	12	0.52	146	0.26	D	18*	979	112	6	15	0.63	226	0.85
C	14	651	63	5	10	0.74	85	1.59	C	12	571	115	2	7	0.78	148	0.35	F	9	613	159	0	5	0.79	227	0.
D	3*	95	44	4	5	0.52	85	1.82	B	8	519	75	3	8	0.49	153	0.80	F	9	610	98	6	9	0.43	228	1.23
C	6	365	18	1	0	0.21	86	1.11	D	3*	205	137	6	26	0.89	154	0.88	C	1*	39	7	1	1	0.03	231	2.86
B	8	517	26	0	3	0.29	89	0.	E	17	939	72	6	22	0.46	156	1.66	F	7	397	188	2	5	0.80	235	0.21
E	17*	945	17	3	2	0.19	90	3.53	C	11	755	128	2	18	0.81	158	0.31	B	8	477	221	2	19	0.94	235	0.18
D	3*	105	22	3	3	0.24	94	2.73	D	3*	113	62	0	7	0.39	159	0.	B	13	711	112	1	5	0.47	238	0.18
D	3*	136	23	4	2	0.23	100	3.48	C	11	757	119	2	6	0.75	159	0.34	D	11*	441	179	4	9	0.75	238	0.45
B	8*	559	10	3	6	0.10	100	6.00	C	1*	63	106	4	4	0.66	160	0.75	B	2A	147	193	0	9	0.82	238	0.
F	15*	809	3	0	0	0.03	100	0.	C	14	765	70	3	9	0.43	163	0.86	F	9	569	235	1	8	0.97	242	0.09
E	17	901	9	0	2	0.09	100	0.	C	1	43	30	0	2	0.19	163	0.	C	14	563	68	3	10	0.28	243	0.88

D	18*	1105	4	0	1	0.04	100	0.	*C*	14	733	74	1	6	0.45	164	0.27	*C*	12	641	32	0	2	0.13	246	0.
C	14	819	47	9	14	0.46	102	3.83	*C*	14	703	71	3	8	0.43	166	0.85	*A*	10*	523	118	3	14	0.47	249	0.51
E	5*	273	32	2	12	0.31	103	1.25	*D*	3*	207	139	1	25	0.84	167	0.14	*B*	2A	213	227	1	10	0.94	250	0.09
E	17*	947	33	1	5	0.32	103	0.61	*D*	3*	173	161	7	19	0.96	167	0.86	*F*	4	281	238	5	13	0.95	250	0.42
D	18*	1017	60	6	14	0.55	109	2.	*B*	8A	315	116	2	10	0.72	167	0.33	*C*	14	869	53	1	4	0.21	252	0.39
E	17	893	65	12	29	0.59	110	3.69	*B*	2A	145	120	8	16	0.73	167	1.29	*F*	4	251	129	2	4	0.51	253	0.31
B	8*	601	33	2	7	0.30	110	1.21	*B*	2A	109	148	2	8	0.86	172	0.27	*F*	9	611	129	4	19	0.51	253	0.62
D	3*	168	22	2	6	0.20	110	1.82	*C*	14	821	85	3	11	0.49	174	0.71	*B*	2A	179	204	3	4	0.80	255	0.29
C	14	817	31	1	2	0.28	111	0.65	*D*	3*	243	171	2	15	0.98	174	0.23	*D*	3*	209	161	2	11	0.63	256	0.25
C	14	865	20	2	11	0.18	111	2.	*C*	14	737	54	1	5	0.31	175	0.37	*A*	10*	443	203	3	11	0.78	259	0.30
D	3*	235	48	4	5	0.43	112	1.67	*D*	18*	1099	14	3	1	0.08	175	4.28	*D*	11*	479	129	3	9	0.49	263	0.47
C	1*	41	47	1	9	0.42	112	0.42	*F*	4	287	132	0	5	0.75	176	0.	*A*	10*	483	153	1	13	0.57	269	0.13
C	14	653	86	4	13	0.77	112	0.93	*E*	17	907	74	3	8	0.42	176	0.81	*C*	14	731	108	1	4	0.39	277	0.19
D	3*	94	9	2	0	0.08	113	0.44	*C*	14	823	16	0	3	0.09	177	0.	*C*	6	399	263	3	16	0.95	277	0.23
D	3*	139	25	4	3	0.22	114	3.20	*F*	9	445	25	1	2	0.14	179	0.80	*F*	4	283	267	1	18	0.96	278	0.08
D	3*	239	24	0	1	0.21	114	0.	*B*	2A	107	47	2	7	0.29	179	0.77	*F*	9	567	224	6	22	0.79	286	0.54
D	3*	137	62	5	11	0.54	115	1.61	*B*	8	475	106	2	15	0.59	180	0.38	*D*	11*	439	183	0	11	0.64	286	0.
E	17	857	51	6	16	0.44	116	2.35	*C*	6	367	9	0	1	0.05	180	0.	*F*	4	249	287	7	17	0.99	289	0.49
F	15*	727	52	5	6	0.45	116	1.92	*B*	8	435	85	4	10	0.47	180	0.84	*C*	6	323	183	2	9	0.63	291	0.22
F	16	863	29	4	4	0.25	116	2.76	*E*	17*	905	45	1	14	0.25	180	0.44	*C*	6	321	284	10	23	0.95	298	0.70
E	17	935	22	2	6	0.19	116	1.82	*F*	7	357	140	0	8	0.77	181	0.	*C*	12	665	6	0	0	0.02	300	0.
D	3*	199	41	4	4	0.35	117	1.95	*D*	3*	175	161	7	16	0.88	183	0.87	*C*	6	359	226	2	15	0.75	303	0.18
C	14	649	41	8	8	0.35	117	3.90	*C*	14	655	132	11	17	0.72	184	1.67	*B*	13	707	119	1	6	0.39	305	0.17
D	18*	1019	25	1	6	0.21	119	0.80	*C*	14	735	32	2	1	0.17	188	1.25	*F*	4	285	243	7	15	0.77	316	0.58
C	14	701	42	2	5	0.35	120	0.95	*F*	7	317	176	2	10	0.93	190	0.23	*C*	6	363	264	7	12	0.82	322	0.53
E	17	897	36	6	31	0.30	120	3.33	*E*	5*	277	166	4	15	0.87	191	0.48	*B*	11*	481	113	0	8	0.35	323	0.
B	8	515	12	1	0	0.10	120	1.66	*C*	14	705	176	2	8	0.91	193	0.23	*C*	6	401	315	5	20	0.95	325	0.32
F	15*	723	6	1	2	0.05	120	3.33	*C*	12	663	70	1	3	0.36	195	0.29	*C*	6	361	318	5	27	0.95	335	0.31
E	17	933	35	2	7	0.29	121	1.14	*C*	6	403	166	1	8	0.83	199	0.12	*B*	13	687	98	0	2	0.29	338	0.
D	3*	203	88	7	13	0.73	121	1.59	*B*	8	661	123	0	7	0.62	199	0.	*C*	14	565	21	0	3	0.06	350	0.
C	14	699	45	2	9	0.37	122	0.89	*D*	18*	1015	18	0	4	0.09	199	0.	*E*	17	941	4	0	1	0.01	400	0.
D	3*	201	53	4	4	0.43	123	1.51	*C*	6	407	2	0	2	0.01	200	0.	*F*	9	527	32	2	0	0.05	640	1.25
B	8A	394	32	0	8	0.27	123	0.	*B*	2A	215	77	2	7	0.38	202	0.52									
E	17	975	14	2	5	0.11	127	2.86	*B*	8A	395	185	2	12	0.94	202	0.21									
E	17	855	35	6	22	0.27	130	3.43	*B*	13	709	65	1	1	0.32	203	0.31									

Total and Averages, 17,529, 529, 1,702, 92.88, 190, 0.60
Total number of Section 192

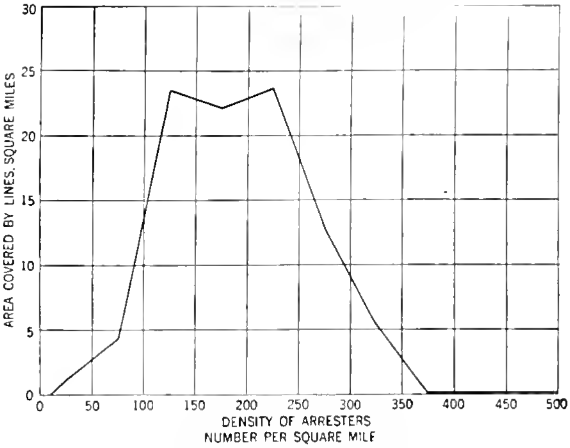


Fig. 9. Diagram Showing the Area Actually Covered by the Distribution System for Various Densities of Arresters

The number of arresters for various densities and for each type of arrester is shown in Fig. 10. In this drawing it will be noted that arrester *A* was installed in sections with a very narrow range in density. The section numbers given in the third column in Table I are shown in Fig. 8. The stars preceding the section numbers in Table I indicate the sections in which a change in the type of lightning arrester was made preceding the lightning season of 1917 for the purpose of permitting the installation of an additional type of arrester and securing a better distribution of the several types of arresters in different portions of the city.

In Fig. 11 there has been plotted for each section the density of arresters as shown in the eighth column in Table I and the average per cent of burn-outs as shown in the last column. The final curve for all arresters showing the variation in the performance of arresters with their density is also shown in the same figure, but the curve cannot be drawn directly from the points shown in this figure because these points, representing different areas and different numbers of transformers, are not of equal weight. Nothing in the tables or records shows the wide variation in the distribution and intensity of the lightning quite so well as the plotting of these points in Fig. 11. Out of the 192 sections it will be noted that in about one-sixth of them the points are on the line of zero burn-outs, showing that there were no burn-outs whatever in these sections during the five-year period.

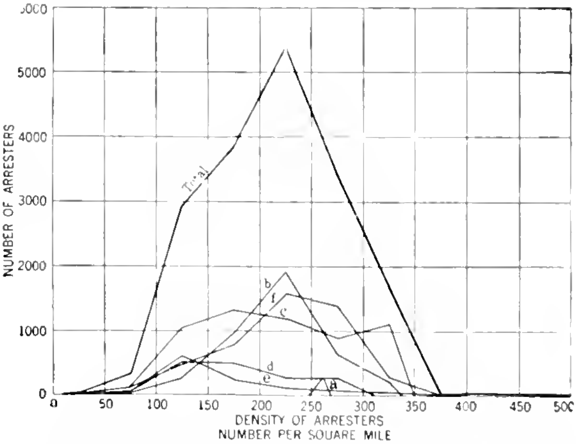


Fig. 10. Diagram Showing for Various Densities of Arresters the Number of Each Type of Arrester and of all Types Connected to the Distribution System

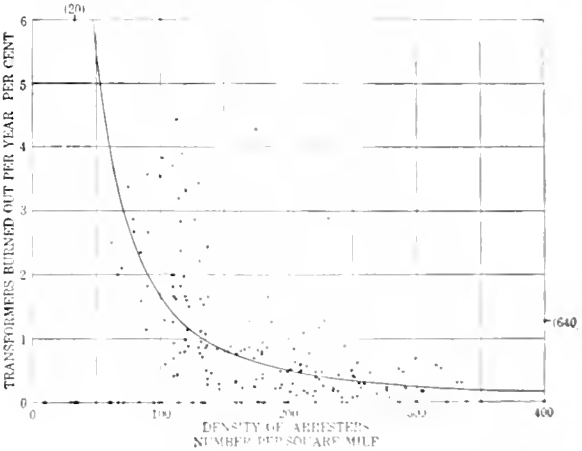


Fig. 11. Diagram Showing for Each of 192 Sections the Average Per Cent of Transformer Burn-outs Due to Lightning for the Five-year Period Plotted Against the Density of Arresters. The curve shows for all types of arresters the final determination of the relation between density of arresters and transformer burn-outs due to lightning. The curve cannot be plotted directly from the points shown in the figure as they are not of equal weight

In order to secure points of equal weight for the purpose of drawing the curve, it was decided to have each point represent the experience with the same number of transformers. At first trial it was agreed to assemble the data so as to get 18 points, each of which would therefore include the data from approximately 1000 transformers. Data for the first point were obtained by starting at the top of Table I and including enough sections to get a total of about 1000 transformers. Then the figures showing the area covered and the number of burn-outs was totaled for these sections, from which could be determined the average density of the arresters and the average per cent of burn-

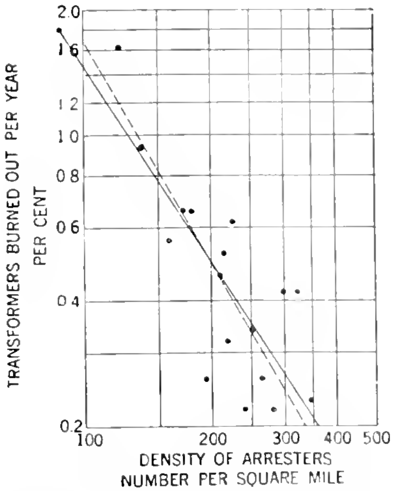


Fig. 12. Diagram to Logarithmic Scale Showing the Data in Table 11 and Fig. 8. Assembled into Eighteen Points Each Covering the Experience for the Five-year Period with Approximately the Same Number of Transformers

outs for this group of transformers. This was equivalent to taking a vertical band of Fig. 11 which would include enough points to make a total of 1000 transformers and finding one point to represent the average experience for the entire band. In the same way the other 17 points were calculated and are shown plotted to logarithmic coordinates in Fig. 12. The use of logarithmic coordinate paper was adopted for the purpose as it was found to greatly facilitate the work. There was some question as to whether the number of points selected for assembling the data in this manner had any effect on the resulting curve, but it appeared that if practically the same line were obtained by using a different number of points that there would be no serious error in the method. The same data were therefore assembled in a similar manner in 7 points, 4 points and 2 points and the results are shown respectively in Figs. 13, 14, 15. After a number of attempts to draw curves through these points in the several

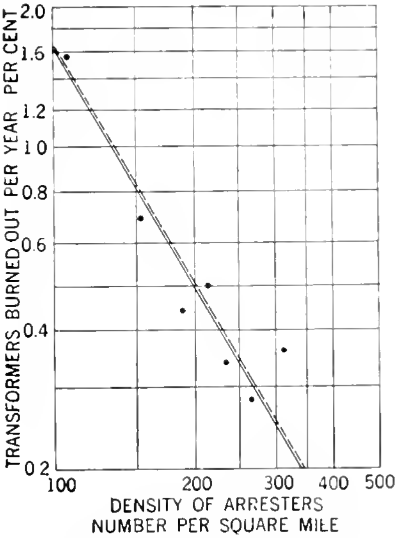


Fig. 13. Same as Fig. 12 Except That Data Are Assembled Into Seven Points of Equal Weight

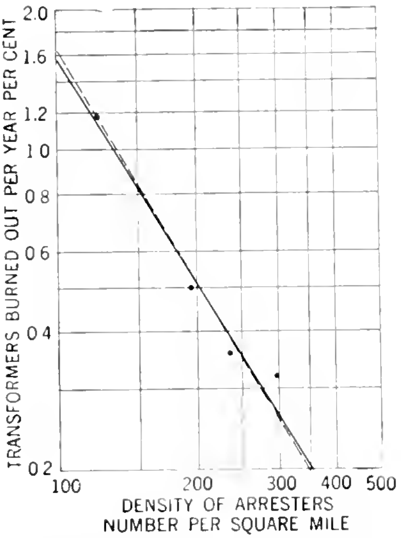


Fig. 14. Same as Fig. 12 Except That Data Are Assembled Into Four Points of Equal Weight

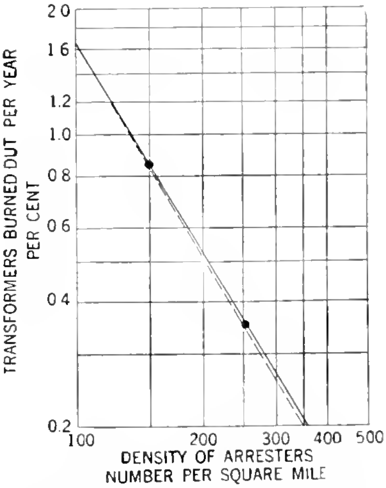


Fig. 15. Same as Fig. 12 Except That the Data Are Assembled Into Two Points of Equal Weight

figures, it was found that a straight line would properly represent the results just as well as any curve which might be drawn; and it was, therefore, assumed that the curve when drawn on logarithmic coordinate paper was a straight line, which is equivalent to assuming that the relation between the quantities is an exponential function. In each of the four figures the full line is determined by the points in that figure and the dashed line is the average of all of the four. It will be noted that the variation of the points through the straight line decreases as the number of points decreases, or in other words, as the number of transformers represented by one point increases. The average curve represented by the dashed line in these four figures transferred to arithmetical coordinates is shown in Fig. 11.

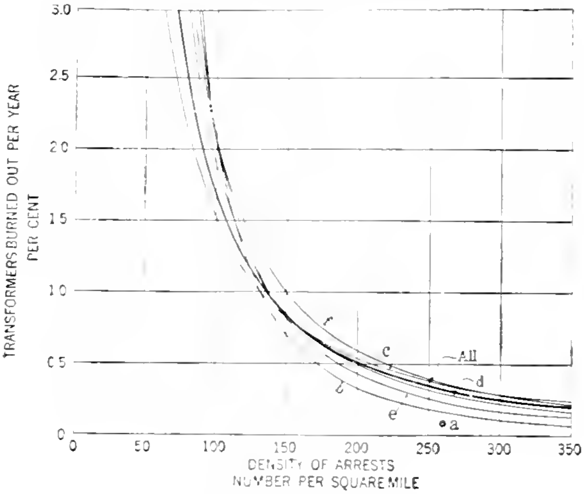


Fig. 16. Diagram Showing the First Approximation of the Relation Between the Density of Arresters and the Percentage of Transformers Burned Out by Lightning for the Five-year Period, 1915-1919 Inclusive

The curve for all arresters is plotted from the dashed line in Figs. 12 to 15 inclusive. The curves for the individual types of arresters were derived in a similar manner from logarithmic diagrams which are not reproduced.

A point instead of a line is shown for arrester A as the records for this type include only one transformer burn-out in the three years in which the arresters have been in service.

While one engineer was engaged in the task of assembling the data and drawing the lines on logarithmic coordinate paper as above described, another engineer was given the task of assembling the data in a similar manner except that he used for each point the experience from an equal area covered by the lines as given in column seven of Table I, instead of an equal number of transformers. This was done with the idea that any serious personal errors or any error due to the assumption made in drawing the curves or in transferring them to arithmetical coordinate paper would be indicated by differences in the final curves. After these two engineers had independently drawn final curves similar to the one shown in Fig. 11 the two curves were then transferred to the same sheet and found to be practically superposed. The equation of the curve in Fig. 11 is:

$$Y = \frac{5450}{X^{1.75}}$$

where X = the number of arresters per square mile, and

Y = the average per cent of transformers burnt out by lightning per year during the five-year period.

This equation means that the density of arresters has a very important influence on the results secured by lightning arresters. If we assume for example that there are 1000 transformers installed in an area of 10 square miles each protected by an arrester on the same pole, and that later the number of transformers in this area is doubled and at the same time uniformly distributed, the results of the change are shown in Table II. From this table it will be noted that although the number of transformers in the area has been doubled, the percentage of burn-outs has decreased from 1.67 per cent to 0.5 per cent and that the actual number of burn-outs

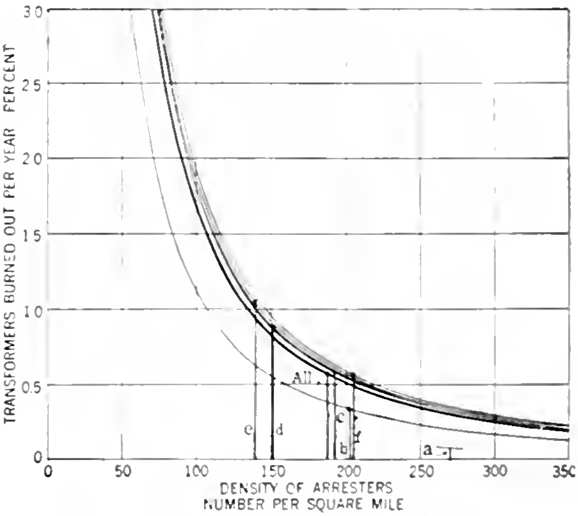


Fig 17. Diagram Showing the Final Determination of the Relation Between the Density of Arresters and the Percentage of Transformers Burned Out by Lightning

These are the curves shown in Fig. 16 modified by the assumption that the lines representing the data on logarithmic paper should be parallel to the dashed line in Figs. 12 to 13 inclusive, showing the experience with all types of arrester.

has decreased from 17 to 10 per annum. In other words, the doubling of the number of transformers and arresters in a given area will not result in more transformers being burnt out by lightning per year as might be supposed but will result in an actual reduction of about 40 per cent in the number of such burn-outs per year.

The data for each type of arrester were then plotted in a similar manner, a set of four curves similar to Figs. 12, 13, 14 and 15 being drawn for each type of arrester. As might be expected with a smaller number of observations, the variation of the points from a straight line when plotted on logarithmic paper and the variation of the four lines from their average was somewhat greater than in the case of the corresponding lines for all types of arresters. These straight lines for the different types of arresters were not parallel, and when transferred to arithmetical coordinate paper as shown in Fig. 16, the curves cross each other in a confusing manner. While the curves thus drawn may be mathematically accurate, they appear to be physically impossible as there seems to be no sufficient reason why one type of arrester should be better than another at one density and poorer at another density. It seems more reasonable to suppose that if one arrester is better than another at any particular density of arresters, it will be better throughout the entire range of densities. After giving this subject considerable study it was decided to assume that the straight line representing the experience with any type of arrester, when plotted on logarithmic coordinate paper should be parallel to the line showing the results for all types of arresters, that is, the dashed line in Fig. 12. To make this change: the midpoint of the line for each arrester was found, which is a point so located that there are an equal number of arresters represented by the line on either side of the point. The line which was finally taken as representing the experience with this type of arrester was then drawn through this midpoint and parallel to the dashed line in Fig. 12. The results of this assumption when transferred to arithmetical coordinate paper are shown in Fig. 17. If these several assumptions are reasonably accurate, and they appear to do no violence to the facts, then the methods which have been used result in curves which can be taken as representing the performance of each of the arresters with varying densities, and the most troublesome variable, that is, the variation in the distribution and intensity of the lightning has been eliminated by the method of assembling the data and drawing the curves. From these curves it will be noted that four of the arresters designated as *C*, *D*, *E* and *F* are so close together that the differences may be considered as well within the possible errors of observation.

In Fig. 17 an ordinate has been drawn to the midpoint of each of the curves as above defined or at the position corresponding to the average density for that curve, that is, for each type of arrester the number of arresters to the right of the ordinate is the same as the number to the left. These ordinates represent the same values that were given in the previous paper as showing the average experience for each type of arrester, but it is now seen that in the case of the four arresters *C*, *D*, *E* and *F*, the curves are so close together that the ordinates for these curves, instead of correctly representing the relative merits of the four arresters, are practically four different ordinates of the same curve. The four arresters are therefore of practically equal protective value.

It will be noted that the ordinates for curve *B* in Fig. 17 are about 40 per cent of the corresponding ordinates of the average of curves *C*, *D*, *E* and *F*. Arrester *B* is one of the oldest types on the lines and the arresters are fairly well distributed over a wide range of density as shown in Fig. 10. It is, therefore, considered that this difference of about 40 per cent as compared with the other four is a real difference due to the value of the arrester as a protective device and is not due to an error in the observations or calculations.

In the case of arrester *A*, Fig. 5 shows that this arrester was installed in only three contiguous sections and Fig. 10 shows that these sections had a narrow range in arrester density. In addition the arresters had been in our service for only three years and in view of all of these circumstances, it appears that the data regarding this particular type of arrester are not conclusive. For the purpose of securing more conclusive data regarding this type of arrester, additional arresters were installed early in 1920 in the areas shown by the heavy shading in Fig. 5. The light shading in the same figure shows the areas in which an additional type of arrester was installed early in 1920.

Comments on the Designs of Lightning Arresters Covered by This Investigation

It is possible that the experience with the several types of arresters covered by these investigations, as well as the earlier types which they replaced, may be best summarized in the form of a tentative specification for lightning arresters, which would state some of the important points to be included and to be avoided in such design. Such a specification would read about as follows:

1. The arrester must consist of a number of gaps in series with a resistance, with the number of gaps and the amount of resistance properly adjusted to the line voltage so that the dynamic arc following a lightning discharge will be quickly broken without damage to the arrester.

2. The resistance rod must have the resistance uniformly distributed throughout its length, so as to prevent the progressive short-circuiting of the rod with heavy lightning discharges and the destruction of the arrester which will follow.

3. The amount of resistance in the resistance rod should not be seriously affected by repeated heavy discharges.

4. The leads for connecting the arrester to the line should leave the arrester so that they will form drip loops, and the leads should be so arranged that the arrester can be connected to a line wire on either side of the arrester.

For low maintenance cost the following features are desirable:

5. The enclosing case should be of fireproof insulating material that is not affected by the weather, and it should be constructed so as to protect effectually the metal parts from the weather, and to prevent accumulation of dust on the gaps.

6. The gaps in the arrester should be between parallel plates, disks, or rings instead of between cylinders or spheres so as to permit repeated heavy discharges without seriously altering the length of the gaps.

7. The arrester should be constructed so that in the event of the failure of the arrester to interrupt the dynamic arc the enclosing case will be shattered by the heat so as to give some visual evidence of the trouble and result in the opening of the circuit.

8. The arrester should be without moving parts or parts which require inspection, renewal or adjustment and should preferably be made in the form which cannot be inspected or repaired without removing it from the pole.

The experience with the arresters covered by this investigation indicates that several types of arresters are now available which comply with all of these specifications.

Conclusion

The conclusions from the investigations described in this paper, together with the more important conclusions from the previous paper, some of which have been modified and extended by these investigations, may be summarized as follows:

1. Transformer troubles during lightning storms may be reduced (a) by the removal of transformer primary terminal boards, (b) by the installation of lightning arresters, (c) by the use of larger bushings on the primary leads of transformers where they enter the case.

2. Lightning arresters installed on transformer poles are considerably more effective than if installed on the line poles.

3. Even in the most severe lightning storms, which apparently cover the given territory quite completely, there will be numerous extended areas within this territory which will be entirely free from lightning disturbances. Careful records extending over a period of several years are, therefore, necessary in order to determine definitely whether immunity from troubles due to lightning is due to the efficiency of the lightning protection or to the absence of lightning.

4. There is a very marked improvement in the effect of lightning arrester protection with an increase in density, that is, the number per square mile, and this effect is such an important factor in their performance that no accurate comparison of the relative merits of various types of arresters can be made without giving this point proper consideration.

5. Where the number of transformers, each of which is protected by an arrester on the same pole, is large per square mile so that the transformers and arresters are on the average only a few hundred feet apart, the total combined effect of all of the adjacent arresters is greater than that of the arrester on the same pole with the transformer.

6. In districts where transformers are widely scattered, that is, where the local density is materially below 100 per square mile and where continuous service is important, it will probably be found desirable to install arresters on line poles in addition to an arrester on the same pole with each transformer; where the local density is of the order of 50 per square mile, or lower, the installation of such additional arresters will probably be found to be warranted solely by the reduction in operating expenses.

7. The increase in the density of lightning arresters also results in a marked decrease in the percentage of burn-outs due to lightning of underground cables connected to overhead distribution circuits, and while the exact figures for the early years are not available, the percentage has been reduced from several per cent per annum with a very low density to a figure running well below one-tenth of one per cent per annum with the density averaging about 200 per square mile.

8. In the case of high-voltage cables, that is cables operating at voltages ranging up to 25,000, and where the present practice in this country calls for a maximum of one arrester at the point where the underground cable connects with the overhead line, the installation of additional arresters in the vicinity of the cable pole would in all probability cause a marked reduction in the percentage of burn-outs of such cables due to lightning.

9. The effect of density of arresters, of the shielding effect of high buildings, trees, etc., and perhaps also other features, have such an important effect on the amount of trouble from lightning that no accurate comparisons of the results secured in different cities can be made without giving due consideration to all such features of the conditions under which the lightning arresters are installed.

10. For use in the protection of transformers in districts where each transformer is protected by an arrester on the same pole and where the density of arresters ranges above 200 per square mile, the most economical arrester of the several types covered by this investigation is probably the cheapest arrester. It is entirely possible and even probable that the local conditions will have an important bearing in determining the best type of arrester to be used in any given locality, and that where the amount of shielding from buildings, trees, wires of other companies, etc., is very slight and where the securing of adequate ground connections for the arresters is expensive it would be preferable, even in areas of low density, to use arresters whose discharge capacity is considerably greater and whose discharge potential is considerably lower than the arresters covered by these investigations and to confine the installation of the arresters to the transformer poles.

11. It is possible, by carefully distributing the various types of lightning arresters over a large area and by securing the results of the performance of arresters over a period of years, to place the several types of lightning arresters used for the protection of transformers under conditions that are practically identical as regards the features which would affect the relative performance of the various types of lightning arresters, and to secure data which will permit a comparison of the relative merits of the several types of lightning arresters as protective devices.

12. It is entirely possible to make lightning arresters of the self-contained type, that is, of a type not requiring an external protecting box and so constructed as not to require or permit inspection. The annual maintenance cost of such arresters is practically limited to the replacing of damaged arresters, and the total annual maintenance cost as indicated by an experience of five years with several thousand such arresters is well below 1 per cent of their original cost of installation. The adoption of such types of arresters will result in a material reduction in the annual maintenance cost as compared with the older types.

13. A change in the form of lightning arrester gap from a cylindrical or spherical shape to parallel flat surfaces which was adopted by the manufacturers when changing from the wooden box type to the self-contained type of arrester, appears to result in a form of design which allows repeated heavy discharges without requiring renewal or adjustment of the parts, and has been an important factor in changing the design from a type requiring annual inspection, renewal and adjustment to a type which does not permit or require such annual attention.

14. The four types of arresters which have been designated by the letters *C*, *D*, *E* and *F* and which consist essentially of a resistance in series with a number of gaps, together with such additional features as antennas, compression chambers, expulsion chambers, and solenoids to vary the length of the gap following dynamic discharge, all appear to be practically identical in their value as devices to protect line transformers.

15. The type of arrester designated by *B*, which consists of a large number of gaps in series without any resistance, in addition to two other paths through a high and a low resistance shunting a large and a small number of gaps, appears to be considerably better protective device than arresters designated by *C*, *D*, *E* and *F*, and as far as can be determined from present information, this difference in its value as protective device appears to be due to features of its design.

16. With the aid of the data contained in this paper it should be possible to make estimates of the cost and results of lightning protection in Chicago with the same degree of accuracy as the estimates of cost of construction or maintenance of overhead lines, when the figures are averaged over a period of years.

17. The shielding effect of high buildings, trees and other similar features which might be considered as determining the exposure of the lines to lightning have an important bearing on the amount of damage that will be caused by lightning. In local areas in a distribution system which have for years shown a high percentage of troubles caused by lightning and where the troubles have been allowed to persist because of the thought that some mysterious influence local to the neighborhood attracted the lightning, it will probably be found that a large percentage of troubles is due to the lack of shielding from the surroundings or a low density of arresters, and that the trouble can be materially reduced by increasing the density of the arresters in the locality.

18. Great caution should be used in attempting to compare the results secured by lightning arrester protection in Chicago with results secured in other localities without giving due consideration to all of the factors which might affect lightning arrester performance.

In conclusion the author desires to express his appreciation to the General Electric Company and the Electric Service Supplies Company for their many helpful suggestions and hearty co-operation during the progress of the investigations.

DISCUSSION BY CHARLES P. STEINMETZ

Chief Consulting Engineer, General Electric Company

For some years we have realized that the conditions of lightning protection in primary distribution networks are in some respects materially different from those in high voltage transmission lines. Many of the phenomena, which are of serious danger in the high potential transmission line, such as steep wave front impulses, high frequency, traveling or standing waves, recurrent and cumulative oscillations, etc., can not develop to a dangerous magnitude in the primary distribution circuits. Dissipation due to leakage and the low voltage character of the insulation, and interference within the network of circuits and apparatus dampen oscillations. Because of the relatively low circuit voltage the electrostatic energy is small, and the most serious source or aggravating cause of lightning trouble in high potential circuits, the arcing ground or oscillatory spark, cannot develop. On the other hand, due to the low circuit voltage, the insulation strength is low compared with the disruptive strength of lightning voltages, and the transformers distributed all over the circuits make the system vulnerable throughout its entire extent.

The material given in Mr. Roper's paper is, therefore, the most valuable contribution ever made to the study of lightning disturbances in primary distribution networks, as it contains the exact performance records of nearly 90,000 lightning arrester years comprising 529 apparatus failures; that is, an amount of data greater than has ever before been collected on lightning disturbances in primary distribution systems.

I wish to say that all the phenomena observed by Mr. Roper are in complete agreement with, and all the conclusions which he drew from his experimental observations follow as theoretical conclusions the statement:

In primary distribution circuits, lightning is the discharge of a very high voltage (of the magnitude of hundred thousand volts) and correspondingly high electrostatic charge, instantaneously produced over a large part of the distribution system.

These voltages are far higher than the insulation of the transformers can stand for any appreciable time. It is thus a race between the time lag of the transformer insulation and the rate at which the lightning arresters can discharge the excessive voltage.

Thence immediately follows the all-dominant character of the lightning arrester density, that is, the number of lightning arresters per square mile or per lineal mile of circuit. The rate at which the excess voltage decreases is directly proportional to the number of discharge paths, that is, the number of arresters, and the time during which the transformer is exposed to excess voltage is therefore inversely proportional to the number of arresters.

Also follows the explanation of why transformer terminal boards and transformer bushings, though standing a higher sustained voltage than the transformer windings, are more vulnerable, since their insulation is air, which does not have the high time lag of the oil and solid insulation of transformer windings.

With 100,000 volts instantaneously impressed upon a 2300-volt lightning arrester, differences in the number, length or shape of the spark gaps, in the discharge voltage or equivalent sphere gap, within the range which may be expected between different types of such arresters, can have little effect, as the excessive overvoltage causes the discharge to begin instantly. An appreciable difference in the protective value, however, may be expected from the discharge rate of the arrester. It is interesting to note that the arrester (Type B) which shows a superiority sufficiently great not to be overshadowed by the effect of the arrester density—a 40 per cent decrease in transformer losses—is the only one in which the discharge capacity is not limited by a series resistance.

An arrester not at the transformer, but at a small distance from it, would have the same effect in discharging the excessive voltage of the circuit as an arrester at the transformer, and could thus differ in protective value only by the time lag required by the charge to travel the distance from the transformer to the arrester — about one ten-millionth of a second per 100 feet. Aside from this, all the arresters within the area covered by the instantaneously produced excessive voltage would equally share in protective value.

The question which then arises is that of the origin of such a very high voltage instantaneously produced over a considerable part of the distribution system.

I have given the phenomena of the thunder storm and the origin of the lightning flash considerable study for a number of years and find that such voltages must be produced on lines as a result of the equalization of cloud potential by the lightning flash.

Let *L*, Fig. 1, represent a wire of the primary distribution circuit, 6 meters above the ground *G*. Let *C* be a thunder cloud at an elevation of 1000 meters above ground *G*, having a potential difference of 20 megavolts against ground. There is thus an electrostatic field between cloud and ground, of a gradient of 20 kilovolts per meter. If the line *L* were perfectly insulated by its position in the electrostatic field 6 meters above ground, it would have a potential difference of 120 kilovolts against ground. It is, however, not insulated for such voltages, and while the cloud gradually builds up to 20 megavolts, a bound charge accumulates on the line *L*, by leakage through the insulation, corona, static sparks over the arresters, etc., and therefore keeps the line substantially at ground potential. The cloud discharges by a lightning flash, its voltage disappears, and the electrostatic field between cloud and ground collapses. The bound charge on the line *L* then becomes a free charge. Since as bound charge it kept *L* at ground potential, though by its position in the electrostatic field it would have had a potential difference of 120 kilovolts, as free charge it now raises the line *L* to 120 kilovolts above ground. Hence instantaneously, that is, with the rapidity with which the lightning flash discharges the cloud, a voltage of 120,000 volts is produced over that part of the distribution system which was in the electrostatic field of the thunder cloud.

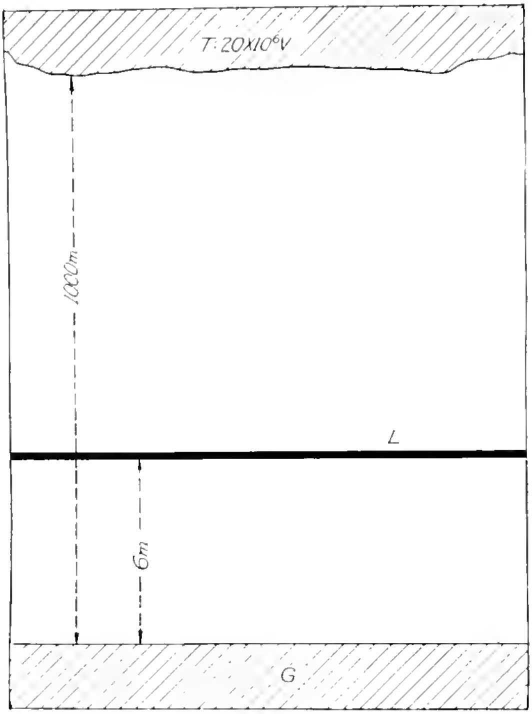


Fig. 1

This is the origin of the very high voltage instantaneously produced over a large part of the distribution system.*

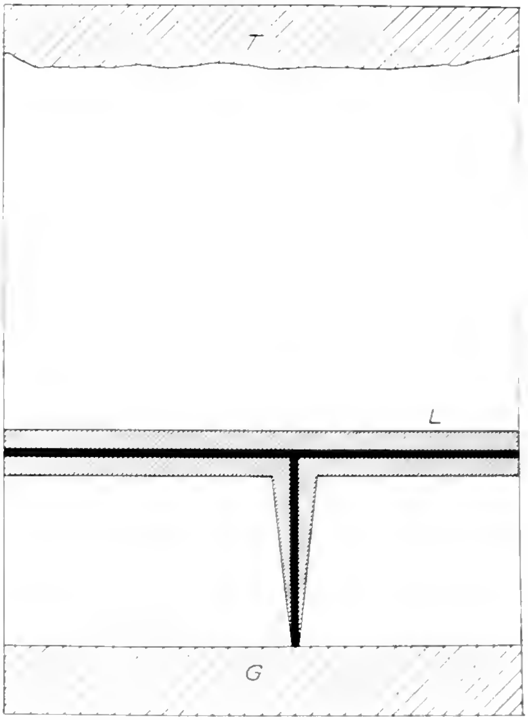


Fig. 2

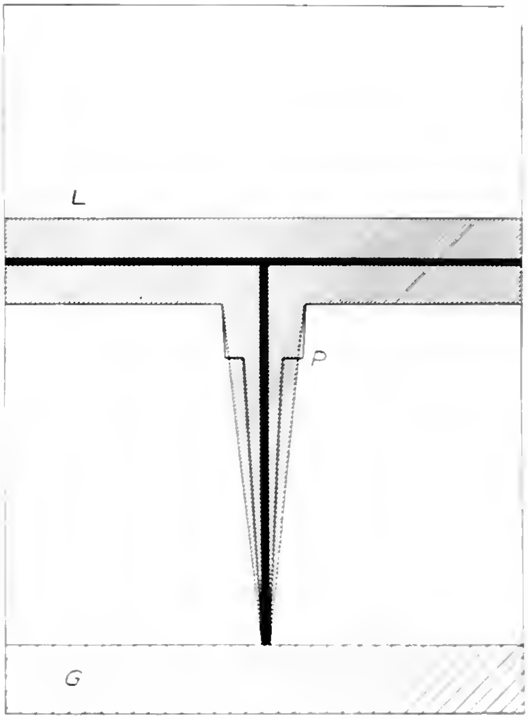


Fig. 3

This also explains why the impedance of the ground wire—which should be extremely high at the extreme rapidity of the discharge—seems to have so little effect, while even a small series resistance in the lightning arrester (small compared with the surge impedance of the line)—has a marked effect. The ground wire also is in the electrostatic field between cloud and ground, and thus accumulates a bound charge which becomes free charge by the lightning flash. This, however, is a tapering charge, increasing from zero (or rather equality with the bound charge of the ground surface) at the bottom to equality with the charge of the line at the top. This charge and the voltage produced by it are shown by the shaded area in Fig. 2. This, however, is the distribution of voltage and thus electrostatic charge (or dielectric field) existing on the ground wire during the discharge of the lightning arrester; that is, there is no transient retarding the starting of the discharge current in the ground wire, since the energy which the transient stores is already present in the free charge left on the wire. The discharge current thus starts simultaneously throughout the length of the ground wire, at a rate depending on the initial potential gradient, viz., 20 kilovolts per meter. Its rate of rise is given by:

$$e = L\frac{di}{dt}$$

or, with $L = 1.34 \times 10^{-9}$; $e = 200$ volts per cm. this gives:

$$\frac{di}{dt} = 150 \times 10^9 \text{ amperes per second.}$$

With a surge impedance of the distribution lines of 400 to 500 ohms, and the lightning arrester connected into the line so that the discharge current can reach it from two

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*In reality, the phenomena in the cloud are not as simple. As the result of rain formation, potential differences against ground build up in the cloud, varying in magnitude probably between 10 to 100 megavolts in the various parts of the cloud, depending on the moisture content and thus the rate of rain formation. These potential differences between different areas of the cloud are equalized by the lightning flash, so that in some parts of the cloud the potential difference against ground is instantaneously lowered, in others probably raised. Thus if in some part of the cloud the potential difference against ground is lowered by the equalizing lightning flash from 60 megavolts to 40 megavolts, the bound charge on the line under this part of the cloud decreases from that corresponding to 60 megavolts to that corresponding to 40 megavolts, and a free charge corresponding to 20 megavolts thus appears. In other parts of the cloud, by the same lightning flash, the potential difference against ground may be raised from 20 to 40 megavolts, setting free on the line under this part of the cloud a charge of opposite polarity.

wires, giving a surge impedance of 200 to 250 ohms, a voltage of 120 kilovolts would give a discharge current of 480 to 600 amperes. It would thus require about one three-hundred-millionth of a second for the current in the ground wire to build up. That is, the time lag of the ground wire would be of the magnitude of one three-hundred-millionth of a second.

Suppose, however, a series resistance is used in the lightning arrester. The distribution of the bound charge (set free by the lightning flash) along the ground wire would still be the same as shown in Fig. 2, or by the shaded area in Fig. 3. The distribution of voltage during the discharge of the lightning arrester, however, would be as shown by the heavy drawn line in Fig. 3, having a break equal to the voltage drop across the series resistance at the point P, where the arrester is located. That is, a rearrangement of the charge and voltage distribution in the ground wire becomes necessary, resulting in a transient retarding the discharge, that is, a time lag which limits the protective value in this case, though the resistance may be far below the surge impedance of the lines.

From this explanation of the phenomena we can realize the limitations within which the conclusions of Mr. Roper's paper apply. They probably apply to all extended primary distribution systems, that is, networks of relatively low voltage, with about the same magnitude, and the numerical values are modified only by the climatic conditions, that is, by the frequency and severity of thunder storms, and in this respect Mr. Roper's statement is rather too modest. They would not, however, apply to circuits of materially high voltage, in which the insulation strength of the circuits and the discharge voltage of the arresters are not negligible compared with the instantaneous voltage of the free charge produced by the lightning flash. Also they would not apply to high voltage transmission lines, in which the apparatus is localized at the terminals, where the area affected by the free charge is only a part of the line, and where dissipation through leakage, interference, etc., is small and secondary effects such as sparks produced by the charge predominate; and where oscillatory waves piling up the voltage by reflection, etc., and secondary effects produced by the discharge, such as oscillatory arcs, make available for destructive action the engine power back of the generators.

DISCUSSION BY J. L. R. HAYDEN

General Engineering Laboratory, General Electric Company

The large amount of data given in Mr. Roper's paper enables us to investigate some further features. Some information on the protective screening effects of buildings, trees, etc., may be expected from the following reasoning: Column 7 of Mr. Roper's paper gives the area covered by the lines in each of the 192 sections. As most of the sections are one square mile, these values represent the area covered by the lines (except in a few smaller sections, where correction is easily made). In general, where all or a large part of the section is covered by the lines, it may be expected that the section is well built up, and the screening effect of buildings, etc., therefore a maximum. Inversely, sections of which only a small part is covered by the lines probably are sparsely built up, and the screening effect therefore a minimum. By dividing the data into two parts, for small and for large area of section covered by the lines, and working up the two separately, a difference in the results should indicate the difference between low and high screening.

The material was divided into eight groups by the arrester density, so that each group contained about the same number of failures. Then each group was divided into two sub groups of about the same number of failures, one comprising the sections of small area covered by the lines, that is, probably low screening, the other the sections of large area covered by the lines, that is, probably high screening. The total material, and the two subgroups separately, were then worked up into empirical curves of the form proposed by Mr. Roper, by the $\Sigma\Delta$ method[1] and gave the three curves shown in Fig. 1, of the respective equations:

T: Total data $y=\frac{1.62}{x^{1.6}}$

S: Small part of sections covered by the lines; probably low screening $y=\frac{1.64}{x^{1.35}}$

G: Great part of sections covered by the lines, probably high screening $y=\frac{1.59}{x^{1.85}}$

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[1] Steinmetz, Engineering Mathematics, Chapter VI, C.

where

y = percentage of failures per year;
x = arrester density, hundreds per square mile.

It is interesting to note the difference of the exponents, which means that curve G is much steeper than S. At low arrester densities the three curves come together, but increasingly separate with increasing arrester density, so that with 120 arresters per square mile there is a difference of 12 per cent; 38 per cent at 200 arresters; and 59 per cent difference in the percentage of failures at 300 density.

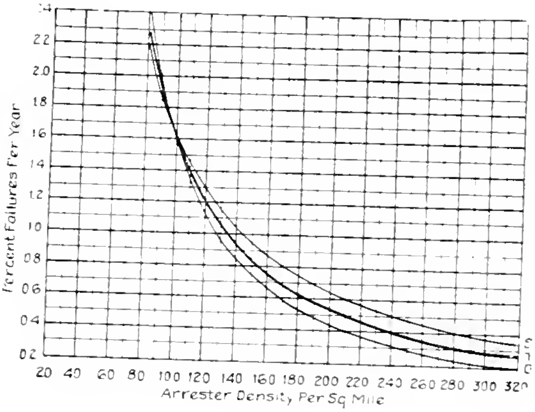


Fig. 1

We may account for the increase of screening with increasing arrester density thus: At low arrester density each arrester has to drain a considerable length of line, and the freedom from charge of its immediate neighborhood, due to the screening, has little effect on the total charge which the arrester has to carry off. With high density of arresters, however, each arrester drains only a small area, and the reduction of the volume of the discharge by the screened area is much more appreciable.

The exponent 1.6 differs slightly from the value 1.75 found by Mr. Roper, probably due to the different grouping of the data here used. This suggests a change of the curve shape between high and low arrester density. Therefore the data were worked up separately for the range of low density, medium density and high density. This gives the three curves shown in Fig. 2, together with the average curve T, of the respective equations:

L: Low arrester density $y = \frac{1.71}{x^{2.12}}$

M: Medium arrester density $y = \frac{1.48}{x^{1.6}}$

H: High arrester density $y = \frac{1.04}{x^{1.07}}$

As seen, the low density curve is very much steeper, about twice as steep, as the high density curve. In other words, increasing the number of arresters has much more effect at low than at high arrester density: At low density a 1 per cent increase of arrester decreases the failures by 2 per cent, while at high density it reduces the percentage of failures by 1 per cent only.

When using all the data, Mr. Roper's equation of failures gives:

$$y = \frac{A}{x^a}$$

the constants

$$a = 1.6 \text{ and } A = 1.62$$

When using the exponent 1.6, but using only a portion of the data for the calculation A, the value of A so derived compared with the average $A = 1.62$ shows how the failures of this group compare with the average.

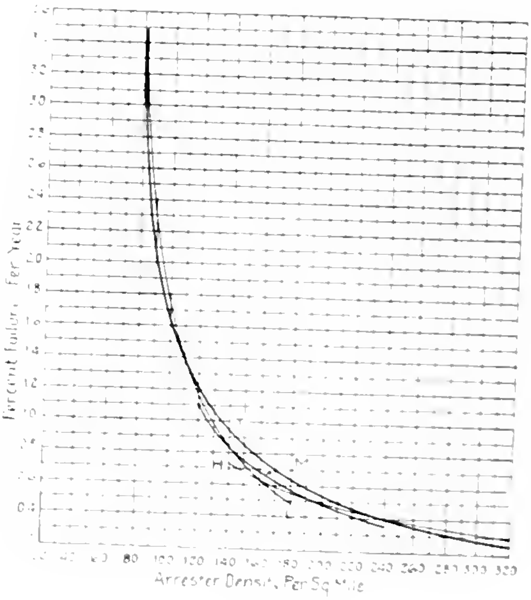


Fig. 2

In Table I are given the values of A for the 9 conditions, viz., low density, high density and total, low screening, high screening and total. While the numerical values

TABLE I

$$y = \frac{A}{x^{1.6}}$$

$A =$	Low Density	Total	High Density
Small Area	1.69	1.86	2.05
Total	1.61	1.62	1.63
Great area	1.54	1.41	1.29
Max. dif.	.15	.45	.76
Per cent:	9.3	27.8	46.7

themselves have little meaning, their general trend seems to be decidedly significant in indicating the relative increase of failures with decreasing arrester density and increasing screening, and the increased effect of screening at higher arrester density as shown by the percentage difference given in the table.

At high arrester density, the exponent a in Mr. Roper's equation approaches 1. That is, the percentage of failures decreases inversely proportional to the number of arresters; or in other words, the total number of failures approaches constancy. This suggests plotting not the percentage of failures but the total number of failures as function of the number of transformers or arresters per square mile. This is done in Fig. 3. Approach to constancy suggests the exponential function. This is the more clearly indicated, as the phenomenon is one of probability, and the probability function is exponential.

If then t = number of transformers lost per square mile per year, by the $\Sigma\triangle$ method the equation is derived:

$$t = 6.8 \times 10^{-.94x} + 0.92$$

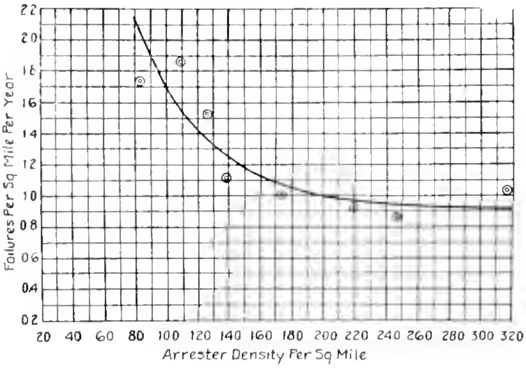


Fig. 3

that is, for extremely high lightning arrester densities the average failures approach a minimum of 0.92 transformers per square mile per year. For very low arrester densities they approach 7.7 transformers.

This equation is given by the curve in Fig. 3, and the 8 groups of data marked by the circles.

DISCUSSION BY V. E. GOODWIN

Lightning Arrester Engineering Department, General Electric Company

The art of protecting electrical apparatus against voltage disturbances has made material progress during the past ten years. This progress has been due, not only to the development of new protection methods, but also to a wider knowledge of the nature and character of the effects of lightning on electric circuits. We have had a good conception of these effects on high voltage circuits, but until recently have had little accurate data on low voltage distribution circuits. Low voltage arresters have therefore been designed to handle a wide range of impulse and high frequency conditions. These arresters must have low cost and reliability; hence it is difficult to incorporate all the best protection features for this entire range of conditions and still have an arrester which is cheap enough for the service.

In this paper, Mr. Roper has given us the most complete operating record which has ever been collected. This paper is of greatest value since it shows the failure of transformers and fuses blown during lightning storms covering a period of five years and includes an average of some fifteen thousand installations. This paper clearly shows the futility of trying to draw conclusions on the relative merits of protective schemes without the most careful study of operating data including several thousand installations and comparing each year's operation with each successive year. A study of this report shows that with high density of arresters, transformer failures are reduced to a fraction of a per cent per year. These and other data show the prevalence of a certain class of disturbance having high rates of change of potential and large destructive charges. Such disturbances as these require the use of either a few arresters having high discharge rates or the use of a larger number of low discharge rate arresters in parallel. This point is further brought out by the fact that the Type B arrester is shown by Mr. Roper's paper to be superior to all the other types.

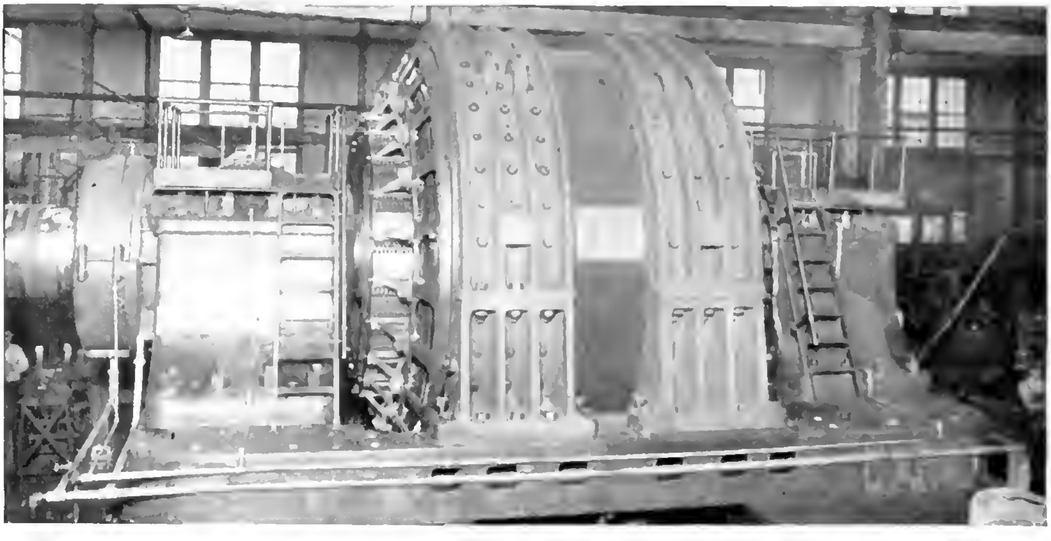
As these tests progressed we have been able to better understand the nature of disturbances on these circuits and to work on the development of a protector which will have even greater discharge rates and at the same time incorporate the best features of the all-porcelain enclosed type.

By studying the transformer losses by storms and by years, it is noted that the losses seem to be confined to certain storms and that these losses for a given storm are grouped into a few square miles. The thought naturally comes to mind as to the possibility of many of these failures having been caused simultaneously by one unusually heavy lightning discharge. Such a discharge would release a very large bound charge on a system as large as the Commonwealth Edison Company. Such a condition would suggest the application of a few additional arresters having a high discharge rate, as, for example, the aluminum or oxide film types, these arresters to be distributed about the city in the most important points. The same result could be obtained by the use of a greater number of arresters having a discharge rate intermediate between the aluminum and the multigap types.

The data presented in this paper, while collected on a four-wire grounded neutral system, probably represent conditions common to most low-voltage distribution circuits. However, non-grounded circuits may present slightly different results and it would be most interesting if some of the large companies operating non-grounded systems would tabulate their results.

New Direct-current Reversing Motor for Steel Mill Drive

The motor illustrated below has just been completed by the General Electric Company for the Tata Iron & Steel Company, Sakchi, India. It is a double unit machine rated 6300 h.p., 80 r.p.m. with a speed range from 60 to 100 r.p.m. Speeds from 60 to 80 r.p.m. are secured by means of generator field control and from 80 to 120 r.p.m. by motor field control. Power is supplied by a flywheel motor-generator set, consisting of a 6500 h.p., 375 r.p.m. induction motor and two 2500-kw. generators. The flywheel weighs 50 tons and the motor is normally operated non-reversing, but may be quickly stopped and reversed when necessary. The armature of the motor weighs 132 tons and was the heaviest crane lift on record in the shop in which it was built.



6300-h.p., 80 r.p.m., Direct-current Reversing Motor for Steel Mill Drive; 22,000-h.p. Momentary

The Bowl-enameled Mazda C Lamp

A NEW DEVELOPMENT IN ILLUMINATION

By Ward Harrison

Illuminating Engineer, National Lamp Works of General Electric Company

The new lamp described in this article was developed to provide a high-powered light source for industrial plants which would be free from the objectionable glare that is common with existing types of lamps. The enameling on the lower half of the bowl effects almost complete diffusion of the transmitted light, and when the lamp is used with special steel reflectors the resulting illumination is noticeably free from glare and sharp shadows. The enamel forms a smooth surface which does not collect dirt; it withstands the action of water, acid fumes, and ordinary mechanical abrasion incident to shipping and handling.—Editor.

Recent tests and experience have shown the desirability of much higher illuminations in industrial processes than were considered necessary a few years ago. Increases in production of from 8 to 25 per cent have been registered in specific cases where improved lighting systems providing more foot-candles on the work have been installed. However, in nearly every case, the greater illumination has made necessary the use of higher powered lamps. This has brought about a serious increase in glare in those instances where the larger lamps were used in the older styles of open reflectors designed for smaller lamps of a less brilliant type. In fact, in extreme cases the change has so increased the glare as to have actually resulted in an installation of reduced effectiveness.

In the early days of tungsten-filament lamps, practically half of those sold were frosted to reduce the amount of glare. During recent years, however, this proportion has gradually dwindled with the result that today the proportion of frosted lamps used is very low indeed, even though the size and power of the lamps used have increased materially.

Various other means have been employed in industrial lighting to secure better diffusion than that provided by clear lamps in open reflectors. Diffusing globe units, reflecto-cap diffusers, opal-cap units and even semi-indirect and totally indirect lighting systems have been adopted in industrial locations suited to their use. However, even though these installations were often highly successful where intelligent supervision was given to the use of the equipment, no one of these types has appeared to be sufficiently desirable from all the different standpoints of diffusion, efficiency, cost of maintenance, and adaptability to have become recognized as a standard type for general industrial lighting. By far the greatest percentage of industrial lighting was still done by clear lamps and open reflectors.

The recent RLM standardization effected the production of a steel reflector more suited to the Mazda C lamps than the previous types of shallow and deep-bowl reflectors. Used in conjunction with the RLM dome reflector, the newly developed bowl-enameled lamp presents a lighting unit which has great possibilities as a standard unit for a wide variety of industrial locations. In fact, it is estimated that this combination meets the lighting requirements of at least 85 per cent of industrial plants.

Fig. 1 The Bowl-enameled Lamp

In appearance the bowl-enameled lamp differs from a bowl-frosted lamp in that the bowl is decidedly white and might be described as having an egg-shell finish. When lighted, the lamp can be viewed end-on at close range without discomfort; there is a decided contrast in this respect between a frosted lamp of a given wattage and a bowl-enameled lamp of the same wattage.

The enamel is superficially applied. Its edge is vignetted or shaded off as indicated in Fig. 1, thus avoiding the possibility of a sharp line of cut-off on the reflector. As regards durability, it will resist practically any mechanical abrasion it is likely to encounter; it can be scratched or scraped only by deliberate effort with a sharp knife or similar tool. It will not chip off. Repeated tests have shown it to be proof against deterioration by acid fumes. Lamps have been immersed for a considerable period of time in boiling water without any damage resulting to the enamel. From all test data available, it is safe to conclude that the enamel will not discolor whatever during the life of the lamp.

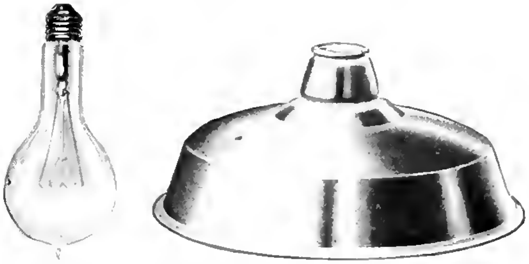


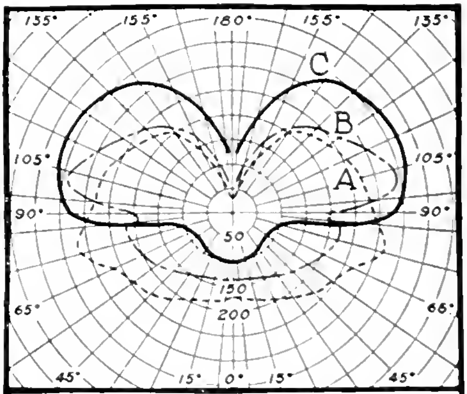
Fig. 2. This Combination Will Meet the Requirements of at Least 85 Per Cent of Industrial Plants

The lamp can be readily washed. It differs from a bowl-frosted lamp in this respect. A frosted lamp when placed under water becomes almost transparent, with the result that it is very difficult to detect the presence of dirt or grease, which will show up only after the lamp is dry. The bowl-enameling, on the other hand, appears decidedly white even under water, and dirt is easily detected and, also, easily removed. Because of its smoother surface, the new lamp does not collect dirt as readily as a frosted lamp.

The bowl-enameled lamp was designed principally for use with open reflectors. When used in this manner, the lower part of the lamp acts as a reflecting and diffusing surface, serving the same purpose as the opal cap. Its advantages over the opal cap are greater ease and decreased breakage in cleaning, and the absence of any space between the lamp and the cap in which dust may collect.

Bowl-frosting of Mazda C lamps, particularly n the larger sizes and in industrial lighting, has not sufficiently reduced the brightness of the lamps as to fully meet the requirements in many locations. Bowl-frosted lamps of the 100-watt size have a maximum brightness of something like 75 candle-power per square inch. The bowl-enameled lamp has a brightness of about 10 or 12 candle-power per square inch. If one looks at a lighted bowl-frosted lamp, he will observe that the diffusion is by no means complete, for at the center of the frosted area there will be seen a brighter spot an inch or so in diameter, whereas with complete diffusion, as in the case of the bowl-enameled lamp, the entire area is of the same order of brightness.

The distribution curves for the clear, bowl-frosted and bowl-enameled lamps form an interesting comparison of their light-directing properties. In Fig. 3 are shown typical distribution curves for these lamps, each of the same size. In the clear-bulb lamp, the amount of upward and downward light is, of course, practically the same, so that when it is used in an open reflector a large amount of the illumination comes directly from the concentrated lamp filament. Shadows are therefore comparatively sharp and reflected glare from polished surfaces is likely to be serious. Bowl-frosting partially diffuses the downward light from the filament, but redirects upward only a very small proportion of the light flux.



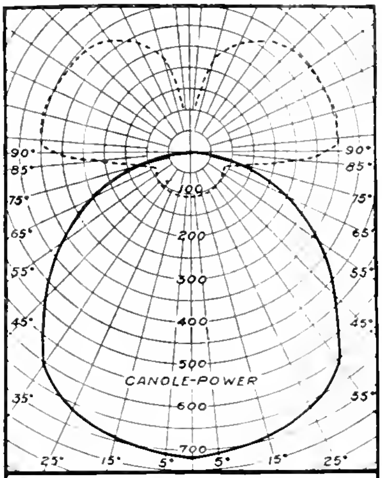
PERCENT TOTAL LUMENS OF CLEAR LAMP

ZONE	A (CLEAR LAMP)	B (BOWL FROSTED)	C (BOWL ENAMELED)
0-60	21	17	9
0-90	51	40	25
90-180	49	56	69
0-180	100	96	94

Fig 3. Comparative Candle power Distribution Curves for Mazda C Lamps. (A) Clear, (B) Bowl frosted, (C) Bowl-enameled

Bowl-enameling on the other hand not only diffuses the downward light coming from the bowl of the lamp, but what is very important, serves to redirect a large portion of the light from the filament against the upper reflector.

For a given light flux, the brightness is, of course, inversely proportional to the area of the source. In the combination employing the bowl-enameled lamp with the RLM dome reflector, the major portion of the effective light comes from the surface of the large diameter reflector instead of directly from the lamp filament. The larger light source of lower brightness has the direct result also of softening the reflections of the source from polished or oily surfaces. These specular reflections, resulting in what is termed reflected glare, are often the cause of more serious eyestrain than direct glare. Even where the lamps are properly shielded by reflectors or shades so that a workman does not encounter the direct glare of the source, the lamp's position may often be such that he will be greatly hampered by the reflected glare, which comes from his work or tools and is in his line of vision throughout the day. This can only be insured against by some means such as the bowl-enameled lamp, which well diffuses the downward light rays from the filament of the lamp.



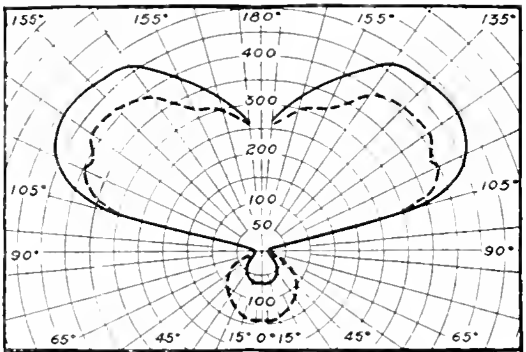
—RLM STANDARD DOME-200 WATT BOWL-ENAMELED MAZDA C LAMP

----200 WATT BOWL-ENAMELED MAZDA C LAMP WITHOUT REFLECTOR

ZONE	LUMENS	% TOTAL CLEAR LAMP
0-60	1649	53
0-90	2055	66

Fig. 4. Candle-power Distribution Curve of the Bowl-enameled Lamp in an RLM Standard Dome Reflector

The comparatively large light source of low brilliancy provided by this unit has an added important advantage in softening shadows and in avoiding the characteristic denseness and sharp edges which come from concentrated light sources, and which are often both annoying and dangerous in industrial locations. Dark sharp shadows interfere with fast work and increase spoilage. In some instances the shadows cast by moving parts may be so sharp and dense as to cause confusion between the object and the shadow, with consequent likelihood of injury to the workman. The softer shadows with shaded edges, characteristic of larger effective light sources such as the bowl-enameled lamp RLM dome combination, avoid these undesirable results and are important factors in popularizing the use of this unit.



---200 WATT, CLEAR MAZDA C LAMP IN INDIRECT LIGHTING FIXTURE

—200 WATT, BOWL ENAMELED MAZDA C LAMP IN SAME FIXTURE

PERCENT TOTAL LUMENS OF CLEAR LAMP

ZONE	CLEAR LAMP	BOWL-ENAMELED
0-60	11	5
0-90	14	6
90-180	61	69
0-180	75	75

Fig. 5. Comparative Candle-power Distribution Curves of a Semi-indirect Lighting Fixture.
(a) Fitted with Clear Mazda C Lamp,
(b) Fitted with Bowl-enameled Mazda C Lamp

From the standpoint of absorption, the total output of an RLM standard dome reflector equipped with a bowl-enameled lamp will be of the order of 10 to 12 per cent less than for the same reflector equipped with a clear lamp. This increased absorption is about the same as that obtaining with the opal cap and about twice that obtaining with a bowl-frosted lamp. A reasonable amount of light can well be sacrificed for a major gain in avoidance of glare effects and in softness of shadows. It is important to note, however, that with a deep-bowl steel reflector, a bowl-frosted lamp results in a loss of about 10 per cent of the light, while a bowl-enameled lamp results in a loss of from 25 to 30 per cent of the light. This is due in both cases to the bottling-up of the light in the narrow reflector by the frosted or enameled area of the bulb. Distribution curves show, however, that most of this loss occurs above the angle of 25 degrees with the vertical, so that there will be exceptional cases where the bowl-enameled lamp can be used to good advantage in a deep-bowl steel reflector, but only in such cases is this combination to be recommended.

Bowl-enameled lamps are now available in seven sizes; viz., the 100, 150, 200, 300, 500, 750 and 1000-watt lamps.

While, as has been suggested above, one of the most important fields of application of the bowl-enameled lamp is its use in conjunction with steel reflectors for industrial lighting, its possibilities are by no means limited to this field. When used in place of clear bowl-frosted lamps in direct lighting opal glass reflectors, it provides illumination characterized by the same order of improvement in diffusion and avoidance of glare that is obtained when used with steel reflectors.

Another interesting possibility is the use of bowl-enameled lamps in semi-indirect fixtures which have a rather large downward component, such as is found in the case of light-density glass equipment. Since the bowl-enameling in itself redirects upward a considerable amount of the light flux from the lamp, the result of placing a lamp of this kind in a light density semi-indirect bowl is to change the distribution by throwing more light on the ceiling, thus lessening the direct light and the apparent brightness of the fixture. Fig. 5 illustrates the distribution curve of a popular semi-indirect unit used with a clear lamp and the same fixture when equipped with a bowl-enameled lamp. In installations such as offices and drafting rooms, where the maximum diffusion and low brightness of the fixture are often considered highly desirable, existing equipments considered lacking in these characteristics can be readily adapted by the use of the bowl-enameled lamp, to give an improved light distribution.

Fig. 6. A Modern Lighting Installation in an Armature-winding Room RLM Standard Dome Reflectors and 300-watt Bowl-enameled Lamps. Spaced 10 by 12½ feet. Mounted 11 feet above floor Average illumination obtained, 17 Foot candles

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