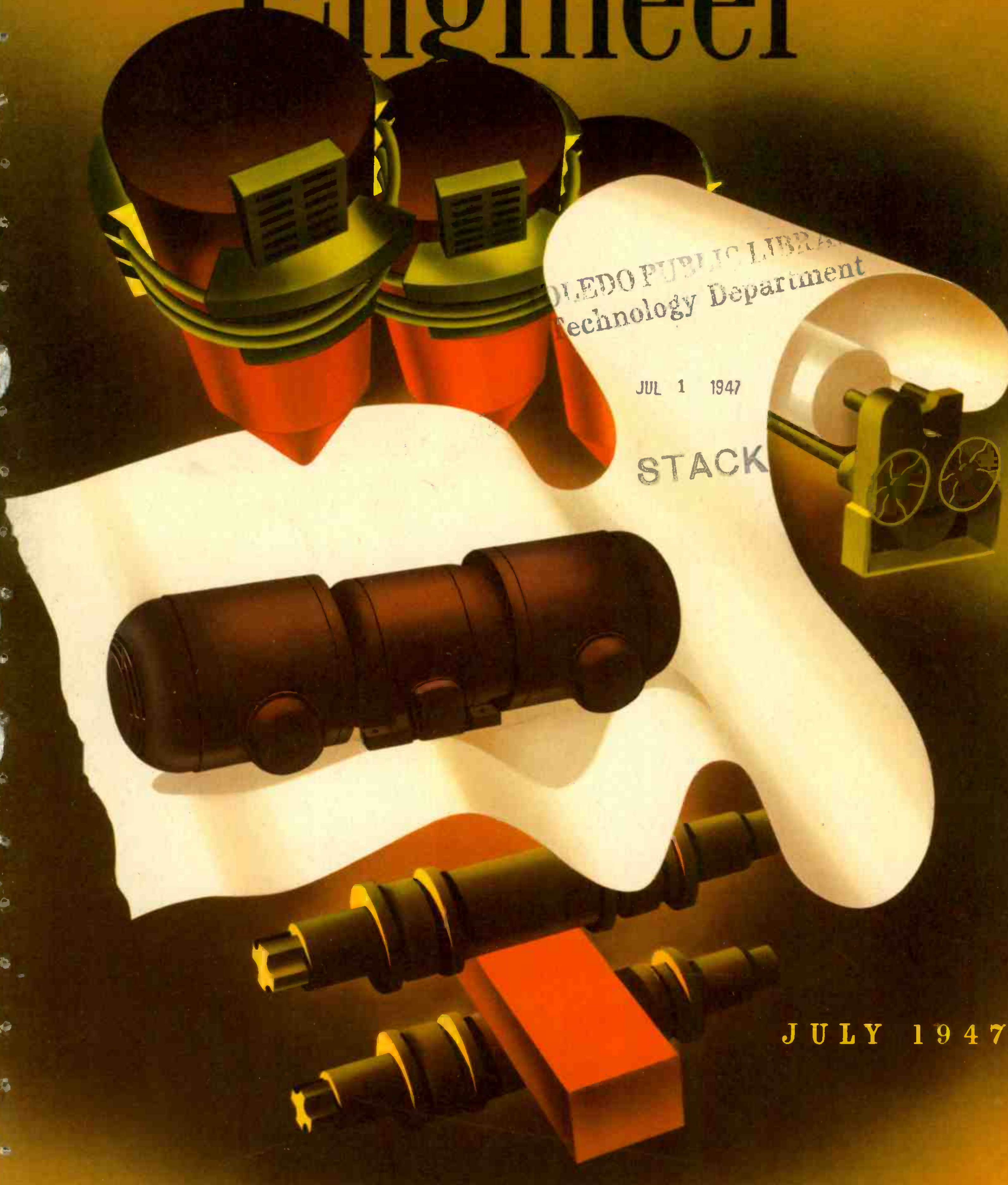
WESTINGHOUSE

Engineer



JULY 1947

Circuit Interruption

Few pieces of apparatus have presented more problems, or been more difficult to build than circuit breakers. This comes about to a large extent because of the necessity of stopping the electron stampede on short notice and very quickly. Of course there was a time when speed of interruption of an arc was not held to be important. A circuit breaker was asked only to put out the arc; the time didn't matter much. If it took the better part of a second or even more than a second no one cared except the maintenance men who had to repair the burned contacts and clean up the carbonized oil, if oil was used.

When systems grew large and interconnection between them began, a fault not quickly isolated resulted in instability, meaning that the tie between different parts of a system or the interconnection between systems was severed, impairing interrupting service. Engineers became aware of the importance of circuit clearing time. In 1926 the 220-kv Conowingo breakers capable of interrupting 2½ million kva were heralded for their fast operation—25 cycles. Before long this was considered too slow, and by 1930 breaker-operation times of 15 cycles became standard. In 1932 the rated time was lowered to 8 cycles for practically all outdoor, high-voltage breakers. Since 1940 five-cycle breakers have been standard at voltages of 115 kv and above. Now we have the three-cycle breaker for high-voltage systems whose stability conditions require it. On recent tests of Westinghouse 220-kv breakers at Grand Coulee Dam a total of 35 interruptions were made, all of them in less than three cycles. The heaviest current interruption was achieved in 1.85 cycles, although this was unusual.

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Engineers quaintly refer to any visible evidence of breaker operation as "demonstration." Of this there used to be plenty. It doesn't require overlong memories to recall when a breaker spewing out a barrel or so of oil resulted in no more concern than a few cuss words and calling out the mop brigade. Smoke, bulging tanks, trembling of the foundations—anything short of a fire—was simply evidence that a breaker had successfully performed a tough job. But not today. Anything more than an audible thud is a black mark against the breaker. On one of the recent tests at Grand Coulee Dam the observers couldn't be sure whether the breaker had performed a high-current interruption until the oscillogram had been developed. It showed an interruption of 7½ million kva, a record.

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Engineers used circuit-interrupting devices for 40 years before they had a clear idea of how they worked. Of theories there were aplenty, but even up to the late '20s the conceptions of arc extinction were, in short, cockeyed. About that time Dr. Joseph Slepian began some fundamental studies of arcs and their habits. Those studies resulted in the classic papers on short and long arcs presented to the AIEE in 1928 and 1930, and which laid the groundwork upon which such designers as J. B. MacNeill, R. C. Dickinson, B. P. Baker, H. M. Wilcox, L. W. Dyer, and others fashioned the now large family of De-ion interrupting devices.

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Slepian introduced the concept of extinction of an a-c arc as a race at each current zero between recovery of dielectric strength of the arc path and the rising voltage, with dielectric recovery having an invaluable head start of about 250 volts (peak) at the instant of current zero.

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Another of the new concepts was that in the interruption of a short a-c arc to a "cold" cathode, most of the dielectric strength occurs in a thin positive space-charge layer of less than 1/32 inch next to the cathode, this layer being developed as electrons move out of the space with great speed—in a few microseconds at most. This led Slepian and his associates to suggest that one good way to interrupt an arc would be to chop it into many short ones and by magnetic action keep the arcs hustling over cold contact surfaces, i.e., cold cathodes, each one of which provides its quota of approximately 250 crest volts dielectric strength essentially instantaneously after each current zero. The familiar metallic-plate De-ion air circuit breaker thereupon was born.

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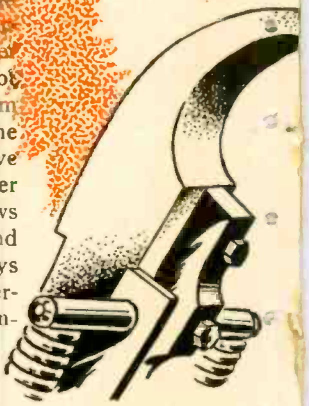
The role of oil in circuit interruption had not been understood up until about 1930. It was generally held that the gasification of the oil by the hot arc was a nuisance to be lived with. Slepian proved the arc to be indispensable to circuit interruption. In his words, "The decomposition of the oil mixed turbulently with the arc space . . . is the principal cause of the arc-interrupting capacity of the oil circuit breaker. The oil circuit breaker is a gas-blast switch, the gas blast arising from the decomposing oil.

"This point of view leads to conclusions diametrically opposite to those usually held as to desirable and undesirable features in oil circuit breakers. From this point of view, the decomposition of the oil instead of being entirely undesirable is the very feature which makes the oil breaker function. To improve the oil breaker, the rate of formation of gas should be increased, not decreased, provided of course that the gas formed is thoroughly mixed with the ionized gas which is carrying the arc."

From this the designers built the De-ion grid in which the arc is confined and forced to meet, throughout its full length, ample quantities of fresh oil for gasification and arc-space deionization. The task has been to make oil available for gasification but to keep the arcing time short to reduce arc energy and oil deterioration.

The arc, itself, had long been held to be a nuisance. Many schemes had been tried—such as variable resistances and high vacuum—to interrupt circuits without it. Slepian proved this unwise even if it were possible. As he stated the matter: "In the past the impression has been general that the arc is an obstacle and a nuisance which annoyingly intrudes itself and prevents easy control of high-power circuits. It is believed that if the arc did not appear of itself, or could be prevented from appearing by some simple means, then the problem of circuit interruption would have an easy and ideal solution. However, closer scrutiny of the fundamentals involved shows that this impression is altogether false, and that far from being all nuisance, the arc plays a very necessary and useful role in circuit interruption and that if the arc did not occur spontaneously it would have to be invented."



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Interrupting capacities have come a long way since the days of the first Niagara Falls plants, where the first appreciable concentration of current appeared. The interrupter used there was an air switch, rated at 5000 horsepower, as was the early custom. Since then interrupting capacities have risen as steadily as the generating capacity behind potential faults has mounted. It rose in reasonable increments to 3½ million kva, where it has stood for several years. The tests at Grand Coulee Dam raised this to 7½ million.

And the end is not yet. Engineers planning water-power developments of the Pacific Northwest envision tightly connected generating capacities that, if they materialize, will call for ten million kva or even higher. Circuit-breaker designers are quite calm about all this. They anticipate they can meet the occasion without requiring any new interrupting principle or a fundamental change in mechanisms.

WESTINGHOUSE Engineer

VOLUME SEVEN JULY, 1947 NUMBER FOUR

On the Side

The Cover—The decision having been made to feature the Rototrol on the cover of this issue (as well as on the inside—see p. 121), the problem became not what to include but what to omit. The Rototrol has so many regulating functions that the choice is difficult. The artist, Dick Marsh, has portrayed but three: rolling of steel, making of paper, and arc-furnace production of alloy steel.

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The most powerful fighter plane ever built is the McDonnell "Banshee" (XF2D) recently announced by the Navy. Without disclosing details of engine or plane performance, the Navy simply says that the engines provide more thrust than available in the previous most powerful jet-propelled fighter plane. The output is more than equivalent to a reciprocating-engine output of 5500 hp. The Banshee employs two Westinghouse 24C jet engines, the 24 representing the diameter in inches. Like its predecessors, the 9A, 19B, and 19XB (which powered the Navy's first all-jet plane, the Phantom), the 24C consists essentially of an in-line arrangement of an axial-flow compressor, a combustor, a gas turbine, and a tail-pipe. Its small diameter for its high thrust permits the engines to be buried in the wings, cutting drag to a small figure.

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A sheet of steel 42 inches wide emerges at a speed of a mile a minute from the new tandem continuous cold strip mill of the Weirton Steel Company. The six motors driving the five stands and the reel aggregate the most power ever applied to such a mill—17 550 hp. The last stand is driven by a 4500-hp twin motor.

Editor
Charles A. Scarlott

Editorial Advisors
R. C. Bergvall
T. Fort

In This Issue

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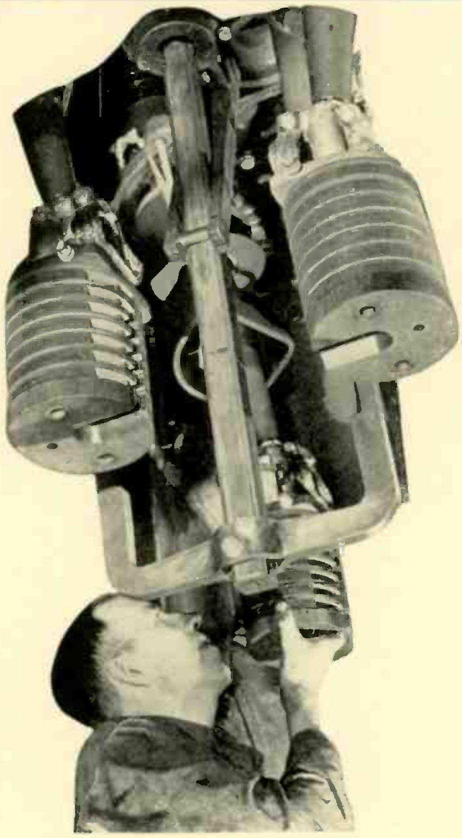
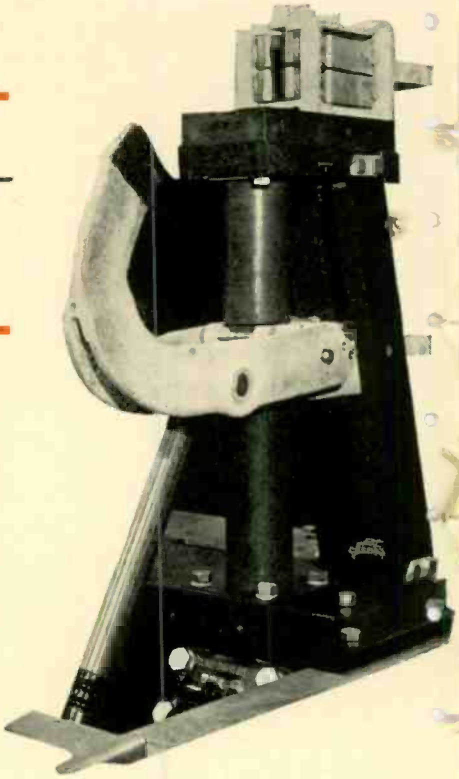


Circuit Breakers—Oil or Oilless?



The degree to which the oilless circuit breaker, still a relative newcomer, has muscled in on the field of the oil breakers, particularly for low and medium voltages, might suggest the doom of the oil breaker. A close examination of the high-voltage, heavy interrupting duty application, however, does not support that extrapolation.

M. H. Hobbs
Manager, Switchgear Engineering
Westinghouse Electric Corporation

Now is a good time to review the record of the oil and the oilless circuit breaker to see if a definite pattern is evident as to the field of application of the different types. The oil breaker has the longest history, but the oilless variety has come along rapidly since the introduction of the De-ion air circuit breaker for high-voltage (13.8-kv) service in 1929. In the ensuing years a large amount of research and development work has been done on various forms of oilless circuit interrupters, both in the United States and abroad. For voltages up to 600, air breakers have been available for many years. More recently commercial lines of breakers for 2.3- to 34.5-kv indoor service have been produced. A few high-voltage breakers have been installed outdoors. These have been largely of an experimental nature to provide service experience for comparison with that of oil breakers.

Circuit breakers can be considered in four major classes, each of which covers a definite field and presents its own problems of design and application:

a—Low voltage, 600 volts and below, as used for station auxiliary circuits and industrial plants of all types.

b—Medium voltage and capacity, 2.3 to 15 kv, for distribution substations, small generating stations, and industrial plant primary circuits.

c—Heavy capacity for large generating stations and substations, 15 to 34.5 kv.

d—High voltage for outdoor service, 15 to 287 kv.

Low-Voltage Circuit Breakers

For service voltages below 600, air circuit breakers have a long, satisfactory service record, and have become the standard for this class of duty. This does not mean that oil breakers have not been used in considerable quantity, as they continue to be preferred in some refineries and chemical plants where atmospheres are corrosive or explosive. However, the large majority of low-voltage circuits are served by air breakers, even when outdoor installation in weatherproof housings is required.

The favorable position of the air type has been maintained and improved in recent years by several advances in design. For example, ten years ago the open arc was replaced by multiple-plate arc chutes, which provided limitation and control of the arc gases during circuit interruption. This permitted mounting of breakers in metal enclosures of reasonable size, later in metal-enclosed switchgear with the draw-out method of disconnecting and removal, which has become standard for central-station and industrial structures.

At the same time, the carbon-tipped arcing contacts used with the completely open-type breaker were superseded by metal contacts, using arc-resisting alloys such as copper tungsten. The main contacts were changed to solid silver-to-silver line type that supplanted the multiple leaf elliptical brush, which was difficult to manufacture and maintain.

More recently there has been a change to pole units mounted on individual bases of Moldarta, which incorporate the terminal studs and permit supporting the breaker on steel instead of a slab of slate, ebony asbestos, or other insulation. The design at present is being developed for the smaller ratings, and will also be extended to the higher capacities.

Particular attention is now being given to the selective tripping of low-voltage air breakers. This becomes of great importance on generating-station auxiliary circuits and in large industrial plants. The problem differs somewhat from that on high-voltage breakers where protective relays and simple shunt trip coils are universally used for selectivity. For low-voltage breakers the overcurrent and time-delay tripping characteristics are self-contained on the breaker, except in the few cases where relays and current transformers are used. In addition, the low-voltage currents are high. If full selectivity is to be obtained breakers located in the circuits nearest the power source must have adequate short-time current-carrying capacity to permit their remaining closed while breakers farther from the source are tripped, thus clearing faults with the least possible service interruption. While the need for this has been recognized to a certain extent in the past, it has not received the attention merited.

The newer breakers will adequately provide both for selective tripping devices and for the short-time current-carrying capacity. The air breakers thus will be even better equipped than before to serve the varied applications of low-voltage circuits, and with high current-interrupting capacities.

Power Circuit Breakers of Medium Voltage and Capacity

The breakers of medium voltage and capacity comprise those of 5, 7.5, and 15 kv, with interrupting ratings from 25 000 to 500 000 kva. For public-utility systems, the applications include 2300-volt circuits for station auxiliaries, primary distribution substations of both the indoor and outdoor type, and main switchgear for smaller generating stations, of 2300 to 13 800 volts. Municipal plants, as well as industrial plants and steel mills, use many breakers in this class, the steel-mill circuits usually requiring interruption of 500 000 kva at 6600 or 13 200 volts.

In this range of capacities, oil and magnetic-blowout oilless breakers have almost parallel ratings, although all are not available in both types. For example, in the smallest—25 000-kva step—there is no oilless breaker, because a 50 000-kva rating is about the lowest that can be manufactured economically. Putting it another way, an air breaker suitable for circuits of 5 kv automatically has at least 50 000-kva interrupting capacity.

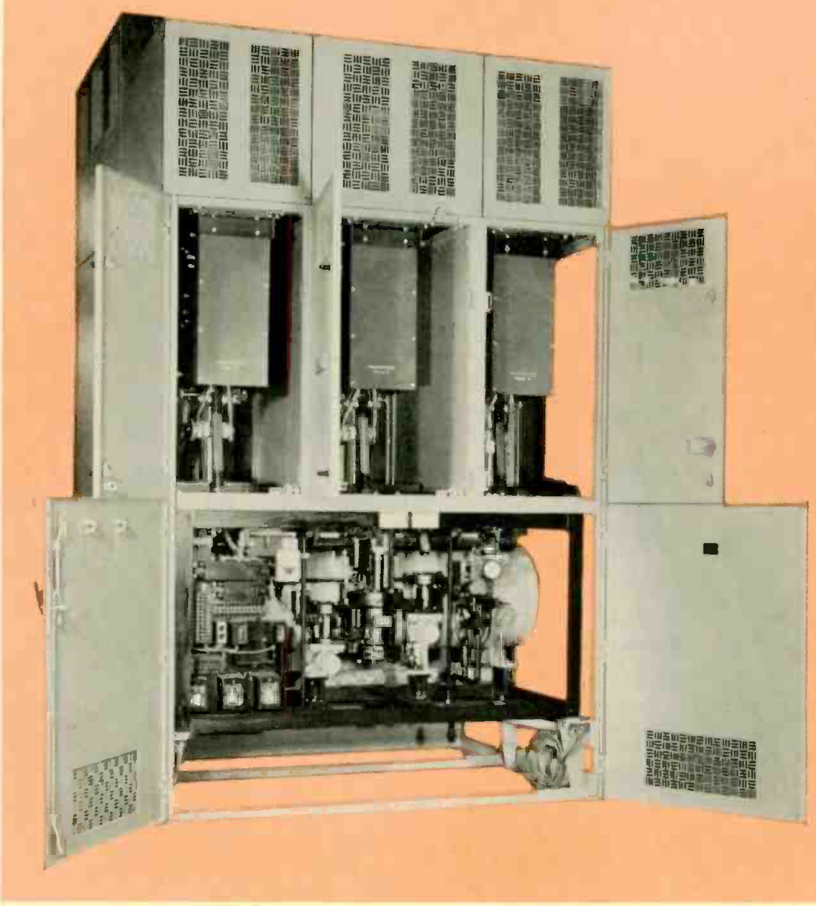
In the medium-capacity, 15-kv class the insulation is the so-called 15L, or "low" 15-kv level (36-kv, 60-cycle, 95-kv, impulse), and normally should be limited in application to systems having effectively grounded neutrals if the line-to-line voltage exceeds 7.5 kv. This is recognized in the circuit-breaker tables of American Standards Association C37, Power Circuit Breaker Standards, applying to both oil and oilless types of interrupters.

To obtain even this insulation level is difficult in small dimensions comparable with those of the corresponding oil breakers of the single-tank type. For air breakers of these ratings, the standard insulation level across the open contacts has been one step lower than the full insulation phase-to-phase and to ground, although present designs of breakers meet this with some margin to spare. Even so, this has placed some limitation on application to ungrounded circuits above 7.5 kv, where one pole may have to interrupt voltage approaching the full line-to-line value. The number of ungrounded 13.8-kv systems is decreasing, it being recognized that grounding of the neutral provides more positive relay operation and permits more effective application of lightning arresters. Development work is being carried on to enhance the insulation level of air breakers as their increasingly broad application on power systems requires.

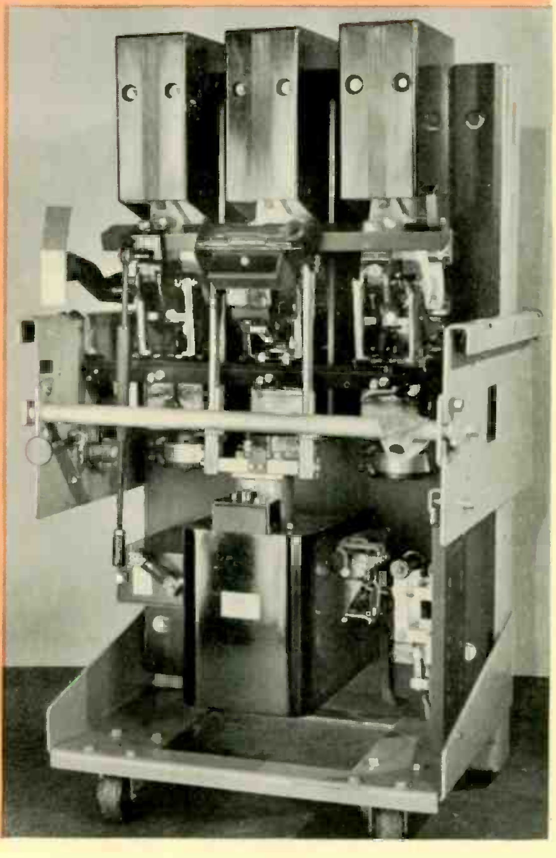
The general construction of the oilless breaker for 2.3- to 13.8-kv operation somewhat resembles that of the low-voltage device, with a hinged moving-contact arm, primary, secondary, and arcing contacts, and multiple-plate arc chutes to confine and control the arc. This is brought about by the magnetic-blowout coil through which the current passes. This action drives the arc into the slotted plates of the arc chute. Copper-tungsten arcing contacts are used and silver-to-silver main contacts. Each breaker is mounted on its own wheeled truck that withdraws horizontally from its metalclad housing, providing convenient disconnection and accessibility for inspection and maintenance.

For general application, in distribution substations and industrial plants, the oilless magnetic-blowout breaker defi-

The compressed-air breaker (type CA), less than ten years old, is rapidly sweeping the field in the medium-voltage classes. It is used on a 15-kv circuit and has interrupting capacity of 1 500 000 kva. It is mounted in a station cubicle with bus above, and disconnecting switches at the rear.



A typical low-voltage solenoid-operated, three-pole circuit breaker mounted on draw-out truck for metal-enclosed switchgear. It is rated at 600 volts, 50 000 amperes interrupting capacity. This type has become a standard for most low-voltage uses.



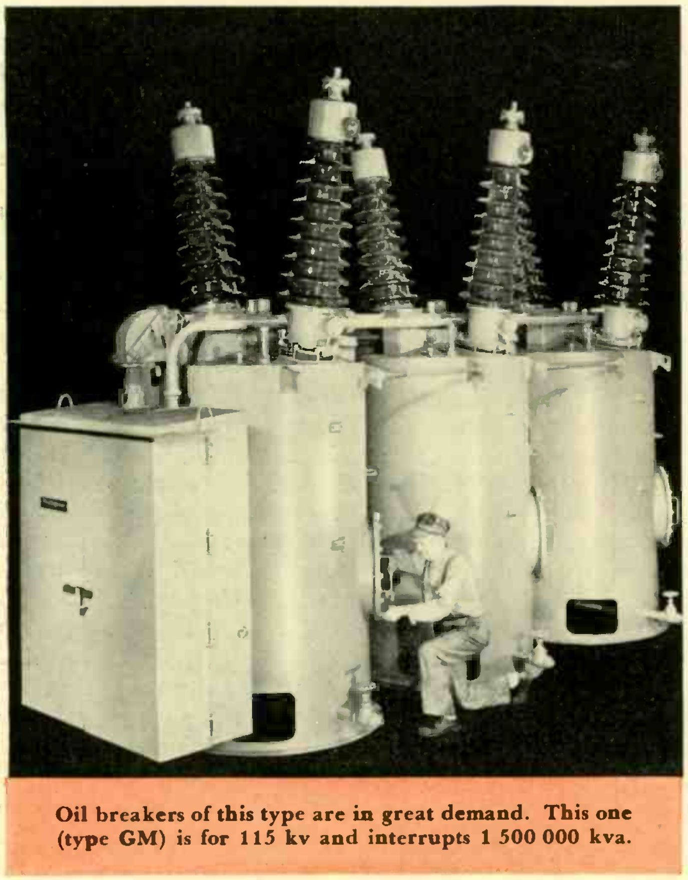
nitely has become the favored type as compared to oil, and already comprises the majority of breakers manufactured in this class. For certain locations in corrosive or explosive atmospheres, the oil breakers may continue to be preferred, and there may be additions to existing installations for which the air breaker, (which is manufactured only in draw-out design for metalclad structures) may not be physically adaptable. Otherwise the air type seems definitely to have "taken over" the 5- to 15-kv, small- and medium-capacity field.

The situation in the United States is somewhat different from that in England and the Continent. There has been relatively little development of magnetic-blowout air breakers for the higher voltages in Europe. In those countries, the bulk of the breakers for medium-voltage service are oil, with some oil-poor, water, and compressed-air types. However, recent reports from England indicate some development work on the magnetic-blowout air type and a greater interest in it.

Circuit Breakers for Heavy-Capacity Stations at Generator Voltage

For the generating station and substation that require larger breakers, oilless breakers again are favored. The ratings here are 15 and 34.5 kv with interrupting capacities of 500 000 to 2 500 000 kva. For this duty the oilless design is the compressed-air or air-blast type with pneumatic mechanism. The oil breaker is solenoid operated with a tank per pole. The insulation for this class of breaker for 15 kv is the 15H, or "high level," with a 60-cycle, "one minute withstand" rating of 50 kv, and an impulse level of 110 kv. This provides a more conservative rating for these heavy-capacity installations than the "low level" mentioned previously.

Oil circuit breakers supplied for such applications have been developed over the years into thoroughly reliable devices, and their operation record is excellent. The modern breaker with De-ion grids is entirely a different performer from the old plain-break type that developed high pressure in the tank, and, when interrupting heavy currents, was prone to throw oil. Many old breakers have been modernized by the addition of De-ion grids, new mechanisms, and condenser bushings.



Oil breakers of this type are in great demand. This one (type GM) is for 115 kv and interrupts 1 500 000 kva.

Prior to the oilless breaker, much study was given to the structures for mounting heavy-capacity oil breakers, with special cell construction even to the extent of locating phases on separate floors or isolated from the other phases by several feet horizontally. The compressed-air breaker is responsible for the recent return to group-phase construction, with metal isolation of the phases.

During development of heavy, power-station breakers to reduce or eliminate the oil hazard, several types of interrupters were studied, and experimental models of some were tested. Among these were the water breaker, and the "oil-poor" type. However, because the compressed-air or air-blast appeared to offer the most promise, intensive development work continued along that line.

The compressed-air breaker appeared in 1940. Even in this short time it has achieved such popularity that oil breakers are now given serious consideration only for additions to existing installations with structural limitations, and even here the air blast is often used. The reason for this is simply that, although oil breakers have generally a good record, even a small oil fire generates a considerable quantity of smoke and soot deposit, and, for indoor service, elimination of such possibilities with attendant shutdown for cleaning is of first importance with most operators.

The compressed-air breaker for 15- and 34.5-kv service is the cross-blast type. That is, the air is released across the open-contact gap at right angles to the movement of the contact. This is done by means of a blast valve and tube that directs the air and is designed to have the shortest direct path between storage tank and contacts. The opening and closing mechanism is pneumatic, and movement of the breaker contacts is mechanically interlocked with the blast valve to insure proper release of air. An air relay prevents operation of the mechanism unless adequate pressure is available.

Several hundred compressed-air breakers have been installed in a large variety of stations, not only on public-utility systems, but also in large industrial plants such as steel mills. In most, the structures for mounting have been factory-assembled steel cubicles, complete with disconnecting switches, instrument transformers, busses and connections. Operating experience has been essentially all that was expected, not only from the standpoint of circuit interruption and reduction of fire hazard by the elimination of oil, but also in low maintenance. The compressed-air breaker for indoor, heavy power-station service has largely supplanted the oil type, and there is every evidence that it will continue to maintain its favored position for all but hazardous atmospheres.

Foreign practice resembles ours except for two differences. First, greater use of oil circuit breakers is made, at least in England. Second, indoor breakers and bus structures are carried to higher voltages (up to 69 kv or higher) than in the United States, where it is universal practice to install equipment outdoors for voltages above 34.5 kv.

High-Voltage Circuit Breakers

It is in the high-voltage service that the outdoor oil circuit breaker seems to be holding its own against the inroads of other types, such as compressed-air or the low-oil content type, also known as oil poor. This comprises the outdoor field from 7.5 kv, 50 000 kva, to 287 kv, 3 500 000 kva, which is the highest commercial rating yet installed, although contracts for 5 000 000-kva oil breakers for 138 kv have been placed in the United States and for 230 kv in Canada. In addition, there is every indication that the heavy-capacity systems of the Northwest will require 7 500 000 kva, or even higher, at 230 kv, more than twice the kva of the present maximum.

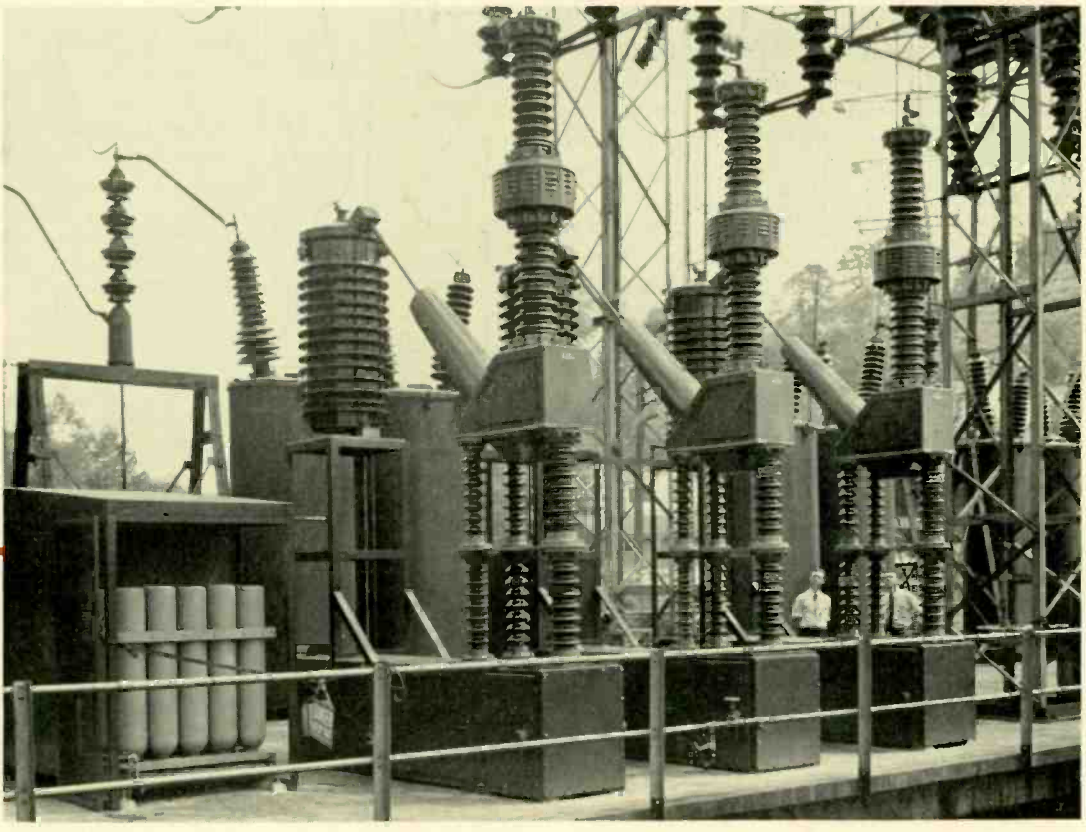
The high-voltage oil circuit breaker has been brought to its present state of development by intensive research and high-power laboratory tests. Improved interrupters have brought about major reductions in tank size and oil content, and now provide standard interrupting times of five and three cycles, not only on heavy fault currents but also on charging current of long lines. Where required, the pneumatic mechanism provides fast reclosing time of 20 cycles or less even on the highest voltages, limited only by the time required to prevent the fault arc from restriking. The simpler solenoid mechanism is available where fast reclosing is not required. Performance of the breakers is consistent over the entire range of current and is, for all practical considerations, independent of voltage-recovery rates.

Interrupters for the higher voltages (115 kv and above) are the "multi-flow De-ion grid" type in which two arcs are drawn in series. The first arc generates gas pressure that forces oil across the second gap, quenching the arc in the shortest possible time. Each pole contains two interrupters. With short arcing time the arc energy is low, resulting in low maintenance required by either contacts or oil. When this is necessary, access has been provided by manholes in the side of each tank. Condenser bushings permit simple, convenient mounting of bushing current transformers to the extent of as many as 12 per breaker. Potential is readily obtained by the tapped bushing-potential device.

Tests on a circuit breaker of this type recently have been completed at Grand Coulee power plant, where, in 35 test interruptions, as many as six 108 000-kva generators and six parallel lines were tied together to produce the maximum kva possible at 230 kv. Single-pole, standard "duty cycle" tests, each comprising a close-open, 15-seconds-delay, close-open, were first made, reaching the maximum of 7 500 000 kva, equivalent three phase. Later, reclosing tests were made under similar conditions with both one-second and 20-cycle reclosing times. Every interruption was successful, with the interrupting time consistently below three cycles, and as low as 1.85 cycles. A similar number of three-phase operations on charging current of a transmission line had been made previously on the same system with the same uniform interrupting time of three cycles or less.

Much development work also has been done in this country and abroad on other types of interrupters, particularly compressed air and oil poor, and some have been installed in England and in Europe. In some cases, as in Germany, development of these types was insisted upon by the government because of shortages of metal and oil. Recently a compressed-air breaker of German A. E. G. manufacture, brought to this country by our Federal Government Technical Mission, was tested on the Bonneville system at Vancouver, Washington. The breaker, rated 2 500 000 kva at 230 kv, interrupted fault currents equivalent to some 2 300 000 kva, although requiring 5½ to 6 cycles interrupting time on a circuit of low voltage-recovery rate (some 200 volts per microsecond), as compared to 3 cycles for an American oil breaker. On charging current, with a relatively short transmission line, interruption was quite unsatisfactory, the time, due to multiple restrikes, being approximately double that on fault currents. Because of this, only three of the scheduled 12 charging-current tests were made at that time.

The A. E. G. design consists of two rotating porcelain columns per pole, each carrying an arm which in turn supports half of the interrupting element enclosed in a porcelain insulator. In the breaker-closed position, cylindrical contacts projecting from these insulators butt against each other. Interruption takes place by withdrawal of the contacts by air pistons, and release of the air blast through the resulting orifices in the interrupters. Following interruption, the contacts are swung apart by the two supporting columns which are rotated by the mechanism in the base, to provide the necessary air space between contacts. A considerable amount of porcelain is required, plus that for separate instrument transformers. The space occupied is much greater than for an equivalent oil breaker of American design.



Compressed-air breakers for high-voltage, outdoor service are being given a thorough trial. This one has been in experimental service several years on the 138-kv lines of the West Penn Power Company at Kittanning (Pa.). The interrupting capacity is 1 500 000 kva.

The principle of operation of other compressed-air high-voltage breakers is somewhat similar, except for variations in the manner in which the blast is applied and the number of interrupters in series. However, contacts after interruption are usually isolated by a separate switch, either a blade type or a rod type withdrawn by a piston, so that the main porcelain columns are stationary.

In the United States several manufacturers have built compressed-air breakers experimentally and have installed them on operating systems for field experience. Such a program was agreed upon with the operators' engineers through the AEIC-EEI-NEMA Joint Committee on Circuit Breakers several years ago, as a basis for possible commercial development. The voltages range from 34.5 to 138 kv. The field experience has been quite completely covered in papers before the AIEE and has been somewhat varied. However, several points seem evident. A large amount of porcelain is required, possibly reinforced by other insulation, resulting in a structure not conducive to strength and ruggedness. Weatherproofing of joints and their maintenance present an important problem. The operating mechanism is relatively complicated, and made more so by the necessity for isolator switches. This has an adverse effect on satisfactory reclosing duty. Separate current and potential transformers are required, increasing both space and cost. All installations have required considerable field service and frequent inspection.

In Canada, the Quebec Hydro Electric Power Commission has several compressed-air breakers and appears to have had satisfactory service from them. On the other hand, the Ontario Hydro Electric Commission has installed oil breakers exclusively, and has indicated its intention to continue to do so.

In England opinion is divided between oil and compressed air, although it is recognized that the cost comparison favors oil, particularly below 138 kv. Until recently the trend was toward the air blast breaker for high voltage. However, the picture is clouded to the extent that at least two manufacturers are now offering new oil breakers similar to the improved American design, and the Scottish Electricity Board has recently purchased breakers of this type.

Designs of oil-poor or low-oil-content breakers have been made in the United States for high-voltage outdoor service, as well as some commercial installations. However, these breakers, since they involve large porcelain insulator enclosures arranged either horizontally or vertically, have similar disadvantages to those of the compressed-air designs, with the additional problem of oil leakage through gasketed joints.

Operable breakers can be developed along the lines of either the compressed-air or the low-oil-content form of construction. That this may be done competitively in cost with the dead-tank oil circuit breaker is questionable, particularly when provision is made for instrument transformers. For high voltage, an oil circuit breaker, which has high permanent insulation, fast, consistent interruption, short-time reclosing, and provision for instrument transformers, is a relatively simple device. It occupies generally less space than a porcelain-clad breaker and has the ruggedness and reliability, without excessive maintenance, held of great importance by American power systems.

Development work, of course, will continue on compressed-air, oil-poor, and on any other principle of arc interruption that offers promise of a better commercial design of circuit breaker than those on the market. Meanwhile, the highly developed, dead-tank oil breaker is widely accepted and present evidence is that some time will elapse before it is supplanted.

ENGINEERING TRENDS

To relieve the strain on tired equipment after the strenuous war loads and to permit some extension of service, 250 new subway cars are being built for New York City's Transit System. For these cars Westinghouse is providing new types of motors and control. Each car will have four 100-hp motors (two 200-hp motors are common) with ball and roller bearings. They will be spring suspended and the gears will be connected through flexible couplings. An important new feature is dynamic braking, which will provide stops that are more rapid yet more comfortable and with vastly reduced brake-shoe wear. Cars will be brought from 30 mph to a stop in 10 seconds instead of 15, as with present airbrakes. The controllers provide 18 steps of acceleration and deceleration in contrast with the nine for acceleration only on existing cars.

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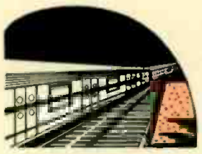

Tomorrow's subway train is in the making. It is to be a sleek, 10-car train, which because of its light-metal construction, lightweight electrical equipment, and other pounds-saving features, will weigh 75 tons less than a similar train of present-day cars. Which means 75 tons less to accelerate and decelerate every few minutes. Among the many new technical features of this train will be a new Westinghouse unit-switch type control that provides dynamic braking to give high-speed deceleration, three mph per second as against the present two. Acceleration rates have been increased by 45 percent; from 1.75 to 2½ mph per second. An entirely new-type ventilating system includes dust removal, via Precipitrons. Fluorescent lamps will provide high illumination levels. A motor-generator set, with flywheel, will provide 60-cycle power on each car, so that the lamps do not go out whenever a car passes over a third-rail gap. The train is being built for New York City's Transit System.

* * *

An application of dry-type air-cooled network transformers in under-the-sidewalk vaults will be made by the Rochester Gas & Electric Corporation. This installation will consist of 500-kva, three-phase, 11 500-volt submersible network units containing no liquids and cooled only by the natural circulation of air through the vault.

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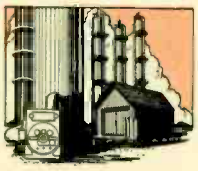
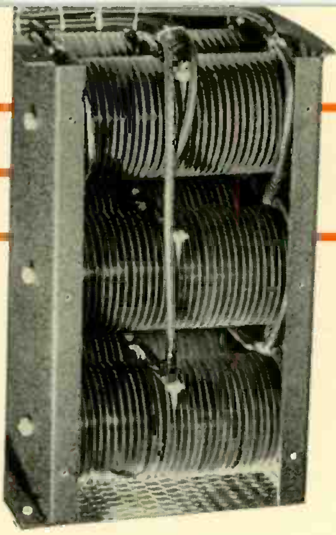


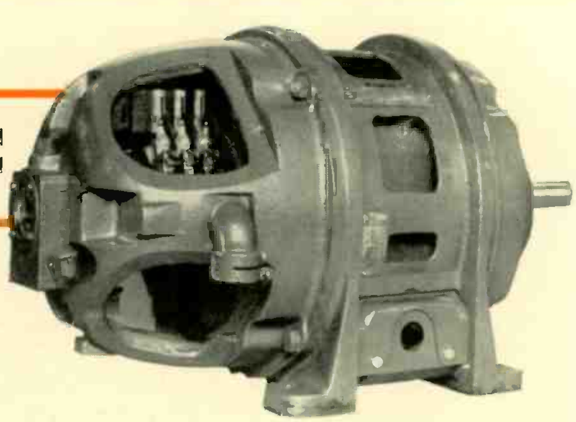
Motors to be nitrogen-cooled are being built for a large oil refinery. These are big motors—2250 hp at 1800 rpm—the largest explosion-proof squirrel-cage motors to date. They are so large that reliance cannot be placed on the ability of the motor walls to resist bursting should an explosion occur inside, as is done with smaller motors where the ratio of outer surface to motor volume is much greater. Hence explosive gases must positively be excluded. The motors will be connected to a supply of nitrogen or other inert gas and an internal pressure maintained slightly above atmospheric. A separate motor-driven oil pump will maintain the seal around the shafts when a motor is shut down.

* * *

Distribution systems are going underground. The winds frequently experienced in southern Florida and the general trend toward elimination of pole structures have prompted the utilities to a large-scale underground distribution system in business and residential areas. Transformers of the regular subway type, provided with CSP distribution-transformer circuit breakers, will be used. The self-protection against short circuits and overloads and the loading of the transformers on the basis of copper temperature, furnished by this scheme, make these units particularly suitable for this service.



D-C Motors on A-C



The Buffalo plant where Westinghouse builds motors has many d-c motors in service, but it has no direct-current distribution system. Where needed, direct current is manufactured on the spot from the alternating-current supply lines by a metallic rectifier of the selenium type.

The selenium rectifier offers a simple, static means of providing on-the-spot direct current for adjustable-speed, field-control motors from the plant a-c system. Over the range of 1 to 15 hp, for which the rectifier unit has been developed and for which it appears most suitable, the rectifier and d-c motor offers several advantages over other methods of obtaining adjustable speed within a four-to-one range. As compared to the motor-generator set, for example, the efficiency is higher, regulation essentially the same, commutation not adversely affected, mounting is less of a problem, and maintenance is simplified.

The complete assembly consisting of autotransformer, rectifier, controls, and (in the larger sizes) motor-driven fan, is contained in a small metal cabinet that may be placed in any convenient location such as on the floor beside the d-c powered machine, or on a light, overhead platform. It is in the use of selenium-cell rectifiers that the saving in size and weight is accomplished, as compared to copper-oxide rectifiers or to motor-generator sets. Control can be reduced to the bare essentials—a standard a-c line starter and a field rheostat. The circuit connections of the rectifier and motor, Figs. 1 and 2, indicate the simplicity of the system.

Six sizes have been developed having 1-, 3-, 5-, 7½-, 10- and 15-hp ratings. These are available for 230-volt d-c output, the source of power being any of the conventional a-c, three-phase system voltages normally found in industrial plants. The small-size power packs (1, 3, and 5 hp) are of the self-cooled type. These consist of an autotransformer and a rectifier. The autotransformer makes it possible to use any a-c system voltage; by suitable choice of transformer, the d-c output will be 230 volts at full load.

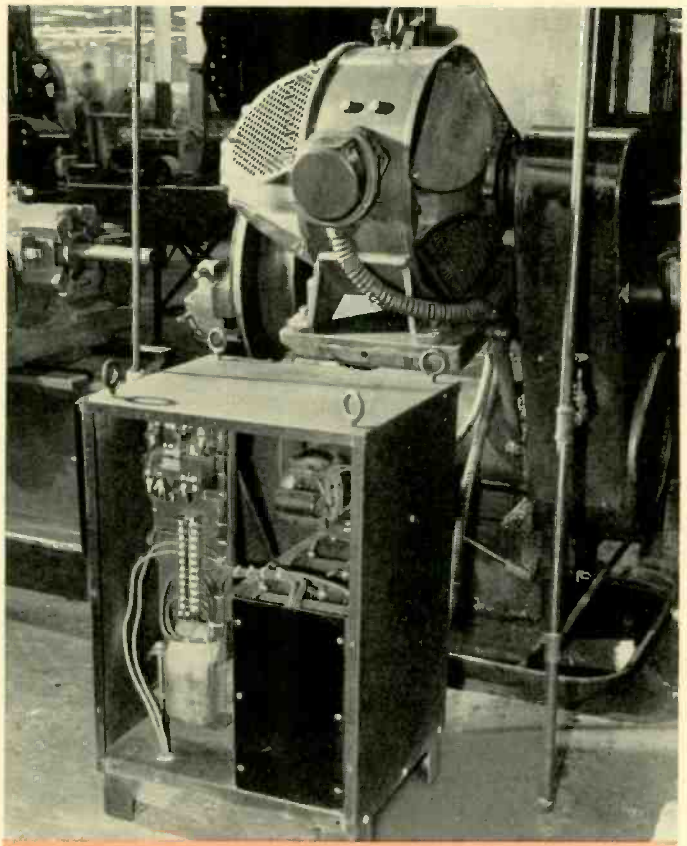
Applications and Performance

When using the metallic rectifier, the conventional d-c control can be supplied, although a simplification takes advantage of the natural internal resistance of the rectifier. It is possible, on the 1- to 7½-hp sizes, to dispense with the d-c control and retain only the field rheostat. A safety switch or magnetic breaker can be installed in the a-c line for starting and stopping, as it is possible to start the motor across the line through the rectifier, even when the shunt-field rheostat is set to give a speed of four times the base or full-field speed. Where dynamic braking or reversing is required, a similar simplification is possible. This consists of omitting the fluttering relay on the shunt field, the starting resistance and all its relays and contactors.

The voltage regulation of the rectifier, Fig. 3, is about the same as would be obtained from a motor-generator set. Regulation of the fan-cooled unit is slightly higher than for the self-cooled unit. This results from working the rectifier cells at a higher load and causing a larger drop in voltage. The voltage from 50-percent load to 100-percent load varies from 240 to 230 volts. The high regulation at the low end of the curve, Fig. 3, is not of too much concern in the average d-c motor application as this has but little effect on the motor-speed regulation.

The speed regulation, Fig. 4, of an m-g set and the rectifier is essentially the same. This results because the motor and rectifier voltage regulations are about equal.

Commutation is a major consideration in d-c motor operation. Rectifier voltage pulsates at a frequency six times the supply frequency—360 cycles for a 60-cycle system because of the six-phase rectifier connection—with a magnitude of ap-



The floor-mounted metallic rectifier power pack used to drive the 15-hp motor of a machine tool. It is cooled by a motor-driven fan located above the stacks of selenium discs.

From a paper presented to the Machine Tool Forum at Buffalo, New York, April 22 and 23, 1947, by E. C. Watson, Section Manager, and F. L. Reed, Engineer, both of the D-C Engineering Dept., Motor Division, Westinghouse Electric Corporation, Buffalo, N.Y.

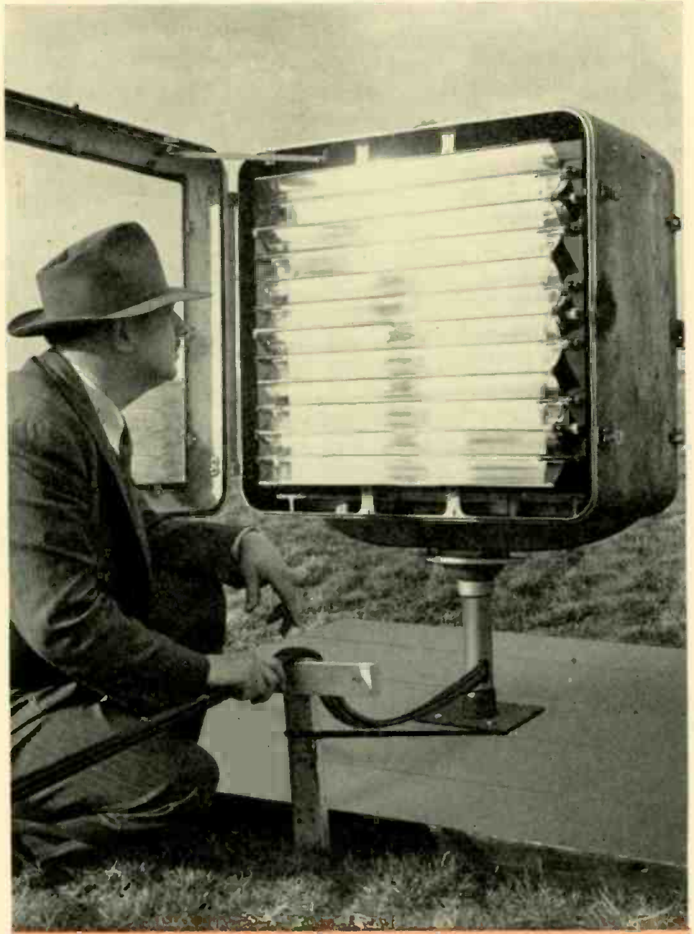
for any airport lights used for navigation or other purposes.

The system requires no additional equipment on the plane. It works equally well with any type of instrument approach system: Instrument Landing System (ILS), Ground Controlled Approach (GCA), or microwave. Thus the all-weather approach lighting system does not conflict with any radio or radar control. In fact it supplements the existing and proposed electronic systems. An airplane must be brought, at times of poor visibility, to the approach portal by radio or other instrument-control system. The proposed new lighting system, in effect, takes over where instrument control leaves off, to guide the pilot through that difficult period of bringing his plane those last few feet before making physical contact with the ground.

The complete all-weather approach lighting system consists of three parts: the approach line, the runway designators, and the high-intensity runway lights.

Approach Lighting

A single row of two entirely new types of lights, called flash and blaze units, extends out from the runway for a distance of 3225 feet. This is the approach line and points the way to the runway available for use. This row of lights consists of 36 each of the flash and blaze units, as they are designated, making 72 in all. Alternate flash and blaze units are spaced close together at the outermost end (where they are most needed) and farther apart near the runway.



Mr. Pennow squats before one of the blaze units mounted in a weatherproof housing similar to the one housing a krypton unit. It consists of six special neon lamps and reflectors. The capacitors and controls are behind the reflector panel.

The flash unit employs a krypton-filled quartz tube about the size of a cigarette. It is equipped with tungsten electrodes, which have high heat-resisting properties, fused into enlarged end chambers. When about 2000 volts are impressed on the tube and the gas ionized, a discharge of capacitor-stored energy occurs through the quartz tube. The discharge produces a white light of astounding brightness. By control of the stored energy discharged through the tube the brightness can be controlled from a relatively low value to as high as nine million candlepower per square inch. At the high value the lamp is nine times brighter than the sun, which has at the earth's surface a brightness of one million candlepower per square inch. The energy absorption is equally "astronomical." At the peak of the discharge about 3000 kw are being delivered to the gas within the quartz tube, only two inches long and about a quarter inch in diameter. This is why the krypton envelope must be made of quartz; any other material would melt, even though the duration of the discharge is short, about 17 millionths of a second. A polished-parabolic reflector concentrates the output of the krypton lamp, when burning at maximum brightness, into a beam of 3.3 billion candlepower.

The second member of the pair of new lights is the so-called blaze unit. This is made up of six tubular lamps, each about two feet long and a half inch in diameter, fitted with a special electrode and filled with neon. Neon lamps have not heretofore been considered as susceptible to intensity variation. However, by variable electronic control of the power supply, these blaze units can be operated at different brightness levels. These lamps resemble the familiar neon tubes and give off, at the lower intensities the characteristic red light. At higher intensities the color shifts toward white, although red is still dominant.

Unlike the krypton units, which are operated only as flashing units, the blaze units can be either flashed intermittently or burned continuously. On steady burning service, they produce either 100, 1000, or 10 000 candlepower, as selected, and on flashing service they operate at about 100 000 or 10 000 000 candlepower, as needed.

The 72 krypton and blaze units, alternately spaced in a line extending two thirds of a mile from the runway, provide an approach-line lighting with the flexibility required to suit any visibility condition. Their controls are synchronized so that, when in flashing service, the units are tripped successively, beginning at the outer unit, each one firing before the one ahead appears to have been extinguished. This flashing is repeated 40 times per minute, so that to an incoming pilot the approach line appears as a streak of light of three-hundredths second apparent duration running for two-thirds of a mile toward the runway and recurring every 1½ seconds.

At times of worst visibility, such as a ground fog in the daytime, the approach line is operated with the krypton and blaze units flashing at their maximum intensity, the krypton lamps emitting flashes of 3.3 billion beam candlepower of white light and the blaze units flashing with a reddish light of ten million beam candlepower. At the other extreme of the visibility scale, i.e., on clear nights when only a relatively faint approach line is desired so as not to produce glare, only the blaze units are turned on. They are burned continuously at their minimum brightness level of 100 candlepower. Between these two conditions the krypton and blaze units can be used in such combinations of intensities as to suit the occasion. At all times the object is to provide sufficient light to assure positive visual identification but not enough to blind the pilot when landing. The degree of reflective density present, i.e., fog, controls the intensity used.

The runway is unmistakably outlined by rows of units of this type. It consists of two powerful incandescent, sealed-beam lamps, for use when visibility is poor, and, on top, one incandescent lamp employed when low-intensity only is required.

Runway Designator

The second part of the system, the runway designator, consists of an assembly of neon (red) and zeon (green) luminous tube elements forming either a green arrow or a flashing red cross. The green arrow indicates that the runway is clear for landing while the flashing red cross shows that it is closed. At all other ends of runways, the designator is a large flashing red cross, showing it is closed for landings. As an airplane passes over the green arrow, the control officer changes the arrow to a flashing red cross, closing the runway until the airplane has landed and been cleared. It is then changed back to the green arrow, instructing the next airplane in the landing-sequence pattern to come in.

During instrument weather the designator is a last-moment safety signal to the approaching airplane. The green arrow is assurance to the pilot that the runway is clear and that he is at the proper position to make a landing. If an emergency arises that makes the runway unsafe for a landing, the flashing red cross is a warning to pull up and resume position in the traffic pattern until the emergency is cleared.

High-Intensity Threshold and Runway Lights

The third part of the system consists of the high-intensity threshold and runway lights spaced at 200-foot intervals, 10 feet out from both sides of the runway borders and producing candlepowers up to 100 000. This is one hundred times the candlepower of the semi-flush runway lights in common use, and nearly three times that of the high-intensity runway light used by the Air Force. The new high-intensity runway light uses three lamps and can be operated as a high-intensity or a low-intensity unit, as visibility conditions require. For high-intensity service, two sealed-beam lamps are used, one for each operating direction on the runway. These lamps, only one of which is used at any time, are operated at five degrees of intensity: 100 000, 30 000, 10 000, 3000, or 1000 candlepower. For low-brightness service the high-intensity lamp is turned off and a single lamp, mounted in a two-directional optical system at the top of the unit, is used. Like the larger lamp, it has five steps of intensity and can be operated to give 500, 150, 50, 15, or 5 candlepower. These ten steps match the ten steps of brightness available in the approach line.

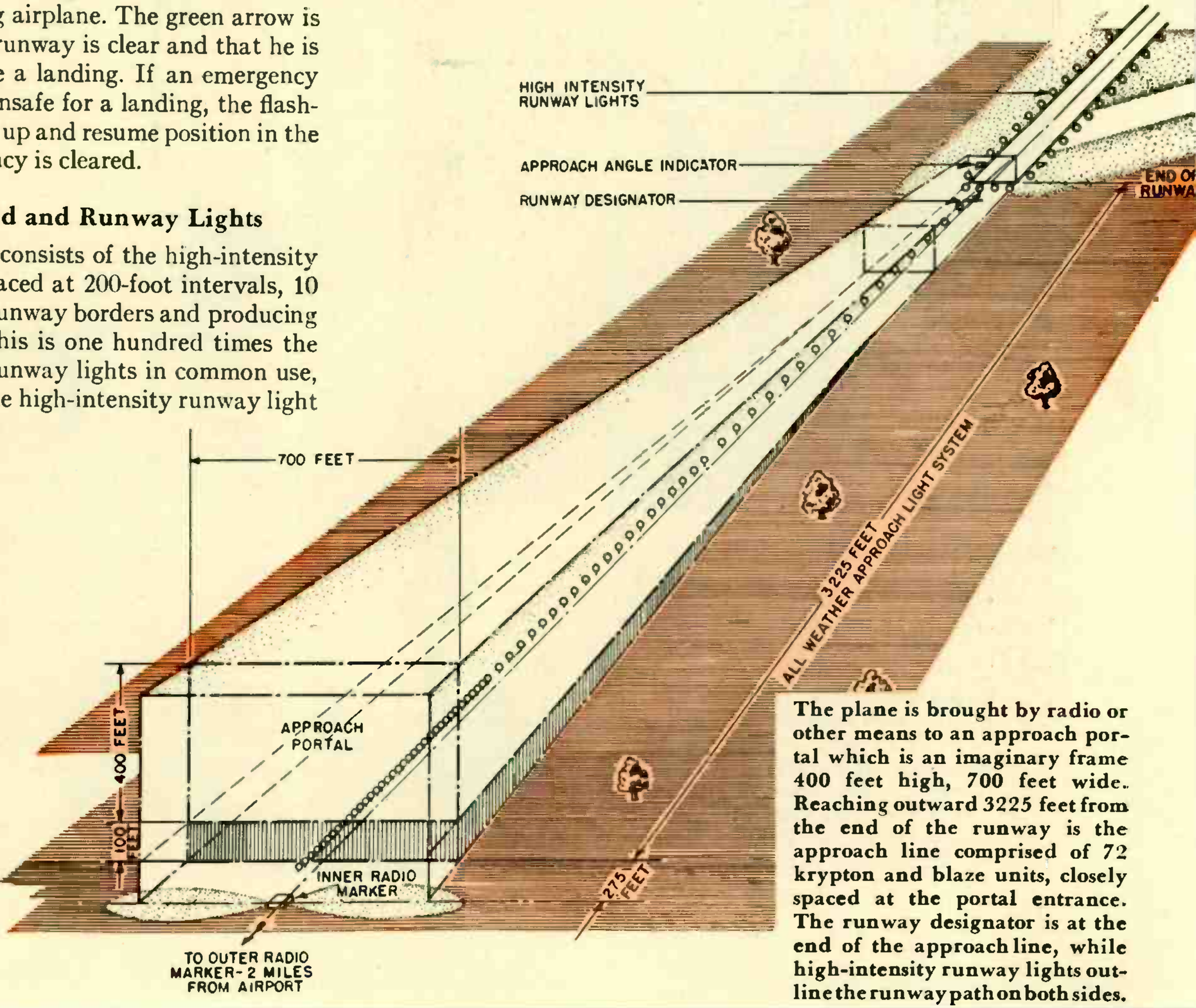
During weather requiring only the top element, the emitted light is in two directions, along the runway, but with some scattered light. In thick weather, when higher candlepowers are used, all emitted light is severely restricted to the direction of approach. This prohibits background lighting and prevents lighted haze or fog curtains behind each light that would reduce perception of the next light in the line.

The color of the lens for the runway lights is chosen by the position of the unit along the runway. Clear light is used along the outermost section of the runway, and yellow indicates to the pilot the last 1500 feet. When used as range lights at the very end of the runway, the lenses are colored green.

Visual Contact with Ground Assured

The all-weather approach lighting system offers pilots positive visual contact with the ground at the critical moment when they must leave instruments and descend to a landing in all conditions of visibility from unlimited to zero-zero. The pilot is assured of positive identification of the runway location through the approach portal until he taxies down the runway. At the end of the runway, while he still has flying speed, the all-weather system runway designator gives the pilot a last-minute traffic signal by telling him to set his plane down, or to circle and come in again when the runway is cleared. When the new system is used, the runway itself is outlined with the powerful lights built to guide him as he lands.

It is expected that air crashes resulting from poor landing visibility will be cut by as much as 90 percent upon the adoption of the all-weather approach lighting system.



The plane is brought by radio or other means to an approach portal which is an imaginary frame 400 feet high, 700 feet wide. Reaching outward 3225 feet from the end of the runway is the approach line comprised of 72 krypton and blaze units, closely spaced at the portal entrance. The runway designator is at the end of the approach line, while high-intensity runway lights outline the runway path on both sides.

STORIES OF RESEARCH

More Light on Fire

Man has known fire for thousands of years. Only recently, however, has he got around to an actual study of its fundamental properties and behavior. And when it comes to an investigation of flame as it comports itself in the gas turbine, the science is really embryonic. However, fundamental research in this field is proceeding rapidly. Dr. W. C. Johnston of the Westinghouse Research Laboratories, for example, is attacking the problem of flame velocities and their relation to the general combustion efficiency of the gas turbine. Such velocities measure the rate at which a flame, moving through a mixture of combustible gases, converts the fuel into heat energy.

For a still flame in a mixture of non-moving gases, this rate may be around five feet a second, resulting in the conversion of 50 to 100 pounds of fuel per hour per square foot of combustion chamber. This seems low in comparison to the total conversion efficiency of present-day jet engines, which burn around 1200 pounds of fuel per hour per square foot. The difference is due mainly to turbulence in the fuel-air stream that breaks up the smooth flame front into a jagged, stair-step arrangement, which presents a much greater burning surface to the fuel. Research men consider flame velocities so fundamental to the problem of total combustion efficiency that, conceivably, a doubling of velocity would result in a doubling of the fuel consumption per hour.

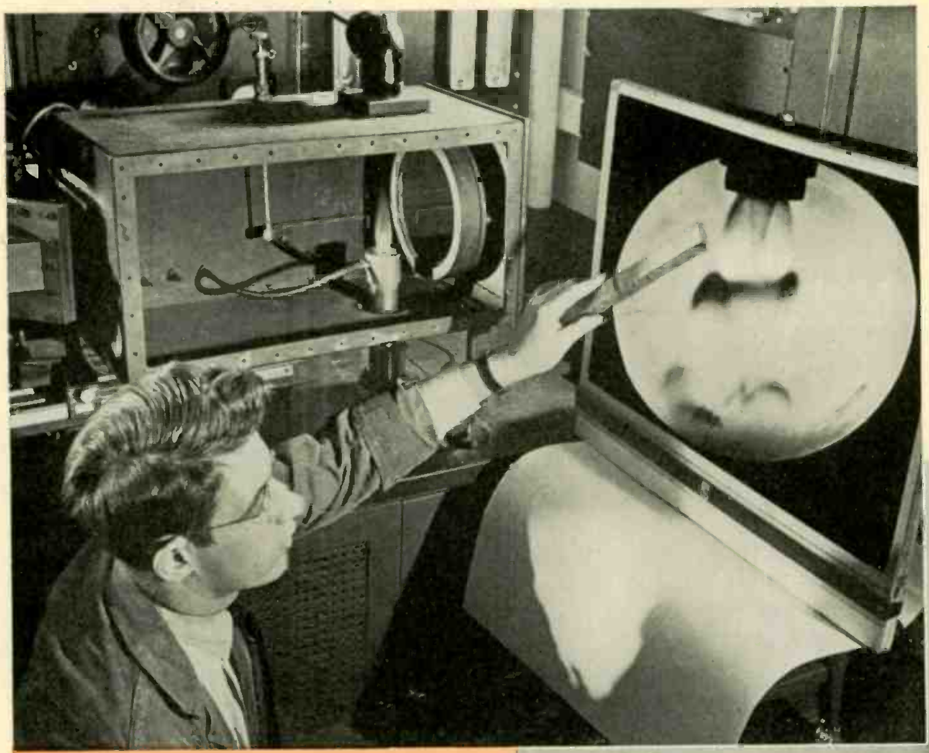
Johnston is seeking the answer to a number of fundamental questions. How does this velocity vary with different fuel-air ratios? What fuels are more likely to give high flame velocities? Here one clue is that fuels with low carbon-to-hydrogen ratios (such as the "saturated" acetylene, C_2H_2) give comparatively high velocities. How does the velocity vary with inlet temperature, with pressure, with blends of gases, with pure types of fuels? How does ionization affect flame velocity?

In digging for his facts, Johnston uses an apparatus employing the so-called "schlieren mirror" technique. The flame is produced by burning the test gas in a Bunsen burner. A 1000-watt mercury-vapor light, situated ahead of the flame, is reflected to a large eight-inch mirror behind the flame. As the light rays are projected forward through the flame, they are refracted upward or downward, depending upon the density or temperature of the hot gases. The resulting image, focussed by a lens on a screen, shows the inverted cone of flame surrounded by light and dark shadows indicative of the different temperatures of the gases above the cone. By measuring the angle of the apex of the cone, Johnston is able to determine the rate at which the fuel is being converted into heat energy.

The fundamental information that Johnston is collecting should fill a gap in the existing knowledge of the behavior of flame in the presence of a moving stream of air. In addition, it should provide the design and development engineer with that basic fund of data he requires to meet a wide range of problems.

Blows Hot and Cold

Scientists currently are intrigued by the performance of a narrow piece of pipe that receives a blast of compressed



Dr. W. C. Johnston of the Westinghouse Research Laboratories uses this equipment to study flame velocities and combustion rates of jet engines.

The "hot-cold pipe" goes through its → mysterious act for Warren Witzig, at the Research Laboratories. The temperature of the air coming out the opposite ends of the pipe is measured by the thermocouples in glass tubes. The temperature difference shows on the voltmeter at the pipe center.

air through a nozzle at its center and neatly divides it into two jets: one as hot as 154 degrees F, the other as cold as 10 degrees F. Aside from its practical applications—at the moment not too promising—the tube produces a startling thermodynamic effect that physicists are eager to explore and understand.

Called the "Hilsch tube," after a German scientist who did experimental work on it, the device recently was brought to America for further study. G. W. Penney of the Research Laboratories has built a revised version of the tube for fundamental research into the thermodynamic principles involved. His model—made several times larger in diameter for easier study—consists of a 15-inch length of brass pipe about an inch in diameter. Compressed air up to 50 or 60 pounds is pumped into a nozzle at one end of the tube to produce a vortex of rapidly spinning gases.

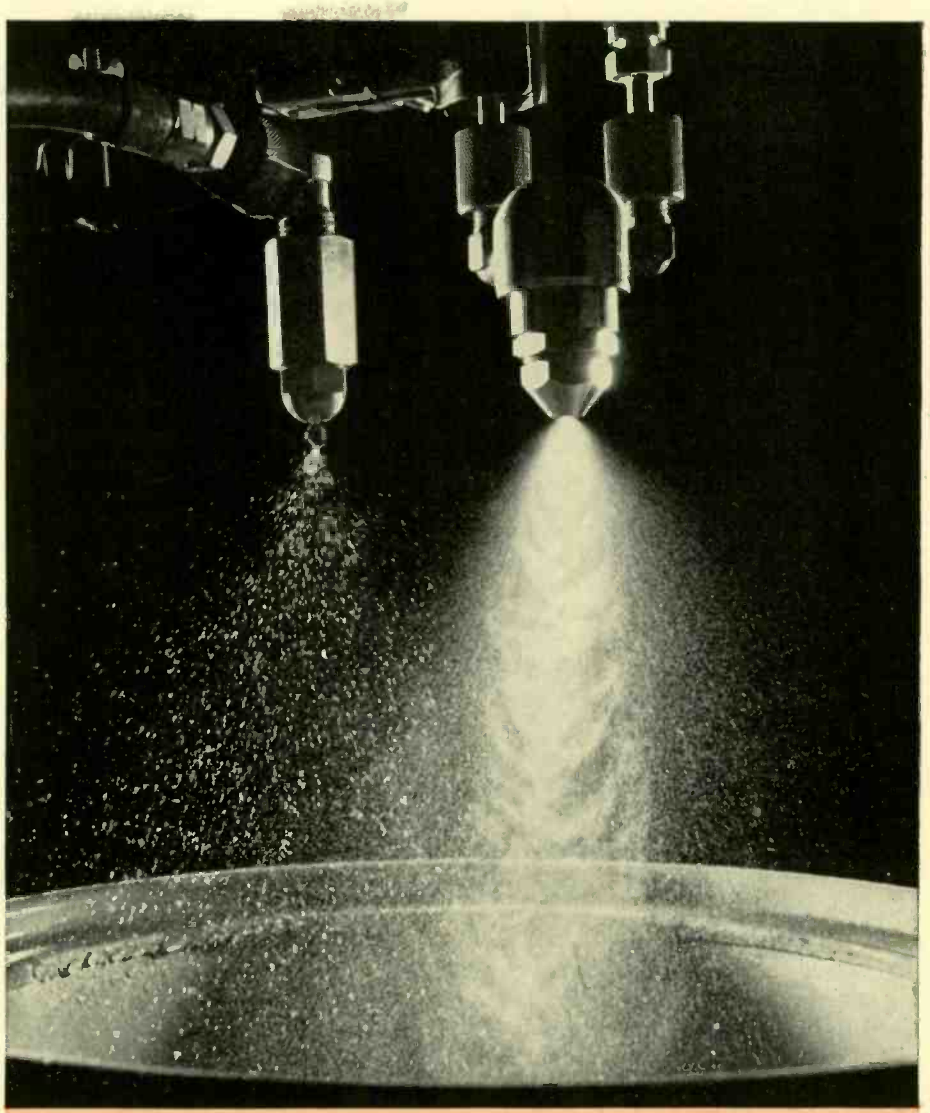
The cooler air concentrated in the center of the whirlpool is drawn out through an opening in the middle of the tube, or at either end if desired. The warm air is driven out through an opening near the walls of the cylinder. Thermocouples inserted in the air stream measure the temperature differences. Because he is more interested in understanding the nature of this separation of heat from cold, Penney's model is not constructed to produce the wide variations observed in the original.

What really happens is not clear. One theory deduces that the various layers of whirling gas have different velocities, rising from virtually zero at the center of the vortex to a peak at some intermediate point and then falling away at the periphery. This may cause the gases of higher velocity to exert a frictional or "shear" effect on those of lower velocity, thus transmitting energy to the latter. The net effect is, then, a considerable warming of the outer layers of gas and a corresponding cooling of the inner layers. The law of conservation is binding here. Whatever heat is extracted to produce the cold stream of air must be added to the warmer end of the flow.

A natural application of this ultra-simple device would seem to lie in the field of refrigeration. But its efficiency is only a small fraction of that attained in household refrigerators and larger cooling units. However, it may be useful as a laboratory tool.

A Super-Fine Fuel Atomizer

The shift from basic research to practical application is neatly illustrated in the development of a unique "fuel atomizer" by Keith V. Smith, Westinghouse Research Engineer. Smith was engaged in research studies for suitable fuel nozzles to use in aviation gas turbines, when he conceived the idea of using air to produce a much finer atomization and distribution of fuel in the combustion chamber. He designed a nozzle that provides a spray of particles so fine that superior distribution and greater combustion efficiency obtains over a range of speeds.



The difference between the old and the new is dramatically evident in this picture. The nozzle at the left sprays fuel that will blow against the firing chamber walls, resulting in caking and the formation of carbon. The nozzle on the right sprays the less than 10 micron particles, assuring complete firing without residue.

The new nozzle seems ideal for the oil-burning gas turbine, now under development by Westinghouse for locomotive applications. Here one of the major problems is to utilize the heavy Bunker C fuel oil to the best advantage. At peak operation of the turbine, the conventional fuel nozzle without air pressure does extremely well, about 96 percent of the fuel being converted into heat. However at low fuel rates, i.e., when the turbine is idling, its performance is poor. Considerable caking of carbon deposits due to imperfect combustion takes place around the nozzle and on the walls of the chamber, with the result that sometimes less than half the fuel is converted into usable heat.

The nozzle developed by Smith appears to solve these problems. It provides an even distribution of fuel throughout the combustion chamber rather than allowing it to blow against the walls. The fine degree of atomization results in complete combustion even when the turbine is idling. Up to 98 percent efficiency over the whole range of fuel rates is obtained.

The key to the new nozzle's efficiency is found in the manner in which high vortex air is created when the streams under pressure enter six pin-hole angled slots, to impinge on a spiral-shaped metal whorl. The incoming fuel, itself whirled around, collides with this high circular velocity air and is ripped into particles smaller than 10 microns in diameter.

The unique feature is the fact that this super-atomization can be obtained at fuel pressures down to 10 pounds per square inch for the heavy oil and lower for the lighter grades. With the conventional nozzle, pressures of at least 50 pounds per square inch are required for satisfactory starting. With the new nozzle maximum fuel pressures required for top-speed operation of the turbine are much reduced.

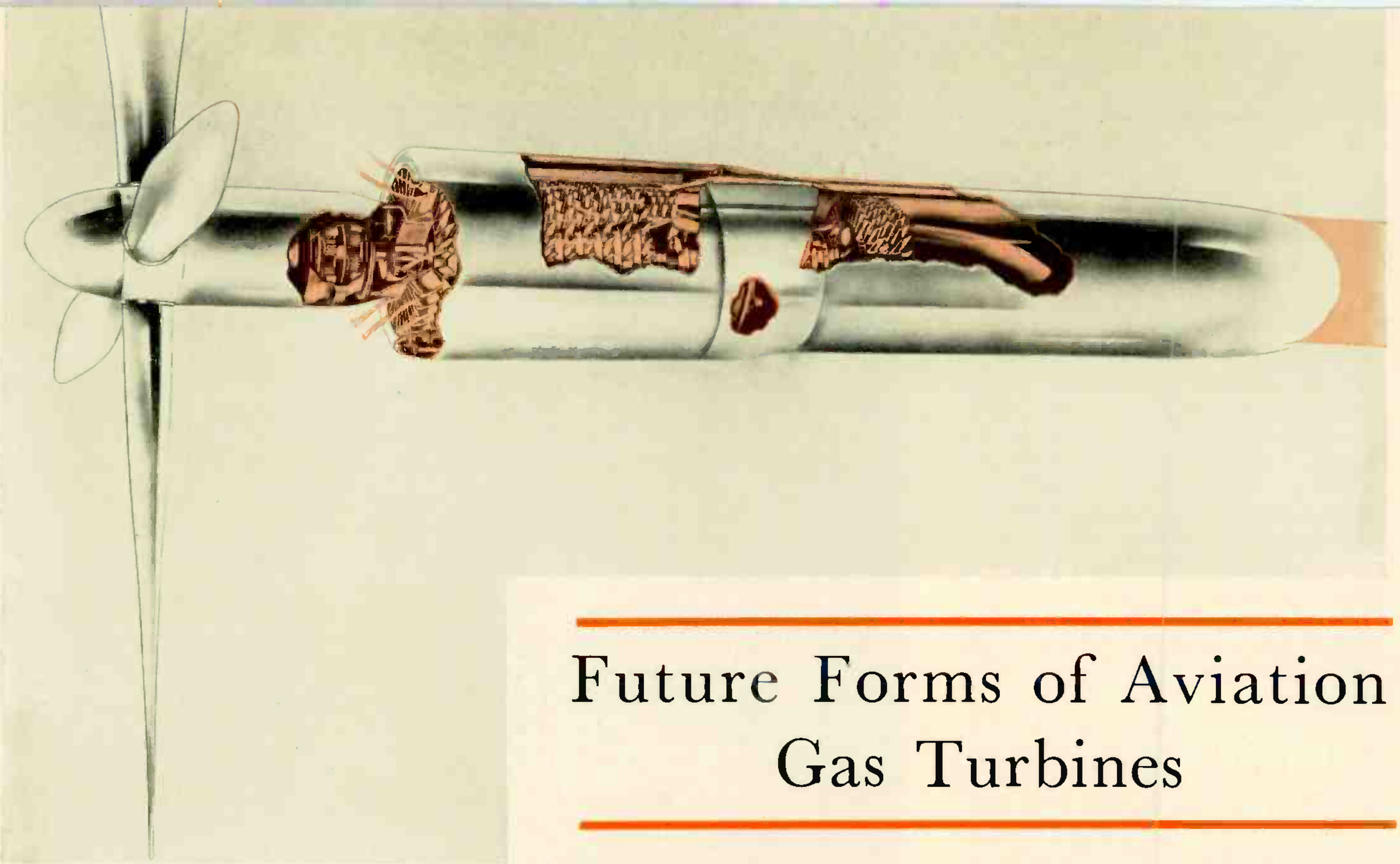


Fig. 1—A turbo-propeller combines the merits of jet propulsion and propeller drive and is especially suitable for rates of 250 to 500 mph.

Future Forms of Aviation Gas Turbines

The reciprocating engine, itself exceedingly complex, is used in aircraft in a single, simple way: it drives a propeller through a gear. The gas turbine, on the other hand, while it is the essence of simplicity, can be used in a variety of ways to propel aircraft. Aircraft gas-turbine versatility is indicated by the numerous combinations of jet and propeller drives and different turbine cycles being studied. They suggest a pending revolution in aircraft propulsion.

A. H. Redding
Development Engineer, Aviation Gas Turbine Division, Westinghouse Electric Corporation

Aircraft propulsion is not the relatively straightforward application of reciprocating engines and propellers it once seemed destined to be. Airplanes have been powered by piston engines driving propellers through gears ever since the Wright Brothers flew at Kittyhawk in 1903, although all three components have been vastly improved both in performance and capacity. The application of the gas turbine to aircraft, on the other hand, is only beginning. Nevertheless, concurrent with the rapid progress in compressors, combustors, gas turbines, and other components, numerous ways of using the new propulsion machinery have been proposed and are undergoing engineering analysis. It is apparent that the gas turbine will be used in different ways, depending on such factors as flight speed, desired range, type of load, and economics.

All present known forms of aircraft propulsion—jet, rocket, or engine-driven propeller—employ one common principle: the acceleration rearward of a large weight of gas causing a reaction on the airplane to result in a forward thrust. The gas can be free air or combustion products, or both. These three propulsion forms differ in the relative amounts of matter handled and the acceleration given it. The rocket carries within it the entire substance (fuel and oxygen) to be accelerated, the propulsion being accomplished by discharging the products of combustion with an extremely high velocity. As indicated in Fig. 2, in a turbo-jet engine a considerably larger mass of free air is mixed with the products of combustion, the total weight being discharged at a lower relative velocity, giving a reaction thrust. The propeller drive obtains its forward motion by giving relatively small acceleration to a far larger mass of free air by the mechanical action of the propeller. In the conventional aircraft some forward thrust is obtained by expulsion of the engine exhaust gases to the rear, but this is only a small portion of the total propulsive effect.

Two important considerations arise in evaluating any propulsion system:

1—How much useful thrust power is developed for a given size and weight of engine and its essential adjuncts?

2—What is the effectiveness with which the energy of the fuel is utilized as useful propulsion energy, as measured by the weight of fuel used per hour or the thrust per horsepower?

The net thrust on the aircraft is proportional to the product of weight of gases accelerated and the change in velocity. Either an increase in mass or a greater change in velocity produces greater propulsive thrust. Power, as always, is force multiplied by velocity, hence useful thrust power is proportional to the net thrust force times flight speed.

Analysis of the performance of a given jet-propulsion system requires consideration of the different components of both power and efficiency. These include thrust, jet, and input powers, and wake and thermal efficiencies. Thrust power is the power that actually propels the vehicle. Jet power is the kinetic energy added to the mass of gases accelerated for propulsion and is, therefore, proportional to the weight of gas handled multiplied by the difference of the squares of the relative velocities before and after acceleration. The input power is the product of the fuel flow times the heating value of the fuel. Wake efficiency is that percentage of the jet power that is utilized to give useful thrust power.

Three numerical examples will clarify these points. In these the thrust and flight speed remain constant, but the weight of gas accelerated in each case is reduced by a factor of 2. The wake efficiency is twice the flight speed divided by twice the flight speed plus the difference between the jet and flight velocity. This difference between the jet and flight velocity is, of course, proportional to the thrust per pound of air accelerated and, if total thrust is kept constant, is inversely proportional to the amount of gas accelerated. For the first condition

$$E_{w1} = \frac{1+1}{2+1/2} = 80 \text{ percent}$$

and for the second condition

$$E_{w2} = \frac{1+1}{2+1} = 66\ 2/3 \text{ percent}$$

While if the weight of accelerated gas is cut again in half, we have for the third case

$$E_{w3} = \frac{1+1}{2+2} = 50 \text{ percent}$$

The jet power in each case is proportional to the mass of gas multiplied by the difference between the squares of the jet and flight velocities. For the first condition

$$P_{j1} = 1\ (1.5^2 - 1^2) = 1.25$$

and for the second condition

$$P_{j2} = 1/2\ (2^2 - 1^2) = 1.5$$

Thus for a given thrust and flight speed, doubling the amount of gases accelerated reduces the amount of power in the jet in this case by a ratio of 6 to 5. The thrust power remains the same

$$P_{t1} = 1\ (1\ 1/2 - 1) = 1/2$$

$$P_{t2} = 1/2\ (2 - 1) = 1/2$$

Thermal efficiency is the one familiar to the power or engine man. It is the efficiency with which chemical energy contained in the fuel is transferred into kinetic energy of the propelling jet. Its determination is complicated because it depends upon many variables such as cycle pressure ratio, cycle temperature, component efficiency, as well as the whole makeup of the thermal cycle modified by the use of intercoolers, gears, propellers, blowers, reheaters, heat exchangers, or accessories.

Gas-Turbine Propulsion Systems

Analysis of any propulsion system must necessarily be made upon the basis of the efficiencies. Several different propulsion systems based on the gas turbine can be compared.

The Simple Turbo-Jet Engine, Fig. 3, consists of four main elements between air intake and exhaust jet: (a) a compressor in which the air used for both the thermal cycle and propulsion is compressed to several atmospheres, (b) a combustion chamber after the compressor where heat of the fuel is added to this compressed gas thereby greatly increasing its volume, (c) a turbine for expanding the gas through a sufficient pressure ratio to give power to drive the compressor, and (d) an exhaust nozzle through which the hot gases complete their expansion to atmospheric pressure and therefore leave with the high-velocity jet reaction necessary for propulsion.

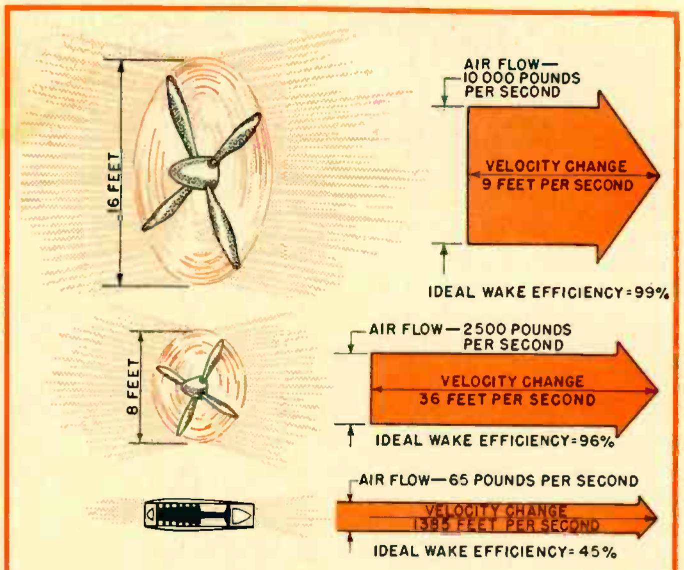


Fig. 2—Propulsive thrust is the product of mass accelerated and the velocity change. The 16-foot and 8-foot propellers, and the small turbo-jet here shown all provide the same thrust, but by widely different masses and velocity changes.

In the simple turbo-jet engine the air ejected to the rear to provide the reaction for propulsion is the same air used in the thermal cycle. Because the turbine exhaust and the jet are the same, the wake efficiency, thermal efficiency, and flight speed are interrelated. In present-day turbo-jet engines operating with a compressor ratio of 4 to 1, jet velocities for aircraft moving at 500 mph are about 2200 feet per second (1500 mph) which gives a wake efficiency of 50 percent. With thermal efficiencies, at high altitude, of 28 percent, this results in an overall propulsion efficiency of about 14 percent. If overall efficiency is to be improved for a given flight speed two alternatives are possible: (1) reduce the jet velocity, which improves the wake efficiency, or (2) improve the thermal efficiency of the machine.

A reduction of the jet velocity can be achieved by reducing the turbine inlet temperature. This improves the wake efficiency but reduces the thermal efficiency. Thermal efficiency can be improved in some cases by selecting more favorable compression ratios, usually higher ones. However, higher pressure ratios present serious problems in coordinating the design of the compressor and turbine for maximum combined performance, particularly at conditions other than those best suited to the specific design. Any method that reduces the thrust per pound of air handled by the main elements of the

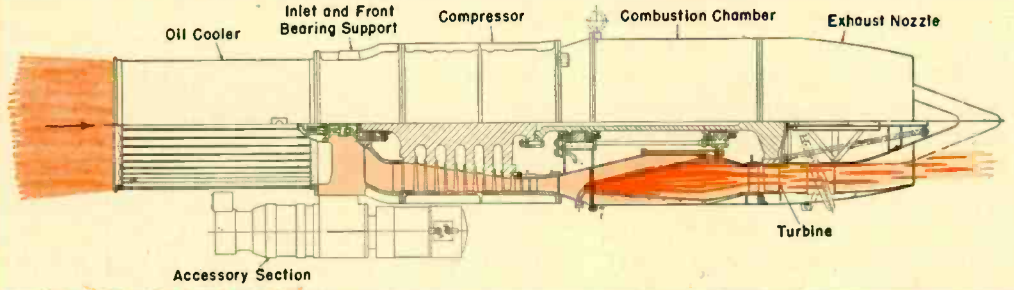


Fig. 3—In the simple turbo-jet, air is compressed, burned, expanded in a turbine that extracts enough energy for compression, and is finally ejected to the rear at high velocity.

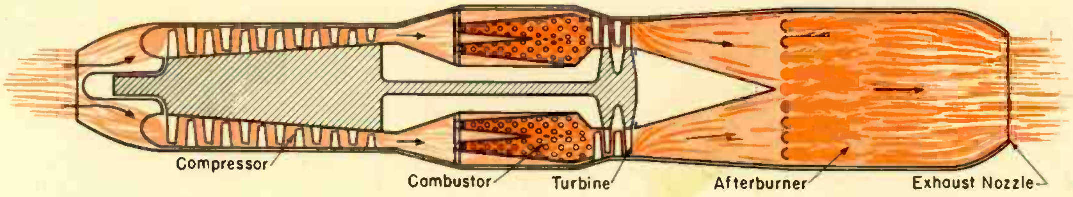
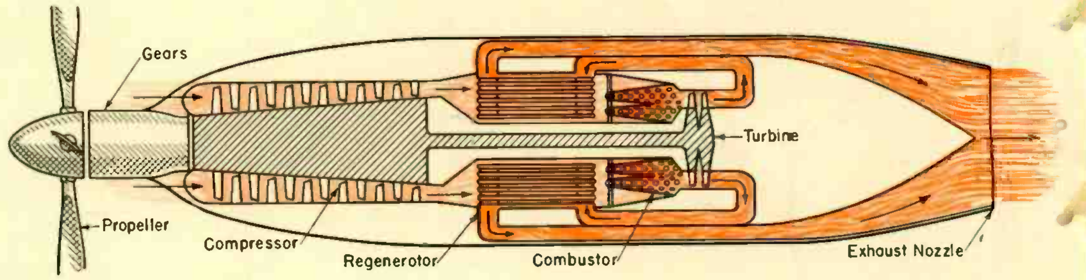


Fig. 4—Burning additional fuel in the tailpipe of a turbo-jet engine greatly augments thrust, at a lowered efficiency acceptable for short periods.

Fig. 6—A regenerator or heat exchanger can also be applied to a turbo-prop.



engine—that is, the compressor, combustion chamber, and turbine—tends to increase the weight of the engine for a given output.

The Simple Turbo-Prop Engine of Fig. 1 is the basic turbo-jet engine built with a larger turbine (i.e., more stages) to allow more complete expansion of the hot gases, plus a reduction gear and a propeller, to utilize the extra power obtained on the turbine shaft. In this arrangement more of the energy in the combustion gases is taken out as mechanical energy to drive the propeller, as well as the compressor, leaving less energy in the jet.

An advantage of the simple turbine-driven propeller is that the thermal engine can be best designed to deliver shaft power while the propeller can be designed to handle large masses of air at high wake efficiency. Unfortunately, the thermal efficiency of the propeller-drive turbine is basically considerably lower than that of the turbo-jet, because, instead of converting pressure energy into jet energy in the highly efficient exhaust nozzle, additional turbine stages must be used with lower expansion efficiency. In addition, gear losses and aerodynamic losses of the propeller must be included with all engine losses.

To compensate for this lower thermal efficiency, however, propeller wake efficiency is extremely high, reaching 98 percent at speeds above 250 mph for present designs. The modern turbo-prop engine has high static take-off thrust for a given size of power plant. It is, in general, superior to the simple turbo-jet for speeds up to about 600 mph, which covers the range for all commercial flight in the foreseeable future. For still higher speeds, which at present, are only of military interest, the turbo-jet is more efficient. Also the weight of the turbo-prop engine per pound of thrust may be two to three times larger because of the additional turbine stage, gears, and propeller. For commercial aircraft where the speeds will not exceed about 550 mph the simple turbo-propeller shows great promise because it is only two thirds as heavy as the reciprocating engine. Also because of the much smaller frontal area of the gas-turbine engine the nacelle drag is significantly less, which should lead eventually to much improved aircraft for both long and short range.

Where speeds above 450 mph are required, low weight per pound and high specific thrust are of paramount importance. While fuel consumption is important at present, it must be sacrificed for low specific weight. Where highest speeds are sought, a simple jet engine operating at the highest possible turbine inlet temperature is indicated. Wake efficiency becomes less important, while extremely high jet velocities or high thrust per unit of mass handled become important. Mechanical limitations of the turbine prohibit the use of excessive turbine inlet temperatures to achieve this aim. Higher temperatures in pure jet engines result in higher thermal efficiencies, also jet velocities are increased, signifying lower wake efficiency. Thus, since overall efficiency is the product of the two, an increase in turbine inlet temperature with present-day jet engines may actually lower the efficiency. With turbo-prop engines, however, increasing the turbine temperature may not mean a boost in jet velocity, and hence overall performance is improved.

Simple Turbo-Jet with Afterburner—A possible solution to the demand for higher powers at flight speeds near and beyond sonic is a simple turbo-jet engine in which fuel is additionally burned in the gases after they leave the turbine exhaust. Such an afterburner or combustor has been added in the tailpipe ahead of the exhaust nozzle of the simple turbo-jet engine, as shown in Fig. 4. This system provides an increase in thermal energy to the gases issuing from the turbine before they have been completely expanded in the exhaust nozzle. Increases of 35 percent in thrust at static sea-level conditions to 60 percent at 500 mph can be realized by using the afterburner. At still higher speeds the percentage thrust increase is proportionally greater. At speeds above that of sound, (742 mph in air at 32°F) thrusts in flight

Fig. 8—Still better performance ov
two cross-compound turbines, with a

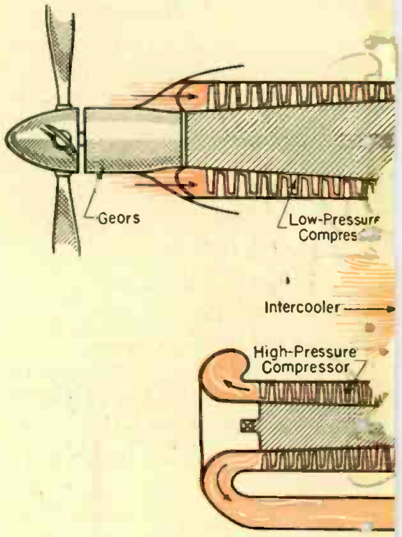


Fig. 9—An engine with separate turbine f

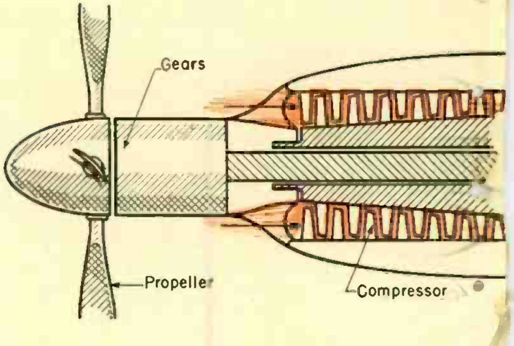


Fig. 10—A unit with propellers located in the air

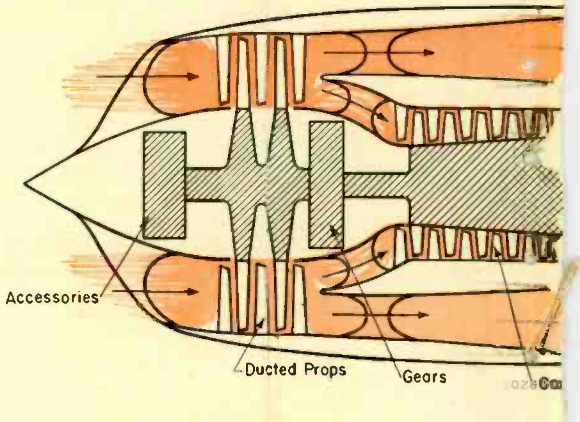


Fig. 5—With a turbo-jet unit, recovery of some of the exhaust energy in a heat exchanger improves thermal efficiency of the cycle but reduces available thrust.

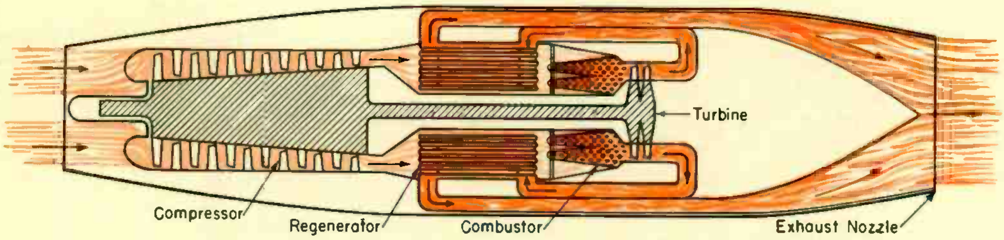
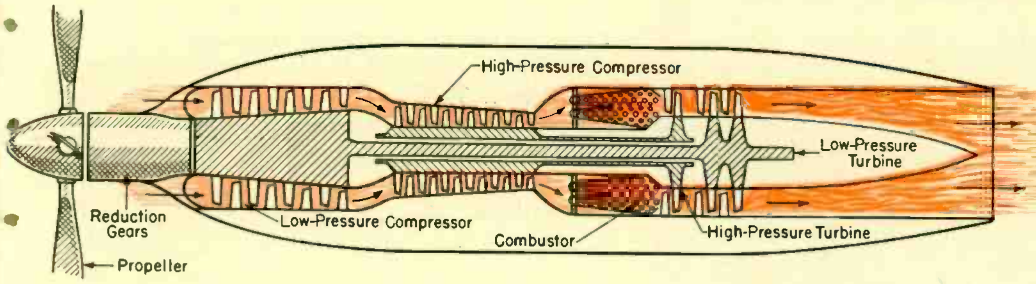
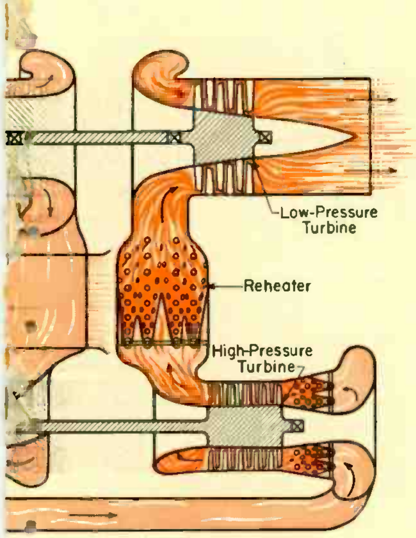


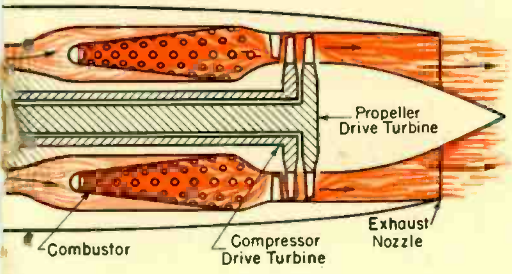
Fig. 7—To obtain better performance over a wide speed range two rbines can be used in tandem.



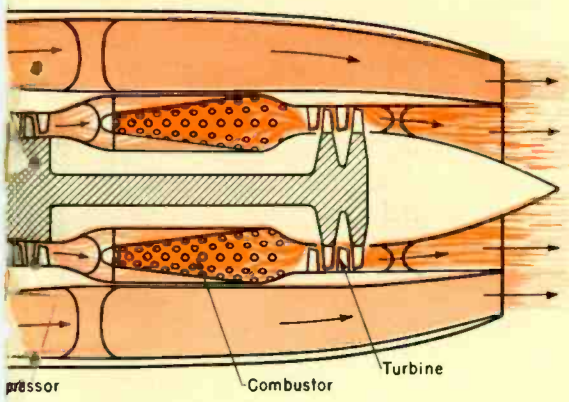
wide ranges in load is secured by addition to ducting complications.



propeller gives greater design flexibility.



the compressor permits elimination of the gears.



can be increased manyfold by this means.

In the subsonic speed range, the afterburner results in considerably increased fuel consumption for a given thrust. However, a turbo-jet engine so equipped normally would cruise at a better specific fuel consumption with the afterburner turned off. The afterburner would be used for short bursts where extremely high powers were required. In the subsonic speed range, the afterburner, in general, results in a considerably lower wake efficiency as well as a somewhat lower thermal-efficiency cycle; this gives a considerably poorer overall efficiency. The additional weight of the afterburner is a further disadvantage to overall performance.

A Turbo-Jet with Heat Exchanger, which in gas-turbine parlance is called a regenerator, as shown in Fig. 5, is one that combines improved thermal efficiency with lowered jet velocity. In this case, the hot gases leaving the turbine are piped forward to a heat exchanger between the compressor and combustion chamber. Here some of the heat of the turbine exhaust gas is removed and is added to the air leaving the compressor. This reduces the heat to be added in the combustion chamber and the amount of fuel burned and reduces the temperature of the gas flowing through the exhaust nozzle. As a consequence total thrust is reduced.

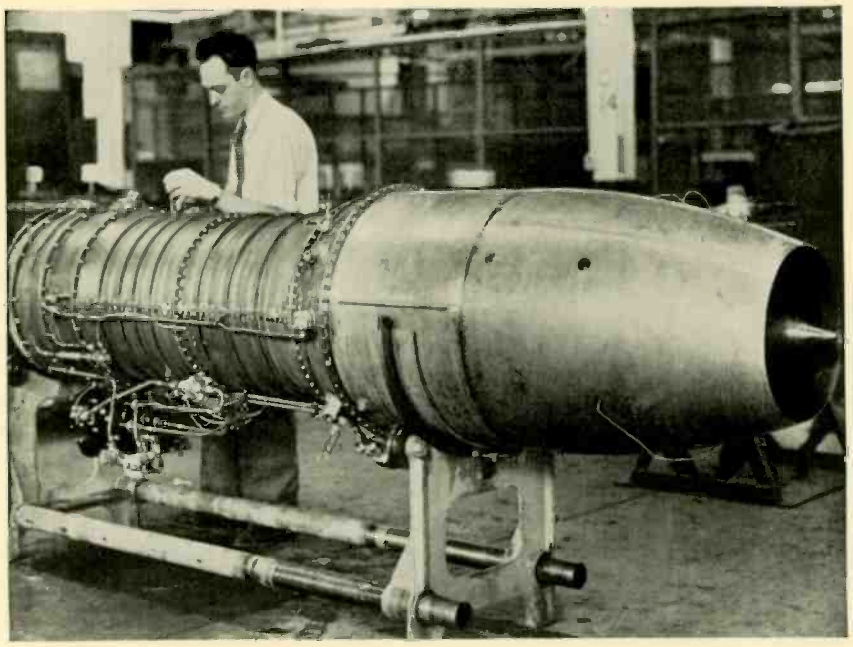
The reduction in fuel heat input per pound of air results in reduced jet velocity and therefore a lowered total thrust. Reduction in jet velocity improves wake efficiency at the same time thermal efficiency is raised. Thus while the jet engine with a heat exchanger is a heavier engine for a given thrust, fuel economy is bettered. With a moderate amount of regeneration, fuel consumption in a given case is decreased by 20 percent, accompanied by a reduction of thrust of the same percentage. This means for 80 percent of the thrust, the fuel rate is reduced to 64 percent.

A Composite Turbo-Jet Engine with Regeneration and Afterburning provides a good fuel economy at low thrusts with the afterburner turned off. It would be capable, with afterburner functioning, of extremely high thrust for short periods of time with large fuel consumptions. Such an engine would be attractive for speeds of 400 mph and upwards.

A Turbo-Propeller Engine with Regenerator—The scheme suggested in Fig. 6 uses a turbo-propeller engine with regenerator. With the ideal case of a regenerator without pressure drop, the temperature entering the turbine is the same as in a simple turbo-propeller. With a full pressure drop across the turbine, the output of the engine is the same as from the simple turbo-propeller engine. Actually, flow losses in the regenerator result in a small drop in available power. The regenerator has little or no influence on the wake efficiency of the propeller in a turbo-propeller combination. The reduction in fuel consumption results in an attractive gain in overall efficiency.

A Tandem-Compound, Turbo-Propeller Engine—As efficiencies of the gas-turbine component parts are improved by development, the most favorable pressure ratio for the simple turbo-propeller engine is increased. However, a major problem exists; a single-cylinder, high-pressure ratio, multi-stage, axial-flow compressor does not perform well at speeds and pressure ratios much below those for which it is designed. Under rated conditions, a compressor suitable for a high-pressure ratio operates with the axial air velocities correct for the peripheral speeds of all stages. However, at lower speeds, the flow of air at the exhaust end of the machine is high compared to peripheral velocity of the blading, while at the low-pressure end of the compressor, gas flows are small compared to the peripheral velocity. A serious loss in compressor efficiency then obtains. This reduction in efficiency is a function of the rated pressure ratio of the machine. The higher the pressure ratio, for which the compressor was intended the lower the partial-speed efficiency.

One solution is to use a compound engine, such as shown in Fig. 7, using two com-



Jet engines of this new type (24C) power the Navy's recently announced "Banshee."

pressors and two turbines. A low-pressure compressor is driven by a low-pressure turbine geared to a propeller. On a concentric hollow shaft a high-pressure compressor is independently driven by a high-pressure turbine. The two shafts are independent and rotate at different speeds. The speed ratio depends on the load or the average speed of the two. With this system, at starting, the low-pressure compressor rotates at relatively low speed while the high-pressure compressor turns much faster. As the speed of the high-pressure set approaches normal, the low-pressure combination increases its speed much more rapidly.

Table 1 - Fundamental Relationships for Propulsion in Air at Sub-Sonic Velocities

$$\text{Net Thrust} = \frac{(W_A + W_F)C - W_A V}{g} \quad \text{or} \quad \frac{W_A(C-V)}{g}$$

(Mass x Change of Velocity)

$$\text{Thrust Power} = \frac{[(W_A + W_F)C - W_A V]\,V}{550\,g} \quad \text{or} \quad \frac{W_A(C-V)V}{550\,g}$$

(Thrust x Flight Speed)

$$\text{Jet Power} = \frac{(W_A + W_F)C^2 - W_A V^2}{2g\,550} \quad \text{or} \quad \frac{W_A(C^2 - V^2)}{2g\,550}$$

(Mass x Velocity Squared)

$$\text{Fuel Input Power} = W_F \times H_F \times \frac{J}{550}$$

(Fuel Flow x Fuel Heating Value)

$$\text{Wake Efficiency} = 2\left[\frac{(W_A + W_F)CV - W_A V^2}{(W_A + W_F)C^2 - W_A V^2}\right] \quad \text{or} \quad \frac{2V}{C+V}$$

(Thrust Power ÷ Jet Power)

$$\text{Thermal Efficiency} = \frac{[(W_A + W_F)CV - W_A V^2]}{2\,W_F H_F g J} \quad \text{or} \quad \frac{W_A(C^2 - V^2)}{2 \times H_F W_F g J}$$

(Jet Power ÷ Fuel Input Power)

$$\text{Overall Efficiency} = \frac{[(W_A + W_F)CV - W_A V^2]}{g J W_F H_F} \quad \text{or} \quad \frac{W_A V(C-V)}{gJ W_F H_F}$$

(Thrust Power ÷ Fuel Input Power)

Symbols

W_A = Free Air Used in Propulsion—Pounds Per Second
W_F = Fuel and Mass Carried in Airframe—Pounds Per Second
g = Acceleration of Gravity—Feet Per Second^2
C = Jet Velocity Relative to Airplane—Feet Per Second = Jet Velocity Relative to Ground + Flight Velocity
V = Flight Velocity—Feet Per Second
H_F = Heating Value of Fuel (Lower Value Usually Used)— British Thermal Units Per Pound
J = Mechanical Equivalent of Heat

Such a system would allow better partial-load operation. It would actually permit use of a turbo-propeller engine designed for pressure ratios of between 16 and 20 to operate satisfactorily from starting speed up to full speed.

A Cross-Compound, Turbo-Prop System, Fig. 8, results in a more complicated ducting problem but a simpler mechanical problem. Between the two compressors is an intercooler to remove heat from the air leaving the low-pressure compressor. This reduces the mechanical work in the high-pressure compressor, leaving a larger excess of power for the propeller. A reheating combustion chamber, shown after the high-pressure turbine, raises the exhaust temperature of the high-pressure turbine to a point corresponding to the mechanical maximum allowable. This enables the low-pressure turbine to deliver more power. The intercooler and regenerator are both aimed at increasing output of the engine. Depending on the effectiveness of these two elements and the cycle in which they are used, a gain or loss in efficiency is realized. More significant is the increase in power.

A Turbo-Propeller with Separate Drive and Compressor Turbines, Fig. 9, is attractive because it simplifies control of the engine. Also it enables the designer to create a turbo-jet engine and then use it as a propeller drive.

A Ducted-Propeller Gas Turbine, Fig. 10, provides a double-rotation multibladed propeller driven from the tips of rotating low-speed turbine elements in such a manner that the reduction gear is eliminated. Such an arrangement illustrates possible variations from the simple turbo-propeller engine.

Ducted-Propeller Turbo-Jet—The simple turbo-jet engines discussed all have low wake efficiency at present-day flight speeds. On the other hand simple turbo-propeller engines have extremely high wake efficiency at such speeds. An intermediate between these two extremes is a ducted-propeller turbo-jet. A two-to-one ratio compressor handles a large mass of air, part of which is sent into the inlet of a compressor of higher pressure ratio, through a combustion chamber, and through a turbine that drives both compressors. The high-pressure-ratio compressor is connected directly to the turbine while the low-pressure-ratio compressor must be driven through a gear. The resulting thrust is obtained from the reaction of the gas used in the combustion cycle as well as from the air handled by the low-pressure-ratio compressor. Thus a thrust at static conditions considerably better than with the straight turbo-propeller is obtained. At medium flight speed, the specific weight is better than with either the turbo-jet or turbo-propeller, while the specific fuel consumption at the high range of intermediate flight speed surpasses that of the turbo-propeller. The possible use of a combustion chamber in the outer flow pass can increase the thrust obtainable by this engine as much as 80 percent at take-off and well over 200 percent at 500 mph.

A great variety of propulsion systems can be developed around the gas turbine. The combinations are almost limitless. The gas turbine, built up of a number of relatively simple components and each susceptible to individual development, allows great latitude to the design engineer in creating an engine for optimum performance for a given application. In the future more successful models of gas-turbine engines can be expected than there were types of reciprocating engines before the last war.

Excitation Systems for Turbine Generators

Excitation facilities for a-c generators demand the utmost in reliability over long periods. Experience over many years with the direct-connected exciter proves its ability to meet the need for reliability in any capacity required. That excellent record, however, does not preclude consideration of other forms of excitation now being tried such as the electronic and the Rototrol pilot exciter. For the largest machines the trend is to higher excitation voltages.

C. Lynn, *Manager • D-C Engineering Department • Transportation & Generator Division • Westinghouse Electric Corporation*

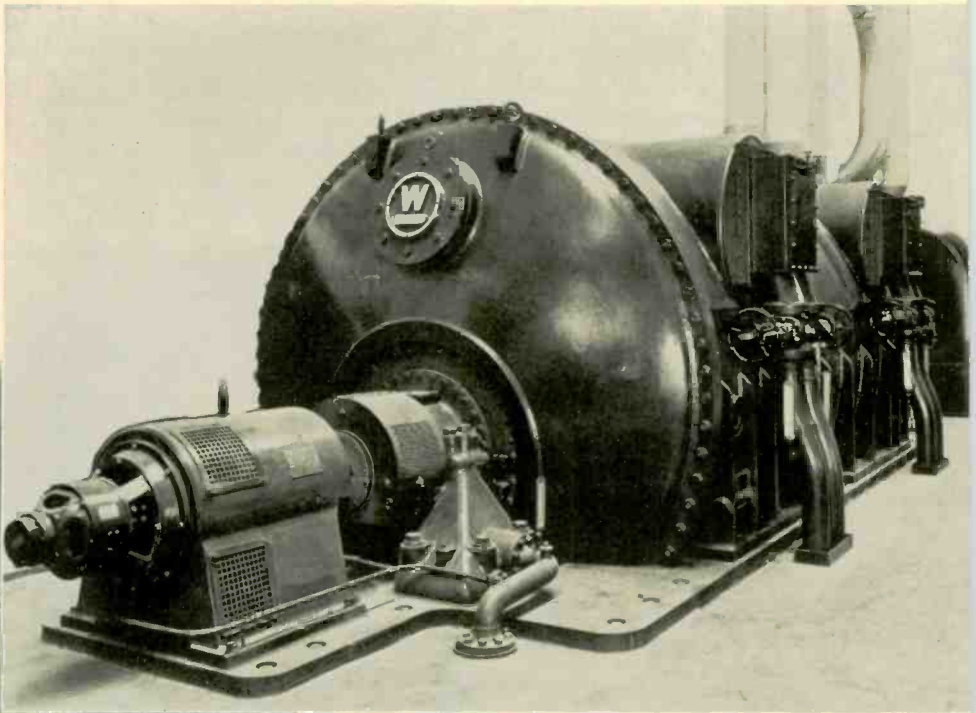
The shaft-driven exciter has been the traditional method of furnishing excitation for a turbo-generator and continues to be the most popular because of its reliability and the ability of turbine, generator, and exciter to function as a unit. Any source of excitation other than mechanical drive direct from the turbine is subject to failure of the drive or other links or units introduced into the system. The one disadvantage of the shaft-driven exciter is that, in case of serious trouble in that unit, the entire turbine generator must be shut down.

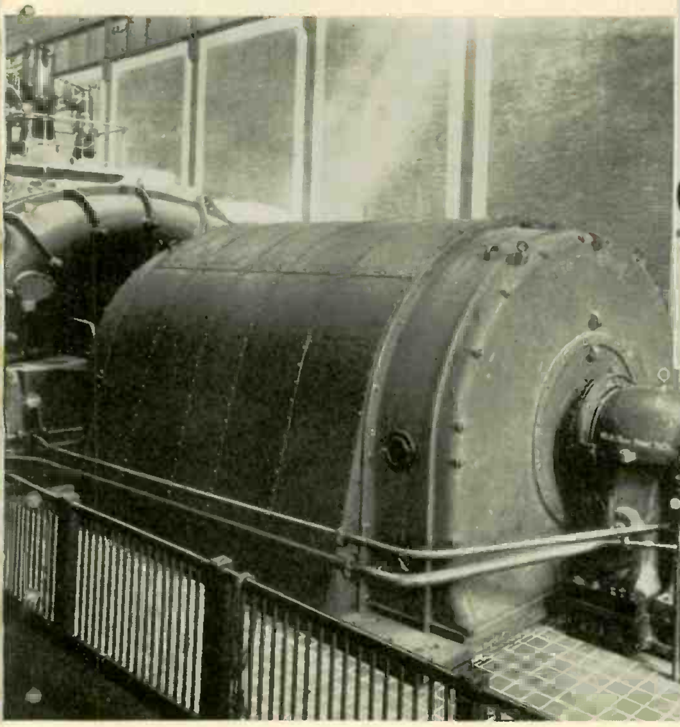
Alternate methods of excitation, until quite recently, always used rotating d-c machines, usually motor driven, although separate small turbines have been used. With this separate system of excitation, either individual exciter units for each a-c machine, or a common exciter bus can be used. More recently the electronic exciter has made its appearance. Meanwhile improvements and modifications have been made to most excitation schemes so that today the choice of excitation systems is quite varied.

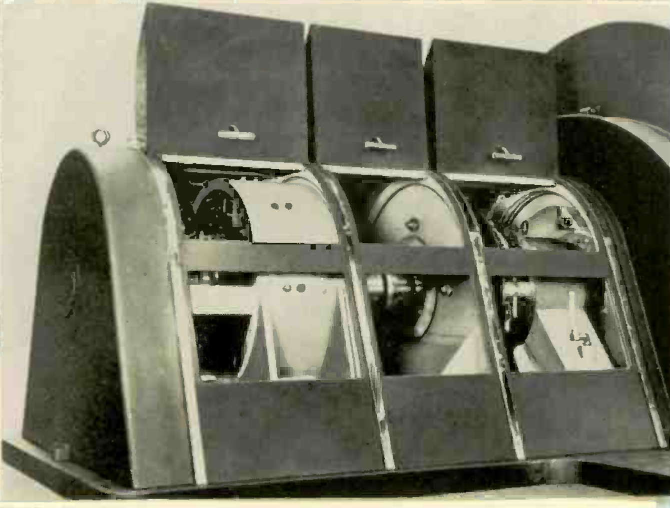
Until the first World War the shaft-driven exciter was easy to build because the generators were small and ran at 1800 rpm or less. By 1917, the largest 3600-rpm machine was only 6250 kva, requiring a direct-connected exciter of 50 kw. By 1927, the appearance of the first superposed turbine-generator unit had raised the exciter requirements to 62½ kw. To date, the largest 1800-rpm generator built is 180 000 kva, using a 375-kw, 250-volt, direct-connected exciter; the largest 3600-rpm unit is 111 800 kva, and the largest direct-connected exciter is 280 kw.

Direct-connected exciters have been built by various manufacturers in sizes up to approximately 150 kw. Beyond this rating some manufacturers have built exciters geared to the turbine shaft and operating at about one-half turbine speed. Westinghouse, however, has built only direct-connected ex-

Figs. 1 to 3 show the development stages of the present fully enclosed Westinghouse direct-connected exciter. Fig. 1 (below) is the early open-type design, Fig. 2 (right) the first enclosed design, and Fig. 3 (lower right) an intermediate development stage, showing unit covers in use before the "roll-away" cover was devised.







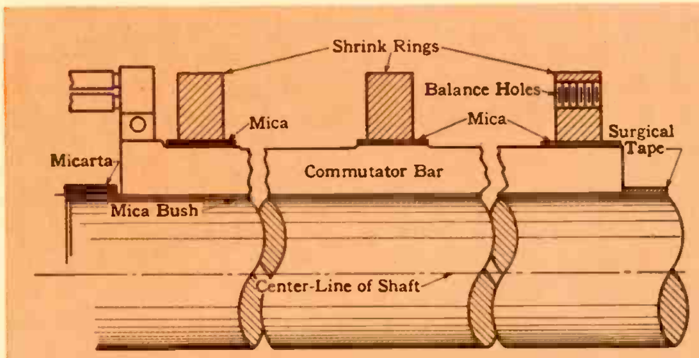


Fig. 6—An early type of high-speed, shrink-ring commutator. Note the positioning of the balance holes.

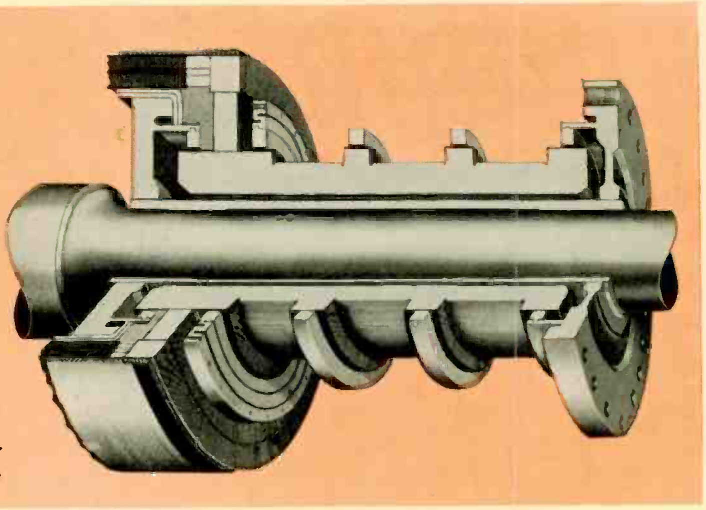


Fig. 7—The shrink-rings of this modern commutator are made of nickel-molybdenum steel.

erator. Various expedients to eliminate the pilot exciter have been tried from time to time, such as notching the poles of the main exciter. The weakness of such schemes has always been the possibility of instability when the main exciter operates at low voltages, self-excited.

The same ease of replacing brushes on the main exciter obtains for pilot exciters, but in a different manner. For reliability on this small, four-pole machine two brushes per arm are used to eliminate any possible loss of pilot-exciter voltage, such as might occur if the operator changed brushes with only one brush per arm.

The current per brush being low—about 2½ amperes—it can be carried directly into the brush from the tip of the brush finger. Standard brushes for the pilot exciter are used, but with the shunts cut off to within about one inch of the brushes to act as a means of removing a worn brush. Flexible shunts are used on the fingers, so that spring and finger bearings are not required to carry any current.

Separately Driven Exciters

Exciters driven by motors or separate turbines have normally been of the open, conventional construction. As an improvement, where motor-driven exciters still are considered, a drive consisting of an oversize induction motor and a direct-coupled flywheel is recommended. This allows the exciter to ride through system disturbances where the motor receives its power from the main generator being served. The a-c voltage can drop to as low as 70 percent of normal for a relatively long period or to zero for 0.3 second without loss of stability. This provision for maintenance of excitation is ample for normal fault contingencies.

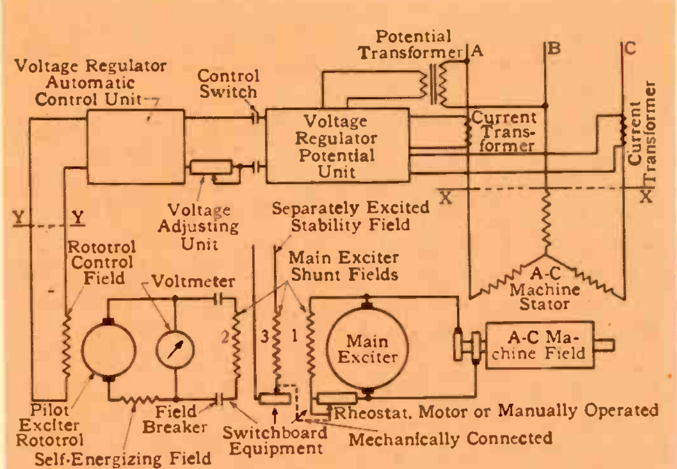


Fig. 8—A schematic drawing showing the components of "buck-boost" Rototrol controlled excitation.

Electronic Exciters

Electronic exciters of the ignitron type have been applied as an excitation source for large generators.* When the ignitron receives its power from the generator it serves, special precautions are necessary against line disturbances because the d-c voltage output of an ignitron bears a definite relation to the a-c voltage. With some electronic exciters a separate, small a-c generator coupled to the shaft of the main generator supplies an independent source of exciter power.

The separately driven exciter and the electronic exciter both are more costly and occupy considerably more space than the direct-connected exciter, although the rectifier unit itself can be located anywhere convenient. Electronic units are subject to normal hazards of rectifier operation. Accordingly they are designed oversize, so that they can operate with part of the unit out of service.

Rototrol Excitation Control

Rotating regulators, usually built to replace the conventional pilot exciter, constitute a recent improvement applicable to rotating exciters. Several schemes employing Rototrols have been or are being applied. In one type, the main exciter is a conventional unit and receives its full excitation from a Rototrol pilot exciter. In a modified scheme the main exciter is conventional but has three shunt fields, as shown in Fig. 8. (Rototrols are additionally described on pp. 121–127.)

In this system shunt field 1 provides most of the main-exciter field excitation. It receives energy from the main-exciter armature as usual. Field 3 is a small, separately excited shunt field fed from the station battery or any other source of approximately constant d-c voltage. This provides stability at low voltages, during starting, or when the unit is under hand control. The arms of the rheostats in fields 1 and 3 are mechanically connected for motor or hand operation, as desired. As the arms are turned, resistance is cut into one field circuit and out of the other. Also, the rheostat for separately excited field 3 is built so that at some point (approximately half voltage on the main exciter), the rheostat is open-circuited and remains so as it is turned further in a direction to

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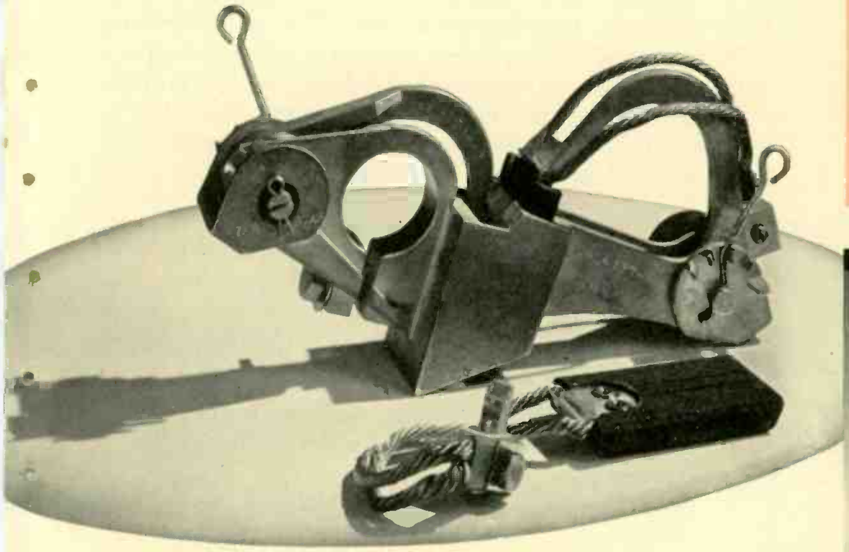
*See "Construction and Tests of an Ignitron Exciter," by R. F. Lawrence and C. R. Marcum, *Westinghouse ENGINEER*, Vol. 6, May, 1946, p. 86 and "Why the Electronic Exciter," by C. M. Laffoon, in the same issue, p. 85.

increase the voltage. This is done because field 3, the stability field, is not needed at the higher exciting voltages. Thus the drain on the station battery or other source for this field is reduced. Shunt field 2 is excited from the Rototrol pilot exciter. This scheme uses a "buck-boost" Rototrol pilot exciter.

In the scheme of Fig. 8, the rheostat on the main exciter is adjusted to provide a base value of excitation for the a-c generator. This can be set to maintain steady-state stability at any load desired on the a-c generator. The Rototrol pilot exciter operates so that field 2 of the main exciter either adds to or subtracts from the excitation of field 1. This requires the pilot exciter to operate at positive or negative polarity and of a magnitude to produce the necessary excitation. A generator static voltage regulator and the "buck-boost" Rototrol pilot exciter produce excitation of correct polarity and magnitude to maintain the a-c generator voltage constant in spite of changing loads.

This system is superior to the type where full excitation for the main exciter is furnished from the Rototrol pilot exciter in that, should anything happen to the Rototrol pilot or to any part of the voltage regulator, complete excitation would not be lost, or load dropped. In this case, the main exciter, operating as a self-excited exciter, provides base value excitation for the a-c generator corresponding to an excitation of the a-c machine when set to carry, for example, 75 percent of rated load at the predetermined voltage. If such a failure occurs and the load is other than 75 percent, the generator continues to carry whatever kilowatt loads are placed on it, within its capacity. However, the power factor then changes, because the a-c generator is under-excited or over-excited depending on whether the load is more or less than that of the initial setting. The equipment continues to function in this manner, even should a short circuit or open circuit develop in the Rototrol pilot exciter. Such would not be the case if fields 1 and 2 of the main exciter were combined, and if the "buck-boost" Rototrol pilot was connected in series with the circuit of self-excited field 1. If a failure does occur, the excitation system can be operated manually.



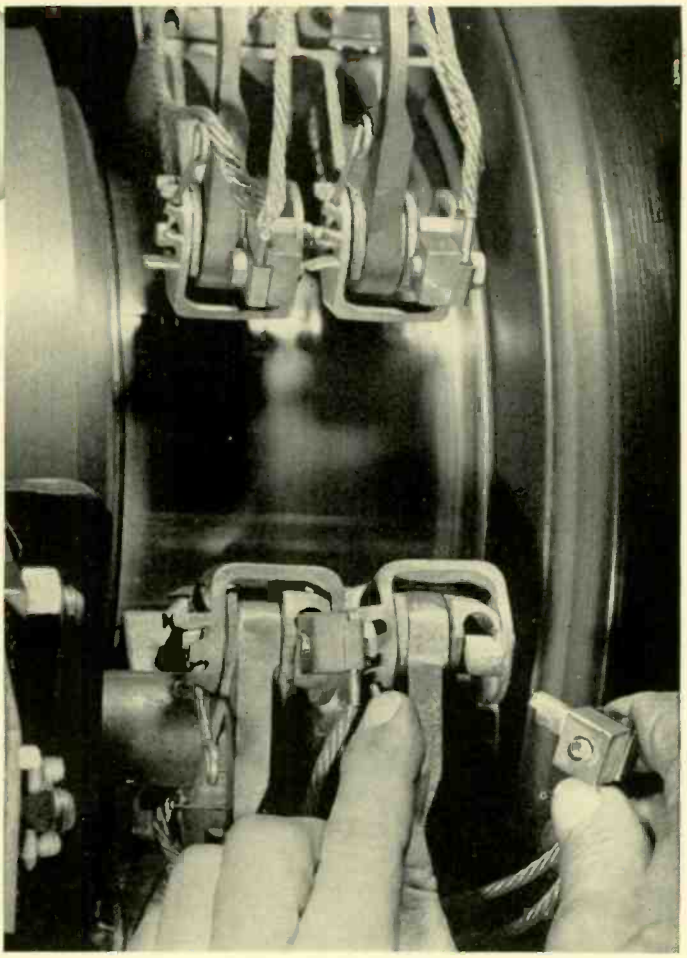
Standby sources of excitation, too, can be made in the form of three-field-winding main exciters and Rototrol pilot exciters, if desired. Where such machines operate at 1200 rpm, the Rototrol pilot can be mounted on the same shaft as the main exciter. Separate motor-driven Rototrol pilot exciters operating at 1200 or 1800 rpm can be used if desired.

In the scheme of Fig. 8, only two fields are used on the Rototrol pilot exciter: a self-energizing series field, and a control field that combines a differential shunt field and a pattern field. Its excitation is secured from the turbine generator through a voltage-regulating potential unit and a voltage-regulating, automatic-control unit. These two devices are adjustable, but have no moving parts in the sense of an ordinary voltage regulator of the contact-making or rheostatic type.

The various component parts of the voltage-regulator potential unit and voltage-regulating automatic control unit function as follows:

Current transformers are located on conductors *A* and *C* while a potential transformer is connected to *A* and *B*. Current transformer *A* supplies a filter reactor. Current transformer *C* is connected through a resistor to half of the same primary winding of the filter reactor. The output voltage of the two current transformers produced in the secondary winding of the filter reactor is combined with the voltage output of the secondary of the potential transformer to make the voltage regulator responsive to three-phase voltage conditions. The final a-c output voltage is a measure of the voltage delivered by the turbine generator compensated for the load being carried. This output voltage is fed through the two control switches and a voltage-adjusting resistor into two imped-

Figs. 9 (left) and 10 (below) show the facility with which brush replacement can be made. The brush shunt is seen to terminate in a jack. A pull on the spring tension key holding plug and jack together, and a lift on the brush-holder finger, allows the brush to be lifted out. Locating one pressure finger on each side of a brushholder (Fig. 9) does away with the awkwardness resulting when pressure-finger centers are located on the same holder side.



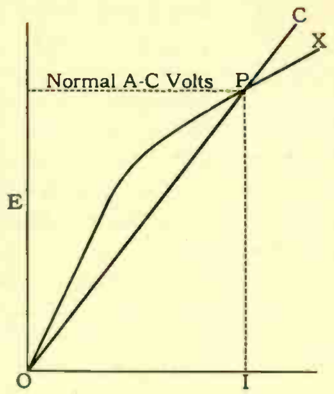


Fig. 11—The curve of a capacitor-reactance impedance for a static voltage regulator. Selection of proper capacitance and reactance values creates an intersection corresponding approximately to the normal a-c voltage on the turbine generator.

ance circuits, one capacitive and the other inductive, each terminating in a Rectox.

The curve of capacitor-reactance impedances for a static voltage regulator is shown in Fig. 11. The relation between the applied a-c voltage *E* and the current *I* through a capacitor is a straight line *OPC*. The curve *OPX* is non-linear, and shows the relation of the a-c applied voltage and the current in a saturated reactor. With the proper capacitance and reactance these two curves intersect as indicated. This point is chosen purposely to correspond approximately to the normal a-c voltage on the turbine generator. The voltage-adjusting resistance unit permits reasonable variations in this voltage as desired by station operation.

The two Rectox units are connected so that their d-c output voltages, which are equal when the a-c generator voltage is normal, are in series through a mid-tapped resistor. Under this condition there is no voltage output at *YY*, (Fig. 8).

If the generator voltage drops, the voltage applied to the capacitor and reactor is reduced so that their delivered voltages change in accordance with the curve of Fig. 11. This produces a different d-c output voltage from each of the two Rectox units. When this occurs, the voltage that appears across points *YY* is fed into the Rototrol control field. The polarity is such as to cause the "buck-boost" Rototrol to increase its voltage in magnitude depending upon the drop in the a-c voltage. The Rototrol pilot exciter thereupon increases its voltage and adds excitation into field 2 of the main exciter. This raises the excitation on the main exciter and in turn the excitation of the a-c machine, until its voltage is returned to normal. There is then no difference in the output from the two rectifiers and thus no voltage is produced at *YY* and the Rototrol control field operates at zero excitation.

If the voltage of the a-c generator increases, say due to reduction in load, the same action takes place, but of opposite polarity, as can be seen in Fig. 8. In this case, the polarity of the voltage from *YY* is reversed and, when delivered to the pilot Rototrol control field, puts a voltage of opposite polarity on field 2 of the main exciter. This bucks its voltage downward and decreases the excitation on the main exciter and on the field of the a-c machine, bringing the a-c voltage back to its normal value.

At very low voltages the currents in the capacitance and the reactance circuits differ appreciably. This means that if conductors *A* and *B* of the turbine generator unit are short circuited, in which case the potential transformer voltage is extremely low, the regulating equipment still provides an additive voltage to cause the Rototrol pilot to boost the excitation on the main exciter in an attempt to return the a-c terminal voltage to normal.

A new Rototrol excitation scheme is under development, in which the functions of the main exciter, the pilot exciter, and the contact-making type of voltage regulator are all incorporated in one two-stage main exciter without a pilot exciter. The automatic voltage-regulating potential and control units have no moving parts. With such a scheme the same stability, speed of operation, and smoothness of control are obtained with only one rotating exciter, as was secured in the past with a main exciter, a pilot exciter, and a voltage regulator.

Higher Excitation Voltages

Direct-connected exciters can readily be built in capacities up to 300 kw at 250 volts. Above these ratings a higher voltage is preferable to simplify exciter current collection and reduce the size of generator collector rings, thus simplifying operation and reducing maintenance. The largest 3600-rpm generator contemplated is 150 000 kw, which requires in the neighborhood of 400-kw excitation.

Adoption of 375 volts as a new standard excitation voltage introduces no problems for either exciter or a-c generator, as it is in the same insulation class as the present lower voltages. The excitation voltage for machines of 12 500 kw and smaller is 125 volts; for larger machines 250 volts has been standard. At present, Westinghouse is building two generators employing 375-volt excitation. One particular advantage of this voltage is that, when used in a station with 250-volt exciters and a 250-volt standby unit, a new 125-volt standby exciter can be provided whose capacity need be only one-third that of the shaft-driven unit. The new 125-volt exciter, connected in series with the existing 250-volt standby unit or bus, provides the desired 375-volt excitation.

Pictorial Wall Chart Eases Electron Tube Studies

For secondary schools, both junior and senior high, a wall chart depicting the theory, basic forms and applications of electron tubes has been made available by the School Service Division of Westinghouse.

The chart gives a complete pictorial story, which is unique inasmuch as one chart never before has contained such a wealth of detail in a form guaranteed to hold the attention and interest of students. It graphically outlines the atomic structure, and gives in a series of illustrations, the manner in which electrons are freed in gas-discharge and photoelectric tubes, field, secondary, and thermionic emissions. It shows the essential parts of tubes, together with the basic structures of four types, the diode, triode, tetrode, and pentode. Six of the important applications are pictorialized from artists' drawings: rectification, amplification, generation, changing light to electricity (sound motion pictures and television), control (welding), changing electricity to radiant energy (x-ray).

Finished in eight colors on heavy linen paper, the 25-inch by 36-inch chart has been priced at a nominal $2.00. It will find many uses in physics classes, electrical theory lectures, radio communication, and in general science classrooms.

Rototrol and Its Applications

ERLING FRISCH
Control Engineering
Westinghouse Electric Corporation

What a difference a few fields make. A direct-current generator equipped with one or more extra field windings becomes a rotating regulator of electrical or mechanical quantities, requiring for the job only a feeble indication. It is capable of enormous amplification, high speed of response, good accuracy, and versatility. Virtually every industry has found use for it.

THE Rototrol is a rotating amplifier suitable for regulating any quantity that can be measured electrically, such as voltage, current, speed, torque, tension, or position. Fundamentally it is similar in design and theory of operation to a standard d-c generator, but has a number of field windings, connected in various ways depending on the regulating problems. The Rototrol performs its regulating functions entirely through interactions of these fields.

The Rototrol Fields

Any regulating device functions on the principle that the regulated quantity is measured and compared to a fixed standard or pattern. If deviation occurs, the regulator produces corrective action to restore the quantity involved. The value of the regulated quantity, as well as of the pattern, must be converted into proportional voltages that are impressed on the Rototrol field windings. The fields are arranged to oppose each other, and are related in strength so that the resultant magnetomotive force is zero when the regulated quantity is correct. Any deviation produces a definite corrective magnetomotive force that alters the output voltage of the Rototrol in a direction to restore the quantity to normal.

In its simplest form the Rototrol, Fig. 1, has the following field windings:

A *self-energizing field*, connected in the Rototrol armature circuit, and described below.

A *pattern field*, commonly energized from a constant-voltage source. It sets the pattern for the regulated quantity.

A *pilot field* measures the regulated quantity and compares it with the pattern. Sometimes the voltages that provide the measurement for the pattern and regulated quantity are compared externally to the Rototrol, and their voltage difference impressed on a single Rototrol control field.

The Self-Energizing Field

To obtain accurate regulation the net ampere-turns of pattern and pilot fields must be zero, or nearly so, when the regulated quantity is as desired. The ampere-turns required for Rototrol excitation, therefore, must be produced by other means. This is the function of the self-energizing field, the heart of the Rototrol, and it is responsible for the sensitivity.

The effect of the self-energizing field is illustrated in Fig. 2. Assume first that the total excitation is supplied by the net ampere-turns AT of pattern and pilot fields, the Rototrol develops voltage V_1. With the effect of the self-energizing field included, the total ampere-turns of all fields equals $AT + (I_s \times T_s)$ and the voltage rises to V_2. If the Rototrol current is now increased by adjustment of tuning resistor R_1, the ampere-turns AT required to develop V_2 volts decrease until they become zero when the resistance line of the self-energizing field circuit coincides with the straight part or air-gap portion of the saturation curve. For this condition the steady-state amplification of the Rototrol is infinite. To obtain satisfactory regulation over the required range the operation, therefore, is usually limited to the air-gap portion of the saturation curve.

Rototrol Intelligence

The principles can be applied to the regulation of any quantity that can be converted into a proportional d-c voltage for supplying intelligence to the Rototrol fields. For example, the delivered torque of a d-c motor with constant excitation is proportional to the armature current and can be measured by the voltage drop across a fixed resistance in the motor-armature circuit. Speed can be measured by the voltage of a pilot generator coupled to the motor.

Two or more fields are sometimes required to measure a given quantity. For example, the speed of a d-c motor with constant excitation is proportional to the counter emf of the motor. This quantity is equal to the generator voltage minus the IR-drop in the armature circuit and can be measured by the combined effect of two properly adjusted Rototrol fields connected differentially across the motor terminals and the motor commutating field respectively.

Other fields on the Rototrol may serve to modify the regulated quantity when conditions change. It may, for example, be desired to reduce the voltage of a regulated generator as a function of load current. This is accomplished by a secondary field connected across the generator commutating field, which modifies the effect of the pattern field when the voltage drop across this field, and consequently load current changes.

Rototrol Amplification and Forcing Action

The regulating ability of the Rototrol depends on amplification factors, which fall into two classifications:

1—The steady-state system amplification, which determines the sensitivity and accuracy of regulation.

2—The dynamic system amplification, which determines the speed at which the regulated quantity is restored after a disturbance. The effect of the dynamic amplification is referred to as Rototrol forcing action.

Amplification on a voltage basis should not be confused with power amplification. It is the change in the generator voltage caused by a one-volt change in pilot-field voltage. If the amplification factor is 10, a change of one volt in field voltage, therefore, produces a 10-volt change at the load.

Dynamic amplification is the system amplification obtained without the benefit of the self-energizing field.

Steady-state amplification is the system amplification obtained with the assistance of the self-energizing field. For a properly tuned Rototrol armature circuit the steady-state amplification is infinite.

The effect of high dynamic amplification on the speed of response for typical values of field-time constants for a simple

Rototrol voltage regulator is illustrated in Fig. 3. With an amplification of 16, the time of recovery to within one percent of the initial voltage is only a small percentage of the corresponding time for unity amplification. With infinite steady-state amplification, the voltage eventually reaches 100 percent regardless of the dynamic amplification.

Although high dynamic amplification greatly increases the accuracy during transients it also tends to increase overshooting and hunting, as Fig. 3 shows. If the dynamic amplification is so high that these effects become objectionable, special stabilizing and anti-hunting circuits or devices must be used.

The forcing effect is illustrated in the lower part of Fig. 3. For unity dynamic amplification the net ampere-turns or magnetomotive force of pattern and pilot fields resulting from the drop in generator voltage are just sufficient to raise the Rototrol voltage by enough to restore generator voltage to 100 percent. For higher amplification, however, the resulting net magnetomotive force equals that actually required, multiplied by the amplification factor. As a consequence, the Rototrol voltage builds up rapidly to a magnitude much higher than that ultimately required for generator excitation. The rate of build-up is limited only by the time delay of the Rototrol fields, which lies within the control of the designer. An excess in Rototrol voltage is thus available to force additional current through the sluggish generator field and hasten voltage build-up. As the generator voltage approaches the correct value the net magnetomotive force of pattern and pilot fields approaches zero, and the additional current through the self-energizing field becomes just sufficient to maintain the generator excitation at the new value.

Two-Stage Rototrol

The dynamic amplification of the standard Rototrol, while it is considerably higher than is required by the large majority of applications, cannot be increased beyond a certain limit without excessive power input to the pattern and pilot fields. Very high amplification with a low power input can be obtained when necessary by two stages of amplification. This can be accomplished by the use of two separate machines, one a conventional exciter and the other a Rototrol. A preferred method, however, is to use a special two-stage Rototrol, where both stages of amplification are obtained with a single armature. Sensitivity and speed of response of such construction are extremely high. Tests have shown that a 10-kw, two-stage Rototrol can be controlled over its entire range with a maximum power input of less than 0.01 watt.

Current-Limit Rototrol

The current-limit Rototrol is often used in regulating systems requiring current-limiting features. It is similar to a normal d-c generator except for the specially designed pole pieces and the magnetic shunts between poles as shown in Fig. 4. Coils *B* on the magnetic shunts and coils *A* on the main coils are connected in series and energized with a current proportional to the generator or motor-armature current.

With correctly adjusted magnetic-shunt air gaps the total main-pole flux passes through the magnetic shunts, and the Rototrol voltage becomes zero. With increasing field current and flux the magnetic shunts become saturated, and further current increase beyond this point produces a flux in the armature air gaps. The unusual saturation curve obtained in this manner is shown in Fig. 5. This characteristic is utilized to limit to a safe value the current of any Rototrol-controlled, d-c machine, when the current-limiting features cannot conveniently be incorporated in the Rototrol.

Fundamental Applications of the Rototrol

Voltage Regulation

A schematic diagram of the simplest form of voltage regulation of a d-c generator by Rototrol is shown in Fig. 1. The pattern field *PF* is energized from a constant-voltage reference bus, and the differentially connected pilot field *VF* is energized by the generator. When the generator voltage is correct, the ampere-turns produced by the two fields are equal, and the actual Rototrol excitation is supplied by the self-energizing field *SF*, assuming that the field circuit is tuned perfectly.

The regulated voltage is a direct function of the pattern-field current. Accuracy of regulation, therefore, depends on variations in reference voltage. If the reference bus is energized from an exciter, an error in regulation of at least two to three percent must be expected. When higher accuracy is required special provisions must be made to obtain a more constant reference voltage, as indicated in Fig. 6.

Current Regulation

Regulation of current is used principally as a means of maintaining strip tension in wind-up and unwind operations utilizing core-type reels in the steel, textile, paper, film, plastic, and rubber industries. Other applications are rapid acceleration and deceleration of high-inertia loads and various electrochemical processes. For practically all of these applications, the Rototrol regulators, which supply excitation for the regulated motor or generator, have a pattern field connected to a constant-voltage, d-c source and a differential pilot field connected across the commutating field of the machines for current measurement. The pilot-field current changes with the temperature of the commutating field, making accurate regulation impossible with this method.

For some electrochemical work, where high direct currents must be regulated within very narrow limits, an interesting method of obtaining accurate intelligence is available as illustrated in Fig. 7. This method requires a saturating three-legged two-coil reactor, with one coil energized by a connection made to a constant-voltage a-c source, while the other is energized by a bus carrying the main d-c generator current and acting as a one-turn coil. Below the saturation point, the reactance of the a-c coil remains nearly constant, independent of the generator current; the coil current does not change. The coil current is rectified in a Rectox rectifier and energizes the Rototrol pilot field. When the generator current exceeds a certain amount the reactor becomes saturated and the reactance of the a-c coil decreases rapidly. As a result the current in the pilot field rises sharply with increasing generator current as illustrated by the Rototrol field curves. The generator current at which saturation occurs can be adjusted by varying the reactor air gap.

The reactor circuit is energized by the secondary voltage of a transformer with two secondary windings. After rectification the output voltage is impressed on the Rototrol pattern field *PF* and the other on the current field *CF*. Ampere-turns of the pattern field are nearly constant and independent of d-c generator current. The Rototrol current and pattern fields are connected to oppose each other, and the generator current is regulated for a value corresponding to the point of intersection of the two field-current curves.

Changes in the a-c bus voltage within reasonable limits do not affect the regulation because the ampere-turns of the pattern and current fields change in the same proportion and the current value at the point of intersection of the field curves remains unchanged. As a result, a given direct current always

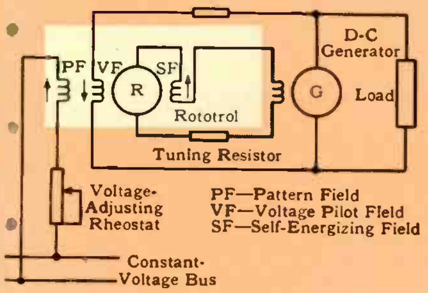


Fig. 1—Schematic of Rototrol when used as a voltage regulator.

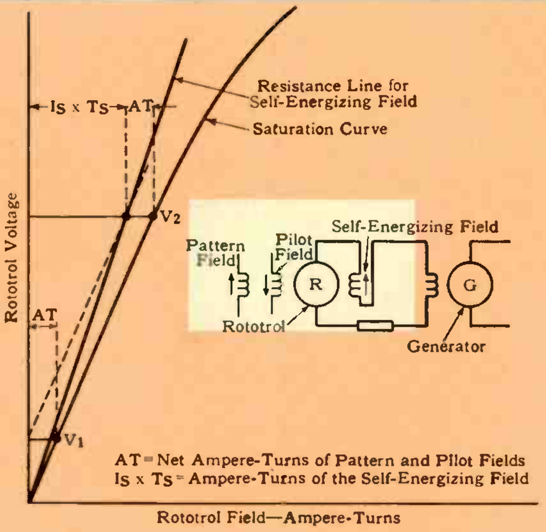


Fig. 2—Saturation curve for Rototrol.

produces the same intelligence; therefore, accurate regulation is possible.

Tension Regulation

Wind-up and unwind operations of core-type reels, such as those in use on the new Sendzimir sheet mills, usually are tension-controlled by regulation of the reel-motor current. This type of tension regulation presents several problems in that it is necessary to compensate for coil build-up and for reel and coil inertia during speed changes. The complications resulting from attempts at compensation can be avoided if tensiometers are used to supply the information required by the Rototrol regulators.

The tensiometers may be spring loaded or, as shown in Fig. 8, compressed-air loaded. The tension in the rolled strip is actually developed by the tensiometer action, and desired tension is obtained by variation of the air pressure. Because of the special lever arrangement, the tension varies with the position of the tensiometer roller above the pass line as indicated by the tension curves. To hold tension accurately the tensiometer must be kept in range as close to the middle position as possible, by regulation of the relative speed of the reel motor. This position should correspond to a point on the flat portion of the tension curves to obtain the highest accuracy.

Tensiometers have two contact units to obtain a measure of the departure from the middle position. The contact units consist of flat phosphor bronze springs with silver contact tips connected to resistors. If the position changes from the middle, the contacts of one or the other close gradually to short circuit the associated resistance.

A schematic diagram of a control scheme for a tension regulator is shown in Fig. 9 where power for the reel motor is supplied by a separate generator. A motor-operated rheostat driven by motor *RHM* controls the reel-motor field to obtain the necessary range in motor speed to compensate for coil build-up. The tension is regulated by control of the generator excitation supplied by Rototrol *R*. To reduce the physical dimensions of reel motor and generator to a minimum the motor field must be controlled during the winding operation so that the generator voltage is maintained at a value approximately proportional to the strip speed as measured by the voltage of pilot generator *PG*.

Before starting the mill, line contactor *M* is open and the rheostat motor is connected to the d-c supply bus by auxiliary relay M_a, which causes the rheostat to be moved to the minimum-field position corresponding to empty-reel speed. With no metal in the mill, the tensiometer is in the extreme low-tension position and limit switch *TLS* is open, and relay *A* is de-energized. When the reel motor is started by closing of contactor *M*, the Rototrol pattern field *PF* is connected to the pilot generator and voltage field *VF* is connected to the reel generator bus, while the tension field *TF* is disconnected. The Rototrol therefore functions as a voltage regulator and regulates the generator voltage to a value proportional to the mill speed. The fields are so designed that the resulting reel-motor "threading" speed is slightly higher than the corresponding operating speed, to obtain a tight initial wrap after the reel

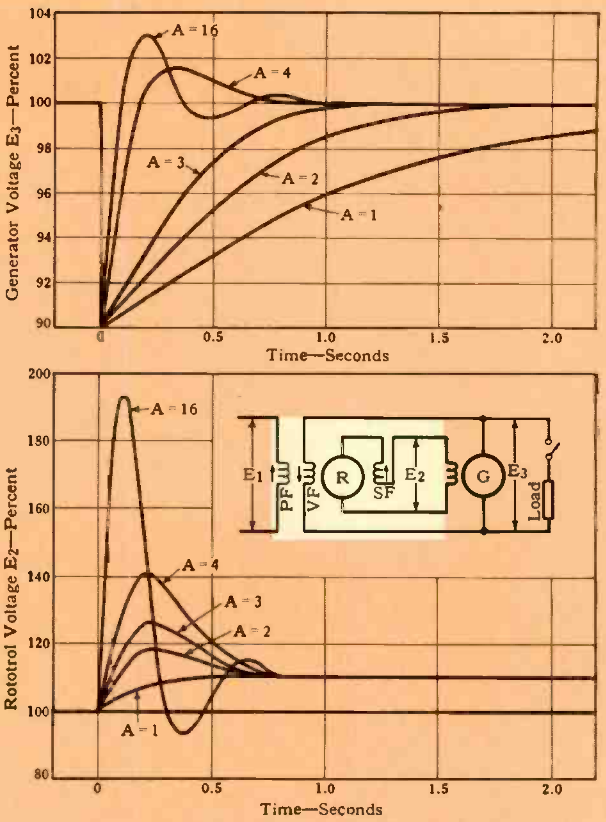


Fig. 3—Schematic view of Rototrol used as voltage regulator. Curves show the effect of dynamic amplification on the speed of response of generator voltage and on Rototrol forcing.

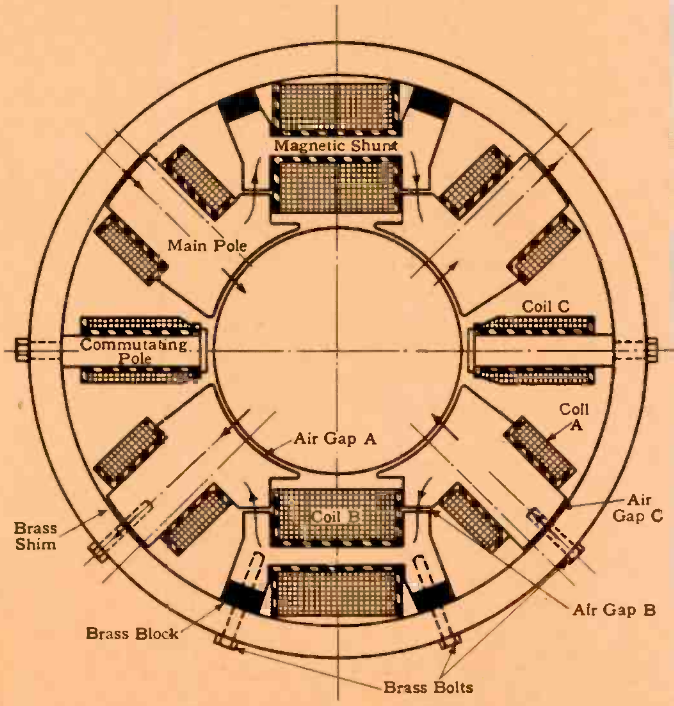
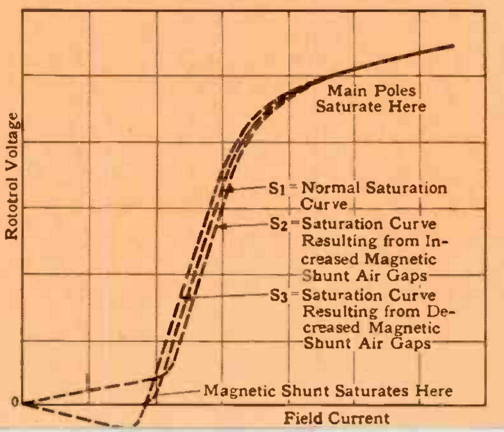


Fig. 4—Pole piece of current-limit Rototrol.

Fig. 5—Saturation curve obtained with special pole piece used on current-limit Rototrols.



has been threaded by the automatic belt wrapper. The speed can be adjusted by a threading-speed rheostat.

When the coil is properly started, tension develops and forces the tensiometer toward the high-tension position and the tensiometer limit switch *TLS* closes. Relay *A* becomes energized and connects the Rototrol tension field *TF* to the tensiometer bridge circuit while disconnecting fields *PF* and *VF*. The bridge circuit consists of the two tensiometer resistor units *LT* and *HT* and the two fixed resistors *RT*. For correct tensiometer position the current in field *TF* is zero, but the field is energized when the position changes and resistor *LT* or *HT* is gradually short circuited as a result of the reel-motor speed being too high or too low. The Rototrol then maintains correct tensiometer position by regulating the generator voltage and, consequently, the reel-motor speed.

As the coil builds up, the generator voltage decreases gradually unless the motor field current is increased sufficiently to compensate for the build-up. For this purpose the driving motor *RHM* for the reel-motor rheostat is connected to generator *RHG* through relay contacts M_a, when the reel motor is started by closing of the line contactor *M*. The generator is actually a Rototrol with a slightly under-tuned shunt self-energizing field *SF* in addition to the pattern field *PF*, connected to the mill-motor pilot generator to obtain a measure of strip speed, and pilot field *VF* which measures the voltage of the reel generator. When the voltage is of the correct value the two latter fields balance and the Rototrol voltage is zero. When the voltage decreases as a result of coil build-up the Rototrol becomes energized and supplies power to the rheostat motor in a direction to increase the reel-motor field. The movement stops as soon as the reel generator voltage again rises to the correct value as a result of tensiometer action. A Rectox block is connected in the rheostat motor circuit to prevent mis-operation or hunting caused by temporary reversal of the Rototrol. This slow step-by-step movement of the rheostat continues until the coil is completed.

The tension regulator maintains tension also when the mill is stopped at any time during the coil build-up. Because the reel motor cannot carry rated current without damage when at standstill, the value of the stalled tension and, consequently, of the motor current, is reduced by lowering the tensiometer air pressure when the mill stops.

Speed Regulation with Current Limit

Where the speed of a motor in a variable-voltage system must be changed or reversed frequently, the motor must be brought to the desired speed as quickly as possible without dangerous overloading of the equipment. This must be accomplished regardless of the speed at which the master controller is moved to the selected speed position. A typical example is a mine-hoist drive, which requires good speed regulation in addition to positive limitation of load current under all conditions including motor stalling and plugging.

A standard Rototrol in combination with a current-limit Rototrol, as described, is well suited for this application and makes possible a control system that, for simplicity and reliability, cannot be matched by other types of control. A schematic diagram of a hoist drive with Rototrol speed and current-limit regulation is shown in Fig. 18.

The generator field is energized by a Rototrol, which operates entirely as a speed regulator for steady-state operation. The speed of a motor with constant excitation is proportional to the counter emf of the motor, which in turn equals the generator voltages less the IR drop in the armature circuit. The Rototrol intelligence for motor speed, therefore, is obtained by two differentially connected fields *VF* and *IRF* designed to measure voltage and current respectively. The combined effect of the fields is compared to the Rototrol pattern field *PF*, and the Rototrol functions to reduce to zero any difference existing between the ampere-turns of the speed-measuring fields and the pattern field. The pattern field is energized by a constant voltage, and the field current is adjusted and reversed by contacts on the master-speed controller. Any change in the pattern-field current causes a similar change in motor speed.

While motor speed is being changed as a result of a rapid change of the pattern-field current, motor accelerating current is safely limited by the current-limit Rototrol. This machine has an unusual saturation curve. The Rototrol voltage remains close to zero as long as the net field ampere-turns are below a certain amount *A* corresponding to the maximum permissible motor current. For currents in excess of this value the voltage rises rapidly and energizes field *CLF* on the main Rototrol. The ampere-turns of this field oppose the net difference in ampere-turns of the speed-measuring fields and

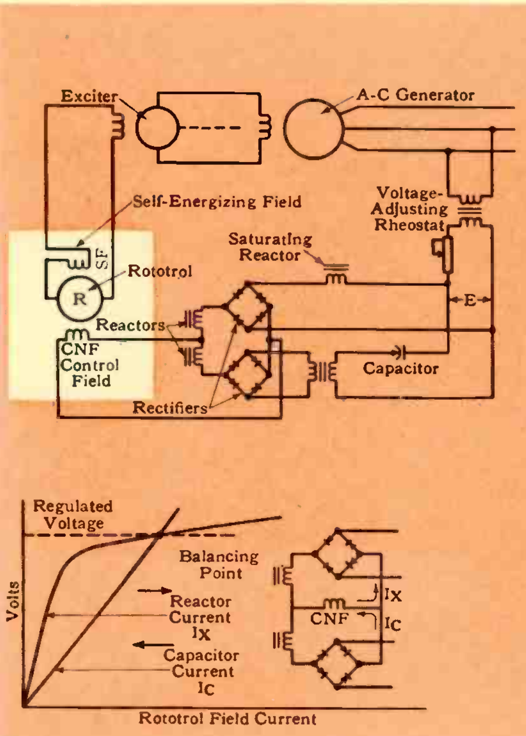


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Fig. 6—Schematic of Rototrol when used as a voltage regulator for large synchronous generators. Also shown is Rototrol field current as a function of the controlled generator voltage.

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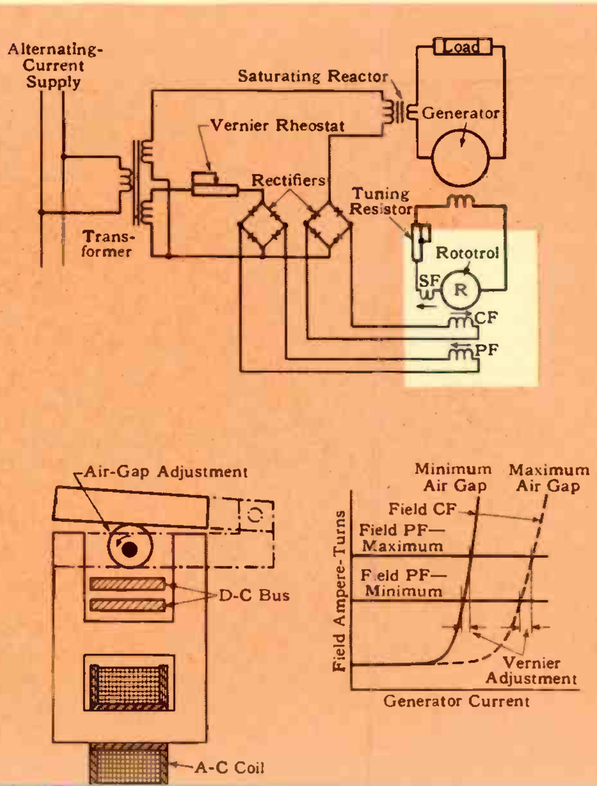
Fig. 7—Schematic view of Rototrol and a saturating reactor where high direct currents must be regulated within narrow limits for certain work.



the pattern field that causes the speed change, and will not permit the motor current to exceed the preset magnitude.

As the motor speed approaches the selected value the net difference in the ampere-turns of the fields decreases gradually, and less voltage is required to produce the required opposing ampere-turns of the current-limiting field. If the current-limit Rototrol were excited by current field *CF* alone, the motor accelerating current would vary considerably throughout the speed range.

To maintain accelerating current constant, independent of speed, the current-limit Rototrol *CLR* has two additional fields *PF* and *VF*, which are connected in series with the pattern and voltage fields on the main Rototrol. For steady-state condition the combined effect of the two fields is zero. For transient conditions, however, the net ampere-turns of the fields produce the necessary increase in Rototrol voltage for energizing the current-limit field *CLF* without any change in accelerating current, as illustrated in Fig. 18. As the motor accelerates to the value set by the pattern field, the voltage field ampere-turns gradually increase until they equal the pattern field ampere-turns, and the voltage of the current-limit Rototrol changes from *B* to *A*.

Power-Factor Regulation

When synchronous motors with constant excitation are used for drives with variable loads, the load-current power factor is subject to wide variations. If the motor is large and depended on for system p-f correction, it becomes necessary to provide automatic p-f regulation by control of the motor field current. Depending on the conditions, it may be necessary to maintain either the power factor or the reactive kva at a constant value.

Rototrol provides a simple and efficient solution for this important regulating problem. As shown in the schematic diagram, Fig. 10, the Rototrol is provided with two differentially connected voltage fields *VF1* and *VF2*, which are in balance when the power factor or the reactive kva is at the preset value. Any deviation causes an increase or a decrease in the motor excitation to produce the necessary correction in the regulated value. The two fields are energized by rectified voltages from a system of potential transformers, current transformers, and rheostats as shown. Vector diagrams have been drawn to illustrate the theory of operation for regulation of power factor and reactive kva.

Letters *A* to *F* are used for corresponding potentials in the schematic diagram and the vector diagrams. Vectors *OA* and *EF* represent the motor current and phase voltage for phase *A*. The two Rototrol fields *VF1* and *VF2* are energized with rectified voltages *CF* and *DF*, respectively, and the Rototrol functions to raise or lower the motor-field current to restore the voltages to equal values whenever a disturbance occurs. Current vector *EF1* produces excess ampere-turns in field *VF2* (vector *DF1* is longer than *CF1*) thereby causing a reduction of the motor excitation until the phase-current vector again coincides with vector *EF*.

Power-Factor Regulator

The reactive-kva adjusting rheostat is placed in the middle position. By means of the p-f adjusting rheostat potential *D* is shifted along vector *AB* and changes the regulated value of the power factor from 50 percent (leading) at point *A* to 100 percent at point *B*.

Reactive-Kva Regulator

The p-f adjusting rheostat is placed in the 100-percent position. (Potential *D* coincides with potential *B*.) By moving the reactive-kva adjusting rheostat away from the middle position potential *E* is shifted on vector *BC* away from the middle point *E1*. Since vectors *DF* and *CF* are regulated to equal values by means of the Rototrol, it follows that the reactive-current component *EE1* is held at a constant value.

Rototrol Electronic Regulation

For many applications where extreme accuracy and speed of response are required, the signal for the Rototrol control fields is supplied through electronic amplifiers. The partnership of Rototrols and electronics has proved very successful in service. Because of the tremendous amplification obtained with this combination, large machines can be controlled with a signal input of less than one ten-thousandth of a watt, thereby simplifying the introduction of the necessary anticipatory and anti-hunt intelligence. Typical applications are sectionalized paper machines, rod mills, side-register winder control, and flying shears.

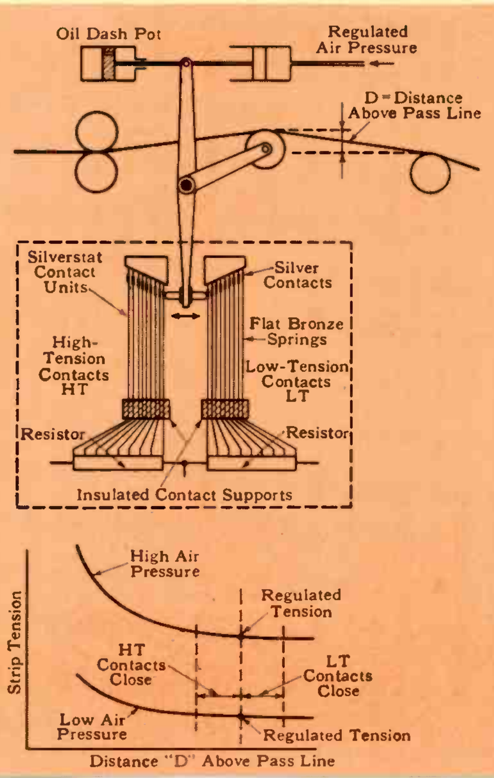


Fig. 8 (left)—Schematic view and tension curves of compressed-air loaded tensiometer, and Fig. 9 (below) tension control where power for reel motor is supplied by a separate generator.

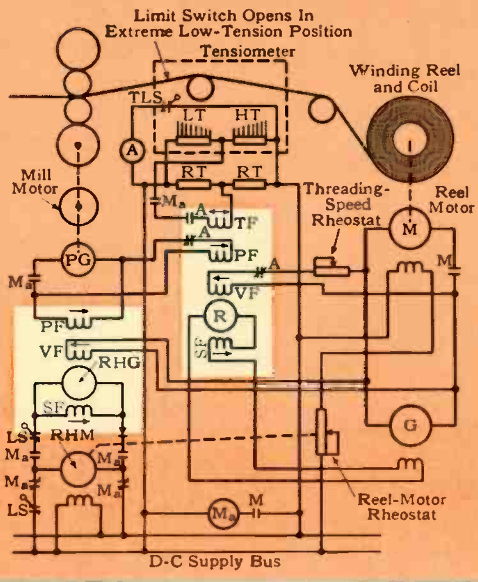


Fig. 10—Simplified version of the Rototrol circuit as used for a-c generator power-factor regulation and vector diagrams for power-factor and reactive kva.

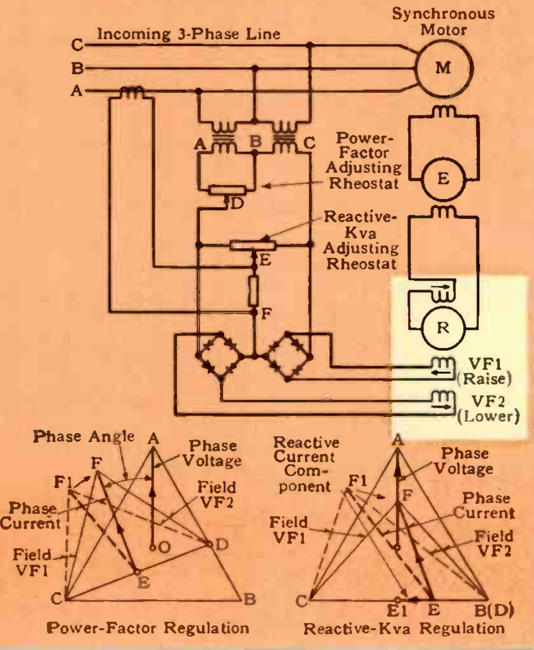


Fig. 11

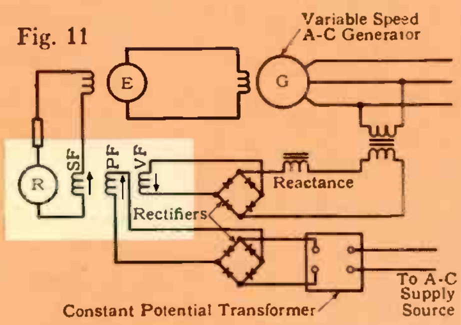


Fig. 13

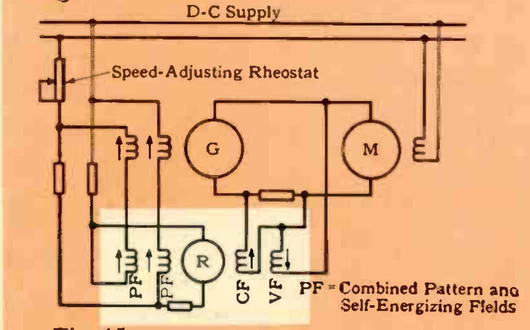
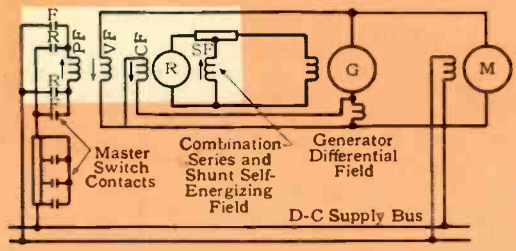


Fig. 15



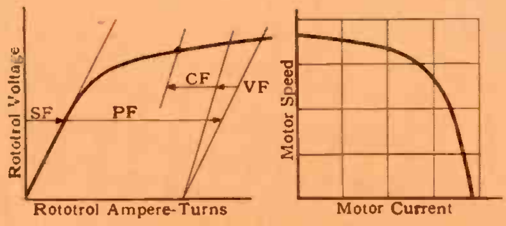
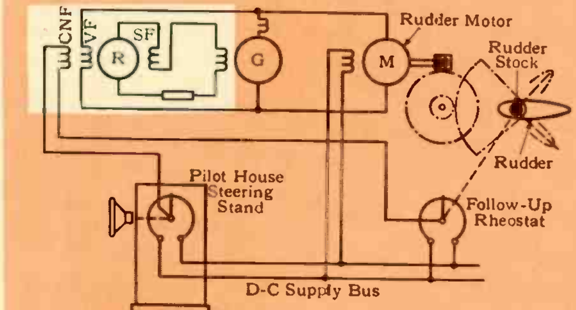
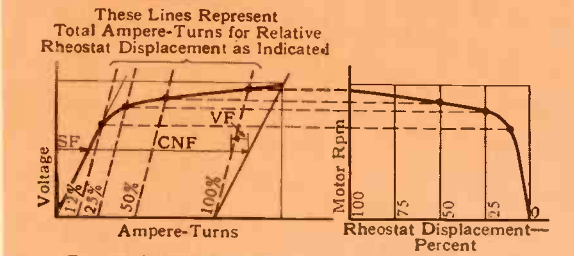


Fig. 17





Rototrol Saturation Curve

Motor Speed Curve

Fig. 12

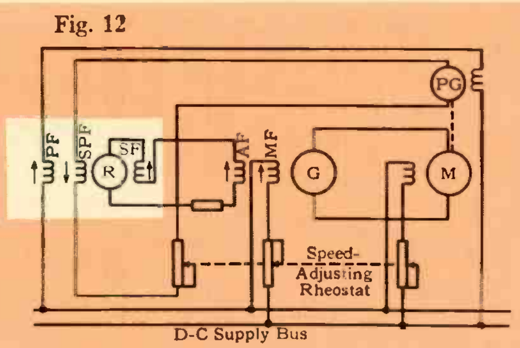


Fig. 14

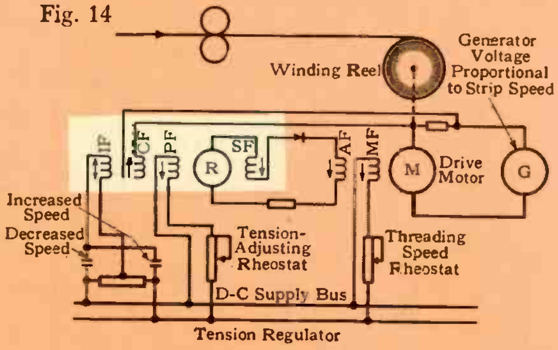


Fig. 16

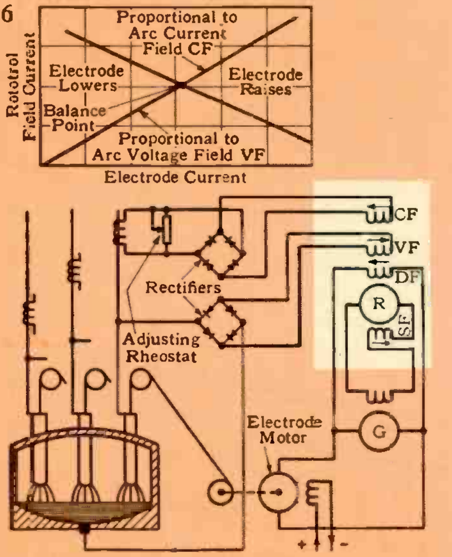
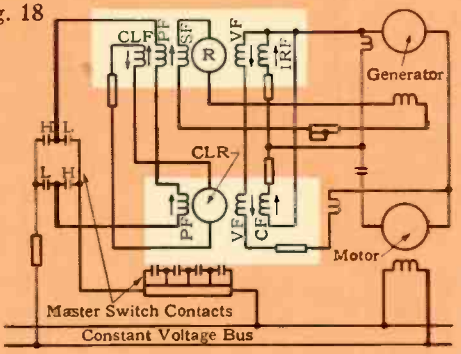
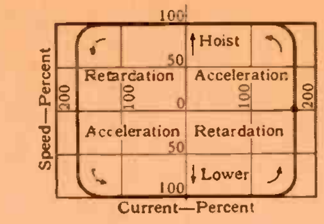


Fig. 18





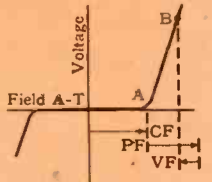


TABLE I—REPRESENTATIVE USES OF

Quantity Regulated	Rototrol Field Intelligence
Voltage	A-c generator voltage.
	D-c generator voltage.
Volts-per-Cycle	A-c generator voltage proportional to frequency.
Speed	Voltage of pilot generator coupled to the regulated motor.
	Motor counter emf measured by the combined effect of motor current and voltage.
Tension	Motor armature current.
	Tensiometer position as measured by operation of Silverstat contact units.
Current	D-c generator armature current.
Speed with Current Limit	Motor counter emf for speed regulation. Current for current limitation.
Speed and Torque	Motor armature current. Motor voltage.
Power	Load current and voltage.
Position	Depending on the particular application.

Typical Applications	Typical Diagram Reference	How Rototrol Performs the Assigned Function	Why Rototrol Is Selected
Central-station generators. High-frequency generators for induction heating. Ships' service generators.	Fig. 6	Generator voltage is impressed on two circuits with a saturating reactor and a capacitor, and supplied through rectifier to the Rototrol control fields with opposing polarities. Capacitor current is a linear function of voltage; reactor current is non-linear. Generator is regulated for voltage corresponding to intersection of field ampere-turn curves.	The control-field current and, consequently, the regulated voltage, is independent of temperature changes, which permits accurate regulation.
Generators to supply variable voltage for speed control reference bus.	Fig. 1	Pattern field *PF*, energized by d-c supply bus, is connected differentially to voltage field *VF*, energized by generator voltage. Generator is regulated for voltage at which the two field ampere-turns are equal.	Great simplicity and stability. Because the regulated voltage depends on temperature variations and supply-bus voltage, accuracy of regulation is limited.
Variable-speed generators for power supply to: wind-tunnel model motors; ships' cargo pump motors.	Fig. 11	A pattern field of fixed magnitude is established by the constant-potential transformer. The differentially connected voltage field is energized by a transformer through an air-gap reactor and a rectifier. Hence, the field current is a function of generator volts-per-cycle, which is regulated for equal field ampere-turns.	The control scheme is simple and gives good accuracy when the frequency range and the volts-per-cycle range are not excessive. Accuracy decreases at low frequencies.
Single-motor paper machine drives; wind-tunnel motors; flying shears; turbo-compressor testing rigs; rubber and plastic calender drives; dynamometers.	Fig. 12	Approximate speed adjustment is obtained by rheostat control of generator main field *MF* and the motor field. The Rototrol, connected to the auxiliary field *AF*, supplies required correction for accurate speed regulation. Rototrol field *SPF* measures the motor speed and compares it to a set pattern as measured by field *PF*. Any deviation in motor speed upsets the field balance and starts corrective action.	Series connection of Rototrol pattern field and pilot generator compensates for changes in supply voltage and field temperature. Accurate regulation of speed over a wide range is possible.
Feed drives on adjustable-voltage planers; high-speed elevators; skip hoists; paper or textile winders; supercalenders.	Fig. 13	Motor current is measured by Rototrol field *CF*. Motor voltage is measured by the differentially connected field *VF*. The resulting total ampere-turns provide a measure of motor emf and, consequently, of motor speed. Good regulation over a wide speed range is obtained by connecting the two Rototrol pattern fields *PF*, which also serve as self-energizing fields, in a bridge circuit with the generator shunt fields.	Because a pilot generator is avoided, this method of speed control is preferred except when the highest accuracy is required. It provides good speed regulation over wide ranges. Drives with speed ranges up to 1:120 are in operation. High running and starting torques are available down to the lowest speed.
Winding and un-wind drives in steel, textile, paper, plastic, and rubber plants where tension of the processed material must be accurately held.	Fig. 14	Reel-motor field *MF* is adjusted to obtain correct threading or empty reel speed. Auxiliary field *AF* is energized by the Rototrol. The Rototrol controls motor flux, to hold the motor current, measured by Rototrol field *CF*, at a fixed preset value. Consequently, strip tension can be adjusted by a rheostat in the pattern-field, *PF*, circuit. Rototrol field *IF* is energized only during acceleration and deceleration and serves to modify the regulated current for inertia compensation.	Tension is automatically held within close limits while the reel speed gradually increases to compensate for coil build-up. The strip speed can be increased without danger to the machinery and without sacrificing the quality of the coils.
	Figs. 8 and 9	The necessary tension in the strip is developed by compressed-air loaded tensiometer, and control of tension is reduced to regulation of the tensiometer position. Changes in position affect the resistance of *LT* and *HT*, connected in a bridge circuit with the Rototrol field *TF*. The Rototrol controls generator excitation and, consequently, reel motor speed to hold the tensiometer in the middle position. Motor field rheostat automatically compensates for coil build-up. For detail description, see text.	The complications of inertia compensation are avoided by use of tensiometers. Tension can be maintained accurately during speed changes as well as for steady-state operation. The method is recommended where tension must be varied over a wide range. A tandem cold mill with a top speed in excess of 55 mph is in operation.
Electrochemical processes requiring accurate current regulation.	Fig. 7	Rototrol pattern and current fields are energized through rectifiers by a transformer energized by any constant a-c voltage. A three-legged saturating reactor, with one coil energized by the generator current is connected in the current field circuits. The field current rises sharply as a function of generator current after reactor saturation, providing an amplified current indication.	Rototrol current signal is independent of temperature. Accurate regulation (within ½ percent) of high direct currents is possible.
Mine hoists; reversing blooming mills; balancing machines; car dumpers.	Fig. 18	Rototrol acts as a regular counter-emf speed regulator through interaction of fields *PF*, *VF*, and *IRF*. Field *CLF*, energized by the current-limit Rototrol *CLR*, modifies generator excitation to prevent excessive current peaks during speed changes or when the motor torque exceeds a safe value.	The control provides: 1—maximum acceleration or deceleration with safe motor current; 2—good speed regulation at all speeds; 3—full protection during periods of slugging and stalling.
Electric shovels; electric draglines; steel-mill table drives; reversing-mill screwdown drives; crop shear drives.	Fig. 15	Unlike most applications, the Rototrol operates beyond the saturation point at no load. When the drive-motor load increases, the differential current field *CF* gradually reduces the Rototrol and the generator voltage until it reaches near zero value, when the current reaches the maximum permissible stall value. The differential voltage field *VF* provides the desired slope of the load curve at low speeds.	Because of the high forcing effect of the Rototrol, motor acceleration, and deceleration are extremely fast, thereby producing 20% reduction in the time for a swing cycle of a shovel using conventional magnetic control. The stall and plugging current peaks are reduced nearly 50%.
Electric-arc furnace.	Fig. 16	Because of the relationship existing between arc-furnace power and electrode position it is possible to control the power input by positioning of the electrodes. Rectified voltages proportional to electrode current and arc voltage are impressed on the differentially connected Rototrol fields *CF* and *VF*. The net ampere-turns at the field are zero for the desired value of power input. A change in this value produces a voltage in the Rototrol and causes the electrode motor to restore balance in the field ampere-turns.	Accurate control of the furnace power results in a drastic reduction in electrode breakage and general maintenance. There is an appreciable increase in furnace output and the power consumption per ton of steel is reduced.
Positioning of the cutters on ship-propeller milling machines in response to a tracer following a master pattern. Side-register control for accurate coil winding. Positioning of ship rudders.	Fig. 17	Duplicate potentiometer rheostats are coupled to the pilot house wheel and the rudder stack. The Rototrol control field *CNF* measures the relative displacement between the two rheostat contact arms. The Rototrol energizes the generator and turns the rudder motor to reduce the displacement nearly to zero. The Rototrol operates beyond the point of saturation to obtain reasonably constant motor speed for large displacements. The purpose of field is to slow down the motor shortly before reaching the final position, thereby preventing overtravel and hunting.	Rototrol steering-gear control, while extremely simple, provides better than ¼° accuracy in rudder positioning. For propeller-milling machines, where the Rototrol operates in partnership with an electronic amplifier, extreme accuracy and speed of response is obtained. The milling cutter follows the master pattern with an accuracy of 0.002 inch.

What's New!

A More Rugged Mill Motor

Mill motors must be able to take it, with a margin of reserve strength considered unnecessary for other applications. The grueling work they perform—driving bloom rolls in a steel mill; supplying power to massive shears; powering high-speed, hot-cut saws, ladle-hoist cranes, traveling cranes—any of the hundred and one jobs that must be done in grimy, muck-laden atmospheres—demands a construction robustness far exceeding the normal.

Present-day mill motors have done and continue to do an eminently satisfactory job—steel production at today's astronomical figures would be impossible without them. However, advances in motor-manufacturing techniques, development of new insulations, modifications suggested by operating practices, have resulted in a new mill motor in the 5- to 200-hp range that, while keeping the excellent characteristics of the earlier design, embodies new features in armature, field, brush and body construction.

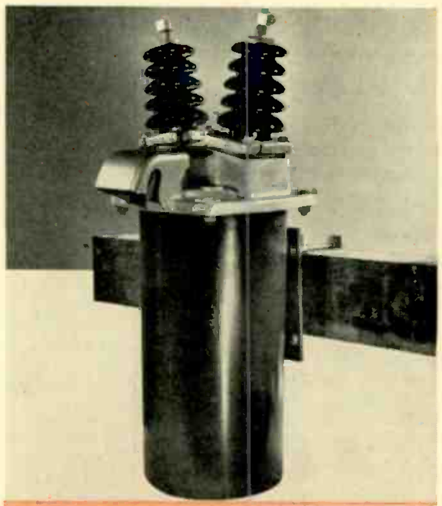
Instead of holding armature coils in the slots with core bands they are now held in place by wedges made of class B material, designed to give the armature as high a safe maximum speed as if bands were used; the wedges reduce armature losses and increase efficiency. The commutator continues to be of bolted construction, with a fit directly on the shaft. Liberal wearing depth of bars and an extraordinary length of neck, provide for a great number of refacings, and still allow adequate contact area between coil ends and the bars.

The new field-coil design has the entire coil wrapped with tape. The coils are first wound on a mould, each turn separated by asbestos paper. Mica and glass tape are then wound on, but before impregnating, the coil is assembled over a steel shell. A steel washer is then placed on top and tack-welded at several places. Thus the coil becomes a solid mass with the edges of the conductors lined up even before impregnation. Vacuum and pressure impregnating in Thermoset varnish fills all crevices and voids.

The brushholders are now of cast brass and are machined accurately for close brush fit. The triple-paired brushes are held in place by pressure fingers, essentially a part of the spring which winds and unwinds as the brushes ride in the box. Heavy porcelain insulating bushings mount over a Micarta tube fitted on supporting pins.

The old thrust washers and collars on bearing housings have been removed, and the center moved about two inches toward the shaft extension, reducing shaft stress greatly. The new cylindrical roller bearing is narrower than the old. Grease is introduced on the outboard side where it is stored in an annular recess; from here it works through the bearing to be stored in a similar recess on the inboard side.

The bearing housings are so constructed that, in normal maintenance, the entire housing with outer race and rollers can be pulled away from the armature without dismantling. The cast steel frame is split, which allows the upper frame to be swung back on its hinge, an important convenience in accessibility for normal maintenance.



The automatic rural line recloser breaker mounted on a pole cross-arm.

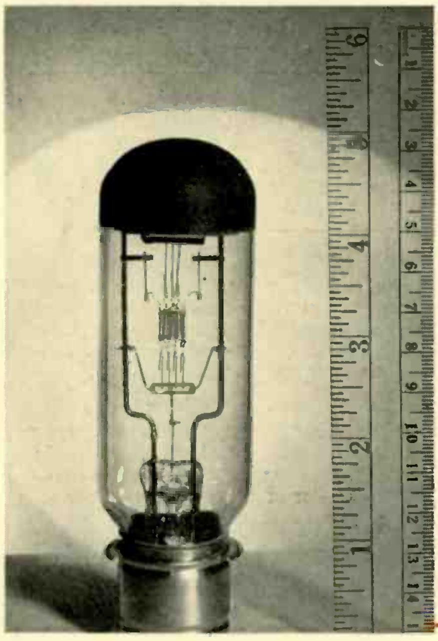
Rural Line Recloser

The old adage, "Out of sight; out of mind," is particularly fitting when viewing the new Westinghouse single-pole automatic reclosing breaker, which can be hung on a cross arm or directly on the pole to protect circuits operating at voltages up to 15 000—and then forgotten. Fully enclosed in a metallic tank and weighing only 65 pounds, in many respects it is quite similar to its big brothers the heavy-duty power breakers, in its use of De-ion grid arc interrupters, and its fast operation. It is capable of reclosing the circuit three times before locking out.

No auxiliary power source is needed, the force of the overload current opening the breaker and at the same time storing energy for reclosing. Either four time-lag tripping operations before lockout or two time delays followed by two slow operations and a lockout, can be selected by changing a pipe plug, an adjustment that can be done in the field in less than a minute. When fast tripping is chosen, the first cycle, from parting of contacts until they close again, is accomplished in the ultra-short time of twelve cycles or less; close coordination with fuses is thus, possible.

The breaker is completely self-protected against burnouts and damage by lightning. The trip coil can carry minimum trip current continuously and is shunted by a De-ion coil for protection against lightning surges. Oil and contact burning are kept to a minimum by the use of the De-ion grid arc interrupters.

A Concentrated-Filament Projection Lamp



This five-inch 300-watt lamp does a man-size job in the slide-film projection field. The high-efficiency tungsten "biplane" filament for home motion pictures has been adapted for this new use. Composed of twin series of three tungsten coils on a floating-bridge suspension, a 25-hour lamp life at high brightness is assured because the filament is free to move under heat-expansion pressure. The extreme light concentration—twice that of the former 300-watt lamp—requires natural convection cooling only, making unnecessary expensive blowers and ducts. The new lamp promises bigger and brighter screening to meet the demand for a longer projection "throw" in schools, at public lectures, and for sales-training classes.

PERSONALITY PROFILES

Kansas University has two of its alumni writing for this issue: *M. H. Hobbs* and C. Lynn. Both studied electrical engineering. They arrived at their present posts as managers of large and important Westinghouse departments by different routes.

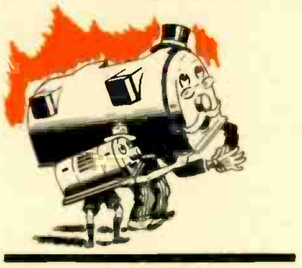
Hobbs, after the dean handed him his "sheepskin" in 1913, set out for Montana. For nine years he worked for the Montana Power Company, most of that time in construction and operation of power plants. Curiously enough, he helped build many a heavy masonry switchgear cell, a construction his later work at Westinghouse was to make obsolete. When Hobbs joined Westinghouse in 1922, it was as a designer of central-station switchgear. He has since received major promotions at almost exactly seven-year intervals. In 1929 he was placed in charge of metalclad switchgear design; in 1937 he was made head of the Switchboard Engineering Department; and then in 1944, promoted to the managership of all Switchgear Engineering. Hobbs has been associated with switching equipment for most of the big power installations in the country. Most glamorous was the Manhattan Project. However, Hobbs is best known for his many contributions to metalclad switchgear construction, with which he was associated almost from the birth of the idea.

• • •

C. Lynn saw Europe in both wars, but under very different circumstances. On the first occasion it was as a Lieutenant not long after he left Kansas University in 1918. The second time it was as a member of the Navy's Technical Commission sent into Europe on the heels of the retreating Nazis to scout their technical accomplishments in the field in which Lynn is preeminent—d-c machinery. Lynn was in the first wave of such observers sent into Nazi-overrun Europe. As he tells it: "We flew to Kiel before all the shooting was over, and found the town so bomb-wrecked that there was no place for us to sleep. We spent the first night aboard a German ship that had grounded on top a sunken submarine."

Between these two wars lies a career in design and application of d-c machinery. Particularly a-c generator exciters. Wherever exciters are discussed in the United States, Lynn is known. He has campaigned aggressively for the direct-connected exciter, and backed it up with machines that are by far the largest high-speed exciters built, and which have set an almost perfect service record. But his personal contributions in the d-c field do not stop there. He has had much to do with the really big d-c stuff, such as the 7000-hp steel-mill motors and with d-c machinery for marine service.

Lynn can best be described as a dynamic engineer. He walks fast, thinks fast; his ideas come fast. He believes that time, like machines, should be used efficiently. He is noted for his home-movie work, entering this field in 1930 when home-movies were all but unknown. He has 18 000 feet of 16-mm film and has since graduated to sound-film recording and reproduction. At present, he is building his own recording system. His pictures combine artistry with engineering ingenuity. When he wanted to show movies to friends at a cabin, the lack of electric power deterred him not at all. He mounted a d-c generator under the hood of his automobile, belted it to the engine, and led a cable from the generator through a cabin window. Presto, 110-volt power!



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Arnold H. Redding was born in Zamboanga, Philippine Islands, of American parents, and came to the States in 1925. He received his mechanical-engineering training at Columbia University, graduating in 1938, and immediately moved to Philadelphia, to work in the plant where Westinghouse builds steam turbines. Being of a particularly analytical turn of mind, Redding was well adapted to development work concerned primarily with improving the efficiency and flow characteristics of steam-turbine blades. Then came Pearl Harbor day—and with it the need for a new type of jet-propulsion unit. Redding was given the large job of creating a practical, high-pressure axial-flow compressor for the first American-designed jet-propulsion power plant.

Much of the success of these aircraft gas turbines is due to Redding's ability to develop satisfactory compressor designs in a short time from sketchy experiments.

He was early interested in developing ways to improve gas turbines to make them more suitable for aircraft propulsion. Such is his major concern as Section Engineer in charge of Preliminary Design and Flow Research.

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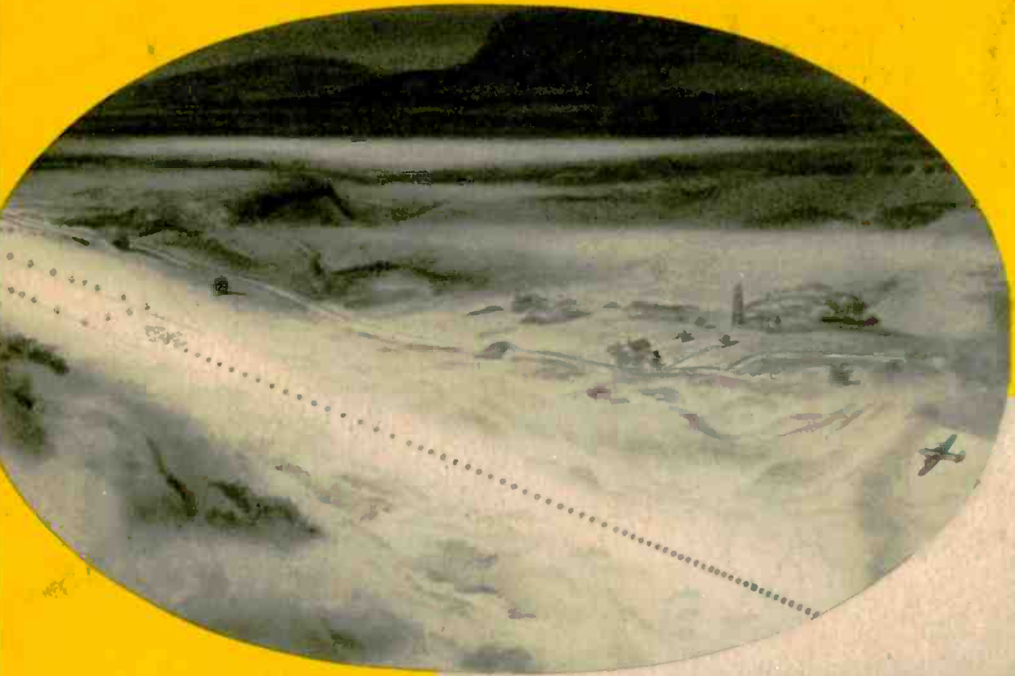
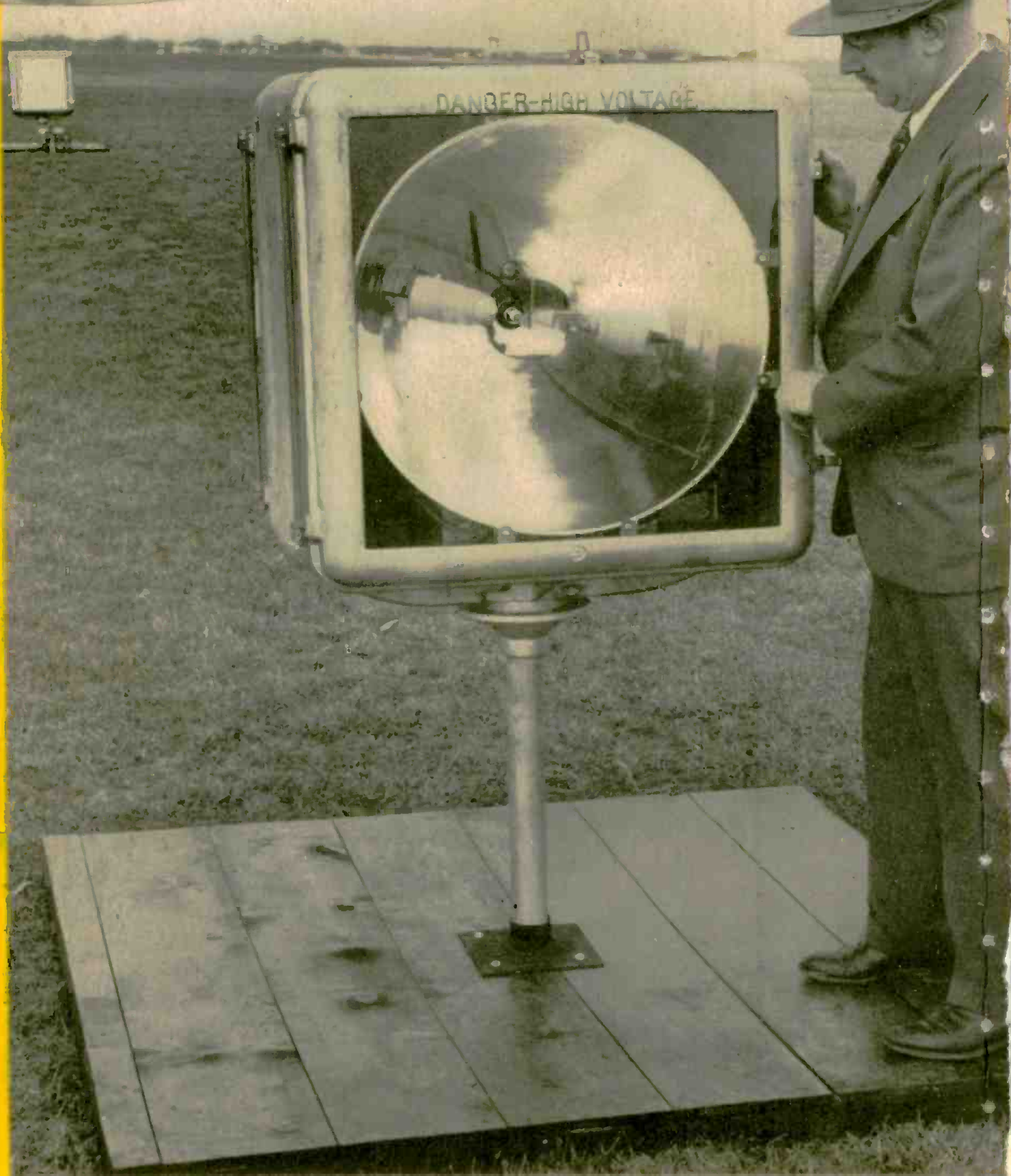
W. A. Pennow's experience in the first war—he was seventeen months with the famous 364th Pursuit Group which had 216 replacements for an original complement of 64; only 19 came back—reads like the saga it is, adventure in the days when aviation was a risky business with its wire-and-wood airplanes. Although he laughs off any belief that he was born lucky, the fact that a German machine-gun bullet early in 1918 did nothing more than put a crease in his shin bone, caroming off to aid its lethal brethren in smashing his plane to kindling, and the fact that he literally walked away from another crash in a treetop, must be taken as a fair measure of his good fortune.

After the war he entered college and in 1922 graduated from Milwaukee School of Engineering with a B. S. in electrical engineering. He took his B. A. from University of Wisconsin in 1924, and in 1926 won his master's degree from Yale. He joined Westinghouse at the South Bend Lighting Division on January 1, 1930. Pennow has been associated with floodlights, searchlights, both lamp and arc, beacons, and a wide variety of special-purpose lights for marine, aviation, and airport use. He has a superlative knowledge of optics, which he combines with a good understanding of materials, mechanics, and light sources, to produce unbelievable results. He was able, for example, to raise the crushing strength of runway "contact" lights from 35 000 pounds to 200 000 pounds without increasing their size. Engineers know that a 28-volt arc is not stable; nevertheless, he made an entirely practical arc searchlight for operation at that voltage. He was primarily responsible for the lighting of the gigantic airport built in the woods of Newfoundland, that in the war proved invaluable in ferrying planes, men, and materials to Europe. He now offers a new solution, startling in concept, to the problem of landing airplanes when visibility is bad.

His home is an orderly maze of electrical labor-saving devices. What with air conditioning and Sterilamps installed throughout the house, he insists he has himself so healthy that the germs give up in disgust.





FOG PIERCERS

The worst enemy of commercial flying—fogged-in airports—may be substantially overcome by a new All-Weather Approach Lighting System. Standing beside one of these powerful krypton lamps is W. A. Pennow who conceived the system and who describes it in this issue.