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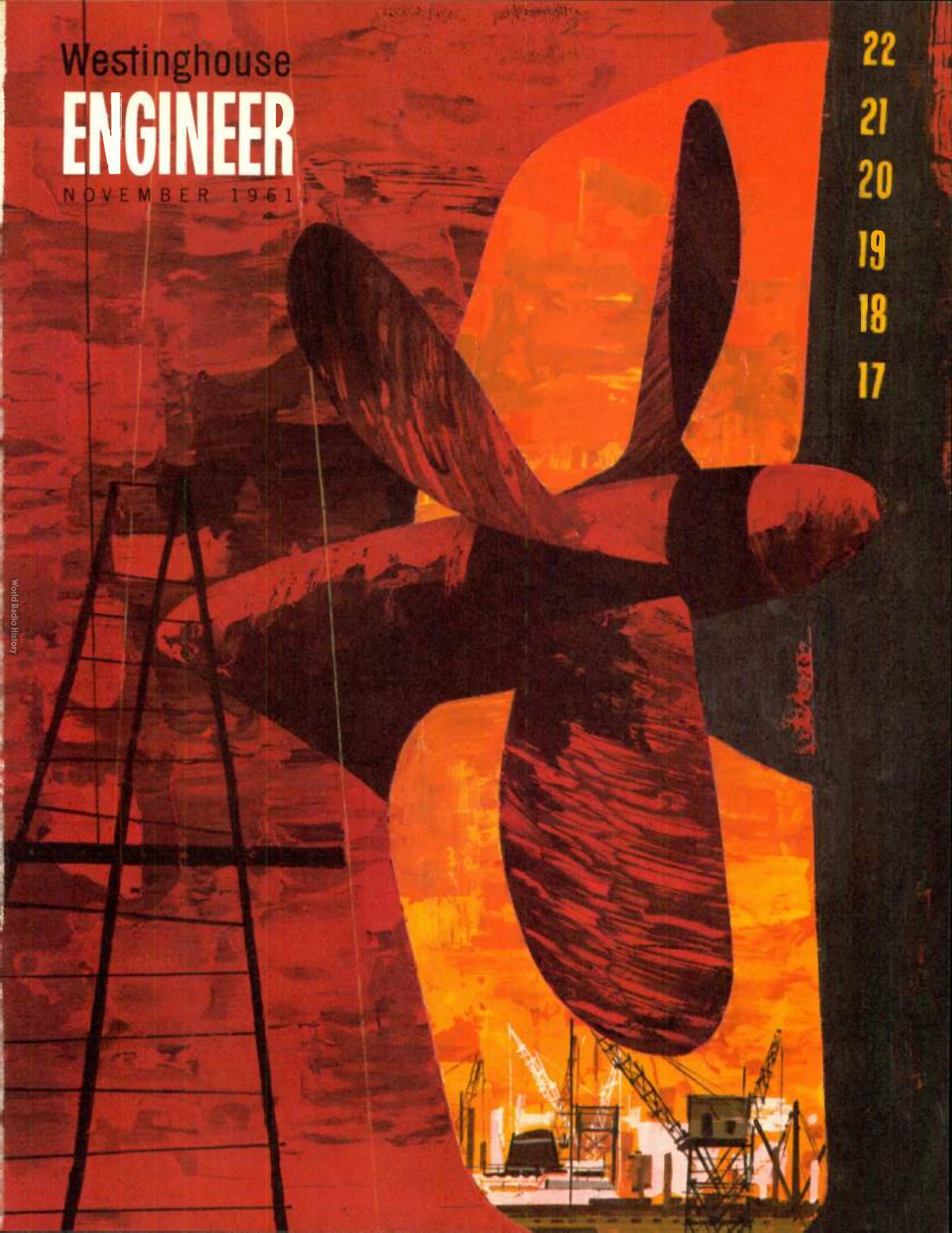
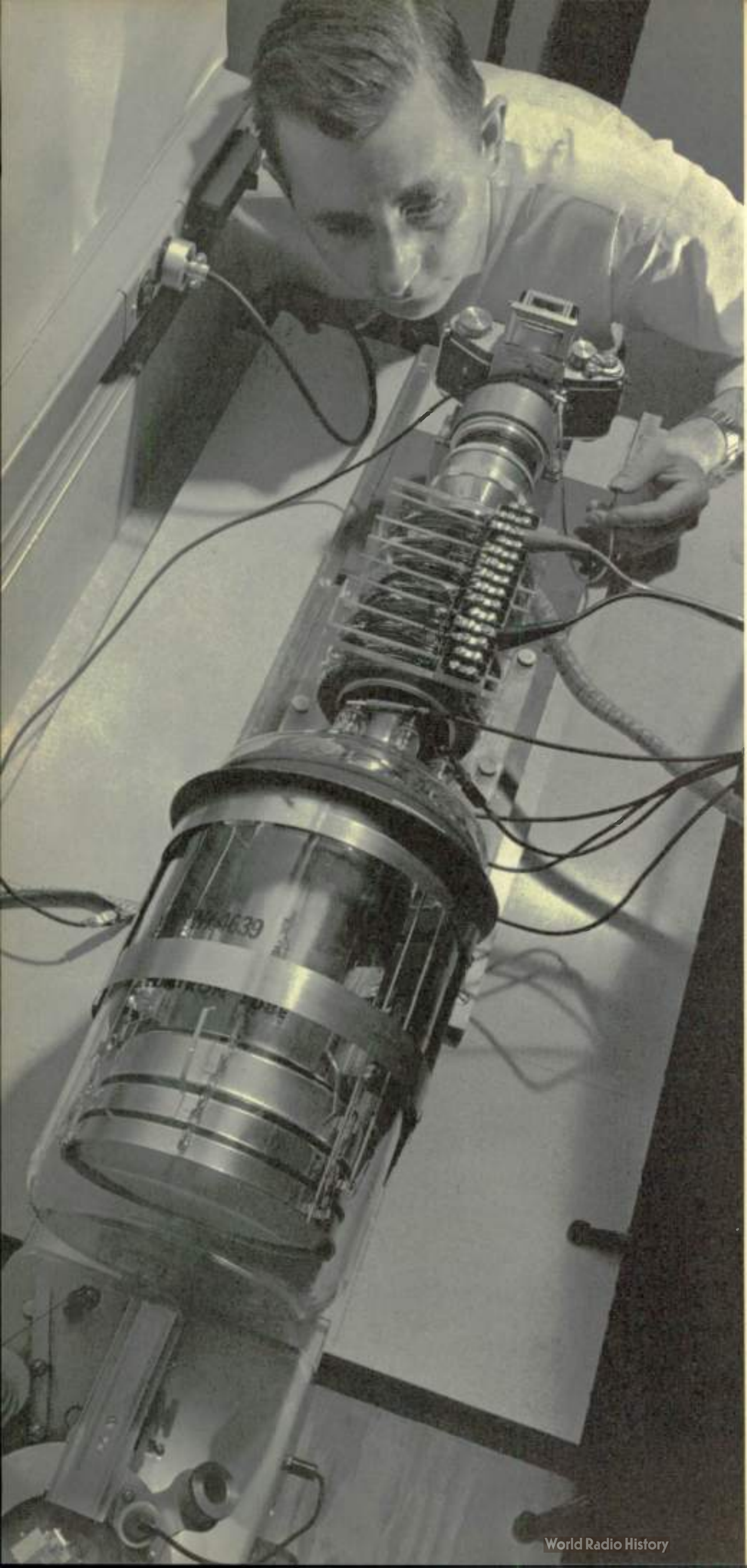
ENGINEER

NOVEMBER 1961





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X-ray diffraction, an extremely valuable laboratory tool, has been made more versatile by the addition of electronic image-intensifying equipment that makes the diffraction pattern many times brighter. The images formed are bright enough to be seen clearly, and they can be photographed in fractions of seconds instead of with the exposures of an hour or more presently needed.

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The strengthened electron pattern is then electrically accelerated and directed onto a sensitive screen that converts it to visible light. The result is a visible image of the original diffraction pattern hundreds of times brighter than the patterns from non-intensified diffraction apparatus.

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Cover Design The American merchant marine industry, illustrated symbolically by cover artist Dick Marsh, is turning toward automation and increased mechanization to improve its competitive position. Some promising possibilities are described in this issue.

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AUTOMATION FOR CARGO SHIPS Application of modern technology promises to improve the competitive position of the American merchant fleet.

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The U. S. merchant marine's rapid increase in operating costs in recent years has made it difficult for the industry to compete with other types of freight carriers and with foreign merchant fleets. Under present economic conditions, the solution to the problem may well lie in two modernization techniques. One is the automation of certain shipboard operations to reduce operating costs; the other is the automation of cargo handling to reduce handling costs and turnaround time.

Automation of shipboard operations will increase the initial cost of a ship, but it also will improve operating efficiency. A study by the Maritime Research Advisory Committee[1] showed that over the 20-year life span of a *Mariner*-class ship, a net of $5 730 000 could be saved by automation. Part of this improved efficiency will result from more effective use of manpower. In addition, automation of engine-room controls should save fuel. Automation of navigation should reduce straying from the desired course and thus save fuel and time.

Although insurance would now be more expensive for an automated ship because of the greater replacement cost, the premiums could well decrease as the number of collisions is reduced by more use of electronic gear, and the number of personal liability claims is reduced because of smaller crews. Such benefits can be fully evaluated only after an automated ship has been in operation several years.

Another major benefit is the elimination of repairs presently necessitated by human error. Automatic equipment may include some errors that also will inflict damage, but, unlike humans, automated systems can be altered so that the same mistake is never repeated.

Cargo handling now consumes more than half of every dollar of freight revenue, so reducing this cost will assist greatly in recapturing trade. Here a distinction must be made between shipboard and dock cargo equipment.

Obviously, automated *dock equipment* would be used by ships of all flags, so it would not give American ships any advantage over foreign ships in handling costs. The resulting reduction in turnaround time, though, would benefit American ships more than foreign ships because of the higher operating costs of the American ships. Automated *shipboard* cargo-handling equipment would give American ships an advantage both in handling costs and in turnaround time, and it would be available in every port.

Automation of both types of cargo-handling equipment—shipboard and dock—would make American ships more competitive with railroads and trucks for coastwise and intercoastal trade.

AREAS OF AUTOMATION

navigation

Only two conditions normally require precise navigation—operating near land and operating near other ships. Since these are the limiting cases, this article considers means of navigating under these conditions with only one man, the deck watch officer, on the bridge (except for periods of entering and leaving port when a pilot normally comes aboard, or other times such as in heavy ship traffic when the captain is normally on or near the bridge). The deck watch officer would have the duties of lookout, helmsman, and navigator. No new scientific breakthroughs are required, but presently available devices and techniques will have to be used more effectively.

The helm and navigating duties must be made easy to perform so they will cause minimum distraction from the lookout duties. For navigating near shore, a radar device that permits navigation by superposition must be provided. Extensive tests of this navigation method show an accuracy fully as great as that from the best visual fixes.[2]

Several devices have been used for superposing charts on the radar scope presentation or vice versa. All have one presentation stationary while the other is traversed in two mutually perpendicular directions by accurate screws. The two screws could be driven by gyrocompass and pitometer (speed indicator) signals, with corrections for the effects of wind, current, and waves inserted by the deck watch officer to keep the two presentations superposed. The corrections also could be made automatically and indicated at the bridge for checking. The radar presentation would show any other ship traffic in the area, so evading action could be recommended or initiated by automatic solution of the point of closest approach.

Electronic devices have limitations, however, so the deck officer must continue to collect all the available data, judge its relative merit, and form his own conclusions. Sources of data would include his own experience, his visual observations, depth readings, and the Loran track. The bridge should provide a good view throughout the entire 360 degree azimuth.

Radar navigation cannot be used on ocean crossings because of the great distances to the fixed objects used as radar targets. In the past two decades, however, great advances have been made in electronic navigation aids for ocean crossings. Loran, Decca, or other long-range radio navigation aids are now installed on nearly all ocean-going ships. Further advances are in progress, including navigation experiments with a Transit satellite.

The author acknowledges the important contributions to this article made by R. M. Mentz, D. W. Drews, E. C. Mericas, and H. H. Hansen of the Marine, Transportation, and Aviation Facilities Engineering Department, East Pittsburgh, Pennsylvania, and by L. B. Podolsky of the Marine Turbine Engineering Department, South Philadelphia, Pennsylvania.

Again, if certain information is automatically provided on the bridge, only the deck watch officer will be needed. The most effective navigation aid will be one that plots the position of the vessel continuously, marking a track on a chart so the navigator can see at a glance his present position in relation to all other points on the chart. This can also serve as a check for coastal radar navigation, though it will not be as accurate.

Present Loran navigation requires that the operator obtain lines from at least two shore stations and locate the ship's position on a Loran chart. This fix can ordinarily be taken in about five minutes. Reading the Loran position and switching from one set of stations to another could be done automatically. These two inputs could then be fed into a device such as the dead reckoning tracer (DRT) that marks a continuous track on a chart. The DRT presently is fed information from the gyrocompass and the pitometer, but it should be no great problem to convert the inputs to Loran readings. A switch could be provided to enable the deck watch officer to reconnect the DRT to the pitometer and gyrocompass and automatically enlarge the scale. This would permit the ship to get back on course accurately after performing a small-diameter turn such as is required for recovering a man overboard.

As with radar navigation, a Loran track can be made very reliable but cannot be assumed to be infallible. A periodic check by celestial navigation should be made. Eventually, this could be done automatically.

With these automatic navigation aids and the automatic steering already installed on most merchant ships, there should be sufficient time available for the deck watch officer to serve as lookout and to perform periodic checks on the automatic equipment.

cargo handling and care

The bulk carriers of liquids, coal, grain, and other such cargoes already have modern cargo-handling equipment (pumps and conveyors) that gives them remarkable short turnaround time. This equipment is readily automated, so bulk carriers have a head start toward automation.

The mixed general cargo vessel presents a different picture. Its standard cargo-handling equipment is the boom winch, which has changed little in principle since the age of the sailing ship. The boom winch requires appreciable time and labor to set up ready to operate and to stow ready for sea, and this in itself makes it incompatible with the objective of efficient use of manpower. Cargo-handling cranes, which do not have to be rigged for operation and then stowed for sea, are fully as effective as boom winches. Some American ships already have such cranes (Fig. 1). Their adoption contributes substantially to the automation goals.

More and more mixed general cargo is packed in semistandard containers about the size of a truck trailer. These containers can be transported on almost any vessel, but, for optimum utilization of the concept, a ship designed for the purpose should be used. Such container ships will be

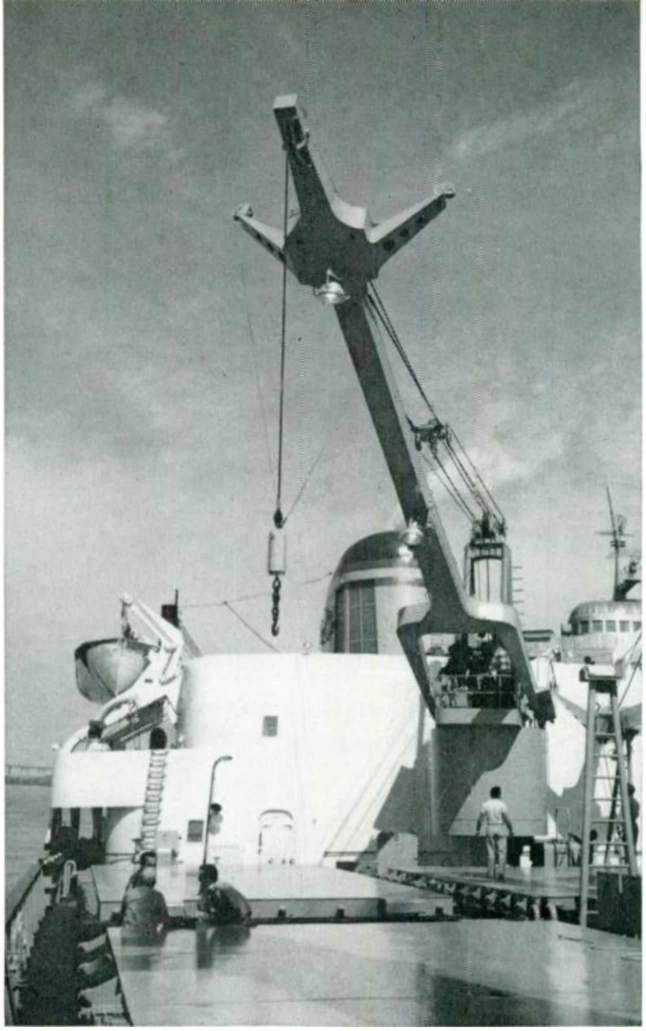


Fig. 1 This modern five-ton cargo crane rotates to transfer cargo between holds and dock.

Photo courtesy Avondale Shipyards, Inc.

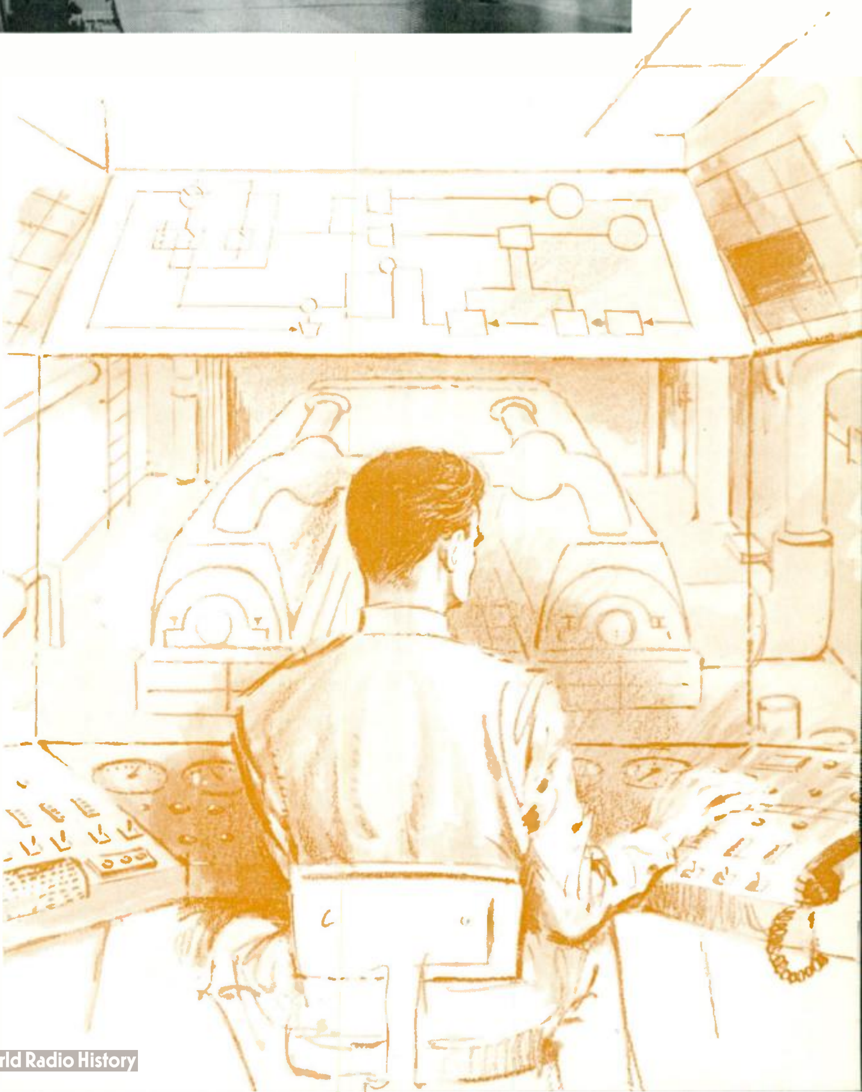


Fig. 2 Artist's conception of a central control console for a ship's engine room.

equipped with gantry cranes for loading and unloading the containers, and these cranes are adaptable to some degree of automation. The loading and unloading can be so programmed as to maintain the ship's stability and trim.

Modern air conditioning, ventilation, refrigeration, dehumidification, and other machinery for cargo care has reliable control and monitoring equipment. This machinery will not require extensive modification to make it suitable for an automated ship.

anchor windlass

The anchor windlass should be considered a component of a system that performs all functions related to the ship's anchors. The chain's weight can be utilized to achieve proper stowage in the chain locker without human supervision. Controls must be expanded from the present local speed and direction control to integrated remote and local controls for the entire system. This should include instruments required for control from the bridge, such as indicators that show the amount of chain out and the anchor's position from a reference point. All of this can be achieved by applying existing control devices.

engineering plant

The engine room contains an array of energy conversion systems, each designed for a specific function and each operating largely independently of the others. Many of these systems are now controlled by elaborate automatic regulators. For example, combustion and steam-generating systems employ automatic regulators for controlling fuel and air. Condensate and feedwater systems maintain proper vacuum and proper water level. The electric generating plant has regulators to maintain constant voltage and frequency.

Surprisingly, though, one of the largest pieces of machinery—the main propulsion turbine—is usually completely hand operated. Power is controlled by varying the flow of steam through the turbine with valves operated from one or more large handwheels.

Turning the manipulation of these maneuvering valves over to the bridge by remote control systems is one obvious step toward automation. It would relieve the engine-room crew of its only remaining full-time task; its duties then would consist of setting up equipment for operation, monitoring its performance, correcting malfunctions, and occasionally rotating the duty among the various pieces of standby equipment.

The next step is to provide a central location through which all engine-room functions can be monitored and controlled. (An artist's conception of a central control console is shown in Fig. 2.) This requires remotely operated valves and switches and visual displays of all the quantities that must be observed. Remote actuators and sensory equipment are the basis for automation, so the transition from central control to the next step, complete automation, may not be so great as it first appears.

Complete engine-room automation employing an electronic control device will improve plant reliability besides centralizing the control functions. In the electric utility industry, the justification for investment in computer control is found in the increased reliability that it brings. The growing size of boiler-turbine-generator units and their complexity has increased the danger of serious operating errors and has made the damage resulting from a mistake more expensive. The expense is not only in the materials and labor required for repairs, but also in the down time of generating capacity.

The very fact that units start and stop only at long intervals is an argument for automatic equipment, because operators sometimes forget procedures that they use only occasionally. The control computer will give visual or audible alarms when limits are exceeded. Special printout programs can also be initiated, giving the numerical values of the deviations from desired levels.

Under certain conditions, such as equipment failure, a history of events preceding the failure is desirable; the computer can be programmed to preserve its readings for a set time. When an abnormality is encountered, the

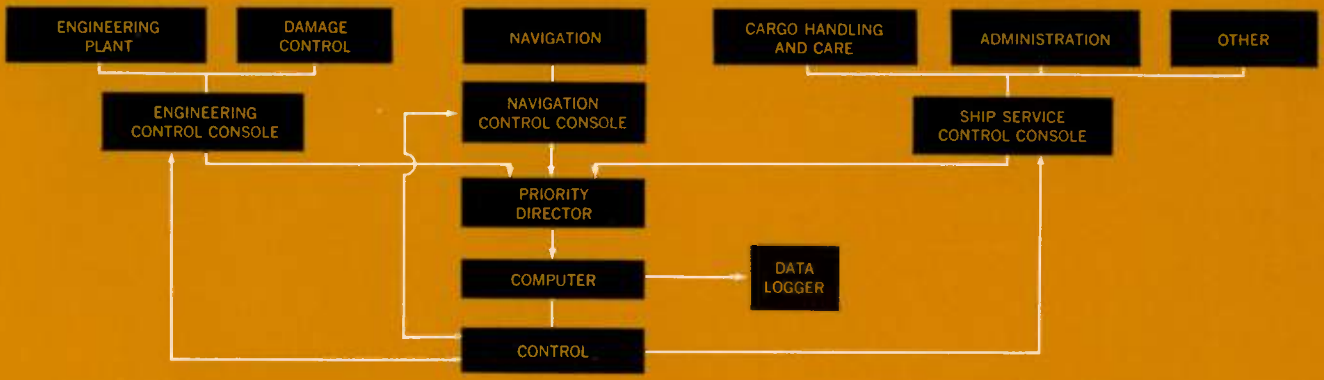


Fig. 3 Most shipboard operations could be supervised and monitored through consoles for each major system. Complete control of each system would be available at its control console, and overall direction could be supplied by a central computer.

computer can examine the surrounding conditions, print out an analysis of the situation, and even take corrective action if so programmed. This eliminates errors caused by hurried decisions, increases personnel safety, and reduces or eliminates equipment damage.

During normal operation, optimum engine-room control would be maintained through continuous computer adjustment of subloop control set points. Some examples of self-regulated subloops now used are the controls for boiler combustion, auxiliary generator sets, refrigeration and air conditioning equipment, and compressor air supply.

TECHNICAL ASPECTS

general

Automation will encompass a number of areas, and its application will be evolutionary—probably through use of more integrated control in each area leading finally to integration of the various areas. All operations might be supervised and monitored through a console assigned to each department, as shown in Fig. 3. Complete control is available within each department through its console, but normally all recording, supervising, logical sequencing, and control are performed by programs stored within a central computer. Input data is directed through a priority director that permits the computer to be shared among the various shipboard systems.

engineering plant

The engineering plant's major systems will have to be studied in detail to determine the extent of automation necessary. These systems are diagrammed in Fig. 4. The flow lines show input information entering the central control console and proceeding to data-logging equipment or a control computer. Both data-logging and computer equipment provide output information; however, new control setpoints are available only with the computer.

The *data-logging* type of equipment would periodically scan incoming signals, check for normal operating conditions, and print out pertinent operational and historical data as required. In off-limit conditions, it would warn the operator by an annunciator or display and type out the off-limit conditions. Action would then be taken by the operator to correct the off-limit condition.

If the degree of automation desired is such that a *computer* would best fulfill the requirements, the size of computer required and the economics will determine whether a wired type or stored-program type should be applied.

The wired sequence control system is specifically designed and wired to perform the necessary control, sequencing, and operating functions. The stored-program computer control system is more flexible. It receives the same number of inputs and provides the same number of outputs as the wired sequence control system, but for complex procedures it has many advantages. A major one is the simplicity of changing the control sequence by modifying the program. Program modification is accomplished by punched-card, tape, typewriter, or switch input. Modifying the control sequence in a wired control system requires rewiring and probably could not be economically justified in most cases. Some versatility in wired control may be achieved through modular design, but the degree of modification still would be limited and the chance of error increased.

The stored-program digital control computer undoubtedly would fulfill all of the requirements. It has a tremendous capacity to scan, monitor, and perform operations simultaneously. This capacity also makes it practical to consider supervision of functions normally overlooked. Duplicating this capability by wired sequence control would lead to such complexity that it would be impractical, if not altogether impossible.

The computer performs three types of functions—recording, supervising, and control. In recording, the computer presents tabulated information ranging from raw data to complex process engineering data. In supervising, the computer acts as an important link between system and operator—rapidly scanning input voltages that repre-

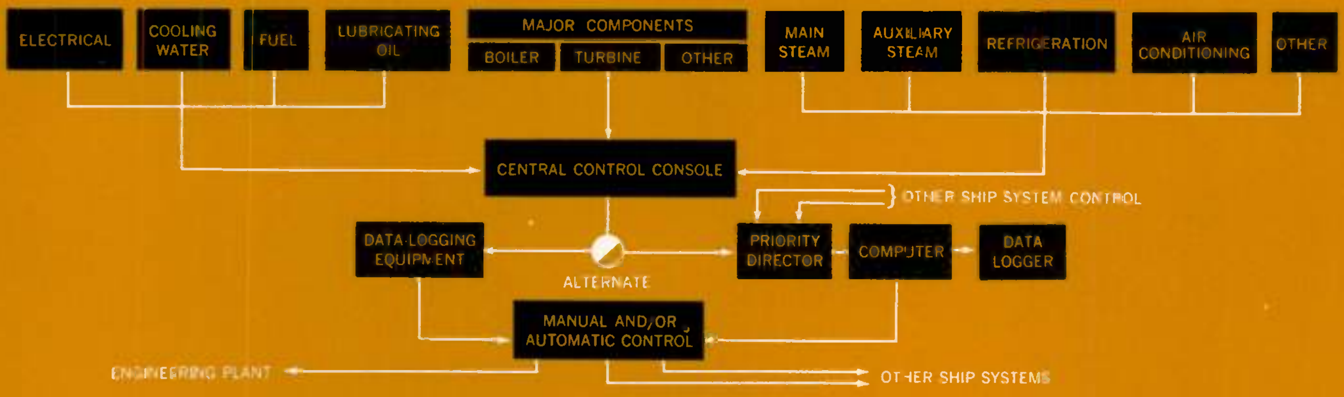
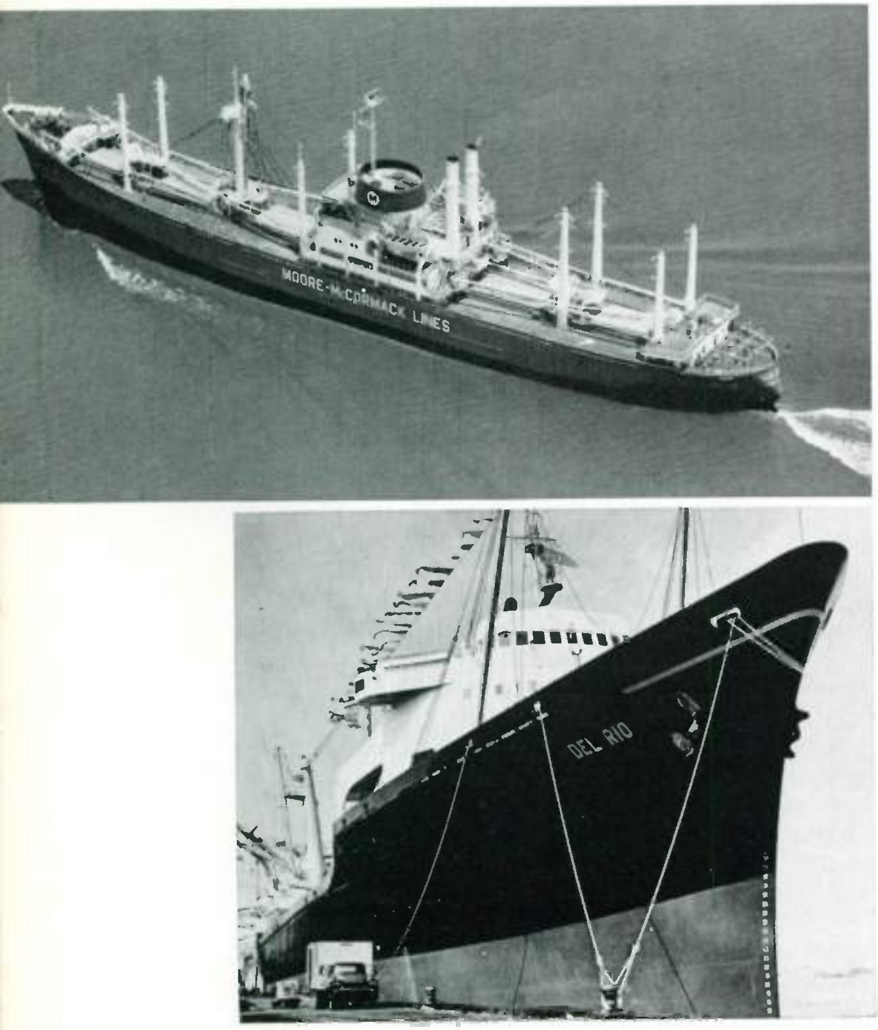


Fig. 4 One of the major shipboard systems, the engineering plant, is diagrammed here with alternate control means—data-logging plus manual control or automatic central computer control.



Two new American merchant ships are (top) the Moore-McCormack Lines' *S. S. Mormaccove* and (bottom) the *S. S. Del Rio* built by Avondale Shipyards, Inc.

sent physical variables and comparing each with the correct voltage stored as a digital number in the computer memory. The control functions involve logical decisions in carrying out emergency actions, starting up and shutting down equipment, and changing the mode of operation of equipment.

Maneuvering and steady-state operation under computer control illustrates these functions. The computer would supervise the operation of the automatic control subloops and make any necessary adjustments, similar to the adjustments presently made by the firemen, for optimum fuel utilization. It would be an almost perfect supervisor because it could scan all possible points of any concern in the steam power plant as frequently as deemed advisable. In some cases, this scanning might be many times a second to determine a trend; in other cases, perhaps only once in minutes, hours, or days. The computer can handle very rapid changes, for it can act on the basis of trends in the course of seconds or fractions of a second. This means that plant variables, such as temperature and pressure, do not have to exceed fixed settings; the computer can anticipate the extent to which these settings might be exceeded and compensate immediately.

In addition to scanning all critical areas of the steam plant, the computer would take over the operation of any subloop that failed to function properly. An alternate computer program would then be initiated to perform the regular scanning function. If a component of the steam plant failed and would not allow the plant to function properly, the computer would institute a program to shut the plant down. It would also notify the operator of this condition and print out the reasons for the shutdown.

systems integration

The installation of an automated system involves more than placing a computer or control coordinator aboard ship. Although the control device and its operating console form the heart of the system, many other innovations are required to carry out the desired program.

Actuators must be provided to receive control signals for operation. The signals may be contact closures or analog voltages from the computer. Sensors are needed for computer monitoring of conditions such as temperature, pressure, position, and speed. Shipboard machinery will have to be modified to accept these actuators and sensors. Some existing systems need to be simplified to accommodate the computer program.

Suitable turbine supervisory instruments such as vibration meters, eccentricity meters, and spindle position meters will be needed for monitoring turbine conditions, especially during the startup period. This type of instrumentation has not been used on shipboard, so development of a shockproof line is required.

Also needed is a wide-range speed control system for operating the turbine during startup. One system, developed for central station turbine units, uses an electric governor to position a throttle valve as dictated by a startup program. An automatic synchronizer, already developed for land turbines, can be applied for placing the generator on the load bus.

Maintenance and repairs will be scheduled for in-port periods. More vigorous and frequent maintenance checks probably will be needed to minimize outages at sea.

Consideration must be given to the degree of automation that is feasible from a cost standpoint. Certain small functions or procedures may be handled by one operator if the cost to automate them would not be economically justified. For example, an automatic subprogram to check the overspeed trip system at startup would be rather involved, but one operator could check it in a few minutes.

Certain subsystems that normally are manually controlled can be adapted to analog control to keep the computer as simple as possible. Where an analog control system exists or can be applied, its function is not delegated to the computer. An example of this type system is the gland seal control, which at present is usually a manual control. A control system would regulate the gland seal system independently of the computer and only require monitoring or startup by the computer program.

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[1] "Proposed Program for Maritime Administration Research," Vols. 1 and 2, 1960. Prepared by Maritime Research Advisory Committee; National Academy of Science; National Research Council.

[2] "Radar Aids to Navigation," MIT Radiation Laboratory Series.

OPTIMUM ENERGY UTILIZATION IN PAPER PRODUCTION

Applying the systems concept leads to better control of energy flows and improved efficiency.

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When the traditional approaches to a process have been developed to a high state, a radical departure from those approaches is needed if significant process improvements are to be made. Such a departure in the papermaking process is the energy-systems concept. Treating the process as an energy system improves control of energy flow, increases efficiency, and consequently lowers production cost for the process.

Approximately 90 percent of the energy consumed in the entire papermaking process is absorbed by the vacuum-pump drives, paper-machine drive, and dryers. The vacuum pumps are usually driven by one or more electric motors or constant-speed turbines. The paper-machine drive is usually a line-shaft turbine or an all-electric system with ac motors as prime movers for dc generators. Steam for dryer heating is obtained directly from a boiler and, when a drive turbine is used, from the turbine exhaust.

These conventional approaches to energy use in papermaking keep the steam and electric power energy flows separate (Fig. 1). When properly applied, such systems assure a good return on investment so long as the initial mill conditions exist. However, changing costs of steam and electric energy, changes in machine tonnage, and changes in machine speed find these systems quite inflexible, and this may increase power costs per ton of product.

A better approach is to treat the papermaking operation as an energy-consuming system whose demands change with time, seasons, tonnages, and machine speeds and whose energy flows can be integrated. This leads logically to combining steam turbines and ac electric machines on the same shafts, a major step toward the goal of better control of energy flow and consequent increase in efficiency.

Two possible energy flows resulting when turbines and electric machines are combined are illustrated in Fig. 2. The electric machine, coupled to the turbine, functions as a motor or as a generator, depending on available steam, exhaust steam requirements, and power required to drive the paper machine or pumps. For simplicity, Figs. 1 and 2 illustrate energy flows only; a number of electrical and mechanical connections are possible in the paper-machine drive systems.

A few similar systems are now used in the paper industry. A large midwestern mill has been using a combination synchronous motor and constant-speed turbine as a paper-machine prime mover for several years. Another uses a constant-speed turbine coupled to a synchronous motor to drive the entire line of vacuum pumps. A high-speed electric sectional paper-machine drive in New England has a combination synchronous machine and constant-speed turbine as the prime mover. However, these installations are not well known nor well understood except in the mills where they are installed.

advantages

The prime-mover speed in combination steam and electric systems is normally set by the synchronous machine, and the turbine operates under the control of an exhaust pressure regulator. Thus, the turbine maintains a constant pressure in the exhaust header and, if necessary, causes the ac machine to generate power.

When process steam demand decreases, the turbine valves operate to maintain constant pressure in the exhaust header and the synchronous machine motors as required to supply power to the connected load. This allows closer control of steam costs when there are large variations in winter-summer heat loads and when other paper machines in the mill are starting, stopping, or idle.

Either prime mover can take over the load in case of ac power failure or loss of steam. Also, in a paper-machine drive, the machine can be run for maintenance work when only ac power or only steam is available.

Operation at reduced paper-machine speed at constant tonnage automatically reduces prime-mover load, but the dryer steam requirement is relatively unchanged. The synchronous machine acts as a generator in this situation and, in effect, recovers the steam power.

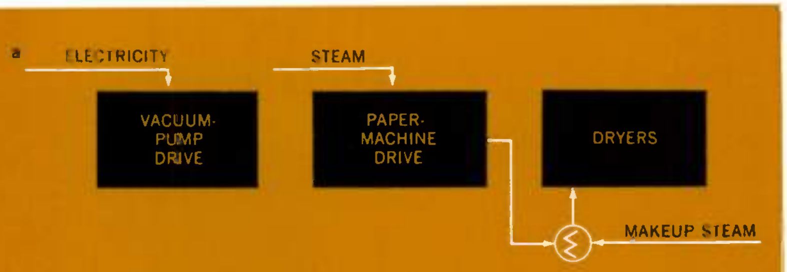
This prime mover system has the inherent capability of providing considerable extra power for short-time overloads. It also provides maximum versatility for increased machine production either in the form of increased tonnage (steam) or machine speed (horsepower).

A typical example might be a paper machine 200 inches wide designed to run at 2500 feet per minute (fpm) and requiring 55 000 pounds of steam per hour for drying 300 tons of paper per day. Both the drive power and steam requirements of the paper machine are supplied by a turbine prime mover. The machine operates 50 percent of the time at half speed, requiring a power input of 1250 horsepower, and 50 percent of the time at top speed, requiring 2500 horsepower. Half-speed and top-speed tons of production, dryer steam requirements, and vacuum-pump load are relatively constant. Energy input to the machine is proportional to machine speed. (See Fig. 3).

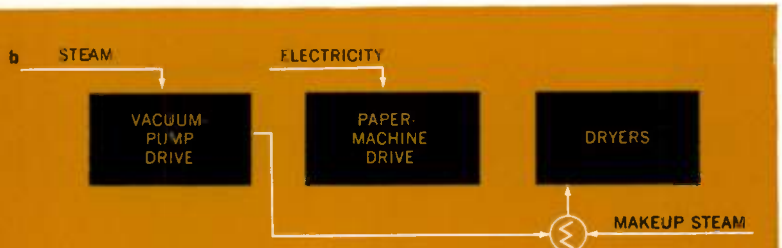
The conventional approaches to this energy input problem result, at best, in nearly constant cost per ton of product for half-speed and top-speed production. This comes about from lack of consideration of the fact that the drive horsepower-hour (hp-hr) input to the paper machine is proportional to line speed. As shown in Fig. 4a,

$$(\$/\text{hp-hr}) \times (\text{hp-hr}/\text{ton}) = \text{constant}.$$

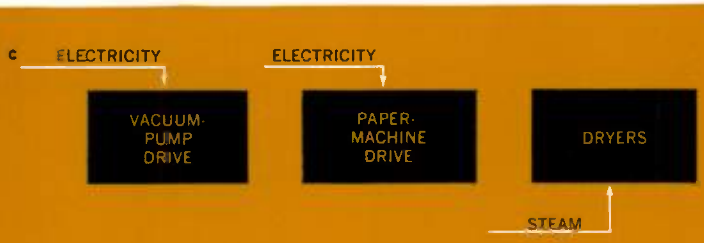
In the energy-systems approach, a combination prime mover consisting of a steam turbine and a synchronous machine is applied. The synchronous machine generates



Motor drive for vacuum pumps, turbine drive for paper machine



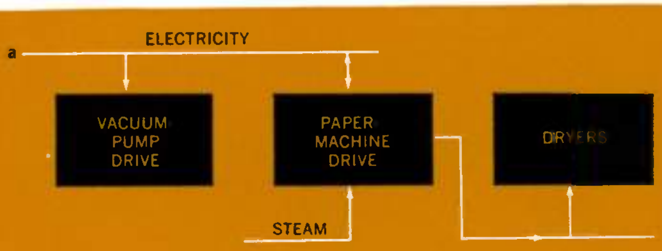
Turbine drive for vacuum pumps, motor drive for paper machine



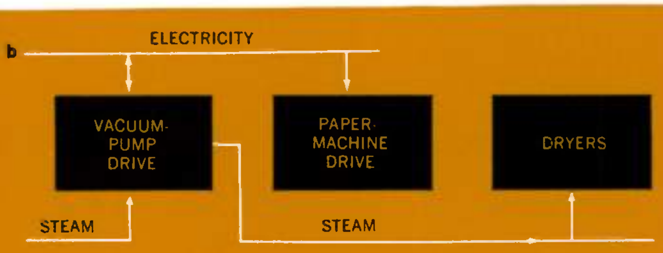
Motor drive for vacuum pumps and paper machine

Fig. 1 These three conventional energy flow systems for the paper-making process keep the steam and electrical energy flows completely separate. Such systems are quite inflexible, and this may increase power cost per ton of product when changes occur in costs of steam and electric energy, machine tonnage, and machine speed.

Fig. 2 All energy-consuming loads are interconnected in these energy-flow systems that use steam turbines and ac electric machines on the same shafts. The electric machine functions as a motor or as a generator, depending on available steam, exhaust steam requirements, and power requirements.



Motor drive for vacuum pumps, turbine/synchronous-machine drive for paper machine



Turbine/synchronous-machine drive for vacuum pumps, motor drive for paper machine power and the turbine remains fully loaded when the paper machine is running at half speed. The result is constant cost per drive hp-hr. Therefore, the cost per ton of product is proportional to machine speed. As shown in Fig. 4b,

$\$/\text{hp-hr} = \text{constant}$

$(\$/\text{hp-hr}) \times (\text{hp-hr/ton}) = (\text{constant}) \times (\text{hp-hr/ton})$.

The addition of a synchronous machine rated at one-half the turbine rating (1250 hp for this example) would result in generation of 3.7×10^6 kilowatt-hours of by-product power if the machine operated at half speed for 165 days a year. Since this by-product power is produced with no increase in operating costs, it constitutes an annual saving in the order of $18 500 if the cost of powerhouse condensing-cycle generation or purchased utility power is conservatively estimated at 5 mills per kilowatt-hour. This is a saving of $0.37 per ton of paper produced at half speed.

controls

The systems approach is also used in selecting controls and operator's functions for the combination prime mover. The synchronous machine normally determines the speed of the set, so the turbine should operate under the control of a back-pressure regulator to maintain constant pressure in the exhaust header.

The synchronous machine can be started as a motor by an ordinary starter with or without the turbine operating. When it is to be started as a generator, the operator adjusts the turbine speed and the synchronous machine field to synchronize the machine with the power bus before paralleling the machine with the line.

Either prime mover can be removed from the line with paper on the machine. To minimize transients, the operator adjusts the steam valve so as to unload the machine that is to be removed.

A constant-speed turbine governor is required if the paper machine is to be run without the synchronous machine in operation. The governor is permanently set slightly above the synchronous speed of the synchronous machine. This allows the governor to function also as a reserve overspeed protection device when the synchronous machine is being used.

When the set is driven by the synchronous machine only, the churning action of the turbine blades could cause a temperature rise in the turbine. A sensing device monitors the temperature of the turbine housing and sounds an alarm if safety limits are approached. The operator can then pass cooling steam through the turbine.

The back-pressure regulator must not be allowed to overload the synchronous machine, because this would trip the overload protective devices and cause transients at the paper machine. A synchronous-machine load limiter prevents this. It recalibrates the back-pressure regulator as required to limit the load on the synchronous machine to some predetermined value less than the setting of the overload protective devices.

conclusion

The combination prime mover matches the steam and horsepower characteristics of the load to those of the turbine. This systems approach, a radical departure from traditional approaches, improves efficiency with consequent lowering of production costs.

Westinghouse
ENGINEER
Nov. 1961

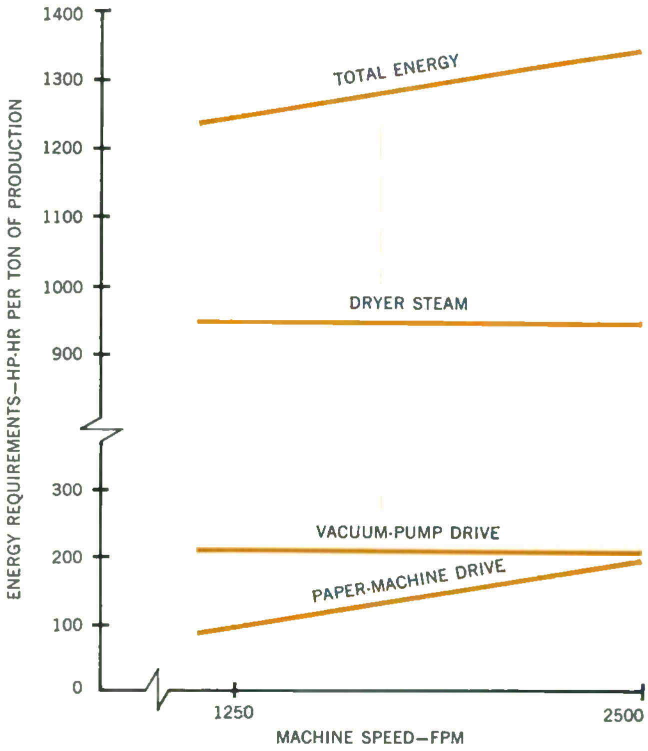
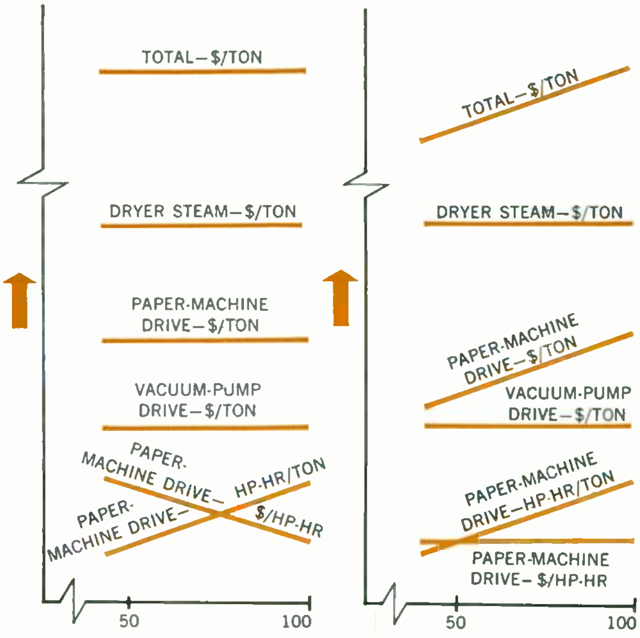


Fig. 3 Typical energy requirements for making paper.



a Conventional approach

b Energy-systems approach

Fig. 4 A comparison of energy requirements for a conventional and an energy-systems approach reveals the latter's advantage. It makes total cost per ton of product proportional to paper-machine speed, and this saves money when the machine is operated at less than full speed.

SIMULATION OF THE STEAM POWER PLANT A systems-engineering approach to the design of the entire power plant is required to obtain the ultimate benefits from computer control.

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The optimum use of computers for power plant control does not come from merely replacing human functions, but from applying computers as an integral part of an overall system. An optimum plant will not result from perfecting control computer and plant apparatus separately—but rather, each must be accommodated to the other. This coordinated approach will combine theory, equipment, and environment to create an integrated system. With this overall approach to power plant design, new control concepts will originate, based on recognizing the peculiar abilities and limitations of the process-control computer and the steam plant process itself. Design of plant apparatus will be modified to better adapt it to automatic control. The result of this approach will be an optimized, automated power plant.

The first step in the systems approach is to understand thoroughly the physical processes carried out in the steam power plant. Once the thermodynamic and mathematical principles are understood, a mathematical model of the plant can be formulated. This requires a complete set of partial differential equations, involving both time and space, to describe power plant operation. Such a set of equations had never before been written.

Such a mathematical model would permit plant equipment and proposed control to be simulated, tested, and evaluated on a general-purpose computer. Design changes could be conceived and tested without construction of a single piece of equipment. The model will also facilitate the optimization of control computer and plant equipment.

Two years ago Westinghouse organized an operations research study team to evaluate steam plant automation and to develop an approach for the most fruitful development of new control concepts. The study was a joint venture, with engineers of Philadelphia Electric Company, Combustion Engineering, Inc., and Westinghouse participating. The primary objectives of the study were:

1. Perform analytical study of dynamic characteristics and sequential-operation requirements of the basic steam-power-plant process.
2. Develop sequential logic diagrams for starting, stopping, and operating a power plant.
3. Develop a mathematical model of a steam power plant suitable for transient analyses on a general-purpose digital computer.
4. Establish validity of the mathematical model by dynamic tests on an existing power plant.
5. Develop and evaluate new concepts of plant control, and compare with existing control.
6. Determine additional cost to automate a new unit of a specified design.
7. Indicate problem areas in equipment design, station design, and control design where changes will facilitate development of the optimum automated plant.

The study activities required to achieve these objectives were divided into three broad areas. The first area is that of analyzing required *sequential operations*. This area relates particularly to startup and shutdown sequences, protective and safety requirements, and various steady-state operating phases of plant equipment. Second is the area of *thermodynamic analyses and mathematical representation*. The third area deals with the *"on-line" control and operation* of the plant. Problems in this area primarily concern dynamic analysis and control of complex processes.

sequential operation requirements

Control of a steam power plant involves two types of action—*sequential* and *dynamic*. Power plants must have both types of control whether they are automated or not. Either or both can be automated to varying degrees.

In a conventional plant, human operators exercise sequential control when they put a plant on the line, shut it down, change load or operating conditions manually, or deal with emergency situations. Sequential control involves particular sequences of closing and opening valves, starting and stopping drive motors, or opening and closing circuit breakers supplying plant auxiliaries. One of the first steps in the study was the development of logic flow diagrams to describe the complete sequence of actions required in starting, stopping, and on-line operation of a specific unit, the Philadelphia Electric Company's Cromby No. 2. A portion of this sequence is shown in the flow chart in Fig. 1.

In considering sequential operations requirements, contingency and corrective actions (for emergency situations) are fully as important as startup and shutdown sequences (normal operations). Both emergency and normal operations require fast access to a large amount of plant operating data. The computer inputs must be capable of indicating the condition of the plant component parts and the operating variables. If an operating function is not completed or if a variable is outside a given range during startup, shutdown, or on-line operation, a plant contingency exists that must be recognized by the control computer.

In conventional plants a detected deterioration of a plant variable causes an alarm or annunciator signal to bring the new operating condition to the operator's attention. The operator then determines the steps to be taken, unless the condition is so serious that protective interlocks immediately remove the equipment from service.

In automated plants, plant interlocking relay schemes also will be used for backup action under contingency con-

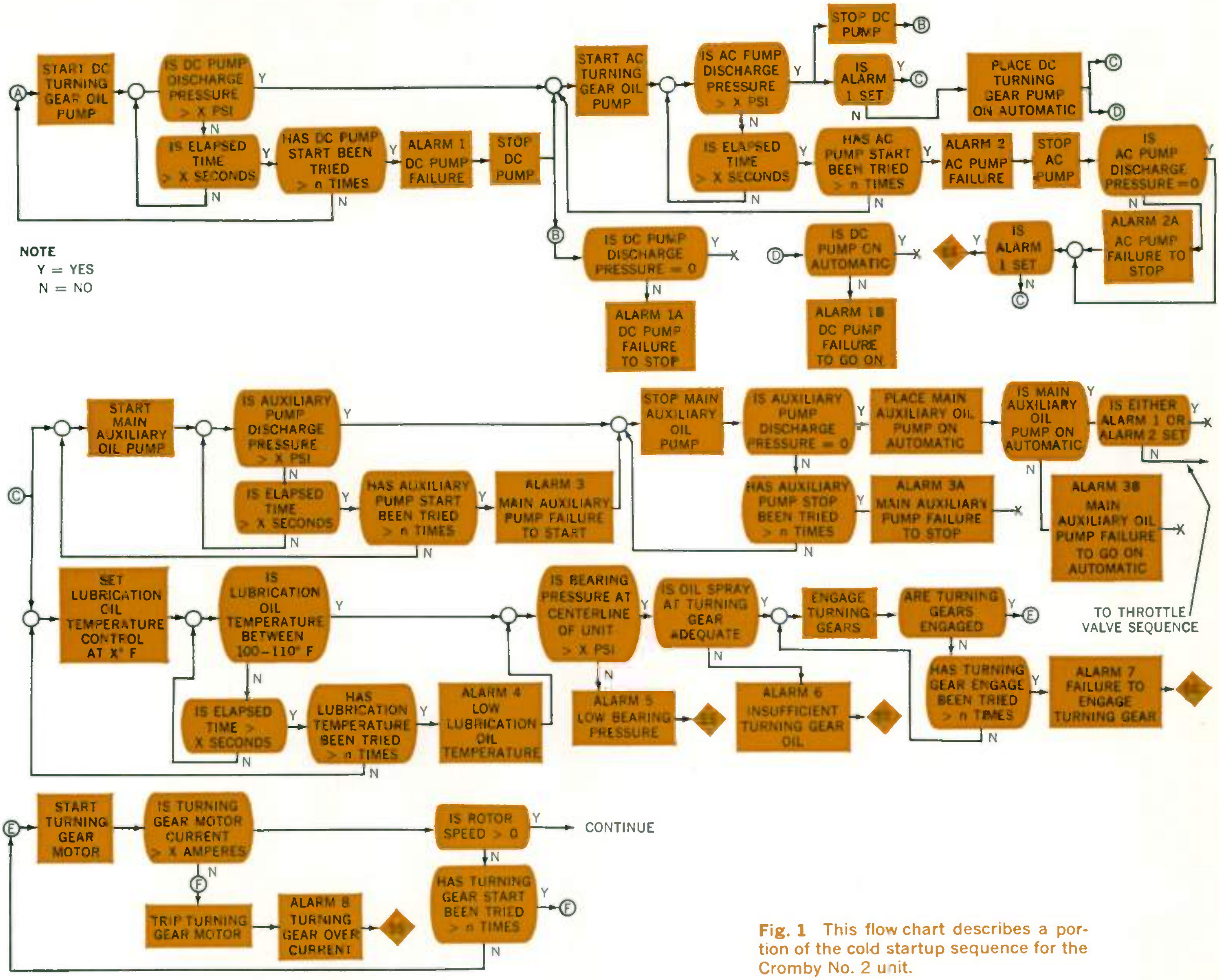

Fig. 1 This flow chart describes a portion of the cold startup sequence for the Cromby No. 2 unit.

ditions, but the computer is capable of taking preventive action if time permits a diagnosis and subsequent corrective actions. Thus, the speed at which plant variables deteriorate and the measurement techniques employed will determine the extent to which the computer can recognize and correct a contingency.

In contingency control programs, the following actions would be performed:

1. Scan plant conditions for the existence and nature of contingency, and determine whether it is single or multiple.
2. Determine priority of contingency to other alarmed conditions.
3. Initiate protective actions, such as shutdown, reduction in load, or use of spare equipment, etc.
4. If the rate of change of plant conditions permit, transfer to diagnostic routines to initiate specific scan sequences that can locate a faulty device.

dynamic process representation

Dynamic control is used during on-line operation to minimize fluctuations of temperature, pressure, and other variables as plant output is changed or as disturbances occur in the plant. Dynamic control is accomplished in present plants by analog devices controlling each variable, usually by a separate control loop. If an error occurs in one variable, only one plant actuator is moved to eliminate this error. But because of the couplings between plant variables, the action of any one actuator creates errors in other individual loops. The actuators in these other loops act to correct, and the controls gradually fight it out until a new steady-state condition is reached.

To study dynamic control, the complete dynamic steam-power-plant process was simulated by an extensive mathematical model on a data-processing computer. The model includes the complete boiler and turbine—drum, waterwalls, superheater, reheater, furnace, coal feeders and pulverizers, fans, air heaters, economizers, high-pressure turbine, low-pressure turbine, and feedwater heaters. Measurable variables include superheat and reheat steam temperature, pressure, flow, turbine power, excess air, and drum level. A flow diagram showing the equipment included in the dynamic analysis is shown in Fig. 2.

The mathematical representation is composed of 120 linear differential equations suitable for digital computer solution. (An equation is *linear* if the dependent variables and their differential coefficients are first degree only.) It also includes logic to obtain real-time results when one or more of the plant variables is subjected to a disturbance.

Thus, the model simulates dynamic performance of a power plant during transient conditions, and can have superimposed on it a control system. The model can read out such variables as pressure, temperature, and flow following a load change. In short, the model behaves almost like the plant itself for realistic changes in plant variables.

Model Development—The dynamic behavior of the physical apparatus and processes in a steam power plant should be represented by a set of nonlinear, partial differential equations (dependent variables and their differential coefficients are greater than first degree). Several difficulties arise, however, in the direct use of these equations. The difficulties are of two types:

(a) Formal solution of nonlinear partial differential equations is generally impossible, so that numerical (step-by-step) solutions must be employed. However, for the number and complexity of equations required to describe a steam power unit, computer time and cost for numerical solution would be prohibitive.

(b) While control-system synthesis techniques are highly developed for *linear* multivariable systems, straightforward synthesis of a *nonlinear* system is limited to low-order systems with but one or two controlled variables.

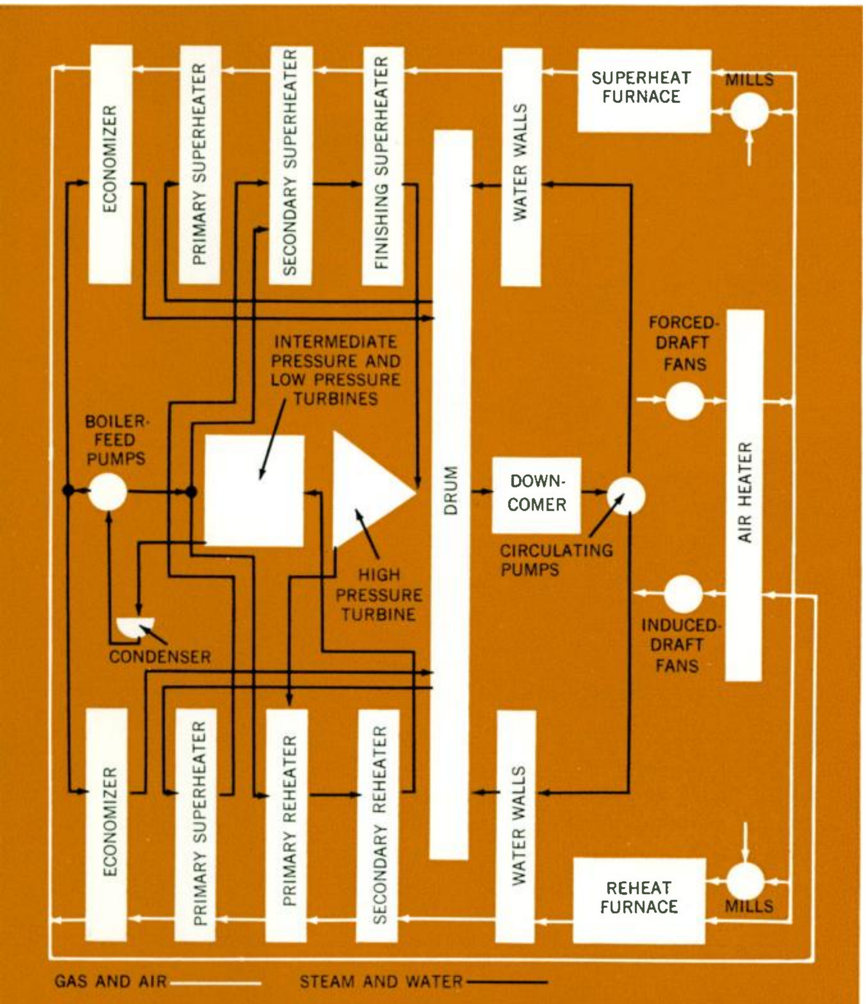

Fig. 2 Flow diagram of all the equipment included in the dynamic analysis of the Cromby No. 2 unit. Equations are written describing the dynamic performance of each component; these equations are then combined to form the entire plant model.

Table I TEST VARIABLES AND TYPES OF TRANSDUCERS

Location	*Type of Transducer*
*Flows**	
Feedwater	Variable Reluctance
Throttle Flow	Strain Gauge
Air Flow	Variable Reluctance
Pressures	
Drum	Strain Gauge
Throttle	Strain Gauge
H.P. Turbine Exhaust	Strain Gauge
Inlet to I.P. Turbine	Strain Gauge
Temperatures	
Primary S.H. Outlet	Thermocouple
Secondary S.H. Inlet—A	Thermocouple
Secondary S.H. Inlet—B	Thermocouple
Superheater Outlet	Thermocouple
Throttle	Thermocouple
H.P. Turbine Exhaust	Thermocouple
Reheater Inlet	Thermocouple
Reheater Outlet	Thermocouple
I.P. Turbine Inlet	Thermocouple
Gas Leaving Primary S.H.—A	Thermocouple
Gas Leaving Primary S.H.—B	Thermocouple
Miscellaneous	
Drum Level	Strain Gauge
Turbine Power	Hall Generator
Turbine Valve Position	Potentiometer
Feedwater Valve Position	Potentiometer
Coal Feeder Stroke—A	Potentiometer
Coal Feeder Stroke—E	Potentiometer
F.D. Fan Vane Position	Potentiometer
I.D. Fan Louvre Position	Potentiometer
Oxygen—R.H. Furnace	D.C. Potential From Control Room Recorder
Oxygen—S.H. Furnace	D.C. Potential From Control Room Recorder

*By Differential Pressure Measurement

Both considerations suggested the development of a linear model to approximate the nonlinear power plant system. This was accomplished by first writing the nonlinear, ordinary differential equations which apply, and then linearizing these equations about a steady-state operating point by partial differentiation. However, care had to be exercised in the use of these linearized equations since they behave like the nonlinear equations only at the base operating point and for small excursions around it.

The errors introduced by linearization can be calculated for a given case by comparing the size of increments obtained with the linear and nonlinear equations. The highest degree in these equations is found in the radiant heat-transfer terms, where temperature is taken to the fourth power. A temperature change of 2 percent, which corresponds to a 20- to 50-degree F variation, produces an error in the increment of heat transfer of 4.9 percent. In equations of lower degree, a smaller error results, or a larger increment can be used with the same error.

The variables in the basic partial differential equations governing fluid flow and heat transfer are, in their most general form, not only functions of time but of all three space dimensions. While the problem of determining temperature at the outlet of a long tube can be reduced practically to a function of only time and the length dimension, an algebraic solution for any but the simplest of configurations is a formidable problem.

A frequently used device is the "lumped-parameter" representation in which the physical device is divided into parts, the number depending on accuracy and frequency-response requirements. Outputs are represented as a function of the fixed parameters and the time variable only. The "π-section" model for a long transmission line is a familiar example from the electrical transmission field.

This first model developed by the study team employs lumped-parameter representation. Accuracy of the transient response can be improved if the waterwalls, superheater, reheater, and associated piping are divided into more sections, or a distributed-parameter representation is used. These improvements are under study.

field testing for model verification

To prove the validity of the mathematical model technique, all equations were tailored to Philadelphia Electric's Cromby No. 2 unit. Model performance could then be verified by a series of field tests of selected transient conditions. For the field tests, the Cromby unit was instrumented in the most accurate and sensitive manner ever attempted. The required data could not possibly have been obtained from a conventionally-instrumented plant. Test results were good, and many aspects of the mathematical model were verified. The field tests also revealed areas where more extensive mathematical analysis and model refinement are required.

Since 120 dependent variables are contained in the mathematical model, a complete check of all variables by test would be an economic and physical impossibility. The variables listed in Table I were chosen as being the most important for verification. All sections of the model had one or more variables recorded for fifteen different tests. A brief description of each test is given in Table II. A test consisted of recording the incremental value of the variables for an incremental step change in an independent variable of the plant. Since a check on the linearity of the plant was desired, certain tests were performed with positive and negative step changes of the independent variable.

The purpose of the model is control synthesis, i.e., the complete design of the control system, built up from the various requirements of the process. Therefore, the model of the boiler-turbine generator unit was constructed with actuator positions or speeds as independent variables rather than control error signals. Thus, execution of the plant tests for model verification required the elimination of all controls. Preliminary testing showed adequate open-loop plant stability to permit the full-scale tests.

comparison of results

Since the model was prepared principally for control evaluation, the criteria used in judging the adequacy of the model were established with this goal in mind rather than the high accuracies expected in heat-balance work. In single-variable feedback-control systems, overall performance of the control system can be made insensitive to inaccuracies in the representation of the process. For example, a variation of 2 or 3 to 1 in the major process time constants and gain can be made to have negligible effect by proper controller design. Minor time constants can have even greater variations. Thus, for the multiple-variable process contained in a power plant, variations equal to or less than those quoted as permissible for a single-variable process can be tolerated in the results from the model.

Using these control-evaluation criteria, good agreement was obtained for most areas of the plant. Areas for model refinement were pinpointed.

Typical test results compared with calculated responses from the model are shown in Figs. 3, 4, and 5. Only the incremental changes in plant variables are plotted.

An example of an area requiring model refinement is illustrated by the drum level plots of Figs. 3 and 4. The increased rate of change of level calculated over that determined by test is attributed to increased pressure changes computed by the model. The studies suggest that further exploration of the relationships between drum level, drum pressure, and feedwater flow should consider the effect of feedwater flow mixing in the drum. The existing model assumes that all mixing occurs in the downcomer. Furthermore, the effect of surface evaporation in the drum should be studied.

Another example (Figs. 3 and 4) shows that calculated throttle-pressure change rates are greater than the rates found by testing. The effect can be partly attributed to the waterwall mass used in the model. A review of the boiler-design data indicated that waterwall buckstays and skin casing have a significant mass and should be included. If the effective wall heat capacitances were raised in this proportion, pressure change would be slowed to a rate more nearly corresponding to the test results. Inclusion of the heat capacity of the downcomers and other tubes in the circulating loop would effect a further retardation.

Throttle temperature studies generally reveal longer dead times than those calculated. These characteristics indicate that the number of lumped-parameter sections used in the model to represent the dynamics of heated sections may not be adequate. Future work incorporating

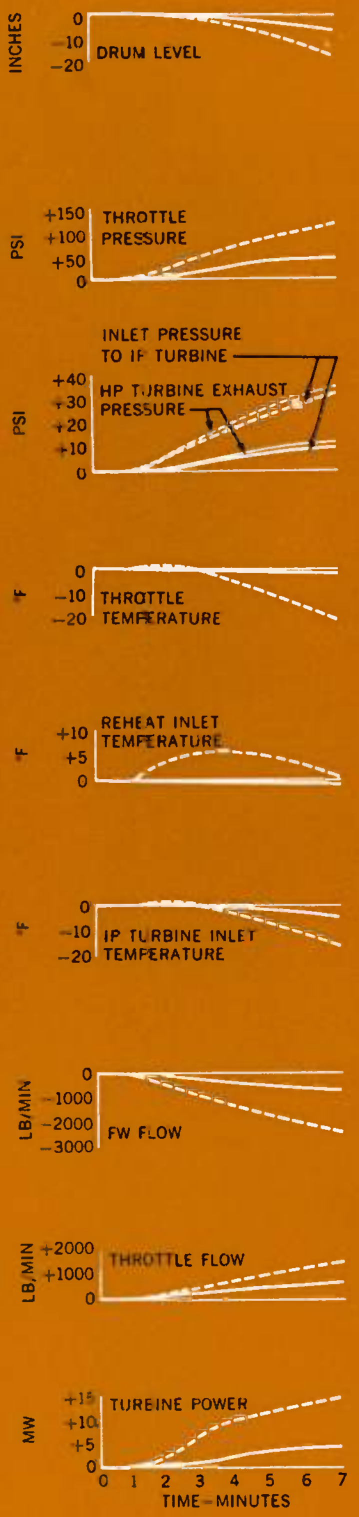

Fig. 3 Comparison of calculated (dashed curve) and field test results (solid curve) for a step change in feeder stroke resulting in a three percent increase in fuel flow to both furnaces. A one minute transport lag was added to all calculated variables.

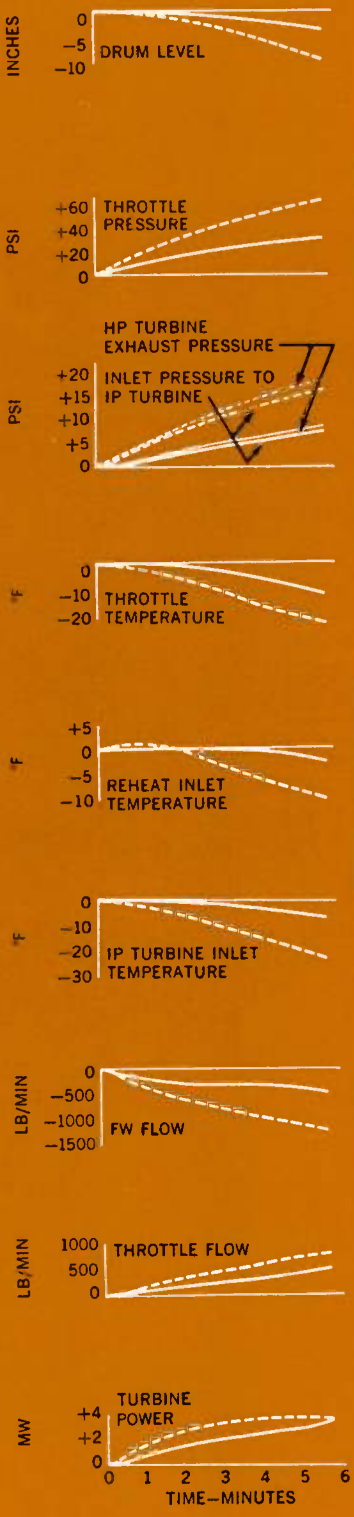

Fig. 4 Comparison of calculated (dashed curve) and field test results (solid curve) for a step change in induced and forced draft fan louvres resulting in a 6.5 percent decrease in air flow. Actual time required for step change in actuator position was 10 seconds.

Table II DESCRIPTION OF VARIOUS TESTS PERFORMED

Test	*Description*
1	Increase steam flow approximately 800 lbs/min by opening the turbine load limit valve one-half turn (at the turbine). Initial conditions will be 1825/980/980, with drum level 2 inches above normal.
2	Decrease steam flow approximately 800 lbs/min by closing the turbine load limit valve one-quarter turn (at the turbine). Initial conditions will be 1775/980/980, with drum level 3 inches below normal.
3	Increase feedwater flow approximately 1000 lbs/min by increasing the 2-A Bailey Feedwater Valve control pressure 2 psig. Initial conditions will be 1800/980/980 with drum level 3 inches below normal.
4	Increase superheat spray from zero to approximately 400 lbs/min by moving 2-A and 2-B Spray Valves simultaneously to 35 percent open. Initial conditions will be 1800/1000/1000 with normal drum level.
5	Increase reheat spray from zero to approximately 400 lbs/min by moving the spray valve to 20 percent open. Initial conditions will be 1800/1000/1000 with normal drum level.
6	Increase air flow by opening the induced draft louvers on both fans approximately 5 percent. Initial conditions will be 1800/960/960 with normal drum level and 3.0 percent O_2 in each furnace.
7	Decrease air flow by closing the induced draft fan louvers on both fans approximately 5 percent. Initial conditions will be 1775/980/980 with normal drum level and 4.5 percent O_2 in each furnace.
8	Increase coal flow to the 2-A and 2-E pulverizers by moving the handwheel on the Feeder Positioner ¾ turns. Initial conditions will be 1775/960/960 with drum level 2 inches above normal and 4.5 percent O_2 in each furnace.
9	Decrease coal flow to the 2-A and 2-E pulverizers by moving the handwheel on the Feeder Positioner ¾ turns. Initial conditions will be 1800/980/980 with drum level 2 inches below normal and 3.0 percent O_2 in each furnace.
10	Same as Test 9 using 2-D and 2-H pulverizers in place of 2-A and 2-E.
11	Open the exhauster output dampers on all pulverizers from 50 percent to 60 percent. Initial conditions will be 1800/980/980 with normal drum level and 3.5 percent O_2 in each furnace.
12	Raise superheat furnace burner tilts from +10 to +20 degrees. Initial conditions will be 1800/970/970 with normal drum level.
13	Lower superheat furnace burner tilts from zero to −10 degrees. Initial conditions will be 1800/980/980 with normal drum level.
14	Raise reheat furnace burner tilts from zero to +10 degrees. Initial conditions will be 1800/970/970 with normal drum level.
15	Lower reheat furnace burner tilts from zero to −10 degrees. Initial conditions will be 1800/980/980 with normal drum level.

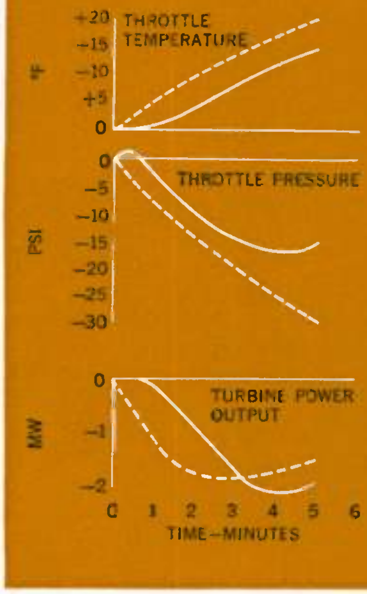

Fig. 5 Comparison of calculated (dashed curve) and field test results (solid curve) for a 10 degree change in superheat furnace burner tilt position. The change was from plus 10 degrees to plus 20 degrees, and required 18 seconds.

distributed parameter effects should provide a better representation of these temperatures. Since the model was based upon design information, commercially clean walls and superheat sections were assumed. Future analysis should be directed to determine the effect of soot and slag accumulation upon the transient temperature performance of these sections of the boiler.

Many other improvements in the model were suggested, and much more was learned about the process from the field tests. Major areas for future investigation are:

1. In the furnace region the basic phenomena of pulverization, transportation, and combustion should be studied further.
2. The fast response calculated for temperatures in both the superheater and reheater indicates that distributed parameter representation should be favored over lumped parameter.
3. The feedwater circuit design constants must be modified, based upon actual performance. Also a better representation of the drum, downcomer, and waterwall loop is required.

When the foregoing areas are more fully explored, power engineers should have about as thorough an understanding of the dynamics of the steam-generation process as they presently have of steady-state plant heat balance.

new control concepts

While the primary objective of the study was development of the mathematical model, a second major accomplishment has been realized. This is the conception of a new scientific procedure for designing large-scale control systems analytically. The new procedure synthesizes controller functions that will give the desired plant outputs for changes in set points. The synthesis problem is to choose a controller that is stable and physically realizable. This problem is solved by reducing the 120 plant equations to a set of transfer functions between the independent plant inputs and the outputs to be controlled.

How will these new control concepts be put to work? The model provides the means for testing designs of control systems for any unit before any are built. The need for expensive prototype equipment and field tests should be markedly reduced.

Perhaps more important, the process analysis that preceded model development has given more information about the physics of equipment, particularly from a systems viewpoint. This knowledge ultimately will be reflected in design changes of the steam-cycle components, changes that will make components more compatible with the overall system and its control requirements.

And there is bright prospect for the new procedure in large-scale control-system design. One application is the design of *noninteracting* control. This type of control achieves noninteraction between plant variables by having all the control functions interact so that *all* plant actuators move in a coordinated fashion to eliminate an error in *one* plant variable. The new scientific procedure is used to arrive at controller functions which will allow each plant variable to be changed without any effect upon the other variables.

Newly developed control schemes will improve the reliability, efficiency, and controllability of the steam power stations of the future. Systems designed and set with the aid of mathematical models can reduce the field adjustments required and shorten the shakedown period.

Automatic power plants designed with these new concepts will permit much more efficient use of operating personnel. Ultimately, complete reliance on automatic control equipment will eliminate much of the manual control apparatus and instrumentation now being installed which, in turn, will reduce the first cost of automating power plants. An additional financial benefit will come from the reduction in cost of generation apparatus when it is designed for strictly automatic operation.

future plans

A mathematical model has been developed for a complete power station, a new scientific procedure has been conceived for the design of control systems, and this new procedure is being applied to the design of promising new systems. Future work will exploit these accomplishments. Advanced control systems of the noninteracting type will be designed, tested on the mathematical model, and evaluated. Their technical and economic feasibility will be compared with conventional automation schemes. This will be done with the ultimate objective of constructing a second-generation automatic plant based on these new design concepts.

To accomplish these goals, some refinements in the mathematical model will be necessary, e.g., extension to the lower load level range and improved representation of certain distributed parameter heat transfer loops. With the major job completed, these improvements will be made as required.

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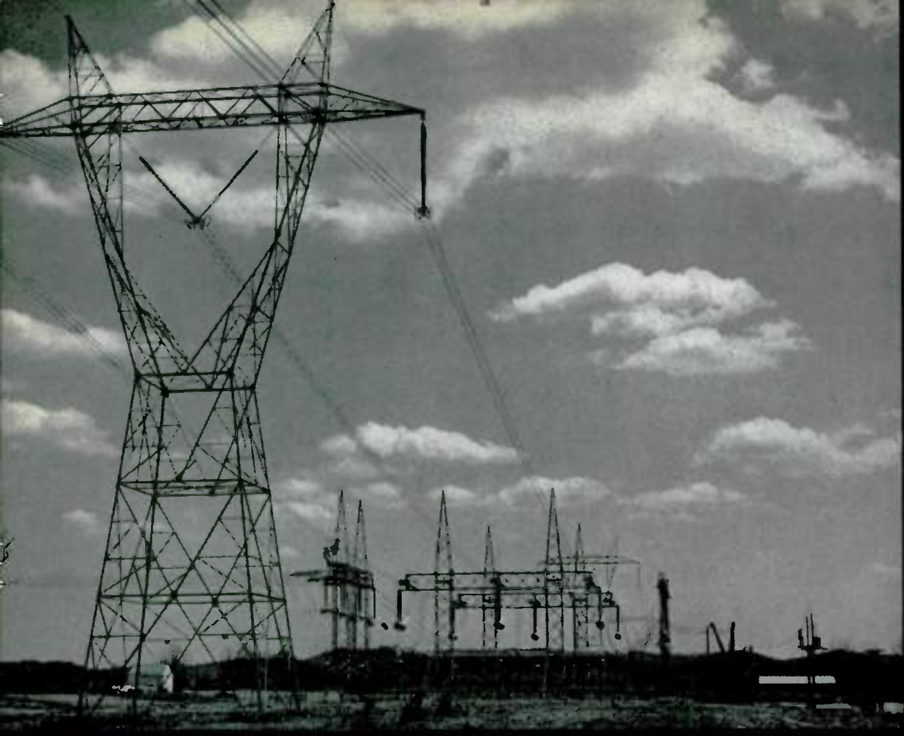
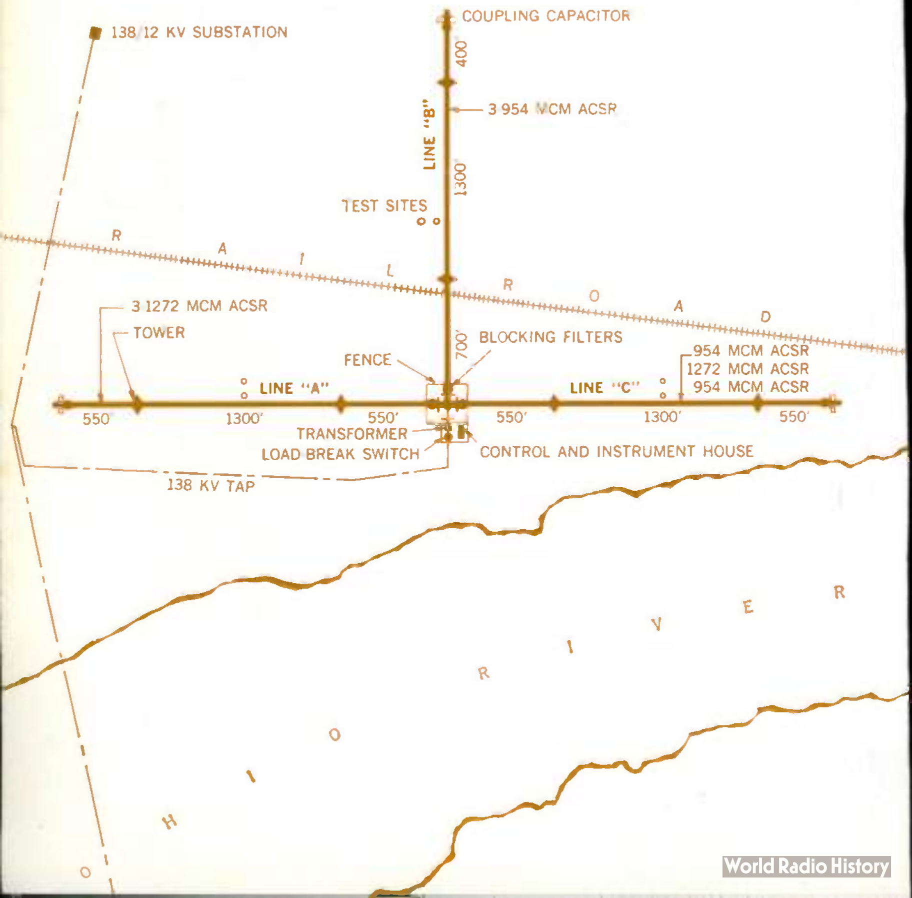


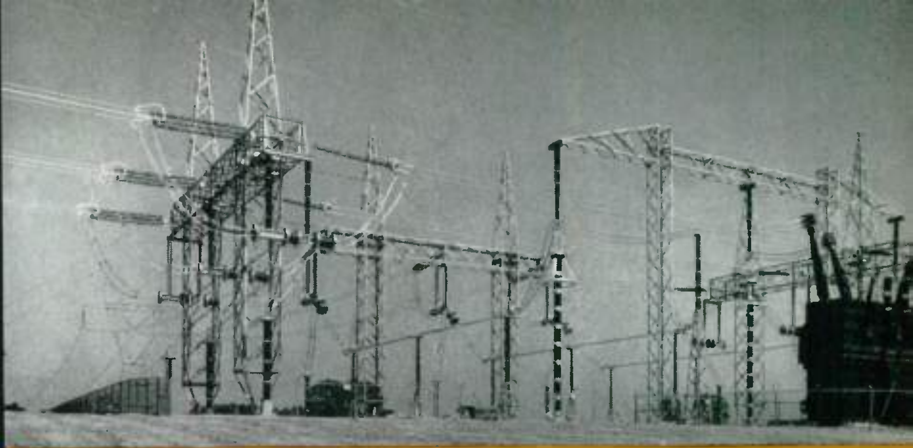
LINE A is shown here, with the substation in the background. Note the V-string suspension for the center phase; this prevents sideswing of the conductor and permits a more economical, smaller tower.

PHYSICAL LAYOUT of the 750-kv Apple Grove Project is shown in this sketch. Test line and associated equipment are shown in heavy line.



RADIO INFLUENCE NOISE is measured by meters in instrument houses. Three houses are 100 feet from the center phase, the other three, 200 feet.

DECOUPLER at left is used to isolate the three lines from each other for radio-influence measurements. Near section is housing for the corona-loss wattmeter, heating transformer, and series capacitor. At far end are chokes for the decoupler. Here the coupling capacitor is not connected.



▲ **SUBSTATION** for the test project is at the juncture of the three 2400-foot line sections. In photo, lines run to left, right, and behind the substation. At right is the 138/750-kv transformer.

◀ **INSTRUMENT AND CONTROL PANEL** includes (from left to right): instrument panel; station control panel; data logger; and, in closed cabinet, the tape transport, digital clock, and scanner.

APPLE GROVE TEST LINES ENERGIZED AT 775 KV

The extra-high-voltage test transmission line shown on these pages was energized in June at 775 000 volts—the first time this voltage has been used on a transmission line in the United States, and probably the first time in the world. A five-year research and test program will develop the information and experience needed to transmit large blocks of power at voltages up to 750 kv—more than twice the operating voltage of commercial systems in this country today.

Prime objective of the project is to obtain data on corona loss and radio influence (RI) performance of conductors at a nominal voltage of 750 kv to determine the technical and economic feasibility of transmitting large blocks of power at this extra-high voltage.

Information on conductor size and configuration, insulators, spacers, bushings, connectors, hardware, and structural data will be of value in determining line design. Operating experience on transformers, lightning arresters, coupling capacitors, and line traps will help in the future design of terminal apparatus for 750-kv operation.

The new test line is constructed on a possible future generating site for Appalachian Power Company at Apple Grove, West Virginia, about 25 miles up the Ohio River from Huntington, West Virginia. Appalachian Power Company is one of six operating companies in the American Electric Power system.

The test line is connected to a tap off of a double-circuit line between South Point, Ohio and the Philip Sporn plant at Graham Station, West Virginia. As shown at left, the 138-kv tap feeds the test line through a three-pole load-break disconnect switch to the 138/750-kv autotransformer and then to a 750-kv bus structure. Originating at the substation bus and extending from it are three 2400-foot-long three-phase lines, forming a "T." Conductor sizes on the three line sections are all different. A control and instrument house is located in the 138-kv switchyard near the 138-kv load-break switch and 750-kv autotransformer.

Two special features of the line are: Simultaneous independent RI readings can be taken on each of the three lines; and since no load is supplied by the line, heating current is provided to simulate actual system operation.

The tests will be completely instrumented, using magnetic-tape data logging equipment to allow maximum information to be accumulated and analyzed. Effects of various atmospheric conditions will be assimilated into this data for proper statistical analysis. Comparison of the data with that of previous high-voltage projects, such as the Leadville and Tidd lines, will allow evaluation of test procedures, instrumentation, and verification of results.

Readings of about 50 test quantities on the line will be taken by the data logger and recorded every twenty minutes. Whenever test readings fall outside predetermined limits, the data logger will scan and record readings every two minutes until the values fall back into line.

Readings taken will include: temperature, relative humidity, air pressure, wind direction and velocity, radio influence, corona loss, rainfall, and air contamination.

The 750-kv project was announced last spring by American Electric Power Service Corporation and Westinghouse—co-sponsors of the program. The new test project will provide a continuation of the investigations begun by the two companies at Brilliant, Ohio, in 1946 when they built and operated the 500-kv Tidd test project.

Other companies participating in the project are: American Bridge Division of United States Steel; Armco Steel Corporation; Kaiser Aluminum and Chemical Corporation; Lapp Insulator Company, Inc.; Ohio Brass Company; and The Thomas & Betts Company, Inc.

ELECTROMAGNETIC POWER SYSTEMS FOR SPACE VEHICLES

Interacting effects of subsystem characteristics must be evaluated when designing space power systems.

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The experience accumulated in aircraft design is often applicable to space vehicles, but the degree of applicability varies. A case in point is the electric system. The basic requirements of light weight, compactness, and high performance remain, but beyond this there is little similarity.

Fundamentally, any electric system consists of three basic subsystems—power generation, distribution, and utilization. This article is concerned primarily with power generation, so that subsystem is discussed more fully than the others. The type of system discussed is the large system for the electrically propelled vehicles that may be used for interplanetary trips, not the smaller systems required in present earth-escape and orbital vehicles.

In an aircraft, the electric power generation system is a secondary system (Fig. 1). The generator is an engine-mounted accessory that requires only about one or two percent of the prime mover's developed power for rated operation. A typical electric power requirement of a large transport-type aircraft is 160 kilovolt-amperes, and the power is used for guidance, communications, and utility systems of various kinds.

In a large electrically propelled space vehicle, the electric power system is the primary power system. It provides power not only for guidance, communications, and utility systems but, most important, for ion or plasma propulsion. Recent publications indicate that electric power requirements for such a vehicle probably will fall in the 1 to 2 megawatt range and may go as high as 10 megawatts. A possible electric system is diagrammed in Fig. 2. The entire output of the heat engine is converted by the electric generator, so the generation system is a prime factor in the successful operation of the space vehicle as contrasted to its secondary status in an aircraft.

Much effort is being expended in the development of space electric power generation systems. The greatest emphasis appears to be on nuclear reactors, turbines, liquid-metal working fluids, and heat transfer. These are critical areas, but, if compatible systems are to be developed, equal attention must be given to the electric equipment. Consider, then, the problems of design and selection of the electric generator and its controls and conversion equipment.

generator

System Considerations—Since the power losses within the generator must be removed from the system by heat radiation, the system designer intuitively desires the generator operating temperature to be as high as possible. The need for a maximum operating temperature can be illustrated by the Stefan-Boltzman radiation equation:

$$q=\sigma\epsilon A T^4$$

where: q = time rate of thermal energy exchange, Btu/hr,
σ = Stefan-Boltzman constant, 1.72×10^{-9} Btu $\mathrm{hr}^{-1}\,\mathrm{ft}^{-2}\,\mathrm{R}^{-4}$,
A = radiating surface area in square feet,
T = absolute temperature of the heat-rejection area,
ϵ = radiating surface emissivity.

This equation shows that the thermal energy dissipated per unit area is proportional to the fourth power of the absolute radiating temperature.

Therefore, increasing the generator operating temperature tends to reduce the system weight by reducing the size of the heat-rejection radiator. An additional gain is realized because reducing heat-rejection area also reduces the amount of meteoroid protection that must be provided for the radiator. Another advantage of high temperature is that it increases the resistivity of magnetic materials, reducing core loss and increasing generator efficiency.

On the other hand, electrical resistivity of conductors increases with temperature and this reduces generator efficiency. Allowable rotor diameters are reduced as a result of lower mechanical strength of magnetic materials at high temperatures, and the increased length-to-diameter ratio increases generator weight. Finally, the permeability of magnetic materials decreases as temperature increases, causing increased generator weight.

A second consideration is generator operating speed. Minimum-weight rotating equipment (turbine and generator) generally result at maximum operating speeds. However, rotational speed is not the only factor. Developed shaft power or conversion efficiency must also be taken into account in attempting to minimize complete system weight.

Studies[1] have revealed the necessity of evaluating the effects of the major generator parameters—speed, operating temperatures, and input power—on total system performance. For example, a minimum-weight generator will not always result in a minimum-weight conversion system.

This can be understood by considering the effects of generator weight and efficiency on the overall power system. A minimum-weight generator has a given efficiency, so certain power losses must be rejected to space as heat by direct radiation. Increasing the generator efficiency adds weight to the machine. However, the resulting reduction in generator losses has two compensating effects on the overall system: (1) the heat-rejection radiator is made smaller and therefore lighter, and (2) the shaft power required by the generator is reduced, which results in a smaller turbine and its associated thermal-to-mechanical energy conversion equipment.

The problem is to find the generator weight and efficiency that result in a minimum-weight energy-conversion system. This optimum combination results only when compromises are made in individual components.

Design Selection—The selection of the type of electromagnetic generator to use is limited by the application. The desired high operating speeds and temperatures require that the generator be brushless and contain no rotating windings. Generator brushes have had to be eliminated in high-performance aircraft because they deteriorate rapidly in the thin air of high altitudes. Their use is out of the question in the near-vacuum of outer space. Rotating windings have serious problems of high stress in conductors and insulation. Conductor creep would produce large unbalanced forces leading to severe bearing loads.

A number of design analyses of brushless, nonrotating-winding generators have been made, and the inductor generator has been selected as the most suitable (see Figs. 3 and 4). Its solid rotor enables it to operate at the speed and temperature required by any rating.

The inductor generator has two stator stacks, each containing a common ac output winding, and a toroidal dc field winding placed between the two stators. Each stator stack is only 50 percent effective because of unidirectional magnetic flux passing through the stator. The solid rotor has north magnetic poles protruding from one end and south magnetic poles from the opposite end. The three-phase ac winding sees alternate north and south flux as the rotor revolves, inducing a voltage.

Inductor generator weights in the range of 0.5 to 0.9 pounds per kilovolt-ampere are obtainable.

Problem Areas—The main operational limitation of the inductor generator is the mechanical strength of the rotor magnetic material at the desired speeds and temperatures. As a general rule, the electromagnetic weight of an ac generator decreases with increase in speed until such factors as limited rotor diameters or poor armature slot combinations cause weight to increase. Operating temperature is limited by the Curie point of the magnetic materials and by mechanical stresses.

The possible use of an alkali metal as a heat-engine working fluid introduces an electrical insulation problem. Because of imperfect rotating seals, the interior of the generator is exposed to metallic vapors. The insulation must either withstand the corrosive effects of the hot vapor or be enclosed, perhaps in a ceramic container. In the latter case, the ceramic material must withstand the vapors.

Eddy currents, and hence power losses, in the generator air-gap region must be held to a minimum. A vapor normally has relatively low electrical conductivity unless it is ionized by extremely high temperature or radiation, and then its conductivity exceeds that of copper. Therefore, once the generator air-gap vapor ionizes, induced losses increase significantly. This is readily seen from previous rotating machinery evaluations[2]. The system design must prevent ionization within the generator.

generator excitation and control

System Considerations—The criteria for selecting an excitation and control system can be summarized as follows:

1. Minimum generator and excitation system weight
2. No requirement for generator overloads or faults
3. Minimum excitation system power loss
4. Solid-state rectifiers outside the ac generator
5. Generator voltage control required over the power factor and load range.

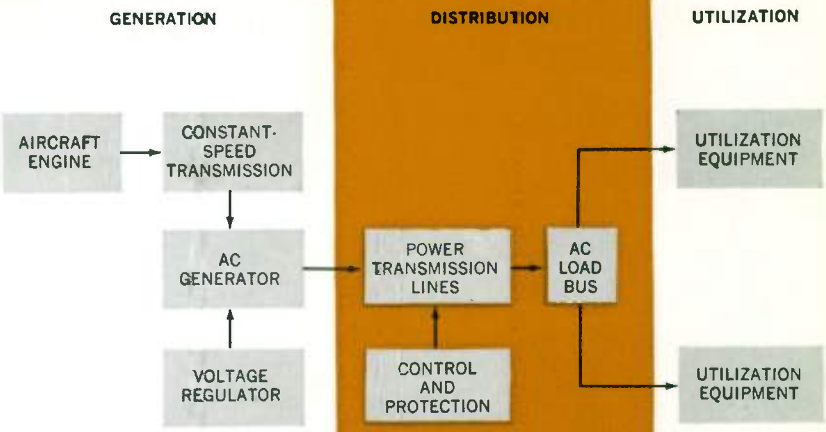


Fig. 1 Typical aircraft electric system is a secondary power system, driven by an engine whose main function is propulsion.

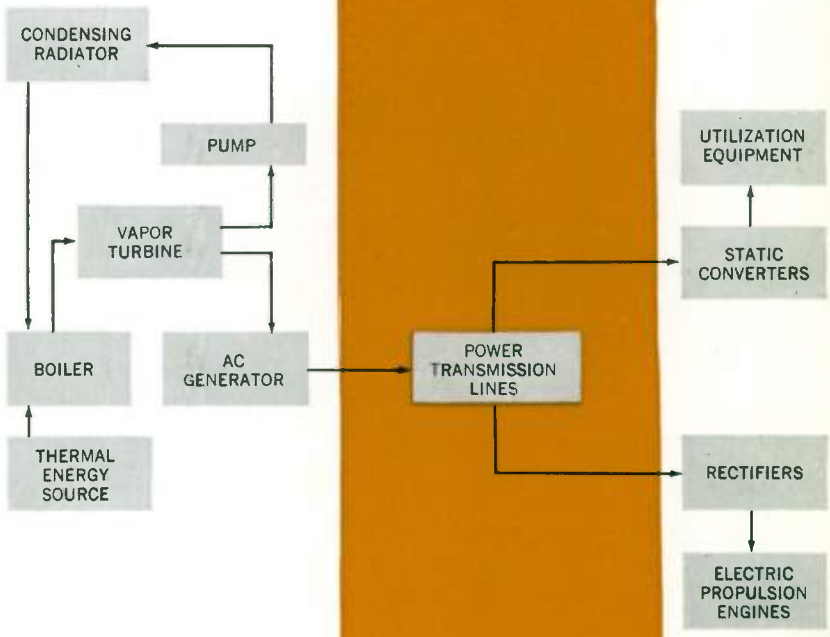


Fig 2 An electrically propelled space vehicle's electric system is the primary power system, converting the entire output of the heat engine to electricity.

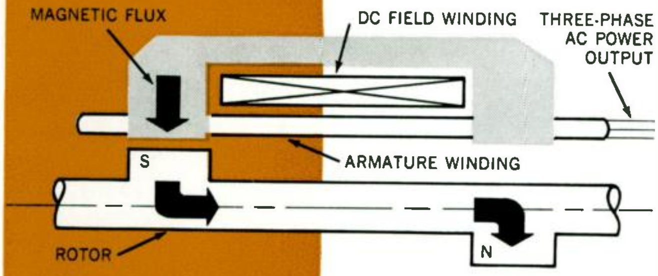
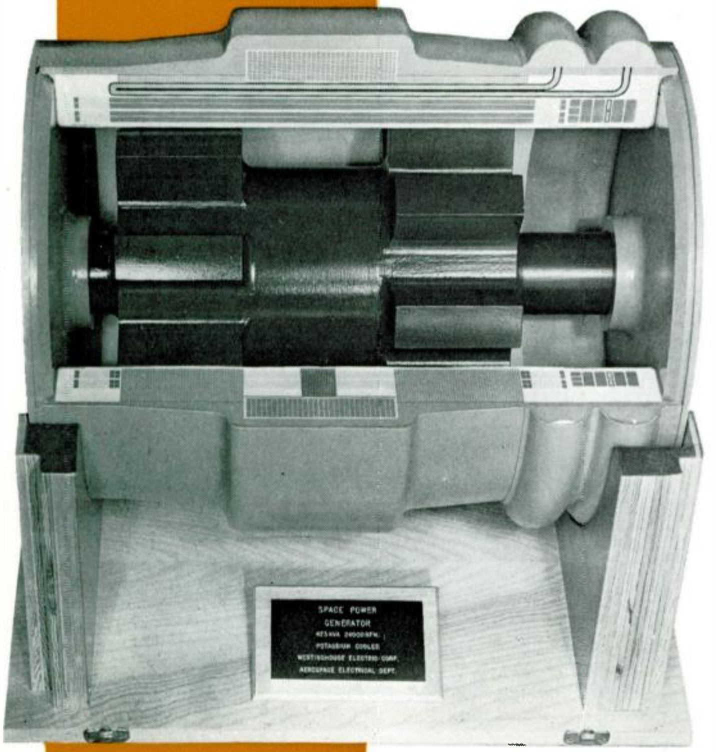


Fig. 3 Diagram of the inductor generator.

Fig. 4 This cutaway model of an inductor generator for space power represents a 423-kva unit designed to operate at 24 000 rpm and 1000 degrees F. The generator is cooled by liquid potassium and weighs 355 pounds. The active electromagnetic portion would be about 18 inches in diameter and 15 inches long.



Design Selection—Generator excitation systems can be classified in two categories—rotary and static.

The rotary exciter is another inductor generator mounted on the same shaft as the main generator (Fig. 5). With the exception of its excitation power, it receives all of its power from the rotating shaft. The main advantage of the rotary exciter is the low power that the static exciter and its associated voltage regulator must supply and control. Its major disadvantages are added weight, system complexity resulting from locating the exciter output rectifiers outside the rotating structures to stay within the rectifier temperature limitations, and increased shaft length required to support the exciter.

A static excitation system using high-power rectifiers is diagrammed in Fig. 6. Studies show that it produces a minimum-weight power system and is more suitable for use with the inductor generator than the rotary exciter is. A comparison of the two excitation systems is shown below:

	Rotary Exciter	Static Exciter
Weight (lb)	32	12
High-Temperature Losses (watts)	1100	500
Low-Temperature Losses (watts)	200	200

The high-temperature losses are in the generator and are rejected at temperatures corresponding to the generator coolant temperatures. The low-temperature losses are in the solid-state devices and are rejected at the temperatures corresponding to the limitations of semiconductors (presently about 200 degrees F).

Problem Areas—An excitation system must supply generator field power of about 0.5 to 1.0 percent of the generator rating. For a one-megawatt generator, the excitation power is approximately 10 kilowatts. This is a sizeable amount of power to be handled by solid-state devices.

Another area of consideration is the method and temperature of heat rejection. The semiconductors used in the static exciter are not capable of operating at generator temperatures. Present silicon semiconductors have maximum junction temperatures of approximately 300 degrees F and require coolant temperatures in the order of 200 degrees F. Practical high-power semiconductor rectifiers cannot be predicted for the time period under consideration. At temperatures suitable for silicon rectifiers, the heat rejection area and weight become large for any large amounts of power. Thus, it is necessary to minimize power losses or develop high-temperature semiconductors for these applications. Finally, the long-term degradation of these components when exposed to radiation must be considered.

power transmission

System Considerations—Conductors for carrying megawatts of electric power are quite large, especially for transmission distances of 50 to 100 feet. Conductor spacing and operating frequency determine the system impedance. Aircraft power systems operate at 400 cycles per second; system frequencies of 3200 cycles per second are being considered for space applications. However, electric propul-

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REFERENCES:
[1] "Space Electric Power Application Study," H. B. Saldin, N. F. Schuh, ASME Publication 60-AU-33, April 1960.
[2] "The Calculation of Can Losses in Canned Motors," R. C. Robinson, I. Rowe, L. E. Donelan, *AIEE Transactions*, Vol. 76, Part III, 1957, pp. 312–315.

sion engines now being considered require dc power, so the generated frequency selected should be the value that minimizes weight when generators, transformers, transmission lines, rectifiers, and power-system control are considered.

High frequency, while tending to reduce electromagnetic weights, increases transmission line impedances. These impedances affect the generator size and the quality of power supplied. Operating temperatures and methods of removing conductor losses must also be analyzed.

Design Selection—While copper has been used extensively in aircraft, aluminum or some other material may be more suitable for space vehicles. Even though minimum weight is important, secondary considerations such as performance must also be evaluated.

Problem Areas—These appear to be less serious than those related to generators and control apparatus. However, insulation, conductor flexibility, operating temperatures, power loss removal, and electrical performance must be considered.

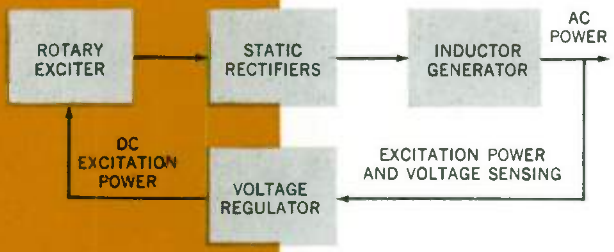

Fig. 5 In a rotary excitation system, the exciter is a small inductor generator mounted on the same shaft as the main generator.

power conversion and utilization

System Considerations—The bulk of the power used by a vehicle of the type discussed in this article would be consumed by ion or plasmajet electric propulsion engines that require dc voltage levels in the range of 5000 to 50 000 volts, possibly higher. Since there is a limit to the ac voltage that can be generated at the operating conditions being considered, step-up transformers must be employed. Therefore, the combined generator and transformer weight must be analyzed for possible trade-offs that will minimize system weight. Also, the ac generator output must be rectified for the propulsion system.

Lesser amounts of power (10 to 20 percent of the generated power) will be required by guidance, communications, and utility loads. Since these loads are smaller than the propulsion loads, they should receive only secondary consideration in selecting the system operating parameters. It may be necessary to incorporate static conversion units to supply the secondary loads.

Problem Areas—The major problem will be coping with the high operating temperatures. Power losses must be absorbed by a heat transport fluid, transmitted to a heat rejection radiator, and radiated to space. Solid-state devices with power ratings suitable for these applications must be devised. Development of high-temperature semiconductors would simplify the problem.

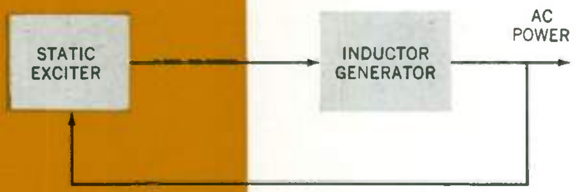

Fig. 6 The static excitation system employs high-power rectifiers. It is simpler and lighter than the rotary type, and these and other considerations make it more suitable for use in a space power system.

conclusions

To provide a light, compact, energy-conversion system for space propulsion, careful consideration must be given to each system component. Such parameters as rotational speed, operating temperatures, efficiency, and output power characteristics in the electric conversion equipment have considerable effect on overall conversion-system weight. Developing a space power system in the megawatt power level will require extensive development of application and fabrication techniques for translating the basic materials into compact apparatus.

A minimum-weight energy-conversion system results only from an integrated system analysis. This analysis must evaluate the weight penalties associated with different operating parameters.

VOLTAGE CONTROL OF SILICON RECTIFIER UNITS Three basic types of voltage control can be applied in a variety of arrangements.

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Two-electrode silicon rectifying devices have won wide acceptance for ac-to-dc power conversion in applications requiring large blocks of direct current. Many of these applications require that the dc voltage be adjustable over a range of values—sometimes by only a few percent, often as much as 30 to 60 percent, and occasionally even more. Since output voltage of the two-element silicon rectifier cannot be altered by such methods as field control or phase delay, some means must be incorporated in the overall conversion equipment to adjust ac voltage at the input terminals to the rectifier assembly. This can be accomplished with three basic types of voltage-controlling equipment—induction regulators, transformer tap-changing equipment, or variable reactors. The Trinistor controlled rectifier is a future possibility. However, this device at the present time does not have sufficient ampere rating to handle large blocks of dc power.

induction regulators

The three-phase induction regulator has the general construction of a wound-rotor induction motor; the regulator consists of a rotor excited from the source, and a stator in series with the source (Fig. 1a). The voltage induced in the stator is essentially constant for all rotor positions and is proportional to supply voltage. Stator voltage can be varied from in-phase to 180 degrees out-of-phase with supply voltage. When stator voltage is in phase with supply voltage, the maximum regulated voltage is available; minimum regulated voltage occurs when stator voltage and source voltage are 180 degrees out of phase. At intermediate positions of the rotor, regulated voltage is the vector sum of source voltage and stator voltage (Fig. 1b). All values of regulated voltage between the maximum and minimum positions are available, so induction regulators can provide smooth control of rectifier output voltage.

For some three-phase kva ratings a triplex unit may be desirable from a manufacturing standpoint. This unit consists of three single-phase units in one tank or cubicle. In a single-phase unit, the voltage induced in the rotor is always in phase with the supply voltage, but the magnitude changes with rotor position. Thus, an in-phase voltage of variable magnitude is either added to or subtracted from the supply voltage.

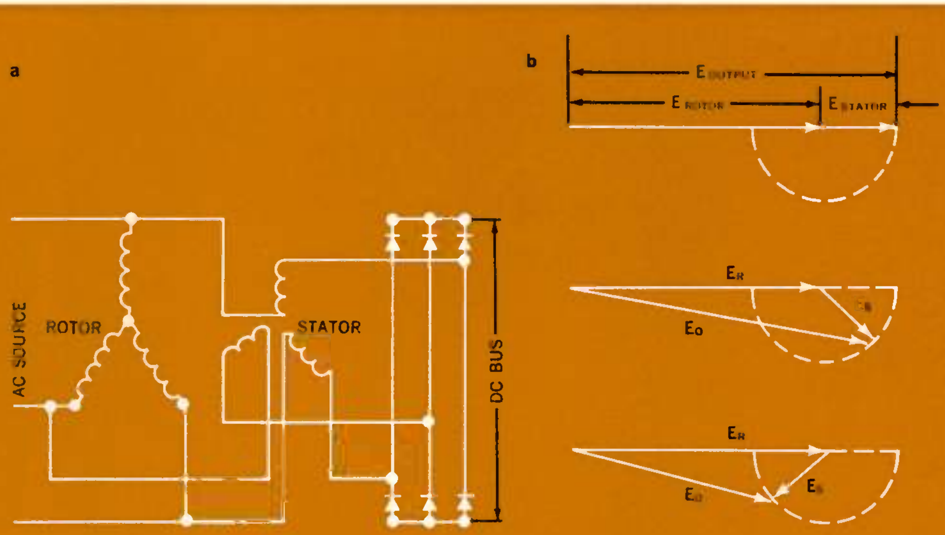

Fig. 1 (a) Diagram of a typical three-phase induction regulator. (b) Voltage vector diagram of induction regulator.

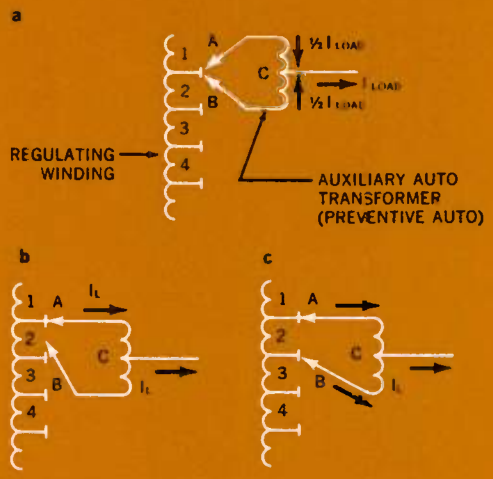

Fig. 2 Schematic diagram of load tap-changing transformer: The LTC transformer is shown before tap change (a), during tap change (b), and in the bridging position (c).

The three-phase induction regulator changes both magnitude and phase relationship of the output voltage with respect to source voltage. In general, this is of no practical consequence, but it may be a consideration in a large multi-phase installation with individual induction regulators for each rectifier.

Induction regulators, because of their motor-like construction, are seldom used at voltages higher than 15 000 volts. When supply voltage exceeds this value, the induction regulator can be used in the secondary side of a rectifier transformer. Regulators of this type are also limited to currents of 1000 amperes; therefore, when current exceeds this limit, a series transformer in the same container with the regulator can reduce current to the regulator rating. Regulators of the induction type are available in ratings up to 2500 kva of regulation in one tank.

The regulator is motor operated in most rectifier applications. A voltage change may require several seconds—for example, to go from minimum to maximum position requires 50 or 60 seconds. If fast response is required on widely swinging loads, this type of voltage adjustment may not be suitable.

Since the induction regulator depends on the relative position between rotor and stator to effect regulation, it is subject to mechanical wear and therefore requires routine maintenance and periodic inspection.

transformer tap-changing equipment

Tap-changing equipment provides a means for altering transformer output voltage over a given range in a definite number of steps. The two basic types of equipment are no-load tap changers (NLTC) and load tap changers (LTC). A no-load tap changer alters the turns ratio of a transformer and should be operated only when the transformer is de-energized. A load tap changer (in conjunction with an auxiliary center-tapped autotransformer) alters the turns ratio of a transformer without interrupting load current.

A load tap-changer is shown in Fig. 2. Load current flows from tap *1* through parallel paths *A* and *B*. To change from position *1*, contact *B* is disconnected and contact *A* assumes total load current (Fig. 2b); contact *B* is then connected to tap *2* (Fig. 2c). In this *bridging position*, the auxiliary autotransformer straddles taps *1* and *2*. The potential at *C* is halfway between taps *1* and *2* and load current divides between contacts *A* and *B*. Use of bridging positions doubles the number of positions available with a given regulating winding.

Reversing switches, shown in Fig. 3, are often used to add or subtract the regulating voltage from a fixed voltage, making it possible to double again the number of positions available from a given winding. Hence, with an eight-section regulating winding, 33 positions are possible using bridging connections and a reversing switch.

As described above, the selector contacts interrupt current during a tap change, although uninterrupted current is supplied to the load. At the higher current ratings, it is more economical to confine current interruption to *transfer switches*. A transfer switch is connected in series with each end of the autotransformer, as shown in Fig. 3. Current through the selector switch is always broken by the transfer switch before the selector switch moves to its new position. The transfer switch then closes after the selector switch is in position.

Basically, three types of LTC are used in rectifier applications—tap changers without transfer switches, tap changers with oil-insulated transfer switches, and tap changers with air-insulated transfer switches.

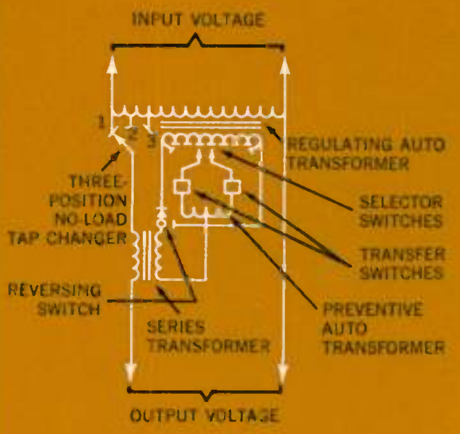

Fig. 3 Schematic diagram of regulating autotransformer equipment.

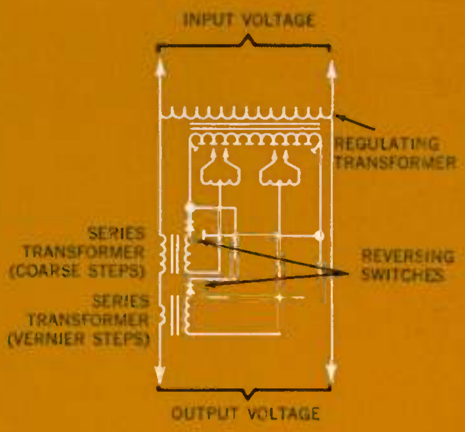

Fig. 4 Schematic diagram of regulating transformer with coarse and vernier LTC.

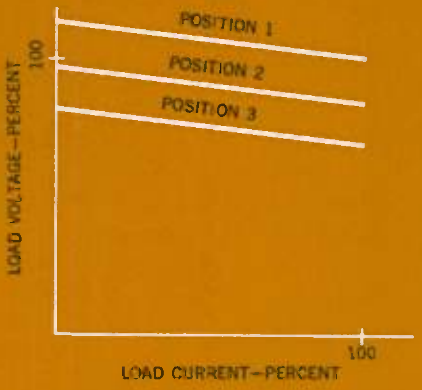

Fig. 5 The voltage characteristics shown are typical of a rectifier unit with an induction regulator or transformer tap changer.

The LTC without transfer switches is generally used below 1500 kva of regulation; oil-insulated transfer switches are most commonly used where the kva of regulation is between 1500 and 6000; air-insulated transfer switches are used with conventional oil-insulated selector switches. The advantages of the air transfer switch over the oil transfer switch are its better contact life at higher kva of regulation and its accessibility for quick inspection. The air transfer switch is recommended for electrochemical service where regulation exceeds 6000 kva.

Load-tap-changing equipment usually has 32 steps available, the magnitude of each step depending on the voltage range required. If the voltage range is large, or very smooth control is desired, the LTC may not be suitable. A voltage range of 50 to 100 percent of rated voltage requires that each step be approximately 1½ percent.

In many applications involving a larger voltage range, an LTC in conjunction with a no-load tap changer can be used to provide finer control. When a 50 to 100 percent voltage range is desired, ¾-percent steps are possible with the addition of a two-position no-load tap changer; ½-percent steps are possible with a three-position no-load tap changer. This arrangement, shown in Fig. 3, is useful when momentary interruption of load current can be tolerated and no-load tap change is not frequently required.

Extremely fine voltage control is possible with two load-tap-changing equipments, as illustrated in Fig. 4, where one provides coarse control, and the other vernier control. This scheme will cover a 50 percent voltage range in 0.05-percent steps.

LTC equipment with ratings up to 60 000 kva of regulation are available. This permits the use of master LTC equipment to control several rectifiers operating in parallel on large capacity installations. In addition to simplifying control, master LTC is more economical than using tap-changing equipment on each rectifier transformer. LTC can be applied at much higher voltages than induction regulators; voltages of 46 and 69 kv can be regulated with existing equipment. Series transformers are frequently used to transform voltage or current to within the rating of standardized tap-changing equipments.

LTC equipment, a mechanical device, requires routine maintenance and periodic inspection for trouble-free operation. Contact life is a function of the number of operations, load current during operation, voltage, insulating medium, and other parameters. Even for electrochemical applications, where the load current is nearly always held at rated value, a contact life of 2 000 000 operations can be expected with air transfer switches; up to 400 000 operations can be obtained with oil transfer switches.

variable reactors

The most common type of variable reactor is the saturable-core reactor, which has a control winding and a reactor winding on a common magnetic circuit. Reactance is altered by changing the magnitude of dc current in the control winding. Maximum reactance occurs when the control (or bias) current is at zero, and minimum reactance occurs with maximum control current. All values of reactance between the upper and lower limit are obtained by varying control winding current. Smooth control is characteristic of this device.

When used in a rectifier circuit (Fig. 6a), a full-range saturable reactor will provide approximately 100 percent voltage control. Regulation curves for this circuit with several values of control winding current are shown in Fig. 6b. The reactor may be either in the primary or secondary circuit of the rectifier transformer. Besides providing voltage control, it limits fault current because of the high reactance available.

Although the full-range saturable reactor is a completely static device requiring practically no maintenance, it is not generally acceptable because of its low power factor and high cost. Where the rectifier is small and power factor and efficiency are not important considerations, this arrangement may be satisfactory. The excellent constant-current characteristics of the full-capacity saturable reactor circuit are indicated in Fig. 6b. In applications where load resistance varies substantially and constant current is desired, this circuit may be advantageous.

voltage control with Seri-Actrol

If a narrow range of voltage control is required—for example, industrial applications requiring flat regulation, or electrochemical applications requiring a smooth vernier control in conjunction with LTC—a variable-reactor circuit called Seri-Actrol (Fig. 7a) can be applied.

In the Seri-Actrol circuit, a tertiary winding on the rectifier transformer core supplies a small portion of the power to the rectifier through a series transformer. Interposed between the tertiary winding and the series transformer is a saturable reactor designed for the same kva as the tertiary winding and the series transformer. The saturable reactor controls the amount of voltage added to the secondary voltage through the series transformer.

In applications where compensation is required to offset the inherent drooping characteristics of the rectifier unit, maximum reactance is inserted in the circuit at light loads and decreased smoothly as load current is increased. For applications of this type, ten-percent range of voltage control has been found to be adequate. Regulation curves obtained with various degrees of control current are shown in Fig. 7b. As indicated by the horizontal dashed line, 100-percent voltage can be maintained from light load to full load. Approximately ½ percent additional loss is introduced to the rectifier unit by this scheme. As illustrated in Fig. 7c, power factor is good for all values of load current. Power factor does not change greatly because as reactance is increased, load current is decreased. Consequently, the reactance factor, IX/E_S, which depends on the product of load current and total reactance, remains relatively constant.

The Seri-Actrol circuit has a light-load voltage rise characteristic; i.e., at currents less than about one percent of rated value, voltage rises sharply from the regulated level to the open-circuit or no-load voltage. On installations where load current often falls below one percent, a loading resistor can be automatically connected across the rectifier at a predetermined value of load current to prevent this voltage rise.

Seri-Actrol gives completely static control with better power factor, better efficiency and lower first cost than comparable control using full-range saturable reactors. The rectifier transformer and Seri-Actrol apparatus can be

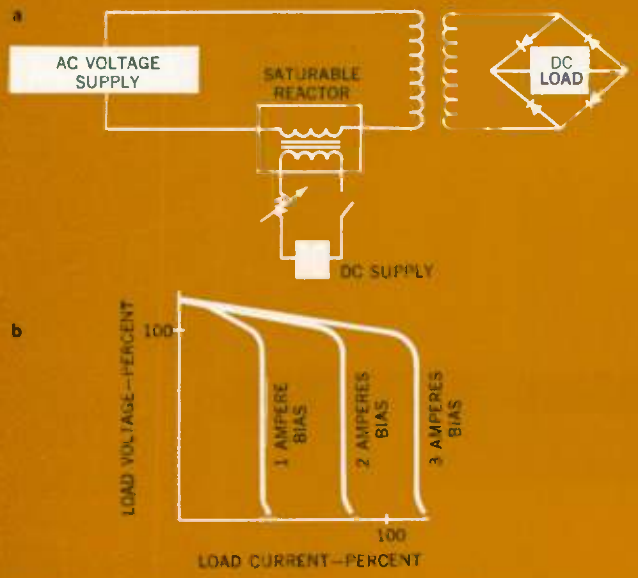

Fig. 6 (a) Schematic diagram showing control of dc circuit with saturable reactor. (b) Voltage characteristics of rectifier units with saturable reactors.

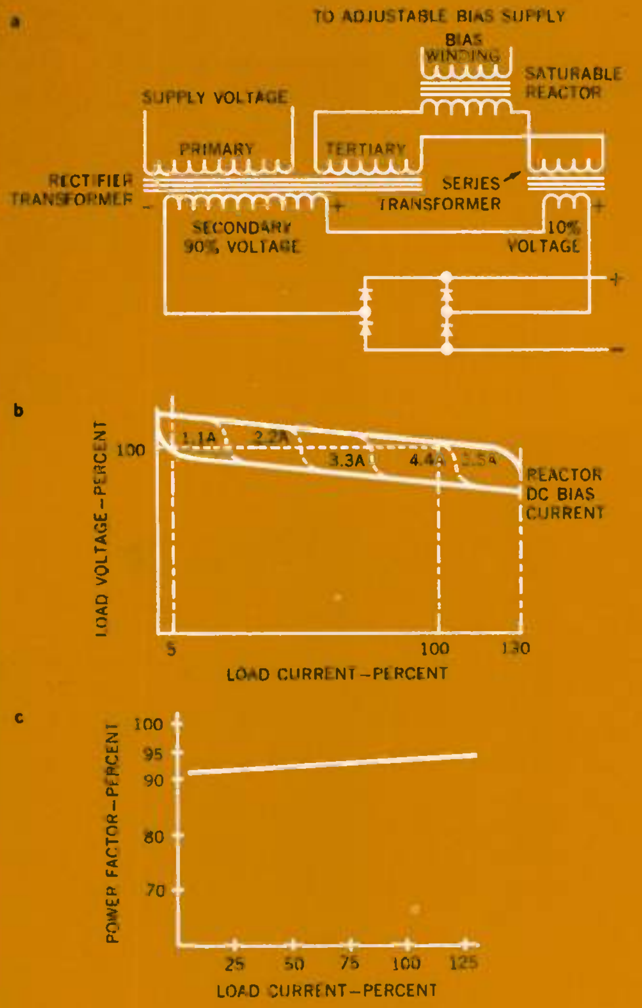

Fig. 7 (a) Schematic diagram of control of dc circuit with Seri-Actrol control. (b) Voltage characteristics of rectifier units with Seri-Actrol control. (c) Power factor of a constant voltage rectifier unit with Seri-Actrol control.

combined into one liquid-insulated or air-insulated unit.

In electrochemical applications, where output voltage is adjusted to maintain rated current, Seri-Actrol can be used to advantage within certain limitations. In this type of service, an increase in reactance results in an increase in the reactance factor and a corresponding decrease in power factor. Seri-Actrol, therefore, should be limited to a maximum range of three or four percent in electrochemical service where power factor is of prime importance. The effect on power factor, with this limited range, is comparable to that obtained with limited phase control for small adjustments on ignitron installations.

Seri-Actrol is well suited for use as an individual vernier voltage-adjusting device on rectifier transformers where several transformers are fed from a master regulating transformer. In such applications where frequent voltage adjustments are required, the static nature of Seri-Actrol makes it particularly attractive. Here, three-percent range is normally sufficient to bridge the steps on the master regulating transformer and still permit compensation for any inherent unbalance between paralleled units. Where automatic regulation of cell line current is required, the saturable-reactor control windings on all parallel units can be connected in series and controlled by one regulator, thereby simplifying the regulating scheme. To obtain proper load balancing between units, variable resistors across the reactor control windings can be adjusted to provide the control current in each reactor necessary for equal load division. These resistors need be adjusted only during initial startup.

general comparison

In considering the overall matter of voltage adjustment, the difficult problem is to select that particular scheme or apparatus that is best suited for a specific application. Both economic and performance factors must be evaluated from an integrated point of view. Some broad general comparisons provide benchmarks to guide the user:

Power Factor—Any of the voltage-control schemes discussed will lower power factor somewhat, since each introduces reactance in the rectifier circuit. Furthermore, the effect on power factor becomes more pronounced as the voltage adjustment range is increased. A comparison of power factor for several methods of voltage regulation is shown in Fig. 8.

Equipment Costs—This parameter will vary considerably depending upon local circumstances. However, a general summary of the relative costs of voltage-adjusting equipment is shown in Fig. 9. The curve ordinates show only the relative costs of voltage-adjusting apparatus—not the entire rectifier unit. The abscissa represents through put power. The adjustment ranges noted are in the dc output volts from the rectifier unit. The comparisons, shown for a 13.8-kv supply, would be similar for 5-kv equipment.

Multiunit Installations—The costs shown in Fig. 9 are for installations where the complete range of adjustment is obtained from a single voltage-adjusting assembly. Relatively large installations (of about 100 000 amperes dc) requiring several rectifier units should be considered also. Here, a master adjusting means for the entire installation can be used in conjunction with adjusting means in each individual unit. The relative costs of various schemes for

TABLE I COMPARISON OF SEVERAL TYPES OF VOLTAGE ADJUSTING APPARATUS

Parameter	Equipment Type			
	Induction Regulator	Transformer Tap-Changing Equipment	Full-Range Saturable Reactor	Seri-Actrol
Maximum Kva of Regulation	2500	60 000	5000	1000
Approximate Speed of Adjustment—Maximum to Minimum	60 seconds	60 seconds	10 seconds	3 seconds
Number of Steps	Very large	Usually 32	Infinite	Infinite
Reliability	Good	Good	Excellent	Excellent
Recommended Maximum Frequency of Operation	Hundreds/Day	Hundreds/Day	No Limit	No limit
Losses per Kva of Regulation	Very small	Very small	Appreciable	Small
Mechanical Features	Motor driven rotor (vibration)	Motor driven contacts (erosion)	No moving parts	No moving parts
Space Requirements	Large	Large	Large	Small

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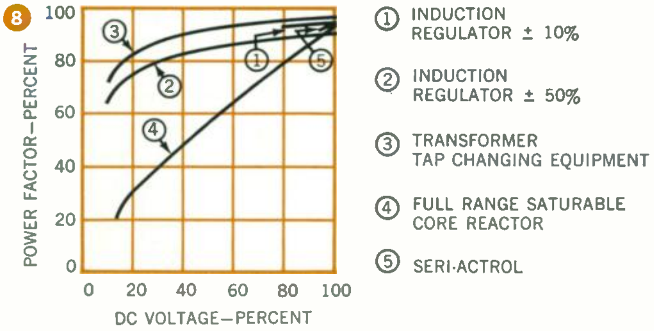

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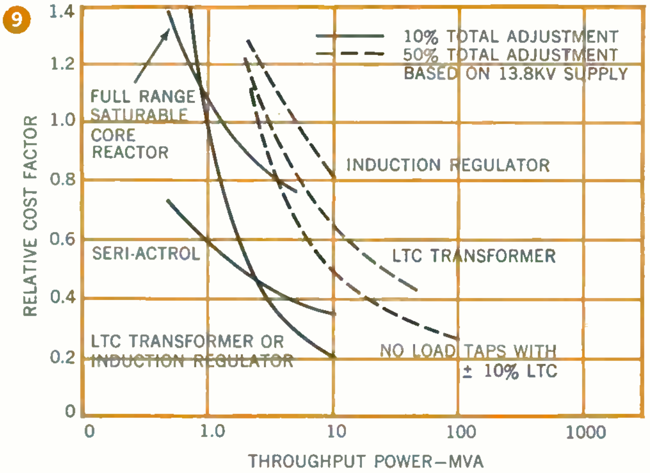

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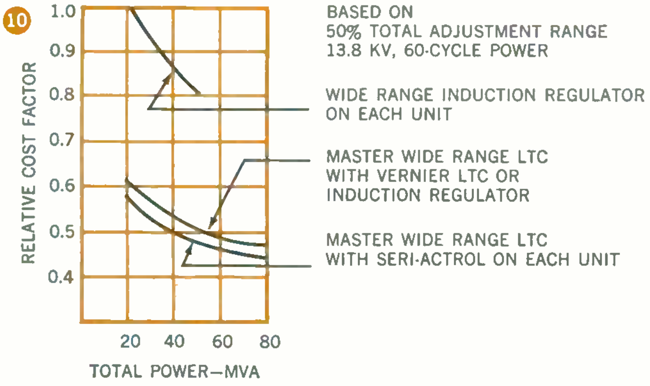

Fig. 8 Comparison of power factor of constant-current rectifier units with various methods of voltage control.

Fig. 9 Cost comparison of various methods of voltage adjustment utilizing a single adjusting apparatus.

Fig. 10 Cost comparison of various methods of voltage adjustment to give stepless control on a multiunit installation.

such installations, where a total adjustment range of 50 percent is required and apparatus is chosen to give essentially stepless adjustment, is shown in Fig. 10. The installation is assumed to consist of five rectifier units in parallel. The curves can be compared directly with those in Fig. 9, since the ordinates have the same relative value.

Additional comparisons of the various voltage-adjusting methods are listed in Table I. The speed of adjustment listed for the reactor equipment represents the time for the flux to change from one steady state level to another. Gearing backlash and mechanical inertia do not permit an infinite number of steps for the induction regulator—hence it is listed as "very large." Specific values of losses are not listed since they depend upon installation size and range of voltage adjustment. However, the losses of the induction regulator, transformer-tap-changing equipment, or Seri-Actrol schemes seldom cause more than a one-half percent loss in overall efficiency. The remarks listed under *space requirements* are meant only to portray relative sizes of the various schemes. Actually, the space needed for voltage-adjusting apparatus is usually only a minor fraction of the total space required for large installations of rectifier equipment.

conclusions

Despite the fact that only three basic types of voltage adjustment equipment are in current use, selection of the best type or combination of types for a given application often is not a simple matter. For example, a large capacity installation requiring several rectifier units to furnish the total power over a wide range of adjustment can be accomplished in at least 12 different combinations of these three basic schemes. A sound functional and economical choice must be based on a thorough understanding of the advantages, limitations, and relative costs of the voltage-adjusting apparatus and on realistic knowledge of the requirements of the application.

INNER COOLED POWER TRANSFORMERS This new design concept has led to smaller and lighter power transformers, and holds promise for further improvement.

HAROLD R. MOORE, Advisory Engineer
Power Transformer Department
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Muncie, Indiana

Several years ago, because of the continuing trend to higher voltages and larger kva capacities in power transformers, engineers began a search for better designs to cope with future needs. Since the insulation space is a large percentage of the total volume of the core and coil structure in a high-voltage transformer, the insulation structure was a logical area for further development. Out of this has come a new design concept for power transformers—an *inner cooled* insulation structure—which provides better insulation in a smaller space than the conventional structure.

Basically, power transformer insulation has been made of oil-impregnated pressboard sheets and oil spaces in series for over fifty years. A section of a shell-form transformer winding using this type insulation is shown in Fig. 1. Note that large oil spaces exist adjacent to the coil edges and surfaces because cooling ducts are provided on each side of each coil for efficient cooling. High voltages exist at coil edges and other points when a winding is subjected to impulse voltages or low-frequency overvoltages. The strength of the structure is determined by the strength of the oil spaces because the oil has lower dielectric strength than the oil-impregnated pressboard. Also, the division of voltage across an insulation space is inversely proportional to the dielectric constant of each material. Since the dielectric constant of oil is about one half that of oil-impregnated pressboard, the voltage across the oil space will be greater than the voltage across the pressboard space if the two spaces are equal.

The shell-form transformer has inherent advantages such as good impulse voltage distribution and thermal characteristics, and is the basic configuration for the new design.

The conventional shell-form design with oil and pressboard in series has been highly successful and is quite simple and effective, but it does not make maximum use of the high-strength pressboard insulation in the higher voltage designs. A more efficient design is obtained when the oil spaces are removed from the areas of high-voltage stress and the spaces filled with the high-strength pressboard.

inner cooled design concept

The inner cooled design is based on the elimination of all large oil spaces around coil edges and other areas of high voltage stress, and the substitution of oil-impregnated pressboard in these areas. However, some means must be provided for removing heat losses generated in the coils if pressboard is used between coils and around coil edges.

Each turn in a large power transformer consists of multiple conductors in parallel, and the approach used is to wind each coil in two sections so that an internal oil cooling duct

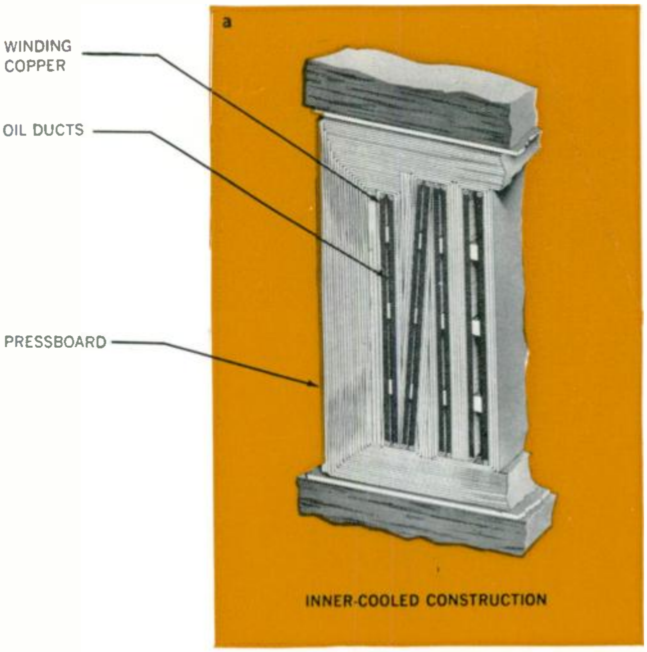
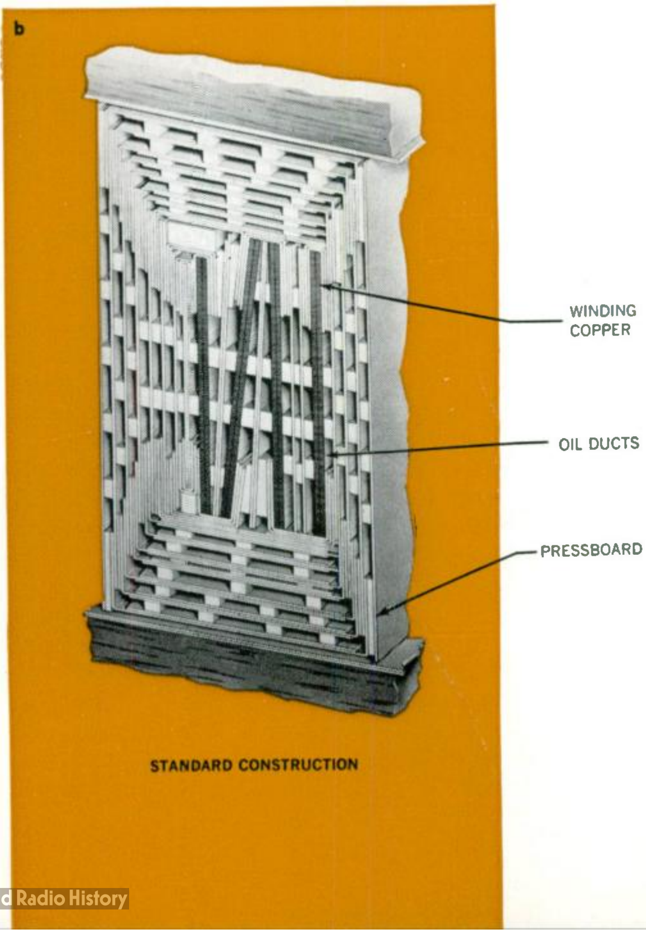


Fig. 1 (a) A cross section of an inner cooled coil; (b) a section of a standard shell form winding.



is provided between sections of each coil. Cross sections of a conventional coil and an inner cooled coil are shown in Fig. 2. The two sections of the inner cooled coil are effectively connected in parallel so that the voltage across the oil duct between sections is low even when an impulse voltage is applied to the winding. Therefore, the lower strength oil for cooling the losses generated in the copper windings is between the two sections of each coil where the stress is low. The term inner cooled comes from the fact that the coils are cooled by the internal duct in each coil.

A section of a shell-form transformer winding using the new inner cooled construction appears in Fig. 2. Since a path has been provided for the cooling oil, the high strength pressboard can be used in spaces of high stress. The puncture strength of pressboard is considerably higher than its creep strength. Around the coil edges where the stress is maximum, the insulation is used in direct puncture where it attains its maximum strength. By taking advantage of the high dielectric strength of the pressboard, the space required for insulation can be reduced, with the same or higher dielectric strength; thus a more efficient insulation structure is obtained.

Since a major development was being undertaken, an improved cooling system, improved electrode shapes, and reduction of circulating current losses were included in the design program.

The insulation must fit tight around coil edges and other points of high stress so that large oil voids are eliminated. Specially designed and manufactured pressboard pieces are used around all points of high stress so that oil voids are kept to a tolerable film thickness. There are some variations in the manufacture of large coils and insulation pieces, and special tapered joints are used where one insulation item joins another to allow for some small amount of variation and still limit the oil voids. Since coil edges are not continuous and connections have to be made between coils, special compounds have been developed with approximately the same characteristics as pressboard so that voids at points of discontinuity can be filled. Therefore, the spaces around the coils are filled with essentially void-free insulation.

test schedule

In addition to an extensive theoretical investigation of the new design, practical considerations required tests to determine the optimum structure, since the new design was to have improved electrical, thermal, and mechanical characteristics. Approximately 100 full-sized coil and insulation structures were given impulse, low frequency, and corona tests to determine the most practical coil and insulation design, as well as to obtain design data.

Data from these tests was then used to build two full-sized single phase experimental transformers; extensive tests were made with these units before the first commercial inner cooled transformer was built in 1958.

dielectric heating

When a voltage is applied across a solid insulation material, heat is generated within the material, since there is no such thing as a perfect insulator. Dielectric insulators are, in general, good thermal insulators and it is difficult to remove the heat within a large mass of insulation. When the voltage and the thickness of the solid material exceed a critical limit, the heat generated exceeds the heat that can be removed and the temperature of the material increases. As the temperature of the material increases, the amount of heat generated also increases, which causes further increases in temperature. The process may become accumulative and the space will become conducting and the structure will fail as an insulator.

The amount of "solid insulation" should be limited to eliminate this dielectric heating. The stress is highest at the coil edges and becomes uniform at some distance away from the edges. Where the stress becomes uniform, small controlled oil spaces can be applied in the structure to break up the solid insulation. Thin oil films have high strengths in terms of volts per mil, and these small oil spaces are carefully controlled so that they will not ionize even when an impulse voltage is applied to the winding. These oil spaces also aid in the removal of moisture from the insulation. Therefore, the inner cooled structure is designed to take full advantage of void-free insulation in areas of high stress and at the same time eliminate the problems resulting from dielectric heating.

limitation of corona

The effectiveness of the insulation structure is also improved in the inner cooled design by using improved electrode shapes. All coil edges have special shields that increase their effective radius, which improves corona and ionization characteristics. Static shields used to distribute impulse voltage across the coils have special round edges to prevent corona from starting. Other sharp points such as the edges of the core and supporting members are also shielded to prevent corona when the transformer is subjected to the various types of overvoltages.

Extensive corona tests were made in the early stages of this development to aid in the development of more effective corona shields to prevent damaging corona in any part of the inner cooled structure.

improved cooling efficiency

Since the inner cooled coils are made in two sections with a cooling duct between sections, two sides of each coil are exposed to oil flow so that no new cooling problems are encountered. As shown by Fig. 1, all of the insulation items are applied on the outside of the coils so that there are no channels or other items to blanket coil edges, thereby reducing hot spot temperatures. To further improve the cooling efficiency, all spaces except the cooling ducts between sections and the cooling spaces around the core are blocked so that the oil is forced to flow past the coil surfaces and the core. These improvements in conjunction with the large surface, vertically mounted shell-form coils results in a cooling system with superior thermal characteristics on both self- and forced-oil-cooled ratings.

reduction of copper losses

The double section inner cooled coils are transposed and connected to reduce circulating currents resulting from leakage flux. Losses caused by circulating currents may be an appreciable percentage of the total load loss in large power transformers if the proper transpositions are not used. Consider the coil section represented by Fig. 2. Three conductors are connected in parallel in each layer, and all conductors are not perfectly transposed. Thus voltages will be induced between conductors by the leakage flux, which will cause circulating currents to flow.

Now consider the double section inner cooled coil represented by Fig. 2b. Two conductors are used in each layer of each coil section, and the coils are perfectly transposed by a transposition at the magnetic center of the coil, if it is assumed that all of the flux is perpendicular to the width of the coil. Since the area of the turn in both coils is approximately equal, four narrow conductors are used in the inner cooled coil rather than three wider conductors in the conventional coil. The eddy current loss in a conductor is represented by:

$$W_e = K\,B^2\,W^2$$

W_e = Eddy current loss.
B = Leakage flux density.
W = Width of the conductor.

Since the width of each conductor is less in the inner cooled coil, the eddy current loss will be less by the ratio $(W_{ic}/W_c)^2$. If each conductor in the inner cooled coil is $\frac{3}{4}$ the width of the conductor in the conventional coil, the eddy loss will be reduced to $(\frac{3}{4})^2$ or about 56 percent.

This, of course, assumes no circulating current between the sections of each coil, since a voltage will be induced between the coil sections if the start and finish leads are connected together as shown in Fig. 3 and if a transposition is not made between the sections. The circulating current that would flow in the loop formed by the two sections of each coil is eliminated by separating the start and finish connections of each coil, so that current has to circulate around the loop formed by the entire winding rather than in each coil. The leakage voltage between the sections of each coil is calculated, and the various connections are made so that the net voltage around the loop to circulate current is essentially zero. This low net induced voltage in conjunction with the high series resistance of the entire loop effectively isolates each coil section as far as circulating currents are concerned. Note that the coil sections are still effectively in parallel for dielectric considerations.

Therefore, the eddy and circulating current losses are reduced by a large percentage by isolating the coil sections from each other, improving the transposition in each section, and using the inherent narrow conductors of the inner cooled coil.

All inner cooled coils are designed in this manner, and these basic ideas have now been applied to coils in conventional windings so that advantage can be taken of this loss reduction.

The reduction in insulation space also reduces the mean length of the turns, which inherently reduces the resistance of the winding and the I²R loss. The inner cooled design has higher efficiency since the reduced copper weight and stray losses results in lower load losses.

reduction of impedance

As the trend to higher voltages and larger capacities continues, the impedance of the transformer should be reduced so that voltage regulation can be kept to a reasonable value. The inner cooled design inherently has lower leakage reactance between windings due to the reduced spaces between windings. Therefore, the impedance of the

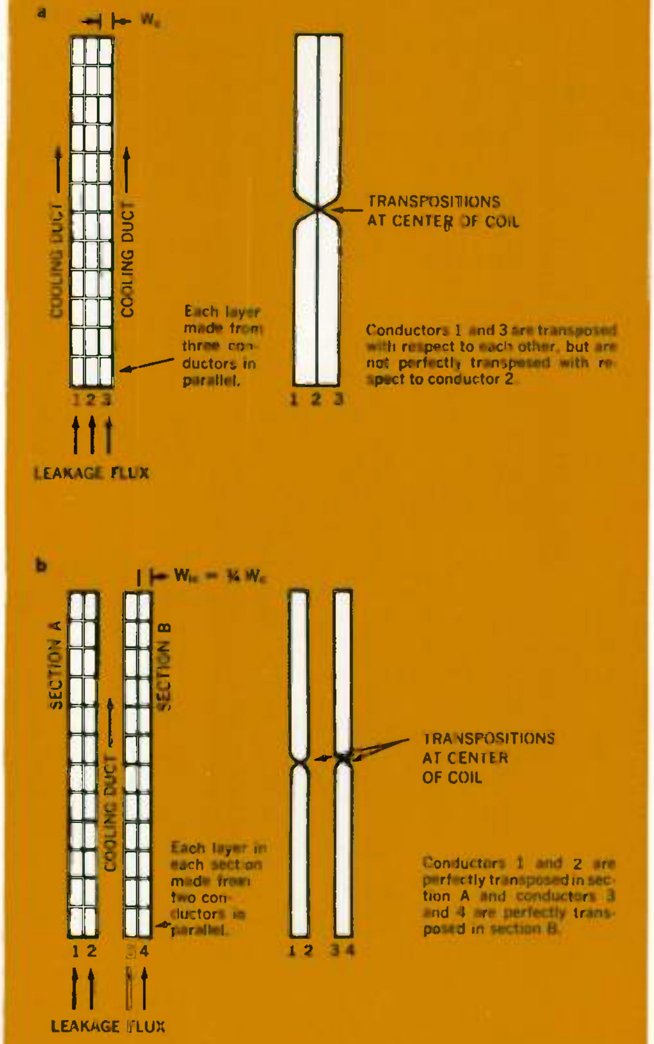


Fig. 2 (a) A cross section of a conventional shell-form coil with three conductors per layer; (b) a similar view of a double section inner cooled coil with two conductors per layer in each section.

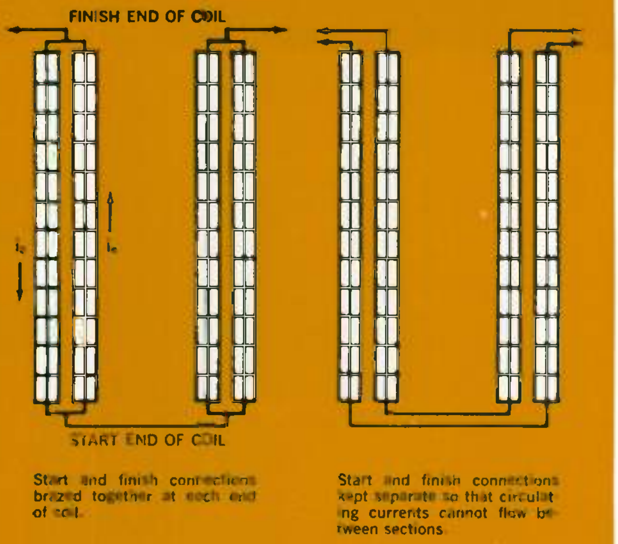


Fig. 3 By proper design, circulating currents between sections of inner cooled coils can be eliminated, as shown at right.

Table 1 COMPARISON OF STANDARD AND INNER COOLED TRANSFORMERS

	Standard Design	*Inner Cooled Design*	*Percent Reduction*
Core, Coil and Insulation Weight—Pounds	153 000	133 000	13.1
Tank, Bushings, Coolers, Auxiliaries Weight—Pounds	68 200	60 200	11.7
Oil Weight—Pounds	76 000	46 500	38.9
Total Weight—Pounds	297 200	239 700	19.4
Tested Load Loss—Watts*	375 215 Watts	322 817 Watts	14.0

*The no load loss is not shown because improvements made in core steel would distort the comparison.

transformer can be reduced without distorting the design and increasing the cost.

recent inner cooled developments

Improvements in the basic inner cooled design are still under way although commercial units have been built and shipped since 1958. New design principles are now in use which reduce the stresses at various points in the structure. Improvements have been made in the static shields so that the stresses are reduced at the edges of the electrodes which improves the overall strength of the structure. Developments in manufacturing techniques have made it possible to obtain better fitting insulation where the stresses are highest. These developments have made it possible to reduce insulation clearances, thereby further improving the efficiency of the transformer.

A full-sized experimental single-phase transformer complete with core, lead structure, bushings, cooling system, etc., was built early in 1961, using all of the latest improvements in the inner cooled design. The major insulation clearances were reduced approximately 10 percent as compared to an identical inner cooled phase built previously. The high voltage winding was rated at 1175 BIL, and impulse tests were made at 1175 BIL and above until the structure was proved adequate. Full wave, chopped wave, and front of wave impulse tests were made as well as low frequency and corona tests.

Through this extensive testing program, it was found that more than ample margin of safety existed in this design to allow for manufacturing variations and overvoltages above the test ratings that might occur in service. Therefore, another significant step has been made in the development of extra high voltage insulation structures.

comparison of standard and inner cooled designs

By coordinating the electrical, thermal, and mechanical considerations in the new design, a transformer with superior characteristics that is considerably smaller and lighter than the conventional design is obtained. These size and weight reductions are important in three important areas.

First, inner cooled construction makes it possible to build large power transformers at higher voltages than has been possible up to the present time. This development is a large factor in making extra high voltage transmission economically feasible. The 750 000-volt transformer for the Apple Grove project has inner cooled construction.

Second, inner cooled construction makes it possible to build larger capacity units for use at existing transmission voltages. Up to 35 percent more kva can be built in a given tank size with inner cooled construction in the voltage classes where it is applicable.

Third, the shipment problems encountered with small and medium size units in some locations are minimized with inner cooled designs due to the reduction in shipping weight and dimensions.

The large reductions that result from the inner cooled design are shown in Table 1. The transformers used for the comparison are two units with identical characteristics and ratings. The standard unit was built in 1958 and the inner cooled unit was built in 1960.

Since inner cooled construction was developed for higher voltage ratings where insulation spaces are large, it is applied in windings 650 BIL and above. Many improvements also have been made in the conventional design as a result of the inner cooled project.

future possibilities with inner cooling

This design depends on the tight-fitting, high-strength, insulation around coils, and the most obvious area for improvement is new and improved ways to apply the insulation around the coils. At present, oil-impregnated cellulose is the most practical material from both electrical and economical viewpoints for large transformer insulation. However, the development of new higher strength materials will permit the application of insulation directly on and around the coils to improve the strength of the structure. Many improvements are still possible in the field of static shielding, which will reduce the stress in the insulation making further savings in space possible.

Since the cooling medium flows in paths where the voltage stress is low, it may be possible to develop new cooling fluids that improve the thermal characteristics. Although eddy and circulating current losses have been reduced, work is underway to further reduce these losses.

conclusions

By using the two basic and proven materials—oil for cooling and oil-impregnated pressboard for insulation—in the most efficient manner, an insulation structure with equal or improved dielectric strength is obtained within smaller dimensions than has been possible in the past. Coordination of the electrical, thermal, and mechanical design in the new structure results in a transformer with lower weights and smaller dimensions and at the same time makes possible better cooling, lower losses, lower reactance, and improved corona and ionization characteristics.

WHAT'S NEW IN ENGINEERING

THIS EXPERIMENTAL MOLECULAR-ELECTRONIC FUNCTIONAL BLOCK, made from a solid slice of silicon, performs multiplication and division by adding and subtracting logarithms, the same process used in the familiar mechanical slide rule. An electric current fed into it produces a voltage across a junction that is proportional to the logarithm of the current. An input of two currents into two junctions can be made to produce a voltage that is their logarithmic sum. The antilogarithm, measured at the output of the functional block, is the product of the input currents. Division is the reverse process—currents are introduced in such a way that their logarithms subtract. The device has an input range of 10 to 1 and an output range of 100 to 1 when used for multiplication and division, and its accuracy is within 5 percent. The multiplying and dividing function performed by the functional block is equivalent to that done by an array of four separate diodes, or three diodes and a transistor.

Sun-Powered Electric Plant For Underdeveloped Areas

Underdeveloped areas that lack central-station electric power can meet some of their basic needs with a small self-contained thermoelectric power plant and pumping unit operated by the sun's heat. The system could irrigate land for villages or families and supply their household water.

The water pumping application was selected because it is one of the most critical in terms of human welfare and one of the most feasible scientifically. A water pump does not have to operate every day, so there is no need to provide electrical storage equipment for cloudy days. Also, some of the water pumped is used to cool the thermoelectric elements, increasing the generator's efficiency and lowering its size and cost.

The system was developed in cooperation with the Solar Energy Laboratory of the University of Wisconsin. A 50-watt prototype has been built and tested, and a full-scale unit with a power output of up to 200 watts is being developed. Larger units could be developed for village industries.

The 200-watt unit could pump enough water from a depth of 20 feet to irrigate about four acres of land at the rate of 24 inches a year. Or, from the same depth, it could supply the personal needs of 1200 people at five gallons of water per person per day. The system would have to operate 10 hours a day for only 250 days a year to supply this amount of water, which leaves a safe enough cloudy-day margin in the parts of the world where it is most likely to be needed.

An eight-foot parabolic mirror focuses sunlight on the thermoelectric generator (see photograph on back cover). The generator contains 72 thermoelectric couples connected in series. It can operate with a hot-side temperature as high as 1100 degrees F, but, to extend generator life and reduce the initial cost of the system, a temperature of 840 degrees F was selected. The cool side operates at 150 degrees F. The power thus generated energizes an electric motor that has a water pump connected directly to it.

Present estimates place the cost of thermoelectric power well above that of power generated by large central power stations in the United States. Development of improved thermoelectric materials and mass-production techniques should reduce the cost, but cost is not the only consideration.

One important factor is that in many parts of the world central generation and distribution cannot be technically or economically justified, but even a little electric power would relieve people of such burdens as hand irrigation and free them for more productive activity. Also, the simple static system requires little skill to install and operate, so power generation would not be bottlenecked in underdeveloped areas by a shortage of technically trained personnel. ■ ■ ■

Versatile Oceanographic Ships

With the growing awareness of the sea as one of the few unexplored domains remaining in inner space, the long-neglected science of oceanography is coming into its own. Three new ships being built for the U. S. Navy are specifically designed for the unique requirements of oceanographic research. Their Westinghouse-supplied propulsion drives and other electrical equipment provide great maneuverability, flexible control, and quiet operation when required.

The ships, designated AGOR-3, -4, and -5, are the first in a new series of Navy research vessels. They are fitted for such tasks as charting ocean currents and temperatures, mapping the ocean bottom, collecting marine life, taking floor samples, and analyzing water samples.

Two main propulsion diesel engines power two dc generators, and these supply a double-armature 1000-hp motor to drive the single screw. A control system regulates the propulsion motor output by varying generator voltage and engine speed. Complete control can be applied from the pilot house or bridge wing.

A separate propulsion unit in the bow provides thrust in any direction for maneuvering. Its propeller is housed in the hull when not in use and is lowered beneath the hull when it is to be used. Rotating the unit changes the thrust direction, and varying the propeller speed controls thrust magnitude. Power for the 175-horsepower motor is supplied by a gas turbine-generator. This dc generator can also be used to energize the main propulsion motor at reduced power when quiet propulsion is desired.

Three 200-kw ac diesel generators supply ship's service power. These can be shut down for quiet-ship operation; an ac generator driven by the bow-propulsion gas turbine then provides power for minimum needs.

Two ac-dc 20-kw m-g sets round out the electrical equipment. Operating as ac motors driving dc generators, these units charge batteries. Operating as dc motors driving ac generators, they take power from the batteries to produce ac power for shipboard uses. AGOR-3 is being built by Gibbs Corporation, Jacksonville, Florida, and AGOR-4 and -5 by Christy Corporation, Sturgeon Bay, Wisconsin. ■ ■ ■

Computer Provides Flexible Automatic Elevator Control

Automatic elevator control systems have been developed to the point where little additional improvement can be made within the framework of conventional systems. Consequently, an entirely new concept has been applied to make service significantly faster and more efficient.

In conventional automatic elevator systems, groups of cars are operated by controls that use the experience of the immediate past to predict elevator demand for the immediate future. This prediction is used to place the system in the most suitable of several operating patterns until changing experience causes the system to change to another operating pattern. The number of operating patterns is limited, and some time elapses between development of a new traffic pattern and the system's response to it. Cars are dispatched only from the top and bottom terminals and at predetermined intervals. The cars do no useful work during these intervals, they make useless trips to terminals when there is no traffic demand, and they run more than is necessary when traffic is light.

The new Selectomatic Mark IV control system teams a memory device with a computer. The memory device records every traffic demand, the length of time the demand has been registered, and the load of each car. The computer assimilates this information and dispatches cars to answer calls from any location according to the demand at that moment. The system is not committed to operate in a specified pattern for a specified time, so it can decide whether each car should run or remain stationary, answer up or down calls, or travel up or down. It also determines which calls should be answered first to minimize waiting time. Consequently, the control system takes any number of traffic conditions in stride and responds to changes instantly.

The control system can reverse a car at any floor if there is no demand beyond that floor, so cars do not have to make the full trip between terminals. Cars can travel up to answer a down call and down to answer an up call.

The Mark IV system is especially well suited for large buildings with heavy and erratic traffic conditions, such as office buildings, department stores, hotels, hospitals, and large apartment buildings. In a test comparison with a conventional control system under identical conditions, the Mark IV system reduced average waiting time by 30.6 percent. It reduced long waits (more than 50 seconds) by 78 percent. ■ ■ ■

TE Generator Protects Gas Well

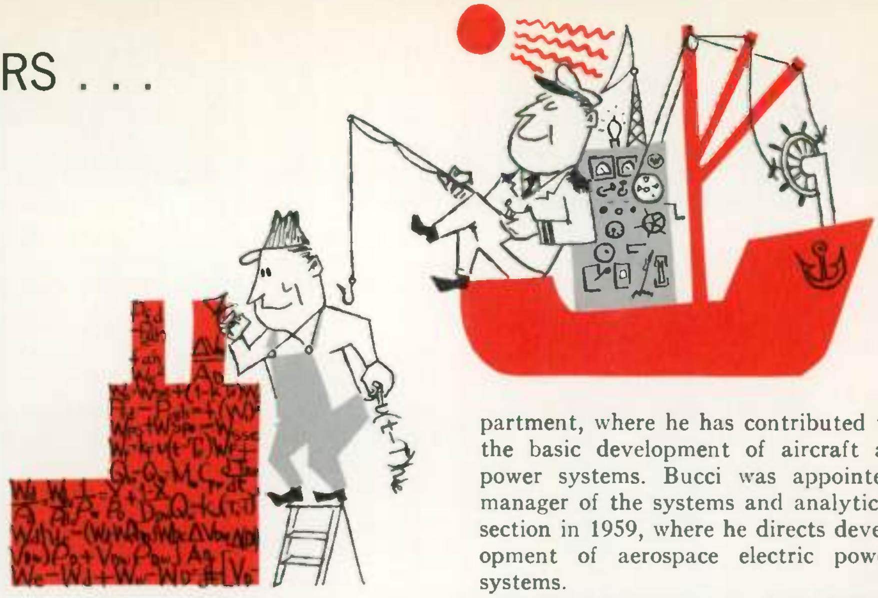
A thermoelectric generator supplies electric current for cathodic protection of a gas well's casing in a remote region of New Mexico. A small amount of the gas coming from the well is burned to heat the thermoelectric generator, which converts the heat directly into electricity to safeguard the well.

The unit is connected between the 5000-foot well casing and a ground bed consisting of silicon-iron anodes packed vertically in a hole 200 feet deep. The potential reverses the flow of current that would normally be set up by the casing as it reacted chemically with the soil. Thus, the easily replaced ground bed is slowly eaten away instead of the casing.

Protection is accomplished with about six amperes at eight volts dc. This power is generated at 800 degrees F on the hot side of the generator; the cool side operates at 200 degrees F.

The installation is a cooperative project with El Paso Natural Gas Company, El Paso, Texas. Its purpose is to evaluate this new method of power generation for gas-well and pipeline protection in isolated regions that do not have conventional electric power service. The simple, static thermoelectric generator is well suited for unattended operation in such areas.

ABOUT THE AUTHORS . . .



R. E. STILLWAGON brings a varied background of experience in transportation system design to his discussion of ship automation in this issue. He joined Westinghouse in 1946 on the Graduate Student Course after graduating from Worcester Polytechnic Institute with a BSEE degree. He served first as a diesel-electric design engineer in the Transportation Engineering Department, developing locomotive control systems, railway control devices, and crane drive systems. Later, he helped set up computer operations in the data-processing department at East Pittsburgh. Stillwagon was assigned to the Marine, Transportation, and Aviation Facilities Engineering Department in 1956. He developed computer techniques for solving application problems and is now in charge of advanced development.

S. J. CAMPBELL and V. S. BUXTON are in their element in this issue, for both are especially interested in the pulp and paper industry.

Campbell is engineer in charge of pulp and paper systems in the general mill section, Industrial Engineering Department. As he puts it, this makes him responsible for the engineering aspects of everything that is moved or rotated by Westinghouse in the pulp and paper industry. Some assignments have been record breakers, as the application of the world's largest supercalender drives.

Campbell earned his BSEE at the University of Wisconsin in 1950 and his MSEE at the University of Pittsburgh in 1954. He joined Westinghouse in 1950.

Buxton graduated from the University of Southwestern Louisiana in 1957 with a BSME degree. He joined Westinghouse on the Graduate Student Course and then was assigned to a consulting and application training program. He joined the general mill section, Industrial Engineering Department, in 1959.

For the past two years, engineers from the Philadelphia Electric Company and Westinghouse have been studying steam plant automation. Appropriately, the article describing the results of these studies is a joint effort by J. L. EVERETT and J. K. DILLARD.

J. L. Everett was first intimately associated with power plant controls and their operation while a member of the Mechanical Engineering Division of the Philadelphia Electric Company. Later, he was concerned with the operation and adjustment of control systems. While he was Engineer in Charge of Mechanical Research, his group undertook a project of measuring the dynamic response of some of the components of power plant control systems.

Mr. Everett graduated from Penn State University in the School of Mechanical Engineering in 1948, and received an MS degree in 1949. In 1950 he joined the Engineering Department of Philadelphia Electric Company. When Philadelphia Electric joined the atomic power study team in Detroit, Michigan, in 1952, Mr. Everett was assigned to the group. He returned to Philadelphia Electric in 1955, and was assigned to the Station Operating Department. In 1956 he was appointed Engineer in Charge of Mechanical Research. From June 1958 to June 1959 he attended the Industrial Management School of MIT on a Sloan Fellowship. After returning to Philadelphia Electric Company, he was named Staff Engineer of the Research and Development Department. In October 1960 he was appointed Director of Research of Philadelphia Electric.

Dillard, manager of the Electric Utility Engineering Department, is a regular contributor to these pages. Dillard is an EE graduate of Georgia Tech, and has an MS degree from MIT. He joined Westinghouse in 1950, after three years on the staff of the Department of Electrical Engineering at MIT.

N. W. BUCCI is an oldtimer, relatively speaking, in the new field of electric power systems for high-performance aircraft and space vehicles. After earning his BSEE degree from Drexel Institute of Technology in 1950 he served for three years as an aircraft electric power systems engineer at the U. S. Naval Air Development Center, Johnsville, Pennsylvania. He then joined the Westinghouse Aerospace Electrical Department, where he has contributed to the basic development of aircraft ac power systems. Bucci was appointed manager of the systems and analytical section in 1959, where he directs development of aerospace electric power systems.

R. W. BRIGGS received his BSEE from Ohio Northern University in 1957. He joined the Aircraft Equipment Department in 1957 to work on computer analyses of electric power systems. He is now a systems engineer, designing and developing static and rotary electric power systems for space applications.

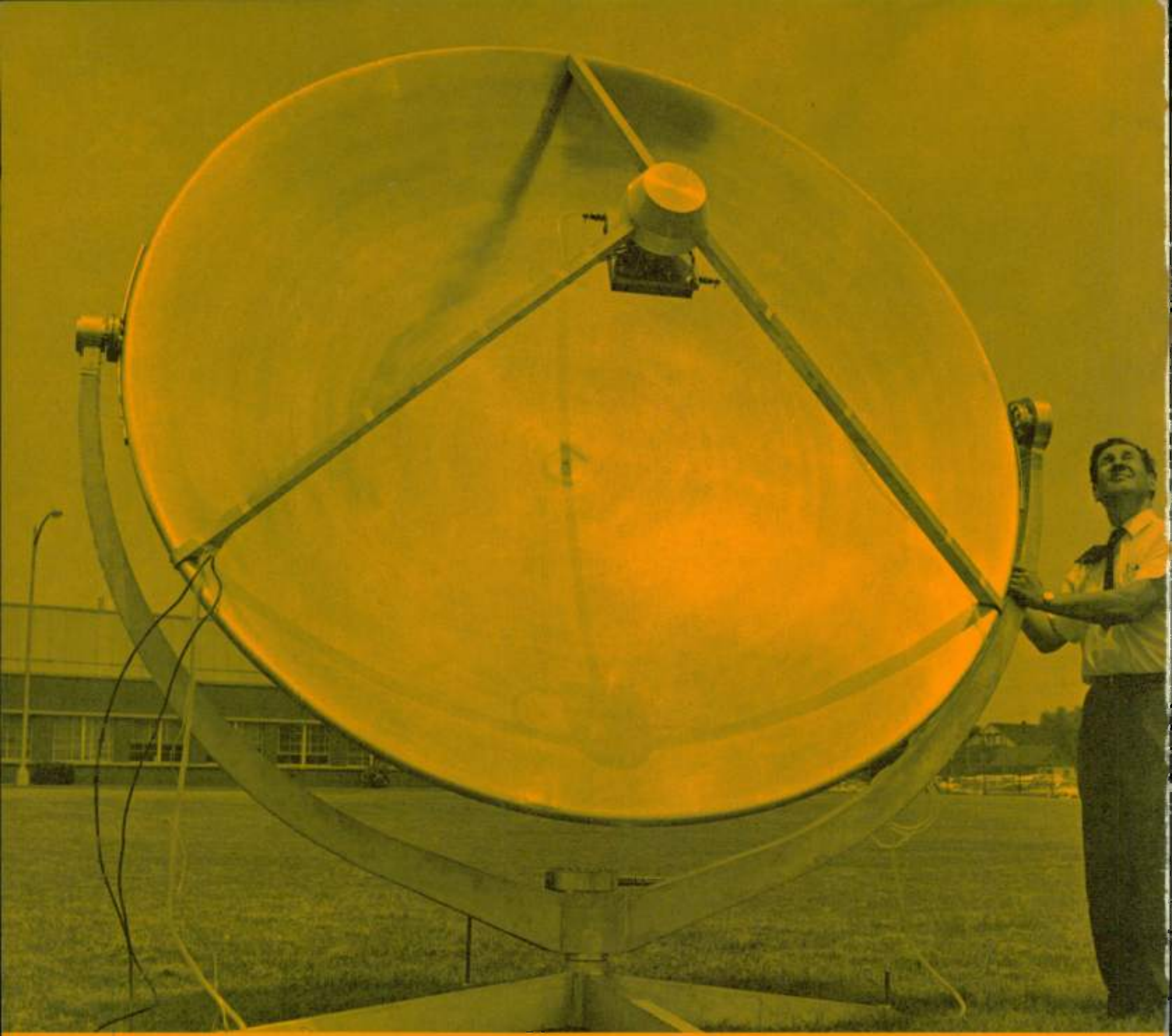
C. S. HAGUE is back on the ENGINEER pages for a return engagement on his favorite subject, silicon rectifiers (previous showing, November 1959). He is joined by K. F. FRIEDRICH.

Kevin Friedrich graduated from Carnegie Tech in 1954 and came directly on the Graduate Student Course. After attending the Westinghouse design school, Friedrich went to the Transformer Division to become a design engineer in the power transformer department. In 1961, Friedrich moved to the distribution department.

C. S. Hague is manager of the power conversion section of the Rectifier and Traction Equipment Department. Before joining the power conversion section in 1952, Hague served in the industry engineering and sales departments.

HAROLD R. MOORE began work on inner cooling for transformers when the project was first initiated, and stayed with it through the entire development stage and into production.

Moore began his career at Westinghouse shortly after earning his BS degree in electrical engineering at Mississippi State University in 1951 (he later earned an MS from the University of Pittsburgh in 1957). Early in 1952 he moved to the Transformer Division at Sharon, Pennsylvania, where he worked on several assignments before transferring to the development group in 1954. Here Moore was concerned with high-voltage insulation and eddy current losses.



SOLAR-ELECTRIC POWER PLANT

This solar-powered thermoelectric power generator under development at the Westinghouse new products laboratories is proposed as a power source for pumping water in underdeveloped areas. Such a system could irrigate farm land and supply water for household needs in the many places where there are no central generation systems. The unit can do the job more efficiently than the muscle-powered systems now in use, freeing people for more productive work. (See story on p. 195.)