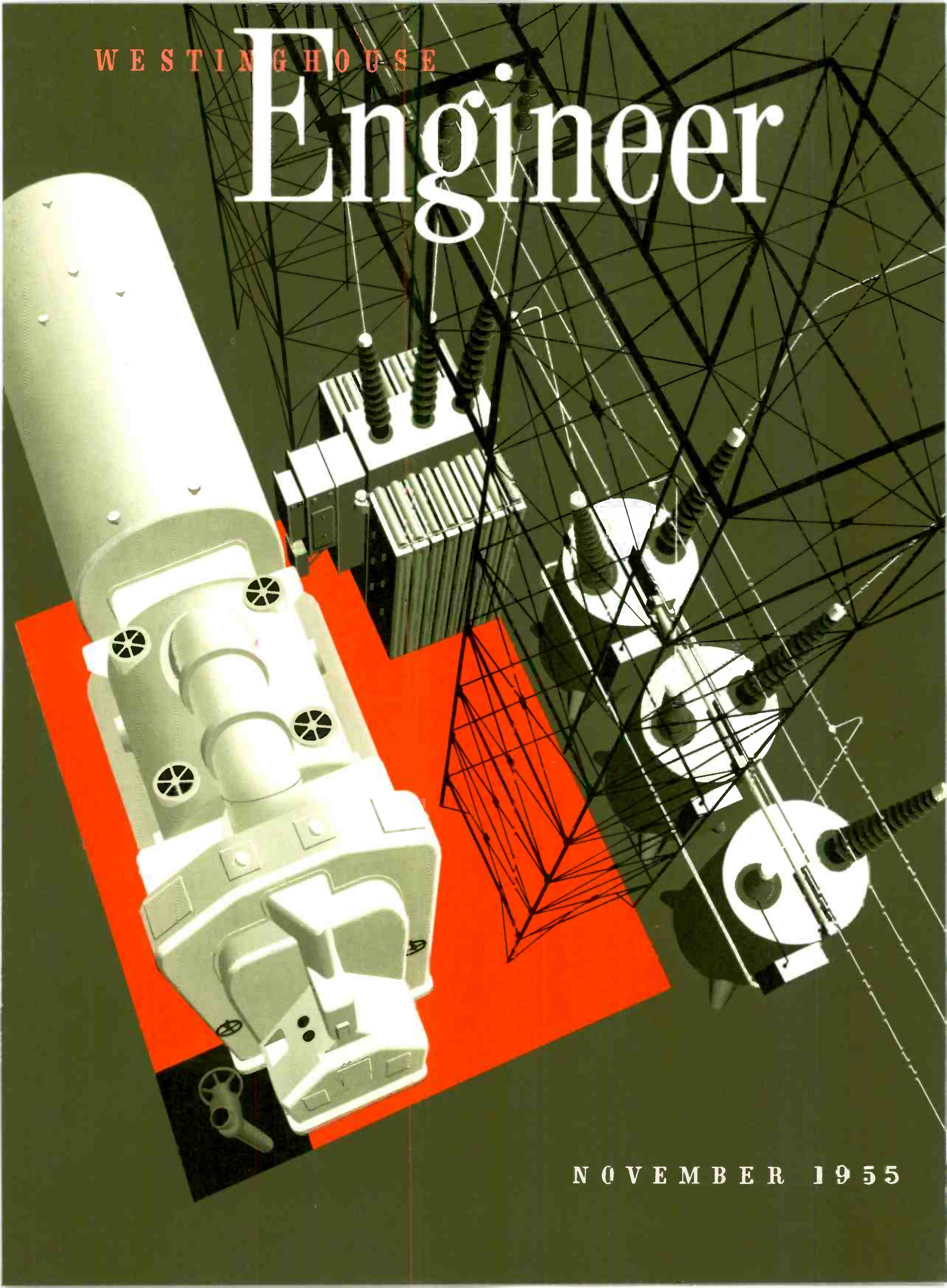
WESTINGHOUSE Engineer



NOVEMBER 1955

TODAY AND TOMORROW are critical days. For what is accomplished then by scientists in all fields may well set the stage for the world of the future. The amount of creative effort put forth and the new knowledge uncovered will be key factors in producing that world, whatever it may be.

But new knowledge alone will not produce the miracles foreseen for the future. That knowledge must be applied—and it must be applied with originality, ingenuity, and skill comparable to the creative effort that produced it. In short, *creative engineering* must put the knowledge to practical use.

• • • Consider, for example, the ever-rising energy consumption in this country, which is closely tied to expanding technology. Projected demands indicate that the total installed generating capacity in 1965 will be 215 million kilowatts, or double today's figure. Energy consumption will be about 850 billion kilowatt-hours, or about twice last year's figure. In 1975 the installed capacity will probably be over 400 million kilowatts. Beyond that, anyone's guess is good. By the year 2000 installed capacity could well be 10 to 15 times that of today. To the engineer these figures mean some new concepts are needed. Problems in areas now familiar will become vastly more complex; but more important, the number of areas requiring creative engineering attention will increase. Simple extrapolation of today's practices won't always work. There will be new problems in generation, transmission, and distribution of power, and of system integration.

CREATIVE ENGINEERING

. . . A Key to the Future

• • • But the problem is by no means confined to one segment of industry. The increasing trend toward automation, for example, brings with it the absolute necessity for creative engineering. For automation is not merely a matter of connecting an automatic control to a group of machines and expecting the system to perform efficiently, and economically. Each task to which automation is applied must be individually considered in all its many technical aspects. New circuit elements, and new circuits will be needed in abundance. New concepts will be even more important. The opportunity—the necessity—for creative engineering in this one field alone are almost limitless.

The growing complexity of machines, devices, and systems, in itself, offers tremendous possibilities for creative engineering. The need for creating simplicity from complexity is already great, and will grow more urgent.

The ever-increasing demand for creative engineering is partly accounted for by the fact that each new scientific discovery more often than not opens the way for a whole host of new engineering possibilities. A bit of basic new knowledge about the conduction of metals, for example, could conceivably affect a whole raft of electrical products—and in many cases could also have a profound effect on their application, and in turn on the end result of another industrial process. But the results do not accrue automatically—they must be engineered.

• • • A good example of this effect is the case of the magnetic amplifier. Since new magnetic materials made the Magamp a practical device, applications have cropped up in a wide range of industries. And the possibilities have by no means been exhausted. Creative engineering was required not only to produce the device itself in its various forms, but also to put it to work as a control element.

A similar case is that of Cypak systems, a new static control intended as a replacement for relay systems. In fact this is almost a sequel to the Magamp development. A practical magnetic amplifier, new solid-state devices, plus much new circuitry led to Cypak systems. But again, the necessary factor was the ability to conceive a new system. The development is now going through the second stage, that of application. Here again, new concepts are necessary, as the system is applied in a wide variety of applications—from the control of elevators to machine tools—each requiring a different approach.

• • • Roadblocks—often due to lack of better materials—frequently exist temporarily in the path of development of a specific piece of equipment. But when that roadblock is removed, almost invariably roadblocks in other areas are removed simultaneously. More often than not a chain reaction is set off. A new semiconductor material may make possible a new rectifier that is a fraction of the size of comparable rectifiers. This, in turn, may mean that many types of equipment using those rectifiers can be made smaller, which may well open up new applications for them. Concurrently, the same rectifier may, by virtue of its size, make possible new devices or systems.

WESTINGHOUSE Engineer

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In This Issue

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THE COVER

Symbolic of electric-power production is the arrangement of heavy apparatus on this month's cover—turbine generator, transformer, circuit breakers, and transmission lines. The cover design is by Dick Marsh.

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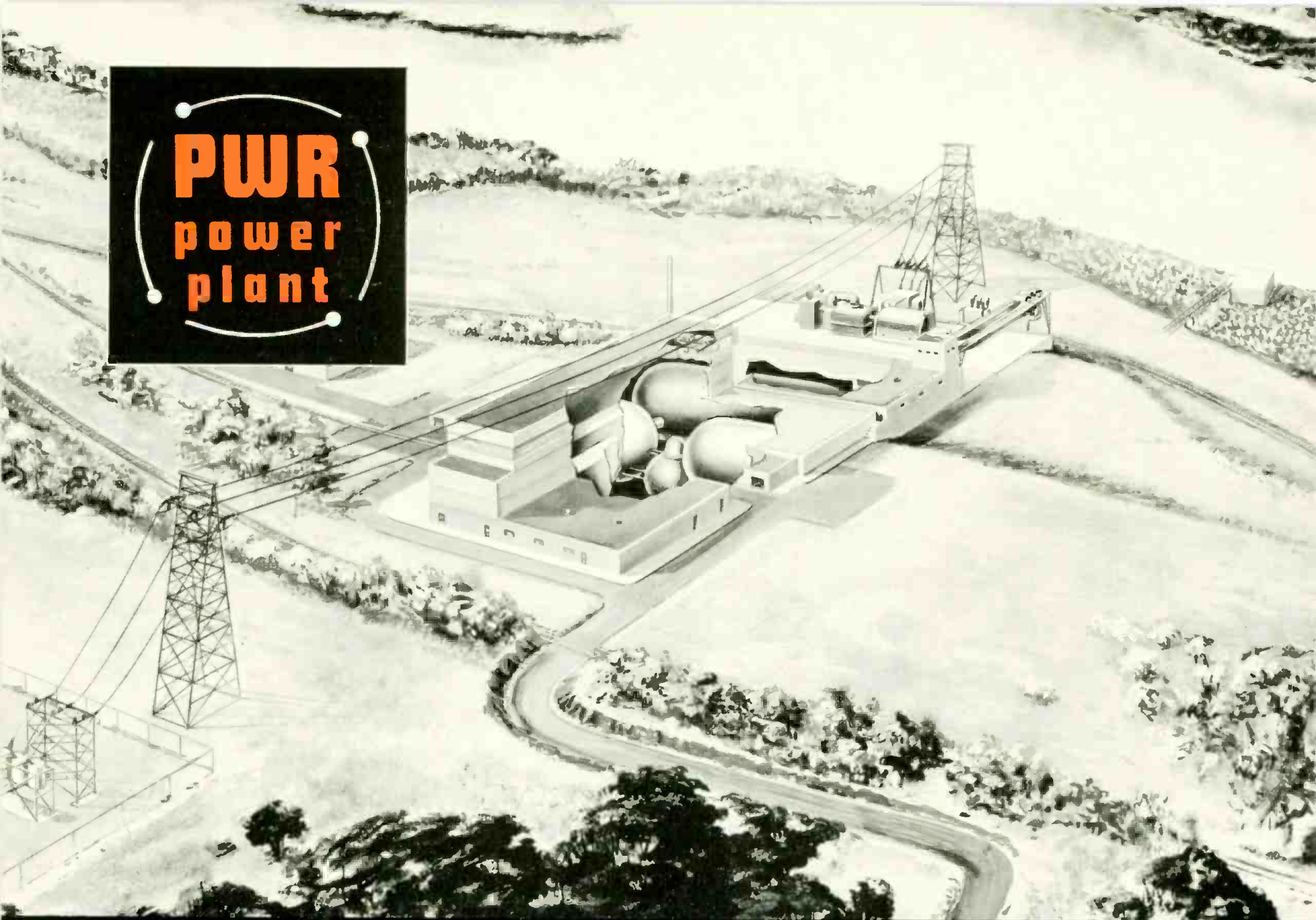
PWR power plant



PART ONE . . . . . the Nuclear Power Generator

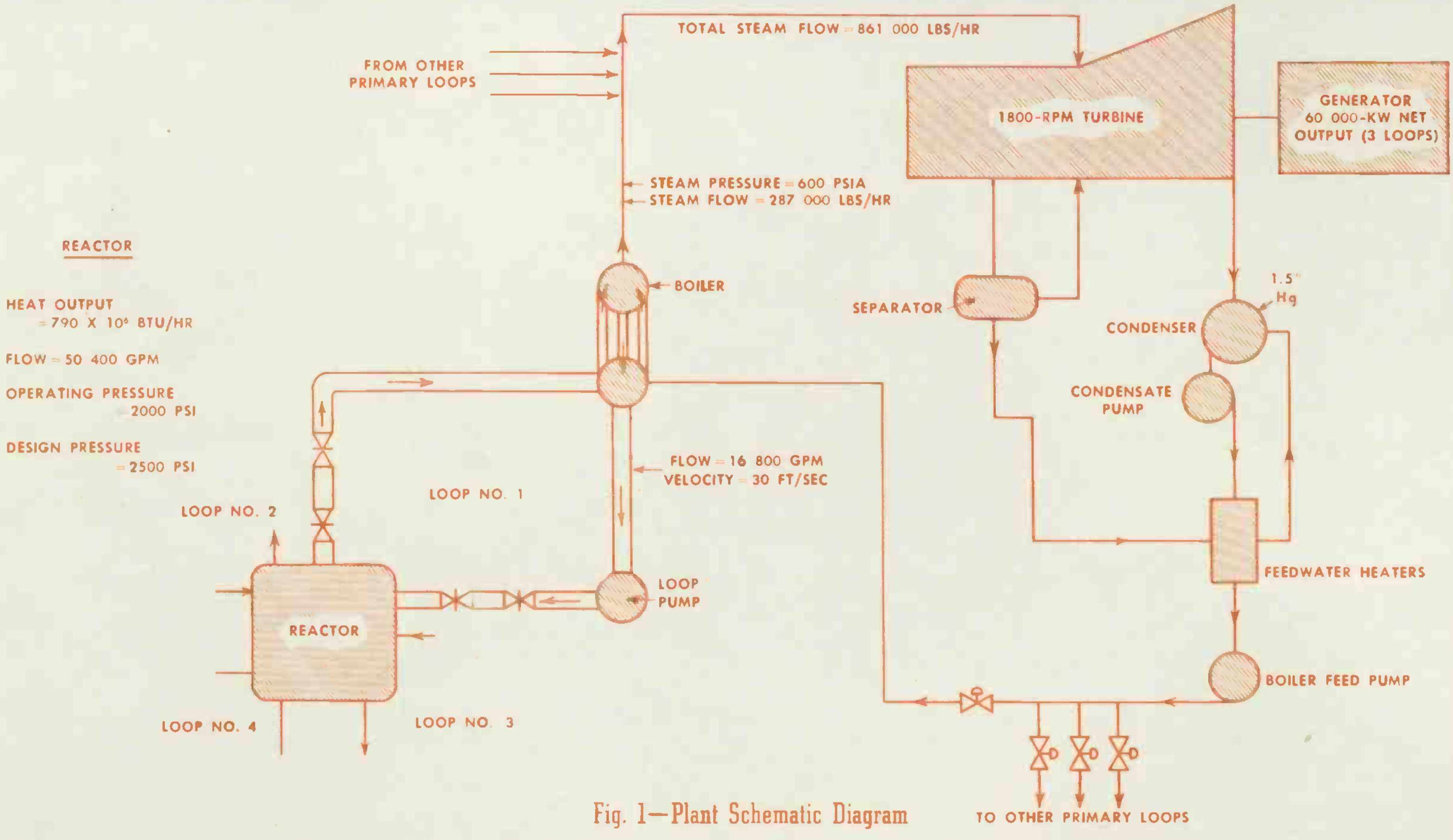


Fig. 1—Plant Schematic Diagram

THE SHIPPINGPORT POWER PLANT is sponsored by the United States Atomic Energy Commission to further the peacetime use of atomic energy in the field of electric power generation. The design, construction, and operation of this full-scale nuclear-power plant will provide much knowledge in the fields of reactor physics, fuel-element and core technology, and component and system design. By actually designing, manufacturing, operating, and maintaining the full-scale components required for such a power plant, future plants of a similar type can be developed and evaluated with greater accuracy. The plant organization will serve as a pattern for the establishment of operation forces for nuclear-power stations, and the facility will also provide training for personnel for future plants.

General Description

Basic Plant Cycle—The basic schematic diagram of the reactor and the steam plant is shown in Fig. 1. The nuclear reactor is the heat source and produces a minimum full power rating of 790×10^6 Btu/hr. This heat is produced in a nuclear core, which is a right circular cylinder consisting of assemblies of enriched uranium in clad plates and natural uranium in tubes. These assemblies are supported in a bottom plate and top grid, which, in turn, are supported from a ledge of the reactor pressure vessel. This reactor vessel is a cylinder with a hemispherical bottom and a removable hemispherical top closure. Coolant enters through four nozzles at the bottom of the reactor and leaves through four nozzles at the top.

The reactor plant consists of a single reactor heat source with four main coolant loops. Three of these loops are required for producing the 60 000-kw minimum design power. Each loop consists of a single-stage centrifugal canned-motor pump, a heat-exchanger section of a steam generator, 16-inch gate-type isolation valves, and the necessary 18-inch outside diameter interconnecting piping.

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High-purity light water serves as both coolant and moderator in this plant. This water is under a pressure of 2000 psi. The flow through the nuclear core is 45 000 gpm for three loops. At full power the inlet water temperature to the reactor is 508 degrees F and the outlet temperature is 524 degrees F. The water velocity in the 18-inch pipes is approximately 30 ft/sec, with a velocity of between 10 and 20 ft/sec in various parts of the nuclear core. The total pressure drop around the main coolant loop is 105 psi, and this drop is divided roughly equally between core, steam generators, and piping.

The coolant enters the bottom of the reactor vessel where 90 percent of the water flows upward between the fuel plates and rods, with the remainder bypassing the core in order to adequately cool the walls of the reactor vessel and the thermal shield. After having absorbed heat as it goes through the core, the water leaves the top of the reactor vessel through the outlet nozzles. It then passes through two 16-inch isolation valves in series and goes through the heat-exchanger section of the steam generator. The water then flows through the canned-motor pump and back through the inlet isolation valve to the bottom of the reactor, completing the cycle.

Isolation valves are located immediately adjacent to the reactor inlet and outlet nozzles of each of the four loops. These valves permit isolation of any loop of the reactor plant, to provide maximum protection to the reactor and so that maintenance can be performed while the remainder of the loops are in operation. Shielding is provided to permit this.

The main coolant flows through the inside of many hundreds of small stainless-steel tubes in the heat-exchanger section of the steam generators. These heat-exchanger tubes are surrounded by the water of the secondary system, which is heated by the primary coolant in the tubes. Wet steam is formed, which passes upward through the risers and enters the steam-separator portion of the steam generator. Here the moisture is removed and returned to the heat-exchanger section through the downcomers. The dry and saturated steam at 600 psia at full power leaves the top of the steam separator and goes to the steam turbine.

Considerations in Selection of Major Plant Parameters—The selection of the primary and secondary system temperatures and pressures is a compromise of many conflicting factors. To achieve highest thermal efficiency, steam-system pressure and temperature should be as high as possible. This gives the most efficient utilization of nuclear fuel and also, in the pressure range under consideration, the lowest cost for steam-plant equipment per kilowatt. In general, the cost of the primary system components increases with pressure, and 2500 psi represents about the highest practical pressure with present-day technology. Above this pressure the cost of components rises quite rapidly. The nominal operating pressure consistent with a 2500-psi design pressure is 2000 psi, for which the saturation temperature is 636 degrees F. The maximum metal-surface temperature for the fuel selected is, therefore, a few degrees below this value. The cost of a core usually increases with increase in metal-surface temperature.

The primary coolant temperature and flow are determined by a proper balance between such factors as cost of core as influenced by core surface area, pumping-power costs, and steam-generator costs. Increasing the flow of coolant for a given inlet temperature and power causes a decrease in core cost. The higher the inlet temperature, however, the higher the core cost. Increasing the inlet temperature gives lower steam-generator costs. By a series of design approximations, the most economical overall design parameters for the given set of conditions was obtained.

In general, cost of equipment can be minimized by making the individual units larger and thus reducing the number required. There is, however, a competing factor in the increased mechanical complexity and fabrication difficulty associated with increased component size. The four loops selected give units such as primary coolant pumps, valves, and piping that are about as large as is practical with present technology.

The use of four loops gives the plant considerable operating flexibility because any one or even two loops can be shut down and even repaired without shutting down the remaining loops. The shielding between loops in the plant container makes this possible from a radiation standpoint.

One advantage of the design chosen is flexibility. This means that at any time, even after operation has begun, the core can be rearranged and the number of control rods changed to take advantage of knowledge gained in the critical experiment program. It also may be desirable to rearrange the fuel subassemblies at various times during the core life to compensate for reactivity changes or equalize fuel burnup.

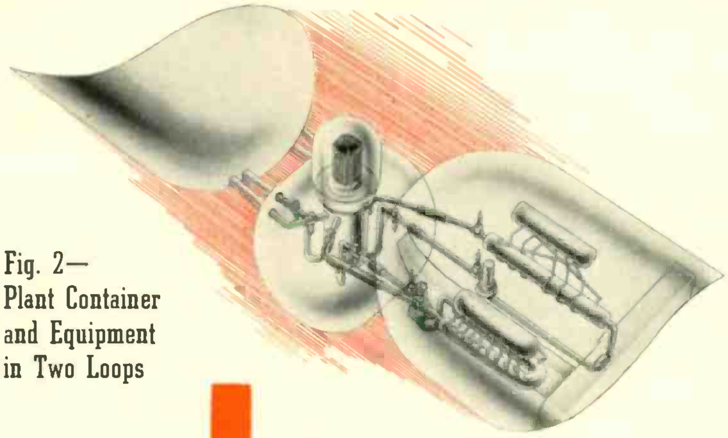


Fig. 2—Plant Container and Equipment in Two Loops

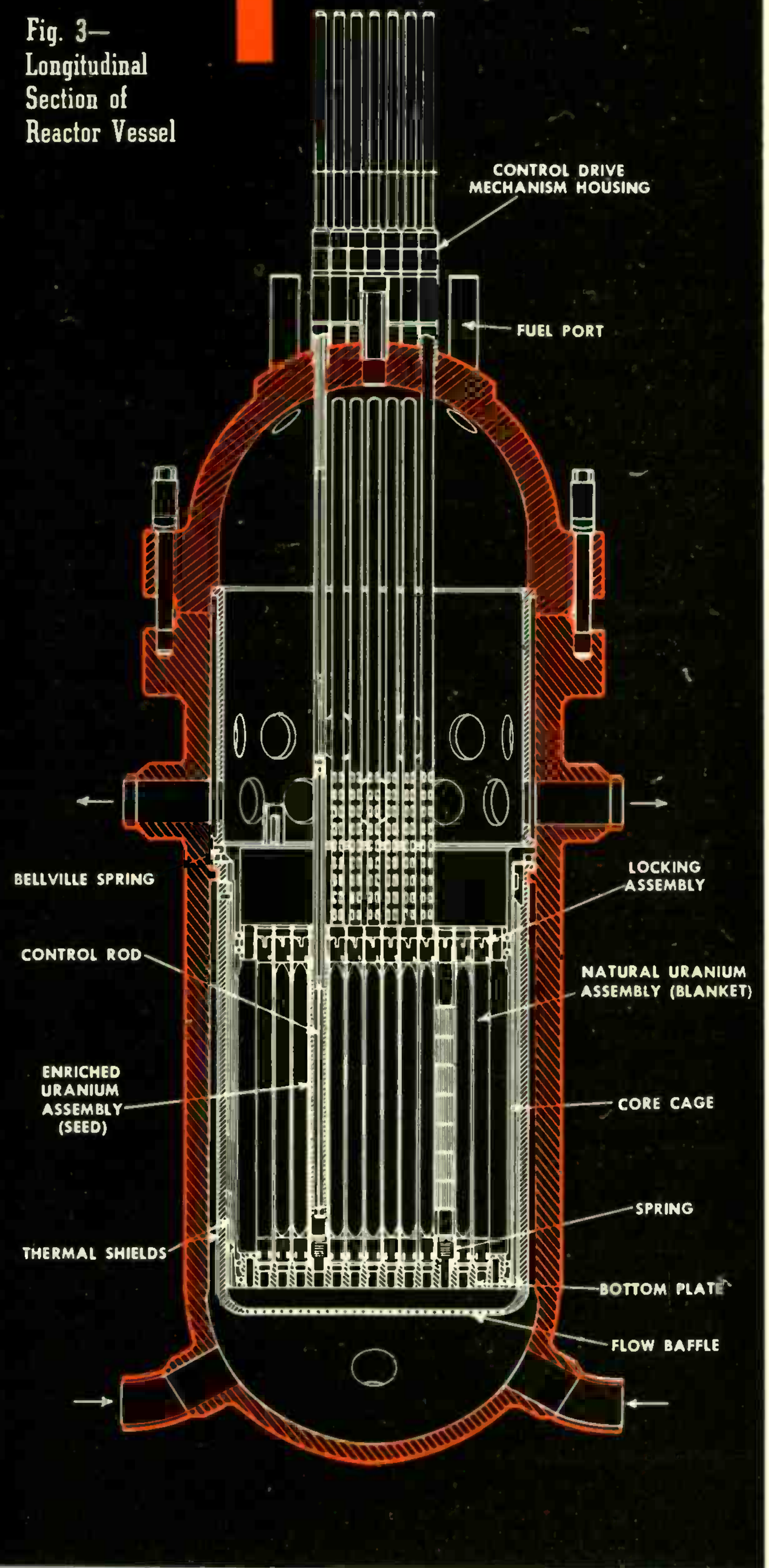


Fig. 3—Longitudinal Section of Reactor Vessel

Great improvements probably can be made in the nuclear cores for this plant. To take advantage of this, the reactor vessel and the primary coolant system have been arranged to accommodate cores considerably larger than the first and with flow and pressure drop requirements covering a broad range. It is expected that the first core will produce substantially more power than the 60 000-kilowatt minimum plant rating. It is also expected that sufficient information will be obtained from the operation and test of the first core so that subsequent cores may produce sufficient heat energy to be compatible with the 100 000-kilowatt rating of the turbine generator.

Due to lack of basic knowledge on pressurized water reactor plants, a considerable number of rather costly safety features, such as the plant container, have been included. The experience gained in operation of this plant will enable such features to be evaluated and therefore possibly removed from future plants.

Major Components

Physical Layout of Plant Components—To restrict the spread of radioactivity in the event of a dual casualty (i.e., rupture of the primary coolant system and subsequent melting of the nuclear core with attendant release of fission products) the nuclear part of the plant is completely inside a steel container (Fig. 2). This container is sized to contain the pressure created by a rupture of the primary coolant system of the most adverse size, including the effect of the stored energy in the water and the metal as well as any conceivable energy release due to a zirconium-water reaction.

The plant container is divided into four units connected by large tubular ducts. The reactor vessel is located in the spherical section, as shown in Fig. 2, and two of the main coolant loops are in each of the adjacent cylindrical sections. The fourth cylindrical section is connected into the other three and contains the auxiliary systems.

Reactor Vessel—The reactor vessel, as shown in Fig. 3, has an overall height of 33 feet, with a cylindrical section with an internal diameter of about 9 feet and a nominal wall thickness of 8½ inches. The total estimated dry weight of the reactor vessel is 250 tons.

The vessel is formed of carbon-steel plates and forgings with a 0.25-inch stainless-steel cladding. The flange for the closure will be 9 feet internal diameter and 23 inches square in cross section. The hemispherical closure head will be forged, and have a final thickness of about 10 inches, with adequate reinforcement for the 24 control-rod penetrations and the 9 fuel-port tubes.

The vessel is supported by the neutron shield tank at a point just below the vessel flange. This permits the vessel to grow due to thermal expansion with a minimum increase in main-loop piping stresses. The entire vessel is thermally insulated with about four inches of glass-wool insulation.

The core assemblies are supported in a stainless-steel cage consisting of a barrel, a bottom plate, and a support grid. The cage is nearly 8 feet in outside diameter and slightly over 13 feet high.

Main Coolant Pumps—A pump in each of the loops circulates coolant. The pump utilizes a single-winding motor of 1200-kw capacity, which can be connected for two speeds. Power supply is 2300 volts, 60 cycles per second, 3 phase for both speeds. The motor, weighing about 20 000 pounds, is mounted in the cast stainless-steel volute.

Main Stop Valves—Two hydraulically operated main stop valves are required in each loop, or eight for the plant. One of these valves is a parallel-disc gate valve, hermetically sealed and provided with an integral cylinder and piston type of operation. Latches hold it in the closed position. The nominal size of the valve opening is 16 inches, with ports tapered to an 18-inch pipe size.

The valve is designed for normal operation at differential pressures of 600 to 1000 psi across the piston, but can withstand stresses resulting from emergency application of a 3000 psi differential pressure. This valve will shut off against a maximum differential gate pressure of 600 psi, although normal shutoff pressure is a maximum of 210 psia. Position indicators show when the valve is fully open or fully closed. Eight manual valves serve as backups for the hydraulically-operated stop valves.

Steam Generators—The steam generators are each rated at 263 × 10^6 Btu/hr and provide 600 psia full-power steam pressure; this pressure rises to 885 psia at no load. The secondary-side design pressure is 975 psia. The primary-side operating pressure is 2000 psi, with a design pressure of 2500 psi. Six and a half million pounds, or approximately one million gallons per hour of primary cooling water pass through the tubes, entering at a temperature of 542 degrees F and leaving at 508 degrees F. Two of these units are entirely of stainless steel and are of a straight tube, fixed-tube sheet design. They are 36 feet long and 43 inches in diameter.

The other two units are of a return bend or U-tube type. The overall length is 28 feet, and the diameter is 39 inches.

Steam generators of the two different types are used so that experience can be gained in the design, manufacture, and operation of both types to give more knowledge on which to base the design of future plants.

Pressurizing Tank—A cutaway perspective of the pressurizing tank is shown in Fig. 4. The tank is 18 feet high and 5 feet in inside diameter, with a total volume of 300 cubic feet, of which about 150 cubic feet is the steam dome volume with maximum water level. Normal surges will be as great as plus or minus 10 cubic feet under design plant-load fluctuations. Under these design conditions primary system pressures will be held within limits of 1850 to 2185 psia. A 6-inch surge line in the bottom head connects this tank with the primary coolant system.

The heater section contains 200 heater wells, into which are inserted 500 kilowatts of replaceable electric heaters. These are arranged electrically into three groups for operational convenience and are controlled to maintain a saturation temperature of 636 degrees F (corresponding to a pressure of 2000 psia), and to form a steam bubble in the top of the tank. A spray nozzle at the top sprays colder (500 degrees F) water into the steam during positive surges to help limit maximum pressures. Located in the center of the tank is a standpipe for use as a reference leg for water-level measurement. A low-level alarm warns the operator to add water to the system before the level drops to a point where negative surges could uncover heater wells.

Core Design

Mechanical Design—The active portion of the nuclear core is in the form of a right circular cylinder 6 feet in mean diameter and 6 feet high. To minimize the amount of enriched U^{235} used, the core consists of some highly enriched seed and some natural blanket assemblies. The highly enriched, or seed assemblies are located in a square annular region about 6 inches thick. The area inside and outside of the annulus is filled with natural uranium oxide subassemblies. A cross-section of the core is shown in Fig. 5.

Each seed subassembly consists of several plates welded together to form a box. Four of these box-type units are welded together, with separation maintained by spacers, to form a central cruciform-shaped area. In each of these areas is located a cruciform-shaped hafnium control rod.

The uranium oxide, or blanket assemblies use a rod as the basic element (see Fig. 6.) These rods are Zircaloy-2 tubing. The tubes are filled with UO_2 pellets and have Zircaloy-2 end plugs welded to each end to form fuel rods. These rods are assembled into bundles of 100 rods each; the assembly is made by mechanically fastening together a stack of seven bundles, each 10 inches long, for a total of about 6 feet.

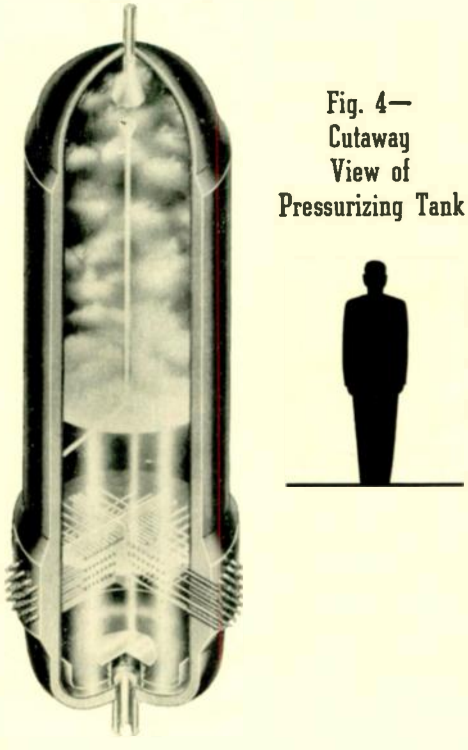


Fig. 4—Cutaway View of Pressurizing Tank

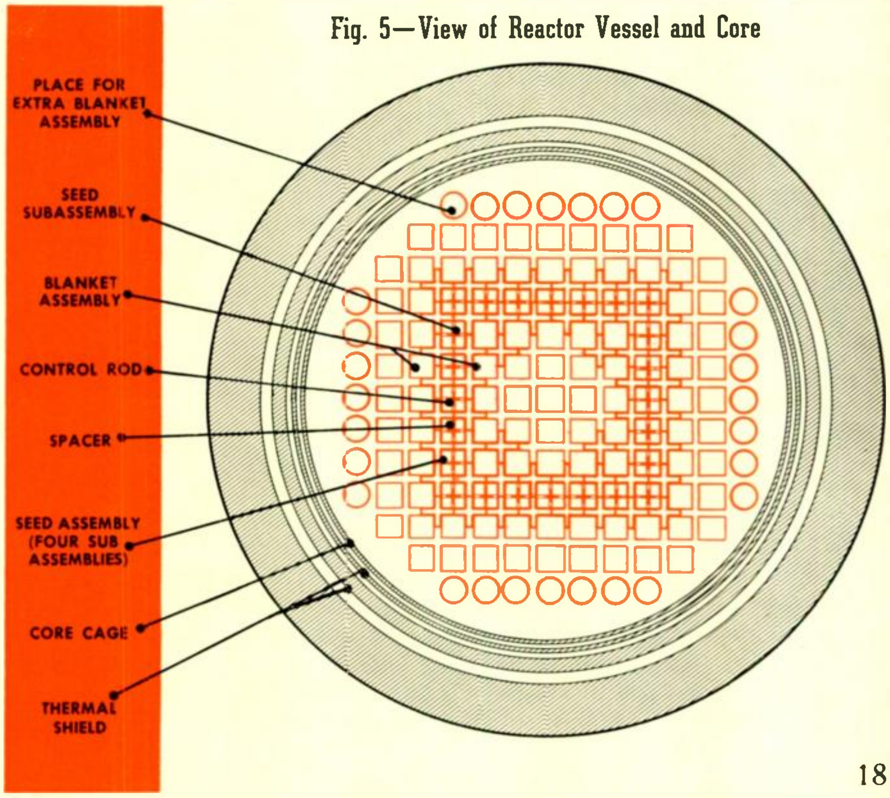


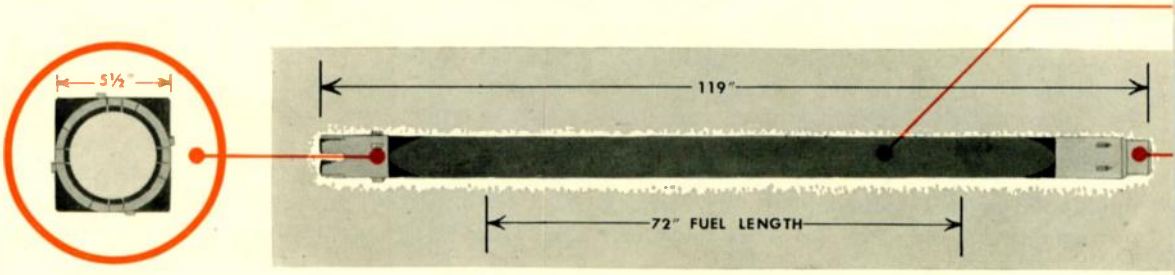
Fig. 5—View of Reactor Vessel and Core

Provisions are made for removing any individual seed or blanket assembly. The area above the pressure-vessel head is flooded with water during the removal operation, and the assembly is transferred to the fuel canal, with this water acting as shielding. Provisions are also available for removing the reactor vessel head and then removing the entire core as a unit, or any assemblies as desired.

A major problem in the operation of a nuclear-power plant is the difficulty of determining exactly what is taking place within the reactor vessel with respect to coolant flow, boiling of the coolant, temperature of the fuel elements, or failure of these elements. Suitable instruments for making these determinations are therefore provided.

Physics Design—The seed assemblies contain a total of 52 kilograms of enriched U^{235}, and the blanket contains twelve tons of uranium in the form of UO$_2$. At the start of reactor life approximately 60 percent of the power will be produced in blanket assemblies and 40 percent in the seed assemblies. The power distribution is a function of reactor life, inasmuch as the reactivity of both the seed and blanket vary with reactor life. The percentage of power produced in the blanket is expected to increase with time. Obviously, power distribution is also a function of the reactor temperature and the position of the reactor control rods.

Fig. 6—Blanket UO$_2$ Fuel Assembly



TOP VIEW

BLANKET SUBASSEMBLY

In the PWR reactor most of the power comes from the fissioning of U^{235}. However, approximately 8 percent comes from the fast fissioning of U^{238}, and a substantial fraction comes from the fissioning of plutonium. This latter effect increases with the lifetime of the reactor and is expected to reach a substantial fraction after 3000 mw days/ton average burnup in the blanket assemblies. At the start of life, approximately 0.8 atoms of plutonium are formed for each atom of U^{235} that is fissioned.

The PWR reactor has a negative temperature coefficient of $2 \times 10^{-4} \Delta K$/degree F, or possibly higher. This temperature coefficient is of sufficient magnitude to materially reduce the seriousness of the control problem. The reactivity will vary throughout the life of the reactor core, tending to increase during the early part of the reactor life and then decrease. The highly enriched assemblies must be replaced at least once to get maximum life out of the uranium-oxide blanket assemblies.

Obviously, sufficient control-rod area must be provided to permit the reactor to be subcritical with a reasonable margin in its most reactive condition. Inasmuch as each additional control rod imposes a severe penalty in the mechanical design, it has been necessary to keep the number of rods to an absolute minimum. To increase the loading of the highly enriched assemblies and thus give them increased life, burnable poisons have been added to these fuel plates. This poison is removed by capture of neutrons during the life of the reactor. Sufficient control must be provided to compensate for the equilibrium xenon poisoning. The control-drive mechanism functional requirements include the following:

a. Number of rods—24, with provisions for 4 more
b. Rod speeds—20 inches per minute
c. Minimum scram rate—200 inches per minute
d. Permissible delay after scram signal—0.1 second
e. Fail safe on loss of power
f. Accuracy of position indicator—1.5 inches

Thermal and Hydraulic Design—The basic criteria for the thermal design of the PWR are as follows:

a. Nucleate boiling must not occur at the hot spots during steady-state operation.
b. Bulk boiling must not occur in water leaving the hot channel during loss of coolant flow transient.
c. Fuel-element internal and surface temperature must be compatible with the properties of the selected fuel-element material.

To prevent nucleate boiling, the maximum coolant temperatures must be below 636 degrees F, which is the saturation temperature for the 2000 psi operating pressure.

To calculate the maximum metal-surface temperature for a given assumed set of parameters, the core hot-channel factors must be known. These factors represent such items as the peak-to-average flux ratio and the maximum permissible deviation from the average with respect to coolant channel width, fuel-element thickness, eccentricity of fuel within an element, and variation in fuel loading within the element itself.

In the seed assemblies, the peak power density is 277 watts per cubic centimeter, with an average power density of 81 watts per cubic centimeter. In the blanket the peak power density is 120 watts per cubic centimeter, and the average power density is 32 watts per cubic centimeter. In the seed assemblies the maximum heat flux is 382 000 Btu/hr/ft^2, and the average heat flux is 112 000 Btu/hr/ft^2. In the blanket the maximum heat flux is 240 000 Btu/hr/ft^2, and the average is 65 000 Btu/hr/ft^2.

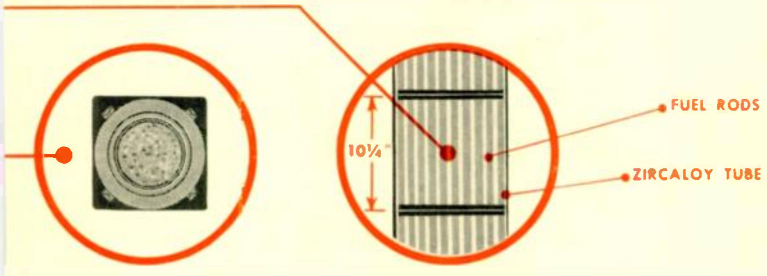
Thirty-three percent of the flow through the fuel elements of the nuclear core goes through the seed assemblies, which, however, represent only about twenty percent of the area. The water velocity in the seed assemblies is 20 ft/sec, and that in the blanket assemblies is only 9.8 ft/sec.

Materials

A great many new and unusual materials are employed in the design of nuclear reactors. The need for their use comes from the requirement that structural materials, heat-transfer fluids, shielding materials, and nuclear fuel and moderating materials must have certain nuclear properties. Numerous materials that, in the past, have been rare and little known from the standpoint of engineering properties are now being used in varying degrees.

Fuel—The highly enriched assemblies consist of zirconium-uranium alloy plates clad with Zircaloy-2. The zirconium-uranium alloy fuel sections of these plates are relatively corrosion-resistant and are also metallurgically compatible with the Zircaloy-2 cladding. This increases the probability of a good bond between the center section and the clad. No imperfections in clad surfaces are expected. However, if there should be, this would cause only minor corrosion of the center section, would not cause any mechanical deformation of the plates and would release only negligible quantities of fissionable material into the coolant stream. The plate design was chosen to give high heat-transfer area, which was required because of the high power density in the seed assemblies.

For the blanket assemblies, a material that permits the highest possible multiplication constant is desirable. This is because the ratio of power produced in the blanket to power produced in the seed varies approximately as $k/(1-k)$. Pure natural uranium would, therefore, from a nuclear sense be the most desirable material. Such natural uranium is, however, extremely unsatisfactory both from a corrosion and a radiation damage viewpoint. There are two possible solutions. The uranium can be clad sufficiently well that the coolant water never reaches the uranium surface, and with sufficient strength to prevent any dimensional changes due to radiation damage. However, it is highly unlikely that cladding can be sufficiently perfect to never expose the uranium to the coolant water. Also, whether or not radiation damage can be prevented by mechanical restraint is not known. The other possible solution is to add something to the uranium to improve its characteristics, which can be done by making a uranium alloy, such as uranium-molybdenum, uranium-silicon, or uranium-niobium, or by utilizing the uranium in the form of uranium-oxide.



BOTTOM VIEW

SECTION THROUGH FUEL ROD BUNDLES

All alloying elements that improve the radiation-damage resistance or the corrosion-resistance properties of uranium alloys tend to give poor neutron economy, inasmuch as the alloying elements have relatively high cross-sections for capture of neutrons. Even if neutron economy is ignored, none of the alloys are suitable from both a corrosion-resistant and radiation-damage viewpoint. This means that the life is seriously limited either by radiation damage or by corrosion, or both. The radiation may cause a rupture of the cladding and subsequent failure of one element due to corrosion, or the corrosion may be initiated by a cladding defect. In either event, after several days of exposure to the hot water all of the uranium alloy and the contained fission products in the affected fuel element might be released to the coolant stream. Uranium alloys are also, in general, more expensive than the uranium-oxide fuel elements and also give less power production in the blanket assemblies than uranium oxide.

Uranium oxide is an excellent material for the blanket fuel elements, because it is completely inert in high-temperature water and is also satisfactory from a radiation-damage viewpoint for a relatively high burnup. The uranium oxide can be readily cold compacted into pellet form and then sintered to increase the density to in excess of ninety percent of theoretical density. By mass-production techniques the dimensions can be ground to extreme accuracy and the uranium oxide loaded into Zircaloy tubing. The center temperatures of the uranium-oxide fuel elements may be as high as 2200 degrees F, but this appears to cause no difficulty because it is still approximately 3000 degrees F below the melting temperature of uranium oxide. The Zircaloy-2 tubing is ideal from a performance viewpoint. Its inherently high cost is a disadvantage; however, this disadvantage is more than compensated for by its decreased cross-section for capture of neutrons.

Control Rods—Control rods can be made of hafnium, boron steel, or stainless-steel-clad cadmium-silver alloy. The PWR control rods are made of crystal-bar hafnium and are homogeneous rods. The hafnium has ideal mechanical properties and is also extremely corrosion-resistant.

Other Materials—For application to components such as mechanisms, valves, and pumps, it is necessary to have materials that not only will withstand the corrosive effects of the high-temperature water but also have good wear characteristics when in rubbing contact with other than the high-temperature water itself. Inasmuch as most of the materials that have the best corrosion-resistance have inherently poor wear-resistance and vice versa, a thorough investigation was required to determine the combination of metals that presented the best compromise for the various applications. First, a large number of tests were made for short periods by means of simple shapes; later, actual full-size components were made and tested under actual service wearing conditions in the high-temperature water.

The basic material for the static parts of the reactor plant, such as heat-exchanger vessels, exchanger tubes, and pipes is AISI Type 304 (18-8 chrome-nickel steel with very low carbon content). Stressed parts, such as springs, are made of Inconel or Inconel-X. Rubbing parts, such as those in the control-drive mechanisms, are made of hardened stainless steel, chrome-plated stainless steel, and the various grades of Stellite. Magnetic parts, such as magnetic slugs, for control-rod position indicators are made of martensitic stainless steels.

Primary Auxiliary Systems

A number of auxiliary systems are connected into the primary coolant circuit to insure proper operation of the plant. Some of these, such as the pressurizing system and the purification system, are in use continuously, while others are required for intermittent operation. In addition, there are the usual power-plant auxiliary systems such as cooling water, compressed air, and electrical.

Coolant Charging System—The coolant charging system is used for filling the primary plant prior to operation and for maintaining the proper fluid level in the pressurizer. One 100-gpm low-head pump is used for filling and two 25-gpm high-pressure pumps are required for the intermittent makeup function. The charging system also contains facilities for charging fresh resin into the purification demineralizer and back-flushing the primary loops. No purification equipment is provided in this system, as the water from the boiler makeup-water equipment meets primary water specifications.

Pressurizing System—Changes in the core average temperature due to power excursions and changes in reactivity, and subsequent correction by control-rod movement make the system coolant volume a variable. These volume changes would cause wide variations in coolant-system pressure if the plant were operated as a solid system. The function of the pressurizer is to regulate the system pressure within a lower limit set by the reactor hot-spot temperature, and an upper limit determined by the safety and relief-valve settings. Relief pressurizing system, (Fig. 7), maintains a 2000-psi saturation steam head in a separately heated pressurizing vessel. This vessel has a volume of approximately 300 cubic feet, and contains about 100 cubic feet of water. The size is a function of the total volume of coolant and the transport time of water in loops, as well as the rate of change of power. The heat to the pressurizing vessel is supplied by 500 kw of electric immersion heaters, which are sufficient to raise the temperature of the water in the pressurized tank consistent with a 200 degrees F/hr heating rate for the entire plant.

Purification System—A fraction of the coolant that passes through the nuclear core must be purified to limit the activity buildup of the long-lived impurities in the water. This is done by passing a certain quantity of the coolant through a bypass demineralizer, which removes soluble and insoluble matter. The reactor coolant-purification system consists of two parallel loops, each of which provides purification for two of the four reactor coolant loops.

Waste-Disposal System—The activity in the ion-exchange resin from the purification system and in the decontamination fluids and primary system effluent will be too high to permit dumping in the river. The volumes involved make packaging and subsequent disposal at sea infeasible. The waste disposal system now being developed will consist of two-stage evaporation, to reduce bulk, and subsequent underground storage of high-activity evaporator bottoms at the site.

Spent resin from the demineralizers will be transferred by flushing, in the form of a slurry, directly to underground storage. Provision for collection and storage of radioactive gases is being made. Dilution and discharge through a vent stack will be used when meteorological conditions permit. The evaporator feed will be from 9000 to 21 000 cubic feet per month depending primarily on decontamination procedure. Evaporator vapor will be condensed and then diluted with condenser cooling water before release to the river. The permissible activity released to the river is being taken at ten percent of the standard tolerance. A study is underway to determine the most economical method for disposing of combustible radioactive waste. The methods being considered are an incinerator at the site, or baling and shipping for disposal at sea. High and low activity laboratory wastes will be separated at the source and processed through the evaporator or diluted and dumped as dictated by the activity.

Reactor Control

The reactor plant will be controlled to maintain a constant average temperature of the primary coolant as shown in Fig. 8. Therefore, the control method used is one of average-temperature error detection and correction. On-off control of rods is initiated at plus or minus 3 degrees F error, with a plus or minus 2 degrees F deadband. Because of the slow response of the temperature-sensing elements and of heat transfer around the loops, the corrective action of the control would produce overshoot and oscillation of the system even if a considerably wider range of temperature variations were permitted. For this reason a damping effect is provided by incorporating the rate of nuclear level change into the control signal.

The normal mode of operation in the power range and during low-power standby is by automatic control of rods, as described. Manual control can be employed by the operator.

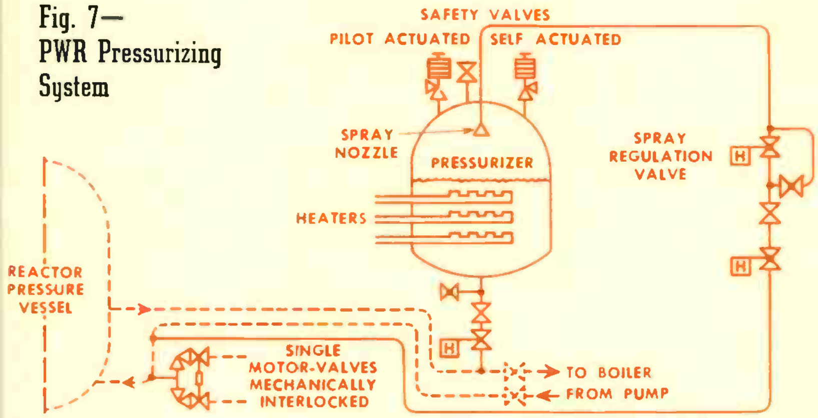
As designed, the external temperature-control loop permits the negative temperature coefficient of reactivity to adjust power without motion of the rods for load changes of the order of 10 to 20 percent of full-power rating. For larger load changes, the external loop assists the temperature coefficient by introducing rod motion to make a more rapid adjustment of reactor power.

Temperature measurements for the control system are made by resistance thermometers in the loops. Temperatures are measured at boiler and reactor exits and averaged.

Emergency Shutdown System—The function of the emergency shutdown system is to prevent the nuclear source from destroying or damaging itself. To perform this function the system must eliminate the possibility of any condition wherein the reactor generates more power than the load can absorb and the plant can safely handle. The action of the shutdown system is to reduce the source power level in anticipation of a damaging energy-conversion process.

The paramount requirement on a nuclear-reactor shutdown system is reliability. A system is reliable if it provides

Fig. 7—PWR Pressurizing System



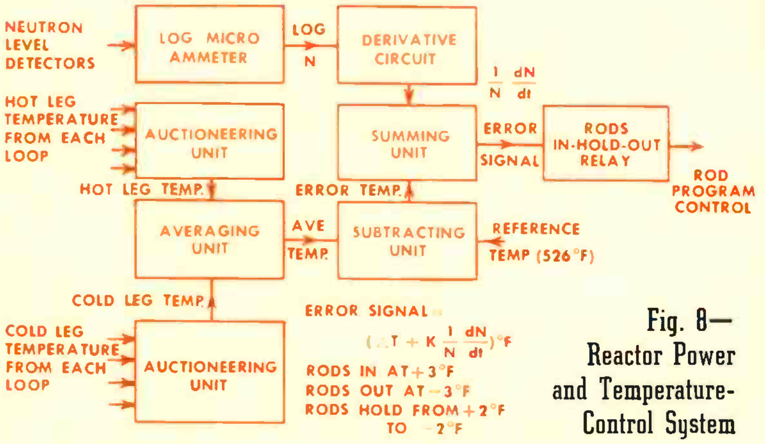


Fig. 8—Reactor Power and Temperature-Control System

action when, and only when, such action is warranted. Accordingly, the objective in designing the PWR emergency shutdown system is to provide a system that protects the reactor against all damaging conditions, while in no way affecting normal plant operation, by utilizing the scramming function of the control-drive mechanism.

If the emergency shutdown system is to be reliable, it must receive accurate information concerning the status of the plant and correctly interpret, transmit, and respond to this information. Inasmuch as all the conditions that endanger the reactor are manifested by excessive core temperatures, the shutdown system signals must relate to temperature directly or to plant variables that can be correlated to it. The limitations imposed by presently available temperature detectors make the direct core temperature signals inadequate for shutdown. Shutdown signals must therefore be obtained from the behavior of plant variables that determine core temperatures.

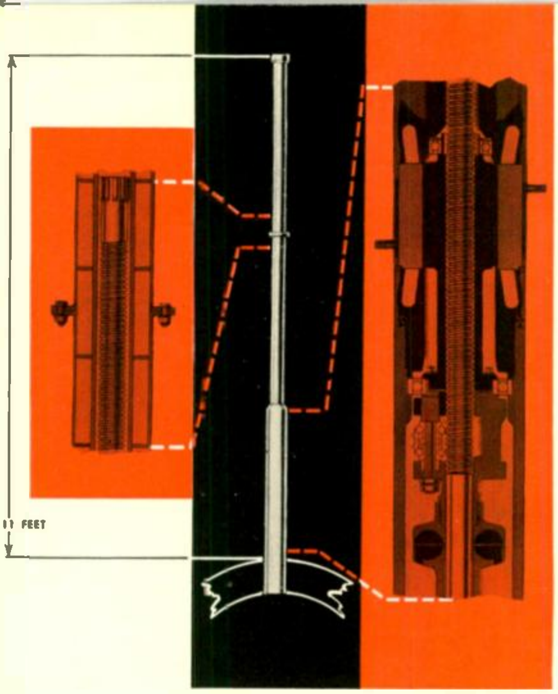


Fig. 9—Control-Drive Mechanism

The time required to detect, transmit, and actuate a shutdown signal is of the utmost importance because it determines the maximum permissible ratio of steady-state plant power output to maximum safe transient output. In PWR, the steady-state power limits have been extended very close to the transient limits, and therefore, the need exists for a very fast responding shutdown system.

The most reliable components and systems are not in general the fastest responding, and conversely the fastest responding systems have a tendency to respond to noise signals. The requirement that the shutdown system incorporate fail-safe features imposes further conflicting requirements.

Plant Container and Site Facilities

Plant Container—The nuclear part of the power station is housed in four steel plant containers, which, in turn, are in concrete compartments partially below ground level.

The reactor vessel is in a spherical shell 38 feet in diameter with an 18-foot cylindrical dome on the top to accommodate the extra height of the control-drive mechanisms. Located on each side of the sphere is a 50-foot diameter cylinder, 97 feet long, in which are located two of the primary coolant loops and their associated equipment. An additional auxiliary container is located between the nuclear equipment containers mentioned above and the turbine generator. This container is a cylinder 50 feet in diameter and 147 feet long. The coolant pressurizing tank and other minor auxiliary equipment are located in it. All of these containers are interconnected by several eight- and twelve-foot diameter ducts. Total gross volume is 600 000 cubic feet, and net free volume is 473 000 cubic feet.

The plant-container air-cooling system is designed to control the air temperature within the plant container to 122 degrees F maximum and to provide means for filtering all air exhausted from the plant container.

Access to the vapor container is permitted and interlocking access doors are provided so that the integrity of the container is not jeopardized by conventional entrance doors.

Design Considerations—The problem of containment is derived from safeguard considerations for protection of personnel against radioactive fallout outside of the 400-acre Shippingport exclusion area. The container is designed to prevent escape of any radioactive gases or vapor containing fission products that may be accidentally released as a result of any major plant casualty. The fission products normally remain in the fuel elements. They will only be released in any major quantities if a significantly large number of fuel elements fail during operation or if a large part of the core should melt. Both cases must be accompanied by a major primary coolant system boundary rupture; and in addition, the second case must be caused by a combination of high residual heat and loss of coolant. Both cases are considered as highly unlikely, but until more definite information is obtained, it is an eventuality against which some protection is desirable.

The container is designed to handle the release of the energy in the approximately 20 000 gallons of primary coolant water at 535 degrees F average temperature and 2000 psi pressure, the heat energy stored in the metal of the plant, and the energy of the worst conceivable chemical reaction between the zirconium and water.

The pressure build-up in the container will vary in both magnitude and time, depending on the size of the break in the coolant system. The additional transfer of heat energy to the water for an intermediate-sized break makes this the worst case. The maximum pressure reached for the design volume is slightly over 50 psi.

If a rupture of the system occurs, a few seconds thereafter a spray will be started, and this will cause the pressure to decrease more rapidly after the first few seconds. This reduction of pressure makes it possible to take care of any likely chemical reaction between the zirconium and water, as this component of the total pressure comes into play only after

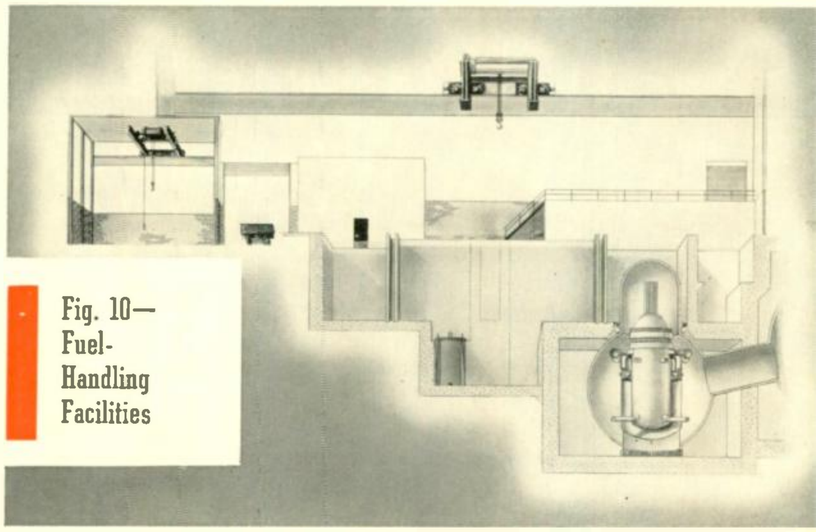


Fig. 10—Fuel-Handling Facilities

an appreciable delay. With an adequate spray the total pressure will be no higher than the original peak.

Shield—The radiation level permitted throughout the plant varies depending on the amount of access required for operation or maintenance. In operating spaces the radiation level is held to less than 2 mr per hour. In spaces where only intermittent access is required the radiation is maintained at less than 5 mr per hour. Areas, however, which must be occupied very infrequently and for short periods of time may have a radiation level as high as 50 mr per hour.

The reactor vessel is surrounded by an annular neutron shield tank providing a three-foot-thick water layer. Other internal shields, such as provided between isolable loops, are concrete. In general, the external shield consists of the concrete structure surrounding the plant container. The thickness of the concrete required for structural purposes in supporting the load of earth on the outside is sufficient for biological shielding except in a very few places.

Radiation-monitoring equipment is provided as required throughout the plant area to determine the existing radiation levels and to warn the operating personnel of any unusual conditions.

Site Facilities—The fuel-handling building, which is the largest building on the site, is 44 feet wide, 182 feet long, and has an overall height of 60 feet. This building and the fuel-handling canal and cranes are shown in Fig. 10. A 100-ton crane is provided for removing any fuel assembly or group of assemblies or for rearranging them, either through the fuel ports in the closure head, or with the head removed.

The fuel assemblies will be removed from the reactor vessel under water and moved to the appropriate section of the canal for storage, disassembly, repair, or examination.

PWR power plant

PART TWO

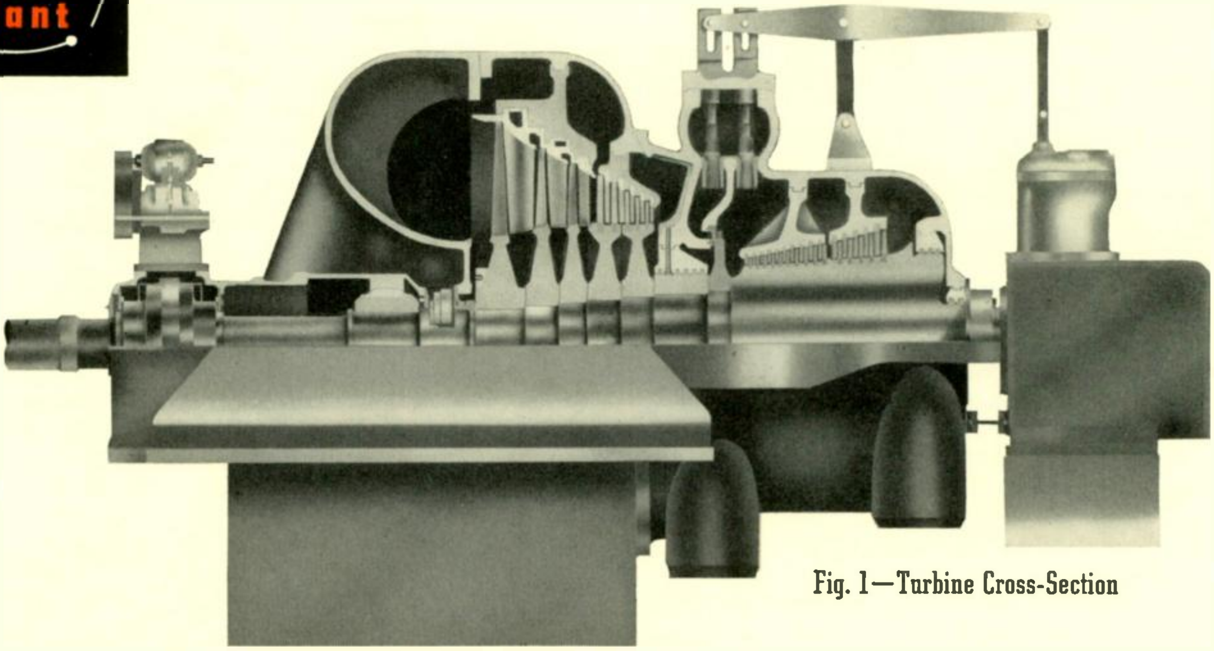


Fig. 1—Turbine Cross-Section

. . . Turbine-Generator Plant

R. B. Donworth, W. J. Lyman
Duquesne Light Company
Pittsburgh, Pa.

The non-nuclear portion of the Shippingport power station is unconventional in many respects: It utilizes saturated steam at low pressure, and this pressure is not constant but rises substantially as the load is reduced; due to the requirements of the nuclear portion, the station service power supply is much greater than is customary for a plant of this kilowatt rating, and a small separate diesel-driven generator is also provided for extreme emergencies; the control, although essentially through a standard turbine governor, must recognize that the heat source is a reactor instead of a boiler fired by combustible fuel; and of course there is no conventional boiler with its fuel and ash-handling equipment, fuel storage, dust collector, air heater, and stack for combustion gases.

The turbine-generator is rated at 100 megawatts maximum capability and is a single-cylinder, 1800-rpm unit with direct-connected exciter. The turbine has three points of steam extraction for feed-water heating. As shown in Fig. 1, steam is admitted at some distance from the thrust-bearing end of the rotor, flows toward the thrust-bearing, and passes to an external moisture separator. It then passes back into the turbine at a point near the original point of entrance, from which it flows in a direction away from the thrust-bearing to exhaust at the coupling end.

The cylinder barrel, between blade rows, will be lined with stainless steel, and all blades will be Stellite-faced on the leading edges wherever moisture content of the steam exceeds six percent and blade-tip speed is 900 feet per second or higher. These precautions are expected to minimize the effects of wet steam on life of the turbine parts.

The full-load-throttle steam pressure is 545 psig, and the corresponding feed-water temperature is 342 degrees F. The moisture content at the second extraction point, where the moisture separator is located, will be about 11.6 percent, and this will be reduced to approximately one percent for the steam returned to the turbine. Under these same full-load conditions the exhaust moisture will be on the order of 13.2 percent. This information, together with performance heat rates, is shown in Table I for two loads, and the turbine steam-cycle diagram is shown in Fig. 2.

As load is reduced slowly under normal conditions of extraction and exhaust back-pressure, the steam flow, the heat transmitted in the boiler heat exchangers, and the temperature difference from coolant to steam will all become less. Except during transients, the mean temperature of the reactor primary-coolant water will remain constant, and hence the boiling-water temperature and pressure will rise. This rise is approximately linear and reaches a maximum of 870 psig at zero steam flow.

The thermal efficiency of a simple condensing cycle utilizing steam at 545 psig saturated and exhausting at 1½ inches of mercury absolute is 26.5 percent. This is raised to 29.5 percent by converting to the regenerative cycle of the type described. Since thermal losses of the reactor and its appurtenances are low, the turbine-cycle efficiency after allowance for auxiliary requirements may be considered for practical purposes to be the thermal efficiency of the overall plant.

The station-service power requirements are estimated to be 6000 kw for the nuclear portion of the station, and 3500 kw for the turbine-generator portion. The principal items in the former are the four primary-coolant pump drives totaling 4800 kw. In the turbine-generator portion, the largest auxiliaries are the main-condenser circulating-water pumps, of which there are two at 900 hp each. These pumps operate at a substantially higher head than is usual for such pumps, due to characteristics of the terrain and the plant elevation required by occasional floods of the Ohio River at this point.

The turbine generator will be an outdoor type located on a deck, below which the condenser and auxiliary equipment will be housed. A semi-gantry crane will operate above the deck for handling turbine-generator equipment for maintenance purposes. The main and station-service transformers will be located at ground level along the river side of the turbine structure. To protect the turbine generator and personnel in this area from the effects of a possible transformer-oil fire, a heat-resisting barrier will be placed along the turbine side of the transformer area.

The station-service buses supplying power for auxiliaries in both the nuclear and turbine-generator portions of the station will be arranged in four sections, two served from separate secondaries of a transformer connected to the main-generator leads, and two served from separate secondaries of a transformer connected to the 138-kv transmission bus. The four primary-coolant pumps will then be served, one from each of these four sections, and supply to other auxiliaries will be divided among them in such a way as to provide maximum security of service. A diesel generator of approximately 750-kw capacity will be provided to operate certain essential plant components in the remote possibility of total loss of other power sources. These components and their functions are: coolant pumps for reactor decay heat, emergency lighting, storage-battery charging, and turbine-generator turning-gear operation.

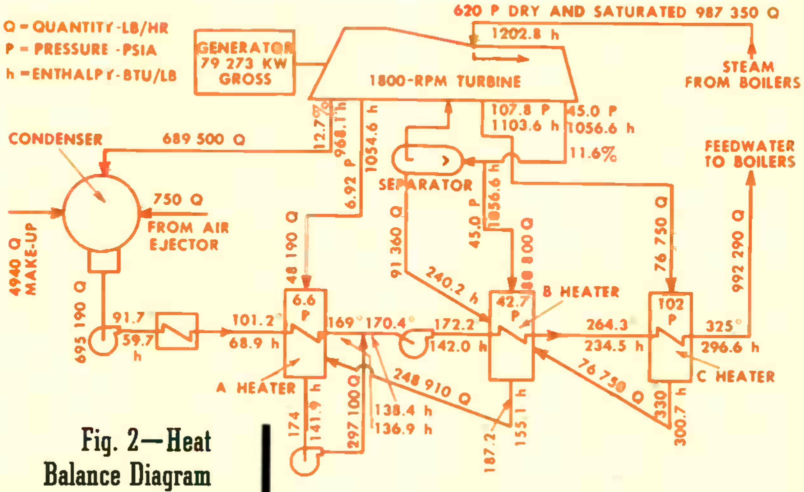


Fig. 2—Heat Balance Diagram

In addition to the systems described above, there are many close connections between the turbine-generator and reactor portions of the power station. In general, the supplies of water for charging, cooling, and other purposes originate in the turbine-generator portion, as well as communications arrangements involving the telephone and loud-speaker systems, sources for electric power, and main and emergency lighting of the plant.

A single control room will be provided for centering control of the reactor and its appurtenances, the turbine-generator station service, and the outgoing power circuits. The principal electric circuits and piping arrangements for steam and water will be shown pictorially on the control boards, with equipment, processes, switches, and valves shown, and suitable indicating lights placed thereon. This is a safety precaution to aid in minimizing operating errors, and it also presents at a glance the operating setup of the station for guidance of the operators.

Electric Utility Company System

The Duquesne Light Company system is a metropolitan-type system serving an area of 816 square miles, which includes the city of Pittsburgh. The system capacity before the

Table I

	GROSS GENERATOR LOAD—MEGAWATTS	
	79.3	100
Turbine Heat Rate, Gross (Btu/kwh).....	11 272	11 385
Throttle Pressure (Psia)...............	620	560
Throttle Flow (Pounds per Hour)........	987 350	1 286 900
Boiler Feed Temperature (Degrees F)....	325	342
Condenser Vacuum (Inches of Mercury)..	1.5	1.5

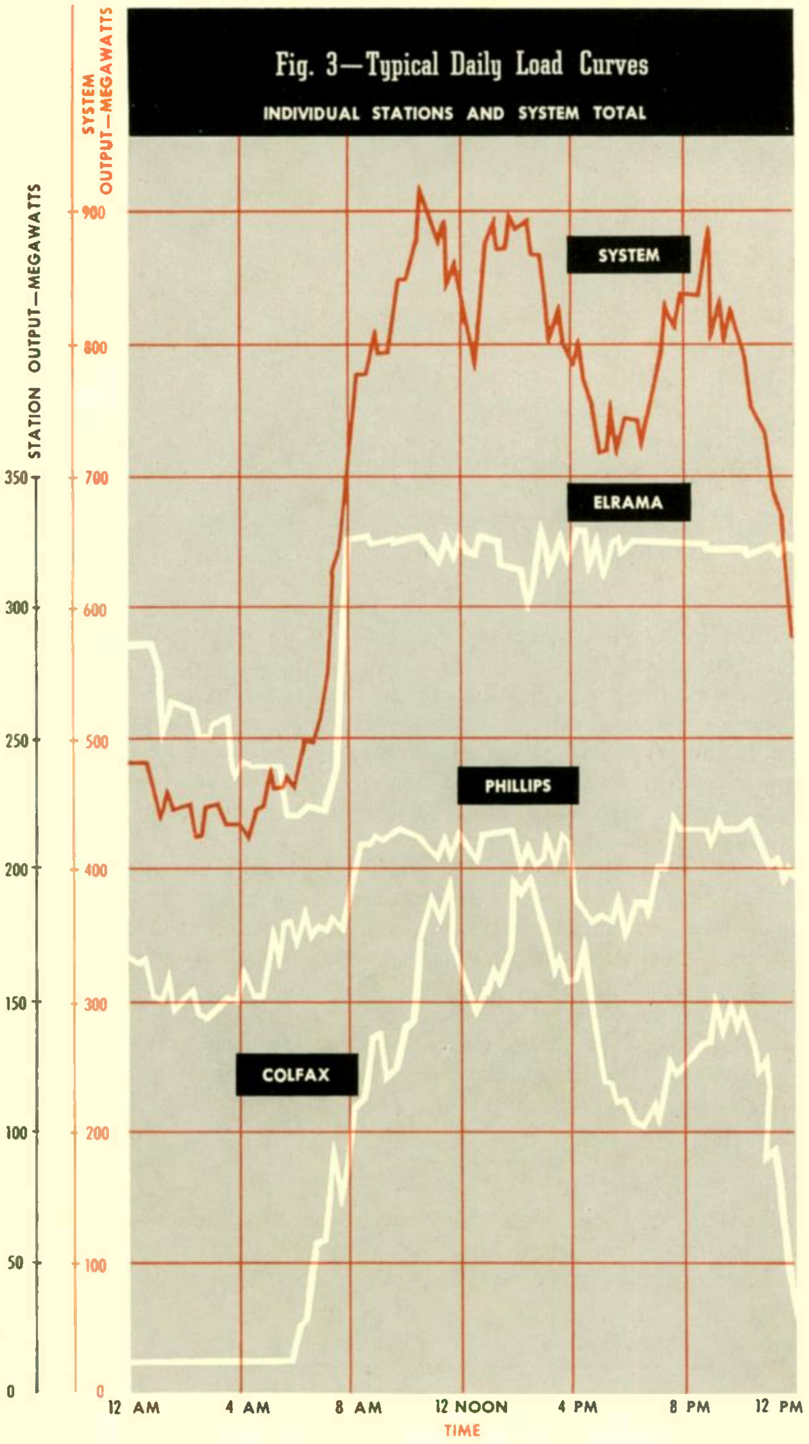


Fig. 3—Typical Daily Load Curves

INDIVIDUAL STATIONS AND SYSTEM TOTAL

Shippingport Power Station is installed will be 1 207 000 kw. The bulk-transmission system consists of 138- and 69-kv transmission lines with lower-voltage distribution at 22, 11, and 4 kv. Large industrial customers are connected to the 69-kv transmission system and smaller industrial customers to the lower-voltage distribution systems.

The system normally operates as part of a large interconnection, with 32-million kilowatts of connected capacity, extending through the entire east-central section of the United States. In order to provide adequate reserve capacity, each system must have a minimum reserve capacity equivalent to ten percent of its total installed capacity. The Duquesne Light Company system is tied to the interconnected systems through two tie lines, one at 69 kv and one at 132 kv, which have a combined capability of 130 megawatts.

The operating reserve capacity is based on replacing the output of the largest operating unit, which during the initial operation of the Shippingport Station will be 150 mw. Of this total, 100 mw will be required from the Duquesne Light Company system, and during emergencies 50 mw will be supplied by the interconnection. Duquesne Light, on the otherhand, is prepared to supply 50 mw to the interconnection during emergencies on connected systems. Since the capability of the Shippingport station will be lower than the operating reserve capacity, the loss of this station due to a forced shutdown would not present a serious problem to the utility system.

The system load characteristics are of interest, as they have influenced the design of the Shippingport Station. The usual daily load cycle occurs with the system maximum load usually occurring during the day as a result of the large industrial load. The week-day minimum night loads are about 50 percent of the maximum day load, and the minimum weekend loads are about 42 percent of the maximum. The heavy industrial load, which accounts for about 55 percent of the system output, includes several continuous-strip rolling mills and many large electric furnaces. These result in a load that is very erratic and has a variable demand. To meet these load requirements, system output must be changed rapidly through a range of 60 to 80 mw at frequent intervals. This is illustrated in the typical daily load cycle that is shown in Fig. 3, at left.

The several stations and the units within a station are assigned system load in accordance with the incremental cost of fuel. Adherence to this loading schedule, which produces the lowest fuel cost per kilowatthour of output, results in the less efficient units or stations regulating load changes during maximum-load periods, and the more efficient base-load units aiding in load regulation during minimum-load periods. It is necessary, therefore, that all operating units be capable of sharing system load regulation. This requirement becomes more essential when consideration is given to the future system expansion. As newer and more efficient units are added, older units initially operated as base-load units shift to peak-load operation, and are required to share more fully in the regulation of system load.

The actual change of station output to adjust to system load is accomplished by the automatic-load-control equipment. The tie-line interchanges are telemetered to the system operator's office, compared to the scheduled interchange, and the deviation between actual and scheduled loads causes the turbo-generator-unit outputs to increase or decrease until the tie-line loads equal the scheduled loads. Load control equipment also allocates load changes to follow the incremental fuel cost loading schedule. The automatically regulated output of a peak-load station during part of a typical day is shown in Fig. 4.

Emergency conditions usually involve the loss of generating capacity, the loss of one or more tie lines, or the loss of a block of system load. These conditions result in sudden changes of output, which may equal the load of the largest unit, and are often accompanied by system speed variation, causing rapid governor action. All units operating on the system must be capable of assisting in the adjustment of these load changes.

The addition of a generating unit to a system such as the Shippingport Station involves several considerations. In general the unit must share with all other units the demands for power and reactive kva in proportion to the unit capacity. Also the energy sources, reactors or conventional boilers, must not restrict the load adjustments within the specified limits. Otherwise additional capacity must be installed and operated to cover deficiencies.

Design specifications for the Shippingport Station required a definition of the concepts outlined above in terms of significant numbers. The parameters were defined to cover the following basic requirements: (1) Overall performance with respect to load-changing ability should equal that of the average high-pressure steam station using conventional boilers; (2) load-response characteristics of the nuclear portion of the station should provide for stable operation through system emergencies of normal magnitude; and (3) the range of load changes and rate of response to load changes should permit the nuclear station to assist other stations in regulating system output.

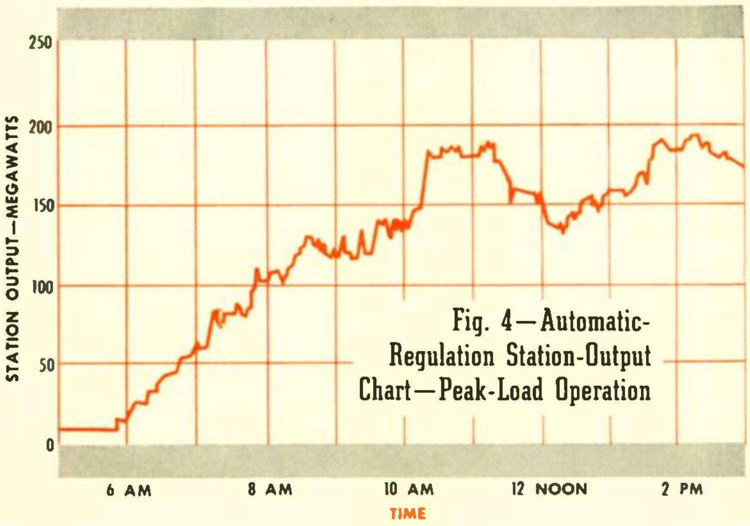


Fig. 4—Automatic-Regulation Station-Output Chart—Peak-Load Operation

Conditions stated for the emergency limits are as follows: (1) Loss of the largest operating unit with the system operating isolated from the interconnection (This is the Phillips No. 4 unit, which is about 15 percent of the expected maximum system output. Shippingport must increase its output 15 percent, or 15 mw for this condition.); and (2) loss of a fully loaded tie line or one of several large substation loads. This emergency involves the loss of 100 to 125 mw, and Shippingport must reduce its output about 12 percent, or 12 mw.

Conditions for normal load-change limits are as follows: (1) A change of 10 percent of the system load regulated on 50 percent of the operating capacity requires a 20 percent load change of the Shippingport output (this is about 20 mw); (2) a load change due to automatic load control will be limited to an increase or decrease of 20 mw and will occur at an average rate of 24 mw per minute; and (3) a load change due to manual control will be limited to an increase or decrease of 15 mw for a block change. Further load changes will be limited to an average rate of three mw per minute.

The manual load changes may occur at a rate of three mw per second. The load changes due to automatic load control will not exceed a rate of 0.4 mw per second or 24 mw per minute. The difference between response rates of manual and automatic control allows a higher load range for automatic control.

Operation of Shippingport Power Station

The Shippingport Power Station is being designed to meet all conditions outlined above. Load-changing characteristics of the overall station will be comparable to those of conventional station equipment. The reactor proper, having a negative temperature coefficient of reactivity, will be essentially self-regulating, and will possess a stability during load changes in excess of that found in conventional coal-fired utility equipment.

The station will have a range of automatic operation extending from 20 to 100 percent of full load. When operating within these limits, it will be capable of following daily system-load changes at an overall average rate of 3 mw per minute, and of accepting load swings of 20 mw maximum at a rate of 24 mw per minute. Also, it will handle a proportional part of the step-change load swings imposed on the various stations by casualties on the system.

The start-up and shut-down requirements will compare favorably to those of conventional station equipment. The time required for the station to reach the operating range from a cold shut-down condition will be approximately $3\frac{1}{2}$ hours; following an overnight shut-down, $1\frac{3}{4}$ hours will be required. The time necessary to perform these operations on conventional equipment of this size is $5\frac{1}{2}$ and $2\frac{1}{2}$ hours, respectively. The required time for shut-down of this and conventional station equipment is essentially the same; however, provision must be made in this station to remove heat that is generated by the reactor for a period of time following shutdown.

These requirements and the load-changing characteristics outlined above indicate that the reactor plant, although differing in many respects from conventional equipment, has no characteristic that would limit its ability to serve as either a base- or peak-load station on the system.

The presence of radioactivity requires that shielding be placed around the reactor plant equipment. This shielding and the presence of radioactive contamination after shutdown will complicate maintenance of this portion of the station. The shielding is so designed that minor maintenance can be performed on certain portions of the plant with the remainder operating. For those items requiring plant shutdown, adequate time will be available during the light week-end load periods to carry out the necessary decontamination procedures, perform minor maintenance, and return the plant to service.

The test program planned for the first few years of operation may prevent maximum utilization of the station due to the reduced outputs necessary for conducting certain tests and inspections. This program is designed to determine characteristics of the entire station, to provide detailed information on the core and associated equipment, and to determine operating costs.

an Engineering personality

THOSE who size up a man's personal characteristics strictly by outward indications would ring a bell on many of the traits of John H. Chiles. But, barring some unusual insight, they would miss by a country mile on some of the most important ones. For while Chiles' usually calm, soft-spoken demeanor suggests a relaxed, "things take care of themselves" attitude, nothing could be further from the truth. For his manner conceals the fact that Chiles likes to leave as little as possible to chance, and works diligently and with quiet persistence toward that ultimate goal.

Chiles was born in the small town of Brentwood, near Nashville, Tennessee. Much of his early life was spent on a farm and as Chiles says, "I've never quite gotten over being a farm boy—in fact, I never want to." When Chiles' family moved to Nashville, naturally it was not to his liking, and it became a regular habit for him to take the interurban to the country and then hike the three miles out to his uncle's farm after school, especially since it gave him the opportunity to tinker with the farm machinery. Later Chiles moved to Fredericksburg, Virginia, where he attended high school; from here he moved on to Virginia Polytechnic Institute, where he obtained his degree in electrical engineering in 1925.

As engineering manager of the Transformer Division, Chiles is responsible for the product engineering of instrument, distribution, and power transformers, and related apparatus. He served a thorough "apprenticeship" for his present position, having had a hand in many transformer developments. He joined Westinghouse in 1925, and after spending the customary time on the Graduate Student Course, was assigned to the Transformer Division. As a section engineer, he had numerous assignments in transformer design, particularly for instrument transformers; he also participated in the development of new insulations and impulse-testing techniques. In 1934 Chiles was made a section manager of the engineering group who specialized in instrument transformers and dry-type distribution transformers. This was followed, in 1942, by his appointment as engineering division manager of the instrument transformer and regulator group. Here, under his supervision, were developed new lines of lightweight, shock-proof instrument transformers for war service. In 1949 Chiles became engineering manager of all transformer activities, his present position.

Chiles is currently engaged in many extracurricular activities, both in professional societies and in community affairs. He is a Fellow of the AIEE, and is currently secretary of the association's committee on transformers. Chiles has been an active proponent of standardization, and is now chairman of the American Standards Association working group on instrument transformers, as well as chairman of the ASA's committee on transformers. The "quiet persistence" we mentioned as characteristic of Chiles shows up in his personal affairs as well; recently, given the task of raising what was considered an "impossible" sum of money for a church building fund, Chiles in his usual fashion rounded up the full amount, with some to spare.

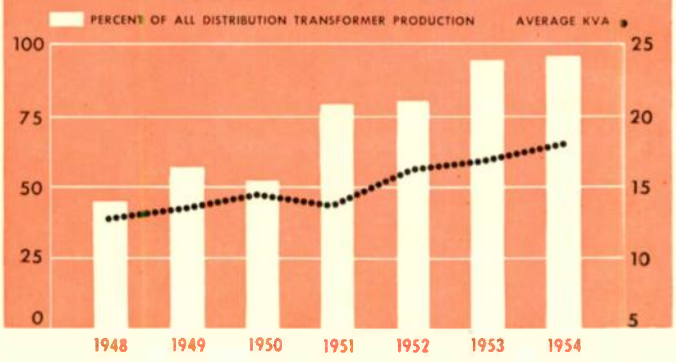
As is the case with so many men whose work is more mental than physical, Chiles finds relaxation in working with his hands. In his case, the effort has largely been expended in one activity. Eighteen years ago, he bought a hundred-year-old house that showed promise but was in need of repair. Since that time Chiles has gradually refurbished the whole house and grounds, of which he is justly proud.

A problem any manager of a large activity faces is keeping engineering projects rolling smoothly on schedule, and at the same time keeping informed on their progress. There are, of course, many good communication techniques, and Chiles uses many of them to advantage. One, in particular, however, is worthy of mention. He's an inveterate note writer, and there are few of his engineers who have not received his penciled notes asking their progress on a specific project. Because he expects and receives an answer, the notes supplement other methods of communication and help him to keep up on all the various projects. Equally important, however, is the fact that these notes have a subtle, but positive prodding effect on his engineers. As one engineer put it, "It didn't take me long to learn that Chiles expected a definite and positive answer to these questions, and that it was a lot easier to keep my work on schedule than to try and find reasons why it wasn't." Sounds like the technique really works!

John H. Chiles, Jr.

TRANSFORMER trends

1 TRENDS IN DISTRIBUTION TRANSFORMERS OF 5 TO 50 KVA RATING



Distribution Transformers include ratings from 1 to 167 kva. The percentage of 75 to 167 kva production has remained essentially constant over this period.

John H. Chiles, Jr.
Manager, Transformer Engineering
Westinghouse Electric Corporation
Sharon, Pennsylvania

Nearly every trend in the use of electric power is reflected in the equipment that provides the power. Nowhere is this more evident than in the transformer field. The relation of the size and design of transformers produced to the tremendous growth in usage of electric power is clearly apparent when comparative figures are surveyed. However, figures often indicate more than just growth; they also indicate direction of growth, from which changes in design or application practices can often be detected. Consider some of these trends, as represented by transformer production.*

Increased use of electricity in the home has accelerated the pace to larger kilovolt-ampere ratings for distribution transformers. In 1948 approximately 40 percent of the distribution transformers produced in the 1- through 167-kva ratings were in the range of 5 to 50 kva; in 1954, over 90 percent fell in this range (Fig. 1) Since the percentage of transformers produced in the 75- through 167-kva region remained essentially constant, the trend is obviously toward an increase in average rating in the smaller sizes. This is borne out by figures that show that the average kilovolt-ampere rating in the range from 5 through 50 kva has increased from 13 kva in 1948 to 18 kva in 1954, an increase of 40 percent (Fig. 1).

Logically, this trend to higher kilovolt-ampere ratings has been accompanied by a trend to higher voltages. Over the same period, production of transformers in the 12 000-volt rating and above has remained essentially constant at three to four percent of the total. On the other hand, the 7200- and 7620-volt ratings have increased from 35 to 53 percent of the total. As the curves show, this has been at the expense of the 4800-volt rating, which dropped from a high of 25 percent to about 12 or 13 percent last year, and the 2400-volt rating, which dropped from about 47 percent to about 32 percent of the total transformers sold (see Fig. 2, shown on page 192).

The use of *sealed dry-type transformers* has increased rapidly. The fact that they are inherently fireproof and moistureproof and require little maintenance has resulted in increasing application in mines, as part of generating station auxiliaries' power supply, and similar applications.

A strong preference now exists for dry-type transformers over askarel-filled units. For power centers and unit substations, this preference for dry types has ranged from 70 to 90 percent of the total of dry and askarel types. In 1949, the area in which askarel showed its greatest activity was in network transformers, with 90 percent askarel and 10 percent dry type; in 1954 each percentage was approximately 50 percent.

In single-circuit CSP unit substations, the 1953–54 figures show that 31 percent were 1500-kva units, 41 percent 2000-kva units, with the other 28 percent spread between ratings 500 through 3750 kva (Fig. 3).

Even with the rapid growth in unitized equipment over the past few years, it is still striking to note that such a large percentage of all three-phase transformers in ratings of 750 through 10 000 kva are network transformers, unit substations, CSP power transformers, and power centers. In 1953–54, 67 percent of the total units produced in this range were in the 750-, 1000-, and 1500-kva rating; and these three kilovolt-ampere classes have 50 percent of the total units represented by Fig. 4 in network transformers and unitized equipment. This chart indicates the high acceptance of unitized or packaged equipment, which permits lower installation costs, less expediting, and reduced utility or industrial engineering cost.

Mobile substations were first introduced for emergency service in case of failure of a transformer, but now seem to find their major use for by-passing transformers for maintenance scheduled in the normal work week, rather than for week-end outages. In the period from 1937 to 1954, about 25 percent of the units were in the 3000-kva rating, about 17 percent in the 2000-kva rating, with the others distributed from the smallest rating up through the large railway mobile units through 50 000 kva, 3 phase, and 83 333 kva, single phase (Fig. 5).

The percentage distribution of the various three-phase *power transformers* in 1953–54 for the range of 12 mva through 100 mva is shown in Fig. 6; as indicated the 15-, 20-, and 50-mva ratings predominate, with the other ratings showing in general a lesser percentage with increasing kilovolt-amperes.

Less than ten years ago Westinghouse built the industry's first transformer over 100 mva. Yet this year, two 400-mva, 330-kv transformers were delivered—units rated at least one third larger than previous transformers.

Of the units included on Fig. 7, the 200-mva generating station transformers have been shipped, the 315-mva generating-station units are being manufactured, and the 360-kva transformers are designed.

As a benchmark of progress, a 45-mva unit (forced-air cooling) built some 20 years ago, weighed 590 000 pounds, while each of the 400-mva, 330-kv giants are only about 10 000 pounds heavier. Largely this is a result of the use of form-fit design, Hipersil steel, reduced insulation, and forced-oil cooling in the new units.

The 315- and 360-mva units will be shipped upright in their own one-piece tank, as has been the practice on all the larger transformers for the past several years, where railroad clearances will permit. All of these giants have had impulse tests as well as their normal low-frequency tests.

In 1953–54, 87 percent of all bank ratings 50 mva and above were three phase, while only 13 percent on a bank basis were

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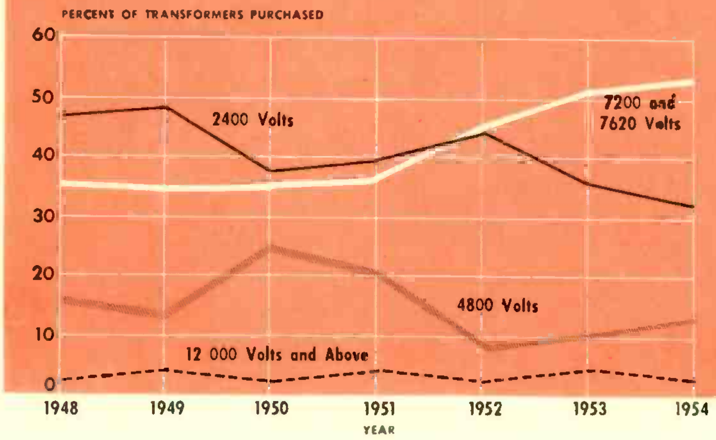
*All graphs, curves, and percentages in this article are based on Westinghouse production and sales figures.

TRANSFORMER trends

(continued)

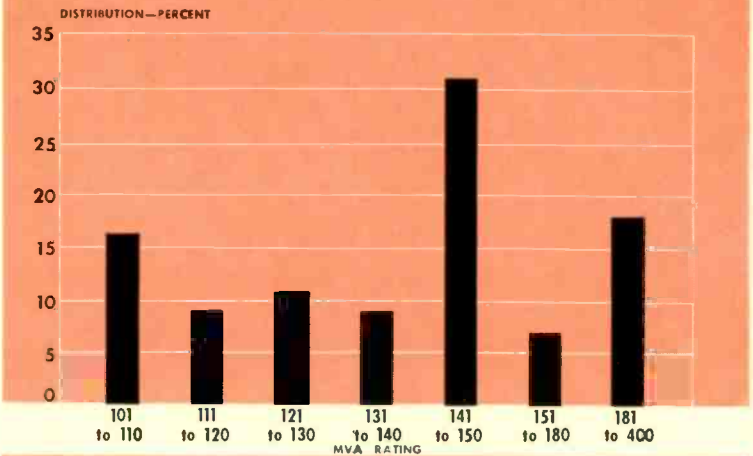
2 PRIMARY VOLTAGE TREND

(10 through 50 Kva Only)



7 DISTRIBUTION OF THREE-PHASE UNITS BY MVA

(1945 through 1954)



single phase. Of the larger units, a striking 20 percent are autotransformers—due undoubtedly to their greater efficiency and lower first cost—while 30 percent to 40 percent have three or more windings. These factors all add to the design complexity to meet the impedance requirements and the impulse distribution necessary to pass the rigid dielectric tests.

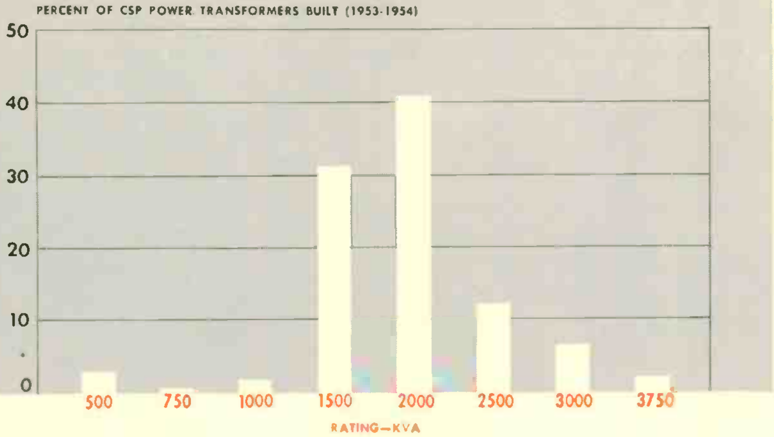
The choice of type of cooling for the units 50 mva and above (Fig. 8) sold during the period from 1952 to 1954 shows only about 5 percent self-cooled, about 19 percent with a self-cooled and forced-air rating, and about 10 percent with one stage of self-cooling and two stages of forced-oil cooling, the other 65 percent being forced oil with forced-air cooling (FOA). Over this period, about 75 percent of the units above 50 mva used forced-oil cooling, as indicated.

For the ratings 50 through 400 mva, three phase, the percentage of the total kilovolt-amperes for each system voltage is shown for the year 1954 in Fig. 9. By far the greatest percentage is for 138-kv systems. Continuing this voltage survey for the year 1954, Fig. 10 shows that only 26 percent of the units in the range 550-kv BIL and above used full insulation, the other 74 percent had one or more levels reduction in insulation. The large capital saving possible with forced-oil cooling and reduced insulation levels have accelerated the trend towards forced-oil cooling and reduced insulation where system conditions permit. The percentage savings with forced-oil cooling over a self-cooled unit on a 100-mva, 230-kv transformer are sizable. With reduced insulation on a self-cooled transformer and with forced-oil-to-air cooling, there is available a total saving of almost 40 percent over the self-cooled, fully-insulated transformer. With such potential saving in first cost, general acceptance of these two methods of reducing capital investment is quite natural. However, from an engineering viewpoint these reduced capital investments cannot be considered direct savings, because it is essential that the higher loss values for an FOA unit be evaluated, as well as the somewhat compensating lower loss values for reduced insulation levels, and reduced insulation at the neutral where system conditions permit their use.

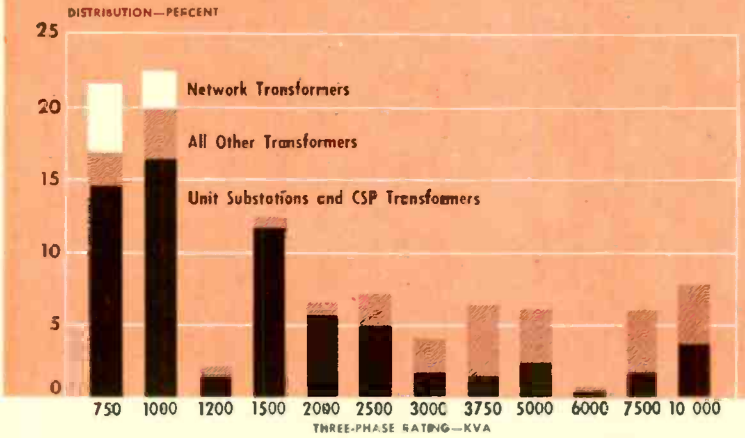
One question often asked is why the size of transformers has increased so rapidly; for instance, why not take advantage of the flexibility of two smaller three-phase transformers instead of one larger unit. In a generating station, there would, of course, be increased installation, handling, and connection costs for two units. With the relative continuity of service of a transformer compared to the turbo-generator and boiler, there is usually no engineering reason for not using a single unit, particularly where the generating unit is a small percentage of the system kilovolt-amperes. One of the basic reasons for the use of larger single units is illustrated in Fig. 11, which shows the savings by the use of a single 300-mva transformer over two 150-mva units. This comparison is given in both the 138- and 230-kv reduced-insulation classes, and shows the percentage savings in basic cost and evaluated cost of losses. Even with such wide-range loss evaluations as iron at $225 per kw and copper at $300 per kw up to iron at $500 per kw and copper at $325 per kw, the total evaluation of first cost and losses shows substantially the same savings—ranging from about 14 to 17 percent—by using one unit of 300 mva instead of two units of 150 mva each. The savings with FOA and reduced insulation, of course, add to these. In the larger power-transformer ratings, these savings over the last six to eight years have accumulated to the point where kilovolt-amperes can be put on the system at less than costs of some ten years or so ago.

Trends, such as these in the transformer field, are caused by many factors, ranging from engineering improvements to user preferences. But although the figures cannot always be correlated with specific changes in design or practice, the overriding influence of increasing use of power is clearly evident.

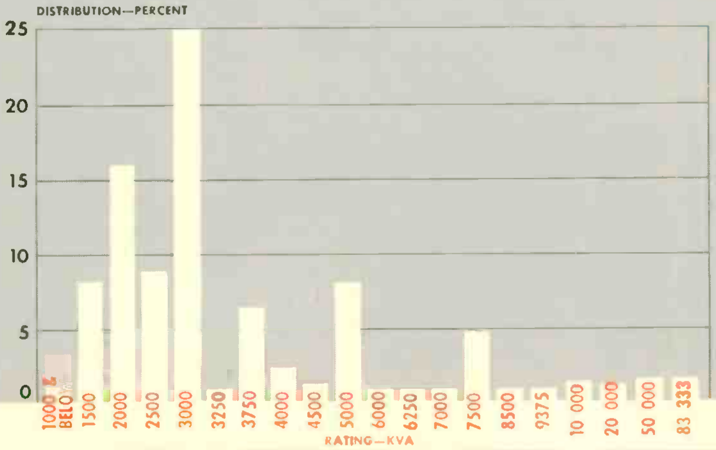
❸ CSP POWER TRANSFORMERS
(Single-Circuit Substations)



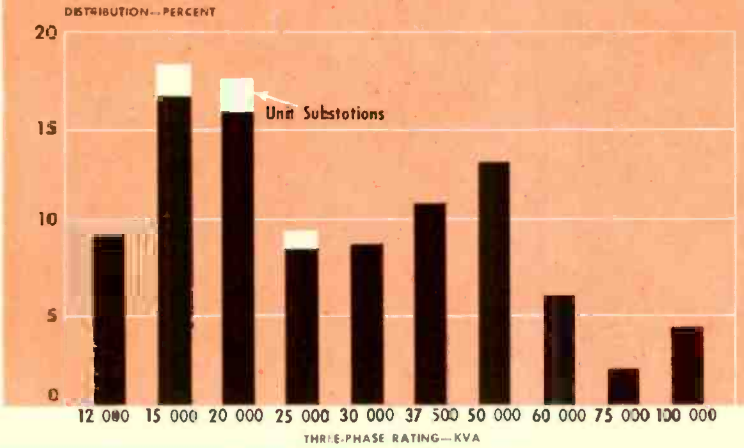
❹ DISTRIBUTION OF UNITS BY KVA RATING FOR 1953-1954
(750 to 10 000 Kva)



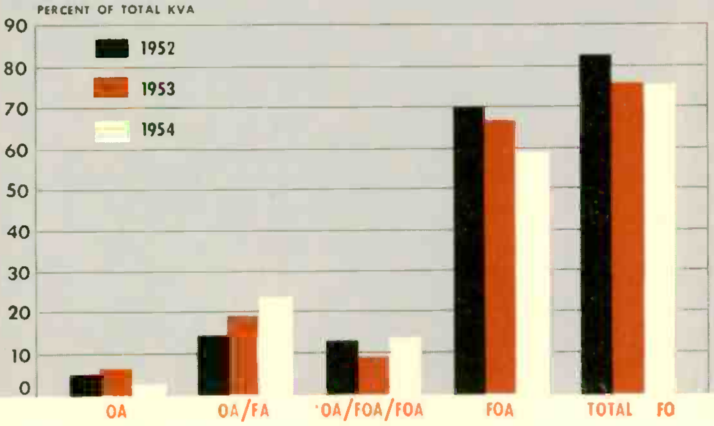
❺ MOBILE TRANSFORMERS—DISTRIBUTION OF UNITS BY KVA
(1937 through 1954)



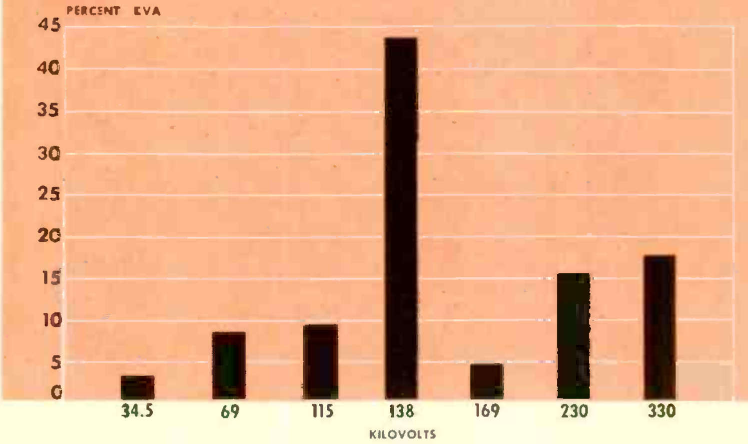
❻ DISTRIBUTION OF UNITS BY KVA RATING FOR 1953-1954
(12 000 to 100 000 Kva)



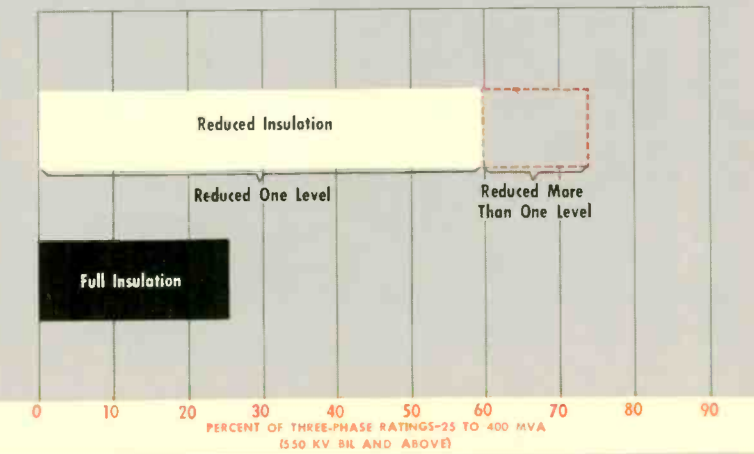
❽ TYPES OF COOLING FOR RATINGS OVER 50 000 KVA
(1952, 1953, 1954)



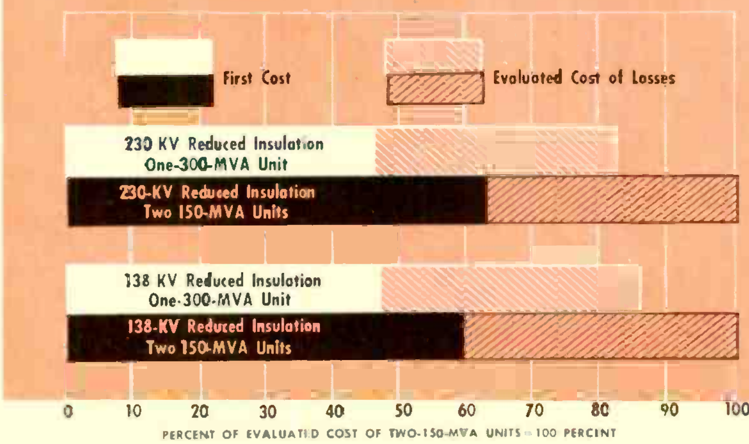
❾ PERCENT OF KVA BY VOLTAGE CLASS FOR 1954
(50 000 to 400 000 Kva, 3 Phase)
(Includes Both Normal and Reduced Insulation)



❿ COMPARISON OF UNITS WITH NORMAL AND REDUCED INSULATION
(1954 Sales)



⓫ COMPARISON OF EVALUATED COSTS FOR 300-MVA GENERATOR STATION TRANSFORMERS



TITANIUM and Vacuum Heat-Treating Furnaces

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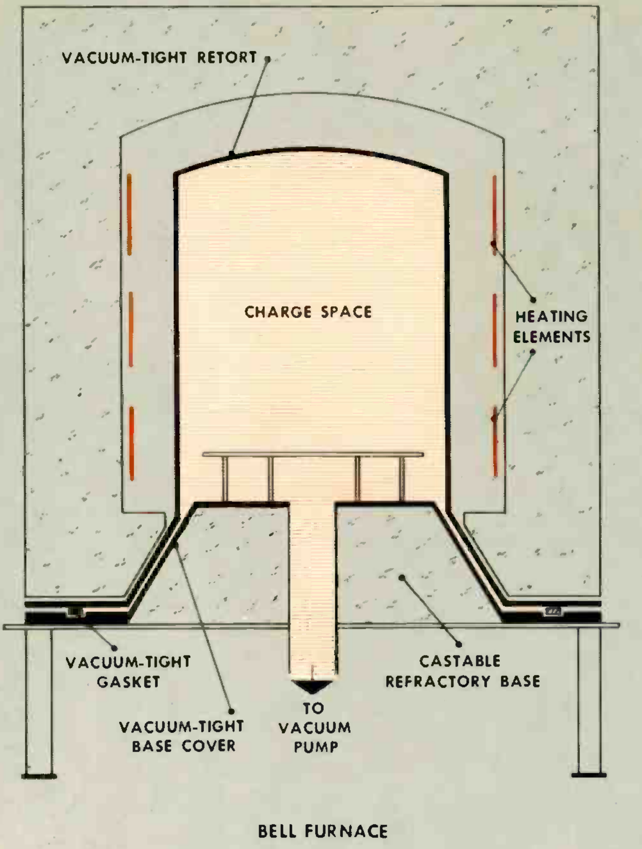

Fig. 1—One type of vacuum furnace resembles the standard bell furnace. Vacuum-tight space (in color) is exhausted through base.

THE ORIGINAL enthusiasm about titanium was dampened somewhat by difficulties encountered in obtaining consistently good results in production of the metal. The metal and its alloys often display erratic physical properties. Investigations showed that the sometimes poor performance of the metal was due to the presence of various contaminants, as has often proved to be the case with more common metals. However, titanium differs from other metals in one important respect—even at moderately high temperatures it reacts with or dissolves all elements other than the inert gases. Thus the problem of preventing contamination is extremely acute, and the protection of titanium during processing is much more complex than most other commercial metals.* Fortunately, methods of reducing or eliminating contamination are being developed; one of these methods involves the use of vacuum heat-treating furnaces.

Vacuum heat treating is a relatively new development on an industrial scale; it came to the fore in the last few years as a result of experience with vacuum techniques in connection with the atomic-energy program. Basically it consists of carrying out heat-treating operations in some type of retort heated internally or externally in a high vacuum. The process is used first to protect the metals from action or reaction due to oxygen or nitrogen in the air, and secondly to remove gases absorbed by the metal or to break up the chemical compounds formed on or in the metal. Thus it actually refines the metal itself.

The Problem in General

Once titanium is in ingot form, the problem of pickup of solid contaminants is lessened; however, preventing gases from being absorbed becomes more difficult, because most subsequent operations are carried out in air.

To prevent gases from embrittling the metal, heating would have to be accomplished in a protective atmosphere. Standard metallurgical atmospheres can be ruled out, since they are composed of gases (CO, CO_2, N_2, H_2) that react with titanium. Since only inert gases can prevent contamination of titanium, the atmosphere would be argon or helium, these two being more readily available than others. However, a protective atmosphere is practical only in the case of annealing, where the

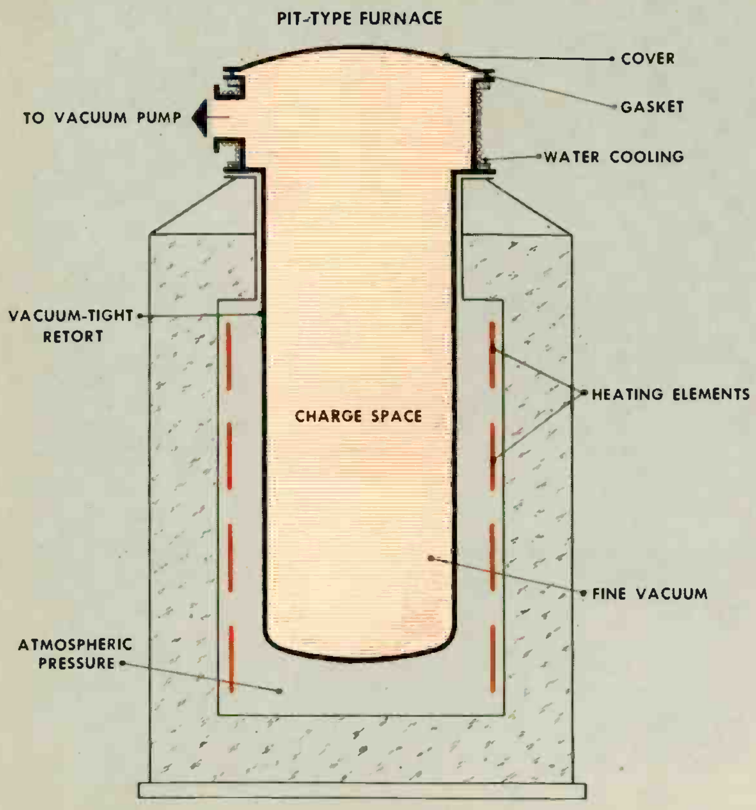

Fig. 2—A pit-type vacuum furnace. Neither the bell type (above) nor the pit-type is suitable for continuous high production.

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*See "The Rise of Titanium," *Westinghouse Engineer*, July, 1952, pp. 114–7.

titanium part is both heated and cooled under some type of protective atmosphere.

In forging or other hot-reduction processes, a protective atmosphere or vacuum only eliminates surface contamination of titanium during the heating period. As soon as the hot metal is taken out of the furnace for hot forming, it begins to scale. At the present time, most hot-forming operations are done in air, and the final product is well oxidized. Attempts have been made to forge in an inert atmosphere, but this process is generally applicable only where a long production run of a small part is required. Tests have also been made to try to temporarily coat the titanium with various metals to prevent contamination by the atmosphere during forging.

One difficulty with titanium is that once the metal has been contaminated, there are a few practical ways to reclaim it. Titanium with an oxidized surface regains its brightness when vacuum annealed. A common assumption is that the oxide film is decomposed by the vacuum under normal operating conditions; however, quite the reverse is true. The oxygen actually diffuses inward, thus lowering the mechanical properties of the titanium.

Removing the scale, which consists largely of titanium oxide and nitride, can be accomplished by either pickling or by mechanical means. Where the part is small, of thin gauge, or has close tolerances, the usual procedure is to pickle. This has one serious drawback. Pickling is usually done in a sodium-hydride descaling bath and a solution of hydrofluoric and nitric acid. To remove the scale, the metal must remain in the hot pickling bath for some time; the result is that hydrogen from the process diffuses into the metal. Pickling leaves the surface of the metal clean and bright, but the additional hydrogen introduced in the metal affects the physical properties adversely.

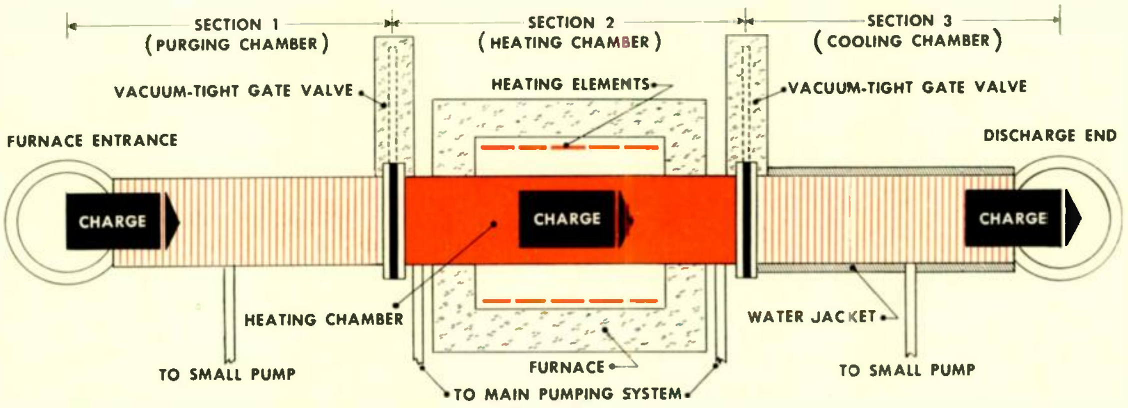


Fig. 3—A three-stage semi-continuous vacuum furnace. The heating area, section 2, is always under vacuum. Gate valves are opened if a vacuum is on both sides.

The presence of hydrogen in titanium in excess of 150 parts per million (by weight) decreases the ductility of the metal and leads to premature failure. While the usual titanium specifications call for less than 150 parts per million, the Air Force has recommended less than 125 parts per million and, in general, the manufacturers are trying to lower that content as much as possible. In spite of their efforts, titanium sometimes contains as much as 500 parts per million and, since it is not acceptable, must be either scrapped or vacuum refined. This operation of refining is generally referred to as *vacuum annealing* and is actually a combination of annealing and degassing treatments in one step.

Vacuum-Annealing Furnaces

The simplest type of vacuum furnace, which is frequently used in the laboratory or for limited production runs, consists of an alloy container with a pipe connected to a pumping system. The work is placed into the retort and then welded vacuum tight and placed inside a standard box-type furnace. After heat-treating, welds are ground off and the work removed.

A typical vacuum furnace based on this principle would be similar to a standard bell furnace (see Fig. 1). The work is placed on the base, which is made of castable refractory covered by an alloy plate. A water-cooled flange and vacuum gasket is located on the periphery away from the heat. A flange on the bottom of the vacuum-tight retort fits on top of the gasket, providing a vacuum-tight enclosure. The furnace proper is then lowered over the hood and the heating cycle is ready to start. The connection for the vacuum pumps is provided through the base.

Obviously, this arrangement is not suitable for high production, but is one example of how vacuum annealing can be done. A pit-type furnace in which the heating section and retort are stationary is another example (Fig. 2). Also, in the case of small-diameter retorts, gas-firing has been used. A more elaborate type is a so-called semi-continuous vacuum furnace, which usually has at least three stages (Fig. 3). In such a furnace, the work is charged into section 1, the entrance door closed, and the chamber evacuated. The gate valve at the end of the chamber is opened, and the work transferred into the heating chamber (section 2). When the heating cycle is complete, the charge is transferred into a water-jacketed cooling chamber (section 3) through a second gate valve. Since the gate valves will be opened only when there is a vacuum on both sides, the heating section is always under vacuum. Three separate pumping systems are required: a small one on the entrance vestibule; one on the cooling chamber to create a vacuum after the charge has been removed and the door reclosed; and a large pumping system connected to the heating chamber where the metal will be degassed and a tremendous volume of gas released at the low pressure required. The size of the semi-continuous furnace is limited at the present time to the size of the largest gate valve available, and is used on parts such as jet-engine compressor blading, tubing, bars, bolts, and other small parts.

In the furnaces described above, heat is supplied to the retort, which in turn reradiates it to the charge. When the size of this retort is large or when higher temperatures are used, the wall thickness has to be increased. This thickness of the retort walls usually ranges from one-half to one inch. A thick retort, while providing increased strength, has also the disadvantage of having more heat storage and slowing down the heating of the charge.

The standard vacuum-furnace design can be modified to make it a double-pumped vacuum furnace. In such a design, in addition to the fine vacuum inside the retort, a rough vacu-

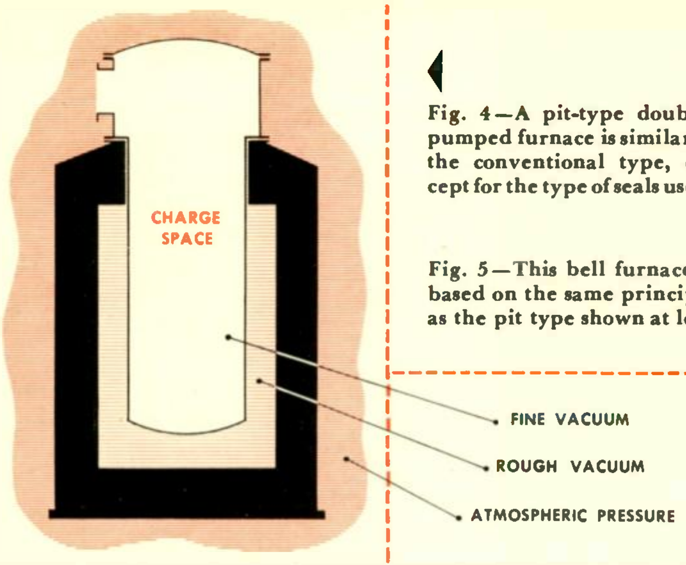


Fig. 4—A pit-type double-pumped furnace is similar to the conventional type, except for the type of seals used.

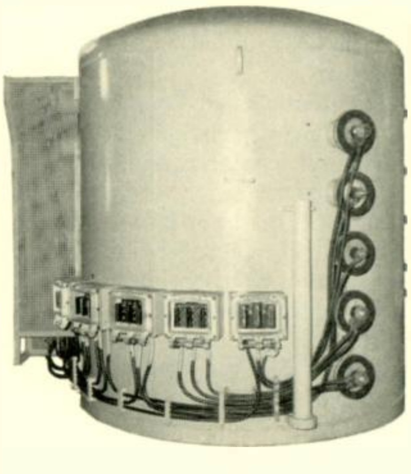


Fig. 5—This bell furnace is based on the same principle as the pit type shown at left.

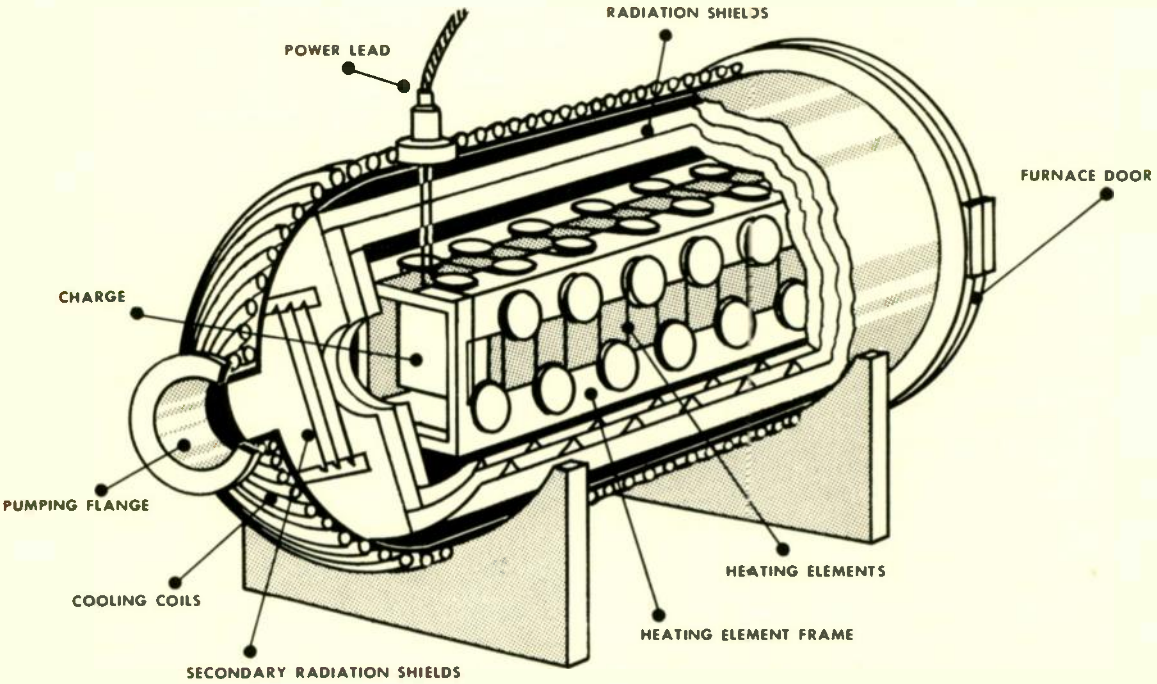


Fig. 6—A schematic representation of the Kold-Retort furnace. In a vacuum furnace, most heat transfer is by radiation. In this furnace, radiation shields reduce the heat losses by reflecting heat inward.

um is maintained between the retort and the furnace shell by a single-stage mechanical pump. By pulling a vacuum around the retort, the atmospheric pressure is transferred from the outside of the retort to the outside of the furnace shell. Since the furnace shell is cold, this pressure does not affect it to any considerable extent. Thus the retort is only subjected to stresses due to its own weight and to repeated heating and cooling. A pit furnace of the double-pumped type would be similar to the one shown in Fig. 4; the main difference between this furnace and that in Fig. 2 is the seal between the furnace and the retort. A vacuum bell furnace based on the same principle is shown in Fig. 5; note also the special seals used for power terminals on double-pumped vacuum furnaces.

The furnaces described above are generally called hot-retort furnaces. They have disadvantages inherent in their designs. The main problem is the life of the hot retort, which is limited because of high-temperature creep of the alloys used. If the retort is distorted, a suitable vacuum seal is difficult to maintain. In actual titanium-sponge distillation installations, the retort took an hour-glass shape after a few cycles, making it impossible to place the rated charge into the chamber.

An unusual furnace—called the Kold-Retort furnace—is designed to overcome that major difficulty. In a vacuum furnace, most heat transfer is by radiation, practically none by convection. The new design, therefore, places the heating elements inside the retort, and uses radiation shields for thermal insulation, eliminating the necessity for refractory brick linings.

The construction of the Kold-Retort furnace is shown schematically in Fig. 6. The charge to be heated is placed on a tray that rests on the heating element frame. That frame is unitized so that it can be removed from the furnace, without being disassembled, for inspection or maintenance. The heating elements are of the sinuous-loop type mounted on special vitreous high-temperature insulators. This frame is supported on the inner radiation shield. Depending on the operating temperature, this frame is made of Hipernik (50 percent Ni and 50 percent Fe) for operation up to 2150 degrees F, and of molybdenum above that temperature.

The radiation shields are cylindrical and made of sheet metal; the number used depends on the operating temperature and the permissible standby losses. These shields have a bright finish, thereby decreasing the emissivity (i.e., increasing reflectivity) and providing better insulating properties. Where a fast heating rate is required, a compromise for the number of shields is reached between the heat losses, which are greater with a small number of shields, and the heat storage, which increases with the number of shields.

Radiation shields are separated from each other and from the shell by small spacers welded to the outside of each one, and arranged to minimize the heat loss by conduction. They are easily removable for cleaning, which is required when surface contamination raises the emissivity to the point where losses increase excessively.

The furnace shell is made of mild steel and since the effect of atmospheric pressure is negligible compared to the tensile strength of steel at room temperature, the shell will have a maximum thickness of one-half inch for the largest furnaces considered. The shell is water cooled by a water jacket for the large units, or by cooling coils for smaller furnaces.

The two main problems encountered in the design of this furnace are the choice of the alloys and the method of cooling. In selecting alloys for structural applications in vacuum furnaces, there are two major differences as compared to ordinary alloys. First, they must have high-temperature strength but resistance to corrosion or oxidation is not required. Second, the presence of chromium in most high-temperature alloys creates a serious problem. Chromium starts to distill out of alloys in appreciable amounts at pressures of the order of one micron of mercury and at temperatures above 1000 degrees C. The problem involved is not as much the contamination of the charge as the danger of arc-over from elements to ground when this high-conductivity distillate deposits on the heating-element supports.

The solution of the alloy problem lies in the use of an alloy composed of metals with low vapor pressure. At the present time, all furnaces are designed with molybdenum or Hipernik depending upon the maximum temperature rating of the furnace. A development program is now under way to find new alloys with the same properties as Hipernik but at lower cost. The biggest problem lies in the heating elements themselves, which operate at the highest temperature encountered in the furnace. Heating elements have the additional requirement that they should have a negligible temperature coefficient of resistivity, to eliminate the needs for transformers with special low-voltage starting taps.

Since the radiation shields are such good insulators, obviously they will slow down the cooling of the furnace considerably. To increase the cooling rate, argon (or preferably helium) is bled into the furnace. In this way, convection cooling is added to the cooling by radiation and the cycle is shortened. Where rapid cooling is required, argon is recirculated through the furnace and through a water-cooled heat exchanger by means of a gas-tight blower. During the heating cycle, this cooling system is separated from the furnace by valves.

At the present time, the Kold-Retort furnaces developed range in size from 2 by 2 by 2 feet of charge space up to 4 by 4 by 15 feet. The temperature range extends up to 3000 degrees F operating temperature.

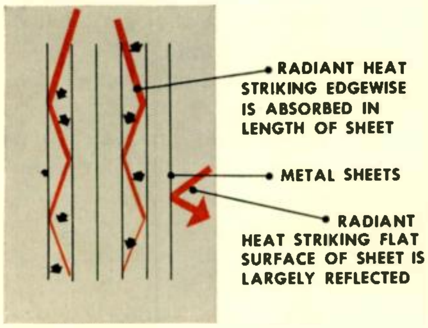
In addition to their main advantage, which is a longer retort life, these furnaces have other interesting features. While in the hot-retort furnace heat is supplied uniformly around the circumference of the retort, the Kold-Retort furnace makes it possible to supply more heat to any given point by suitable distribution of the heating elements or proper zoning of these elements. This feature is important where the charge is composed of titanium sheets. In a vacuum, the flat surface of the sheet does not readily pick up heat, and acts in the same way as the radiation shields used for insulation purposes. Therefore, most of the heating must be done edgewise by conduction through the sheet itself. This is illustrated in Fig. 7.

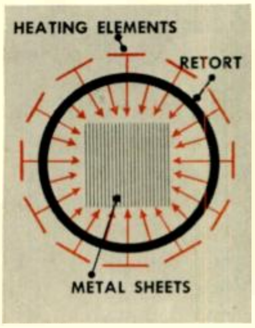
Another feature is the lower impedance to gas flow because of the larger open space around the work. This is very important in annealing where tremendous gas loads are involved.

In general, selection of a furnace for titanium annealing is fairly simple. The primary factors that must be considered are physical dimensions of the furnace, size of charge, heat requirements, and cycle. The main problem is the selection of the proper pump, the difficulties being rate of degassing, pressure at which degassing occurs, removal of adsorbed gases, temperature of gas reaching the pump, exact gas load, temperature of titanium, thickness and shape of titanium. Because of the limited experience in this field, often no two pump manufacturers recommend the same pumping system for a given application. Actually, theoretical computations can be made easily to select the correct pump, but these are outside the scope of this article.

While vacuum heat treating initially entered the commercial field mostly for titanium and zirconium, new applications have appeared recently. One is the bright annealing of stainless steel, which gives better results than any commercial atmosphere, and may result in lower operating costs. Another one is brazing and nicrobrazing, mainly of honey-comb structures for aircraft applications. As the practical experience with vacuum heat treating accumulates, some day the vacuum furnace might replace most of the protective-atmosphere furnaces for the heat treating of metals.

Fig. 7—These diagrams illustrate the principles on which the Kold-Retort furnace are based.



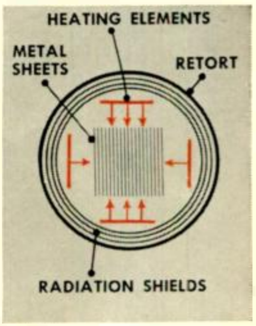


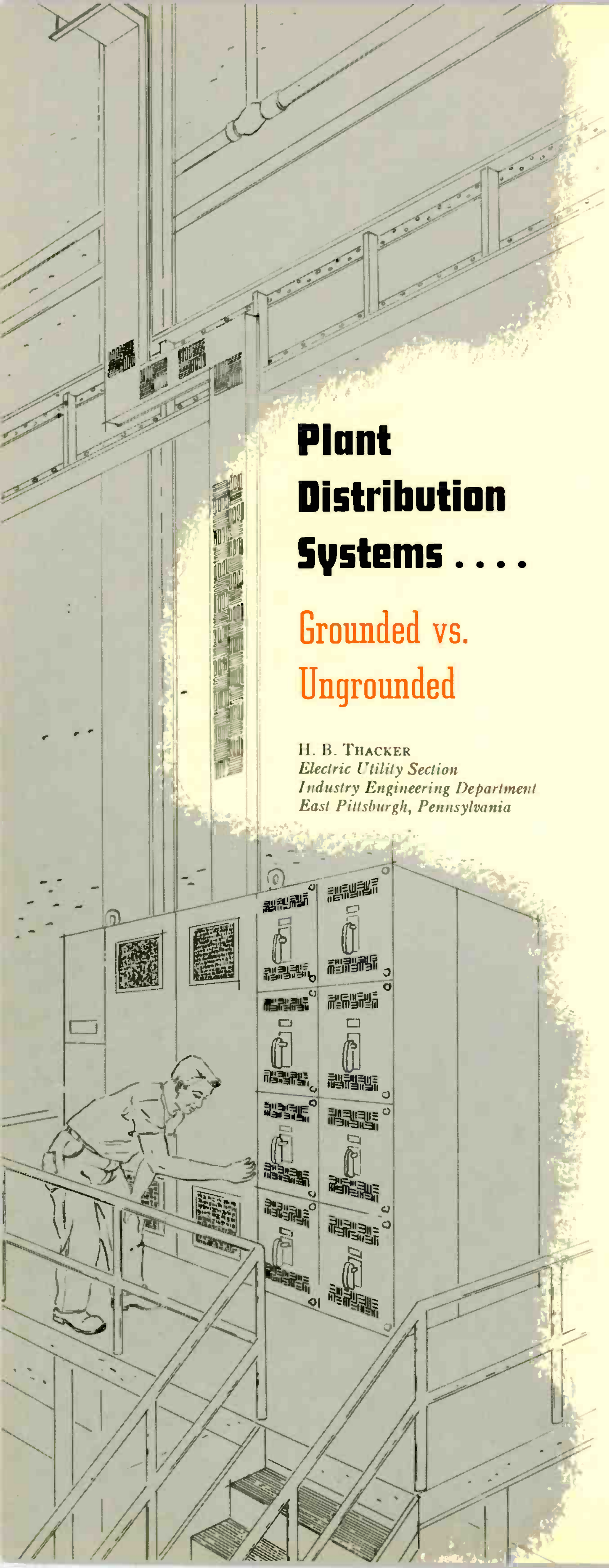
CONVENTIONAL FURNACE

Only radiant heat striking sheet edgewise is useful in heating sheet in vacuum. Since heating elements are outside of retort, heat cannot be applied selectively. Very little heat is radiated inward through the sheet and this region will overheat causing the control thermocouple to turn off the power to the whole furnace and increasing the overall heating time of the charge.

KOLD-RETORT FURNACE

Heat can be applied selectively, i.e., more heat applied edgewise, thereby providing maximum heating rate.





Plant Distribution Systems . . . .

Grounded vs. Ungrounded

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The ungrounded system was used almost universally for low-voltage, a-c plant distribution until approximately 15 years ago; the present trend favors grounded systems, although a number of factors should be considered.

Because of the separate advantages of both grounded and ungrounded low-voltage a-c distribution systems, plant electrical engineers are more and more frequently faced with the problem of choosing the system best suited to their particular needs. This is true whether the engineer is concerned with new construction or expansion of existing facilities. And if the choice is for a grounded system, the companion question of how to ground must be resolved.

A *grounded* system has at least one conductor or point in the system permanently and intentionally connected to ground, either by a solid metallic connection or through some form of current-limiting impedance. The direct opposite is the *ungrounded* system, which has no metallic connection normally existing between any current-carrying conductor, or point in the system, and ground. However, the neutral of an ungrounded three-phase system is normally close to ground potential because of the balanced electrostatic capacitance of each phase conductor to ground.

Two factors are largely responsible for the use of ungrounded systems: (1) Contact between one phase of the system and ground does not cause an immediate outage, and (2) the cost of an ungrounded system is less than that of a grounded system. The first probably represents the principal advantage of the ungrounded system, but its importance varies with the application. The second factor is usually small in relation to overall system cost when a new installation is designed for grounded operation. Grounding may be considerably more costly for an existing ungrounded system unless there is a readily available neutral point.

Possible advantages of the grounded system are: (1) Somewhat more safety for both personnel and equipment; (2) reduced hazards from overvoltages; and (3) easier location of ground faults.

Ground Faults

Ground faults on one phase of an ungrounded system cause no service interruption. However, a second ground fault on a different phase occurring before the first fault has been cleared will result in fault current similar to a phase-to-phase fault and will result in an outage. If both faults are on the same feeder, only that feeder is dropped; if the second fault is on a different feeder, both feeders are dropped.

The longer a single-ground fault is allowed to remain on the ungrounded system, the greater is the likelihood of a second ground on another phase causing an outage of one or possibly two circuits. The effect on the total circuit outage time for the ungrounded system is shown in Fig. 1, with the assumed conditions that every outage on an ungrounded system involves two circuits, which is somewhat pessimistic. This may be partially offset, however, by the assumption that the time an ungrounded circuit is out for repair is the same as for a grounded circuit. If grounds are removed shortly after occurring, the number of grounds experienced per year must be high before the grounded system shows less outage time than the ungrounded system. The practice of ignoring a ground until a second one occurs and repairs are required to restore service has been rather common in some plants operating ungrounded systems. However, the overall result may well be more numerous and extensive outages than if the system had been grounded, thereby eliminating the advantage of the ungrounded system. In order to fully utilize the service-continuity advantages of the ungrounded system, a well-organized maintenance program should be followed to assure that accidental grounds occurring on the system are located and removed soon after detection.

Ground-Fault Location

Many methods have been used to detect and locate ground faults on the ungrounded system. Since only small values of current flow in ground contacts, detection and location by visual disturbance or by observation of load-current meters is generally impossible. The most common method of detecting the presence of a ground employs lamps to indicate the potential between each phase and ground, as shown in Fig. 2a. An extinguished lamp indicates the presence of a ground and the phase involved. However, ground lamps will not indicate the feeder circuit on which the fault has occurred. Locating a ground fault on one feeder among a number of possible feeders out of one step-down substation often requires removal of one feeder at a time until the ground detector indicates the fault has been removed from the system.

If faults exist on the same phase of two different feeders at the same time, a different procedure is required. Usual practice is to de-energize all feeders from the substation concerned, restoring them to service one at a time and checking the ground detector as each feeder is restored. The same general procedure may be used to locate the particular branch circuit containing the ground.

Other schemes have been used successfully to locate the ground point on a particular feeder. These usually involve some form of tracing current, such as an interrupted d-c applied between the grounded phase and ground. The current path is traced to the point of fault by means of a pick-up-coil detection unit.

The location of ground faults without de-energizing feeders is desirable in many plants. Several methods have been used with varying degrees of success. These methods are advantageous because they permit locating grounds without waiting for light-load periods in the plant. One company successfully uses only an inexpensive, low-reading portable voltmeter. While their low-voltage feeders are carrying load current, a small voltage can be read between the grounded phase and ground. This voltage, caused by the load current flowing through the circuit impedance to the point of fault, diminishes to zero at the fault point. The voltage fluctuates exactly in unison with load current fluctuations on the grounded feeder. Hence, this method can be used to first determine which feeder is grounded and then to approximately locate the fault.

An accidental ground in a grounded system is indicated and located approximately by the fault-interrupting devices. In a system having properly coordinated overcurrent devices, such as circuit breakers or fuses, the ground fault should operate only the device nearest to it on the supply side. This together with the possibility of visual indication of the fault itself usually makes fault location on the grounded system relatively simple.

The arcing and burning caused by high ground-fault current in the grounded system may be considered a disadvantage from the standpoint of damage to circuits or equipment. This is particularly true when the ground occurs between winding and core of a motor or generator. The resultant burning of the iron in the core may require complete rebuilding of the unit rather than simply rewinding it. However, the possibility of this happening in low-voltage systems is small, due to the fast opening speed of the overcurrent devices generally used.

Overvoltage

While overvoltages, both transient and sustained, may occur in any system from a number of sources, the problem of equipment failures due to excessive overvoltage in the ungrounded system is often considered a factor in favor of the grounded system.

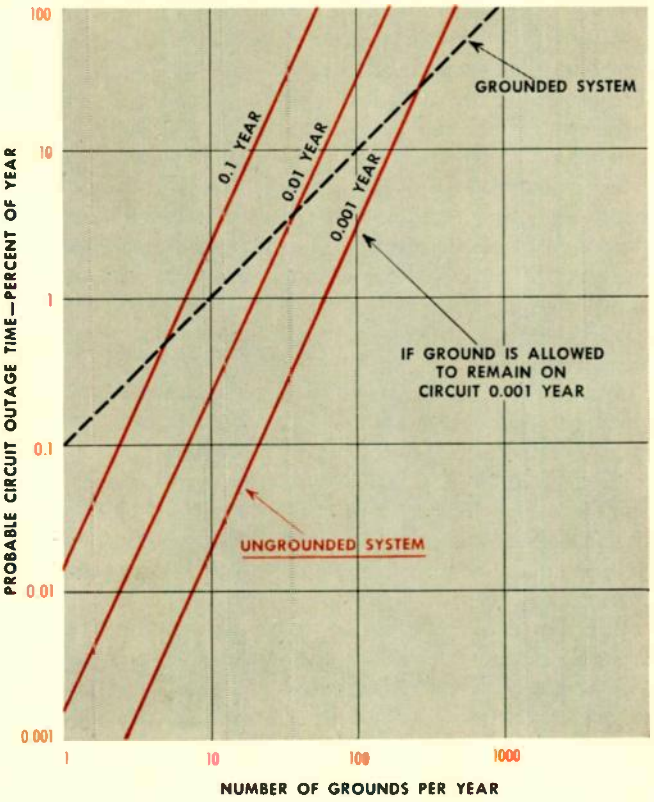


Fig. 1—Comparative annual circuit outage is shown for grounded and ungrounded systems.

Some of the more common sources of overvoltage on a power system are: (1) ground faults, arcing or solid; (2) switching surges; (3) lightning; (4) static; (5) circuit resonance under fault conditions; and (6) contact with a higher voltage system. Some of these overvoltages are transient, and some may be sustained.

A sustained overvoltage occurs on an ungrounded three-phase system when one phase is grounded. The insulation of the other phases is subjected to voltage 73 percent above normal. While the overvoltage seldom approaches the insulation levels of equipment and circuits, the cumulative effect of higher than normal voltage stresses may somewhat reduce insulation life.

Field experience and theoretical studies have shown that under rare conditions arcing-ground faults on ungrounded systems can produce surge voltages as high as six times normal line-to-ground voltage. The condition necessary to produce this overvoltage requires the dielectric strength of the arc path to build up at a higher rate after each arc extinction than it did for the preceding extinction. This phenomenon is not likely to occur in open air between stationary contacts. It may occur in confined arcs where pressure can increase after each conduction period. Neutral grounding is effective in reducing transient-voltage buildup from arcing-ground faults by reducing neutral displacement from ground potential and preventing high-frequency voltage oscillation after each fault initiation or restrike.

Normal switching operations can cause overvoltage. Generally, these are not more than three times normal voltage and are of short duration. Overcurrent devices such as circuit breakers or fuses generally interrupt a circuit at a normal current zero, when the stored energy in the inductance of the circuit is zero. The overvoltages developed result from transient oscillation in circuit capacitance and inductance. More serious overvoltages can be produced by devices which interrupt by forcing current zero. Current-limiting fuses, which tend to force current zero, must be carefully applied.

Most industrial systems are effectively shielded against direct lightning strokes. Many circuits are either underground in ducts or are within grounded metal conduits or raceways. Even open-wire circuits are often shielded by adjacent metallic structures and buildings. Lightning arresters applied at the incoming service limit surge voltages within the plant resulting from strokes to the exposed service lines. Other arrester applications may be necessary within the plant to protect low-impulse-strength apparatus, such as rotating machines and dry-type transformers.

Neutral grounding is not likely to reduce overvoltages caused by lightning and switching surges. It can, however, distribute the overvoltage between phases, thereby reducing the possibility of an excessive stress on the insulation of a particular phase.

Buildup of overvoltage on power-system conductors due to static charge is not usually a problem in modern plants with metal-enclosed circuits and equipment. Static charge on moving belts can build up voltages that can be transmitted to the power system if motor frames are not properly grounded. Overhead open-wire lines may be subject to static overvoltages resulting from certain atmospheric conditions. A system-ground connection, even of relatively high resistance, can effectively prevent static voltage buildup.

Ungrounded systems may be subjected to resonant overvoltages if the system is large. A large amount of circuit capacitance-to-ground can produce a condition of approximate circuit resonance during a line-to-ground fault through an inductance, such as the coil of a motor-starting contactor. The voltage-to-ground of the unfaulted phases will then be considerably higher than line-to-line voltage. On the other hand, the grounded-neutral system prevents overvoltage by holding the phases to their approximate normal voltage above ground.

Contact with a higher voltage system may be caused by a broken high-voltage conductor falling across a low-voltage conductor where both lines are carried on the same poles, or by breakdown between the high- and low-voltage transformer windings. If the low-voltage system is ungrounded, the high voltage will remain on the low-voltage system and cause breakdown of insulation, possibly at several points. A solidly grounded low-voltage system, though resulting in high values of fault current, will hold the system neutral close to ground potential and greatly reduce the overvoltages to ground.

Safety

A solidly-grounded, low-voltage system is probably somewhat less hazardous to personnel than a system that is supposedly ungrounded. If maintenance personnel treat all circuits with equal care and respect, the hazard of shock on an ungrounded circuit is slightly less. However, a subconscious tendency to be less careful in working on a normally ungrounded, energized circuit often exists, even though the impression that one phase of the ungrounded circuit can be safely contacted is often false. The subconscious knowledge that the circuit is grounded usually results in more careful handling by the workmen.

Some hazard of shock to personnel exists should they bridge all or part of a high-impedance ground path during ground faults on either a grounded or ungrounded system. The impedance of the path to ground or between two grounds may be high enough to prevent sufficient current flow to operate protective devices that would open the defective circuit. Another hazard of this same condition is the possibility of fire from sparks, or localized heating in the current path. Adequate grounding of equipment and structures will reduce these hazards even though the system itself is ungrounded.

Methods of Grounding

Low-voltage systems are generally grounded solidly, i.e., with no intentional impedance in the ground connection. Solid grounding is used to obtain sufficient ground-fault current to operate overcurrent protective devices. Ground relaying is rarely used in low-voltage systems, and circuit breakers, operated by self-contained series-trip coils, require relatively high values of fault current in order to recognize a ground fault. Even a small value of grounding impedance is likely to reduce the current below the trip setting of the protective device.

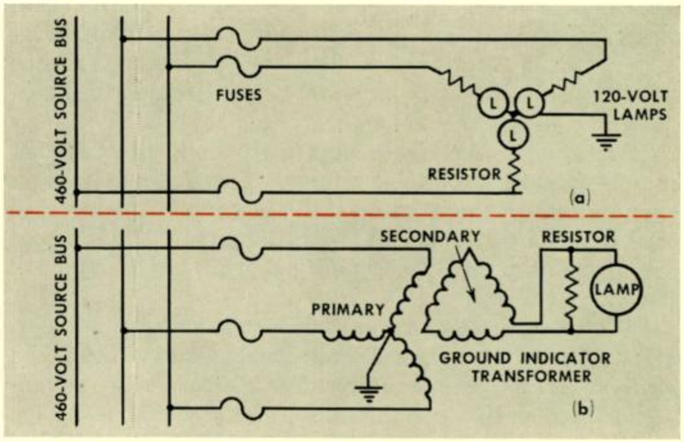


Fig. 2—Two typical ground indication schemes: (a) indicates ground fault in the phase in which a lamp goes out; (b) indicates a ground, but not phase, if lamp lights.

One exception to this occurs when the neutral of a generator is grounded. The phase-to-ground fault current from a generator is likely to be greater than the three-phase fault current for which the generator windings are mechanically braced. The generator neutral should then be grounded through an impedance sufficient to limit the ground fault current to not more than the three-phase value.

One of the two basic methods of grounding low-voltage systems is to connect the secondary sides of the power center transformer in wye, bringing out and grounding the neutral point at each power center; the other is to ground one phase or one corner of the delta-connected power-center secondaries, as shown in Fig. 3.

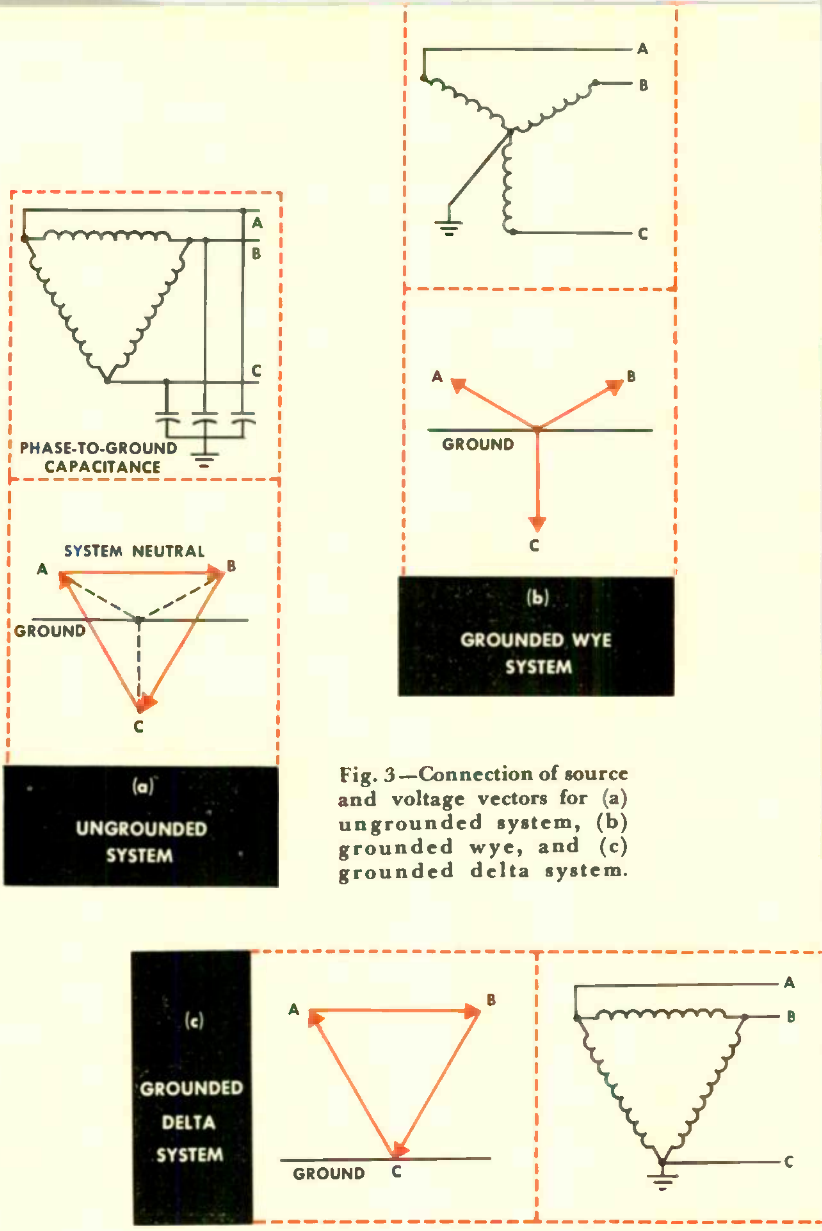


Fig. 3—Connection of source and voltage vectors for (a) ungrounded system, (b) grounded wye, and (c) grounded delta system.

The grounded-wye scheme has several advantages. Most important is that phase conductors normally operate at equal voltage above ground. These voltages are less than the line-to-line voltage and less than the voltage-to-ground from two of the phase conductors when one corner of a delta system is grounded. This is particularly significant in 575-volt circuits where conductor insulation must work at practically full-rated voltage in grounded-delta circuits. The lower voltage stress to ground in the grounded-wye system probably decreases the number of insulation failures in mains and devices operated on 575- and 460-volt circuits.

The chief disadvantage of wye-connected neutral grounding is its somewhat greater cost, compared to delta grounding. Protective devices in the grounded-wye system should be equipped with an over-current element in each phase to recognize all ground-fault conditions. More expensive motor-control devices may be required, but present practice is to provide three overcurrent elements in all low-voltage air circuit breakers. Transformers for grounded-wye service on the low-voltage side cost from one and a half to six percent more than delta-connected transformers. Usually it is not necessary to carry the neutral wire along with the three-phase circuit unless the circuit supplies single-phase loads connected from line-to-neutral, as in 120/208-volt circuits with a 120-volt lighting load. Therefore, there is no additional circuit cost to charge against the grounded-wye arrangement. The additional costs of grounded-wye transformers and controls with three overcurrent elements are appreciable when compared with the cost of the devices, but when these additional costs are considered in the total system cost, they are generally small.

In recent years a substantial percentage of industrial secondary substation transformers for new plant installations have been purchased with wye-connected, low-voltage windings suitable for neutral grounding. In new installations, these transformers offer the advantage of being applicable to an existing ungrounded system while having the neutral available for grounding if desired at some future time. The small additional cost of the grounded-wye over the grounded-delta system can generally be justified in new systems by the advantages of the grounded-wye system.

If the transformers of existing systems have their secondaries wye-connected with the neutral point available outside the tank, there will be little trouble or expense involved when changing to a grounded-wye system. Since this is not generally the case for most existing ungrounded systems, there is considerably more incentive for grounding one phase and operating the system grounded-delta if grounding is considered desirable.

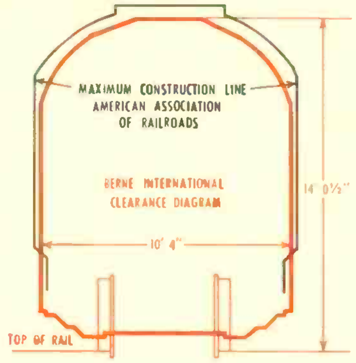
To obtain a neutral point for grounded-wye operation when the secondary substation transformers are delta connected, a grounding transformer is generally used. The transformer windings are connected either in a wye-delta or zig-zag arrangement so that they do not carry load current, but serve as a source of ground-fault current. Grounding transformers for low-voltage systems must be relatively large in kva rating in order to carry ground-fault current necessary to operate low-voltage protective devices.

Conclusions

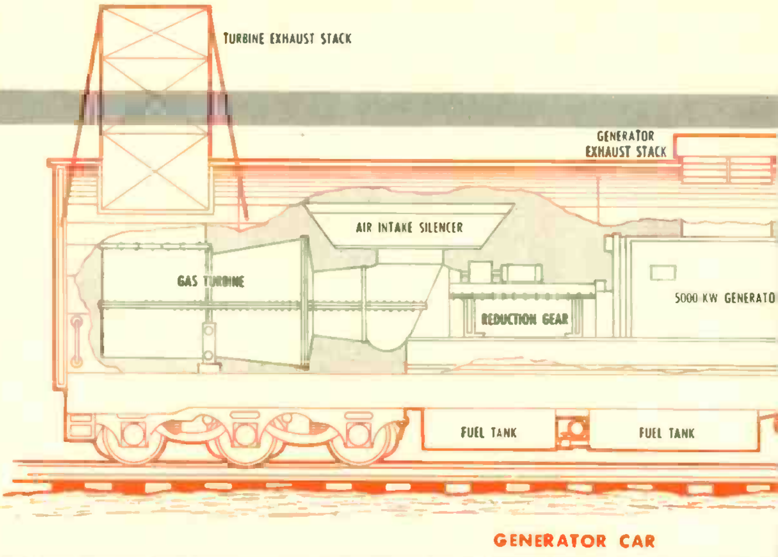
By grounding an industrial system, differences in electrical potential between all uninsulated conducting objects in a local area are limited, isolation of faulty equipment and circuits is provided, and overvoltages are limited. A considerable difference of opinion exists regarding the likelihood of overvoltages occurring and their severity on ungrounded low-voltage systems, especially those cases that result from an arcing or intermittent ground fault. Apparently, relatively few cases are on record of severe, multiple failures of circuits and equipment that can be tied to an arcing or intermittent ground fault. Because of the difficulty of substantiating the existence and magnitude of an overvoltage condition, it may have been the cause of certain "unexplainable" failures in some plants. Even with the wide usage of the ungrounded system, there is no preponderance of evidence to indicate that it is generally unsatisfactory from this standpoint. Nevertheless, overvoltages can and do occur, and system grounding may reduce or eliminate them with less likelihood of damage to equipment or circuit insulation.

The possible advantages of better service continuity and less cost are responsible for the popularity of the ungrounded system. This is particularly true of the low-voltage portions of industrial systems, which until recent years have nearly all been ungrounded. There has been some trend toward grounding low-voltage systems in recent years to overcome some of the disadvantages that are attributed to ungrounded operation.

In general, the grounded system may be preferable, but in plants where service continuity is important, the ungrounded system, properly maintained, can substantially reduce outage time and production losses.



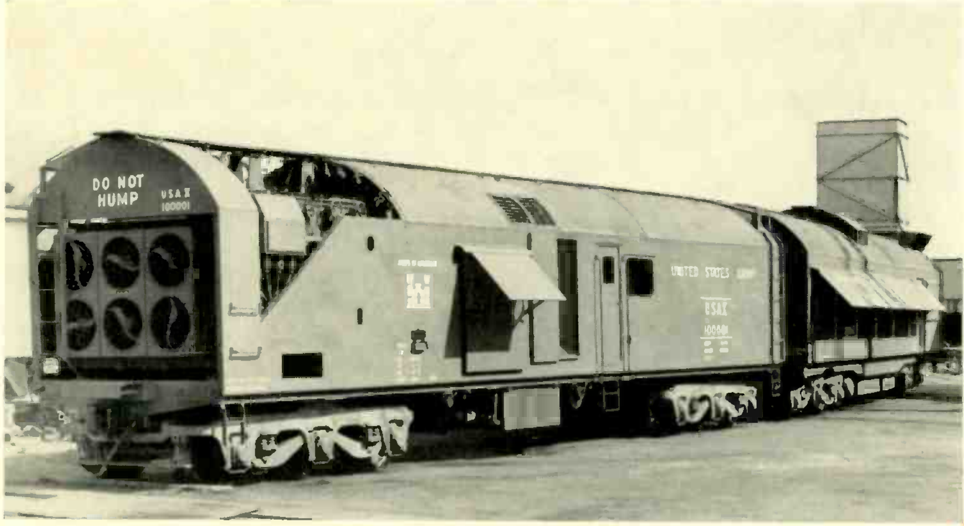
5000-Kw RAILWAY-MOUNTED Gas-Turbine Power Plant



This article is based on an ASME paper presented by C. H. Giroux, Special Assistant to the Chief of Engineers, Washington, D. C., and J. O. Stephens and R. J. Nolte, Westinghouse Electric Corporation.

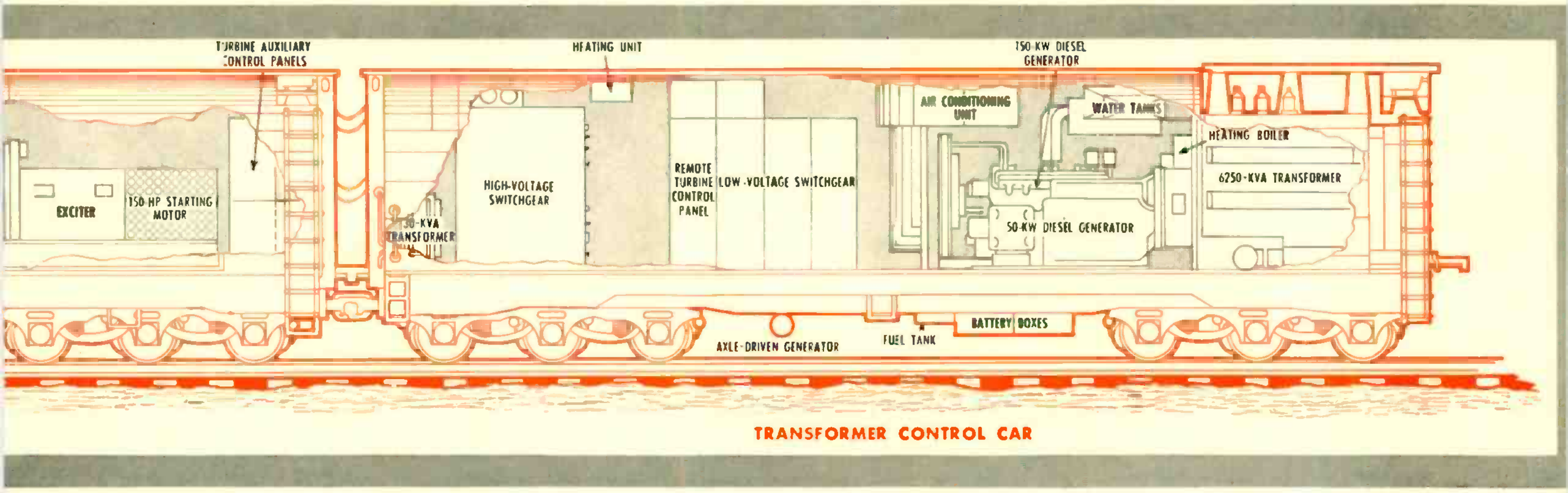
An adequate supply of electric power in military theaters of operation is one of the many responsibilities of the Corps of Engineers. Support of civilian economy in such theaters to the extent necessary to prevent disease and unrest requires operation and maintenance of such facilities as water supply, sewage disposal, lighting, heating, and some industrial activity. All of these require electric power at the voltage and frequency of the locality involved. The need for an intermediate-sized power supply that can be transported readily seems to be best fulfilled by a railway-mounted unit.

Railway-mounted steam plants developed and constructed during World War II appear too complicated and cumbersome for extensive use. (For example, eight cars were required for a 5000-kw steam turbine



The turbine-generator car is shown during construction by the carbuilder, Puget Sound Bridge and Dredging Company, at their yards in Seattle, Wash. The removable roof sections and hinged sides provide for easy access for major maintenance.

This 5000-kw gas-turbine power plant, mounted on two 54-foot railway cars, is suitable for service throughout most parts of the world. The gas turbine offers the most compact railway-mounted power plant of any prime mover of equal capacity.



and its necessary auxiliary equipment.) Recent developments in gas turbines suggested a portable power plant of medium capacity suitable for use anywhere in the world. The gas turbine's simplicity, light weight, compactness, and freedom from cooling-water requirements offer distinct advantages for this kind of service. The many problems of adapting a gas turbine to the application prompted the Corps of Engineers to have a pilot model built, which will be used to establish criteria for further procurement and to train operating personnel.

Many limitations and requirements contributed to the problem of designing and constructing a suitable unit. The car could not be designed around the equipment since length, width, and height of the cars must meet the Berne International Clearances. Consequently, the equipment had to be designed in many cases to conform to these established limits. Other special requirements such as track gauge, type of couplers, and brakes had to be considered to make the plant capable of being transported over foreign as well as American railroad lines.

One of the first problems that had to be solved was the requirement for multi-gauge operation. The cars and their trucks had to be adapted not only for the standard American gauge of 56½ inches but also for 60-, 63-, and 66-inch gauges that are encountered elsewhere in the world. Therefore, the special trucks are adaptable to the four different track gauges named. Additional brake lugs have been cast integral with the truck frames so that the brake equipment can readily be shifted as needed for the various gauges. Each different track gauge will require a different set of axles, with wheels pressed on to the proper dimensions to accommodate the desired track gauge. With axle and wheel sets stored at strategically located overseas depots, it becomes relatively simple to convert the railway cars to the track gauge required. The structures housing the draft gears have been designed to accommodate foreign couplers.

The plant must be self-contained so that no additional equipment is required except that necessary for fuel supply. Power must be produced at either 50 or 60 cycles at the proper voltage, depending upon the locality in which it is used. Since the plant may be called upon to operate in any part of the world, it must be able to start and operate at any temperature encountered in tropical or arctic climates. This presents the problem of ventilation in warm climates, and prevention from freezing in cold climates. During transportation from one location to another and during times when the main unit is not in operation and is disconnected from any external power supply, light, heat, or cooling must be provided for safety and for the comfort of operating personnel.

The components comprising the railway-mounted power plant are arranged on two 54-foot long railway cars. The complete power plant is shown diagrammatically on this page. The turbine-generator car contains the following equipment: (1) 5000-kw turbine-generator unit with exciter; (2) 150-hp wound-rotor starting motor connected to the turbine generator by a clutch-type coupling; and (3) turbine auxiliary control panels.

The transformer-control car contains: (1) 6250-kva outdoor transformer; (2) 150-kw diesel-generator unit; (3) 50-kw diesel-generator unit; (4) 30-kva transformer; (5) high-voltage switchboard; (6) low-voltage switchboard; (7) remote turbine control panel; and (8) all auxiliaries such as car-heating boilers, air conditioning, 32-volt batteries, and 4-kw axle-driven generator.

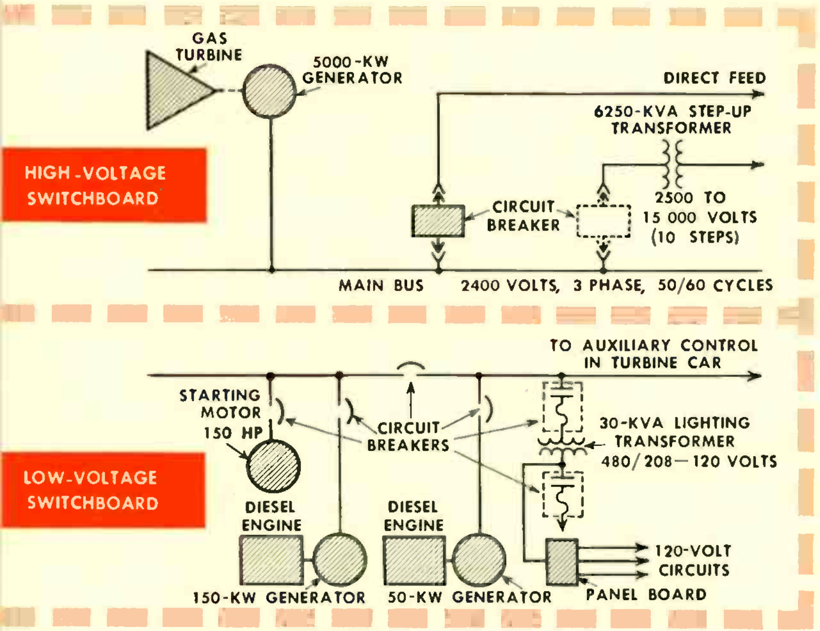
The roofs of both cars are constructed in removable sections to provide access to equipment for major overhaul. The sides of the turbine-generator car are equipped with filters in hinged frames and adapted for easy removal for cleaning. These filters are covered by hinged steel sections when the turbine-generator unit is not in operation. Also, the sides of this car, and of the other car at the diesel-generator sets, fold down to form a catwalk, which facilitates adjustments and minor repairs. The sides of the transformer-control car, except where diesel engines are located, are not hinged and are not removable.

The control room, located in the transformer-control car, is equipped with air conditioning and heating equipment to provide comfortable working conditions for the operator under all ambient temperatures that are likely to be encountered during operation.

The 5000-kw gas turbine takes air from both sides of the car through filters and an inlet silencer. It passes through a 16-stage axial-flow compressor where it is compressed to approximately six atmospheres, then to six combustion chambers enclosed in an annular housing where fuel is burned. The air expands through a five-stage reaction turbine and is discharged to atmosphere through a 12-foot collapsible exhaust stack.

The casing of the compressor, combustor, and turbine is built with sufficient strength to maintain alignment of the rotating parts, thus eliminating the necessity for an additional bedplate under the turbine unit. The compressor and turbine rotor are a single unit with two end bearings, thereby providing access to the bearings without disturbing the main turbine. This two-bearing design also eliminates all high-pressure air seals and bearings adjacent to the hot metal parts of the turbine and combustor, and minimizes the effect of possible external misalignment. Leakage air is not lost from the cycle and a path for the cooling air for the turbine rotor and stator is provided without the need of any external cooling connections.

To facilitate maintenance, a single horizontal joint is provided on the compressor, combustor, and turbine covers so that they can be lifted individually or as a unitized assembly without disturbing the rotating element. The stationary vanes are removable, so that a complete inspection of all blading can be made without disturbing the rotating element.



The bearings are standard pressure-lubricated sleeve type and the residual thrust load of the compressor and turbine combination is carried on a segmental-type thrust bearing at the inlet to the compressor. The compressor casing is fastened rigidly to the reduction-gear case. The turbine end is supported on vertical trunnion supports to allow for axial expansion. The rotating element is connected to the reduction gear through a flexible quill shaft, thus minimizing the effect of any thermal misalignment between the turbine, compressor, and gear.

The reduction gear consists of two sets of double-helical pinions and gears for reducing the speed from 5745 to 3600 rpm for 60-cycle operation, and to 3000 rpm for 50-cycle operation. In order to facilitate changing from 60 to 50 cycles, the reduction-gear sets are interchangeable and designed so that gear-ratio changes can be made without disturbing alignment of the auxiliaries.

The fueling system consists of two 600-gallon day tanks mounted beneath the gas-turbine car from which a fuel pump, direct driven from the gear, takes suction for supply of fuel to the gas turbine. The level of fuel in the day tank is maintained by a rotary pump, controlled by a float switch. Fuel oil can be stored in tank cars spotted alongside the two-car power plant and connected to the day tank through flexible hose. The gas turbine is equipped to burn distillate fuel oil, which requires only a small amount of heat in the day tank to keep the distillate fuel fluid for ambient temperatures as low as —40 degrees F. Since lubricating oil is cooled with an oil-to-air cooler, the gas turbine requires no water, which might cause freezing or corrosion difficulties.

The tested performance of the power plant, based on the higher heating value of fuel oil, shows an overall plant efficiency of 18.5 percent at rated load and 19.5 percent at 125 percent of rated load, including all auxiliaries.

The high-voltage switchboard controls the output from the 5000-kw generator at either 50 or 60 cycles. It provides switching to allow the generator's output to be transmitted directly to the system or to the 6250-kva transformer and then to the system. This switchboard is located at the end of the transformer-control car in the control room. A drawout air circuit breaker, rated at 2000 amperes, may be inserted in either of two locations (see figure at left), thereby providing a foolproof interlock between direct feed and transformer feed. An air circuit breaker was chosen to eliminate the periodic maintenance of oil required for oil breakers. The air circuit breaker is withdrawn to the test position when the power train is in transit to prevent damage from shock. The truck on which the air circuit breaker is mounted is provided with a jacking arrangement to remove the truck wheels from the floor and lock the breaker in the test position. The arc shields are also removed during transit and stored in a rack provided for this purpose.

Two diesel-engine generator sets are provided for starting and auxiliary power. One set, rated 150 kw, 440 volts, 60 cycles, powers the 150-hp wound-rotor starting motor, and the other set, rated 50 kw, 440 volts, 60 cycles, is used for auxiliary power. The diesel-generator sets are installed in a separate room adjacent to the control room. A low-voltage switchboard controls the output and distribution of the two diesel-generator units. The primary and secondary of the 30-kva transformer are also controlled from this switchboard. A remote turbine-control panel is mounted adjacent to the low-voltage switchboard.

The 6250-kva outdoor transformer is mounted on the end of the transformer-control car. It is forced-oil and forced-air cooled and will deliver its full capacity at either 50 or 60 cycles. This transformer, including the high-voltage bushings, had to be designed to fit within the Berne International Clearance limits when mounted on the car. Its nominal voltage rating is 2400 to 13 800 volts. The 13 800-volt winding is provided with a no-load tap changer and series-parallel switch to obtain voltages from 2500 to 15 000 volts, all at full kilovolt-ampere capacity. This combination of a no-load tap changer and series-parallel switch makes possible a large number of voltage combinations from 2500 to 15 000 volts.

The gas turbine offers the most compact railway-mounted power plant of any prime mover for equal capacity. This inherent advantage in portable equipment is a large factor in logistical planning of mobile power in times of an emergency.

The gas-turbine plant can travel with both cars coupled together, requiring a minimum of disconnecting. Erection of the 12-foot exhaust stack and connection of a fuel line and electrical leads are the only major set-up operations required.

As liquid fuels keep increasing in application throughout the world and the gas turbine continues toward the use of wider ranges of liquid fuels, this portable power plant becomes more universal for emergency use.

POWER-SYSTEM STABILITY

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THE POWER-SYSTEM engineer is faced with many complex problems in system design and equipment selection for an electric-utility power system. His basic objective is to provide a means for supplying the anticipated load power and voltage requirements with the desired degree of reliability in the most economical manner. The attainment of this objective requires consideration not only of the thermal limitations of the system and equipment, but also of certain inherent electrical limitations on the amount of power that can be transmitted from the source to the load. These electrical limitations are directly related to the ability of the power system to maintain synchronism between the various sources during normal operation and during system disturbances. They may be generally classified as *stability* limits.

Power-system stability has been the subject of extensive investigation since the early 1920's when the first large hydroelectric installations were being developed. Long lines and relatively slow breaker and relay operation made transient stability a serious problem. The high speed of modern breakers and relays coupled with the close integration of power systems has reduced the relative importance of transient stability.

On the other hand, interest in steady-state stability has increased. Shunt capacitors, high-voltage cables, and extra-high-voltage transmission lines used on modern systems cause high power factors during light-load periods. Since the steady-state stability limit occurs at lower generator outputs in the leading power-factor range, the trend toward operation in this range has reduced the margin between the operating point and the steady-state stability limit.

Factors Affecting Steady-State Stability

The maximum power that can be transmitted into the system is a function of the synchronous reactance of the generator, the equivalent system reactance, and the generator and system internal voltages. During steady-state operation, a generator can be represented by an internal reactance (synchronous reactance) and an internal voltage behind this reactance. The relationship of this reactance to the no-load saturation curve and sustained-fault current of a generator is shown in Fig. 2.

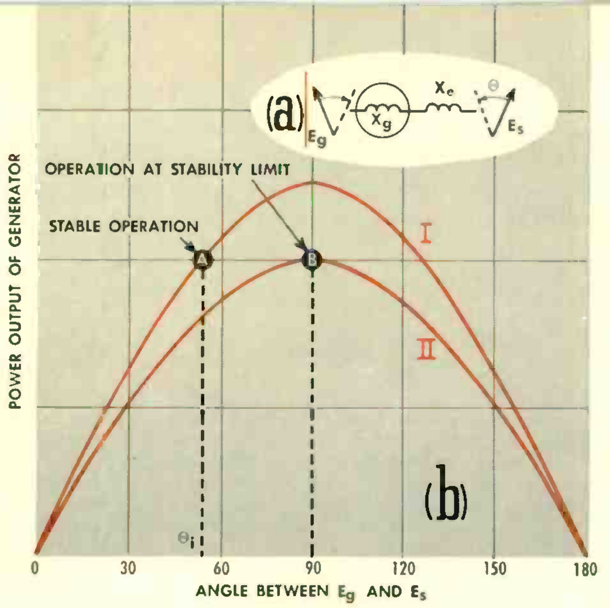


Fig. 1

Steady-State Stability

A typical power system consists of a number of sources or generating stations, interconnected by transmission lines, and supplying loads at various points on the system. The system can be reduced to an equivalent form to simplify consideration of the important factors affecting the stability limits. If attention is focused on a specific generator, the rest of the system can be approximately represented by a fixed voltage, E_s, behind an equivalent reactance, X_e, giving the simple circuit of Fig. 1a. X_g represents the internal reactance of the generator, and E_g the internal voltage. In its simplest terms, the stability problem is reduced to consideration of the limits on the transfer of power through an inductance with certain fixed voltages at the sending and receiving ends. Under these conditions the power transfer is a function of the angle between the two voltages, Θ, as given in Eq. 1 and illustrated by the curves of Fig. 1b.

$$P_s = \frac{E_g \quad E_s}{X_g + X_e} \sin\Theta \qquad \text{(Eq. 1)}$$

The concept of steady-state stability can be illustrated by considering the curves of Fig. 1b. During small, slow load changes the generator can be represented by its synchronous reactance, X_d, and the voltage behind this reactance, which differs from field current only by the saturation in the generator. Assuming the excitation is under manual control, both E_s and E_g will remain constant during a small change in angle. The change in power output can be determined from Eq. 1.

Consider first a machine operating with an angle Θ_i, and an initial loading that results in the power-angle curve as shown by curve I. Any slow system disturbance that results in a small increase in Θ causes an increase in the power output of the generator. Assuming the prime-mover power remains constant, this increase in power causes the generator to slow down and tends to restore the angle to its original value.

If the power output and terminal voltage of the generator are held constant, a change in the reactive power output that causes the generator power factor to become more leading will reduce E_g and increase E_s. The net effect for reasonable values of external reactance is a reduction in the product of the two voltages. This lowers the crest of the power-angle curve. This process can continue until the power-angle curve assumes the shape of curve II in Fig. 1b. A similar change in the power-angle curve would result from a reduction in terminal voltage for a fixed real and reactive power loading.

If a generator initially operates at point B on curve II, any small increase in Θ results in a decrease in the output power. The resultant increase in generator speed for a constant prime-mover input causes a still further increase in the angle Θ, which continues until the machine loses synchronism with the rest of the system. Thus, point B is the *steady-state stability limit*.

Fig. 2

Synchronous Reactance and Short-Circuit Ratio

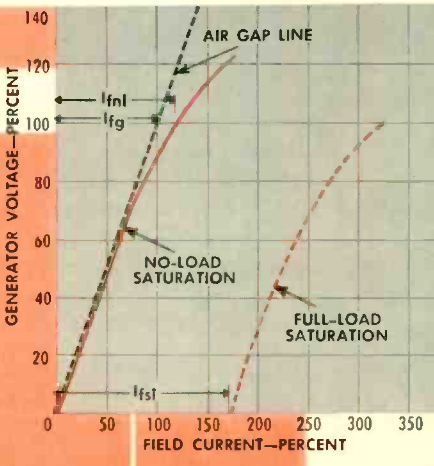
The relationship between synchronous reactance (X_d) and short-circuit ratio (SCR) can be shown on this typical saturation curve for a 0.64-SCR machine.

$$SCR = \frac{I_{fnl}}{I_{fsi}}$$

$$X_d = \frac{I_{fsi}}{I_{fg}} = \frac{I_{fnl}}{I_{fg}} \frac{1}{SCR} \backsimeq \frac{1.2}{SCR}$$

Where:

I_{fg} = field current for rated voltage on air-gap line,
I_{fnl} = field current for rated voltage on saturation curve, and
I_{fsi} = field current required to circulate rated current through a three-phase fault.



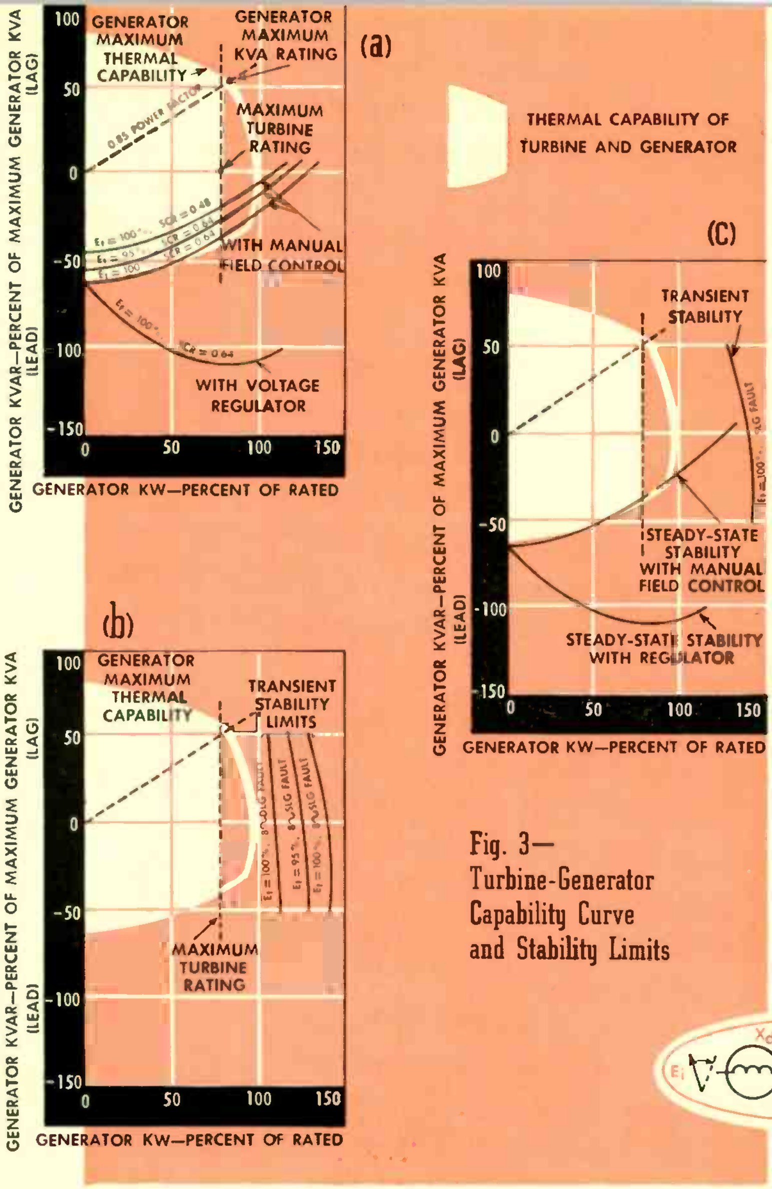


Fig. 3—Turbine-Generator Capability Curve and Stability Limits

The reciprocal of synchronous reactance is proportional to short-circuit ratio. (Greater values of synchronous reactance are associated with smaller values of SCR.) This relationship makes short-circuit ratio a useful guide in evaluating steady-state stability.

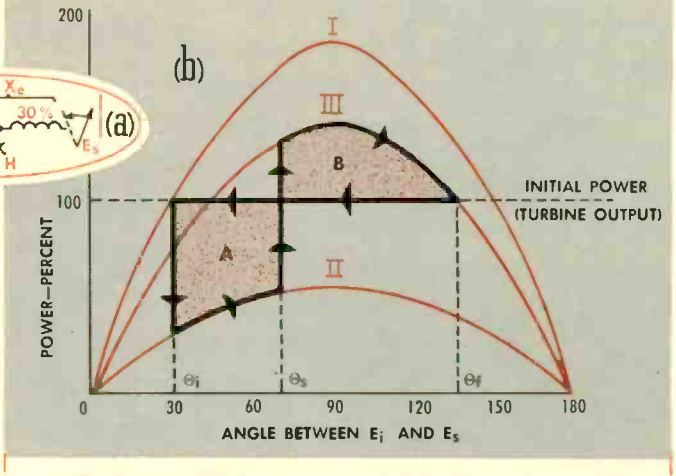
Equivalent external reactance, X_e, is a function of the length and loading of the transmission lines connecting the generator or generating station to the rest of the system. In most systems where the generator and its step-up transformer are operated as a unit, this transformer contributes 10 to 15 percent to the value of X_e. In a typical system with 50- to 100-mile transmission lines between the generator and loads or other sources, values for X_e may be 30 to 50 percent (based on the maximum generator kva rating).

The effect of generator power factor, short-circuit ratio, and terminal voltage on the steady-state stability limit is illustrated by the curves shown in Fig. 3a. These limits are plotted in terms of the real and reactive power output of the generator at the stability limit in percent of the generator maximum kva rating. This would correspond to the 30-psig rating for a conventional hydrogen-cooled generator or the 45-psig rating for a hydrogen inner-cooled generator. The light area indicates thermal limitations on the output of a 0.64 SCR hydrogen inner-cooled generator and turbine, and has as its maximum boundary the maximum generator capability curve and the maximum turbine capability. As can be seen from the steady-state stability curves, lowering either short-circuit ratio or terminal voltage further restricts the region of stable operation. The lowest steady-state stability curve shows the influence of the voltage regulator and excitation system used to supply generator field current.

Fig. 4—Transient Stability

Power systems must be capable of maintaining stability when subjected to severe system disturbances. These disturbances can be caused by sudden load increases, switching operations, loss of field of a neighboring machine, or system faults. The *transient-stability limit* is the maximum power a generator can carry and maintain stability when the power system is subjected to the disturbance that has been selected as a criterion of system stability. In most power systems, this disturbance is some type of fault condition close to the generator under consideration.

Just as in the case of steady-state stability, transient stability is closely related to the ability of the generator to transmit power through generator internal reactance and equivalent system reactance into the system during and following the system disturbance. Flux linkages with the rotor circuits are assumed to remain constant during a transient disturbance of relatively short duration. These linkages are proportional to the voltage behind the generator transient reactance. Therefore, the generator can be represented during transient conditions by an internal reactance, X'_d, the transient reactance, and a voltage E' behind this reactance. The equivalent system reactance X_e and system voltage E_s must be selected to reflect the presence of a fault during the disturbance and the changes in the transmission system caused by removal of the faulted line following the disturbance.



The fundamental phenomena associated with transient stability can be described by considering the three power-angle curves of Fig. 4b. These curves show the variation of transmitted power with the angle between the generator internal voltage and the equivalent system voltage before (I), during (II), and following (III) a transmission-line fault. The constant-power input from the turbine is also indicated.

During a fault the generator output (curve II) is less than the turbine input, and energy is added to the stored rotational energy in the inertia of the unit. This causes generator speed to increase, which increases the angle between the internal generator voltage and the system voltage.

After the fault is cleared at an angle θ_s, the generator output (curve III) exceeds the turbine input, and rotational energy is removed from the inertia of the generator and turbine as the angle continues to increase. If the energy stored in the inertia of the unit during the fault condition can be removed before the generator output is again equal to the turbine torque, (θ_f), the internal angle of the generator will reach some maximum value with respect to the rest of the system and then decrease toward a new stable operating angle.

The increase in the stored rotational energy of the generator during the fault period is directly proportional to the area A in Fig. 4b; area B corresponds to the decrease in stored energy. For any stable condition, these two areas will be equal. At the maximum permissible switching angle (θ_s), the area B extends to θ_f, the angle where the generator power output (III) and the turbine output are equal. Hence, the transient stability limit corresponds to the initial loading of the generator that causes the area B to just extend to the *critical angle*, θ_s, for the fault duration selected as the transient stability criterion.

A generator operating with manual control of field current cannot be loaded beyond the point where the angle between the internal generator voltage (E_g), and the equivalent system voltage (E_s) is equal to 90 degrees. Beyond this point (B of Fig. 1b) a small increase in angle causes a decrease in the power output of the generator and subsequent loss of synchronism. This small increase in angle also causes the terminal voltage to drop. If a voltage regulator is used, it restores terminal voltage by increasing field current of the generator, and consequently increases the internal voltage. This increase in E_g increases the power output of the generator (Equation 1) and tends to offset the decrease in power caused by the increase in angle.

Actually, the time rate of change of both angle and internal voltage must be considered. Generator inertia tends to slow down any changes in the angle while time delays in the generator field and excitation system impede corrective action of the voltage regulator.

A complete analysis of the effect of a voltage regulator on the steady-state stability limits for the simple system in Fig. 1a has shown that the improvement in these limits is not affected as much by the response ratio of the exciter as by the number and relative size of the time delays in the excitation system, and the nature and effectiveness of the various damping loops used in the system.

From the standpoint of improvement in steady-state stability, emphasis must be put on obtaining short time delays in the early stages of the excitation system, and on coordinated design of the entire system including the effects of the generator and the power system itself. These desirable objectives are obtained by the Mag-a-stat generator-voltage regulating system used with large Westinghouse generators.

Transient Stability

The major factors affecting transient stability limits on the output of a generator are: (1) the type of disturbance used as a criterion of stability, (2) the initial loading and terminal voltage of the generator, (3) the equivalent reactance of the system, and (4) the generator transient reactance and inertia constant. To a lesser degree the transient-stability limit is also affected by other generator characteristics and the type of excitation system used.

The system disturbance used as a criterion for transient stability can normally be characterized by the type of fault, fault location, and fault-clearing time. A three-phase fault often is assumed to exist at the high-voltage bus of a proposed new unit. The normal system representation used for load-flow studies on the network calculator can be used directly in making a stability study if this three-phase fault criterion is used. Additional networks must be set up before a double-line-to-ground or a single-line-to-ground fault can be used in making a stability study. Thus, convenience significantly enters into the selection of this criterion.

In terms of system experience the three-phase fault is much too severe. A summary of the percent of line outages per 100 miles of line due to various types of faults or operating conditions is given in Fig. 5[1]. The double-line-to-ground fault provides a much more reasonable criterion covering more than 91 percent of the cases of line outage. The use of a double-line-to-ground fault at the high-voltage bus of the generator is actually still conservative since most faults will occur on the lines themselves rather than at the bus. A strong case can be made for the use of a single-line-to-ground fault since this is the most frequent type of disturbance. This is reflected by the use of a single-line-to-ground fault at the high-voltage bus or worse location by many utilities.

The permissible fault duration is closely related to the inertia of the generating units supplying the system. This inertia is usually given in terms of *H-constant* (the ratio of stored rotational energy at rated speed to the rating of the turbine-generator unit). The inertia determines rate of increase in speed of the unit during a fault, and consequently the time required to reach a certain angular change from the initial operating angle. This time, as well as the permissible fault duration is approximately proportional to the square root of the H-constant. On the other hand, for a given type of fault, the transient-stability limit (maximum allowable pre-fault loading) is less sensitive than fault duration to any variations in H-constant.

The actual fault duration used as a criterion depends on the relaying and breaker clearing time for the type of fault and portion of the system being studied.

The low 6- and 8-cycle combined relaying and breaker times on high-voltage transmission systems have kept transient-stability limitations from exerting an undue influence on power-system design.

The short-circuit ratio and type of excitation system exert some influence on transient-stability limits. Lowering short-circuit ratio reduces the physical size of a machine for a given rating, and also causes some increase in all of the reactances associated with the machine. In particular, transient reactance is increased, thereby decreasing the transient-stability limits. Changes in transient-stability limits caused by in-

TABLE I	Normal Range of Machine Constants for Standard Short-Circuit-Ratio, 0.85-Power Factor			
	30-Psig, 2-Pole, H_2-Cooled Turbine Generators	**30-Psig, 4-Pole, H_2-Cooled Turbine Generators**	**Large Waterwheel Generators**	**45-Psig, Inner-Cooled Turbine Generators**
Short-Circuit Ratio	0.64	0.64	1.05	0.64
Synchronous Reactance (X_d) Percent	165–170	162–168	100–108	166–172
Transient Reactance (X'_d) Percent	15–26	25–35	29–40	24–30
Subtransient Reactance (X''_d) Percent	9–17	15–21	20–34	20–24
Total Prime Mover and Generator H-Constant (kw-sec/kva)	3.4–5.2	4.8–5.5	1.2–3.5	2.4–4.0

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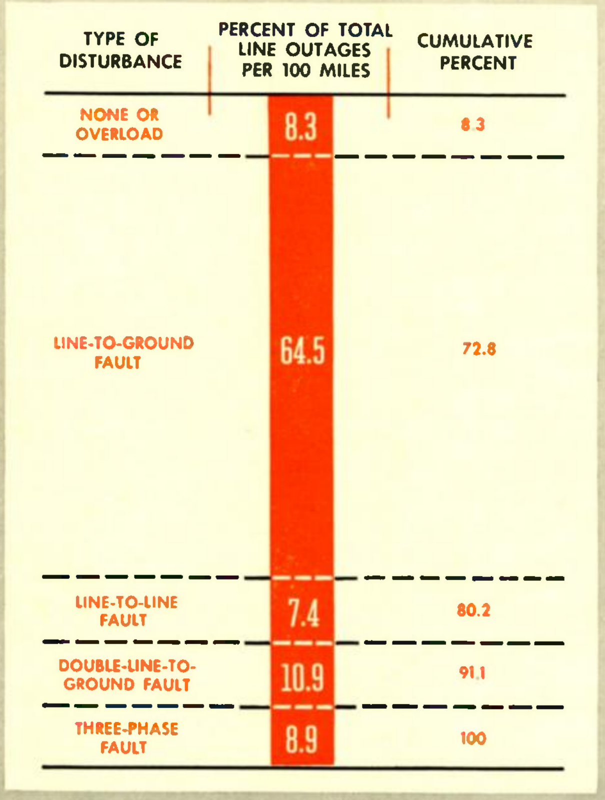
[1] This information was obtained from the report of the joint AIEE-EEI subject committee on line outages (T.P. 52-6).

creased transient reactance in the generator is considerably diluted by the effect of external reactance.

On the other hand, the introduction of high-speed excitation systems tends to increase the ability of a machine to ride through transient disturbances by helping to hold the flux constant in the machine. During severe faults, the excitation system does not have a substantial effect, and fault currents are determined primarily by the flux existing in the generator prior to the fault. The primary action of the excitation system is to restore terminal voltage after the fault is cleared and thereby prevent possible instability due to the increased reactance of the external system.

Fig. 5—Percent of Line Outages Per 100 Miles



A picture of the relative position of transient-stability limits is given by the curves in Fig. 3b, which shows these limits as a function of initial loading and initial generator terminal voltage for a generator connected to the simple system shown in Fig. 4a. The external reactance is assumed to be initially 40 percent, and following clearing of the faulted line, 50 percent. Transient-stability limits are shown for both single-line-to-ground and double-line-to-ground faults at the high-voltage bus (point H in Fig. 4a).

Summary of Generator Characteristics

The preceding sections have briefly pointed out the important factors in determining the stability limitations on the output of a generator unit. The normal range of the important constants for the various types of turbine-generator units is given in Table I. For comparison, these constants are also listed for typical waterwheel installations. The steam-turbine generator unit constants are given on the basis of maximum guaranteed capability while the waterwheel constants are given on the basis of a nominal rating and do not include any emergency overload rating.

From a steady-state stability standpoint, one of the most important constants is the generator short-circuit ratio. It should be noted that the standard short-circuit ratio is the same for all of the turbine-generator units. It differs from the value of 0.64 only if a utility company asks for a different value. For a given generator, the SCR varies inversely with the rating assigned to the unit. The 0.64 SCR based on the maximum generator capability (30 psig rating for conventional generators) is equivalent to the familiar 0.8 SCR associated with the former nominal rating of the generator (0.5 psig rating). Thus experience obtained in the operation of 0.8-SCR turbine generators rated at 0.5-psig hydrogen pressure is directly applicable to the operation of 0.64-SCR units rated on the basis of maximum generator capability.

The transient reactance and H-constant are important from the standpoint of transient stability. Differences in the values of these constants are due to differences in speed in the case of waterwheels and 1800-rpm machines, and reflect the ability to design the same power into a smaller package for 3600-rpm units by using inner-cooling. The significance of these differences in transient reactance from a transient-stability standpoint is reduced by the presence of external reactance.

At the first instant following a sudden change in terminal conditions, the air-gap flux is kept almost constant by eddy currents flowing in the damper windings, or wedges, and other paths in the surface of the rotor of the generator. Thus for the first few cycles after a disturbance, the machine can be represented by an internal voltage behind a reactance determined by these eddy current paths, and called the *subtransient reactance*. While this reactance does not enter directly into the stability picture, it is important to the system designer in determining system short-circuit currents and in circuit-breaker application. Circuit-breaker designers have done an admirable job keeping up with the demands of the power industry for 10- and now 25-million-kva interrupting capacity circuit breakers. However, there is an ever-present need to limit fault currents to the lowest possible values in order to reduce the damage and system shock of extremely high fault currents. A higher value of subtransient reactance is an important asset in meeting this requirement.

Stability Limitations

The relative severity of the various stability limitations is illustrated by a comparison of the capability and stability curves of Fig. 3. In evaluating these curves it should be kept in mind that all values are given in percent of the *maximum* generator kva rating.

From a steady-state stability standpoint, the curves emphasize the importance of modern voltage regulators in providing sufficient margin for operation in the leading power factor range. The margin between the transient-stability limits and the maximum turbine capability clearly reflect the control of these limits afforded by high-speed breakers and relays.

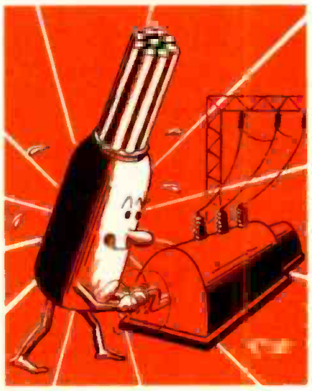
Optimum system design should allow adequate but not excessive margins between anticipated system operating conditions, and thermal and stability limitations. Present systems closely approach this objective. As system patterns change in the future, care should be taken to insure that this balance is maintained.

personality profiles

Walter J. Lyman • *Robert B. Donworth* • *M. Shaw* • *John W. Simpson* • *Roger R. Giler* • *Harry Thacker* • *C. H. Giroux* • *R. J. Nolte*
J. O. Stephens • *J. E. Barkle* • *R. W. Ferguson*

• Four authors team up in this issue to give a complete description of the PWR power plant to be built at Shippingport, Pa. Two of them—*Walter J. Lyman* and *Robert B. Donworth*—are from the Duquesne Light Company; the third, *Milton Shaw*, is from the Atomic Energy Commission; and the fourth, *John W. Simpson* is from Westinghouse.

Walter J. Lyman joined the Duquesne Light Company shortly after his graduation from Carnegie Institute of Technology in 1924 with a B.S. in electrical engineering. In 1930 he received his professional degree in electrical engineering from the same institution. Since joining his company as an apprentice engineer, Lyman has served as a junior engineer, and an assistant field engineer in the Engineering Department; and as a section engineer and as manager of the Planning and Development Department. In 1953 he was elected a vice president of his company, responsible for all activities of the Operating Division.



Robert B. Donworth is a graduate of Yale University (1919), and in 1921 received a B.S. in Engineering Administration from Massachusetts Institute of Technology. After graduation he joined an engineering and construction firm; here he worked on various construction jobs, then on the design of utility and industrial power plants, becoming a supervising engineer in 1926. In 1930 Donworth joined the Duquesne Light Company in the Power Stations Department. After completing a course in the Reactor School at Oak Ridge, Donworth was made manager of his company's Atomic Power Development Department in 1953. Here, of course, he had intimate contact with the plans for the PWR power plant. In 1955, Donworth was elected vice president of the Engineering and Construction Division, the position he now holds.

Milton Shaw is one of the group who served as a member of both the Bureau of Ships and the Reactor Development Division of the Atomic Energy Commission. He is currently head of the plant engineering division of both organizations. Shaw is a graduate of the University of Tennessee, where he received his B.S. in mechanical engineering in 1944. Sandwiched between school terms were periods in which he worked as a mechanical engineer for TVA. After graduation from Tennessee he joined the Navy, and served on engineering duty in the Pacific. After release from active duty in 1946 he went to Pennsylvania State College to earn his Master's degree in mechanical engineering. This accomplished, he became a marine engineer at the Naval Experiment Station. In 1950, he was transferred to the Nuclear Power Division of the Bureau of Ships, where he began his dual role with Buships and the AEC. In this capacity he has worked on many nuclear power plants, including the PWR project.

John W. Simpson is no newcomer to ENGINEER readers, having appeared on these pages as a co-author of an article on the submarine power plant earlier this year. However, in the interim he has become manager of all activities at the Bettis Plant, which is operated by Westinghouse for the AEC. Simpson was a member of the class of 1937 at the Naval Academy, and joined Westinghouse shortly after graduation. He has been a member of the Atomic Power Division since it was formed in 1948.

• The route followed by *Roger R. Giler* in arriving at Westinghouse is far from a simple one. Born in Berlin, Germany, Giler was brought up in France. At a fairly tender age, he served in the French underground, from 1942 to 1944, as a liaison man. He received a B.A. in philosophy from the University of Strasbourg in 1948. Shortly afterward he came to this country and returned to college, this time at Carnegie Institute of Technology. Here he gained a B.S. in metallurgical engineering in 1953, and subsequently entered the Westinghouse Graduate Student Course. In January, 1954 he joined the Industrial Heating Department, where he has been largely concerned with the vacuum furnaces of which he writes in this issue.

Things have happened fast for Giler since early 1954. In chronological order, he went to work in the Industrial Heating Department, received his U.S. citizenship, got married, realized a lifelong ambition by gaining a radio amateur license—and got drafted. The latter happened before the ink was dry on his manuscript.

• As a distribution engineer for the Electric Utility Department, *Harry Thacker* has been doing consulting work on power distribution problems for electric utilities, industrial plants, commercial and institutional buildings, and government and military installations since he joined Westinghouse in 1946. This experience has served him well in his discussion of industrial grounding in this issue.

Thacker graduated with a B.S. in electrical engineering from Penn State in 1941. Prior to joining Westinghouse, he was with Youngstown Sheet and Tube for two years, and then the U.S. Army Signal Corps during the war. Harry is a member of the AIEE and a registered professional engineer in Pennsylvania.

Thacker is an ardent "do-it-yourself-er," and he'll do anything—even to making a six-room house out of five. He also loves to tinker with electronics, and has even carried this so far as to build a television set.

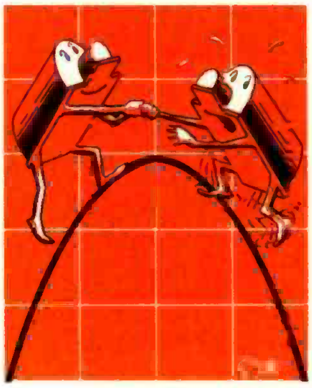
• Development of the railway-mounted gas-turbine power plant was largely due to the recognition of the need for mobile power to support troop operation by *C. H. Giroux*, Special Assistant to the Chief of Engineers, Department of the Army, and Consultant to the Corps of Engineers on electrical and mechanical engineering matters. *R. J. Nolte* and *J. O. Stephens* join Mr. Giroux in describing the unit.

During World War II, Giroux was intimately concerned with the supply of power to military establishments, both in the United States and in foreign occupied countries.

Stephens came with Westinghouse in 1945 from the Army Ordnance Department, where he had served as a Lt. Colonel. Prior to the war, Stephens was a design engineer for Allis-Chalmers (1935–1938) and a maintenance engineer for Gulf Oil Corporation (1939–1941). He is now supervisor of Development and Project Engineering, Industrial Gas Turbine Division.

Nolte has been with Westinghouse since 1936. He was located at the Boston Manufacturing and Repair Department prior to his transfer to Industry Engineering at East Pittsburgh in 1951. Since coming to East Pittsburgh, he has been responsible for several Navy and marine projects and is the project engineer for the railway-mounted power plant.

• Power-system stability is a subject with which *J. E. Barkle* and *R. W. Ferguson* are well acquainted. Barkle helped revise the chapter on the subject in the "Electrical Transmission and Distribution Reference Book." Ferguson has been closely associated with development of techniques for analyzing system stability problems, and has presented talks at a number of utility conferences on the subject.



Since Barkle last appeared in the ENGINEER, he has been made Manager of Electric Utility Engineering. Prior to this, he was a Sponsor Engineer for the Company's Pacific Coast Region, where he assisted utilities in the area in the application of electrical equipment and in the solution of various system problems.

Ferguson likewise put in a stint as a Sponsor Engineer for the Company's New York State District since last appearing on these pages. Early this year, he was made engineer in charge of the Advanced Development Group of Electric Utility Engineering. He works with development of new equipment, and systems for use of this equipment, the extension of knowledge of the fundamental fields, and application problems outside the confines of the electric utility field, but which require a thorough knowledge of power systems.

This huge **200**-MW inner-cooled generator is being prepared for its trip to Philadelphia Electric Company's Cromby Station. The machine weighs over 290 tons, but is only about half the size of a conventionally cooled machine of the same output.