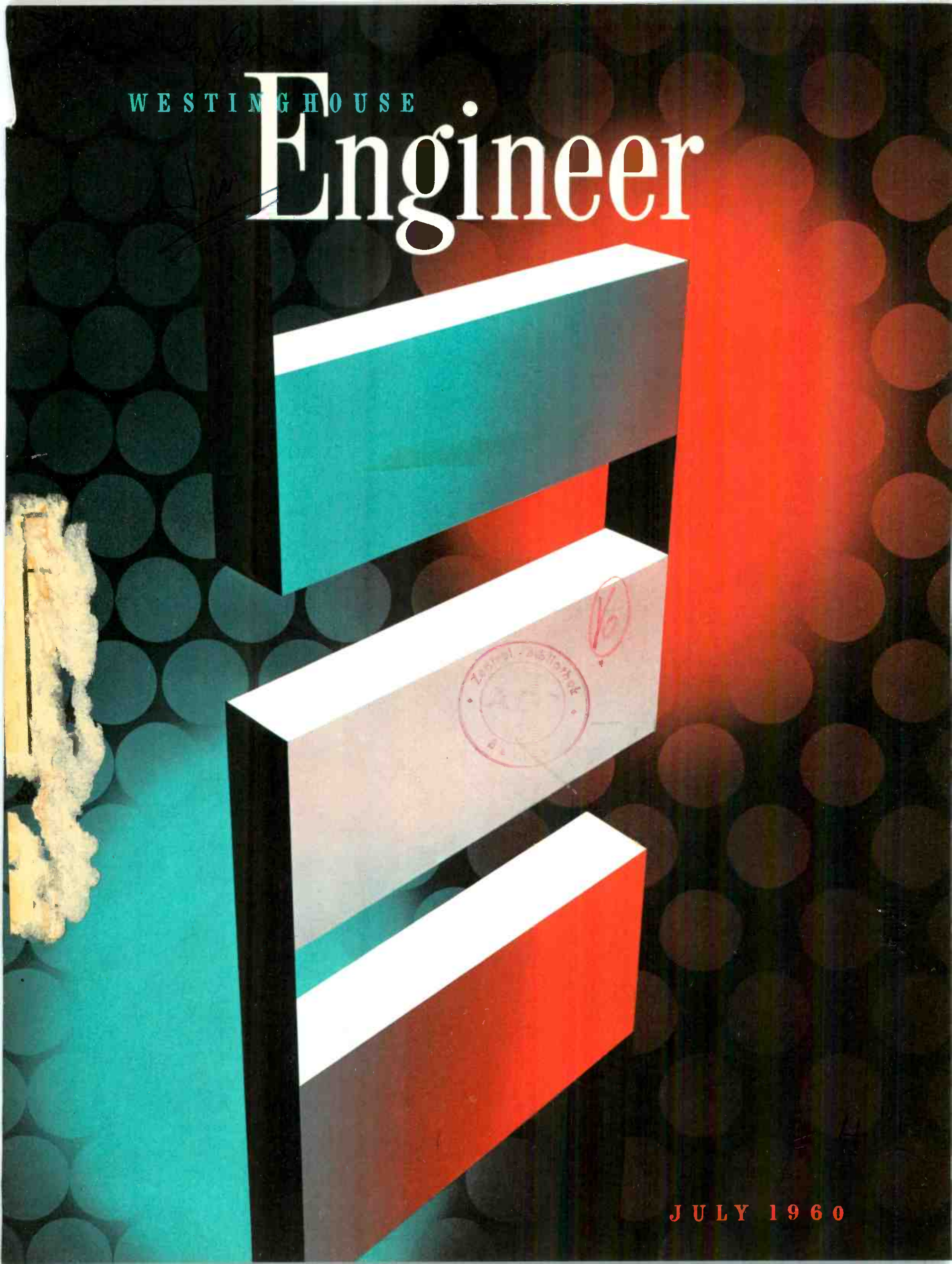
WESTINGHOUSE Engineer



JULY 1960

360 000-KW ATOMIC POWER PLANT

Construction of the nation's largest atomic electric power plant may be started next year by Southern California Edison Company. Following a meeting of the company's board of directors, Harold Quinton, chairman, said that a letter of intent to negotiate contracts for the design and construction of a 360 000-kilowatt nuclear power plant had been sent to the Westinghouse Electric Corporation and to the Bechtel Corporation.

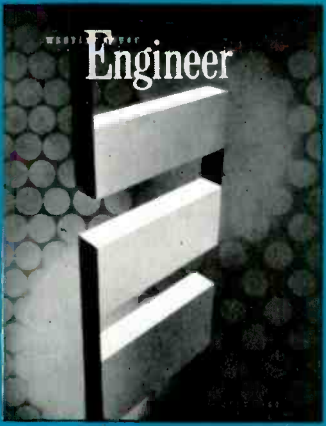
The contemplated plant will use the world's largest nuclear reactor. It would be designed and built by Westinghouse, who also would supply the steam and electrical equipment. The overall plant cost is estimated at approximately $70 000 000. Bechtel Corporation would be the engineering constructors.

Based on Westinghouse and Edison studies, the plant would be economically competitive with conventional plants over its lifetime. According to present estimates, such a plant would require about four years to construct.

The consummation of negotiations and the actual beginning of construction will depend on several factors, including completion of contracts, approval of the Atomic Energy Commission and the California Public Utilities Commission, and selection of a specific site.

The closed-cycle water reactor, which would be used in the plant, has been the subject of the most intensive research and development during the past decade. Edison's interest in this type results from the reactor's history, which indicates a high degree of reliability, safety and control.

Briefly described, this type of plant has a 300-ton reactor vessel in which uranium-oxide fuel elements are suspended. Water under a pressure of 2000 psi is circulated around these fuel elements, through a heat exchanger, and transfers heat to a secondary system where water is converted to steam for the turbine-generator.



COVER DESIGN: The German scientist Seebeck first observed the phenomenon that makes possible the thermoelectric generator. Recently this phenomenon has been receiving increased attention, as evidenced in the article on page 99. Artist Dick Marsh illustrates this principle with a symbolic representation of a thermoelectric device, against a backdrop of electrons "migrating" toward the cool surface of a material, as happens in such a generator.

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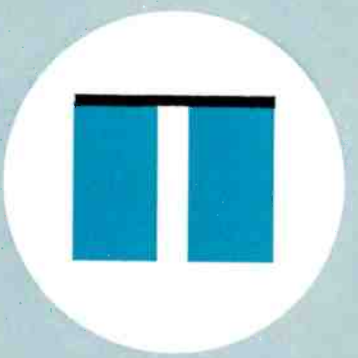

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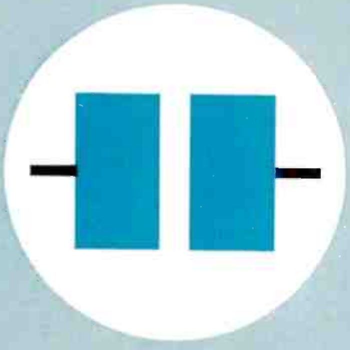

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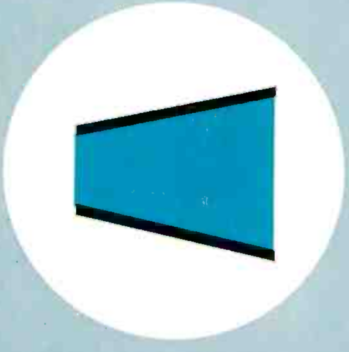
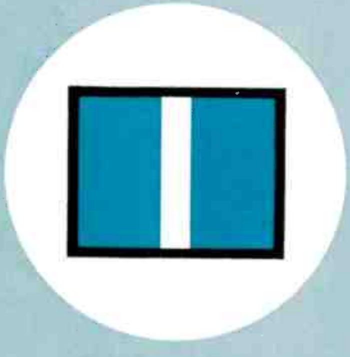


MAGNETOHYDRODYNAMIC



FUEL CELL

Scientists and engineers are devoting an increasing amount of attention to what are commonly called "new" or "unconventional" power sources. The impetus for this development effort stems from many things. In a general way, the continually increasing demand for electric power, and the eventual inability of present energy sources to supply our needs are the dominant factors. However, there are others—the need for specialized power plants to serve in space or in remote land areas, to name one.

Four of the most promising of the "new" power sources—thermoelectric, thermionic, and magnetohydrodynamic generators, and fuel cells—are discussed in the following pages. As most readers will recognize, none of these power generation methods are new in principle. The concept of thermoelectric devices dates back to 1822; the thermionic principle to 1878; magnetohydrodynamics to about 1835, and the fuel cell to 1802. However, only recently have these principles come in for serious attention as the basis for large-scale power generators. The present interest stems largely from a better understanding of the physics and chemistry involved, and our ability to develop new materials to meet the unusual requirements.

In these articles no particular attempt has been made to evaluate each new generating method fully. At this stage of development, any general evaluation would be impractical, because much remains to be learned about each method.

However, much progress is being made in the development of these new power sources, especially for specialized applications. For larger scale power generation, only future developments will determine the feasibility and the practicality of each new system. Because of the wide variety of possible applications for direct conversion, no method is likely to prove the "one way to do it." We will find no one answer to our varied and growing needs for electric power. In fact, each of the methods outlined here might well prove feasible for many power applications.

JAHutcheson

J. A. HUTCHESON
Vice President, Engineering

THERMOELECTRIC GENERATORS . . . Applying the Seebeck Effect to Power Generation

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Almost 150 years ago the German physicist Thomas Seebeck discovered that the flow of heat through a metal segment could produce a voltage difference between its hot and cold ends. Although this Seebeck effect has since become familiar through its uses in instrumentation, the field of application has been severely limited because of its low voltage and power output.

The recent development of new thermoelectric materials has now changed this condition, with the result that both the power output and the efficiency of thermoelectric devices have been raised to levels suitable for the practical generation of power. A year ago, for example, Westinghouse was working with devices whose output was slightly over 1 watt; today a generator rated at 5000 watts has been completed.

The qualities of thermoelectric devices that have impelled these developments, particularly for military applications, include ruggedness and compactness and, of course, the static nature of the devices. Heat is converted into electricity without moving parts. This freedom from moving parts has several significant implications for defense; for example, in military power plants heat could be converted to electricity without noise. In space vehicles and missiles, this characteristic would permit the elimination of gyroscopic forces that occur in rotating machines and so simplify guidance and stability in orbit. An even more basic advantage is that thermoelectric generators are inherently more reliable than rotating machines and may eventually prove lower in first cost.

the basic phenomenon

In any uniformly heated pellet of thermoelectric material, positive and negative electrical charges are uniformly distributed, as in Fig. 1; but when heat is applied to one surface, this distribution changes. Although the positively charged ions in the crystals remain fixed, the negatively charged electrons tend to move to the cooler end. This results in a gradient of electrical charge and a potential difference between the hot and cold ends, which can cause current to flow in an external load. In actual use, thermoelectric devices are arranged in an array of series-connected thermocouples whose materials have been so formulated that their voltages are additive. Through stacking of elements in arrays, voltage outputs adequate for power generation can be achieved.

materials and their parameters

An important factor in the growth of thermoelectric technology is the ability to adjust the number of free electrons in semiconductor materials. The importance of this is due to two basic relationships: First, the *output voltage* of any thermoelectric material is inversely proportional to the number of free electrons in that material; and, second, the *conductivity* of the material is directly proportional to the number of free electrons. Thus, insulators containing 10^{10} electrons per cubic centimeter generate Seebeck (output) voltages of about 10 000 microvolts per degree centigrade of temperature difference between the hot and cold ends; offsetting this, however, is the fact that they have an extremely high internal resistance. On the other hand, the metals give Seebeck voltages of about 5 microvolts per degree, but have extremely low internal resistance. Therefore, to obtain maximum power output or optimum efficiency from a thermoelectric material, the electron density must be adjusted to an acceptable compromise value between high voltage and high electrical conductivity. This is essential to the production of useful power since a combination of high voltage and low current or of low voltage and high current result in little power. The compromise is shown by the efficiency curves in Fig. 2, which indicate that the optimum electron density is about 10^{19} free electrons per cubic centimeter, a value well within the range of good-conducting semiconductors and one that affords Seebeck voltages of about 175 microvolts per degree C. Some typical materials that demonstrate acceptable efficiency are zinc antimony, lead telluride, bismuth telluride, and germanium telluride.

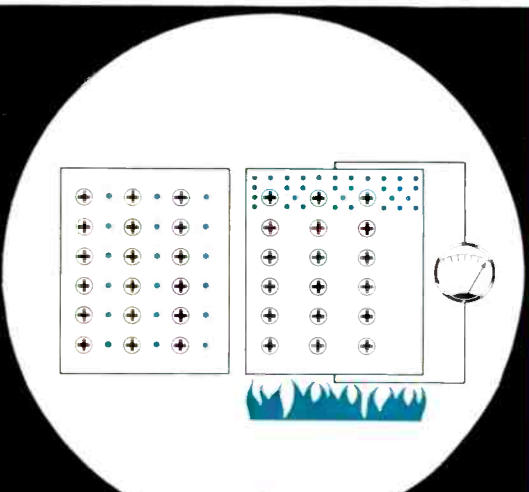
In thermoelectric generators built for practical uses, it is desirable to use a number of different thermoelectric materials, to take advantage of the fact that each has its best range of operating temperatures. This contributes to the increased efficiency that is possible when generators are operated at high temperature. To cover low temperatures, say up to 600 degrees C, several semiconductors have proved satisfactory. However, to go higher, say into the 1000 degree C range, semiconductors are no longer suitable, since at these temperatures they become "intrinsic"; that is, the heat input causes both positive and negative electrical charges to migrate in equal numbers and so no output voltage is possible. As an extreme example, Fig. 3 shows how bismuth telluride's Seebeck voltage falls to zero at 150 degrees C.

Obviously, at higher temperatures materials are required that are free of this behavior. A promising approach is the use of insulator materials that have been modified to become good thermoelectric materials. This is particularly interesting since many insulators do not become intrinsic conductors in the 1000 degree C range. As an illustration of this modification, pure nickel oxide is normally an insulator, but if it is modified by the addition of three percent of lithium, its resistivity decreases to about 0.01 ohm-centimeters. As explanation for this, in normal nickel oxide the nickel has a valence of plus two but the addition of lithium causes the appearance of nickel with valence of plus one. The material's greatly increased conductivity is brought about by an exchange of charges between plus-one nickel and plus-two nickel. Through similar modifications, other materials are being developed for use at higher temperatures. For example, this approach led to one of the newest mixed valence materials, samarium sulphide, which has a good figure of merit at temperatures as high as 1100 degrees C.

devices and design

Despite these developments, the increasing knowledge of semiconductors or mixed-valence materials does not solve all problems of thermoelectricity, for materials are not an end in themselves; they must be fabricated as thermocouples and then be assembled in finished devices. For example, assemblies of thermoelectric materials must be joined so that contact resistance is not excessive, for this would have the same effect as high internal resistivity of the material and would reduce the efficiency. Also, above 300 degrees C, thermoelectric materials must be shielded from the air to prevent corrosion of materials and joints. Another aspect of design is the need to mount thermoelectric devices so that they will withstand shock and vibration. One method used for accomplishing this is to apply compressive forces through spring-loading, Fig. 4.

Turning now from the design of thermocouples to the design of complete generators, some interesting conclusions can be drawn regarding the relationship between power and weight in equipment of the near future. In one of the first generators to be built for the Rome Air Development Center, 100 watts are produced from a 50-pound unit cooled by free convection, for a power-to-weight index of two-to-one. Since performance can be improved considerably by using forced convection of air or water to reject heat, it is feasible for generators designed in this way to produce 15 watts per pound of weight, for a power-to-



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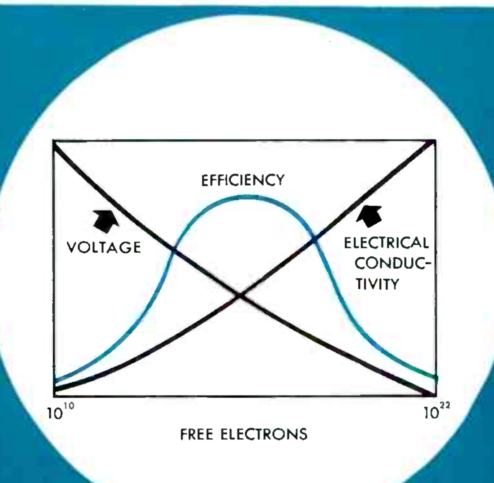

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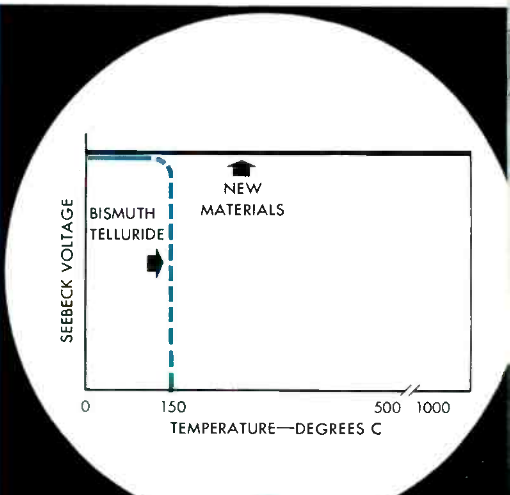

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Fig. 1—Left, in a uniformly heated material, the electrons and positively charged ions are uniformly distributed. Right, distribution of electrons and positively charged ions as it is influenced over a thermal gradient. Electrons concentrate at cold end of the specimen to cause a gradient of electrical charge. **Fig. 2**—Curves showing the relationship between density of free electrons in a material and conductivity and thermoelectric output (Seebeck) voltage. Optimum density for maximum power output is about 10^{19} electrons per cubic centimeter **Fig. 3**—An illustration of the manner in which semiconductors become intrinsic at critical

weight index that is comparable to that for a typical, gasoline-powered 500-watt generator.

Other design problems with high priority grow out of a desire to narrow the gap between the efficiency that is theoretically available from known materials and the efficiency that is actually available when these materials are applied in equipment. Materials available today are capable of an efficiency of about 17 percent, but when assembled as elements of complete generators, the overall efficiency then becomes about six percent. Much of this loss is due to such factors as the stack losses, represented by the discharge of heat-bearing gases from the generator's "chimney," and the fact that some of the energy transferred through the walls of the chimney passes around but not through the thermoelectric elements.

Although continued progress in generator design will reduce losses and increase total efficiency, nuclear reactors seem certain to be much more efficient in thermoelectric applications than conventional heat sources. With nuclear reactors, the heat source can be completely surrounded by thermoelectric elements to eliminate stack losses.

An interesting aspect of the efficiency of thermoelectric generators is that it is independent of power rating, which is in contrast to the power-efficiency relation for conventional machines. As Fig. 5 shows, small conventional power supplies have an efficiency of roughly five percent, the automobile engine is about 15 percent efficient, and large diesel engines and marine steam turbines have efficiencies of about 20 percent. As the most efficient units, large central station power plants have efficiencies of about 42 percent. At present, the efficiency of today's thermoelectric generators is constant at about six percent regardless of rating. Viewed from the standpoint of efficiency only, thermoelectric devices are thus comparable to conventional power sources in applications up to about 10 horsepower.

In about five years, materials should be available with an inherent efficiency of 30 percent, and this 30 percent should not be regarded as an ultimate ceiling. At the same time, to achieve efficiency much above this level will require a major breakthrough. With the 30-percent-efficient materials foreseen for 1965, generators with overall efficiency of 20 percent may be possible, an efficiency level at which there would be many important applications for thermoelectric generators that could operate in the 1000-kilowatt range.

projected applications

In addition to certain military applications of thermoelectric generators that are expected to materialize, some commercial applications appear feasible in the near future. One of these is a thermoelectric power supply for communication and instrumentation equipment at locations along natural gas transmission lines in the many regions of the country where pipe lines and power lines are widely separated. A similar application is thermoelectric power supplies for cathodic protection of oil well and pipeline equipment. Power requirements for such applications range from several watts to about 100 watts and are well within the capacity of today's technology.

Applications involving larger power levels will, of course, depend on an increase in the efficiency of thermoelectric power generation, but it is possible now to visualize thermoelectric power supplies in which a nuclear-reactor-energized thermoelectric generator included within the pile, but equipped with external cooling loops, would approach an overall efficiency of 20 percent for ratings in the megawatt range.

Major problems are ahead before such applications are practical, but thermoelectricity seems certain to be a very important element of the technology of the 1960's. ■ ■ ■

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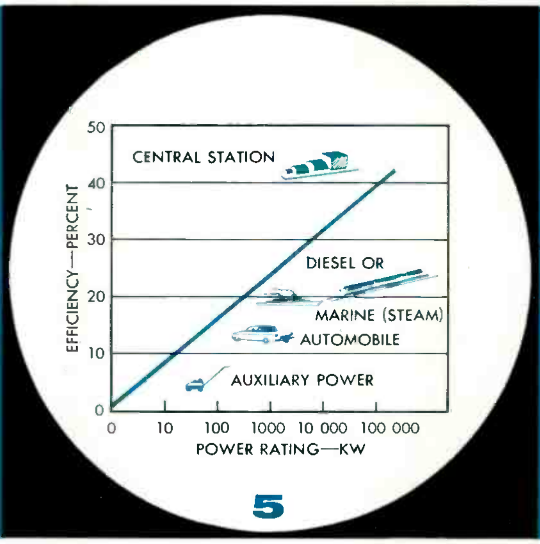

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temperatures. In this extreme example, bismuth telluride's Seebeck voltage plummets to zero at 150 degrees C. **Fig. 4**—Arrangements for mounting arrays of thermocouples to make them mechanically stable are critical to good generator performance. Shown here is one technique for springloading a "ladder" of thermocouples to counter shock and vibration. **Fig. 5**—Efficiency of conventional heat engines as a function of their rating. **Fig. 6**—This thermoelectric generator, shown powering a grinding wheel, is capable of producing 100 watts. The generator is a convection air-cooled device that uses propane gas as a fuel.

THERMIONIC GENERATORS . . . Materials Are the Key to Their Development

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Thermionic generators produce electrical power by using electrons emitted from the surface of a material heated to a high temperature. These generators share with thermoelectric devices the characteristic that the working fluid is electrons; they differ in that the heated electrons are emitted into a vacuum rather than into a solid. Because of the high potential difference between the interior and exterior of a solid, i.e., the "work function," thermionic generators must operate at high temperatures. Their output voltage is correspondingly higher than thermoelectric converters, ranging from 0.5 to 3 volts.

Although still in early stages of development, thermionic generators offer promise as a power source for both military and commercial applications. First, however, materials with a high heat of vaporization combined with a low work function must be found. These materials must be capable of operating for long periods of time at temperatures up to 4500 degrees F.

At present, the thermionic generator is a concept that promises to open up new areas in power generation at high-operating temperature. For military applications where compactness, light weight, simplicity and high efficiency are required, this device offers promise for practical use.

principle of operation

Consider a plate of conductive material containing electrons that are free to move, and stationary positive charges. When this cathode is heated, electrons begin to move in a random jostling fashion until a number escape from the surface of the material. Facing the cathode, and separated from it in an evacuated space, is the anode; an external circuit is connected between them (Fig. 1a).

As the cathode is heated, electron activity increases and electrons escape across the vacuum to the anode. The electrons then flow through the load and through the return circuit to the cathode, thus producing electric power. The concept in this simplified diagram is not new, since emission of electrons from the surface of a heated cathode is a process long used in electron tubes.

A more quantitative picture is offered by a potential diagram that corresponds to the schematic arrangement of the thermionic converter, Fig. 1b. Here the potential energy of the electron is plotted at each point in the diagram. The potential inside the cathode material is taken as zero. The electrons inside the metal are normally prevented from escaping by a potential barrier, ϕ_C, which exists at the surface of the metal.

As the electrons become heated, a few have sufficient energy to surpass the potential barrier and escape into the space between the cathode and anode. When the electron reaches the anode, it falls down the potential barrier corresponding to the anode work function, ϕ_A. The energy thus released is converted into heat at the anode and is lost in the process. If the anode work function is less than that of the cathode, the remaining amount of energy, $\phi_C - \phi_A$, is available to do useful work in the external circuit, and to supply the electrical losses in the return circuit.

Efficiency is not the only parameter of a power converter, but is certainly among the most important, for it establishes the areas of application. To be of much practical interest, the efficiency of a power converter must be at least 10 percent. To determine the efficiency of a thermionic converter, the calculated electric power output that can be delivered to a load can be compared with the total heat input. Some of this heat goes into the useful work; some is transferred to the anode by electron motion; some leaks back through the electrical connection; and most important of all, some is transferred directly to the cold end of the machine by radiation.

Under certain simplifying assumptions, an expression for the efficiency of a thermionic converter can be obtained easily. The output power is given by the current times the output voltage:

$$I(\phi_{\mathrm{C}}-\phi_{\mathrm{A}})$$

The efficiency is this output power divided by the input heat power:

$$\eta=\frac{\textit{Output Power}}{\textit{Input Heat Power}}=\frac{I(\phi_{\mathrm{C}}-\phi_{\mathrm{A}})}{\textit{Input Heat Power}}$$

The first term in the heat input is that necessary to get the electrons over the cathode work function barrier:

$$\eta=\frac{I(\phi_{\mathrm{C}}-\phi_{\mathrm{A}})}{I\phi_{\mathrm{C}}}$$

Because this process of raising electrons over the barrier is a thermal one, there is a statistical spread in energy of the electrons emerging. Many of them, in fact, more than just clear the barrier, and, on the average, those that do get out have an excess energy $2kT$, which they lose in heat to the anode:

$$\eta=\frac{I(\phi_{\mathrm{C}}-\phi_{\mathrm{A}})}{I\phi_{\mathrm{C}}+I2kT}$$

Finally, there is the radiation of heat, which gives a loss independent of the current and is represented by R:

$$\eta=\frac{I(\phi_{\mathrm{C}}-\phi_{\mathrm{A}})}{I\phi_{\mathrm{C}}+I2kT+R}$$

Dividing through by the current the following expression is obtained:

$$\eta=\frac{\phi_{\mathrm{C}}-\phi_{\mathrm{A}}}{\phi_{\mathrm{C}}+2kT+R/I}$$

When the current is small, the radiation term outweighs all the others and reduces the efficiency to a very small value. Also, both the current and the radiation power are proportional to the area, so this term is not affected by the size of the device.

Therefore, the essential condition for an efficient thermionic converter can now be stated rather simply—make the current density large.

The current density depends on thermal agitation overcoming the cathode work function; it is a very steep function of the temperature.

While radiation also increases with temperature, it does so less rapidly than current so that a temperature can be found at which R/I will be satisfactorily small. These temperatures turn out to be very high, which is a characteristic of the thermionic converter.

The equation reveals that an anode of low work function is desirable. Moreover, this anode should have a high reflectivity for infrared radiation, to reduce the radiation losses from the cathode.

The efficiency of conversion depends then on such material properties as the work function, electron emission constants and radiant emissivity, and the operating temperature. The operating temperature is, in turn, limited by the melting point or evaporation rate of the cathode. Thus material properties of the anode and cathode are important in deciding whether an efficient arrangement is practical.

The available combinations of material properties that will result in the optimum device cannot be described in a simple manner. However, Fig. 2 shows some calculated efficiencies for a variety of possible cathode materials as a function of cathode temperature. These calculations, meant to be illustrative only, assume an anode reflection that

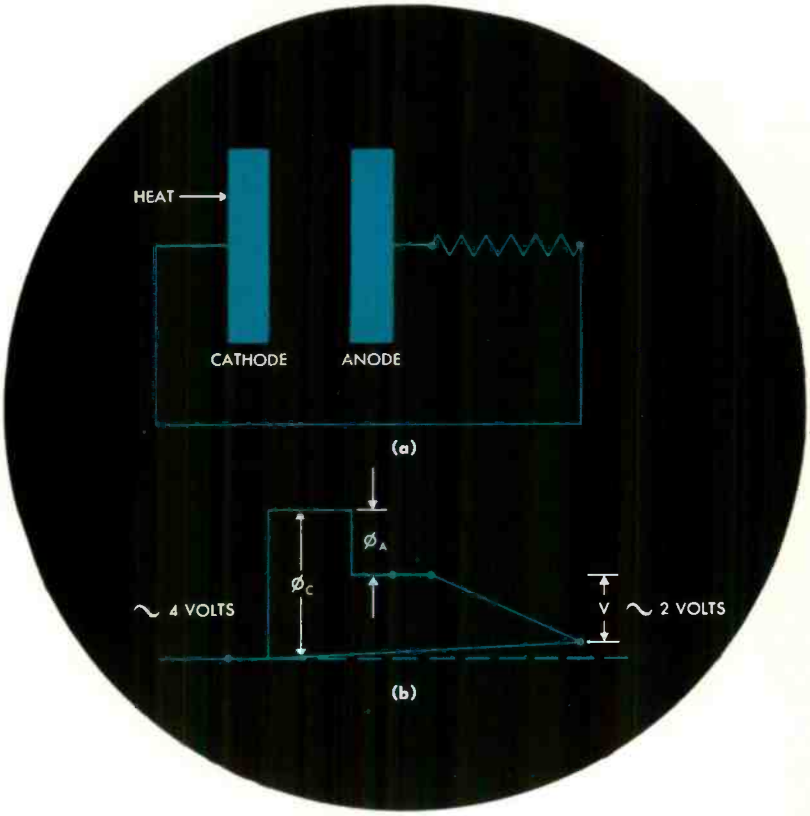

Fig. 1—(**a**) Operating principle of a thermionic generator. (**b**) Potential energy diagram of electrons in the thermionic system.

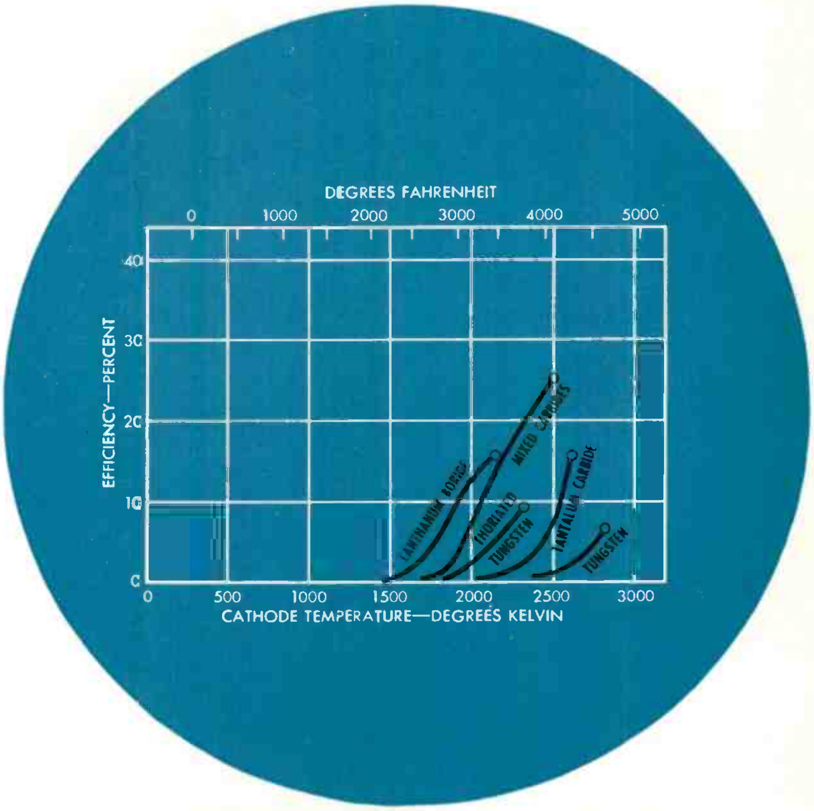

Fig. 2—Plot of efficiency vs. cathode temperature for a number of materials for thermionic generators under investigation at the Westinghouse research laboratories.

gives an effective emissivity of 0.5, and an anode work function of 1.8 volts. Each curve terminates at a point where cathode evaporation becomes high enough to evaporate a millimeter of material from the cathode in 1000 hours, a condition assumed to represent end of life.

Note that each material dictates an operating temperature and that many materials reach excessive evaporation rates before interesting efficiencies can be achieved.

Another important factor determines the current flow in a thermionic converter. This phenomenon is called space charge—the mutual repulsion of electrons. An electron emerging from the cathode finds itself in the company of a swarm of other electrons, all similarly charged, from which it is repelled. This will drive most of the electrons back into the cathode before they have a chance to reach the anode. One practical way for eliminating space charge consists of introducing heavy positive ions in numbers sufficient to neutralize the charge of the electrons.

To date, cesium ions appear to be the easiest to produce. The cesium vapor pressure is controlled by using an excess of cesium metal and keeping the coldest place in the vessel at a few hundred degrees C. Ions may be formed by contact ionization at the hot cathode if its work function is high enough, by impact from the higher energy electrons, or by the temperature of the cesium gas between the plates. Thermionic converters of this type have been called (with some justification) plasma thermocouples. Cesium collected on the anode provides a conveniently low work function.

A typical tube containing free cesium metal is shown in Fig. 3. In operation, the tube is enclosed in an oven, and by keeping the device at the appropriate temperature, sufficient cesium vapor is provided to neutralize the space charge. Such a converter is capable of producing appreciable current, sufficient to run a miniature motor.

The extreme temperatures required for the more efficient thermionic devices militate against their use with fossil fuels. In addition to the difficulty of achieving the required cathode temperature in the face of limited combustion temperatures and convective temperature drops, the permeability of metals to gases at high temperature poses a severe problem in maintaining for long periods a hermetic partition between the vacuum and the combustion spaces. Therefore, such sources as nuclear fuels and solar radiation appear to be more favorable. Solar sources provide very high temperatures, and also allow the use of a transparent vacuum window through which the radiation can be conducted while the window itself remains cool. Such applications will undoubtedly remain in the highly specialized category. Nuclear sources lend themselves to thermionic converters because they can provide temperatures limited only by the structural properties of the materials used. Because the anode of the device can also run at relatively high temperatures without reducing the efficiency, cascading of thermionic units with other lower-temperature converters becomes attractive.

Application of thermionic converters for the commercial generation of power appears most favorable when the thermionic element is used as a topping unit for a nuclear steam plant, thereby taking advantage of the high temperatures available from the fuel.

A thermionic unit operating with 20 percent conversion efficiency and topping a steam unit of 27 percent efficiency would provide an overall efficiency of 42 percent, raising the output of a 50-megawatt plant to 77 megawatts. Consideration of the changed capital costs of the steam portion of the plant, and the inclusion of costs for dc to ac conversion leaves about $190 as a "breakeven" capital cost per electrical kilowatt for thermionic units. Examination of present-day costs for high-power vacuum tubes indicates that achieving such a figure is within reason. The life of the thermionic unit is, of course, a critical factor.

Thermionic conversion offers one possible means of obtaining efficient conversion of heat to electrical power. Whether it becomes competitive with other means will depend largely on the solution of problems concerning the properties of materials. In the past there has been no particular urge to find or produce materials having the peculiar properties demanded by the thermionic converter. The field is therefore largely unexplored and advances of considerable magnitude can be expected. ■ ■ ■

Fig. 3—Small thermionic generator using cesium vapor to overcome space charge. In operation, a small furnace surrounds the tube.

MAGNETOHYDRODYNAMIC GENERATORS . . . Power From High-Temperature Gas

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About 130 years ago, Michael Faraday discovered that a conductor moving in a magnetic field could be made to generate an electric current. This principle has traditionally been applied to produce electric power by mechanically rotating solid copper bars past energized field windings. However, Faraday's experiments also showed that power can be generated by substituting a flowing liquid metal, such as mercury or some other conducting liquid, for the copper bars. A device that uses a fluid conductor to produce an electric current is a magnetohydrodynamic generator.

the MHD generator

The word *magnetohydrodynamics*, abbreviated MHD, stands for the branch of physics that encompasses both electromagnetic and fluid-dynamic phenomena. Practical realization of MHD power generation appears at the present time to depend on the use of a conducting gas. For the gas to be conducting, a certain number of free electrons must be present, along with an equal number of ions, plus the main body of un-ionized gas. The most direct approach to partially ionize a gas, and thereby make it conducting, is to heat it sufficiently. However, the temperatures required for sufficient gas ionization in this case are beyond the limits of use of all known materials.

However, when a gas is "seeded" with an alkali metal, such as potassium or cesium, adequate electrical conductivity can be realized at somewhat lower temperatures—in the range of 4000 to 5000 degrees F. The possibility of MHD generation, as currently conceived, hinges on the small region of overlap between the temperatures that a few materials are able to tolerate, and the temperatures that are necessary, even with seeding, to obtain adequate electrical conductivity.

In an MHD generator, hot ionized gas travels through a magnetic field, which is applied at right angles to the flow, and past electrodes that are in contact with the stream of gas (Fig. 1b). Electrons in the gas are deflected by the field and, between collisions with other particles in the gas, they make their way diagonally to one of the electrodes. An electric current is produced as the electrons move from the anode, through the load, to the cathode, and back again to the gas stream.

The voltage at the terminals of an MHD generator is directly proportional to the intensity of the magnetic field, the gas velocity, and the distance between electrodes. A generator will supply maximum power when the load connected to its terminals has a voltage drop equal to one-half of the open circuit voltage.

Near peak power, the efficiency of a magnetohydrodynamic generator may be as low as 50 percent, because of the $I^2 R$ losses. But efficiencies in the 80- to 90-percent range are possible when the generator is operated somewhat below maximum power. This corresponds to the efficiency of a conventional steam turbine-generator combination, which is about 80 percent.

The overall thermal efficiency of a plant using an MHD generator might be as much as 60 percent, compared with 40 to 42 percent for the most modern conventional power plants. The high efficiency of the MHD plant arises principally from the high temperature that is used; this high temperature is required for gas ionization.

MHD generator cycles

Power systems using MHD generators fall into two categories: *open* systems where the working gas consists of products of combustion, and *closed* systems in which an inert gas, such as argon or helium, is continuously recycled. The complete system in either arrangement requires a com-

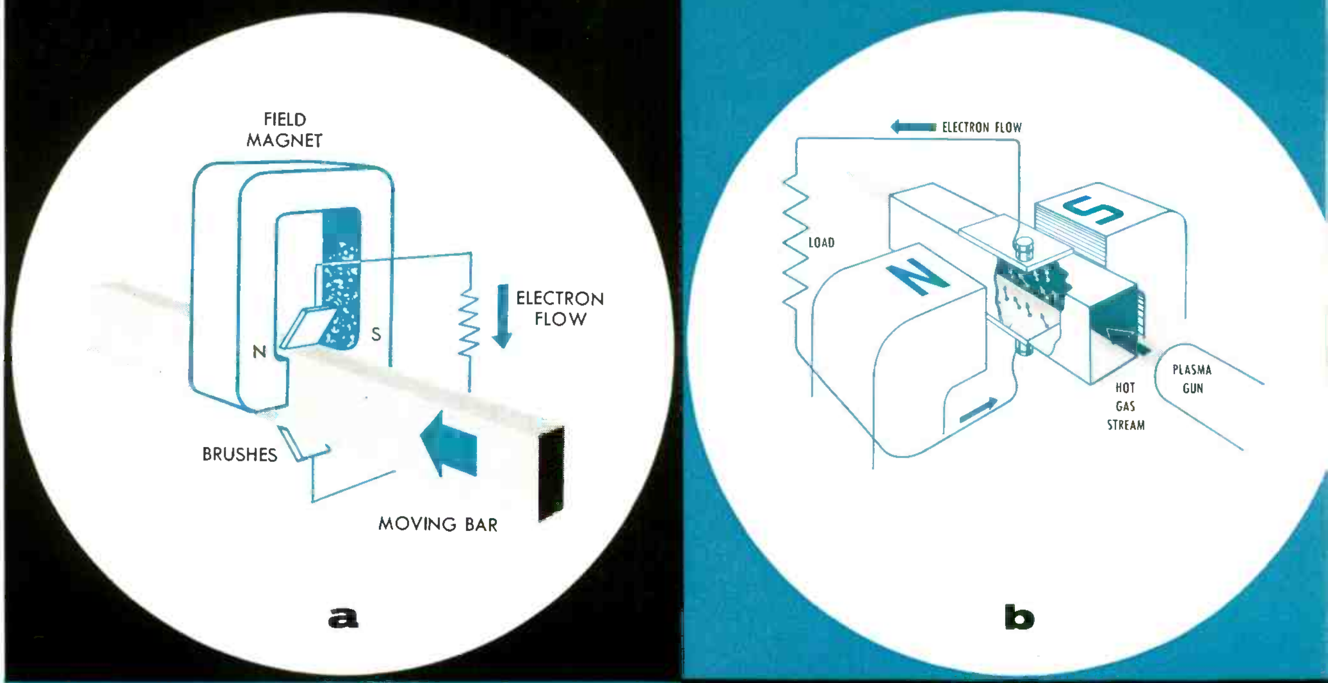

Fig. 1 (**a**)—This sketch illustrates Faraday's original concept, which formed the basis for the unipolar (or homopolar) generator;

(**b**)—The MHD generator employs the same principles, with a conducting gas replacing the moving bar.

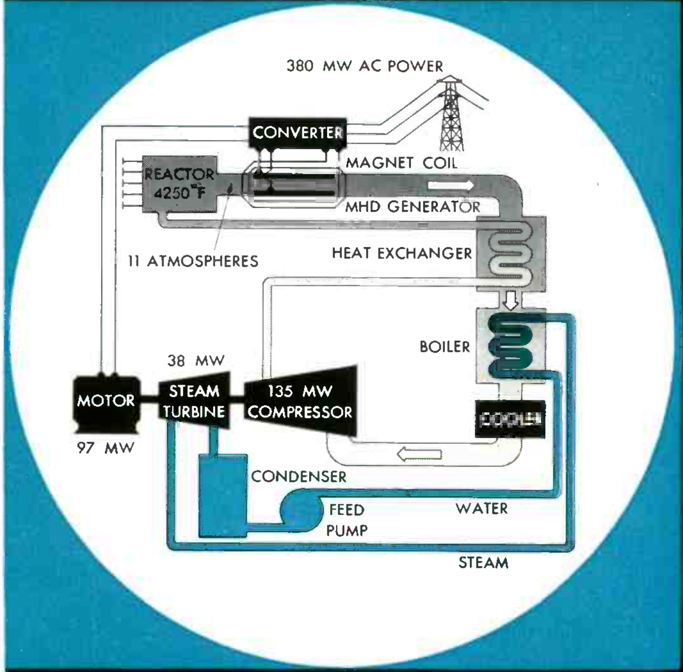

Fig. 2—(**Left**) A proposed 380-mw central station plant using an MHD generator as the power source.

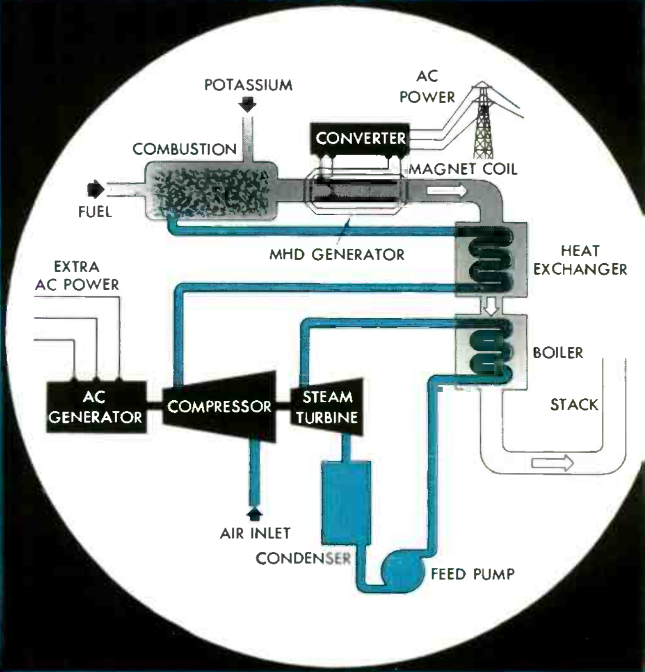

Fig. 3—(**Right**) Magneto-hydrodynamic open system using fossil fuels. Combustion products replace helium-cesium mixtures in conventional units.

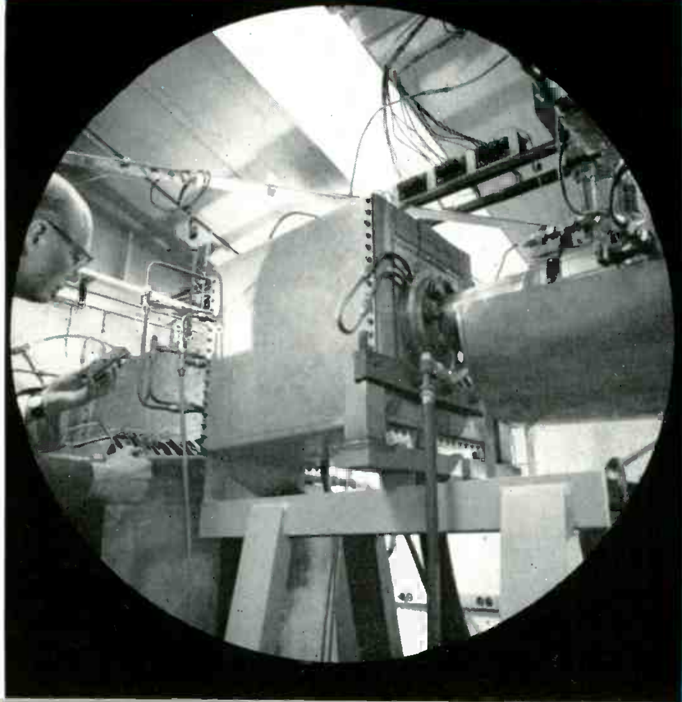

Fig. 4—(**Left**) This MHD power generator is the first to operate in the kilowatt range for a sustained period (four minutes). It is also the first sizable MHD unit to burn natural fuels in producing electricity.

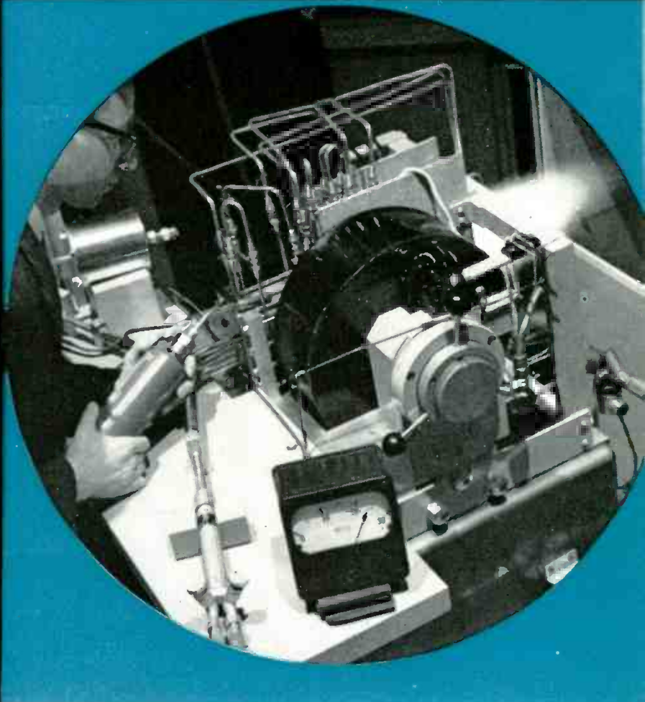

Fig. 5—(**Right**) This MHD generator was especially constructed by scientists at Westinghouse for experiments using combustible fuels. This demonstration device produces about one watt of electric power.

pressor to overcome the pressure drop normally occurring in the MHD generator, and a regenerator and waste heat boiler to recoup maximum energy from the hot gas stream.

One possible arrangement for a closed-cycle MHD plant is shown in Fig. 2. The gas consists of helium, seeded with two-percent cesium. The plant shown would generate 380 megawatts. Since the MHD generator develops direct current, a converter is required to produce an ac output.

The capital cost of the converter would be appreciable, although not prohibitive. Scientists are also studying the possibilities of direct MHD generation of ac power. Several approaches to this problem appear promising.

The MHD generator for the system shown in Fig. 2 would be 50 to 60 feet long, and would operate at about 4000 degrees F. A reactor may be used as the heating device. However, the development problems of this reactor, or of the heat exchanger that preheats the gas stream should not be underestimated.

A boiler is used to recover heat from the gas stream and generate steam. This steam drives a 38-megawatt turbine, which powers the gas compressor. The steam turbine is assisted by a motor, which consumes some of the MHD generator output.

To circumvent reactor development problems, two other possibilities are being considered: (1) a combustion-fired external heater could be used in the closed loop helium system of Fig. 2; or (2) an open system could be used in which the combustion gases pass directly through the MHD generator. The latter arrangement is shown in Fig. 3. In this case, a surplus of power can be generated in the steam loop so that an electric generator is present, replacing the dc motor used in the closed system. Operating temperatures in the MHD generator in the open system must be higher, however, because electron mobility is lower in combustion-product gases than in helium. Another difference is that potassium rather than cesium is used for seeding because cesium is too costly to discharge. In either case, means would have to be taken to avoid air pollution by the hydroxides of the seeding elements.

research in MHD

Problems ahead in MHD generation development are in the general areas of physics, materials, and engineering technology. Further work needs to be done in laboratories to obtain more reliable data on conduction of electricity in gases, and to provide a better understanding of the basic mechanisms of energy and momentum exchange in the MHD generator.

Materials must be developed to better withstand high temperatures, sudden temperature changes, and chemical interaction with the alkali-metal seeding materials. New engineering and design approaches must be found to build durable parts of ceramic, which have conventionally been made of metal. Durable electrodes must be developed to withstand high temperatures and chemical attack, and yet they must be good conductors.

To study these problems, several lines of research are being pursued. First is a basic study of materials and their properties, and investigations in gaseous electronics. Secondly, two experimental MHD generators have been built and are in operation. One of these is relatively small, for laboratory-type studies (Fig. 5); it burns hydrogen and oxygen, seeded with potassium.

The second, generator project (Fig. 4) is a larger machine, which has generated about nine kilowatts. About twice this figure is expected ultimately. The machine has been run for four minutes continuously. This generator burns diesel oil and oxygen, with potassium soap dissolved in the oil as a seeding element. Oxygen, rather than air, is used merely as a convenience to avoid the need for a large air preheater. Flow rates are 0.8 lb/sec of oxygen and 0.3 lb/sec of oil-soap mixture.

The generator field, 14 000 gauss, is produced by an electromagnet, which is mounted on a platform that can be raised or lowered.

Although MHD devices for producing short bursts of power have already been demonstrated and may offer potential in specialized applications, such as in satellite communications systems, a generator must operate continuously for the practical generation of commercial electric power. The machine shown in Fig. 4 is the only MHD generator that has been able to produce kilowatts of power over a sustained period of time. Further, this generator operates on combustion products rather than on a gas heated by an electric arc. In short, it demonstrates generation of electric power directly from a hot gas stream produced by a combustion process.

The generator section proper has a flow cross section of 1⅝ by 4⅞ inches, and is 16 inches long. Three pairs of graphite electrodes are mounted on opposite sides of the stream, with a distance of 4⅝ inches between their faces. The insulating side walls are of 1¼ inch thick zirconia. Flow of the combustion gas is 1.1 pounds per second at the design point, and the temperature is about 4600 degrees F. The velocity is approximately 1800 miles per hour, at a pressure of about one atmosphere (total temperature is 5000 degrees F). The oil-soap mixture is burned with oxygen in a specially designed swirl-type combustion chamber that discharges into a mixing plenum, and then into the generator proper. Water-cooled side walls are used throughout the generator, and zirconia lining is used everywhere except in the combustor flame tube, which is made of stainless steel.

This model is being used to investigate generator sidewall designs, electrode materials and configurations, power distribution in the generator, chemical reactions with the seeded gas, operating characteristics of the MHD generator, electrode potential drops, and potential and temperature distributions.

the future of MHD

Before a practical power source using MHD generation can be built, much work remains to be done on the problems already mentioned.

For straight-through MHD generators, several configurations are possible, including constant pressure, constant area, and constant velocity designs, or various combinations of these. Other geometries also should and will be investigated. The indirect-fired closed-loop system, adapted to direct ac generation, would seem to be one of the most promising arrangements upon which to concentrate vigorous effort.

Scientists are now actively pursuing the background researches, the material studies, and the development work that will be essential if MHD power is to become a practical reality. ■ ■ ■

FUEL CELLS . . . Electrical Energy From an Electrochemical Process

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A fuel cell is similar to a battery because both convert the "free energy" of a chemical reaction directly to electrical energy by an electrochemical process. In contrast to conventional batteries, the fuel cell uses a low-cost fuel and oxidant, which are continuously fed into the system.

Several types of fuel cells exist, but they all exhibit some basic similarities to the cell illustrated in Fig. 1. This schematic diagram illustrates one of the simplest cells, in principle, that can be devised. It is called an oxygen concentration cell. It consists of an electrolyte that conducts an electric charge in the form of oxygen ions, but is an insulator to electrons. The electrolyte is sandwiched between two electrodes. A voltage is created between the electrodes when the oxygen is at different concentrations at the two electrode-electrolyte interfaces.

Table I—COMPARISON OF FUEL CELLS UNDER DEVELOPMENT SHOWING TYPES OF FUEL, ELECTROLYTES, AND POWER OUTPUT PER UNIT VOLUME

FUEL	ELECTROLYTE	OPERATING TEMPERATURE	ESTIMATED KW/FT³ (CELL ONLY)
Hydrogen and oxygen	Aqueous alkaline 50 atm.	200–240°C	2–4
Hydrogen and oxygen	Solid ion exchange membrane 1 atm.	Ambient to 50°C	0.3–1.5
Hydrogen and air	Aqueous alkaline 1–5 atm.	50–80°C	0.2–1
Hydrogen and air Carbonaceous materials and air	Aqueous chemical intermediates (redox) 1 atm.	Ambient to 80°C	0.2–2
Carbonaceous gases	Molten salt 1 atm.	500–850°C	1–4

In operation, an oxygen molecule (O_2) diffuses through the porous cathode to the junction with the electrolyte, where it picks up four electrons to form two oxygen ions. The ions migrate through the electrolyte to the porous anode where they release their electrons and recombine to form an oxygen molecule. The anode that receives the released electrons is the negative electrode. The oxygen combines with a fuel or continues on into the chamber where it is exhausted from the system. If the two electrodes are connected to a load in an external circuit, a current will flow through the load. The current will continue to flow as long as a difference in oxygen concentration exists between the two electrodes.

Although fuel cells that illustrate this simplified principle are in early stages of laboratory research at present, most fuel cells involve electrode reactions that are more complicated than the simple concentration principle illustrated, and are consequently more restricted in the fuels they can use.

For example, consider the cells shown in Table I and Figs. 2–5. These are representative of some of the many different fuel cells being developed in laboratories throughout the world today. As the table shows, they vary in the nature of cell reaction, electrolyte, temperature of operation, and direct or indirect use of cell reactants. At present, the most successful fuel cells are "low-temperature" cells operating below 250 degrees C and using hydrogen and other special fuels. They are subject to critical catalyst problems since a catalyst is required at the electrodes to accelerate the electrode reactions.

These "low-temperature" cells use either aqueous or ion exchange membrane electrolytes and may be pressurized for better efficiencies. Hydrogen-oxygen (KOH electrolyte) cells have the best operating characteristics of all these low-temperature cells at present. However, hydrogen is a high-cost fuel. To improve the economics of this type of fuel cell, a cheaper source of hydrogen must be found. This might be done by improvements in methods of production of hydrogen by reaction of water with fossil fuels or perhaps by photolytic dissociation of water using solar energy and other methods.

high-temperature fuel cells

An alternative approach to economical fuel cells is to use the cheapest available fuels—such as natural gas and coal. This approach could conceivably make the fuel cell economical for production of electric power in the megawatt range.

Recent developments indicate that conversion of certain hydrocarbon fuels such as propane may be feasible with low-temperature fuel cells. However, the use of the low-cost fossil fuels in a fuel cell introduces particularly severe catalytic problems unless the cell operates at high temperatures. The electrode reactions of fuels such as coal or natural gas can occur much faster at high temperatures, so that cells operating over 500 degrees C would seem to have better long range potential as cheap power sources.

Unfortunately, high operating temperatures introduce some severe requirements for components of the system, especially the electrolyte and electrodes. To date most research devices of this type have used molten salt electrolytes, although the use of solid electrolytes is also a possibility. Cell components must be low in cost, highly resistant to corrosion for sustained periods of time at high temperatures, and retain useful conductivity properties. Materials research in laboratories throughout the world is being conducted to produce and investigate physical and chemical properties of fused salts, special ceramics, and metal alloys to satisfy these critical high-temperature requirements. Fuel processing must also be studied to obtain maximum efficiency and to prevent undesirable side reactions, such as carbon deposition at fuel inlets.

operating characteristics and properties

The unique characteristics of the fuel cell offer many advantages for electric power generation. For example, a fuel cell system contains no moving parts, and can operate silently. Efficiency is independent of cell size over a wide range of power output, as contrasted with steam-turbine generators, which have lower efficiency at lower ratings. Fuel cells are low-voltage, direct-current devices, which makes them particularly adaptable for use in the electrochemical industries. The most interesting property of a fuel cell is that it does not operate on a heat cycle, the limiting factor in the efficiency of steam-turbine generators and other heat engines. Thus a high-temperature fuel cell system should theoretically be able to produce over

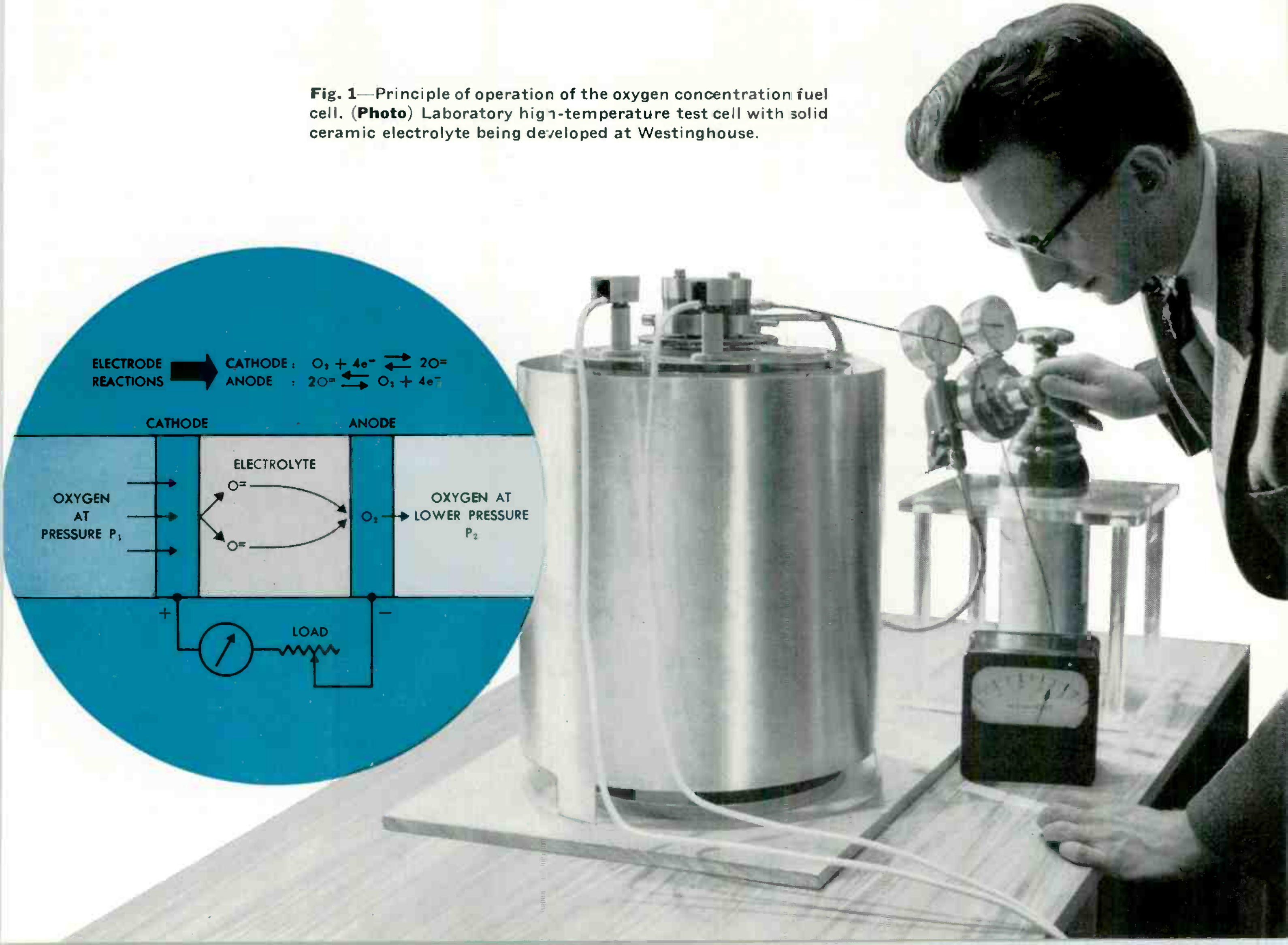

Fig. 1—Principle of operation of the oxygen concentration fuel cell. (**Photo**) Laboratory high-temperature test cell with solid ceramic electrolyte being developed at Westinghouse.

twice as much useful energy from fossil fuels as today's most efficient steam turbine generator unit.

The efficiency of the fuel cell is usually defined as:

$$\textit{Efficiency} = \frac{\textit{Electrical Energy Out}}{\textit{Heat of Combustion of Fuel}}$$

On this basis, fuel cells can theoretically operate at efficiencies as high as 70 to 90 percent, compared with a maximum 42 percent for today's most modern central station plants.

Unfortunately this is not the complete story since cell efficiency is also a function of system load. At higher loads efficiency decreases. An economic compromise must be accepted, where efficiency and capital cost, as affected by size and weight of the cell, are optimized.

summary

Fuel cells offer the possibility of more efficient conversion of chemical to electrical energy than conventional electric power generation methods. An ideal fuel cell would use cheap fuels, be made of economical materials, operate at high efficiency, have high power output per unit volume and weight of cell, and a long life. It appears that the "low-temperature" cells should begin to find special purpose applications within the next few years. The use of fuel cells for large-scale power generation is still in question and will require either a drastic reduction in fuel and capital costs for low-temperature cells, or the development of an inexpensive, long-lived high-temperature cell to utilize low cost fossil fuels. ■ ■ ■

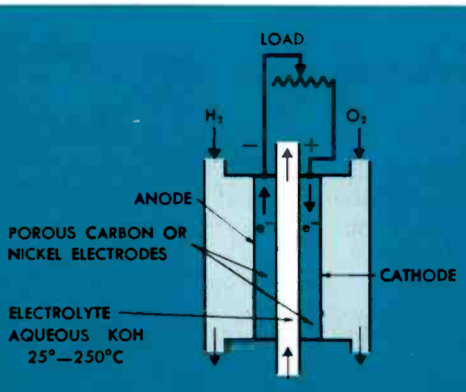

Figure 2

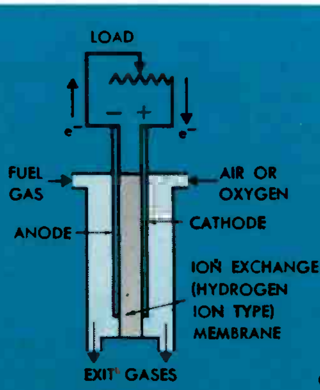

Figure 3

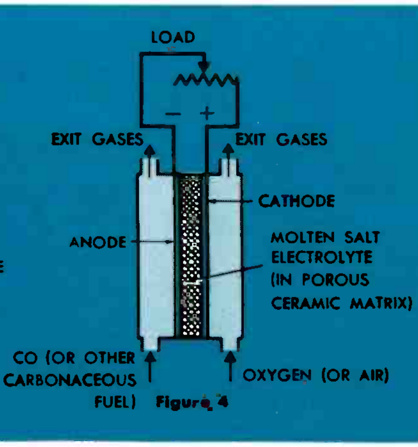

Figure 4

Fig. 2—Hydrogen-oxygen(KOH) fuel cells contain an aqueous potassium hydroxide (KOH) solution as the electrolyte. At the anode, hydrogen is oxidized to H_20 (loses electrons) in the presence of hydroxyl ions (OH^-). At the cathode oxygen is reduced (receives electrons) by a mechanism involving peroxide ions. The electrodes have special porous structures and catalysts. Cells may be pressurized for higher output and efficiency. Excess water is removed by evaporation.

Fig. 3—Ion-exchange membrane fuel cells contain a solid organic membrane that conducts either hydrogen (H^+) or hydroxyl (OH^-) ions. Oxygen (air) at the cathode is reduced (receives electrons). At the anode the fuel gas (e.g., hydrogen) is oxidized. If the electrolyte is H^+ ion conducting, the cell will operate as a hydrogen-oxygen cell with water forming at the cathode (oxygen electrode). If the electrolyte conducts OH^- ions, electrochemical reaction of oxygen with hydrogen or certain carbonaceous gases is possible, and reaction products form at the anode (fuel electrode).

Fig. 4—Molten salt fuel cells contain an electrolyte that is a mixture of molten alkali carbonates contained in the capillary pores of a ceramic matrix. It operates at temperatures above 500 degrees C. Oxygen (air) in the presence of carbon dioxide is reduced (receives electrons) at the cathode to form carbonate (CO_3) ions. Carbonate ions migrate through the electrolyte to the anode. Here the fuel is oxidized, forming carbon dioxide (and water if the fuel contains hydrogen or hydrocarbons).

Fig. 5—Redox fuel cells contain two liquid electrolytes separated by a membrane permeable to a common ion such as hydrogen (H^+). The electrolytes contain dissolved reactants, which are oxidized and reduced at the anode and cathode respectively. The reactants are regenerated from the products of the electrode reactions by the fuel and oxygen (air). This may be accomplished by circulating the electrolytes through regeneration chambers.

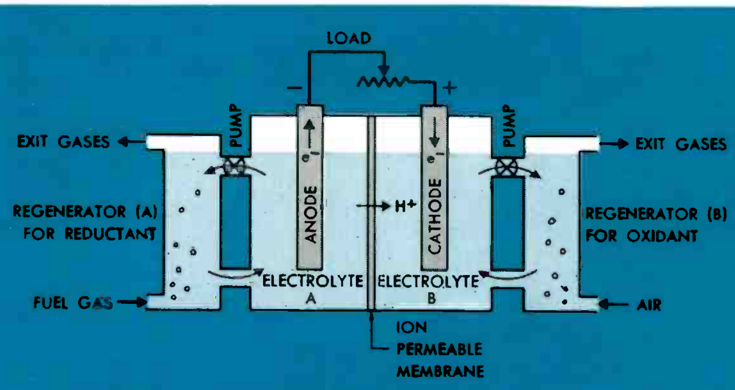

Figure 5

THE ECONOMICS OF VERY LARGE TURBINE GENERATOR UNITS

Today, many electric utilities are installing turbine-generator units of 300 to 500 megawatts capacity; a comprehensive study indicates further economies with much larger units, at least up through 800 megawatts.

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When considering future large turbine generating installations with unit ratings of 400 to 800 megawatts, electric utilities ask a fundamental question: "What advantage does a single large turbine generator unit have over two half-size machines; do real economic considerations justify the installation of a single large machine?"

To obtain a positive answer to the question, a comprehensive study was recently conducted of turbine-generator installations employing 400, 600, and 800-mw machines. The assistance of the boiler manufacturers was enlisted, along with the services of a plant engineering consulting firm, so that the complete costs of building and operating the total plant could be determined.

Five different plant configurations were considered: a single cross-compound 800-mw turbine generator unit; a single 600-mw unit; two 400-mw units; four 600-mw units, and three 800-mw units.

In evaluating the results of the study, it must be assumed that a given electric utility system under consideration can accommodate generators with these large ratings. The size of the system must be great enough to use large blocks of generating capacity effectively, and suitable reserve margins of generating capacity must be available within the system or from neighboring utilities.

study ground rules

To obtain a fair comparison between the various plant configurations, a number of stipulations were adopted. For example, only cross-compound turbines are considered. This restriction avoids building cost inconsistencies that could be caused by the length of the turbine-generator units.

The 400-mw turbine selected for the study is a cross-compound 3600-rpm turbine-generator unit with four sets of 28-inch blades, as illustrated in Fig. 1.

The 600-mw turbine considered is a cross-compound unit, but is a 3600/1800-rpm type, with four sets of 40-inch low-pressure blades, as shown in Fig. 2.

The 800-mw turbine, the largest turbine-generator unit considered, is a cross-compound 3600-rpm machine with eight sets of 28-inch low-pressure blading (Fig. 3).

Steam Conditions and Fuel—The steam conditions are 2400 psig, 1050/1000 degrees F, exhausting at 1.5 inch hg absolute, with eight stages of feedwater heating. The boiler feed pumps are assumed to be driven by noncondensing extraction turbines, which take steam from the main unit.

The fuel for all plants is pulverized coal. Land, water supply, rail facilities, highways, and subsoil conditions are considered identical for all unit sizes.

Turbine and Plant Heat Rates—The plant and turbine heat rates of the three sizes of turbine-generator units studied are listed in Table I. In calculating the energy costs only the heat rates at full load were used.

capital costs

The cost estimates are based on 1959 prices for the major equipment and auxiliaries. In the case of the 2400-mw multi-unit power plants, the equipment was assumed to be erected consecutively; when allowances were made for certain items common to all units, some saving resulted over a single-unit station.

Capital costs of the five plant configurations, reduced to dollars per kilowatt, are shown in Table II. Although disagreements may exist as to the absolute values—for example, cost of the main power building—the size factor is clearly demonstrated by a reduction in kilowatt cost with the larger ratings.

calculated energy costs

Once capital costs and plant heat rates have been established, the energy cost for the various plant sizes can be calculated. A typical calculation for the 800-mw single-unit plant is shown on page 114. In this example, fixed charges are assumed to be 14 percent of capital cost, and fuel cost is assumed to be 25 cents per million Btu.

To evaluate the effect of variations in fuel cost and turbine generator unit sizes, energy costs were calculated for the five different plant sizes, as listed in Table III.

The two major factors that influence electrical energy costs are indicated: *fixed charges* and *fuel cost.* Of the two, the fixed charge increment is of the greatest significance. Fixed charges are computed with current rates of interest, depreciation, and insurance. Any reduction in fixed charges, obtained through larger turbine sizes, design simplification or by any other means, is the most logical way of reducing energy cost.

With present steam conditions, little can be done to reduce the fuel cost increment. Any further advancement in steam conditions, with a resultant reduction in fuel consumption, will often be all or in part offset by the extra cost of the more efficient apparatus. From the vast amount of data available on heat rates and the cost data available on turbines, boilers, and piping, turbine designers see little chance of a marked reduction in the fuel cost increment in the future.

The energy cost of different sized steam plants has been plotted in Fig. 4, using a fuel cost of 25 cents per million Btu. Inasmuch as the heat rates of the three turbine sizes

TABLE I—HEAT RATES FOR TURBINE-GENERATOR UNITS STUDIED

Megawatts	Heat Rate Btu/kwhr.	Boiler Efficiency (%)	Station Auxiliary Power Requirements (%)	Station Heat Rate Btu/kwhr
800	7500	90	3.5	8636
600	7425	90	3.5	8549
400	7510	90	3.5	8647

TABLE II—STEAM POWER CAPITAL COST ESTIMATES

Plant Mw Capability	800	600	800	2400	2400
Number and Mw Capacity	2-400	1-600	1-800	4-600	3-800
Equipment	**Dollars Per Kilowatt**				
Main Power Building Sub-Structure and Miscellaneous	$16.22	$17.11	$15.78	$13.60	$13.37
Boiler Plant Equipment Instrumentation and Controls Feedwater Equipment Coal and Ash Handling Power Station Piping	65.08	62.50	58.29	58.96	56.44
Turbine Generator Unit Condenser and Water System	42.00	41.77	38.77	40.57	38.08
Generator Leads Main Power Transformers Auxiliary Power Equipment Conduit and Wiring Grounding, Switchboard Panels	9.23	9.06	8.12	8.49	7.76
Station Cranes Compressed Air Equipment Shop and Laboratory Equipment Signal and Communication System	1.09	1.46	1.12	.53	.48
Total Direct Cost $/Kw	133.62	131.90	122.08	122.15	116.13
Job Administration, Insurance Engineering and Drafting Purchasing and Expediting	14.00	12.67	10.12	6.72	6.08
Contingency Allowance	7.38	7.10	6.55	6.17	5.70
Total Estimates $/Kw	155.00	151.67	138.75	135.04	127.91

Items not included:

Land, switchyard and transmission facilities beyond main power transformers, allowance for wage and material escalation, interest during construction, power Company's general administrative prorates, waterfront improvements, employe housing during construction.

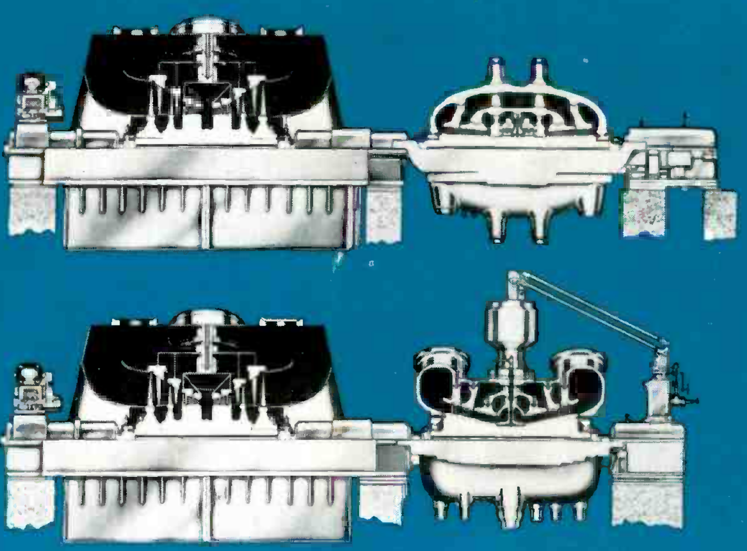

Fig. 1—Longitudinal section of 400-mw, cross-compound, 3600-rpm turbine-generator unit.

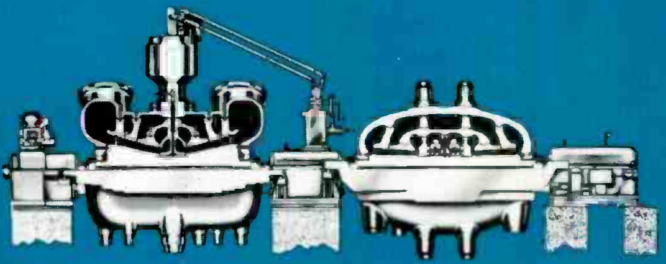

Fig. 2—Longitudinal section of 600-mw, 3600/1800 rpm, turbine-generator unit provided with four 40-inch low-pressure blade rows.

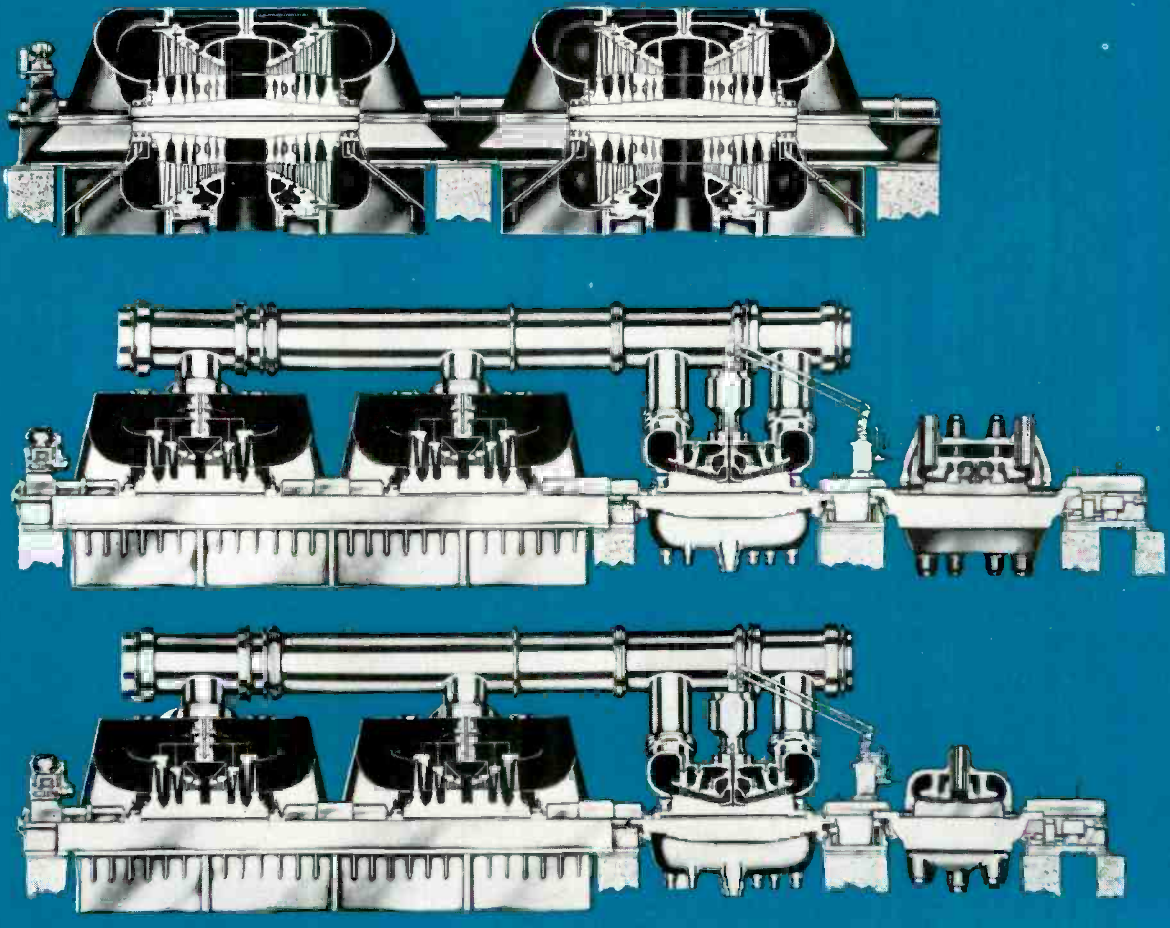

Fig. 3—Longitudinal section of 800-mw, 3600/3600-rpm, cross-compound turbine-generator unit.

Calculation of energy cost for 800-mw unit operating at 80 percent load factor with a fuel cost of 25 cents per million Btu.

A. Fixed charges (14 percent of capital cost):

$$= \frac{\text{Capital Cost} \times 0.14}{\text{Kw Rating} \times 8760 \text{ hrs/yr} \times \text{Load Factor}}$$

$$= \frac{\$111\,000\,000 \times 0.14 \times 1000}{800\,000 \times 8760 \times 0.80} = 2.77 \text{ mills/kwhr}$$

B. Operating and maintenance charges:

$$= \frac{0.30 \text{ mills/kwhr (at 100\% L.F.)}}{\text{L.F.}}$$

$$= \frac{0.30}{0.80} = 0.38 \text{ mills/kwhr}$$

C. Fuel cost:

$$= \frac{\text{fuel cost/million Btu} \times \text{Station heat rate Btu/kwhr}}{1\,000\,000}$$

$$= \frac{\$.25 \times 8636 \times 1000}{1\,000\,000} = 2.16 \text{ mills/kwhr}$$

D. Fuel inventory cost (4.5 percent per year, 90-day storage):

$$= \frac{\text{fuel cost, mills/kwhr} \times 0.045 \times \frac{1}{4}}{\text{L.F.}}$$

$$= \frac{2.16 \times 0.045 \times \frac{1}{4}}{0.80} = 0.03 \text{ mills/kwhr}$$

Total Energy cost:

A. Fixed charges	**2.77**
B. Operating and maintenance	**.38**
C. Fuel	**2.16**
D. Fuel inventory	**.03**
Energy cost	**5.34** mills/kwhr

TABLE III—CALCULATED ENERGY COSTS FOR FIVE DIFFERENT PLANT SIZES

800 MW, 80 PERCENT LOAD FACTOR

Fuel at	25c	30c	35c
Fixed Charges	**2.77**	2.77	2.77
Operation and Maintenance	**.38**	.38	.38
Fuel Cost	**2.16**	2.59	3.02
Fuel Inventory	**.03**	.04	.04
Total	**5.34**	5.78	6.21

600 MW, 80 PERCENT LOAD FACTOR

	25c	30c	35c
Fixed Charges	3.03	3.03	3.03
Operation and Maintenance	.38	.38	.38
Fuel Cost	2.14	2.56	2.99
Fuel Inventory	.03	.04	.04
Total	5.58	6.01	6.44

800 MW (2-400 MW), 80 PERCENT LOAD FACTOR

	25c	30c	35c
Fixed Charges	3.10	3.10	3.10
Operation and Maintenance	.38	.38	.38
Fuel Cost	2.16	2.59	3.03
Fuel Inventory	.03	.04	.04
Total	5.67	6.11	6.55

2400 MW (3-800 MW), 80 PERCENT LOAD FACTOR

	25c	30c	35c
Fixed Charges	2.56	2.56	2.56
Operation and Maintenance	.38	.38	.38
Fuel Cost	2.16	2.59	3.02
Fuel Inventory	.03	.04	.04
Total	5.13	5.57	6.00

2400 MW (4-600 MW), 80 PERCENT LOAD FACTOR

	25c	30c	35c
Fixed Charges	2.70	2.70	2.70
Operation and Maintenance	.38	.38	.38
Fuel Cost	2.14	2.56	2.99
Fuel Inventory	.03	.04	.04
Total	5.25	5.68	6.11

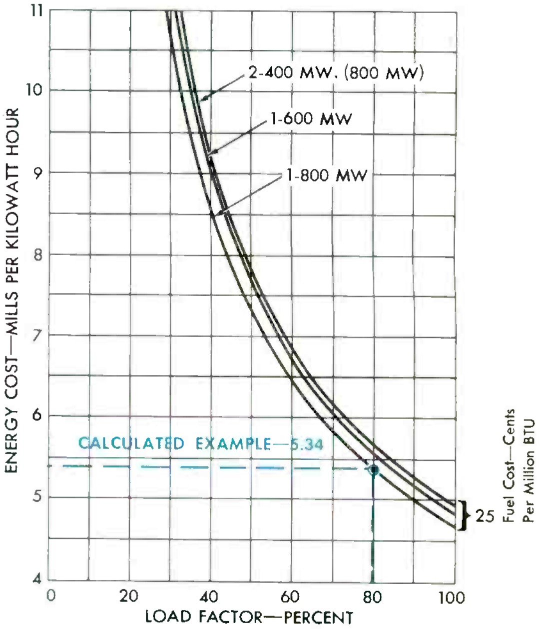

Fig. 4—Chart showing energy cost comparison of two 400-, one 600-, and one 800-mw turbine generator units.

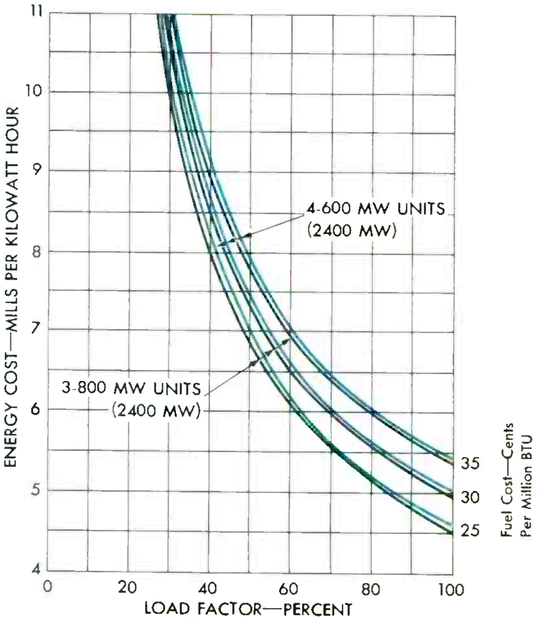

Fig. 5—Chart showing energy cost of 2400-mw steam plant, one of which is comprised of four 600-mw units and the other of three 800-mw units.

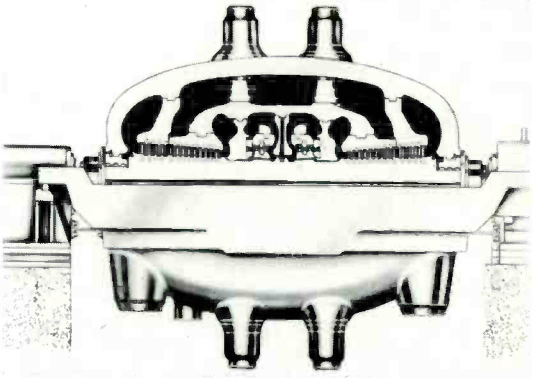

Fig. 6—Longitudinal section of double-flow, high-pressure turbine element.

are about the same, the lower energy costs obtained with larger plants must be credited to a reduction in fixed charges, made possible by use of larger generating units.

A comparison of the energy costs of the two 2400-mw plants, one composed of four 600-mw turbines and the other of three 800-mw turbines, is given in Fig. 5. Again, the plant with the larger generating units has the lower energy cost, because of reduced fixed charges.

reliability

Availability records maintained by the Prime Movers Committee of the Edison Electric Institute for the three-year period ending in 1957 have shown several points reduction in availability for turbines in the top classification of pressure, temperature, and kilowatt size. However, in the classification immediately below the topmost one, where more operating experience has been accumulated, the availability is above 90 percent.

Today, many turbines are operating with initial steam conditions of 2000 to 2400 psig, and with temperatures ranging from 1000 to 1050 degrees, and with ratings of 250 mw and above. These turbines are in the most advanced turbine classification considered by EEI, so that operating experience should be gained rapidly. Except for some turbine pioneering, these subcritical steam conditions probably will be used for the majority of new plants in the immediate future. The general availability of machines operating with these steam conditions should improve materially, and approach that of machines with average operating conditions.

With initial steam conditions held substantially constant for a few years, what would be the effect upon reliability of increased turbine capability to 800 megawatts, or higher?

In some areas, the larger sizes would have little effect. Throttle governor and interceptor valve sizes can be maintained near past proven sizes by merely using a greater number of units. For example, four throttle and interceptor valves could be used instead of the two required on smaller turbines.

Of greatest concern is the size effect upon the reliability of the steam-flow blade path, of which the first and last stages are the most critical areas. Increasing the kilowatt output of a turbine with the same initial pressure means increasing the first-stage nozzle height proportionately. Experience is available today on first-stage nozzles and blading of turbines up through 350 mw. By "double flowing" the high-pressure turbine element, twice the output can be obtained with the same first-stage nozzle height (shown in Fig. 6). Double flowing the high-pressure turbine has another advantage in that the steam torque forces present at reduced loads and partial admission can be balanced. Deflection of the high-pressure turbine shaft becomes a serious problem with large flows and partial admission. This problem is solved by arranging the steam admission to each first-stage wheel 180 degrees apart, thus balancing the steam torque forces; this arrangement cannot be used in single control stages without encountering what might be a worse vibration problem—two steam admissions per revolution of the wheel.

A new turbine blading material, called Nivco, was recently developed for steam turbine application at temperatures of 1200 degrees or higher. However, this high-temperature alloy also has been found to have excellent internal damping characteristics at lower temperatures, such as 1050 and 1000 degrees F. Damping is that characteristic that resists or damps the first-stage blade vibration caused by partial admission. Turbine designers have already had experience with Nivco in 100-percent admission stages; additional experience will soon be obtained on first-stage blades for large single-flow elements. Inasmuch as Nivco cannot be welded, the usual method of welding the first blades into three-blade groups was replaced with a method of attaching individual blades to the rotor. The use of Nivco in an 800-mw high-pressure turbine element would make the first-stage blading even safer than in present high-pressure elements.

Exhaust-end blading for an 800-mw turbine would consist of four sets of double-flow 28-inch blades, as used in a 200-mw tandem-compound single-shaft turbine. In the design stage today is a 3600-rpm cross-compound turbine of 342-mw capacity, which will have two sets of double-flow, 28-inch blading (Fig. 1). The 800-mw turbine would have double this number of low-pressure blades.

By designing very large turbines to use, in multiple, the proven components of other smaller turbines, the potential of trouble or outage is greatly minimized.

manufacturing cost

One of the factors that suggested a re-evaluation of the economic potential of large turbines was the apparent high production cost of some early large turbine designs. The immediate market for 600- and 800-mw turbines is admittedly limited. Therefore, the cost of making special patterns, tools and machine tools for a few turbine Goliaths would be exorbitant. Recognizing the undesirability of this approach, turbine designers initiated a plan about four years ago to develop standard pre-engineered turbine components that could be used singly or in multiples to produce larger machines. This concept, whether the turbine being designed is a 200, 400, 600, or 800-mw unit, is followed today with excellent results in turbine design and manufacture, and is one of the principal reasons why large turbines are again an economic reality.

Generators for the proposed 800-mw turbine generator set would be duplicate 400-mw alternaters of the inner-cooled type. The rotor diameters will not exceed that of generators already in service. Armature coils will be insulated with Thermalastic insulation.

conclusion

The study clearly demonstrates that energy costs can be reduced by installing larger and larger turbine generator units, at least through 800 mw. The reliability of these large turbine generator units will continue to be excellent. Operation of these large turbine generator units will be comparable to the present 250- to 350-mw cross-com-compound turbines.

By building these large turbines from a multiplicity of pre-engineered parts, lower turbine costs and more attractive prices to the user can result.

Experience with the large turbines of the kind discussed in this article will pave the way for the next general advancement in inlet steam conditions to 3500 psig and 1050 degrees F, or higher. ■ ■ ■

A DECADE OF PROGRESS IN MERCURY LIGHTING

Many of the improvements that design engineers make in lamps are literally too small to be apparent to the naked eye. But the effect of the cumulative improvements is something else again. One example: rated life has gone from 4000 to 12 000 hours in ten years.

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Today, nearly everyone has become aware of mercury lighting. It is used in streets and highways in and around cities and towns all over the United States, and in many other countries. Even more important is its widespread use in industrial plants. New installations are being made at an all-time high rate. This acceptance of mercury lighting is due largely to the many technical accomplishments during the past decade.

Light is produced in a mercury lamp by the passage of electric current through vaporized mercury at operating pressures up to several times atmospheric pressure. A small amount of argon gas is included to facilitate starting. The typical lamp has an internal arc tube made of fused silica, a glass-like material with a very high melting temperature. The arc tube is placed into an outer bulb of ordinary glass, which is either clear or inside coated with a phosphor material for enhancement of the lumen output or for improved color rendition. An auxiliary ballast is required with mercury lamps to provide the required voltage to start the arc and to control the arc current. When the lamp is first turned on, the mercury is in the form of liquid droplets, which gradually vaporize. After three or four minutes, the mercury is completely vaporized and full light output is reached.

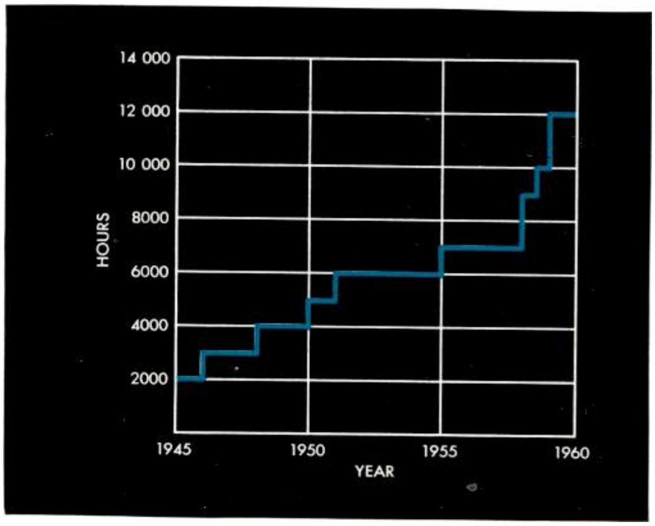


Fig. 1—The rated life of mercury lamps has increased rapidly. This curve is for 400-watt mercury lamps.

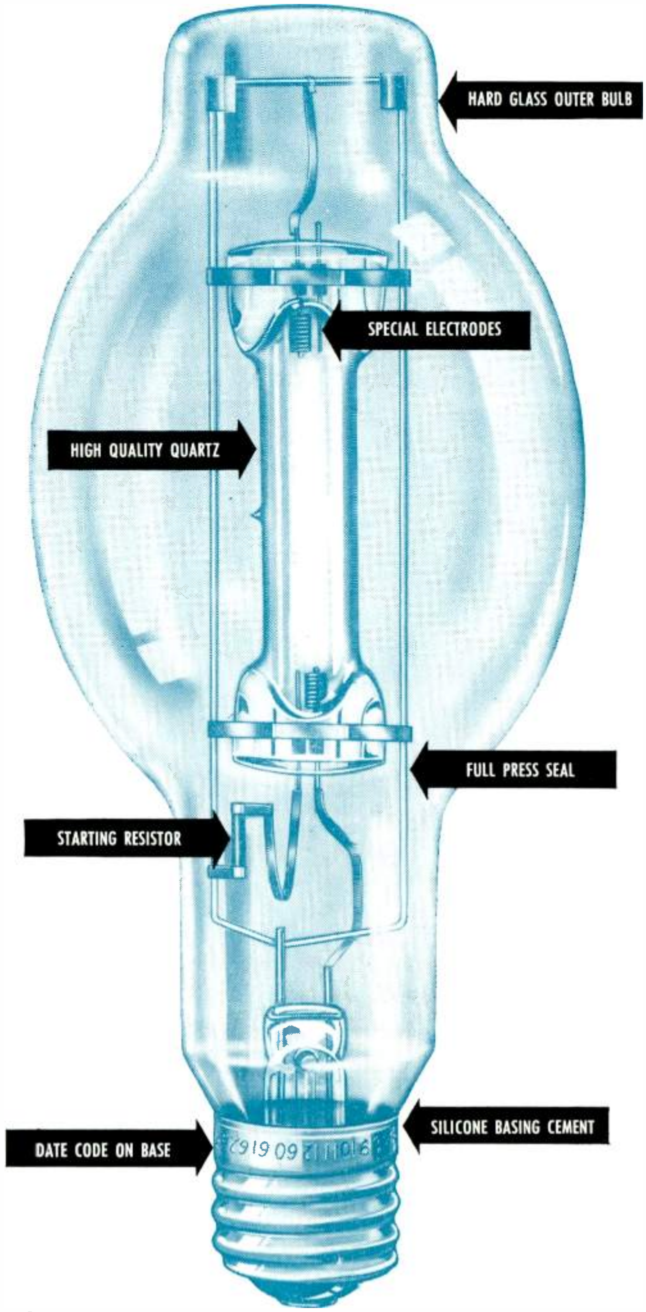


Fig. 2—The 400-watt mercury lamp (H33) has undergone many improvements: Special oxide emission material is embedded in and shielded by the tungsten coils, reducing depositing of electrode material on the quartz wall; quartz made by automatic process insures close tolerance and high purity; the one-piece seal assures greater uniformity; the resistor of high-temperature materials assures dependable starting; the hard glass bulb resists thermal shock; and the silicone basing cement resists heat and holds tight as the lamp ages.

The fundamental advantages of the mercury-vapor light source are long lamp life and a high luminous efficiency with high light output per unit. During the past decade, these characteristics have been improved to the point where they offset the relatively high unit lamp cost and the need of an auxiliary ballast, and result in the lowest cost of light.

In designing most industrial and street lighting installations, a choice exists between three main classes of light sources: incandescent filament, fluorescent, or mercury. Any improvement in one type of light source has the effect of stimulating a comparable improvement in the other two. For example, the advent of the newer fluorescent or mercury classes of lighting about 1940 did not cause a general replacement of the older incandescent filament lamps, as was once predicted. Instead, it stimulated incandescent lamp business, because more attention was given toward designing good lighting, whatever the type. Actually, the three general classes complement each other, and evolutionary processes determine the areas where each type is most suitable.

Increasing labor costs for replacing lamps at the end of life has made the longer life of mercury lamps important in competing with incandescent, particularly for street lighting and industrial lighting. This, in turn, has stimulated the development of new designs and manufacturing methods for extending the advantage. Fluorescent lamps have meanwhile been improved and have been applied in street lighting and even in high-bay industrial lighting competing directly with mercury lamps. At one time, fluorescent lamps had considerably better lumen maintenance throughout life than mercury. Mercury lamps had high lumen output per unit and thus required fewer fixtures, but the lumen maintenance of fluorescent lamps frequently offset this advantage and there was little difference in true cost in many cases. Recently, however, the greatly improved lumen maintenance of mercury lamps has swung the economics strongly in favor of mercury.

In 1950 the rated life of the important mercury lamps was 4000 hours. The fact that the majority of lamps lasted much longer indicated a much higher potential life but ratings were based upon mortality curves, which had to take premature failures into account. The changes in life ratings from 1945 to 1960 are shown in Fig. 1. Even with the present rating as high as 12 000 hours, the potential is known to be still higher.

The lamp improvements mainly responsible are illustrated in Fig. 2 and fall in four categories:

(1) New designs of quartz-to-metal seals for greater reliability and dimensional uniformity in high production.

(2) Better process for making fused quartz tubing from natural crystals, yielding better dimensional control and purity of material.

(3) New electrode design for a major improvement in lumen maintenance.

(4) Use of more durable outer bulbs, basing cement and other parts to complement the other improvements and assure longer life.

seals for fused quartz

The low thermal expansion of fused quartz is both an advantage and a disadvantage. The advantage is that strains from thermal shock are negligible; the disadvantage is that no metal conductor can match this characteristic for easy manufacture of metal seals to fused quartz. The evolution of various types of quartz seals is shown in Fig. 3. Years ago a laboratory type of seal consisted of a very thin molybdenum ribbon (one-half of a thousandths of an inch thick) in an evacuated fused quartz tube, which was flame heated to shrink it down to the metal ribbon. For early production a more sophisticated graded seal using several special glasses was developed, Fig. 3A. Sealing strains often caused unpredictably premature lamp failures, somewhat limiting the general acceptance of mercury lighting. A method was worked out to use the original thin ribbon seal in production, Fig. 3B. This was reported early in the past decade and gave a major boost to the reliability of mercury lamps.

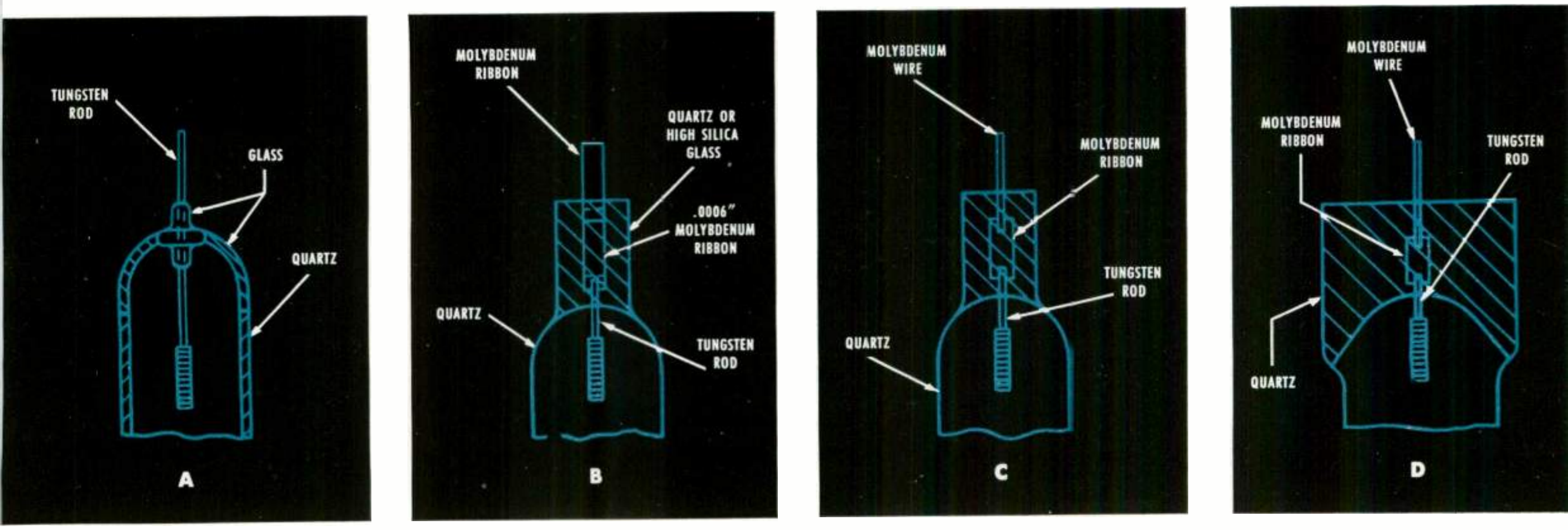


Fig. 3—Types of seals developed for mercury lamps: A, a glass beaded tungsten "graded" seal; B, vacuum shrunk molybdenum foil seal; C, "pressed" seal (narrow); D, "full press" seal.

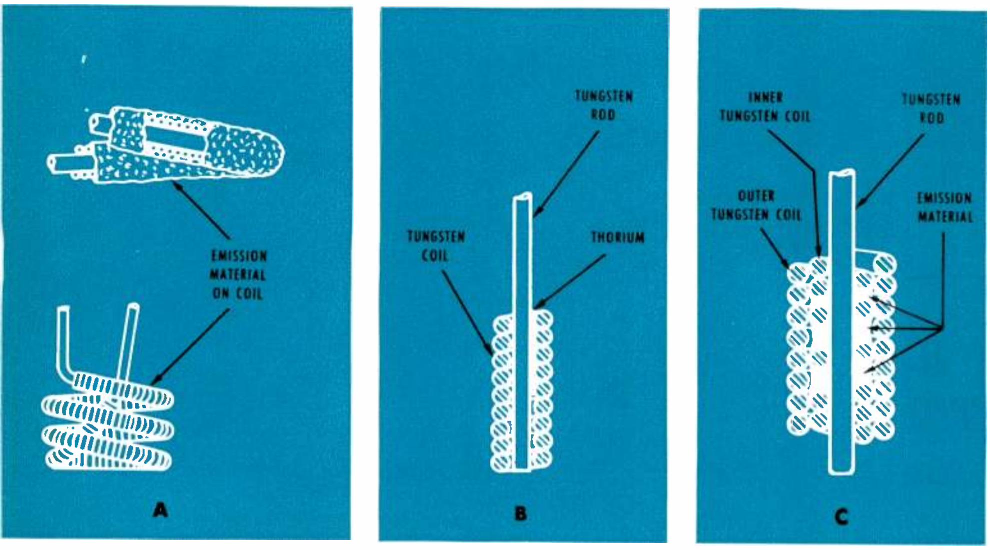


Fig. 4—Types of electrodes for mercury lamps: A, oxide coated tungsten coils, used in lamps with glass arc tubes; B, thorium sliver welded beneath tungsten coil, used in quartz arc tubes; and C, oxide embedded double-coil electrode recently developed for quartz arc tubes.

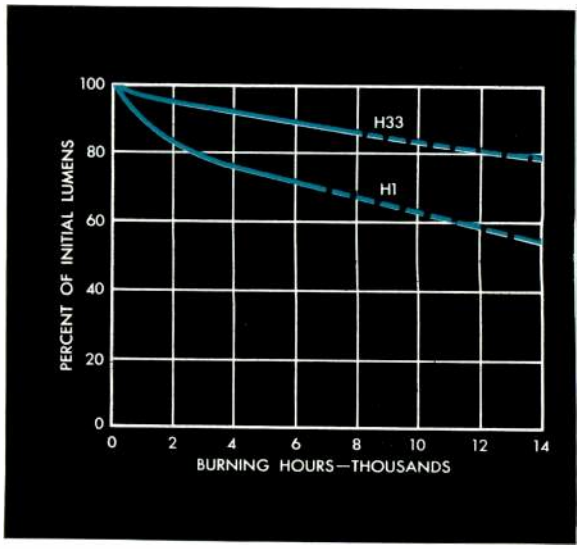


Fig. 5—Top curve shows the lumen maintenance for 400-watt H33 lamps with new oxide embedded emission material. Bottom curve is for 400-watt H1 mercury lamps with thorium electrodes.

After several years, the vacuum-type thin-ribbon seal was replaced with a mechanically pressed seal of more uniform dimensions and better adapted to higher speed manufacture, Fig. 3C. In 1959 came a further improvement; the pressed seal was made directly from a sull-sized piece of the quartz tubing without the necessity of reducing the diameter of the fused quartz arc tube at the ends, Fig. 3D. This latest seal design is even more accurately dimensioned and contributes greatly to quality uniformity.

improved process for making fused quartz tubing

One of the practical requirements in improving mercury lamp reliability is that lamps must be able to give good performance with wattage input as much as 20 percent over the nominal rating. This extreme can result from the possible addition of tolerances in line voltage, ballast transformer, and lamp making.

For many years quartz tubing was drawn with skilled operators on relatively crude equipment where the practical diameter tolerance for tubing was plus or minus eight percent. With a wide diameter tolerance those arc tubes made with quartz tubing at the lower diameter limit will operate at a considerably higher temperature than arc tubes made with larger diameter. The life of a quartz lamp can be adversely affected if quartz is subjected to excessive temperature. The arc tube is designed as small as practical to get maximum luminous efficiency. The diameter tolerance of tubing thus has a bearing on life reliability.

A new process has been developed for drawing the tubing continuously from the bottom of a high-temperature furnace while loading quartz crystals at the top. The process is similar to the drawing of glass tubing. As a result the diameter tolerance is now plus or minus two percent.

new electrode design

The first material tried as an electrode coating for quartz mercury lamps consisted of oxides similar to those used in glass arc-tube lamps developed about 1933. Unfortunately, this oxide material vaporized relatively rapidly, and although suitable for glass arc tubes, proved excessively corrosive when used in quartz arc tubes. A diagram of such an electrode is shown in Fig. 4A. Quartz mercury lamps became practical around 1939 only because of the development of the thorium electrode. In the construction of the electrode, as shown in Fig. 4B, a tiny sliver of metallic thorium is placed beneath a tungsten coil and securely welded. Only one coil of tungsten at each electrode is generally used over the thorium.

The new electrode, shown in Fig. 4C, consists of two coils, one within the other. The inner coil has open turns of tungsten wire. The reservoir of active emission material is deposited in the spaces between these turns. The outer coil has close spacing of turns acting as a protective shield between the arc and the emission material reservoir. The special blend of ingredients, essentially oxides and tungsten powder, and the critical procedures for treating and activating the electrodes were originally developed at OSRAM in Germany. The principal improvement in mercury lamp characteristics resulting from the new electrode is the much better lumen maintenance. This is shown by the curves of Fig. 5 and by the comparison in Fig. 6 of blackening of arc tubes after 7000 hours burning. The better maintenance is the result of two factors. First, the rate of evaporation of material from the new electrode is greatly retarded and, second, any material that does evaporate is of a whitish color rather than black and absorbs less of the light emitted by the arc.

Mercury lamps made with the new electrodes can be started much more readily than with the previous thorium type. This is particularly helpful at the low ambient temperatures to be expected in winter in large areas of the United States. A comparison of the two electrode types on the required open circuit voltage is shown in Fig. 7. Lower starting voltage means lower ballast cost is possible.

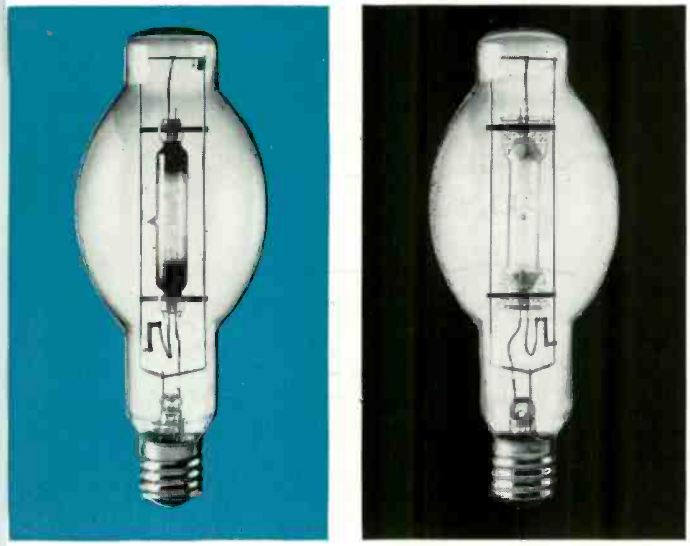


Fig. 6—Left, a 400-watt H1 mercury lamp after 7000 hours burning. Right, a 400-watt H33 mercury lamp after the same operating time and under the same conditions. Note the reduction in blackening of the arc tube.

improved materials for outer bulb assembly

As the mortality experience improved from arc tube improvements, a new look was taken at other aspects of lamp design. For example, the outer bulbs using soft lime glass deteriorated as a function of temperature and time, by weathering or chemical attack by water vapor, sulphur dioxide, and other reactive gases often found in the atmosphere. Methods for preventing this deterioration were investigated. The only permanent way to prevent this was found to be the use of harder borosilicate glass for outer envelopes. Now the "Weather Duty" lamps are made with this glass.

Another factor in lamp life is the basing cement. Ordinary basing cements age in time and no longer hold the lamp base tightly to the bulb. A high-temperature silicone cement was put into use early in the past decade; this retains its strength and adhesive properties almost indefinitely at base temperatures well above those normally encountered in mercury-lamp fixtures.

mortality experience

As a result of all the improvements, the survival data for mercury lamps in actual use has greatly improved. In Fig. 8 the most recent published curve is compared with the published curve for types without the improvements.

color rendition

The light from a mercury arc has a distinctive color that is weak in red but is still widely accepted for street lighting or floodlighting. For many applications, however, color discrimination is involved and some correction is necessary. Originally this was done by intermixing incandescent lamps in the system. However, a more practical solution was found in a magnesium fluorogermanate phosphor, applied to the inside wall of the outer bulb.

The phosphor converts unused ultraviolet radiation of the mercury arc into red light, which adds to the other colors emitted from the arc. The improved color rendition extends the usefulness of mercury lamps to many new applications. The spectral energy distribution of typical mercury lamps can be compared in Table I.

A still further improvement in color rendition has been accomplished by an optional subtractive filter coating that is pink-purple in color and reduces the yellow-green portion of the light output. This coating reduces the lamp efficiency about 20 to 25 percent but extends the use of mercury lamps to still more critical applications in public buildings such as gymnasiums, libraries, and banks.

phosphor for increased lumens

While color improvement is accomplished with magnesium fluorogermanate phosphors, rated lumen output is reduced slightly. However, another phosphor, strontium zinc orthophosphate, has been developed with a broad emission over a large part of the visible spectrum, which increases lumen output. This phosphor provides a degree of color correction by addition of red, but its main advantage is enhanced lumen output by the emission of light in yellow and green, thereby adding to the mercury arc output in these colors of high luminosity. The improvement in luminous efficiency is apparent in the comparison of published ratings of the three principal kinds of 400-watt mercury lamps shown in Table I. The comparison of spectral distribution of radiated energy is also shown.

Fig. 7 Right—Lamps with the new oxide embedded electrodes start more readily than comparable lamps with thorium electrodes. Values shown are neither minimum nor maximum.

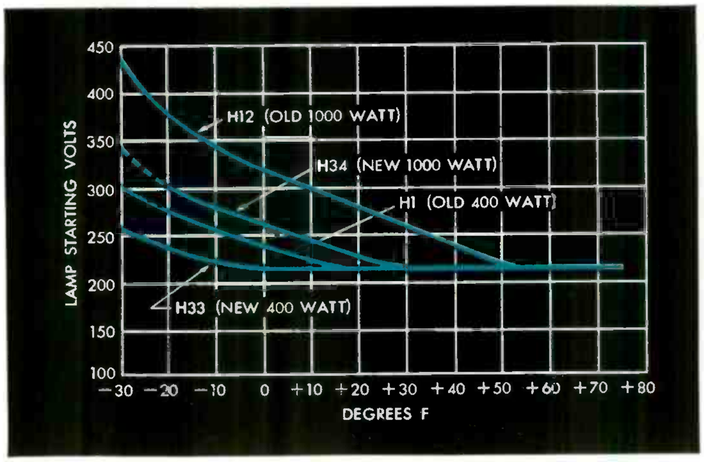


Fig. 8 Far Right—Mortality curves for quartz mercury lamps.

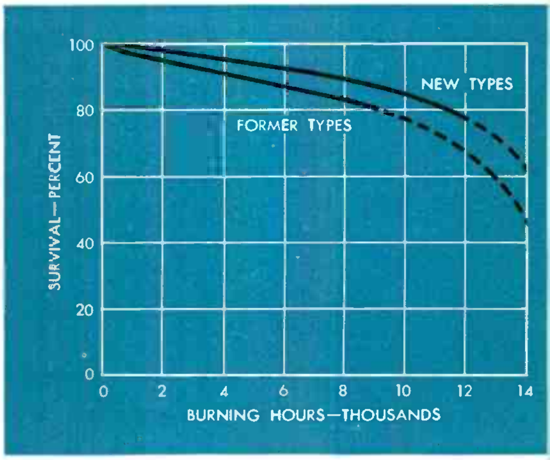


TABLE I—LUMINOUS EFFICIENCY AND SPECTRAL ENERGY DISTRIBUTION

(Comparison of three principal kinds of 400-watt mercury lamps)

		Clear Mercury	Fluoro-Germanate Phosphor	Orthophosphate Phosphor
Rated Lumens		21 500	20 500	25 000
Watts Radiated at Principal Lines & Bands				
6000–7600 Angstroms	(red)	—	23.47	13.41
5770–5790 "	(yellow)	16.12	12.62	15.78
5461 "	(green)	14.05	11.01	13.39
4358 "	(blue)	11.07	6.47	9.89
4047 "	(violet)	6.67	3.83	5.46
3650 "	(ultraviolet)	13.21	7.85	11.18

short-arc lamps

Several special mercury lamps are designed for applications such as photoprinting, sun tanning, and projection use in scientific instruments and searchlights. One is the short-arc mercury lamp, used where extremely high arc brightness is desired. These lamps have arc lengths ranging from a fraction of a millimeter to one centimeter; sizes range from 100 watts to 2500 watts. The arc brightnesses are from 200 to 400 candles per square millimeter.

Two types of short-arc mercury lamps are shown in Fig. 9. The 250-watt size was developed for optical comparators and other instruments, the 1000-watt size for searchlights and projector systems. The larger sizes do not use outer bulbs and therefore have special seal designs for reliable service at high temperatures in air (Fig. 10.)

looking ahead

Research is now directed toward the development of new phosphors for still better color rendition and for still more lumens. An interesting breakthrough might come from the possible development of a phosphor that has good performance at 600 to 700 degrees C; such a phosphor could be applied directly to the arc tube instead of the inside of the outer bulb. This would provide a smaller light source, and optical control of the light from a color corrected lamp could then be achieved as easily as with an uncorrected mercury lamp.

Progress is being made on simplification of ballast transformers, such as having one ballast operate two or more lamps in parallel, so that each can function independently. Ultimately a way may be found to re-start lamps hot after brief power interruptions instead of having to wait about three minutes for lamps to cool off enough to re-start.

Luminaire design has been directed toward more comfortable factory lighting with a portion of the light going upward to white painted ceilings. New street lighting luminaires for the smaller 100, 175 and 250 watt sizes are beginning to find widespread use in residential areas.

As applications develop for higher lighting levels, currently recommended by the Illuminating Engineering Society, higher wattage lamps may be needed and developed. There is no real limit for lamp power if needs arise that require still more lumens per unit. ■ ■ ■

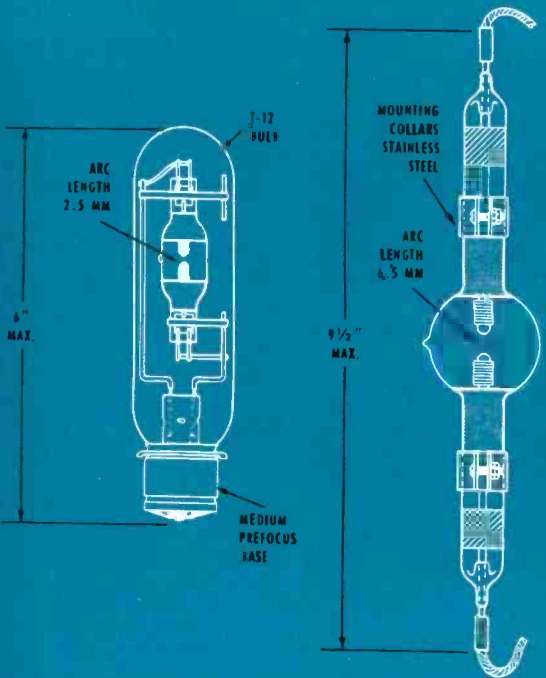
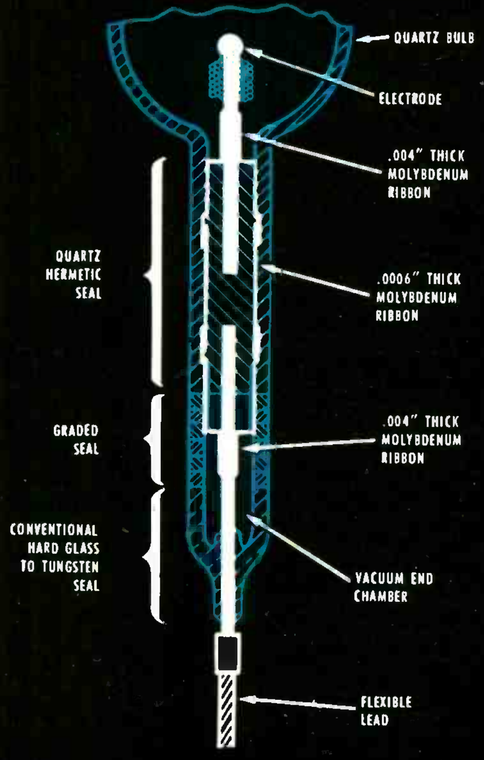


Fig. 9—(Above) Two types of short-arc mercury lamps. Left, a 250-watt lamp with single ended current carrying leads, and right, a 1000-watt lamp with diametrically opposite leads.

Fig. 10—(Below) A cross-section view of the new double hermetic seal.



SAXTON REACTOR PLANT

This small reactor is designed to explore new areas of reactor operating conditions. The information obtained could lead to less expensive designs in the future.

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In its search for ways to attain economically competitive electric power, the fast growing atomic power industry needs reliable engineering information and experience, and needs it vitally. New ideas must be confirmed by demonstration under actual operating conditions before they can be adopted for regular engineering design.

The operation of full-sized power plants yields valuable experience, but does not provide all the necessary information. Their high capital investment cost and dependence of the power system on their generating capacity makes operation at high load factors essential. Steady operation at high power is incompatible with much of the needed experimental operation.

One answer to this problem is the construction and operation of a relatively low-cost, small-scale plant whose output is not essential to the power system. The Saxton Reactor will be just such a plant. Its primary purpose is the production of information and the testing of new modes of operation for water reactors.

background and purpose

As early as 1955 the General Public Utilities Corporation and its subsidiaries studied the economic feasibility of building a commercial-sized nuclear power plant. In August of 1957 they concluded that a commercial-sized nuclear plant was not economically feasible at that time and the GPU management decided to study the possibility of building a small experimental facility that would be hooked on to an existing steam generating station. In December 1958, Westinghouse and GPU, along with the engineering firm Gilbert Associates, Incorporated, decided to undertake such a project, to explore the possibilities of increasing nuclear fuel use efficiencies and economies, and lowering future nuclear power plant capital costs. Also, such a facility would provide training and experience for both Westinghouse and GPU System personnel.

General Public Utilities Corporation chose the Saxton site of the Pennsylvania Electric Company for the experimental plant. Situated in a sparsely settled area, but at a junction of Penelec's transmission lines, the plant will have very reliable power ties and can vary its load freely with little disturbance to the rest of the power system. A coal-burning plant now in operation on the site provides a suitable low-pressure turbine-generator unit.

A five-year joint program of experimental operation was worked out by Westinghouse and the Saxton Nuclear Experimental Corporation, a new corporation formed by the General Public Utilities Corporation subsidiaries, comprising Pennsylvania Electric Company, Metropolitan Edison Company, New Jersey Power & Light Company, and Jersey Central Power & Light Company. Pennsylvania State University and Rutgers University are also participating in the program. The basic theme of this program is to push core operating conditions above the limits now imposed by proven practice. This includes higher specific power and heat flux, boiling of coolant in the core, use of dissolved poison for shim control. Demonstration of the practicability of these operating conditions and the engineering data obtained should then permit sounder and less expensive designs for future atomic power plants.

technical description of the plant

The Saxton Reactor Plant is a complete nuclear steam generating plant, including all essential auxiliaries and controls. It includes the condensate and boiler feed system, but not the turbine-generator or condenser. This reactor system will be similar to, but smaller than, Shippingport, Yankee, and BR-3. However, because the objective is engineering information and the mode of operation will be experimental, the design emphasis is on flexibility.

As shown in Fig. 1, the primary system consists of the reactor, steam generator, coolant circulating pump, and pressurizer. At the nominal power level of 20 mw the canned motor-pump circulates coolant at a rate of 7250 gpm. This coolant enters the reactor at 520 degrees F and leaves at 540 degrees F. It gives up its heat in a vertical U-tube steam generator and returns to the pump.

A cross section of the Saxton reactor core is shown in Fig. 2. The core will be composed of 21 square fuel assemblies, each containing about 72 fuel tubes filled with sintered pellets of uranium oxide. Assembled, the core will have an effective diameter of 28 inches and an effective height of 36 inches.

Six control rods of a silver-indium-cadmium alloy will provide working control for the reactor, and shutdown in the hot-clean condition. Additional neutron absorption in the form of boric acid dissolved in the coolant is required to hold the core safely subcritical in the cold condition. To provide flexibility for future cores and experiments, the core support structure will include positions for eleven extra fuel assemblies and three extra control rods. Fig. 2 shows these positions filled by dummy assemblies. The reactor core will be the principal component under study. Special core instrumentation and removable test assemblies will permit study of temperatures, neutron flux, coolant boiling, and mechanical changes in the fuel. Ten of the fuel assemblies will be located directly below special access ports in the reactor vessel head. In five of these locations the fuel assemblies will be hollow, so that

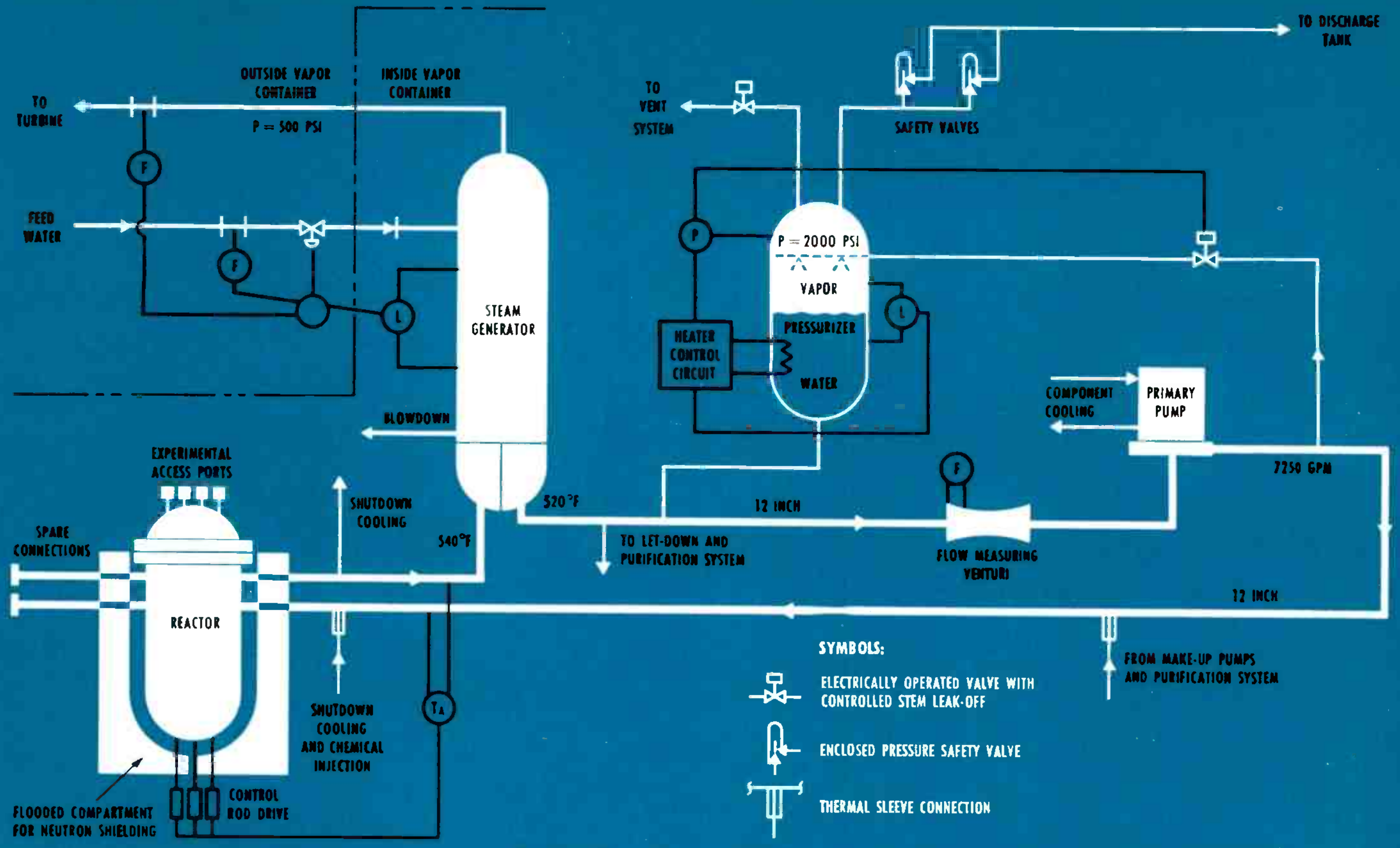


Fig. 1—Flow diagram of primary system.

special square nine-rod test fuel assemblies can be inserted. In the other five locations, special instrumentation will be inserted into the core.

A vertical section through the reactor vessel is shown in Fig. 3. The vessel itself is oversize for a 20-mw reactor; it measures 58 inches inside diameter and 18 feet high. Of particular interest is the bottom-mounted position of the control-rod drive mechanisms. This position was adopted rather than the more common top position for two reasons. First, the top face of the reactor is much more accessible for the insertion of test assemblies and instrumentation. Second, the core can be pushed to boiling modes of operation without interfering with the operation of the control-rod drive mechanisms.

The top head of the vessel will be flanged and gasketed for removal. It will be fitted with eleven special ports to provide access to the core below. As mentioned, ten of these are located above core assemblies. The eleventh is a larger port located just outside one corner of the core, and will accommodate a nuclear superheat test loop.

The reactor vessel itself is somewhat novel in that its cylindrical shell wall is of multi-layer construction. The five-inch thick wall is built up of about 20 layers of one-quarter inch steel, each tightly wrapped and welded over the preceding one. This multi-layer shell will be equipped with special thermocouples and strain gages to detect any abnormal condition arising out of radiation heating within the wall. Demonstration of satisfactory performance in a power reactor should permit the use of multi-layer vessels for large reactors, where considerable cost may be saved.

The steam generator will be a vertical, inverted U-tube type about 4½ feet in diameter and 20 feet high. The primary side will be designed for 2500 psi, as are all primary system components. Ordinarily the steam side of such a generator would be designed for about 900 psi, which would be adequate for normal pressurized water operation. The Saxton steam generator will be built for a maximum steam pressure of 1800 psi. This, plus the use of an oversize (100 cubic foot volume) pressurizer, will enable experimental operation of the reactor and primary system at higher average coolant temperatures and conditions of bulk boiling in the core. It will even be possible to operate and study the behavior of the reactor under conditions of full saturation temperature at the reactor and with some uncondensed steam bubbles carried through the hot leg to the steam generator.

While the reactor core is nominally rated at 20 mw, the steam generator will be designed for 28 mw. This will permit the reactor core to be pushed to at least 140 percent of its design power in experiments intended to determine the limits of satisfactory operation of the core.

One of the important parameters in the primary system is the coolant rate of flow. In the Saxton plant a motor-generator set will supply the canned motor-pump with variable frequency power as a means of coolant flow control. Frequency will be varied from a minimum of about

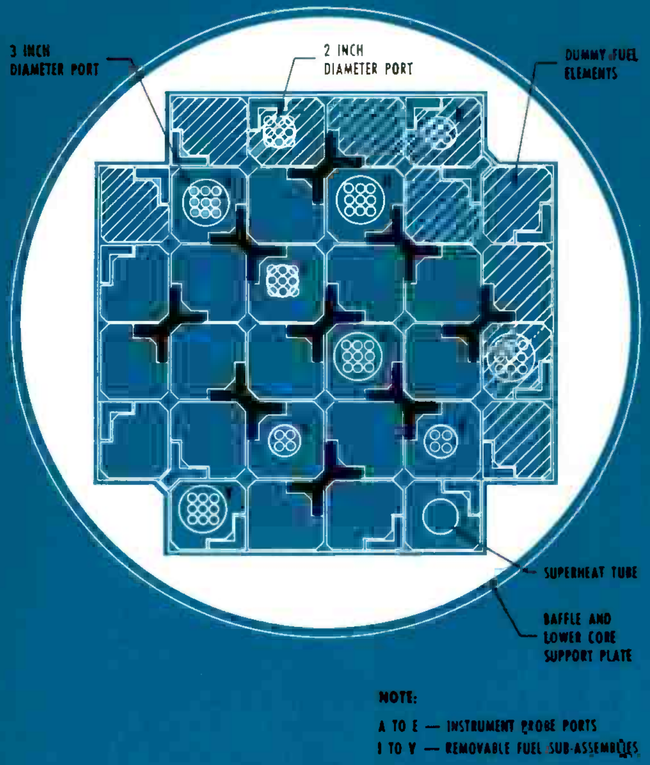


Fig. 2—Cross section of reactor core.

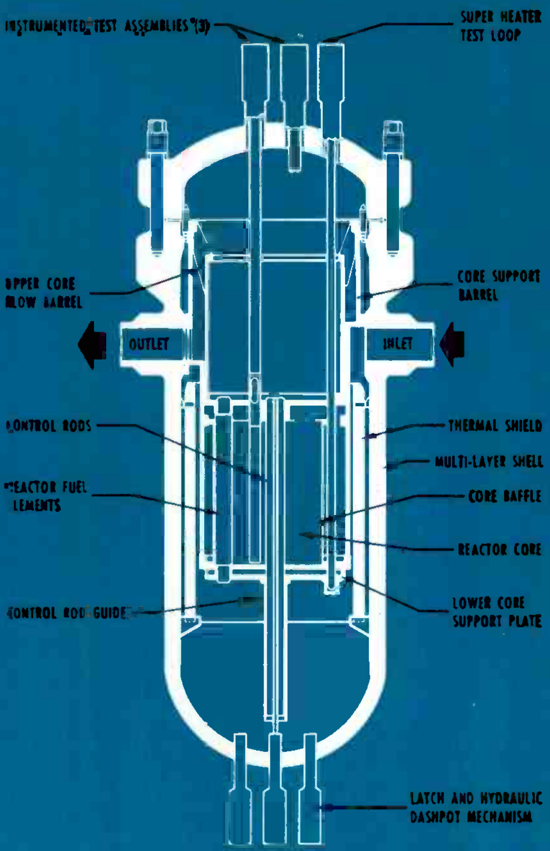


Fig. 3—Vertical section through reactor vessel.

30 cycles up to a maximum of 67 cycles. The upper frequency limit permits a pump design that will deliver maximum horsepower under cold coolant conditions at 60 cycles, and maximum horsepower under hot conditions at 67 cycles.

The fluid auxiliary systems will be similar to those of other closed-cycle water plants. The coolant charging and volume control system will feed high-pressure purified water to the primary loop and bleed out coolant to the purification system and low-pressure storage tank. All components will be inside the vapor container except the low-pressure storage tank and high-pressure charging pumps.

In the event of a leak or break somewhere in the primary system enough coolant might be lost that the reactor core could be uncovered and melt down. To guard against this, a safety injection system is provided. When actuated by the detection of abnormally low pressure in the primary system, two pumps will deliver boronated water directly into the reactor vessel. In the event of failure of one of the control-rod drive mechanisms, the safety injection system will have sufficient capacity to completely fill the compartment directly below the vessel and then maintain the level high enough to keep the core covered.

A flow diagram of the steam and boiler feed system is shown in Fig. 4. Saturated steam will be produced by the Saxton plant at rates up to about 100 000 pounds per hour and at pressures varying from 450 psia to about 1700 psia.

Most operating equipment of the Saxton reactor plant is located inside a steel vapor container in the shape of a vertical cylinder 50 feet in diameter and 110 feet high. A plan view of the interior of the vapor container is shown in Fig. 5. Quadrants I and IV are filled with water to shield the reactor and spent fuel. Quadrants II and III are dry and contain the piping and equipment other than the reactor. Quadrant I shows the reactor vessel immersed in water for neutron shielding and fuel replacement. The 12-inch diameter main loop piping passes through a five-foot concrete shield wall into Quadrant II, which contains the steam generator, canned motor-pump, and pressurizer. In addition to these primary components, Quadrant II contains the regenerative and nonregenerative heat exchangers for the coolant charging and purification systems. This equipment arrangement is intended to put in Quadrant II those components most likely to become radioactive.

Quadrant III, which has three floor levels, contains the pressurizer blowdown tank, shutdown cooling pumps and heat exchangers, component cooling pumps and heat exchangers, and sump pumps.

Quadrant IV is water filled. It contains the storage racks for spent fuel, test assemblies and control rods. Because of their radioactivity, the coolant purification demineralizers will be located under water in this quadrant.

A vertical section through Quadrants I and II of the vapor container is shown in Fig. 6. Immediately below the reactor is the compartment into which the control-rod drive mechanisms project. The steam generator, primary coolant pump, and pressurizer are in the upper part of Quadrant II. The steam generator is purposely located at an elevation higher than the reactor vessel to produce natural circulation of the coolant in the event of pump failure.

Saxton experimental program

The Saxton experimental program is being developed around a basic concept called "pushed operation." The term suggests higher power levels but actually is much broader in meaning. As conceived, it means operation of the reactor under conditions beyond those already known to be satisfactory for regular engineering design. Many design limits are restricted because of uncertain calculations or unreliable experimental results. As a consequence, nuclear reactors and the cost of electric power they produce are penalized by the conservatism and excessive factors of safety presently needed.

In the experimental program, fuel temperatures will be pushed upward, the coolant will be allowed to run hotter or even to boil, and dissolved poisons will be tried for control. Operation will be pushed all the way to such troubles as instability and the beginning of fuel-element failures if necessary, to determine the real limits of possible operation. This can be done at Saxton because the reactor is small and its owner can accept the risk of extended shutdown and cleanup periods. Also, the special core instrumentation and test fuel assemblies will provide good information on core conditions and permit a much safer approach to the threshold of any dangerous conditions.

As now planned, the experimental program will consist of six major groups of tests:

Initial Operation—During this phase zero power critical experiments will be made to determine carefully such properties of the core as reactivity, temperature coefficients, and control-rod worth. Three-dimensional studies of the neutron flux distribution must be made with irradiation wires at gradually increasing power levels. Finally the power level will be brought to the guaranteed thermal output of 20 mw. The objective of this part of the program is operational testing of all parts of the plant and thorough study of the characteristics and behavior of the reactor core under ordinary "nonpushed" operating conditions.

Operation With Soluble Neutron Absorber—One difficult restriction on the design of a reactor for long life and high power level is that of providing enough control rods to control reactivity, and distributing them to produce a desirable distribution of neutron flux and heat generation. An attractive possibility for greatly easing or avoiding this problem is the use of a strong neutron absorber, such as boron, dissolved in the coolant. By adjusting concentration, wide changes in absorption might be produced, while at the same time maintaining a very uniform and favorable space distribution of the absorber.

In this phase of the experimental program, boric acid will be added to the primary coolant water. Tests at power will be run with successively higher boron concentrations until the shim control function is fully transferred to the boron concentration system. An important part of these tests will be a study of the effectiveness and reliability of the systems for measurement and control of boron concentration, the effects on the core characteristics, and the changes in neutron flux distribution. Power operation must be sustained over a period of time long enough to disclose possible problems of chemical instabilities, precipitation of boron on surfaces, or corrosion of materials.

In addition to power operation, tests will be made to determine the safety of using reactor heat in a boron poisoned system for startup from cold conditions.

Boiling of the Coolant—At present, cores for closed-cycle water reactors are designed to produce their rated output with no more than a small amount of local surface boiling in some of the hottest fuel channels. Significant improvements in reactor performance can be expected if the restriction against bulk boiling is removed. Therefore, an

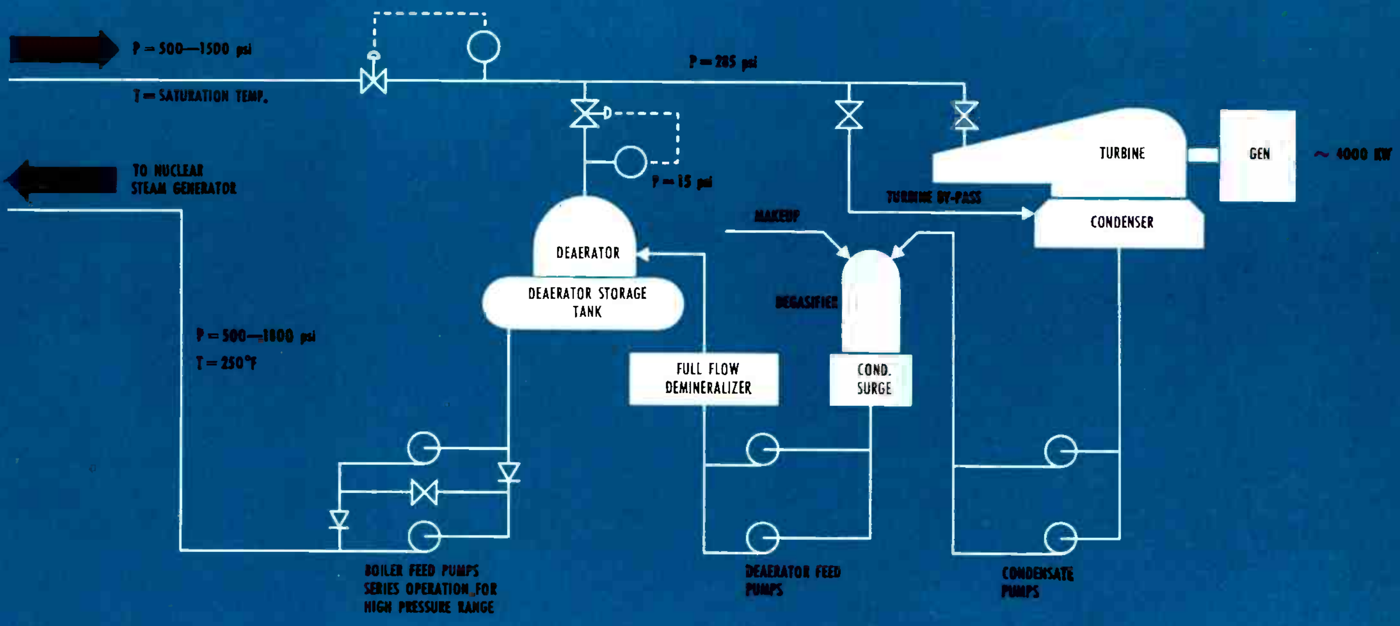


Fig. 4—Steam and boiler feed system.

important phase of the experimental program is the thorough study of reactor behavior under boiling conditions.

Designed within the above limitation, the Saxton core will produce its nominal heat output of 20 mw without boiling. However, during this phase of the program the reactor coolant temperatures will be increased until boiling appears, first in the hottest fuel channel, and then in more and more channels as the reactor coolant inlet temperature is raised. If possible, a program will be carried to the conditions of boiling in the average channel, and carry over of steam bubbles through the hot leg of the primary system to the steam generator.

During boiling tests, measurements will be made with the special core instrumentation to study changes in the coolant flow pattern and neutron flux distribution. Finally, tests will be made to determine the practicability of combined boiling and chemical shim and combined boiling and higher fuel-element heat output.

Fuel-Element Power Capability—The maximum allowable heat output from the individual fuel elements is presently limited to 13.3 kw per foot of fuel tube. This value has been chosen low enough to insure that temperatures at the center of the uranium oxide fuel pellets are safely below about 5000 degrees F, the melting point of the material. Experiments on individual fuel rods in test reactors show that higher heat output should be safe, but the practical limits are not known.

The present design limit will be attained at the nominal reactor power level of 20 mw. Beyond this, a program of stepwise increases in power level will be followed until either the threshold of fuel-element failure is reached in the hottest channels, or until the maximum heat transfer capability of the plant system is reached. If this latter limitation is reached before any fuel element failures are detected, then special nine-rod test assemblies containing slightly higher enrichment fuel will be installed through the test ports. These will run hotter than the rest of the core and permit the determination of the upper limit of fuel capability without the risk of widespread fuel-element failure and the consequent problems of heavy contamination of the fluid systems.

The use of the nine-rod removable test assemblies also allows the determination of heat-output capabilities of special developmental fuel elements.

Advance Design Core—During the five-year program of experimental work in Saxton, two reactor cores will be tested. All of the work described under the first four phases will be performed on the initial core during the first half of the five-year period. Then a second or advanced core will be installed and tests will be made on it during the last two and a half years. As the designation "advanced" suggests, this core will be designed to take full advantage of data and experience gained during the first year or more of the experimental program. During its operation, the advanced core will be pushed beyond conditions attained with the initial core.

Advanced Systems Development—During the latter part of the five-year experimental program several advanced systems experiments are contemplated. Of particular interest is a nuclear superheat test in which a special fuel channel will be installed in the reactor core. Saturated steam from a separate source will be fed to this channel and superheated steam produced. The objective of tests will be the development of fuel assemblies and channel designs, so that future nuclear power plants can be designed to supply high-temperature superheated steam, which can be used more efficiently in modern turbines.

information for the future

The Saxton Plant will provide answers to many current questions. For example, much will be learned about the possibilities of higher fuel temperature and control with dissolved poisons. Information such as this is vital to the construction of better plants in the future. ■ ■ ■

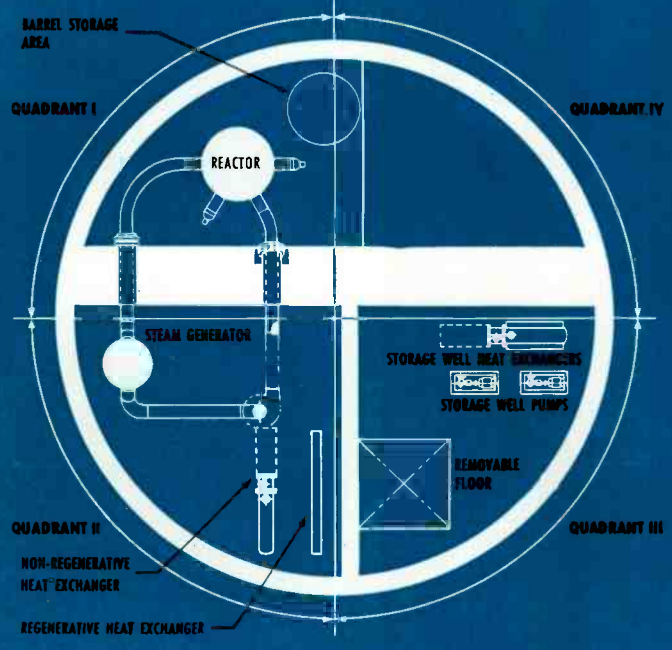


Fig. 5—Plan view of interior of vapor container.

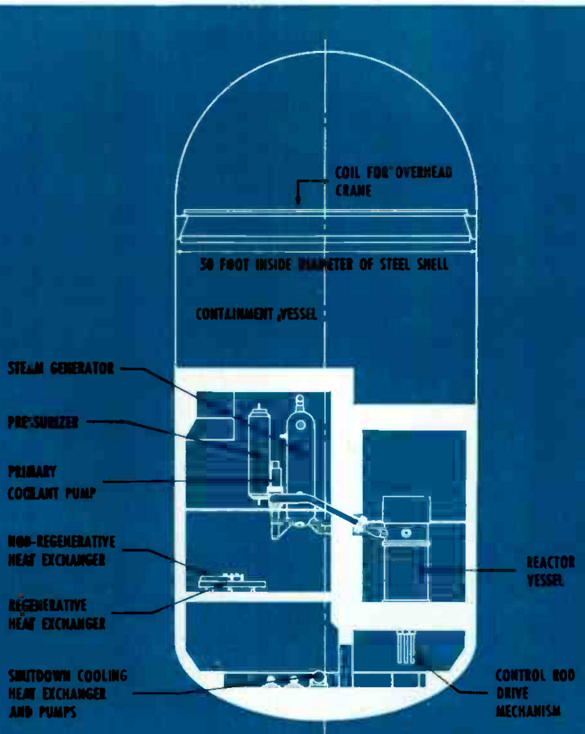


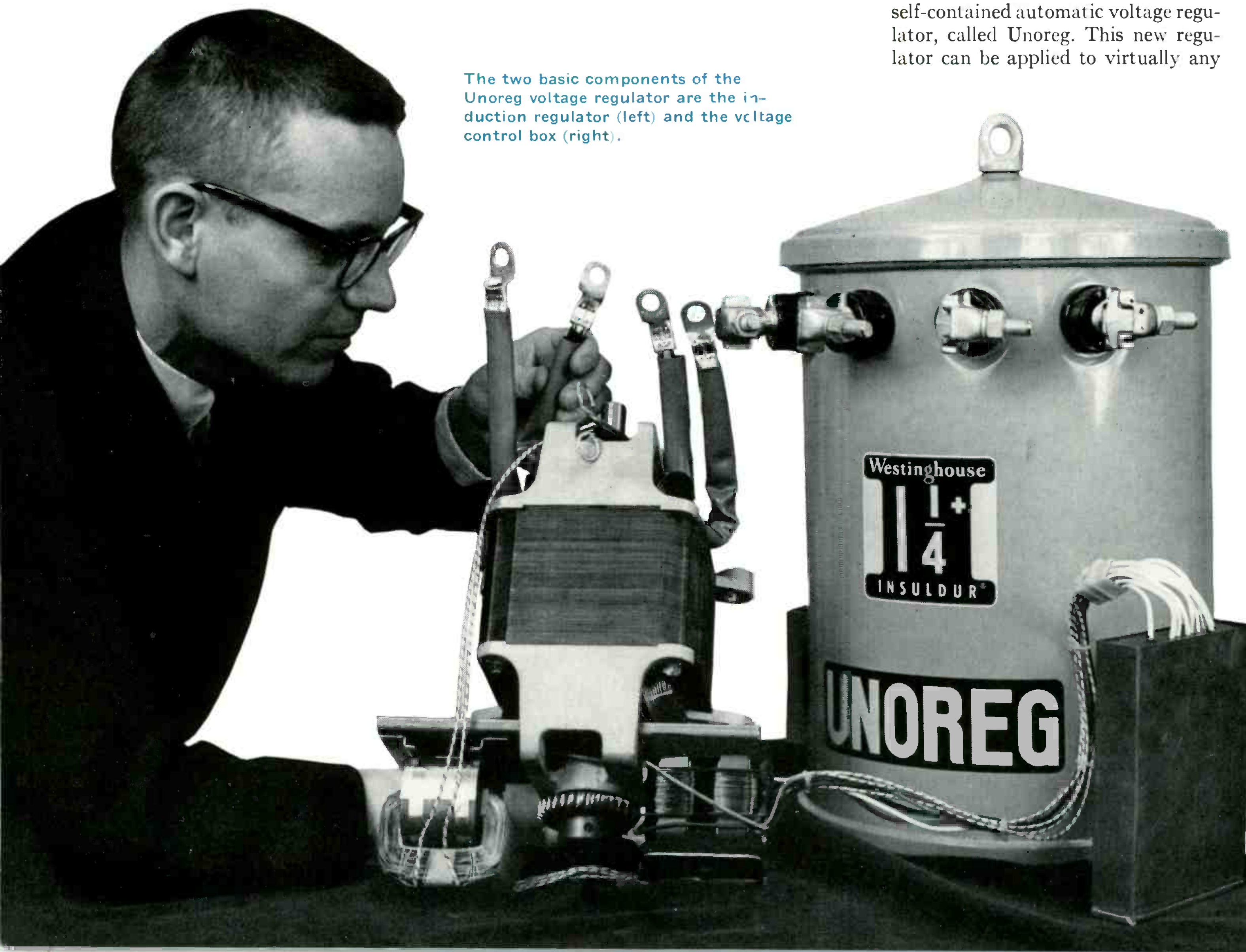
Fig. 6—Vertical section through vapor container.

WHAT'S NEW IN ENGINEERING

UNOREG . . . and a new voltage regulating system

Computer studies of numerous hypothetical distribution systems have pointed the way to a new method of feeder voltage regulation. The studies gave engineers two fundamental facts: First, the most economical system is one that is built to operate without re-regulation, that is, without the use of voltage regulators out on the feeder; but secondly, when re-regulation is necessary, it can be obtained most economically by raising the voltage on the whole system to the level needed by the large outlying areas, and then bucking down the voltage at the head of the feeder with regulators on individual distribution transformers. However, many applications will still require a boost of low secondary voltages at the ends of long or heavily loaded lines.

To meet these system requirements, transformer designers came up with a self-contained automatic voltage regulator, called Unoreg. This new regulator can be applied to virtually any



The two basic components of the Unoreg voltage regulator are the induction regulator (left) and the voltage control box (right).

distribution transformer, regardless of primary feeder voltage, transformer type, or kva rating. Universal application is made possible by applying the regulator on the *low-voltage* side of the distribution transformer. Just two Unoreg regulator ratings—1¼ kva and 2½ kva—can handle distribution transformer sizes up to and including 50 kva.

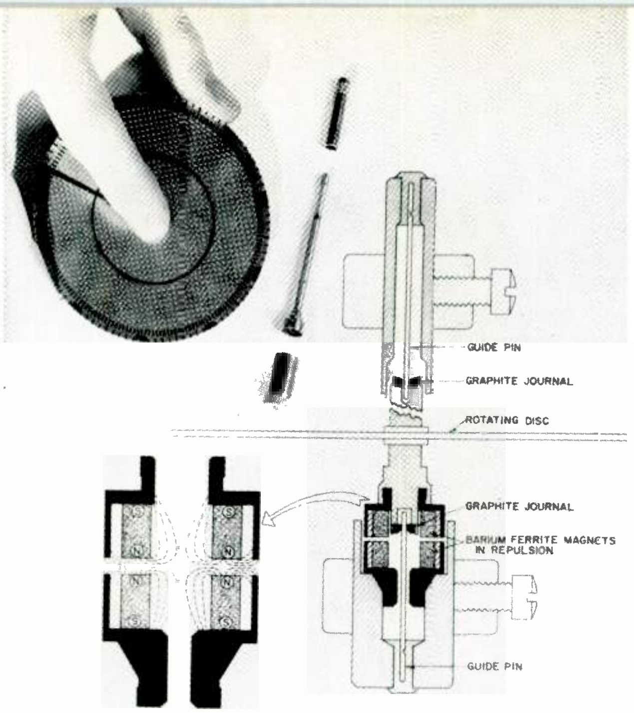
A self-contained design was chosen for economic reasons. Only one style is required for use with a large range of distribution transformers. For example, the 1¼ kva regulator can be used with over 400 standard distribution transformer types.

The Unoreg provides plus and minus five percent regulation of 120/240-volt secondary lines. The regulator smoothly corrects the input voltage without jumps or time delay by inducing a voltage in the series coils of an induction regulator, which either adds to or subtracts from the input voltage.

The midpoint voltage setting of the regulator control is 122 volts, allowing for an average secondary drop of two volts. The control is designed so that the voltage is always corrected back to the center of the bandwidth.

The voltage-control element is a static unit that uses all solid-state components with no moving parts or contacts. For maximum accuracy, the control is temperature compensated and meets the accuracy requirements of a class II voltage-regulating relay as defined by NEMA standards. Encapsulation of the control makes it rugged, reliable, and tamperproof.

Laboratory tests have indicated that every part of the new regulator is capable of operating for at least 20 years without failure. Data obtained from field tests have shown that the control range is held within the specified limit of plus and minus 1¼ volts. ■ ■ ■



Simplified schematic cross section of the magnetic thrust bearing, with key parts shown at left.

FRICTION-FREE MAGNETIC THRUST BEARINGS FOR WATTHOUR METERS

A magnetic bearing system, called Magnethrust, has replaced the conventional ball-and-jewel bearing in Westinghouse single-phase 120/240-volt watthour meters. Disk-and-shaft assemblies are supported by the magnetic repulsion between two tiny rings of barium ferrite, a ceramic permanent-magnet material of exceptional stability and strength. Mounted so that their fields are opposed, these rings serve as the two "working surfaces" of a frictionless thrust bearing. Supplying the slight lateral forces needed to restrict horizontal movement are stationary pins within graphite journals, which serve as guide bearings for the upper and lower ends of the shaft.

Among the advantages of the new bearing system over existing designs are the ability to withstand shock and vibration well above levels encountered during transit, immunity to thermal shock and environmental change, tolerance to off-vertical installation, and, particularly, ability to serve for at least 30 years without maintenance.

The unique properties of barium ferrite, a ceramic magnetic material produced by sintering barium carbonate and iron oxide made the new design possible. Barium ferrite is the only known material that displays its full magnetic stability at its greatest magnetic strength; thus it does not require any back-off of magnetization to achieve maximum magnetic stability. A second important property is that it is nearly impossible to cause any appreciable decrease in magnetic strength of barium ferrite except in a well-equipped laboratory. This feature is particularly desirable in watthour meters since it contributes a high degree of immunity to tampering, or damage by current surges. In addition to its magnetic properties, barium ferrite also is well-suited for use in watthour meters because it is chemically inert, impervious to temperature extremes, and has low density and high electrical resistivity.

In the Magnethrust bearing system, two rings of barium ferrite are in steel flux-return caps, which are precisely machined to close tolerances of concentricity. When assembled as a working bearing, with the rings in repulsion and one-fiftieth of an inch apart, this limited air gap and low flux leakage combine to contribute high magnetic efficiency, vertical "stiffness," and virtually no susceptibility to external magnetic fields.

At the upper and lower ends of the rotating system, the guide bearings that restrain side thrust on the shaft combine polished and hardened chrome steel pins and journals of nearly pure graphite. Both upper and lower pin-and-journal pairs are loaded conservatively, even under maximum-capacity loads. Life tests conducted at maximum torque under a variety of test cycles have produced no discernible wear after 100-million shaft revolutions.

The new Magnethrust bearing will be used in all D2S watthour meters, which include voltage ratings of 120, 240, 480, or 600 volts and current ratings of 2.5, 15, or 30 test amperes.

All meters in the line are designed to accommodate loads up to 667 percent of meter rating. ■ ■ ■

750-KV TEST LINE ANNOUNCED

A project to construct and operate a 750-kv test transmission line at Apple Grove, West Virginia, is being undertaken by American Electric Power Service Corporation and Westinghouse. Objective of the project is to gain information and experience that will help determine both the technical and economic feasibilities of transmitting large blocks of power at voltages up to 750 kv.

The new extra-high-voltage test project will provide a continuation of the investigations begun by the two companies at Brilliant, Ohio in 1946 when they built and operated the 500-kv Tidd test line.

Other companies that are participating in the project and the equipment or materials which they are supplying include: Kaiser Aluminum & Chemical Corporation — conductor; Lapp Insulator Company, Inc. and Ohio Brass Company—insulators and hardware; Thomas & Betts Company, Inc.—connectors; and the American Bridge Division of United States Steel Corporation—towers.

Work on the project will start immediately with first tests scheduled for late 1960 or early 1961. The tests will continue for three to five years.

Based on experience gained on the 500-kv Tidd and Leadville, Colorado test projects, several innovations in testing techniques will be made in the Apple Grove project.

Three test lines will be built at Apple Grove, each using a different conductor configuration. The lines will be energized simultaneously to measure radio-influence voltages and corona losses, permitting a comparison of test results under identical atmospheric conditions.

In addition, all conductors on all three test lines will carry heating current to simulate actual operating conditions. Test results will be processed through automatic data-logging computers and recording instruments.

Apple Grove is on the Ohio River about 25 miles north of Huntington, West Virginia, on the system of Appalachian Power Company, one of the American Electric Power operating companies. ■ ■ ■

NEAR-PERFECT LIGHT AMPLIFIER

A small electronic tube developed by research scientists reaches the near ultimate in the ability to amplify ordinary light. The tube, known as the Astracon, is so sensitive that it makes visible a single electron, released at the tube's input by an individual photon—the smallest unit quantity of light that exists.

The Astracon tube operates upon a unique amplifying principle discovered at the research laboratories five years ago. The image of an object, so dim that it is invisible to the naked eye, is focused by lenses onto a light-sensitive screen, called a photosurface, at the input end of the tube. The individual particles of light, or photons, arriving from the scene strike the surface and eject electrons from it.

Each ejected electron is then accelerated forward by 2000 volts and strikes head-on into a thin two-layer film, only a few millionths of an inch thick. The front surface of the film is aluminum; on its back surface is deposited a slightly thicker layer of an insulating material. When a high-speed electron crashes into the film, it penetrates into the insulator and releases four or five additional electrons. These are accelerated into a second film, or dynode, where the electron multiplication is repeated.

By using five such steps, a single electron is multiplied into about 3000. These are given a final 20 000-volt boost and are aimed into a thin layer of fluorescent material at the output end of the tube. Here they release 20 000 or more photons of visible light. Thus, if the light striking the input photosurface is in the form of a dim, invisible image, the Astracon exactly reproduces that image on its output, only thousands of times brighter.

The Astracon achieves the ultimate in amplification. Individual electrons, released at the tube's input, show up as a separate flash of light. The only way the Astracon's remarkable sensitivity can be increased is to increase the probability that an incident photon will release an electron from the input photosurface.

This remarkable ability to record photons makes the Astracon useful in many fields of research. In astronomy it will increase the effective size, or light gathering ability, of the largest telescopes. In nuclear physics it will, for the first time, permit the viewing of the tracks of high-energy cosmic rays and other particles. Until now there has been no practical method for observing these particles as they flash through solid crystals with a feeble glow. ■ ■ ■

This Astracon tube amplifies light thousands of times.

PERSONALITY PROFILES

Five research scientists join forces in this issue to discuss potential methods for converting stored energy to electrical energy.

DR. S. J. ANGELLO, who describes thermoelectric conversion, has been involved in basic research in thermoelectricity since 1957. Prior to this, he worked in semiconductor development. Dr. Angello was made project manager for the thermoelectric program of the Central Engineering Laboratories in 1959. Recently, he has taken on a new assignment as project manager of the molecular electronics program at the Air Arm Division. Dr. Angello came to the Westinghouse Research Laboratories in 1942, after receiving his PhD from the University of Pennsylvania.

Thermionic conversion is discussed by **DR. J. W. COLTMAN,** manager of the electronics and nuclear physics department of the Research Laboratories. Coltman graduated from the Case School of Applied Science in 1937 with a BS in Physics. He obtained his master's and doctor's degrees in the same field from the University of Illinois, and joined the Research Laboratories in 1941 as a nuclear physicist. Dr. Coltman was responsible for the development of a number of new and unique electronic devices, among which are the electronic fluoroscope tube for image brightness amplification, and the scintillation counter for detecting nuclear radiation.

DR. S. WAY is a consultant in magnetohydrodynamics at the Research Laboratories. Way obtained his BA with a major in mathematics from Stanford University in 1929. He did graduate work at Goettingen University in Germany and also at the University of Michigan, where he obtained his MS and PhD in Engineering Mechanics. Dr. Way joined Westinghouse in 1933, and began working in the field of solid mechanics. From 1940 to 1959, he worked on a variety of problems in fluid mechanics and combustion, and guided research in these areas.

DRS. R. J. RUKA and **J. WEISSBART,** two research scientists at the Research Laboratories, describe the fuel cell. Ruka joined Westinghouse in 1948 after receiving his MS in Physical Chemistry from the University of Wisconsin. He left Westinghouse to obtain his PhD in Physical Chemistry at the University of Michigan, and returned in 1954. Dr. Ruka's research activities have included studies on gas–metal reactions at high temperatures, permanent magnet ferrites at elevated temperatures, electron emission, and fuel cells.

Dr. Weissbart obtained his BA from the University of California at Berkley in 1950. From 1952 to 1955, Weissbart did graduate work at the University of Oregon. He received his MA in 1954, and his PhD in 1956 in Physical Chemistry. Dr. Weissbart joined Westinghouse in 1955, and has engaged in research on metal-oxide systems at high temperatures, high-temperature electrochemistry, and fuel cells.

JOHN R. CARLSON has been working with large steam turbines since 1929, when he was assigned to the large turbine application department of the Steam Division. He was made manager of the application engineering section in 1947, and in 1952 became Engineering Manager for the Steam Division, his present position. Carlson received the Westinghouse Order of Merit, the company's highest honor, in recognition for his efforts in October 1958.

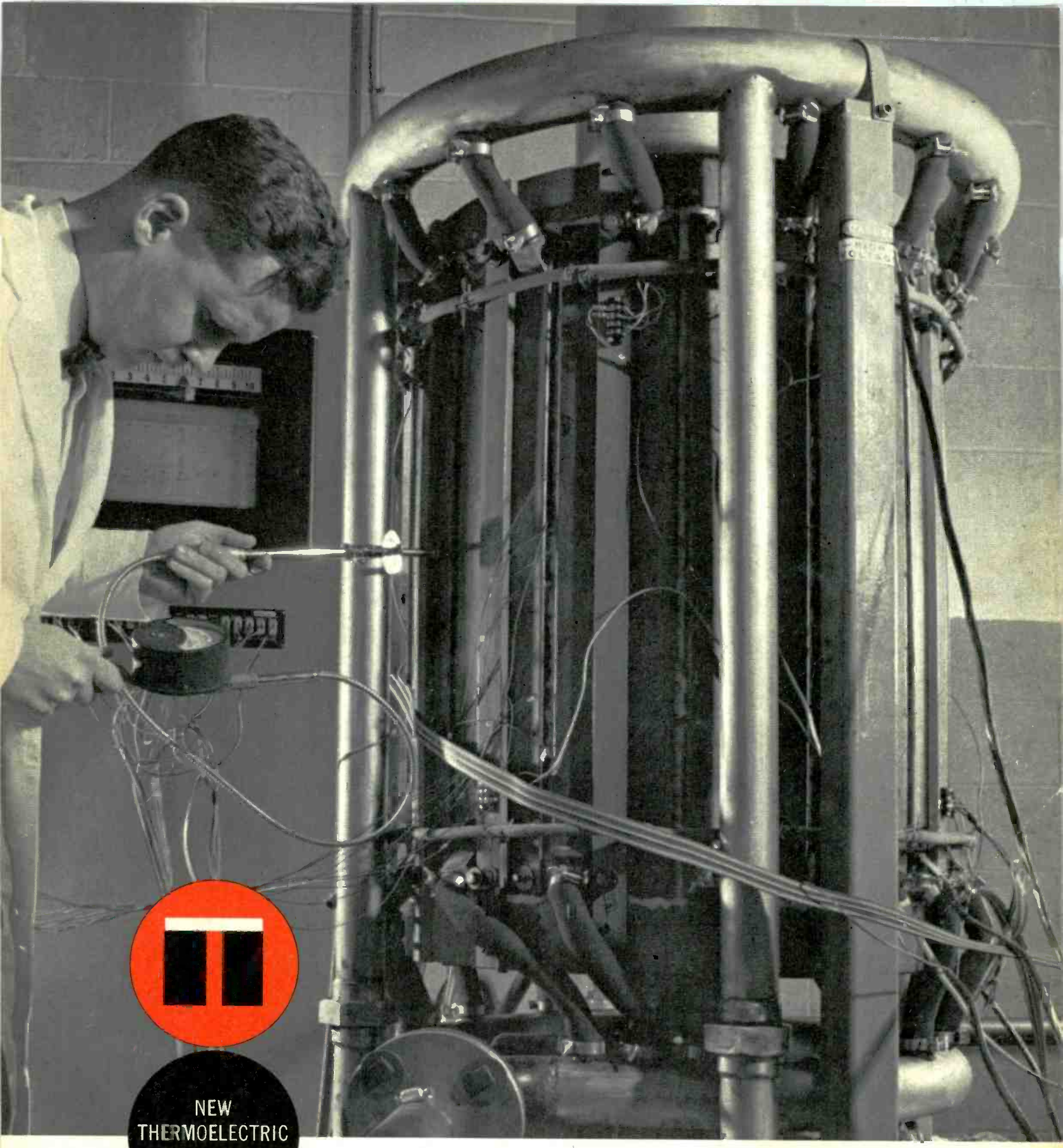
Mercury lamps are a subject that **GEORGE A. FREEMAN** should—and does—know well. When he joined Westinghouse shortly after his graduation from Brown University (BS in EE) in 1933, he first worked on the development of the coiled-coil filament lamp. His first patent resulting from this assignment provided the practical design for long life and shipping strength and is still in use.

In 1935 he began work on the then new mercury vapor lamps and has had a hand in the development of the many improvements and wide variety of types ever since. In 1937 he was co-inventor of the thorium electrode, which became the standard for the industry. Later he played a part in the development of the RS sunlamp and in the development of short-arc high brightness mercury lamps. In 1957 he was made a Fellow of the Illuminating Engineering Society for his contribution in developing the mercury lamp field. At one time or another he has worked on fluorescent lamps and starters, the Sterilamp, glow lamps, flashing lamps for airport approach lighting, as well as mercury vapor lamps.

Freeman is now manager of large incandescent and vapor lamp engineering.

The experience of **EDWARD U. POWELL** in the nuclear reactor field closely parallels that of the company as a whole. After taking a nuclear engineering course at a government facility, he went to work on the submarine reactor project in 1948, the year the Atomic Power Division was formed at Westinghouse. He worked on this project until 1952, when he transferred to a newly formed technical group, whose responsibility was to study the commercial applications of nuclear power. This small study group eventually became the nucleus for the present Atomic Power Department. Powell next became a section manager in the PAR project. He is now the project manager of the Saxton Reactor, where his prime responsibility is planning and coordinating design and construction.

Powell came to Westinghouse in 1940, shortly after graduation from the Polytechnic Institute of Brooklyn with a bachelor's degree in electrical engineering. He was assigned to the Westinghouse Research Laboratories, where he spent the next eight years working in three general areas; ferromagnetism, high-power vacuum tubes, and heat transfer for turbine blade cooling. During this time Powell earned his master's degree at the University of Pittsburgh.



NEW THERMOELECTRIC GENERATOR

ON TEST

One of two 2500-watt "sub-generators" that make up the largest thermoelectric power plant ever constructed is shown under test at the Westinghouse new products laboratories. Developed for the Bureau of Ships, U.S. Navy, the generator is intended as an experimental unit for evaluation of materials and fabrication techniques. The generator is fired by kerosene and operates at a temperature of 1200 degrees F. A modular type of construction has been used, so that the unit can supply a wide variety of output voltages and currents.