Westinghouse
ENGINEER

NOVEMBER 1960

Shown here, by day and by night, is Total Electric Home No. 2 in Canton, Ohio. This is the second of 16 special total electric home plans designed by five of the nation's leading residential architects. The homes serve as total electric showplaces, demonstrating new appliances, entertainment equipment, air conditioning, and especially electric heating. A total electric home like this one requires about 30 000 kwhrs of electricity per year.

In January 1959, Westinghouse introduced the total electric home program. At this time, only a few utility companies were actually encouraging use of electric house heating. Today, Westinghouse has cooperative house-heating programs with 85 of the nation's leading electric utilities.

According to EEI forecast, 100 000 electrically-heated homes will be added to the nation's electric utility load this year.

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Cover Design: The manufacture of electrical porcelain is, in a sense, still an art—but accomplished with modern scientific methods (p. 175) Artist Dick Marsh symbolizes the transformation of a large porcelain weathercasing from a raw clay casting coming out of the mold to the glazed porcelain end product.

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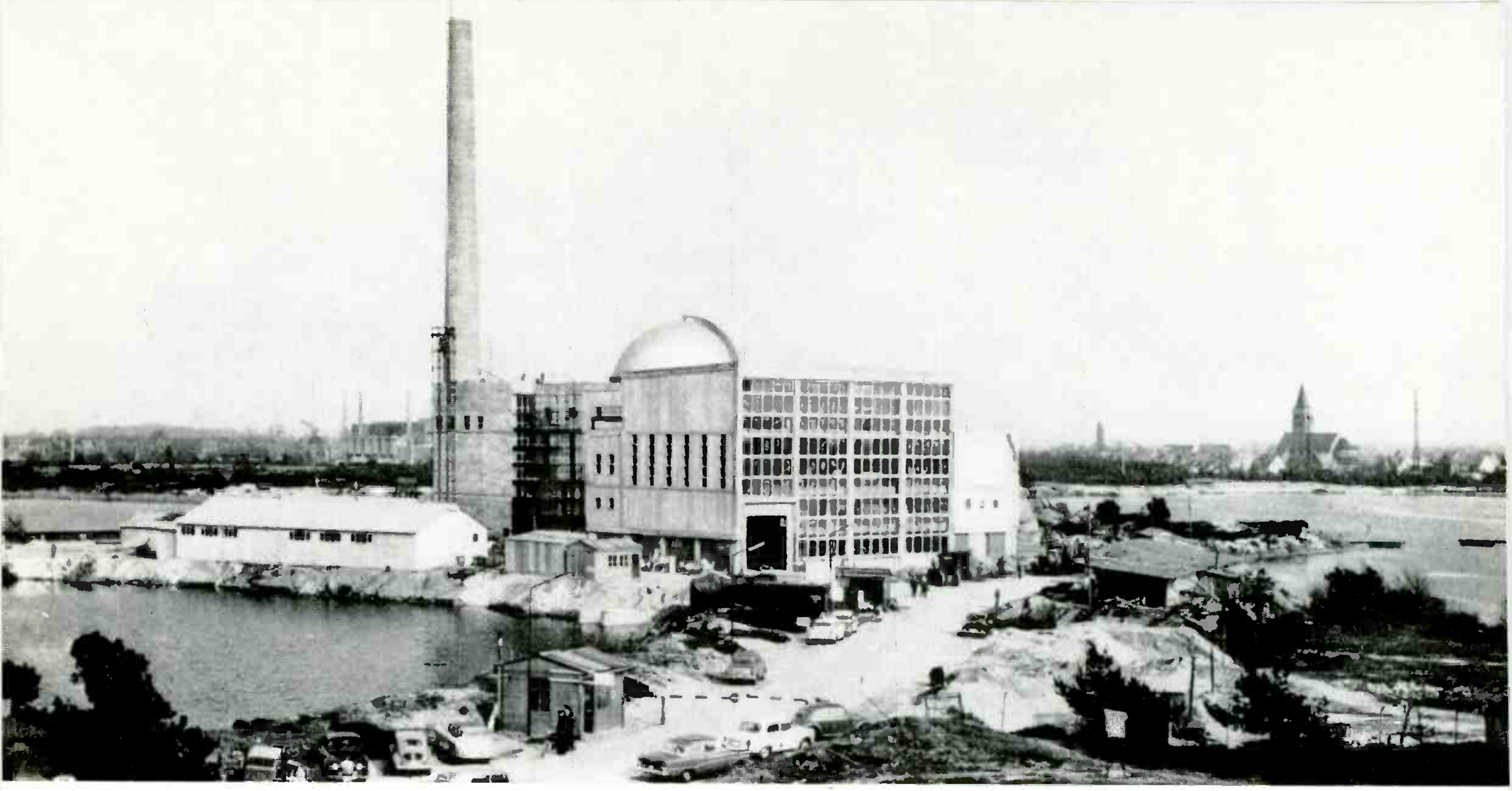
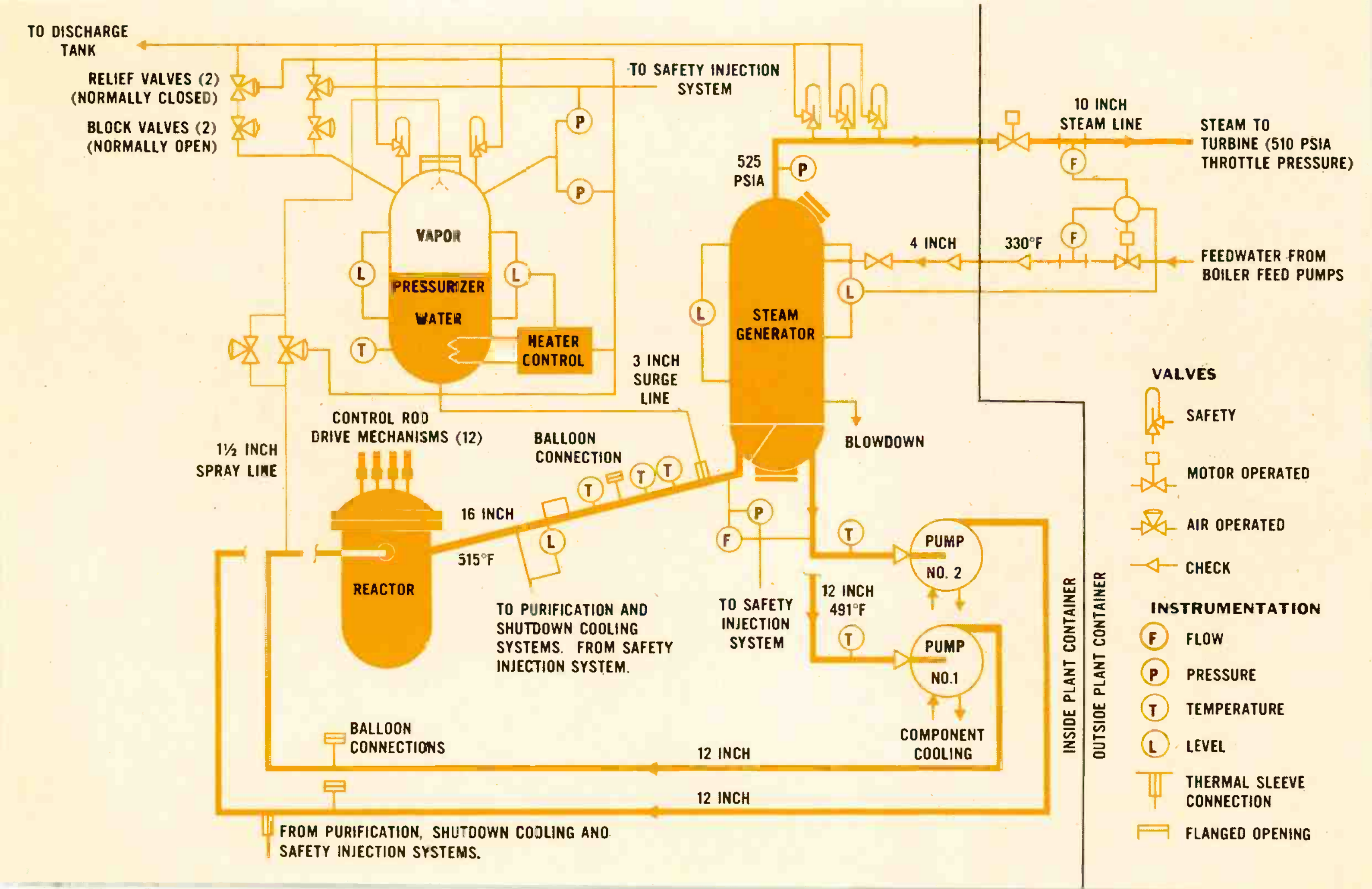


THE BR-3 REACTOR

The first commercial power reactor marketed abroad by an American corporation will go into operation shortly in Belgium.



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The BR-3 reactor, when placed in operation late this year, will give Belgium its first atomic power plant. In addition to the generation of power, this plant will serve as a training facility in power-reactor operation and will provide the means for practical experimentation in reactor technology. The plant is owned by the Centre d'Etudes de l'Energie Nucleaire, a nonprofit Belgian organization for the study and advancement of atomic energy. Together with two other reactors operated by C.E.N., BR-3 is located at a laboratory site near Mol, about 50 miles northeast of Brussels.

primary system

BR-3 is a pressurized water reactor similar to, but smaller than, the Yankee plant. The primary system, shown in Fig. 1, consists of a reactor, steam generator, coolant pumps, and pressurizer. At reactor design power of 41 mw (thermal), two pumps circulate coolant through the system at a rate of 12 500 gpm. Coolant enters the reactor at 491 degrees F and leaves at 515 degrees. The steam generator produces 154 400 lbs/hr of steam at a pressure of 525 psia. This steam, supplied to a turbine, provides a gross electrical generating capability of 11.4 mw. The cylindrical reactor core, composed of 32 replaceable fuel assemblies, is 34 inches in diameter and 56 inches high. Reactor control is provided by 12 control rods.

The core and its supporting structure are housed in a reactor vessel with an inside diameter of 58 inches and a height of 18 feet. This vessel weighs about 50 tons and is fabricated from 4⅜ inch carbon-steel plate clad with stainless steel. Two 12-inch inlet nozzles and one 16-inch outlet nozzle are located above the core. The core support structure, suspended from a ledge near the vessel flange, positions the fuel assemblies and provides the baffling needed for flow distribution. The vessel head is flanged and gasketed to permit removal for refueling. Provision is also made for seal welding if required. Nozzles in the vessel head support the 12 control-rod drive mechanisms. The reactor assembly is shown in Fig. 2.

The layout of the primary system piping provides a single 16-inch "hot" leg carrying coolant from the reactor and two 12-inch "cold" legs that return coolant to it. Stop valves are omitted to minimize thermal stresses and the possibility of a cold water accident. To permit draining the system for maintenance and still keep a level of water above the core for removal of decay heat, the piping rises to a height of 18 inches as it leaves the reactor. Rubber stoppers, inserted in the piping near the reactor during maintenance, prevent any vapor or gas released by the core from reaching parts of the system that may be opened.

A canned motor-pump in each "cold" leg circulates coolant at a rate of 6250 gpm. To increase reliability, power for these pumps is normally taken from two independent sources. Pump 1 is supplied by an auxiliary generator coupled directly to the shaft of the main generator, and pump 2 is supplied by the outside electrical network. In the event of a complete loss of power, the inertia of the main turbine-generator will prolong the flow coastdown of pump 1 to prevent core damage. To prevent backflow in the event of pump shutdown, a center-guided check valve is installed in the suction nozzle of each pump casing. This valve was developed to reduce the pressure-drop and water-hammer effects associated with swing valves. Small passages in each valve permit a limited amount of backflow to maintain temperature in an inoperative loop and avoid the possibility of a cold water accident when the canned motor-pump is restarted.

The steam generator is a vertical, inverted U-tube design and is 5 feet in diameter and 26 feet high. The primary side

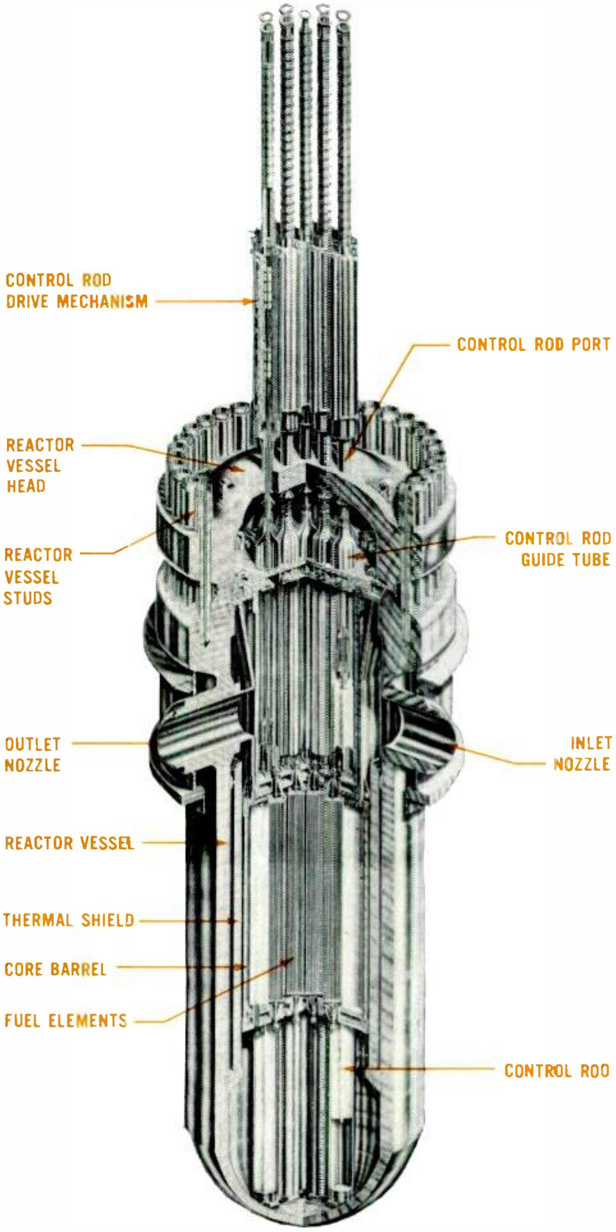


Photo (Top left) Nuclear plant under construction in Belgium.

Fig. 1 (Left) Primary system of the BR-3.

Fig. 2 (Right) A cutaway diagram of the reactor.

is designed for 2500 psia, as are all components of the primary system. The shell or secondary side is designed for 900 psia, and working pressure will vary between 525 psia at full load and 712 psia at no load. Three moisture separating devices on the shell side reduce the moisture content of the leaving steam to less than ¼ percent.

The pressurizer maintains primary system pressure at 2000 psia during operation, and provides the volume needed to accommodate coolant surges resulting from plant load changes. This 93 cubic foot vessel normally contains 51 cubic feet of steam and 42 cubic feet of water. Electric immersion heaters in the lower section of the vessel evaporate the water required to form steam. Safety and relief valves mounted on top of the pressurizer provide overpressure protection for the primary system.

Although welding has been used wherever possible in fabricating and installing the primary system and its components, certain closures are flanged to permit removal, inspection, or maintenance. On these closures, initial operation will be undertaken with gaskets instead of seal welds, although provision is made for seal welding.

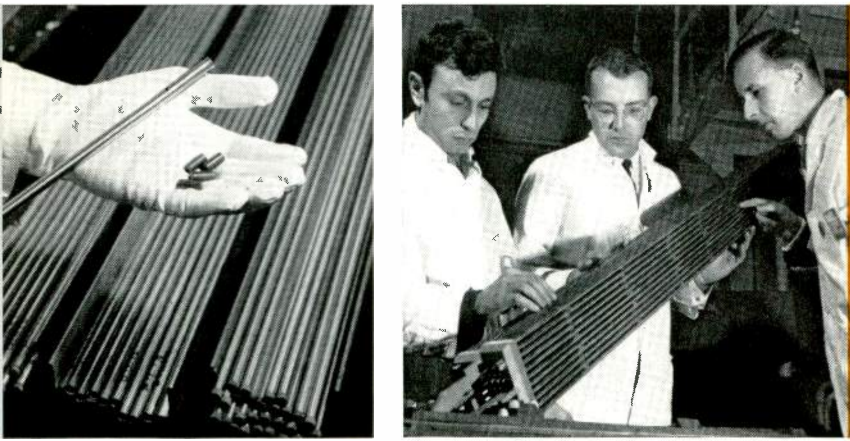


Fig. 3 (Far left) Fuel pellets and tubes for the fuel elements. (Left) A completed fuel element.

Fig. 4 (Right) Critical experiments at the Westinghouse Reactor Evaluation Center.

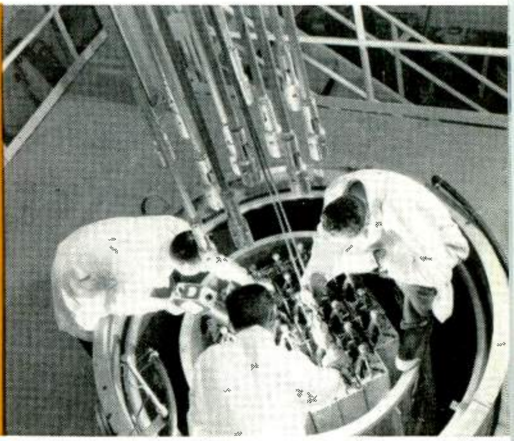


Fig. 5 (Far right) A cross section of the plant container.

auxiliary systems

Auxiliary systems are similar to those of other pressurized water plants. These systems remove and purify the coolant, control the volume, cool the primary system, remove core decay heat, provide cooling water, and dispose of gaseous and liquid wastes.

A safety injection system guards against the possibility of core damage that might result from loss of coolant through a leak or break in the primary system. Started automatically by a drop in primary pressure, this system uses the boiler feed pumps to inject water into the primary system. Hot feedwater taken from the deaerator is supplied initially, followed by refueling canal water from the storage tanks. Water is injected into the system at two locations, so that the core will always remain covered regardless of the location of a leak or break.

Because of uncertainties of control-rod worth as well as the large reactivity change involved in going from a cold condition to full power, the ability of the twelve control rods to hold the core safely subcritical in the cold condition was not certain in the design stage. So a system was provided to inject a chemical neutron absorber (boric acid) into the primary coolant prior to cooling down, to ensure that the reactor would be safely subcritical in the cold condition. During start-up, the bulk of this absorber would be removed by a feed and bleed operation and the remainder by a demineralizer. While the results of the critical experiments have since shown that a chemical neutron absorber is not needed for the first core, the system has been retained for possible use with future cores and for experimental purposes.

core

BR-3 is one of the first commercial power reactors to use stainless steel as a core cladding material. Type 348 stainless tubing, 0.343 inches in outside diameter and 21 mils thick, provides the basic structural element of a fuel assembly. Ninety-one uranium dioxide pellets are contained in each tube, with spacer discs separating the fuel column into four physically distinct but communicating compartments. The ends of the tubes are sealed with type 304 stainless-steel plugs, thus making a fuel rod. Individual rods are brazed into subassemblies using ferrules placed at intervals along the length. Four such subassemblies, when mechanically fastened to nozzles, form a completed fuel assembly. Fuel assemblies contain 110 or 111 rods on a square lattice array with a pitch of 0.480 inches. A total of 3536 fuel rods are contained in the core. The BR-3 fuel assembly is shown in Fig. 3.

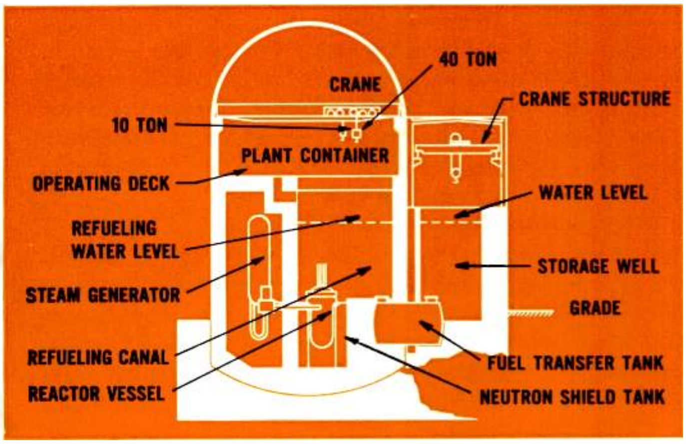
BR-3 has a two-enrichment core with fuel enrichment varied in a radial direction. The inner 16 fuel assemblies of the core are enriched to 3.7 percent U-235 and the outer 16 assemblies to 4.4 percent. The use of two enrichments in the core improves power distribution and reduces hot channel factors. The core contains approximately 5000 pounds of fuel.

The BR-3 core underwent a series of proof test critical experiments at the Westinghouse Reactor Evaluation Center (WREC) (see Fig. 4). Experiments were conducted over a three-month period and provided valuable data on reactivity, rod worth, and power distribution. The experiments also demonstrated that the cold reactor could be shut down by control rods alone and that a chemical neutron absorber would not be required.

reactor control and safety

Automatic control of the BR-3 reactor is based on average temperature of the primary coolant. Deviations greater than 3 degrees F from a reference temperature initiate control rod movement. A power differential override reduces the transients resulting from large swings in plant load. This control compares reactor power with steam flow and initiates rod movement when the difference exceeds a predetermined amount. For safety reasons, this control acts to insert *all* control rods, but will withdraw only the *control* group of rods. The 12 rods are divided into two outer groups of 4 and two inner groups of 2 for control purposes.

The BR-3 control-rod drive mechanisms are of the magnetic jack type. All moving parts are contained within a hermetic pressure housing mounted on the head of the reactor vessel. A bundle of magnetic rods, attached at its lower end to a control rod, extends upward from the core into the pressure housing. Magnetic flux, originating in a series of coils outside the pressure housing, positions and moves the rod bundle and the attached control rod. The magnetic jack mechanism has an inherent safety feature, in that the control rods can be scrammed at any time by simply de-energizing the coils. The rods will fall into the core under the influence of gravity. The lack of latches, gears, or other mechanical devices that might become jammed or broken increases reliability.



Nuclear instrumentation monitors reactor power from start-up through full power and initiates shutdown if safe limits are exceeded. Two duplicate start-up channels are installed, each consisting of a source and an intermediate range section. Reactor scram will occur on fast start-up rate. Three duplicate channels monitor the power range and matching signals of any two are required to initiate scram on power level. The need for this matching reduces the possibility of plant shutdown caused by spurious signals. Automatic control reduces the setting of the power level scram on these channels when the plant is operating on only one primary coolant pump or when pump 1 is not connected to the auxiliary generator. Reactor scram is also initiated by such conditions as high primary coolant temperature, low primary system pressure, loss of coolant flow, loss of vital bus voltage, and operation of the penetration valve master controller.

plant container and site facilities

A cross section of the plant container and storage well area is shown in Fig. 5. The primary system and high-pressure sections of auxiliary systems are located inside the container. This vessel is 54 feet in diameter and 107 feet high and is designed to withstand an internal pressure of 45 psig. Approximately one-quarter of the structure is below ground level. Concrete shielding inside the container reduces radiation to safe levels and permits limited access to the operating deck during plant operation.

To prevent any leakage from the plant container in the event of an accident, all entering lines have two check valves, one inside and one outside the shell. All lines leaving the container have remotely operated isolation valves. Should an accident occur, operation of a penetration valve master controller in the control room will scram the reactor and isolate the plant container.

The storage-well area adjacent to the plant container provides facilities for the storage and handling of spent cores. New fuel for the reactor is brought into the container through this area. The refueling canal inside the container is empty during plant operation but must be flooded during refueling to provide shielding. Refueling is accomplished by long-handled tools supported by the plant container crane and manipulated from a traveling bridge suspended above the canal water level. Individual fuel assemblies and control rods are lifted from the reactor vessel and placed in a carrier in the fuel transfer tank. The carrier then transports the assembly or rod to the storage-well end of the tank where the element is removed and placed in storage racks in the well. New fuel is moved into the plant container by reversing this procedure. Lock and isolation valves on both openings of the transfer tank prevent mixing of the refueling canal water with storage-well water during refueling operations.

An auxiliary building, separating the plant container from the turbine building, provides access to all radioactive areas of the plant. Reactor auxiliary systems are located in the shielded basement of this building to permit inspection and maintenance during operation. A shipping area adjacent to the storage well provides facilities for handling new and spent fuel, and for removal of demineralizers from shielded cells in the basement.

A waste and ventilation building contains the waste hold-up tanks and equipment, the refueling water storage tanks and the ventilation system. Central facilities at the Mol laboratory site are used for the disposal of radioactive waste. A turbine building houses the turbine-generator, secondary plant equipment, the control room from which the entire plant is operated, and required office space.

Despite its relatively small size, the BR-3 is in every respect a power reactor, and will be useful as a source of power as well as a training and experimental facility.

THERMAL PROTECTION FOR AIRBORNE ELECTRONIC SYSTEMS

Most of the power consumed by airborne electronic equipment is eventually transformed into heat, which must be disposed of in an increasingly difficult environment.

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The thermal environment for airborne electronic equipment is created by the natural condition of the atmosphere and the induced effects from aerodynamic heating, electronic equipment heat, and power plant heat. Unfortunately, most electronic equipment, whether heat generating or nonheat generating, is sensitive at some level of temperature. Therefore, some form of protection is required to keep component temperatures low enough to permit satisfactory performance over the desired operating period.

Electronic system designers have three approaches for providing thermal protection: decrease the heat loss from the equipment; develop components suitable for higher operating temperatures; and provide efficient means for heat removal.

equipment heat load

The growing heat load of airborne electronic equipment can be demonstrated by the increase in typical Westinghouse radar systems, shown in Fig. 1. The increased load is largely due to the greater range requirements of modern radar systems. A high percentage of the input electrical power, 85 to 90 percent, is transferred into heat.

The most direct approach is to use electrical components that generate a minimum amount of heat. For example, transistors used in place of electron tubes will reduce heat load. If subminiature tubes in a typical circuit are replaced by transistors, the heat load can be reduced by a factor of 50 to 1. However, this move doesn't necessarily simplify the problem because transistors are more sensitive to high temperature than tubes. Conventional design techniques permit subminiature tubes to operate in an ambient environment of 175 degrees C. However, germanium transistors are limited to 55 degrees C and silicon transistors to 100 degrees C.

Another complication is created by the trend toward miniaturization. Although heat load may be decreased for a particular piece of equipment, the heat density (watts per square inch of surface area) can increase. This condition can result in failure of the natural modes of heat transfer to keep a satisfactory steady-state temperature.

higher operating temperatures

Electronic equipment should be designed to minimize the destructive effects of temperature extremes by considering the combined electrical and thermal problems during preliminary equipment design. Failure to attack thermal problems along positive lines—designing equipment to withstand maximum operating temperatures—will necessitate less desirable methods for providing thermal protection.

Temperature has a most important effect on electronic equipment materials. Structural materials, such as aluminum and steel, lose strength with increased temperatures. The decrease in strength at elevated temperatures for several structural materials is shown in Fig. 2. Temperature likewise affects the characteristics of "electrical" materials. Conductivity decreases as temperature increases, and the nonmagnetic characteristics, or conversely, the magnetic capabilities of a material are affected by high temperatures.

Some protection can be provided for temperature-sensitive equipment by separating heat-generating and nonheat-generating components, either by different physical location, or individual equipment insulation.

Heat transfer principles should be applied to each detail part of the equipment to provide satisfactory heat removal.

For equipment with a short operating period, such as used in missiles, thermal lag principles can often be employed effectively. The use of materials with low thermal conductivity, low density, and high specific heat can offset the effects of aerodynamic heating during high-speed flight.

Thermal insulation of compartments housing electronic equipment can further decrease the rate of temperature rise of ambient air inside the compartment.

removing heat load

Reduced heat load and increased critical temperatures for electronic equipment can only be applied up to the limits of available techniques and materials; beyond this point, heat must be removed from the equipment.

Air-to-Air—One of the simplest and most reliable methods of heat removal is the ram-air pressurized system (Fig. 5) using an air-to-air heat exchanger. If dielectric breakdown is a problem, a gas such as sulfur hexafluoride can be used in place of air in the pressurized cooling loop.

Fig. 1 Growth in heat dissipation of typical airborne radar systems.

Fig. 2 The structural strength of these typical materials is a function of temperature.

Fig. 3 Conductivity of typical insulation materials changes with temperature.

Fig. 4 Ram and bleed air supply for cooling systems.

Fig. 5 Ram air pressurized cooling system.

Fig. 6 Ram air temperature is proportional to the square of aircraft velocity.

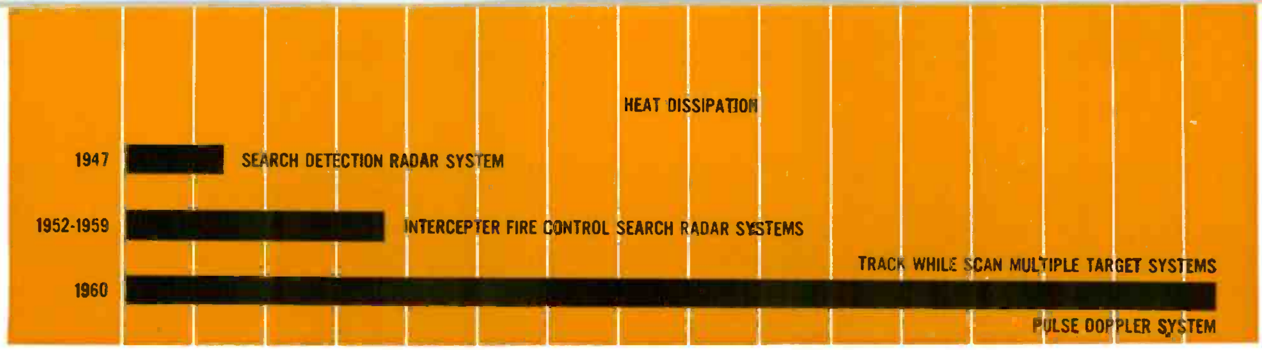

Fig. 1

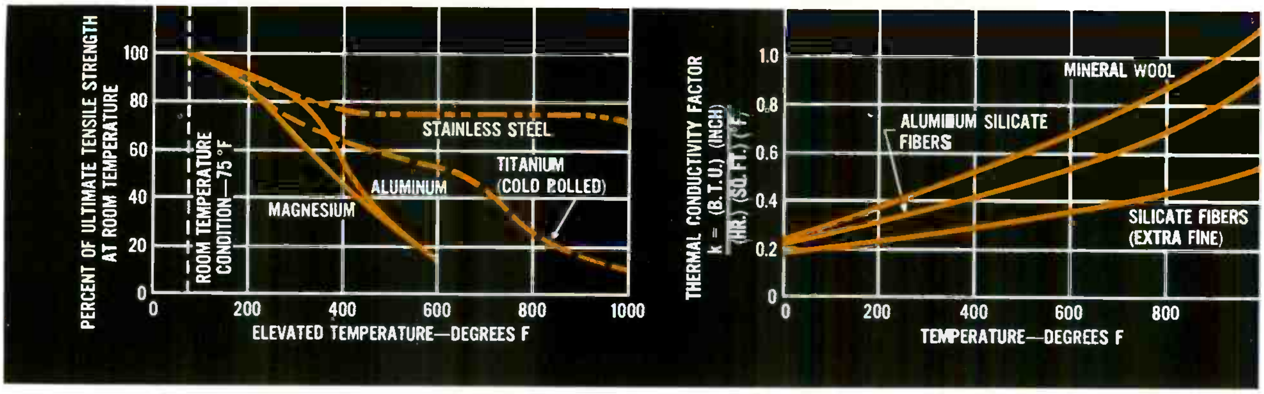

Fig. 2; 3

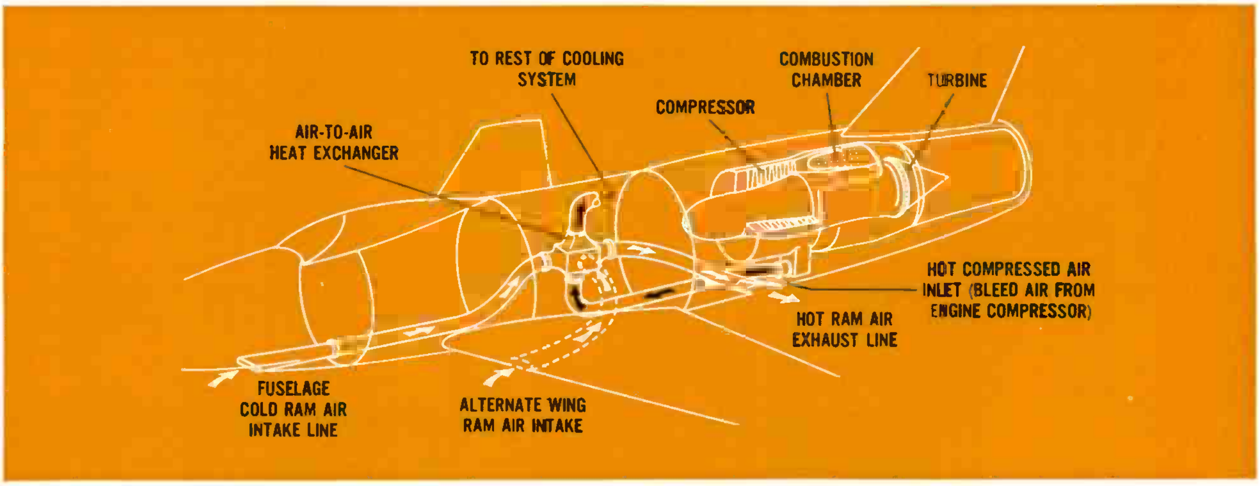

Fig. 4

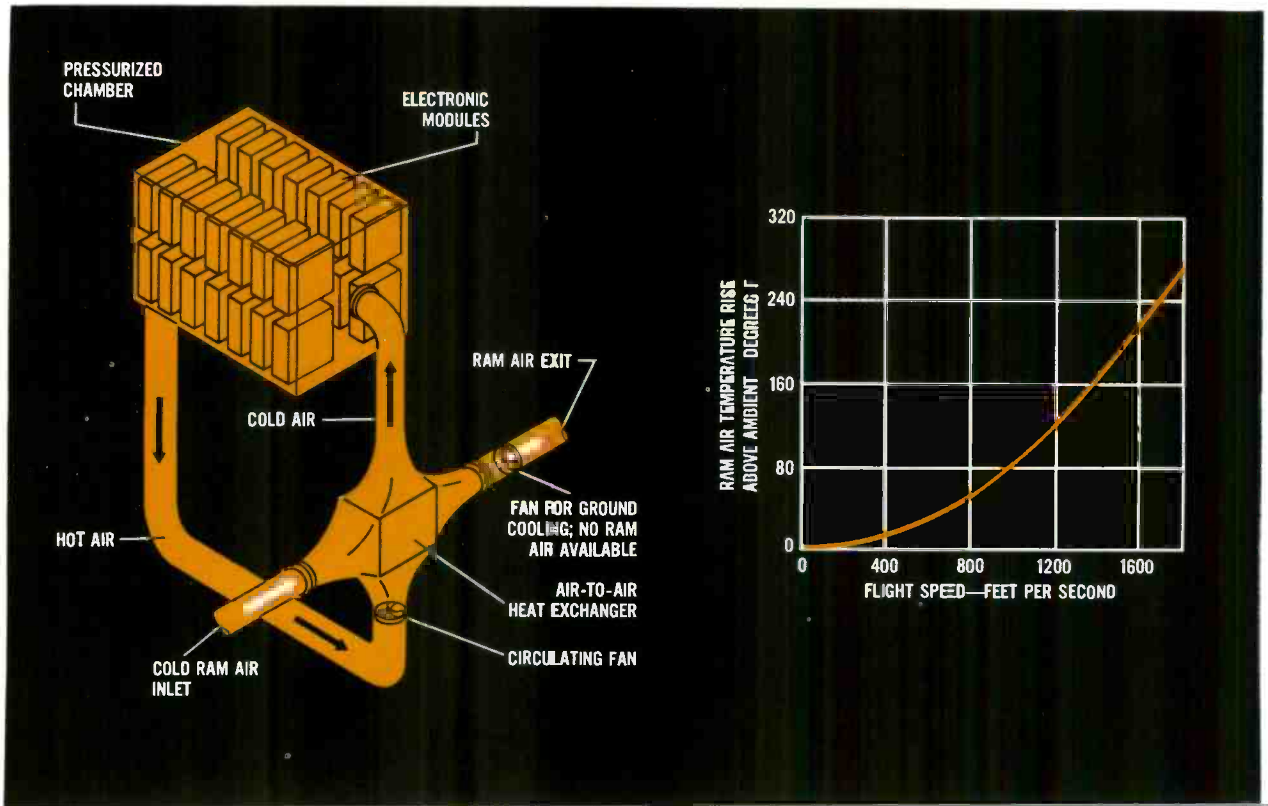

Fig. 5; 6

If the electronic equipment compartment does not need to be pressurized, ram air can be ducted directly into the compartment, eliminating the heat exchanger.

The major disadvantage of this system is the working temperature of the ram air. Excessive speeds produce adiabatic compression of the ram air. The temperature of ram air is a function of the square of aircraft velocity, as shown graphically in Fig. 6.

Air-Cycle Cooling—If inlet ram air temperature approaches the critical component operating temperature, a more complicated cooling cycle is required. One possibility is the air-cycle pressurized system, shown in Fig. 7.

Cooling air is provided by a high-pressure source—in this case, from a stage of the main aircraft jet engine compressor (See Fig. 4). The high-pressure air is first cooled (and pressure slightly reduced) by passing it through an air-to-air heat exchanger. The air next flows through an expansion turbine, where temperature and pressure are reduced to the values needed for cooling.

The turbine shaft horsepower developed during the expansion process is absorbed by a fan, located in the exit duct of the ram air flow. This fan also increases the flow rate of ram air through the heat exchanger.

An auxiliary blower must be provided for cooling during ground operation of electronic equipment.

Liquid Cooling—In some cases, a liquid—such as water or water ethylene glycol—provides the most efficient method of heat removal. Since the heat absorption capacity of a substance is directly proportional to its specific heat, four times as much air as water (by weight) is required for equal cooling performance.

With liquid cooling, each heat-generating component or assembly is connected to heat-conducting rods, which are immersed in the cooling liquid. Heat is removed from the liquid by a liquid-to-air heat exchanger (Fig. 8).

Another method of applying this system is to fasten the liquid pipes directly to the bottom of each chassis supporting heat-generating components. Complete or partial immersion of equipment in liquid is another method sometimes employed.

Evaporative Cooling—An expendable evaporative cooling system possesses a high degree of reliability. Heat is removed by the simple process of vaporizing a liquid at its boiling point. Obviously, the boiling point of the liquid must be below the critical operating temperature of the electrical components. The boiling point of the liquid can be controlled by the pressure to which it is subjected (Fig. 9). Other factors, such as the latent heat of vaporization, density, and freezing point are considered in selecting a suitable liquid.

Use of this cooling method is limited by the operating period; weight of the liquid required for long time periods may make the system undesirable. Evaporative cooling is readily adapted to missiles, where flight time is short.

One type of expendable evaporative system is shown in Fig. 10. Ammonia under pressure is passed through an expansion valve, and the resulting cooling ammonia gas passed through a heat exchanger and exhausted overboard. Other suitable liquids are water, water ethylene glycol, and freon solutions.

Evaporative and Air Cycle—An expendable evaporative system can be used as an intermediate cooling step in the air-cycle system, as shown in Fig. 11. This system uses the combined cooling effects of bleed air (compressed air), ram air, evaporative cooling, and an expansion turbine.

The operation of this system is similar to that shown in

Fig. 7 Air cycle pressurized cooling system.

Fig. 8 Liquid cooling system.

Fig. 9 Boiling point of a liquid is a function of vapor pressure.

Fig. 10 Expendable evaporative cooling system.

Fig. 11 This system employs the combined cooling effects of ram air, bleed air, evaporative cooling, and an expansion turbine.

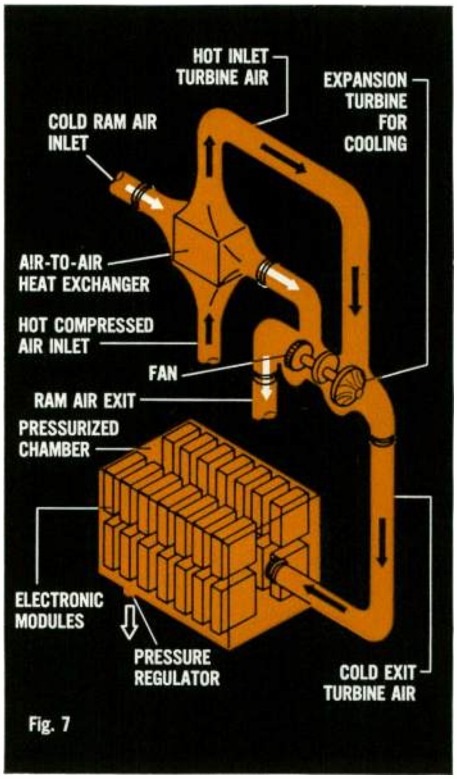

Fig. 7

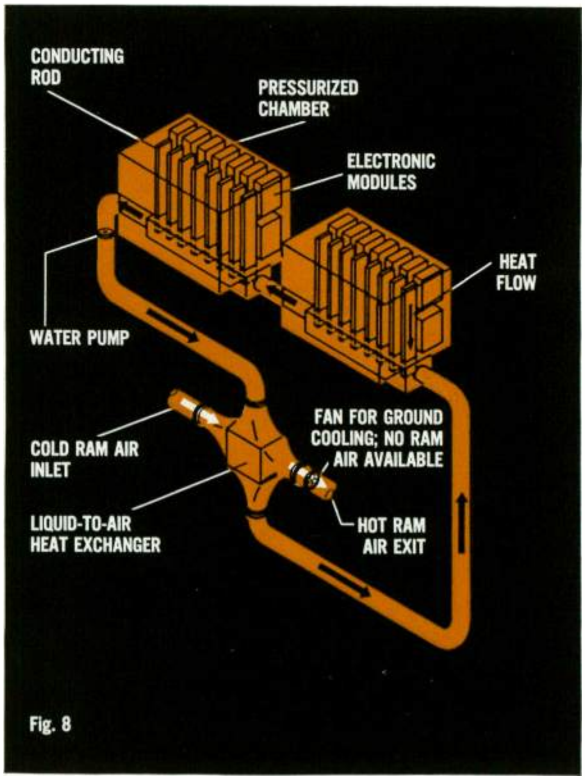

Fig. 8

Fig. 7 except that the evaporative cooler removes heat before the air is passed through the expansion turbine. Hence, in this system, the boiling point of the liquid solution can be higher than the operating temperature of the electrical components. This combined system is capable of controlling high heat loads.

cooling radar systems

In the application of these basic methods to actual design problems, many combinations of the basic modes of heat transfer can result.

A typical application example is an airborne radar system. The antenna can be neglected as a major source of heat generation, so that the system can be divided into transmitter and receiver sections.

In the radar transmitter, the major heat-generating components are the power supply, modulator, and klystron tube. The component parts of the power supply are sealed in a compartment containing sulfur hexafluoride gas under pressure to prevent dielectric breakdown. The gas is circulated through the compartment and passed through a gas-to-air heat exchanger, such as shown in Fig. 5.

The components comprising the modulator are sealed in a compartment with air at a pressure slightly higher than sea level. Compartment air is circulated through an air-to-air heat exchanger.

The klystron tube is designed for liquid cooling. Heat is transferred from the tube parts to the liquid, which is passed through an air-to-liquid heat exchanger (Fig. 8).

The component parts of the receiver are cooled by passing ram air directly over the heat-generating parts. Hence, this typical radar system is cooled by a combination of four different cooling methods.

thermoelectric cooling

The miniaturization of electrical components and circuitry through the use of solid-state devices is being emphasized, and has already suggested the next step in thermal protection. With thermoelectric techniques, small individual cooling systems can be built for temperature-sensitive components. Thermoelectric devices operate on the principle that when an electric current is passed through the junction of two dissimiliar materials, cooling can result. The amount of cooling possible is a direct function of the electric current applied. Herein lies the major problem area for this type of cooling—materials that possess low thermal conductivity, high thermoelectric power, and low electrical resistance. Materials research scientists have already made notable progress in developing these materials.[1]

conclusions

Efficient application of the various types of cooling systems can result in minimum coolant flow requirements for a given heat load and desired temperature rise. The efficiency of any cooling system depends upon the proper distribution of the coolant to each individual heat-producing component. Coolant distribution is not easily achieved, especially in a system with nonuniform heat distribution and complex geometrical design.

The various cooling techniques must be evaluated for each specific application. A combination of several systems is often necessary for a satisfactory solution to a specific thermal problem.

Westinghouse
ENGINEER
Nov. 1960

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[1] "Thermoelectric Modules for Cooling," Westinghouse ENGINEER, May 1960, p. 94.

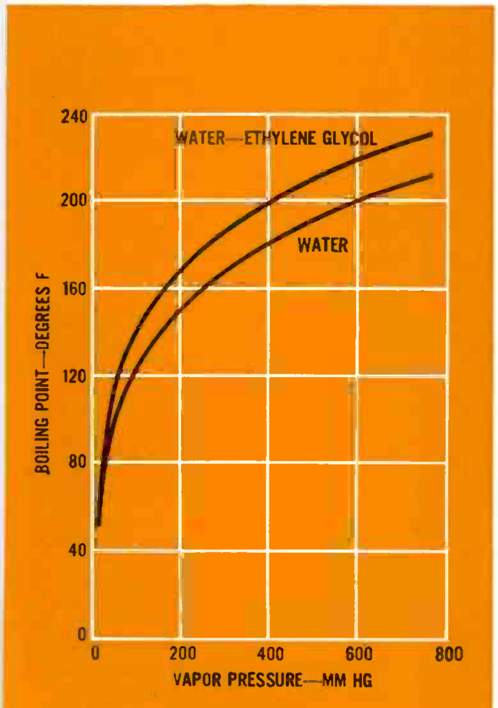

Fig. 9

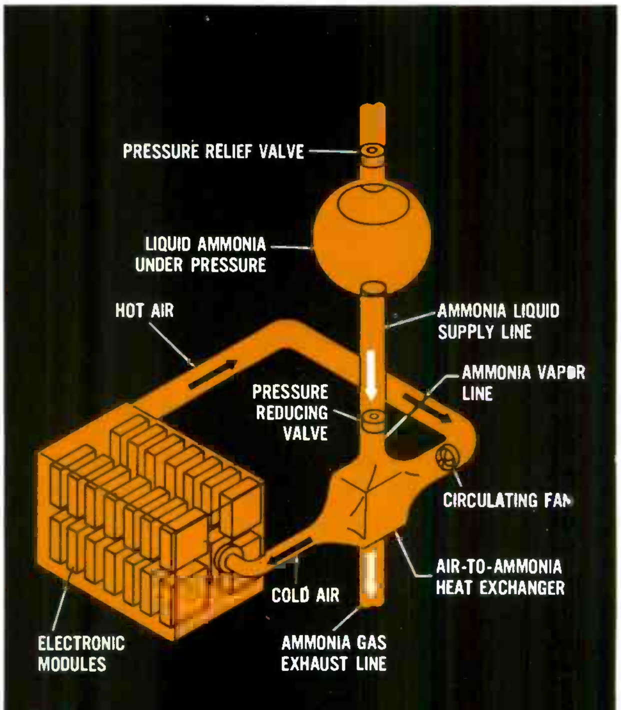

Fig. 10

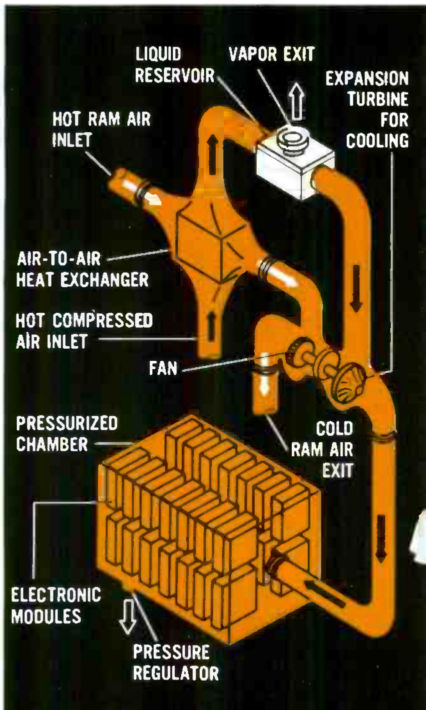

Fig. 11

DC TO AC POWER CONVERSION . . . BY SEMICONDUCTOR INVERTERS

Static semiconductor inverters hold considerable promise for widespread application. For many uses they are practical now; a rapidly advancing technology seems likely to broaden their application in the next few years.

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Westinghouse Electric Corporation
Cheswick, Pennsylvania

Many basic sources of electrical energy today produce direct current. In the future, many of the new methods for direct conversion of thermal to electrical energy will also produce direct current. For example, thermoelectric, thermionic, and magnetohydrodynamic devices, as well as fuel cells, all have one thing in common—they are dc generators. While direct current is useful in some applications, the majority—particularly where large amounts of power are involved—require alternating current.

This situation requires an efficient and economical method for converting direct current to alternating current, i.e., an inverter. Several reliable and efficient inverters are available, and among them is a promising newcomer—the newly developed semiconductor power inverter.

basic differences

Fundamentally, inverters are of three types; the conventional motor-generator set, the mercury arc rectifier (ignitron) inverter, and the new semiconductor power inverter. Both ignitron and the semiconductor inverters are basically static units as opposed to the rotating m-g set.

These three methods can be compared in terms of their present and potential capabilities. The *motor-generator sets* now available represent long engineering development and are an efficient and reliable method for electric power conversion. However, since they are rotating devices, a number of disadvantages are evident. For example, there are bearings to be lubricated, carbon brushes to be replaced periodically, and commutators to be maintained. Also, even a single motor-generator set has a relatively fixed geometry. Therefore it is difficult, or often impossible, to rearrange elements to make the most effective use of space.

Of necessity, the rotating machine has inertia, so the motor-generator set must be brought up to operating conditions; as a result, output power is not immediately available unless the machine is kept rotating constantly. However, the m-g set has the inherent advantage of being able to withstand overload conditions for a reasonable time.

The *ignitron inverter system* is basically a static unit and thus less maintenance is required than for most rotating systems. Presently the cost of the ignitron system is sensitive to operating voltage. In the region of 600 volts, the cost per kilowatt is about $60. However, in the 2500-volt region, the ignitron inverter system may cost as little as $50 per kilowatt.

Since this system is essentially static, its operation is quiet. Because there are no spark-gap commutations, operation of such a device is suitable for areas in which explosive gases might be present. The efficiency of the ignitron system is reasonably high and tends to increase as operating voltage is increased.

The newest of the dc-to-ac inverter systems uses *semiconductor* elements. During recent years, a rapid succession of semiconductors has been developed to perform basic electrical functions.

The silicon diode was the first of these new devices to appear and by combining new materials techniques with improved fabrication methods, the present-day silicon diode has grown from the size that might be used in a portable radio to units that have an operating voltage of about 500 volts and can control over 150 amps. The transistor, too, has developed rapidly, largely because of a far better understanding of the basic physics of semiconductors.

A major contribution to the success of high-powered silicon transistors came about only a few years ago. These devices require extremely pure silicon material—less than one part in 10^9 impurity content is desirable. As a result of materials preparation research, a new method for producing extremely pure silicon was developed, and much better control of the device characteristics can now be obtained. Today the silicon transistor has been operated in the laboratory at as high as 200 volts and can control currents as high as 30 amps. This means that a small amount of power can be used to control 6 kva with a single device; by putting these transistors in parallel-series combinations, considerably more power can be handled.

In the recent past, research and development engineers have produced a new semiconductor, the Trinistor controlled rectifier. This new semiconductor device is similar to the transistor in many ways, but with one basic difference. The control element of the transistor is always active and the transistor can be turned off or on at any time by applying the appropriate voltage to the control element. The Trinistor device, on the other hand, can be turned on by the control element at any time, but the control is lost as soon as conduction begins. Special circuitry is required to turn off the Trinistor device; this causes the primary current to go to zero, and at this point the control element again becomes operative. The transistor behaves in a manner similar to a vacuum tube, but the Trinistor controlled rectifier has characteristics similar to a thyratron. Both transistors and Trinistor devices have been used in semiconductor power inverters, but the Trinistor appears to have the greatest potential for very high power operation.

static semiconductor inverters

Both the transistor and the Trinistor controlled rectifier use a silicon wafer arranged so that a control element can cause the device to go from a high impedance state to a low impedance state.

Considerable study of semiconductor units shows that the internal energy losses are extremely low when the devices are at minimum or maximum conduction conditions; high losses occur only under operating conditions in which the unit is not fully turned on or off. This makes it extremely important that the circuitry permit the semiconductor unit to be operated in only two states—either all on or all off. Switching time from one state to the other must be made as short as possible for minimum dissipated energy and highest efficiency. Since the all-on, all-off type of operation is essentially the behavior of a switch, this type of operation is identified as the "switching mode." All of the semiconductor power conversion equipment has been designed with this type of operation as a basic part of the circuitry. The semiconductor is capable of performing the switching action extremely rapidly with no deterioration at a high repetition rate and with a high efficiency.

Both the transistor and the Trinistor controlled rectifier can be used effectively in inverters. Transistor inverters have been constructed up to the 10 kilowatt level and have performed at frequencies as high as 20 kilocycles per second. Above the 10 kilowatt level, however, the Trinistor device appears to be more suitable, particularly since the technical considerations indicate that extremely high powers can be obtained in single units.

Since the transistor and the Trinistor controlled rectifier are used in essentially the same manner for power conversion, the remainder of this article will be restricted to the Trinistor device.

Generally, an inverter requires a pair of Trinistor units, one of which supplies the positive half-cycle of the alternating current wave, and the other the negative half-cycle. Circuitry developed thus far will permit parallel or series combinations of the Trinistor rectifier to be operated effectively; the output waveforms from the inverters can be made square wave or sine wave.

Trinistor inverters constructed thus far have been operated to approximately 60 kw of power and as high in frequency as 20 kilocycles per second. The Trinistor device is relatively small in size and in most applications must be connected to a heat dissipating element to remove heat generated internally and maintain operating temperatures at a reasonable level.

The semiconductor power inverter has all the advantages generally associated with static units, including high reliability, low maintenance, and minimum noise generation. In addition, weight and volume of the semiconductor inverter may be much less than a motor-generator set. In the future, the Trinistor controlled rectifier will be designed to handle much greater power than present units and, as the operating voltage is increased, the efficiency of the inverter is also increased. In general, the Trinistor inverter is expected to be significantly more efficient than the ignitron inverter.

The basic functional element of the Trinistor device is the specially prepared silicon wafer (Fig. 1). The wafer

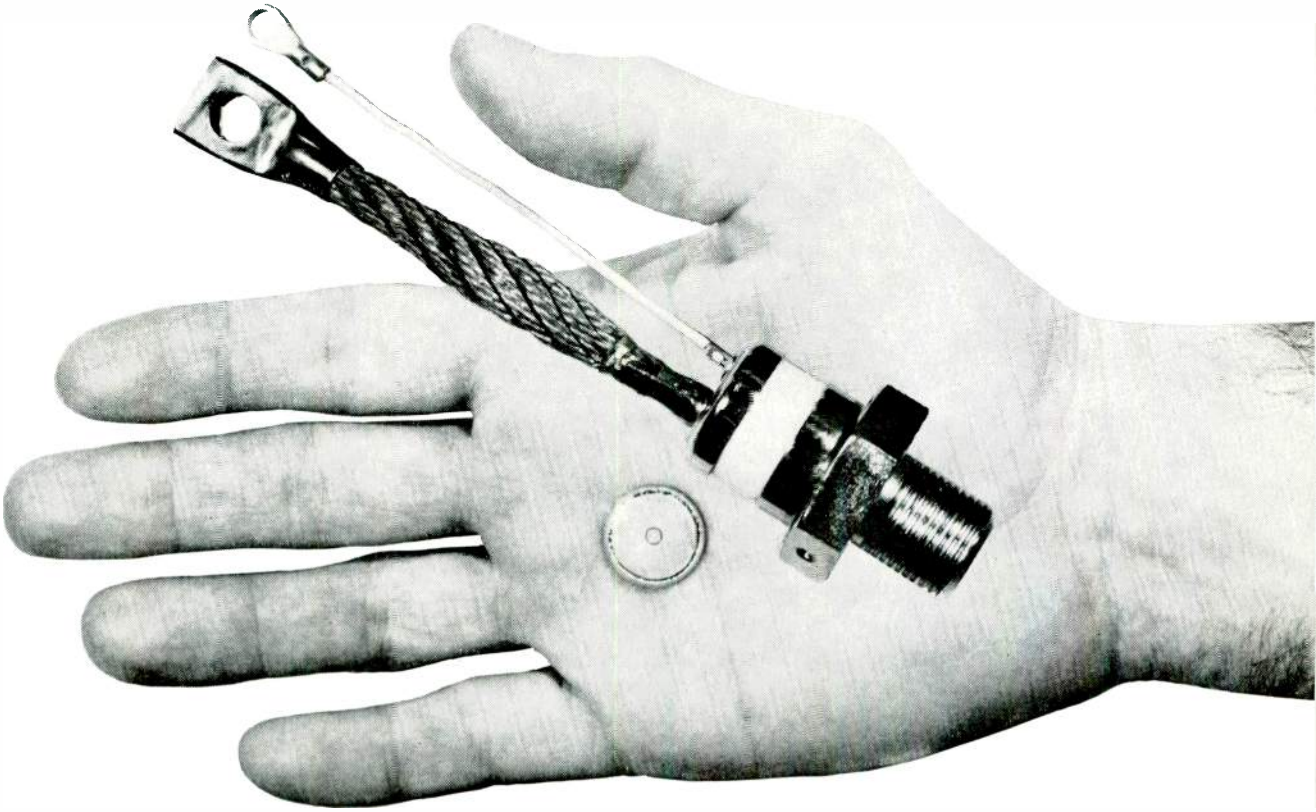
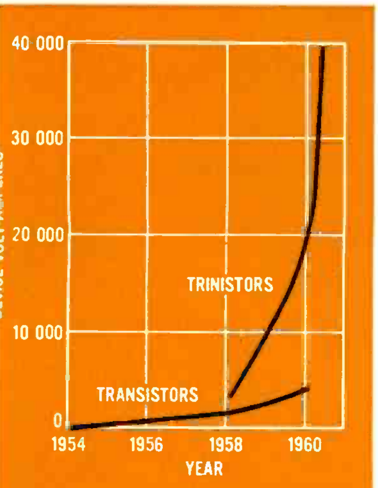


Fig. 1 At top is a Trinistor switch; the basic functional element of the Trinistor is the silicon wafer shown in the man's hand.



ig.2 Semiconductor Device Development

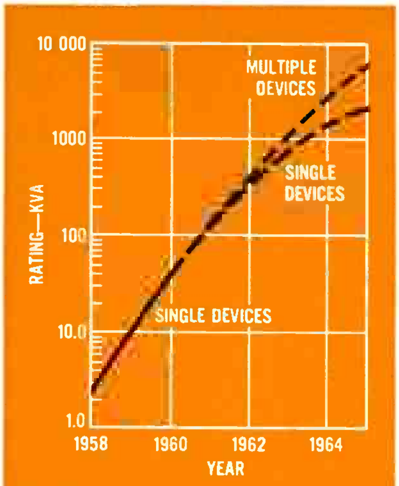


Fig.3 Power Inverter Development

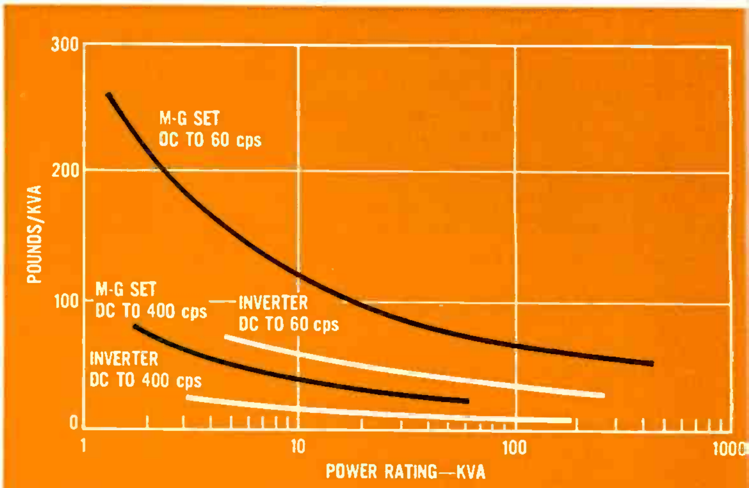


Fig.4 Conversion Equipment Weight vs Power Rating

itself is smaller in diameter and thinner in thickness than a dime, yet is capable of controlling 100 amperes at 200 volts. Semiconductor materials are improving rapidly and, as a result, the power-handling capabilities of Trinistor devices have gone from a relatively small number of watts to today's level of 20 kw in only two or three years. Sustained development will yield even greater increases in the future, and a silicon wafer not much larger than the present unit may be capable of handling as much as 1000 amperes at 1000 volts. At present, the current density in the wafer is about 500 amperes per square inch, and by 1965 this probably will have increased to about 1000 amperes per square inch. In the same time, voltage—now limited to the range of 200 to 400 volts—will be increased to 1000 or more volts.

The rapid growth in the power-handling capabilities of the individual semiconductor devices is illustrated in Fig. 2. The curves show that the capabilities for a single device have been increased by a factor of 10 in the past two years. By 1965 they will have increased by as much as 30 times our present-day limits.

The power-handling capabilities of static inverters using these devices is also increasing rapidly, as shown in Fig. 3—from a few watts a couple of years ago to 10 kilowatts in 1959 and in excess of 75 kilowatts this year. However, these systems offer considerable advantages in other ways as well. One of the more important ones is relatively low weight. A prediction of comparative weights for the future is shown in Fig. 4. Note that the static inverter may be roughly one-half the weight of a motor-generator set for equivalent power rating. The static inverter can operate at frequencies as high as 20 kilocycles, and its weight in that rating will be markedly below that of existing comparable motor-generator sets. Also, the weight of the static inverter is considerably less than existing electronic units for the same frequency and power.

Another advantage of static inverters is small volume. The volume required for the semiconductor static inverter will be roughly one-half that of the motor-generator set, as indicated in Fig. 5. A simple statement of occupied volume, however, is only part of the story. Since the static inverter is made up of small individual components, it can be made in almost any geometric form. This ability to vary the shape of a static inverter is of extreme importance in military applications and also will be of importance in a variety of other applications where space is at a premium.

Perhaps the most important single factor relating to the use of semiconductor static inverters is the matter of efficiency of conversion. In Fig. 6, the efficiency of the motor-generator set at both 60 and 400 cycles is compared with the static inverter for power ratings up to 1000 kva. Note that only one curve is necessary to show static inverter efficiency because it works as well at 60 cycles as at 400 cycles per second. As can be seen, in the range from 10 to 1000 kva the static inverter is capable of extremely high efficiency—87 to 90 percent as compared to 75 to 88 percent for the motor-generator set.

Static inverters are still being improved at a rapid rate. An efficiency of 95 percent is possible as the semiconductor material and circuitry are improved. This, in essence, means that the 10 to 15 percent loss now experienced in power inversion will be reduced by a factor of 2 or 3 to only 5 percent in the future.

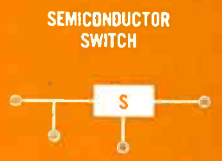
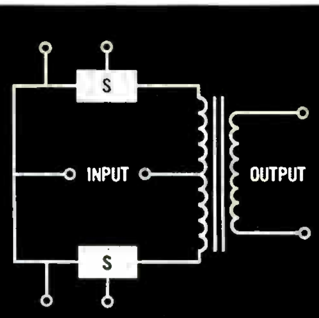


Fig. 7 Several basic inverter circuits.



7a Single Phase Center Tap

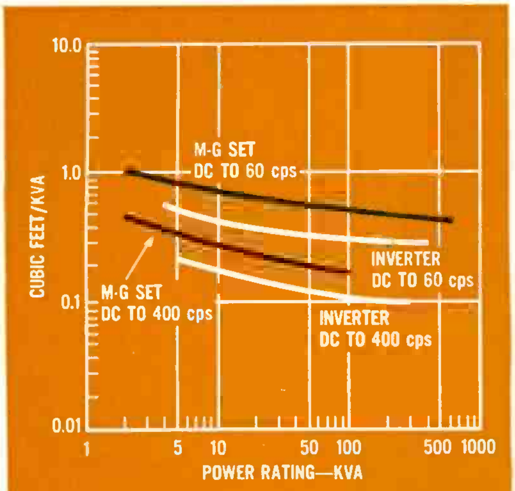


Fig.5 Conversion Equipment Size vs Power Rating

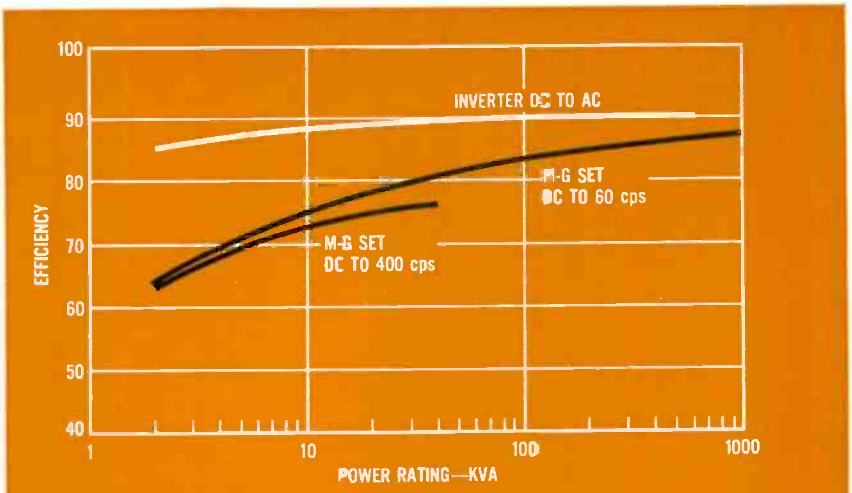


Fig.6 Conversion Equipment Efficiency vs Power Rating

Thus far, only the advantages of static inverters have been described; a complete story must also present the disadvantages. One attribute of static power inverters is their ability to deliver power immediately when required. This is due primarily to the lack of inertial time delay since no rotating parts are involved. However, when overloaded, the system has no inertia and little thermal energy storage and excessive voltages or currents might cause failure of the semi-conductor elements. Thus, some protective circuitry is often necessary, and this increases circuit complexity.

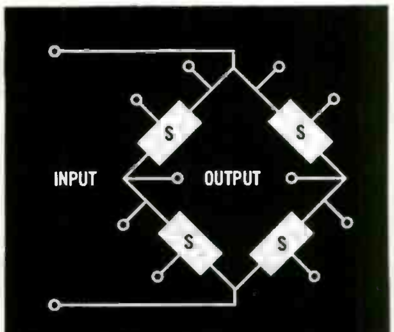
A second possible disadvantage of the static inverter is that under normal conditions the unit may operate for sustained periods of time very close to the maximum allowed limits. Because of this, the designer has a decided tendency to allow very little factor of safety. This difficulty can be minimized, but must be kept in mind throughout the design effort.

Another problem arises from the fact that the semiconductor static inverter employs a completely new concept of electrical circuitry; operating personnel will need to be trained to understand the semiconductor type of apparatus. This should not be an acute problem since maintenance is expected to be extremely small and operating personnel in general will not have much need to provide repairs or maintenance for this apparatus.

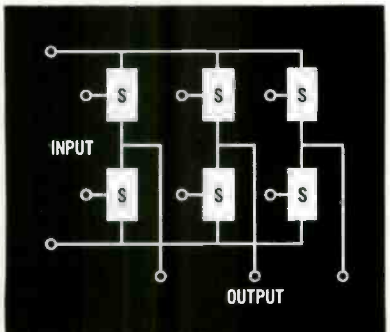
basic circuits

Several circuits are specifically tailored to the semiconductor device characteristics. With transistors, the capability of full control both in the on as well as the off condition has been used in circuits similar to the basic element diagrams shown in Fig. 7. The circuit of Fig. 7a is a single-phase push-pull arrangement using two transistors; this type has found wide application particularly at low and medium power levels. Modifications have been made to this basic circuit to obtain frequency stability and frequency control; this type of circuit is frequently used as the basic oscillator for higher power systems.

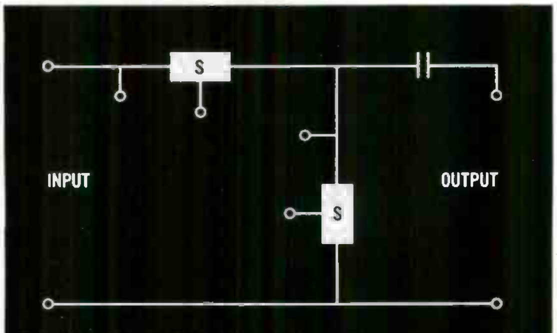
A modification of the basic single-phase, push-pull circuit, using a bridge arrangement, is shown in Fig. 7b. In general, this permits operation at higher voltage more conveniently than a simple series connection of transistors, since series arrays of these devices can present serious problems. In Fig. 7c, the basic circuit has been modified for operation as a three-phase inverter. The circuit shown in



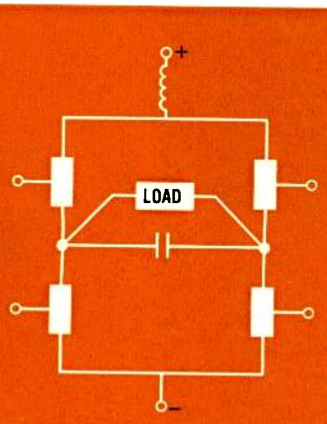
7b Single Phase Bridge



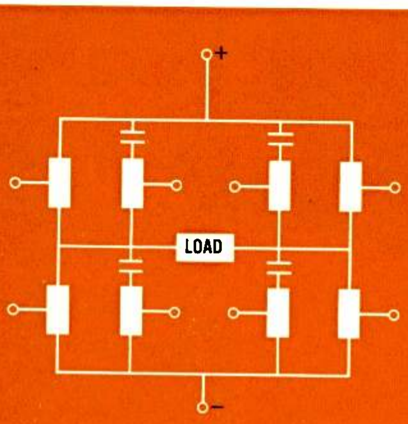
7c Three Phase Bridge



7d Half Wave With Energy Storage



8a Commutating Bridge Inverter



8b Capacitor Turn-Off Inverter

Fig. 7d is termed an "L" type and is most useful when the load is highly reactive so that advantage can be taken of the stored energy in the system. In all of these circuits, maximum power handling capabilities of the devices is obtained when the device is operated in the switching mode and the transfer from one condition to the other is accomplished as rapidly as possible.

The development of circuits for use with Trinistor devices has followed the transistor technique rather closely, but the important difference in lack of turn-off control necessitates special turn-off techniques.

The present state of circuitry is still in the early developmental phase and as applications are investigated in greater detail, many more methods to achieve effective switching action will be evolved.

A bridge circuit of the type shown functionally in Fig. 8a will accomplish turn off of one pair of Trinistor devices when the other pair is turned on. The charge from the capacitor is used to produce essentially zero current in the Trinistor devices for sufficient time for the control element to regain active control. In Fig. 8b, the same kind of control is obtained by effectively shunting a pair momentarily and, as a result, current in the Trinistor devices goes to zero and control is regained. The auxiliary units stop conducting when the capacitor is fully charged. Both of the circuits have been used successfully in equipment, but other circuits now in development appear to have both technical and economical advantages.

The availability of these new semiconductor devices that can handle large power has presented the engineer with new challenges in circuitry. More than ever, it appears that the device and the application should be considered together. The load becomes a fundamental part of the converter circuit and important advantages can be realized if both are used in the optimizing process.

the potential of static inverters

Where does the semiconductor static inverter stand today? The Trinistor switch has grown from the level of watts to the level of kilowatts in two years. Research and development efforts have been directed toward larger power ratings, and in the next few years, semiconductor inverters will be in the 10 000 to 100 000 kilowatt region.

Of major importance to the successful application of the Trinistor switch is the cost picture. Past experience with similar devices has been used to predict costs for the near and distant future. Costs for these new semiconductors have experienced a dramatic reduction in the past few years; during 1959, for example, the cost decreased 75 percent. For the future, rapid reduction of cost is expected to continue.

Since the cost of the static inverter depends largely on that of the Trinistor device, the overall cost will also drop at a rapid rate.

Comparing costs for the 50 000-kilowatt level, the motor-generator set at present has a cost of about $70 per kilowatt and future designs may reduce this to $65. The ignitron static inverter costs about $60 per kilowatt at the 600-volt level. In 15 to 20 years, this cost is expected to drop to about $55.

The cost of the Trinistor static inverter is much higher than high-power conventional systems at the present time. But costs will be reduced rapidly in the years ahead. Somewhere in the 1960's the Trinistor inverter should be at the motor-generator set level, and by the 1970's it should be comparable in cost to the ignitron inverter. Beyond this point, the semiconductor inverter should continue to drop and be substantially more economical than both motor-generator sets and ignitron inverters. The cost of the Trinistor power inverter may eventually drop as low as $40 to $45 per kilowatt.

The preceding figures are for inverters in the 50 000 kilowatt and higher power levels. For many lower power applications, the semiconductor power inverter is already the most economical, and for other applications, it will soon have lower costs than conventional methods.

The new static inverters are now being used for a large number of applications by the military. In missiles, submarines, and emergency power systems, the low volume, weight, and noise, and improved reliability under adverse conditions have established the value of the semiconductor inverter; many more military applications are now being explored and suitable units will soon be in development.

Commercial and industrial use of the new inverters are just beginning to evolve, and these applications are expected to grow rapidly. One of the more important is expected to come as an outgrowth of this engineering effort—the conversion of alternating current from one frequency to another. This gives a new variable to the engineer in his design of electrical equipment. With frequency change, high-frequency lighting, new motor designs, new ac power supplies, lower cost ultrasonic generators, and new concepts in speed control for mill operation all loom as possibilities.

A continuing objective is to increase both the power-handling capability and the application areas for semiconductor static inverters. For power from unconventional generators, for emergency power, for small power systems, for power where noise, weight, and volume must be kept to a minimum, for low maintenance and for high reliability, the semiconductor static inverter provides significant advantages. Even more significant, however, is the rapid rate at which static inverters are being developed. Design engineers should give careful consideration to their use in any future applications.

ELECTRICAL PORCELAIN TODAY A summary of recent developments in the manufacture of this versatile insulating material.

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Despite a parade of plastics that have appeared in recent years, porcelain continues to be one of the most versatile, low cost, high performance insulation materials in use today. Porcelain has retained this position primarily because of several inherent advantages. It is easily formed, light in weight, and low in tool cost; it has zero absorption, good dielectric strength, and excellent chemical resistance; it is nontracking, and remains virtually unchanged in physical or electrical properties after years of exposure to all types of environments.

Porcelain is an extremely versatile material, being used in all types of applications. It has grown and improved with the electrical industry since its inception. The original porcelain insulators were manufactured with basically the same materials and processes that were used for dinnerware and artware industries of that time. These were soon found to be inadequate to meet the growing demands of the electrical industry and, of necessity, a new class of porcelain was developed to meet these demands.

This material with a modulus of elasticity of approximately 10 x 10^6 pounds per square inch is three times as elastic as steel, yet is lighter than aluminum.

One of the major improvements in porcelain over the years has been the development and use of prestressed glazes to improve the strength of insulators. The glazes are closely controlled to have the proper coefficient of contraction or expansion with respect to the body to insure that the glaze is always prestressed in compression. Proper selection and application of glaze although only 0.006 to 0.008 inch thick, can increase the strength of an insulator as much as fifty percent over its unglazed equivalent.

Like other nonductile materials, porcelain is greatly affected in strength by its surface characteristics. The less ductile the material, the more pronounced are the effects of surface conditions.

The raw materials used in porcelain inherently produce a product with a slight surface roughness. To improve the surface and make it easy to clean, a coating of glaze is applied over the porcelain body. These glazes are composed of essentially the same materials as those used in the body of the insulator with additional fluxes and coloring agents. During firing, the glaze becomes molten and flows over the surface of the insulator, coating it with a thin glossy coating that is tightly bonded to the porcelain body. During cooling after firing, the porcelain and glaze attempt to shrink in accordance with their individual coefficients of expansion. If the glaze is made to have a lower coefficient of expansion than the porcelain body, it will be stressed in compression. During cooling, the glaze attempts to shrink less than the porcelain body; but, since it is tightly bonded, it must follow the greater contraction of the body. This prestresses the glaze in compression. This type of glaze improves transverse strength since the tensile stress produced by an applied transverse load will subtract from the residual compressive stress produced in the glaze.

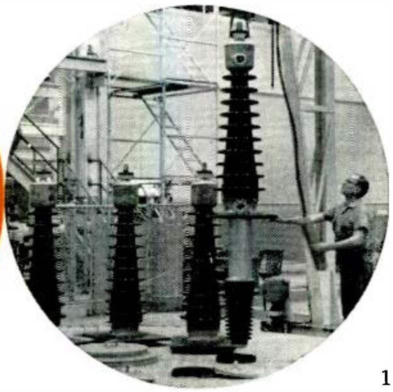
This prestressing of the glaze is quite practical and is the method used by all major electrical porcelain manufacturers today.

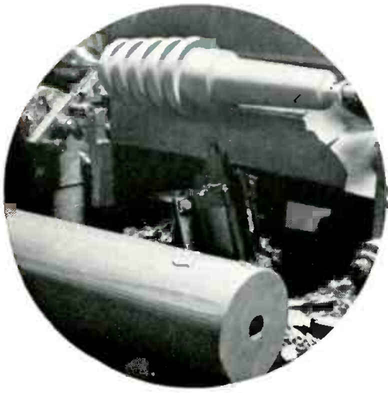
The opposite effect, that of making the glaze with a greater coefficient of expansion than the body is quite possible, but is never used. The stress produced in this manner can be so great that the glazed surface actually fails in tension, and the surface will show a pattern of very fine cracks or craze marks. This type of glaze will reduce transverse strength since the tensile stress produced by an applied transverse load adds to the residual tensile stress in the glaze.

Like metals, the physical and electrical properties of porcelain can be tailored to meet specific requirements. For example, the addition this year of an alumina body provided an electrical porcelain material with essentially the same dielectric strength as the "standard" porcelain, but with approximately double the mechanical strength, good thermal shock characteristics and at least double the impact strength.

Electrical porcelain can be divided into several distinct types of materials. The end properties can be designed in any one type to cover a wide range of end products. The most familiar type, "standard" electrical porcelain, is made of a mixture of clay, feldspar and flint (quartz). Feldspar is a combination of the oxides of sodium, potassium, aluminum and silicon; flint is essentially silicon dioxide; and the clays are complex alumina silicates. These various constituents of porcelain vary in basic composition depending upon where they are mined and these variations permit the composition to be altered to obtain the desired end result. These variations also make it possible to use a variety of processes to form the insulator required. The bodies can be designed for pressing in metal dies to obtain intricate details, or for casting by the use of plaster of paris molds

These assembled bushings are being subjected to high-voltage electrical tests.





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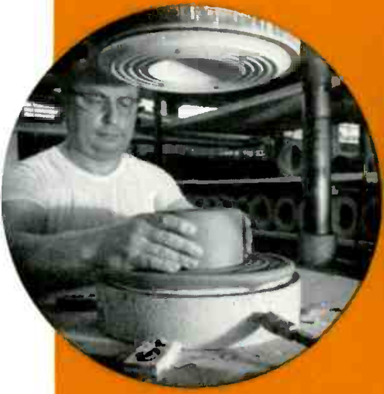

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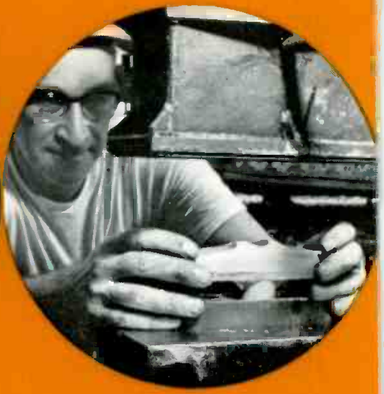


D

or for extrusion and machining. Some of the basic processing methods are outlined in Fig. 1.

Porcelains made with alumina (aluminum oxide, Al_2O_3) form another distinct type. The alumina can be obtained from several sources: it can be used as found in nature as the mineral corundum; bauxite, the alumina hydroxide, can be used; or alumina can be produced from bauxite; a fourth source is one of the alumina silicate forms. The various bodies produced from alumina again cover a wide range of end properties ranging in application from high strength bushings to refractories.

Zircon porcelains (zirconium silicate, $ZrSiO_4$) can be compounded to give excellent physical and electrical properties for use in applications where the parts are subjected to great thermal shock such as in circuit breaker arc chute plates, or for high frequency applications where low loss is a prime consideration.

These examples do not cover all the major types of electrical porcelain, but are indicative of the design potentialities that exist with porcelain materials. The processes used for forming the major types of electrical porcelains are shown in Fig. 2.

Many of the methods used in forming metals—extrusion, spinning, forging, machining, pressing in dies, and casting—have their counterparts in forming porcelain. These processes lend themselves to parts ranging from button size to the huge weathercasings for 345-kv applications.

Small identical parts are formed rapidly from extruded tubes with automatic lathes in which tools and stock are indexed to definite positions by cams. Turning, drilling, forming, counterboring and threading, and many other operations can be performed. This equipment is similar in many respects to a multiple-spindle automatic screw machine. For high-activity items, larger tubes can be machined on semiautomatic lathes that are capable of machining at feeds and speeds in excess of those associated with the better machining metal alloys.

Metals-joining techniques are also possible with porcelain. Soldering is a commonly used method. A solution containing platinum and gold compounds in solvents, together with other compounds to serve as fluxes to attach the metal to the porcelain, is brushed onto the glazed porcelain surface. The piece is then fired in an oxidizing atmosphere to develop a thin metallic band. With proper controls and firing, an intimate bond results between the band and the glazed insulator. The low metal content of the

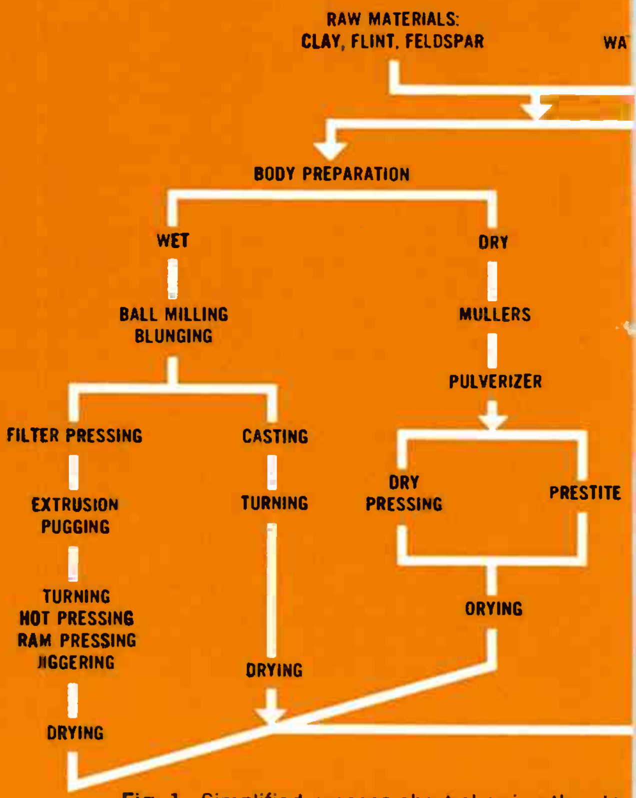


Fig. 1 Simplified process chart showing the step

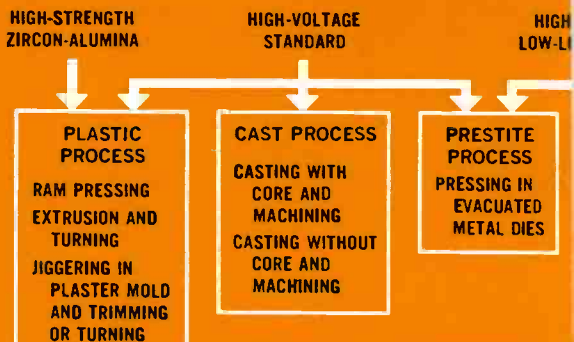
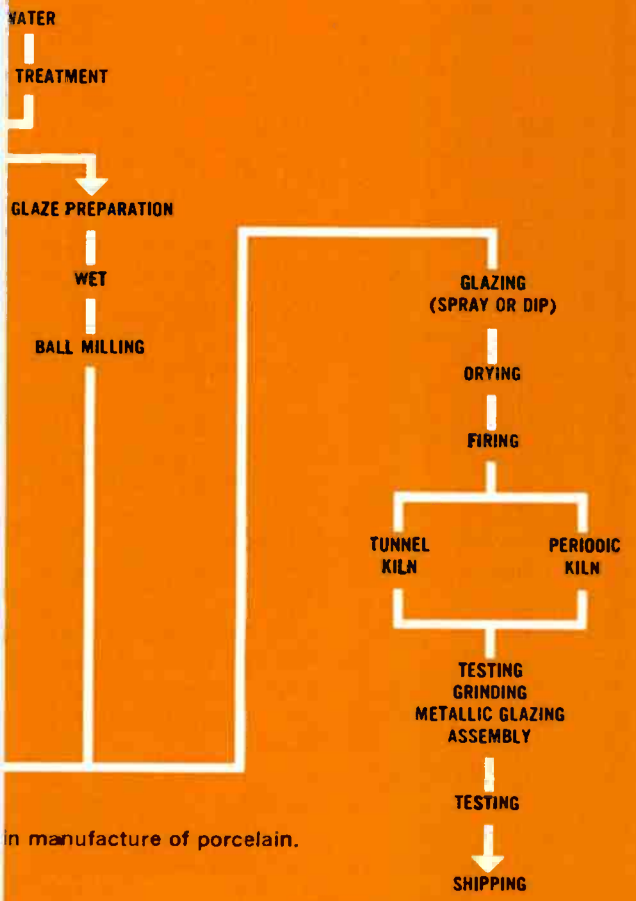
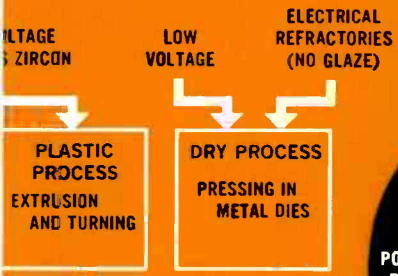


Fig. 2 The manufacturing proc
shown for the principal types of

E



in manufacture of porcelain.



s and methods of forming are
ectrical porcelain.

Photo A Semiautomatic lathes are used for turning distribution transformer bushings. The machine need only be loaded and unloaded by hand.

Photo B Large insulator weathercasings are lathe turned while still in a plastic stage.

Photo C The RAM pressing process uses plaster dies.

Photo D Prestite pressing is done in evacuated dies.

Photo E These 196-kv weathercasings have been removed from the casting molds and are drying in cradle molds.

solutions used produces an extremely thin (one to five micro-inch) metallic band. The band is tinned and metal parts soldered to it.

The large differences in thermal coefficients of expansion between the porcelain insulator and the metal parts make it mandatory that the metal parts be designed as light as possible to minimize the thermal stresses that may be imposed. A typical example of good design is the solder-sealed capacitor bushing, which has given many years of excellent field performance. The use of solder-sealed bushings is almost universal throughout the industry for capacitors. This type of seal is also used on instrument, network, and specialty transformer bushings. The solder-seal has probably the best field record of any metal-to-ceramic seal in use.

designing for porcelain

Porcelain, with its many advantages, also has its disadvantages—it has low tensile and impact strength, and is difficult to hold to close dimensional tolerances. However, these disadvantages often can be overcome through proper design and designer ingenuity.

The rolled seal on many types of bushings is a good example. This seal provides the resilience and shock resistance that is lacking in porcelain (Fig. 3), and it also permits the bushing to be either bolted or welded in place. This same type of mounting has been used for the mounting flange for high-voltage instrument transformers. The

Fig. 3 (Below) Simplified cross section of rolled-seal mounting.

Photo F The unusual stop on this porcelain transformer tap-changer block avoids the problem of low-tensile strength.

Photo G The elongated holes in the porcelain part (left) overcomes the tolerance restrictions of porcelain.

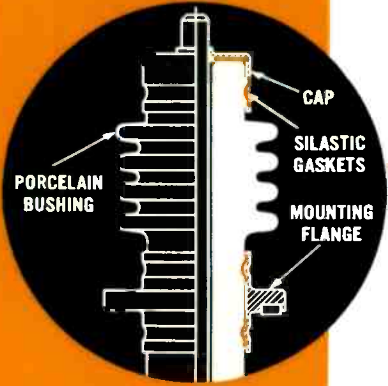
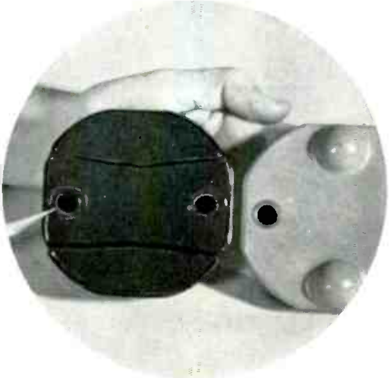


Fig. 3

F



G

rolled-seal design imparts the same qualities of ease of assembly and resilience to these large weathercasings.

Probably the greatest difficulty associated with porcelain is the fact that porcelain parts must be designed with a one to three percent tolerance. In some cases, these tolerances eliminate porcelain from consideration; but in many instances, a close examination of the functional requirements of a device or part will reveal a design that is acceptable. A recently designed porcelain drive coupling is a good example of this type of functional design. The original drive coupling, made of glass polyester, presented a problem because of the close tolerances required on the mounting holes (Photo G). The answer was simple but effective—the holes were elongated. The result is adequate in mechanical strength, is superior in electrical strength, and costs only 25 percent of the original version.

The limitation of low tensile strength can often be overcome through careful design, and proper selection of material and glaze. An example is a tap-changer block now in use on distribution transformers (Photo F). A special stop design permits the porcelain stop to withstand a cantilever load imposed by a lug on a shaft running through the center of the block. The design simply changes the major component of the applied force to one of compression where porcelain is six to eight times as strong as in tension.

aluminum for porcelain assemblies

Aluminum, a relative newcomer in association with porcelain assemblies, is being adopted and used more widely to improve appearance, reduce weight and reduce costs of hardware. From a use of practically zero a few years ago, it has grown to the point where it is one of the major materials in use in porcelain assemblies.

One of the novel applications of aluminum has been the use of die-forged flanges on bushings that use the rolled-seal design. Normally, forgings are associated with applications requiring high tensile and yield strength, high impact strength, endurance and wear resistance; but, for these flanges, ductility, rather than high strength, is the prime requisite. Aluminum alloy 3003 in the "as forged" temper was selected for its excellent forming properties. Roll forming of the gasket seal on these types of bushings requires a material with a low yield strength and a wide range between the ultimate strength and the yield strength. This insures adequate compression of the gaskets without springback, and insures against forming at stresses above the ultimate strength which would cause cracks or complete rupture. The 3003 alloy has the desired properties—a yield strength of 6000 psi and an ultimate strength of 16 000 psi with an elongation of thirty percent.

process improvements

The porcelain-making process consists of five basic steps—mixing the materials, forming into the required shape, drying, applying a glaze (if used), and kiln firing. The steadily increasing demands for electrical porcelain, both in quantity and quality, have resulted in constant engineering development and more precise control of the manufacturing process. For example, new extrusion, boring, and turning equipment has extended the range of extruded sizes to the present limit of 19 inches, outside diameter.

The most radical revision in manufacturing at the Westinghouse porcelain department occurred in the casting department with the installation of automatic temperature-humidity controlled driers. When porcelain castings are released from the mold, they are incapable of supporting their own weight and must be dried until they reach a moisture content of less than one-half of one percent.

Immediately subsequent to casting, the piece is supported in a half mold, which is designed to permit shrinkage of the piece as it dries. These "cradle" molds hold the piece for three days. At this point, drying has progressed to the point where the casting has enough strength to permit some handling, but not enough to permit machining.

Prior to the installation of the driers, the drying process was continued at room temperature for an additional fifteen days plus an additional ten days at higher temperatures to prevent the possibility of differential shrinkage occurring during drying, which could crack the piece. These large cast pieces shrink 15 to 20 percent from the time they are cast until they are fired. For example, a 196-kv weathercasing, which after grinding to length is 68-½ inches long, is originally cast at 90 inches long, or roughly 30 percent greater in length to allow for shrinkage plus turning and grinding stock.

The installation of automatic temperature-humidity controlled driers has eliminated the capriciousness of the weather from the drying cycle, and total drying time has been reduced from about 25 days to 5-½ days.

New semidirect-fired periodic kilns have also helped to decrease lead time and improve the efficiency of firing. Large cast ware was previously fired in muffle-type beehive kilns. In this type of kiln, there is no direct flame impingement on the ware; all heating is indirect from the muffle. This type of firing is inefficient because much of the fuel used to fire the ware is expended in heating the muffle. In the past, however, this type of firing was permissible because of the low cost fuels available.

In the new semidirect-fired kilns, the heated gases travel up the side of the kiln to the top, then down through the ware and out the flues, which are in the bottom of the kilns. This method of firing has reduced the amount of gas required for a "burn" from 750 000 cubic feet to 385 000 cubic feet, and at the same time increased the capacity of the kiln 40 percent. Also, the greater height in these kilns has permitted firing 345-kv weathercasings in one piece.

Through plant rearrangements and additions, straight line assembly techniques are being incorporated into the manufacturing process. For example, the assembly of cap and pin type and station post insulators has been arranged so that component parts are delivered on pallets to the assembly area. These parts are assembled in jigs on a double conveyorized assembly line. After assembly, the insulators move through the initial curing chamber on the conveyors to the exit, where they are removed from the jigs and loaded on monorail trolleys for conveyance through the final days of curing. After curing, the pieces move on conveyors through cleaning, final continuous flashover test, visual inspection, and packing.

Although electrical porcelain manufacture has not yet reached the realm of being one of the mass-production industries, it is now a highly mechanized, high-production industry compared with older methods of porcelain manufacture.

COMMUNICATION TO SPACE VEHICLES A résumé of fundamental factors that must be considered in developing space communications systems.

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The need to communicate from earth to manned space stations and to other extraterrestrial bodies, coupled with the development of low-noise receivers and large-aperture ground antennas, present the communications engineer with a new set of parameters to optimize. The parameters to be evaluated—weight, volume, and reliability—must be considered as a function of frequency, power, duration and range of mission, and the year when the mission is to be accomplished.

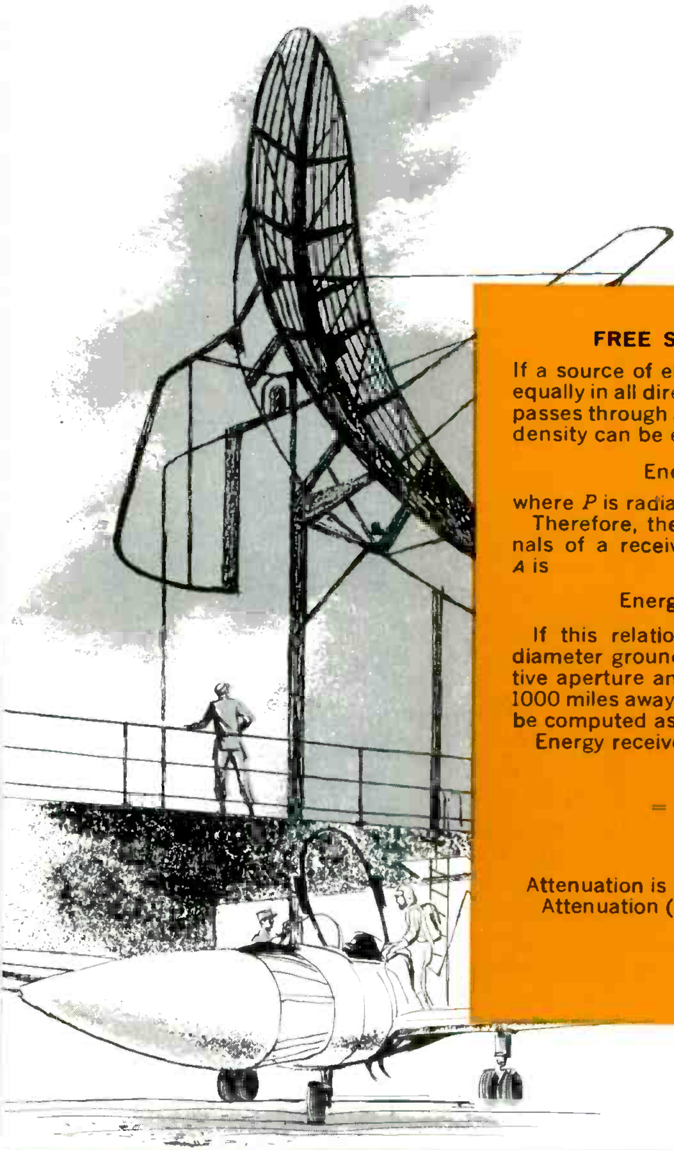
The most critical problem is receiving from the vehicle because of the inherent limitations on size, weight, and primary power for the vehicle transmitter. For the earth installation both the transmitter and the antenna can be large. Furthermore, ground station transmitted power can be increased for a fraction of the cost and effort of an increase in the space vehicle system weight.

For the space end of the communication system, the maximum antenna size is limited by the ability to support and stabilize the antenna and to point the radiated beam of energy. This, in turn, is a problem in weight; can the increased weight of a better antenna stabilization system be offset by an equivalent decrease in weight of the vehicle transmitter and power supply? These trade-offs must be evaluated by a detailed analysis.

In analyzing the communications system the logical divisions are: (1) establishing propagation parameters of the energy from the earth station to the manned space station, and (2) choosing modulation systems to transfer the necessary intelligence with the minimum of power requirements in the space vehicle.

transmission losses

Transmission losses occur from three major causes: free space attenuation, atmospheric attenuation, and attenuation due to ionization.



FREE SPACE ATTENUATION

If a source of electromagnetic energy radiates equally in all directions (isotropically), all energy passes through a sphere of radius r, and energy density can be expressed

$$\text{Energy Density} = \frac{P}{4\pi r^2}$$

where P is radiated energy.

Therefore, the energy available at the terminals of a receiving antenna of effective area A is

$$\text{Energy received} = A \times \frac{P}{4\pi r^2}$$

If this relationship is applied to a 60-foot diameter ground antenna of 50 percent effective aperture and an isotropic vehicle antenna 1000 miles away, the spreading attenuation can be computed as follows:

$$\begin{aligned}\text{Energy received } (P_r) &= A \times \frac{P_t}{4\pi r^2}\\ &= \left(\frac{\pi(30)^2}{2}\right)\left(\frac{P_t}{4\pi(1000\times 5280)^2}\right)\\ &= \frac{P_t}{(2.48\times 10^{11})}\end{aligned}$$

Attenuation is then found:

$$\begin{aligned}\text{Attenuation (db)} &= 10 \log_{10} P_t/P_r\\ &= 10 \log_{10} \frac{P_t}{(P_t/2.48\times 10^{11})}\\ &= 114 \text{ db}\end{aligned}$$

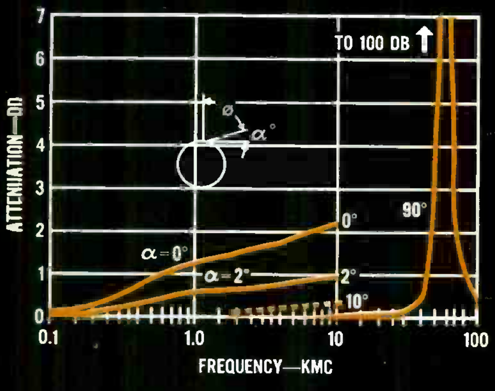


Fig. 1 Computed curves[1] of total attenuation through atmosphere due to oxygen absorption.

[1] Blake, NRL, "Radar Attenuation by Atmospheric Oxygen," URSI—Washington, May 1959.

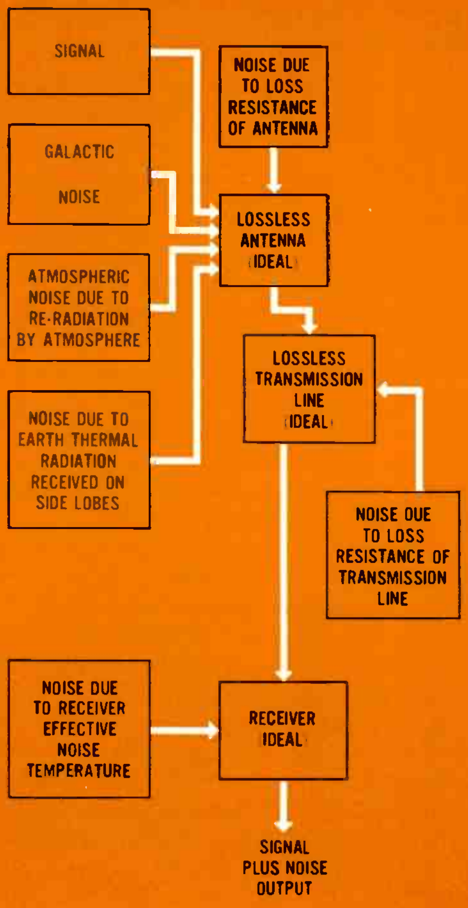
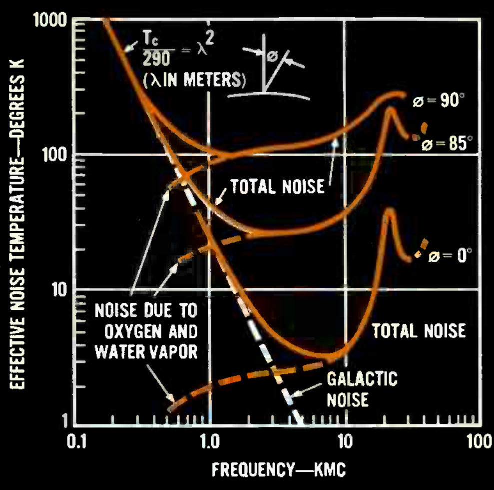


Fig. 2 (Top) Sources of noise in radio communications system.

Fig. 3 (Bottom) Sky temperatures[2] due to galaxy and atmosphere (summer conditions).

[2] Hogg, D. C. and Mumford, W. W., "The Effective Noise Temperature of the Sky," NAECON Proceedings, 1959, p. 580.



Electromagnetic energy radiated into free space spreads as the distance from the source increases, so that power density per unit area is proportional to the inverse square of the distance from the transmitter. The method of calculating free space attenuation is shown in *Free Space Attenuation*, p. 179, which shows that the free space attenuation for an isotropic vehicle antenna transmitting 1000 miles to a 60-foot-diameter ground antenna of 50 percent effective aperture is 114 decibels.

Gases in the atmosphere produce an attenuation that increases as frequency increases, as shown in Fig. 1. For frequencies above 10 kilomegacycles (not of particular interest for earth-to-space communication), molecular absorption bands produce attenuation peaks (e.g., 100 db at 60 kmc due to oxygen absorption). If the radio wave does not pass through the atmosphere at normal incidence, additional attenuation results from the greater path length. Thus, best communication is achieved for earth antenna sites at points where the space vehicle will be near the zenith for the longest period of observation. Equatorial stations are desirable for this reason.

Attenuation by ionization results from the ionized layer in the atmosphere, which is caused by solar radiation and cosmic ray bombardment. This ionospheric attenuation varies with time of year, time of day, and sunspot cycles, but it is generally less than one decibel.

Another attenuation results from the ionized layer that is created in front of a hypersonic vehicle. This attenuation exists even for space vehicles since the ionized layer that the vehicles acquire in the atmosphere is carried with them into space. The attenuation due to this layer decreases from about 0.1 db at 1 kmc to approximately 0.01 db at 10 kmc.

noise sources

A successful communications system must provide a signal at the receiver which is higher than the noise levels occurring at the receiver output. The receiver noise level consists of several parts. One source of noise is the thermal noise of receiver itself; the other sources are noise contributed by the antenna losses at their physical temperature, noise contributed by thermal radiation received on antenna sidelobes, noise contributed by the atmosphere, and galactic noise. The points of entry of these noise sources into the receiving system are shown in Fig. 2.

For analyzing the various noise contributions, noise is usually expressed in terms of *equivalent noise temperature*, so that the effect of a number of noise elements in cascade can be analyzed by summing noise temperatures. The relationship between thermal noise power and equivalent noise temperature is expressed in the equation:

$$P_n = kTB$$

where P_n is incremental available thermal noise power in watts, k is the Boltzman constant (1.38×10^{-23} joules/°K), T is absolute temperature (effective noise temperature) in degrees Kelvin, and B is bandwidth in cycles.

The galactic noise received by an earth antenna (for a typical summer day) is shown in Fig. 4, expressed in terms of effective noise temperature. Galactic noise, electrical noise that enters the earth's atmosphere from interstellar space, varies several db with antenna orientation, but the curve shown in Fig. 3 represents a good mean value.

At frequencies below one kmc, galactic noise is the limiting factor. As frequency increases, atmospheric noise increases, as shown in Fig. 3. Atmospheric noise is caused primarily by oxygen and water vapor, which absorb radiated energy from the sun. This absorption represents a dissipation of the sun's energy in the atmosphere, and this energy is reradiated over the entire electromagnetic spectrum. Atmospheric noise varies with antenna orientation, as shown in Fig. 3. Note that the atmospheric gases therefore degrade performance two ways—by attenuating the signal, and by generating noise.

Antenna noise is caused by losses in the antenna and reception of noise energy from the earth's surface on the antenna side lobes. The effective noise temperature of the antenna when pointed at the zenith is about 20 degrees K. This value is typical for most antenna systems in the 1 to 10 kmc region. However, the energy received from the earth on the lower half of the main beam when the antenna is pointed at the horizon increases the antenna effective noise temperature to about 100 degrees K.

receiver noise characteristics

The required vehicle transmitter power is largely controlled by antenna gain and ground receiver noise level. The lowest ground receiver noise temperatures, about 8 degrees K, have been achieved using maser-type r-f preamplifiers. Parametric (reactance) preamplifiers have also been constructed with noise temperatures of about 100 degrees K.

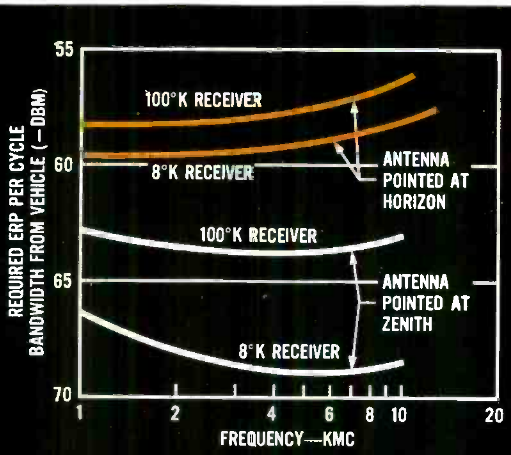
The power requirement for a typical vehicle transmitter and ground antenna combination can be determined by combining noise temperatures, converting these to an equivalent power (expressed in decibels above one milliwatt), and adding attenuation data.

The typical calculation shown in *Effective Radiated Power* (right) for a space station 1000 miles away determines the required effective radiated power (ERP is the product of transmitter power and antenna power gain) from the space vehicle. Since noise is spread uniformly through the band, the data can be normalized to a one-cycle bandwidth as shown. The effective radiated power required from a space vehicle 1000 miles away for an 8 and 100 degree K receiver is shown as a function of frequency in Fig. 4.

The values shown in Fig. 4 are for a signal-to-noise ratio of 0 db. Actually, for a reliable communications system, a carrier-to-noise power ratio of approximately 15 db would be required. Therefore, 15 db would be added to the values shown on the curve (i.e., for 100-degree receiver pointed at zenith at 1 kmc, $P_{dbm} = -63$ dbm (from curve) $+ 15$ db $= -48$ dbm.) The total power required from the space vehicle is obtained by multiplying the required bandwidth in cycles by the required power per cycle of bandwidth.

The values shown in Fig. 4 are based on the assumption that the earth receiver is looking toward a quiet portion of the sky. Considerably increased power is necessary if the trajectory of the space vehicle causes a high noise source, such as the sun, to come within the field of the main beam of the ground-based receiving antenna.

The effective noise temperature of three possible vehicle receiver types is shown in Fig. 5. While the maser shows the lowest effective noise temperature, typical maser amplifier weighs 250 pounds, as compared to 10 pounds for a parametric amplifier, and 4 ounces for a crystal receiver. These weights include only the r-f front end of the receiver.



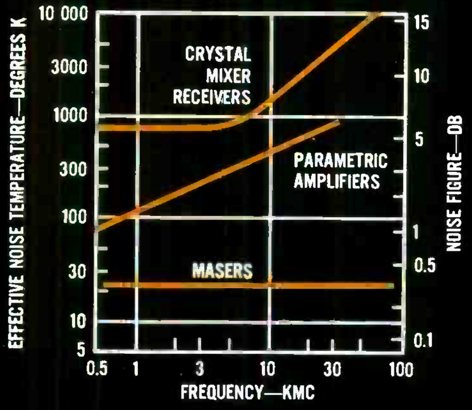


Fig. 4 (Top) Computed vehicle required effective radiated power (for signal-to-noise ratio of 0 db and 1000 miles distance).

Fig. 5 (Bottom) Effective noise temperatures[3] are shown for three vehicle receiver types.

[3] *Varactors*, February 1959.

EFFECTIVE RADIATED POWER

The effective radiated power required for a zero db signal-to-noise ratio (signal to equal noise) for a vehicle 1000 miles from earth transmitting to a parametric amplifier receiver can be found as follows:

The total noise temperature is the sum of:

100° (parametric amplifier equivalent noise temperature)
20° (receiver antenna equivalent noise temperature)
28° (sky noise at 1 kmc with antenna pointed at zenith from Fig. 3)
148°

Converting the total equivalent noise temperature to power:

$P_n = (1.38 \times 10^{-23})(148) = 2.04 \times 10^{-21}$ watts/cycle bandwidth.

Since attenuation is expressed in decibels, power can be more conveniently handled when expressed in its logarithmic equivalent, dbw or dbm. (dbw is in terms of watts, dbm in terms of milliwatts). Therefore, the noise power is:

$$\begin{aligned} P_{dbw} &= 10 \log_{10} 2.04 \times 10^{-2} \\ &= 3.08 - 210 \\ &= -207 \text{ dbw/cycle} \end{aligned}$$

To convert to dbm, multiply by 1000 (add 30 db):

$$\begin{aligned} P_{dbm} &= -207 + 30 \\ &= -177 \text{ dbm/cycle} \end{aligned}$$

Assuming the same conditions for vehicle and ground antenna outlined in *Free Space Attenuation* (p. 179) attenuation will be 114 db. Attenuation through the atmosphere (Fig. 1) for an antenna pointed at zenith can be neglected. Therefore, total required radiated power is:

-177 dbm $+ 114 = -63$ dbm/cycle (See Fig. 4).

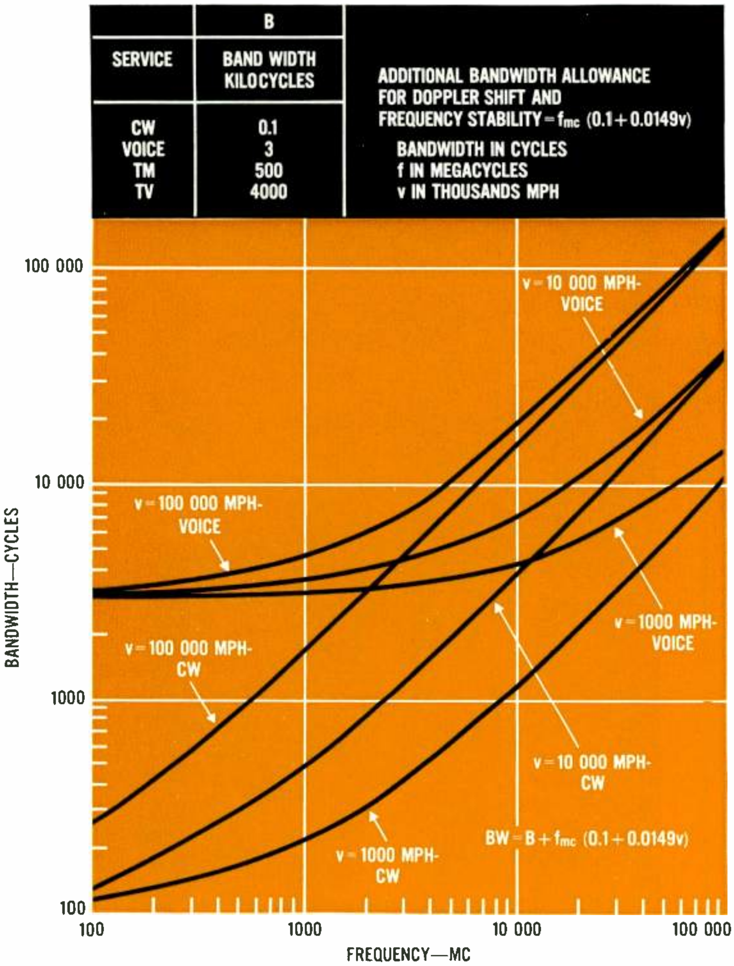


Fig. 6 Computed bandwidth allowance for frequency stability and Doppler shift.

For receiving from the ground transmitter with a vehicle receiver using a crystal mixer, the 750 degree K effective noise temperature is high enough to swamp the noise contributions of the antenna and galactic noise. Assuming the previous set of conditions (space vehicle 1000 miles away, and 114 db space attenuation), the required earth ERP for a 750 degree K space receiver is about −55 dbm per cycle (compared to −63 dbm ERP calculated for vehicle).

The required signal-to-noise ratio is dependent upon the modulation system and information rate required. For example, for continuous wave (CW) operation with speed of about 25 words per minute and a human operator, satisfactory results can be obtained with a bandwidth of 100 cycles and a signal-to-noise ratio of 0 to −10 db. However, for automatic systems in which the transmission rate is the equivalent of 100 five-letter word groups per minute, the required bandwidth is about 1000 cycles with a signal-to-noise ratio of approximately 15 db.

Other typical requirements are 3 kc for voice, and 4000 kc for television.

Doppler effects and bandwidth

In addition to the bandwidth requirements for transmission of intelligence, additional bandwidth is required in either the ground or vehicle receiver to accommodate the Doppler shift of transmitted frequency and allow for frequency instability in the transmitter and receiver.

Instability effects can be minimized by such techniques as phase-lock receivers to lock upon the transmitter carrier frequency. The frequency stability that can be achieved with a crystal-controlled transmitter in the vehicle is a minimum of one part in 10^7. For airborne equipment, stabilities of one part in 10^9 have been achieved on a production basis.

The Doppler shift is proportional to the carrier frequency and to the velocity of the vehicle.

Since space vehicle velocity can be predicted fairly accurately, the frequency of the ground station can be programmed to the vehicle carrier frequency as modified by the Doppler effect.

The additional bandwidth required to allow for frequency instability and Doppler shift can be expressed as a function of carrier frequency and vehicle velocity:

$$B = f\ (0.1 + 0.0149\ v)$$

where B is additional bandwidth in cycles, f is carrier frequency in megacycles, and v is vehicle velocity in thousands of miles per hour. This additional bandwidth allowance must be added to the intelligence bandwidth required (e.g., 3 kilocycles for voice) to obtain total bandwidth requirements. Total bandwidth requirements for CW, voice and TV are shown in Fig. 6.

typical system

The same parameters are involved for transmission from earth to vehicle or from vehicle to earth. The vehicle receiver can be stabilized to approximately one part in 10^7, and the carrier frequency of the ground transmitter can be programmed to take into account the Doppler shift of frequency to the vehicle. Adjusting the frequency of the ground transmitter in accordance with the programmed velocity of the space vehicle eliminates the need for tuning adjustments in the vehicle receiver. For a 5000-mile-per-hour velocity away from earth of the space vehicle and a one-kmc transmitting frequency, the ground transmitter could be adjusted to be approximately 10 kc higher in frequency than the vehicle receiver. Using this approach, the vehicle receiver can be a fixed-frequency receiver considerably less sophisticated than necessary for an unvarying ground transmitter frequency.

For a 5000-mph vehicle using the allowances shown in Fig. 6, and a frequency of one kmc, bandwidths of 450 cycles would be needed for CW, 3000 for voice and 4 megacycles for TV. For an isotropic space antenna on space vehicles 1000 miles from a 60-foot diameter ground-based antenna, the attenuation was shown to be 114 db. The power required from the earth transmitter can be calculated to be about 0.2 mw for code with a 100-cycle (450 cycles including tolerance) intelligence bandwidth and 1.3 mw for voice with 3000 cycles intelligence bandwidth and 2 watts for TV type transmission with a four-mc intelligence bandwidth. These data are based on a 1000-degree Kelvin receiver temperature in the vehicle and a 20-db signal-to-noise ratio at the receiver (values typical of a crystal-type receiver).

For transmission from the vehicle to the earth, the required power is decreased by the ratio of the noise temperature of the vehicle receiving system to the noise temperature of the earth receiving system. A noise temperature of about 20 degrees K should be achieved with a ground-based maser. The system noise temperature would be about 68°K (See *Effective Radiated Power*, p. 181). The power requirements of the vehicle transmitter therefore are reduced by a factor of 15 below those required for the earth transmitter. Thus, for a 20-db signal-to-noise ratio, the vehicle transmitter would require 0.01 mw for code, 0.08 mw for voice, and 0.13 watt for TV. These values are for a 60-foot diameter earth antenna and isotropic vehicle antenna and a frequency of one kmc; if a directive antenna is used on the vehicle or a larger than 60-foot antenna is used on the earth, the power requirements are reduced directly as the ratio of antenna gains.

antennas

In a communication system the antennas convert the electromagnetic energy from a guided mode on a transmission line to an unguided free space propagation mode. In performing this function, the important characteristics are the antenna directivity (effectiveness of concentrating the energy in a narrow sector), the reflection losses, the dissipative losses, and (in an aperture-type antenna) the spillover losses due to part of the energy from the primary feed not being collimated (beamed) by the reflector. The ratio of the net energy received at the terminals of the antenna compared with that which would be received at the terminals of an antenna receiving equally well from all directions (isotropic antenna) is defined as antenna gain.

The dipole antenna has a gain of 1.5 compared to an isotropic antenna. (The most common form of dipole antenna is a conductor of one-half wavelength, separated at the center by an insulator). For lossless, uniformly illuminated apertures, gain equals $4\pi A/\lambda^2$ where A is the effective area of the aperture (the portion of plane surface near the antenna perpendicular to direction of maximum radiation through which the major part of the radiation passes) and λ is the operating wavelength expressed in consistent units.

The most common antenna used for the ground and for satellite communication is the paraboloid, which collimates the non-directional radiation of the primary feed and provides the area necessary to concentrate the radiated energy in a small sector. The paraboloidal surface is broadband in its collimating action. For example, a polished paraboloidal reflector will collimate acoustic energy at audio frequencies as well as it does electromagnetic energy at radio, infrared, and optical frequencies.

On the vehicle, the antenna may be one of two types. A nondirectional antenna, such as a monopole on a metal plane, has low gain and is relatively simple. Typically, a nondirectional antenna for the L-band region has an operating bandwidth of at least 40 percent—two orders of magnitude larger than the bandwidth required for even the broadest modulation system. For flush-mounted antennas reduced to a minimum size, such as a cavity-backed slot, bandwidth is reduced to about one percent, depending on the amount of size reduction. Flush-mounted antennas are essential only in an atmospheric environment at high Mach numbers. A monopole would be a more logical choice for space vehicles because of the higher efficiency and lighter weight. A stub for L-band would be about 2 inches long by 0.25 inch in diameter. The diameter need be only large enough to provide the necessary mechanical strength.

The other alternative, a directional antenna, can be of two general types—an end fire or broadside type. Directional antennas can provide gains of 20 db or more compared with non-directional antennas. Effective areas typically are between 50 and 70 percent of the physical projected area in the direction of the maximum of radiation. An exception to this rule of relationship between effective area and physical area is found in the end-fire antenna. Antennas of this type are commonly seen as home television receiving antennas. These antennas have a radiating element plus directive elements in front of the radiating element which increase the directivity and gain of the antenna system without changing the frontal physical area. However, it is not possible to place other structures in the immediate area of the antenna because the field extent is approximately as great in the virtual apertures as it would be in a physical aperture of equal gain. Typically, gains of the order of 16 to 20 db can be achieved by using end fire arrays of this type.

On the other hand, for a broadside aperture, whether it be a paraboloid or an array, it is seen from the relationship, $4\pi A/\lambda^2$ (or, expressed another way, π times the linear dimensions in half-wave lengths), that an antenna 10 half-wave lengths in height by 10 half-wave lengths in width has a gain in excess of 20 db. This antenna then would be five feet square as compared with the 50-foot long antenna necessary for an end fire array. As a result of these considerations, it is seen that an end fire array is quite feasible for achieving relatively low gains and has a desirable characteristic of being physically small in the broadside dimension. On the other hand, the broadside array or broadside aperture of the paraboloidal type has the advantage of being shallow and of being broad band.

trends in communication equipment for space systems

The first lunar probes have used transistorized fm transmitters with 300 mw output at 100 mc, have 50 percent overall efficiency, and have a typical weight of one pound in a volume of 20 cubic inches. The frequency stability is such that 20 cps bandwidth is accountable to carrier noise and 3000 cps bandwidth to information. Phase lock receivers for these probes have also been transistorized, and have a 7.5-kc lockup range, —130 dbm sensitivity, and one-quarter watt power drain.

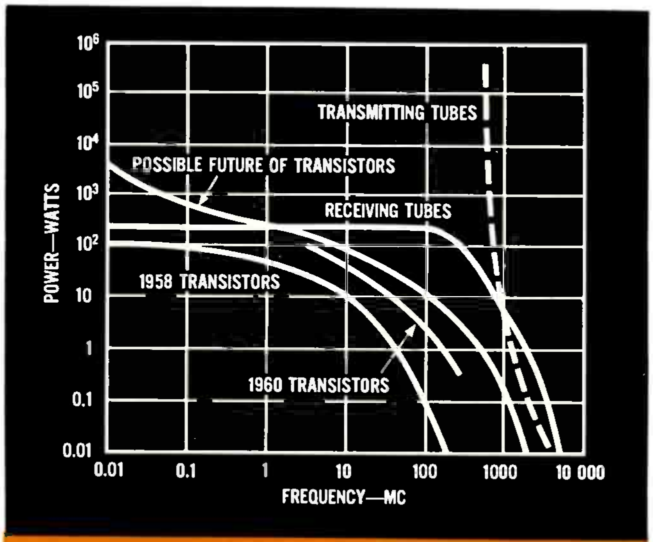
While 300 milliwatts radiated isotropically at 100 mc to a large earth antenna gives adequate telemetry and communication power to 4-kc bandwidth, this is inadequate for wider information bandwidths. Furthermore, as more radiating vehicles orbit the earth, the greater number of channels available at microwave frequencies makes use of these frequencies mandatory to handle the communications traffic without interference.

Transmitter power and weight will also increase as more information bandwidth is required. For a given communication system, the transmitter power required will be proportional to this bandwidth. In fact, the recent *Explorer VI* has gone to a five-watt digital channel to permit intermittent transmitter operation on the many telemetery channels required. The extreme in this process may be a

3-mc television band requiring 300 watts of transmitter power. Thus, future communication links will increase in power and weight and will be time-shared digital channels.

The present and predicted trends in transistors and tubes, shown in Fig. 7, provide means for estimating the weight and input power required. With present experimental transistors, it is possible to get to the one-kmc frequency required. Future transistors may be satisfactory for narrow band telemeter links.

A vehicle receiver includes the following major units: the r-f front end, the i-f and video section, and the power supplies for these units. As presently constituted, the principal elements of the r-f front end are low-loss resonant circuits that imply metallic cavities of one form or another, a crystal mixer, and a local oscillator. An alternative is to use one of the low-noise miniature ceramic triodes as an r-f amplifier for the front end of the receiver. The i-f and video amplifiers of the receiver are presently available as semiconductor circuits using transistors and miniaturized components, and the power supply includes batteries and solar cells to provide the dc voltages necessary for the r-f, i-f, and video portions of the receiver. The present disadvantage of the semiconductors in receiver i-f amplifiers is the high noise figure (approximately 10 db), as compared with 1 to 1½ db for the tube type i-f amplifier. The noise figure or noise temperature of an amplifier is determined primarily by the input stage if this stage has sufficiently large gain. Thus, an i-f amplifier can use a vacuum tube as the first stage to reduce the noise figure to a value comparable to an all electron tube device. A further disadvantage of the solid-state device is the action on them by high-energy radiation, such as is present in the Van Allen belt.



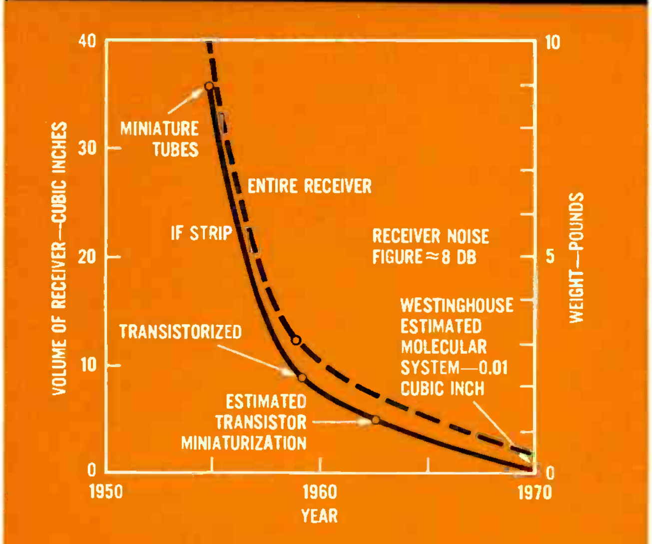


Fig. 7 (Top) Trends in tubes and transistors.

Fig. 8 (Bottom) These curves show the estimated future reductions in receiver volume and weight.

The predicted weight and volume of i-f strips with characteristics suitable for wide band (four megacycles) operation are shown in Fig. 8. Transistorized i-f strips are available with a 10-db noise figure in 9 cubic inches of volume. It is estimated that by 1963 these will be further miniaturized and the volume density relationship improved to the point where the i-f strip takes no more than five cubic inches. Ultimately, by 1970 or 1975, the i-f strips can probably be built using molecular engineering principles. In a molecular system, the i-f strips should have a volume less than 0.01 cubic inch.

The volume of the r-f portion of the receiver will in all probability depend more upon the frequency of operation than upon the advance in techniques. The losses in the r-f circuit (cavity or coaxial resonator) depend upon the ratio of surface area to volume. The cavity size for one kmc (wavelength of 12 inches) might be approximately four cubic inches, decreasing to about 1¼ cubic inches at 3 kmc. The cavity weight will be no more than 0.04 pound. Miniaturization techniques can reduce these sizes.

Power consumption of the receiver will vary from about 1.5 watts for the transistorized version to about 0.15 watt for the molecular system.

Examining the curve of volume required (Fig. 8) shows that as molecular construction comes into use, the limiting factor on the volume of the system will be the r-f front end and the antenna size. Ultimately, the volume of the entire receiver at L band (390 to 1550 mc) may approach about one cubic inch without the antenna.

Of the low noise r-f amplifiers under development at Westinghouse, the parametric amplifier is expected to occupy seven cubic inches and weigh about eight pounds and be available in 1961 with a 1½ db noise figure. The Esaki or tunnel diode appears to offer even more potential, and it is anticipated that an amplifier can be made with a volume of one cubic inch and a weight under one-half pound—such amplifiers should be available by 1963.

Required powers for different intelligence bandwidths are relatively small and well within the state of the art—improvements that must be made in the coming decade are improved reliability, reduced power consumption, and reduced weight and size. All four of these areas can be improved with the molecular engineering approach to the design of electronic systems; the resulting reduction in size, weight, and power consumption will allow increases in reliability even greater than the inherent reliability of the molecular systems by permitting the use of several redundant systems.

HIGH-ENERGY ELECTRIC ARC HEATER DEVELOPED A new device for studying missile re-entry problems.

A machine with the potential capability to supply a stream of gas at temperatures as high as 20 000 degrees F and pressures as great as 15 000 psi has been devised by Westinghouse scientists and engineers. The machine, an electric arc heater, can operate for sustained periods of time at an extremely low level of gas contamination.

The arc heater was developed specifically for use as a high-temperature air supply for the study of missile re-entry problems. However, the device also holds promise as a chemical synthesizer and as a furnace for processing metals with ultra-high melting points.

As a chemical synthesizer, the arc heater could supply the high temperatures necessary for inducing difficult chemical reactions. Nitrogen and oxygen, for example, could be combined in the heat chamber to form nitrous oxide, a compound widely used in chemical processing. A synthesizer of this type could also find application in processing petroleum products.

The unit's potentialities as a furnace might make a number of refractory metals available in ingot form for the first time. Normally used in powder form, metals such as tungsten are difficult to process because of high melting points.

In all of these applications, the success of the arc heater is greatly dependent upon a low level of contamination. One of the major problems involved in units under development during the past two years is that electrodes and walls of the chamber burn and thus contribute impurities amounting to as much as 10 percent of the mass of the gas flowing through the system.

The newly developed unit has a maximum contamination level of 0.2 percent. Still further reductions in this level are contemplated.

basic concept

The basic concept for the new arc heater was proposed by a scientist at the research laboratories. The concept involved a scheme in which an electric arc, dissipating megawatts of electric power, could be maintained for prolonged periods of time to continuously transfer thermal energy to a gas passing through the arc. This is done virtually without erosion of the electrodes, thus all but eliminating this cause of gas contamination.

Main components of the equipment are an arc chamber and a power supply (Fig. 1). The arc chamber consists of a heavy steel envelope in which are housed the electrodes, a magnetic arc-rotator coil, a nozzle, and a variety of auxiliary mechanisms. The power supply for the alternating-current system includes reactors, transformers, switchgear and control circuitry.

A key to the performance of the new machine lies in the design of the two electrodes that form the terminals for the arc. The electrodes are hollow doughnut-shaped rings, placed horizontally, one directly above the other. Water is pumped through the rings for cooling.

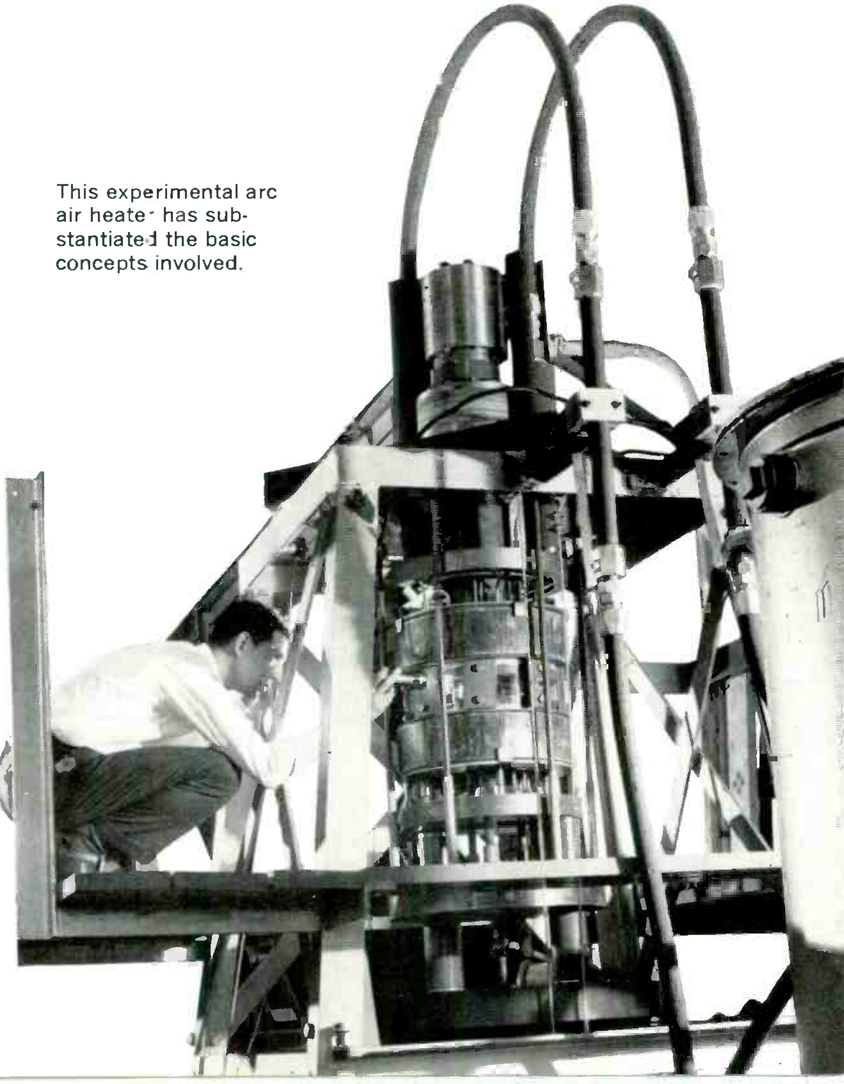
The electric arc is started by drawing it across the gap between the two rings. The arc is then made to rotate around the gap at a high rate of speed. This rotation is caused by the magnetic field from dc coils, which are arranged around the outside of the heat chamber. Arc rotation, combined with water-cooling, prevents the electrodes from heating to a point beyond the structural endurance of the material. Repeated tests of the unit have left the electrodes undamaged, indicating a lack of contamination from this source.

The working fluid, such as air or nitrogen, enters the arc chamber and passes into the arc through openings near a water-cooled copper heat shield. The water-cooled heat shield, which can withstand arc temperatures well above 10 000 degrees F without eroding, protects the walls of the arc chamber. After leaving the arc, the fluid passes through a water-cooled nozzle.

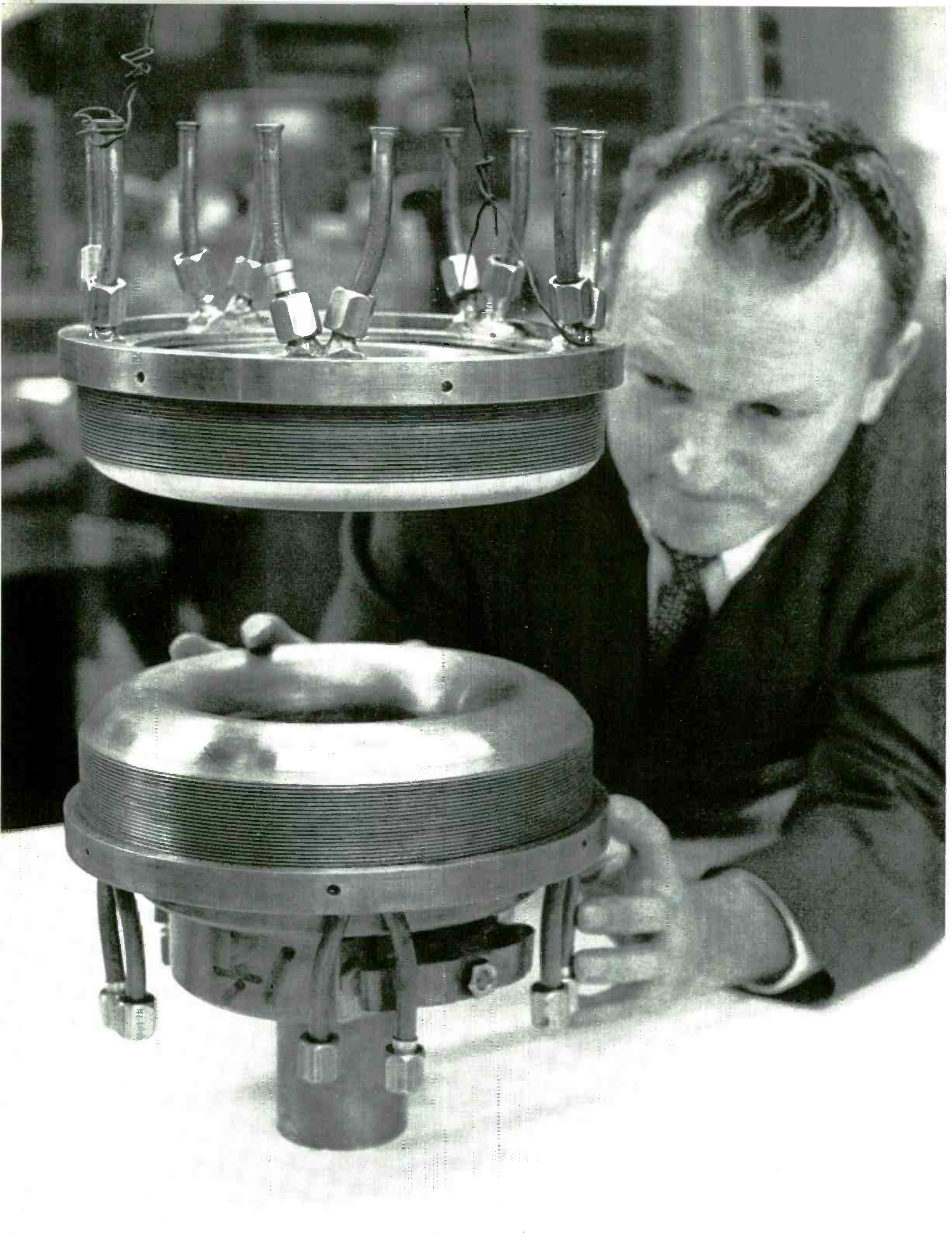
The arc heater is believed to have a uniform temperature "profile" within the heat chamber. This means that temperature at the entrance to the nozzle is constant.

prototype performance

More than 50 tests of the prototype arc heater have been successfully completed, and testing will be continued until the design limits of the equipment have been verified.



This experimental arc air heater has substantiated the basic concepts involved.



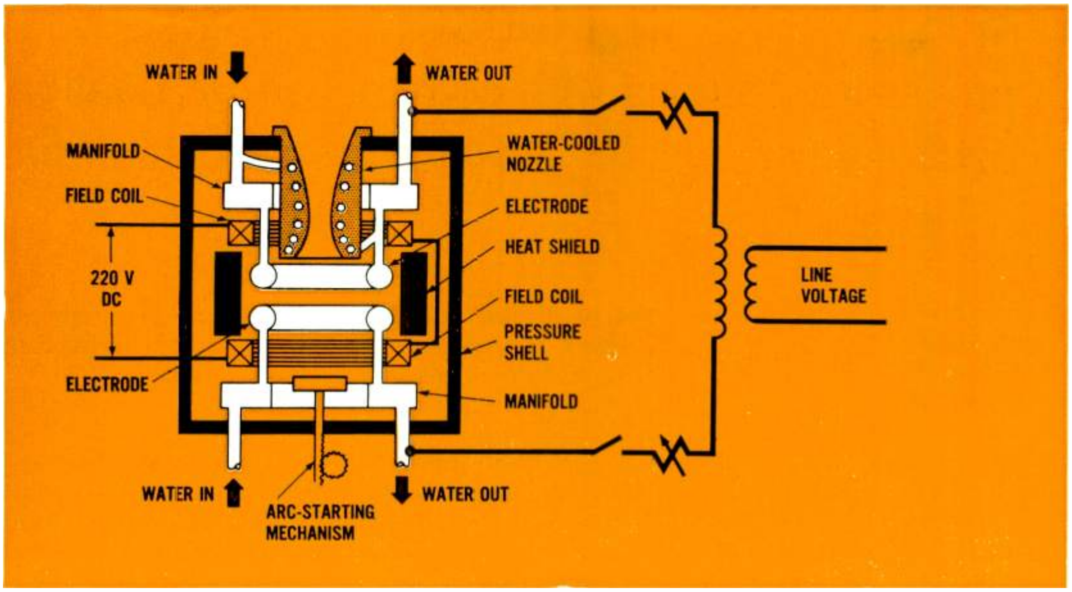


Photo (Left) A key to the performance of the new arc heater lies in the design of the two electrodes, shown here, which form the terminals for the arc.

Fig. 1 This simplified schematic cutaway shows the principal elements of the new device.

Table I EXPECTED AREA OF ARC AIR HEATER OPERATION

Pressure—Psi	10 000 to 15 000
Gas Temperature—°R	10 000 to 20 000
Arc Current—Amperes	30 000
Input Voltage—Volts	13 800

Table II SINGLE-PHASE ARC AIR HEATER

DESIGN PERFORMANCE

Design Pressure—Psi	3000
Design Air Flow—Lbs/Sec	1.2
Enthalpy at 3000 Psi—Btu/Lb	2000
Maximum Contamination at Gas Stream	0.2%
Test Duration	10 minutes out of each 2 hour period
Working Fluid	Air or Nitrogen
Maximum Current Input—Amperes	10 000
Input Voltage—Volts	6900

Table III EXPERIMENTAL ARC AIR HEATER

TEST MILESTONES

Data Point	Highest Pressure Tested	Highest Power Tested
Pressure of Chamber	730 Psia	265 Psia
First Law Enthalpy	No Analysis	4670 Btu/Lb
Arc Voltage	364	549
Arc Current	1620	5046
Flow—Lbs/Sec	0.687	0.186
Working Fluid	Nitrogen	Air
Power/Mass Flow—Mw-Sec/Lb	0.86	9.45

The prototype model has been operated with a power input of 1700 kilowatts, and a high of 30 000 kilowatts is planned. The temperature into the nozzle has been maintained at 10 000 degrees—approximately the surface temperature of the sun.

Flow from the nozzle of the unit has reached a sonic velocity of 3400 miles per hour. Velocities over ten times the speed of sound can be expected when the gases are expanded with a hypersonic exhaust nozzle.

The prototype arc heater was designed to accommodate a 1.2-pound-per-second flow of either air or nitrogen. The unit should be able to supply gas at 1500 psi with a constant enthalpy of more than 2000 Btu per pound for as long as 10 minutes without damage or measurable gas contamination. The efficiency of heat transfer to the gas is in excess of 50 percent.

So far, the highest pressure at which tests have been conducted is 730 psi. Other tests with a power input of 549 volts and 5046 amps (9450 kilowatts per pound per second) have raised the enthalpy of air passing through the chamber 4670 Btu per pound.

ready for wind tunnels

A variation of the prototype model is now ready for use in the aircraft industry. Applied to a wind tunnel, the arc heater can help duplicate the extreme conditions met by missiles and other future space craft upon re-entry into the earth's atmosphere. The arc heater should be capable of operating 10 minutes of each two-hour period. Other performance data are listed in Table II.

Further advances in arc-heater technology should permit the development of a device suitable for application in the metal, chemical and petroleum industries within one or two years. Such a device could be used wherever gases at extremely high temperature and pressure are needed. Presently, these industries have no practical means for producing temperatures of 10 000 to 20 000 degrees F in gases at high pressure over a sustained period of time.

GAS TURBINE APPLICATIONS IN INDUSTRY Inherent advantages in certain processes, coupled with competitive installation and operating costs, are establishing an important position for gas turbines in industry.

D. F. BRUCE, *Section Manager*
Industrial Gas Turbine Engineering
Westinghouse Electric Corporation
Philadelphia, Pennsylvania

The gas turbine has inherent advantages as an industrial power plant that suit it admirably to a number of applications. Paramount among these advantages are its ability to use many different fuels (including the waste gases of some processes), its delivery of large amounts of thermal energy in the exhaust gas at usable temperature and pressure, and its ability to operate in a range of speeds and shaft powers. In addition, the exhaust gas contains about 80 percent of the oxygen of the intake air, so it can be used as preheated combustion air for a boiler, as the energy supply for a process heat exchanger, and in other ways. These factors, coupled with competitive installation and operating costs, make gas turbines extremely attractive for many industrial uses.

The feasibility of using gas turbines in preference to other equipment can be determined by process studies that take into account the heat and power output of the gas turbine and the heat and power requirements of the application. Since requirements vary widely, the choice depends to a great extent on commercial availability of gas turbines with suitable performance characteristics. Fortunately, an increasingly wide selection of gas turbines is available.

In general, industrial gas-turbine power plants supply compressed air, hot gases, mechanical power, or various combinations of these outputs. To simplify discussion, they can be divided into four major application categories: gasifiers, integrated pressurized process units, extraction units, and drives (generator or mechanical).

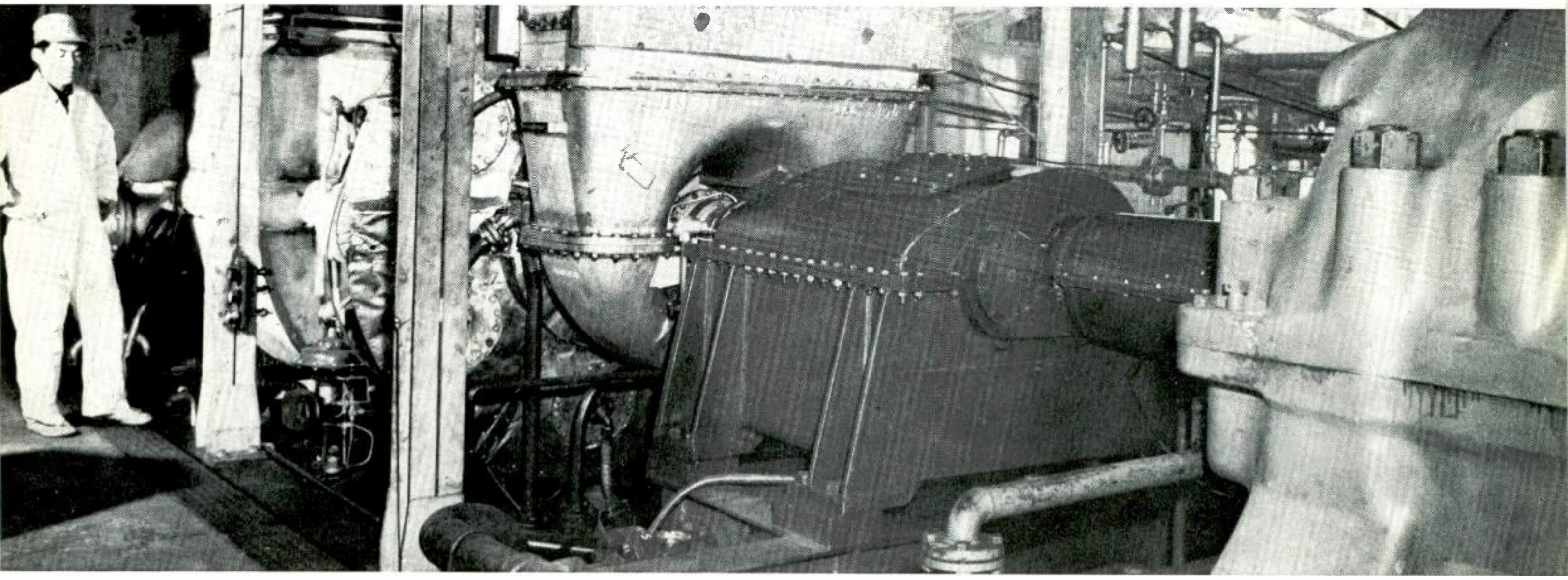
gasifiers

The gas-turbine gasifier supplies large amounts of hot exhaust gases at moderate pressure—up to 28 psia—and at 700 to 1000 degrees F. It is particularly useful with processes that require hot gas with a large amount of the air's oxygen still unused.

A gas-turbine gasifier usually consists of a single-shaft gas turbine modified to deliver a pressurized exhaust. The turbine component drives its air compressor, and part or all of the balance of the energy output is delivered to the process in the form of pressurized high-temperature exhaust gas. The machine can be arranged to deliver mechanical power, to be self-sustaining, or to require boost power; the configuration is determined by such factors as process back pressure, component efficiencies, and metallurgical limitations.

The thermodynamic considerations involved are illustrated in Fig. 1a. Evaluating these with the metallurgical factors that govern permissible operating temperature establishes the limitations of the system.

The air and hot gas circuit of a butadiene process using



Compact installations such as this are typical of industrial gas turbines. This one powers an oil refinery compressor.

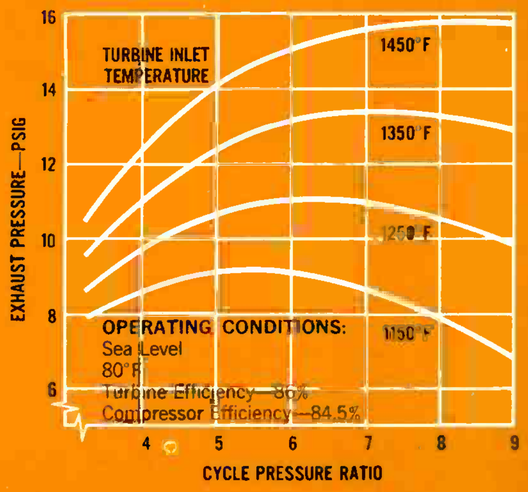
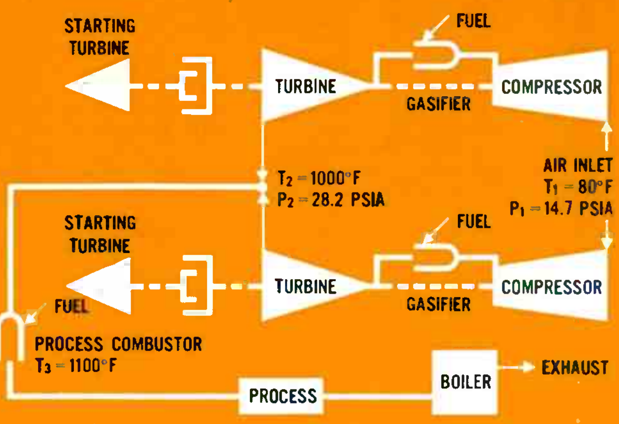


Fig. 1a Exhaust pressure and cycle pressure ratio relationships, with turbine-inlet temperature parameters, for a gas-turbine gasifier.



Conditions Assumed:

Compressor inlet temperature (t_1)—80 degrees F

Required gas temperature to process (t_3)—1100 degrees F

Heat losses—negligible

Specific heat of air (c_p)—0.25 Btu/lb

${}_1h_3$ (fuel energy required for gas temperature rise between compressor inlet and process inlet) $= c_p(t_3 - t_1) = 255$ Btu/lb of gas.

Fig. 1b Schematic diagram of a process using two gas-turbine gasifiers with a common discharge.

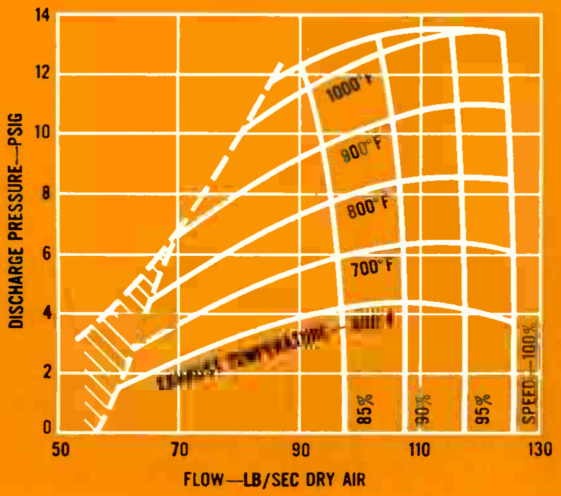


Fig. 1c Gasifier discharge pressure and flow.

two gas-turbine gasifiers is illustrated schematically in Fig. 1b. Each compressor takes air from the atmosphere, and a combuster heats its discharge to the temperature required for the turbine portion to supply mechanical energy equal to that absorbed by the compressor. This temperature, of course, is influenced by the back pressure imposed by the resistance of the process. The characteristics of the gasifiers are shown in Fig. 1c

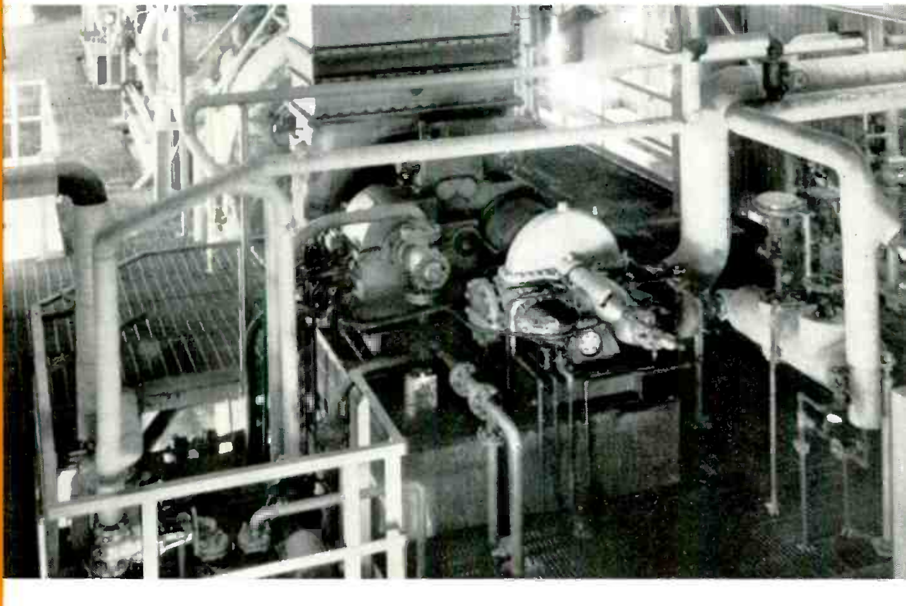
The catalyst bed in the process illustrated is in the exhaust line, so the gasifier must deliver its exhaust at a pressure sufficient to overcome the resistance of the fixed bed, associated piping, and any attached heat-recovery apparatus. The components in this installation are so arranged as to provide a self-sustaining machine; fuel flow is adjusted automatically by a governor to maintain gasifier speed. The process absorbs heat, so air at a temperature exceeding 1000 degrees F must be delivered periodically to the catalyst bed to heat and regenerate the bed.

This application is particularly interesting from a thermodynamic standpoint because of its fuel requirements. The fuel energy required for a given air temperature rise above atmospheric temperature is independent of the path followed on a temperature-entropy diagram. Therefore, the required fuel energy can be determined as shown in Fig. 1b.

Supplying a gas temperature of 1100 degrees F to the process requires 255 Btu per pound of gas delivered. This amount of energy is required regardless of the back pressure. Therefore, at lower back pressures the process combustor would be required to burn additional fuel because the discharge temperature of the gasifier's turbine decreases as back pressure decreases. The total fuel required remains the same, however, whether it be burned in the combustor of the gasifier or in the process combustor.

The advantages of the gas turbine's rejection of usable heat can be demonstrated by comparing the system de-

Two gas turbines in this catalytic refinery installation drive process air blowers. Their exhaust gases heat boiler feedwater and serve as preheated boiler combustion air.



scribed above with other available systems for supplying hot gases. One such system, illustrated in Fig. 2, is a separately driven compressor with a combustor to raise the gas temperature to the level required by the process. This system requires a fuel energy of 365.4 Btu per pound of gas to provide a heat output equal to that of the gas-turbine gasifier.

The ratio of the fuel required by the two configurations for the conditions cited is 1.43 to 1; that is, the separately driven compressor configuration requires 43 percent more fuel per pound of gas delivered to the process. The gas-turbine gasifier would save $230 000 a year in a process requiring 240 pounds of air a second, assuming a fuel cost of 30 cents per million Btu.

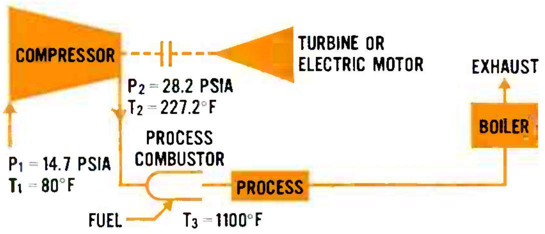
In addition, if the exhaust pressure required is low, the full capability of the gas-turbine power plant can be utilized by arranging it to produce mechanical power as well as hot exhaust gases.

integrated pressurized process units

The gas-turbine integrated pressurized process unit supplies large volumes of air to a process, at pressures of three to eight atmospheres and higher, and it also may produce varying amounts of power according to the system arrangement and pressure drops.

In a typical application (Fig. 3a), the compressor takes air from the atmosphere and delivers it at the required pressure. (In the type of installation illustrated, an intercooler between compressor casings would normally be used for pressure ratios exceeding 6 to 1.) The compressor discharge goes through the process and then to the turbine.

The performance characteristics of an actual installation of this type are illustrated in Fig. 3b. The unit, a rather



Conditions Assumed:

Compressor inlet temperature (t_1)—80 degrees F (539.6 degrees abs.)

Compressor outlet temperature (t_2)—227.2 degrees F

Required gas temperature to process (t_3)—1100 degrees F

Heat losses—negligible

Ambient air pressure (p_1)—14.7 psia

Compressor outlet pressure (p_2)—28.2 psia

Specific heat of air (C_p)—0.25 Btu/lb

Molecular gas constant (K)—1.4

Compressor adiabatic efficiency (η_1)—75 percent

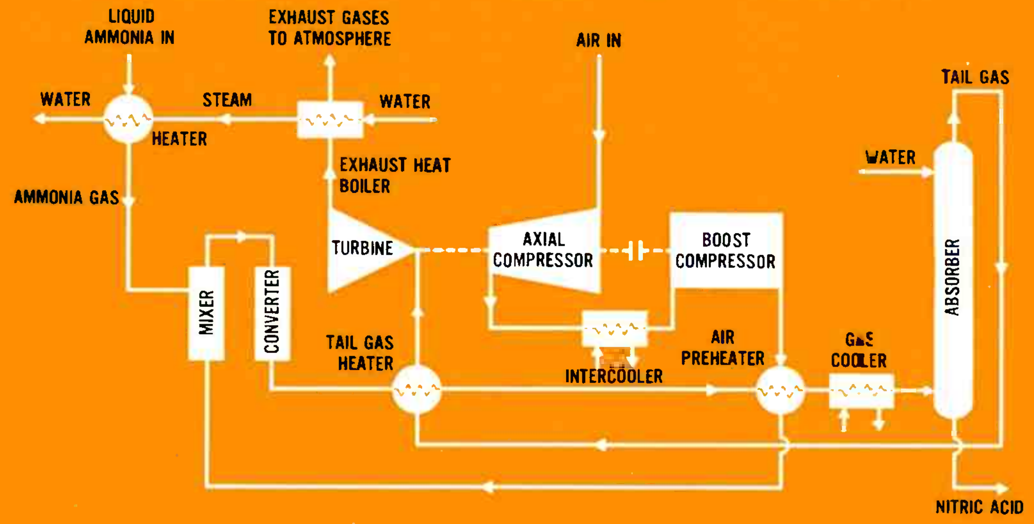
Compressor drive thermodynamic efficiency (η_2)—25 percent

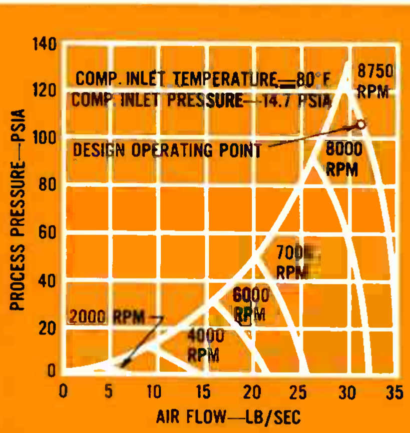
1. ${}_1h_2$ (fuel energy required for gas temperature rise between compressor inlet and compressor outlet) =

$$\frac{C_p t_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{K-1}{K}}-1\right]}{\eta_1} = 36.8 \text{ Btu/lb of gas.}$$

2. Energy required by compressor drive $= \frac{{}_1h_2}{\eta_2} = 147.2$ Btu/lb of gas.
3. ${}_2h_3$ (fuel energy required for gas temperature rise between compressor outlet and process inlet) = $C_p\,(t_3 - t_2) = 218.2$ Btu/lb of gas.
4. Total fuel energy required $= 147.2 + 218.2 = 365.4$ Btu/lb of gas.

Fig. 2 An alternative system for supplying hot gas to a process. This combination of combustor and separately driven compressor is less efficient than the gas-turbine gasifier.





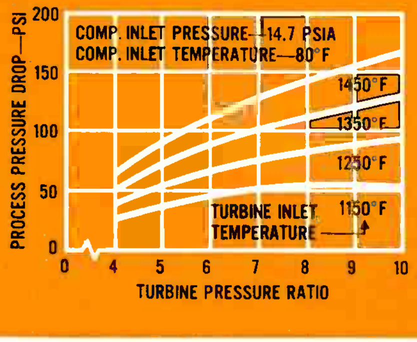


Fig. 3a (Top) Schematic diagram of a gas-turbine integrated pressurized process unit for nitric acid production.

Fig. 3b (Top right) Performance characteristics of a gas-turbine integrated pressurized process.

Fig. 3c (Bottom right) Pressure and temperature relationships in a gas-turbine integrated pressurized process.

small one, produces nitric acid. Its gas turbine is started by a steam turbine. The compressor discharge is delivered to the process at 120 psia and 450 degrees F. The process discharge is heated to 1250 degrees F in a catalytic combustor, passed through the turbine, and routed to a waste-heat boiler. Once started, the process is self-sustaining. Air flow to the process can be varied approximately 30 percent by controlling the gas turbine's speed.

Pressure and temperature relationships in such a system are shown in Fig. 3c.

Air is usually discharged from the process at elevated temperature and appreciable pressure. Fuel required by the gas turbine can be added before or after the process, depending on process requirements. Metallurgical considerations limit the maximum permissible temperature of the gas delivered to the turbine component. The work balance between the compressor and the turbine depends largely on the pressure loss of the process; the balance can either be absorbed or made up as required.

A dust load up to 0.01 grains per cubic foot, with 95 percent of the particles less than 20 microns in size and no particles larger than 100 microns, can be carried without serious turbine erosion. (This assumes that the chemical characteristics of any carryover from the process are not detrimental to the turbine.) Larger particles or heavier load could be tolerated but probably would increase maintenance costs through more frequent replacement of turbine blading.

extraction units

Many processes require large amounts of compressed air, at pressures of 15 to 40 psig, that for various reasons is not directly returnable to the gas-turbine cycle. This need has led to development of extraction gas turbines with stable pressure-flow characteristics from zero to maximum flow.

The gas-turbine cycle of an extraction unit designed to furnish air for blast-furnace blowing is illustrated in Fig. 4a. The air discharge from the compressor is split; approximately one-third is available to the process and the balance is routed through a regenerator, where it is heated by exhaust gas. The heated air then goes to a single external combustor fired with blast-furnace gas compressed to combustor pressure by a direct-driven axial-flow compressor. The combustor discharge passes through the turbine, and the turbine exhaust goes through the regenerator.

This gas turbine is cranked by a steam turbine and assisted to approximately 2000 rpm. It is self-sustaining once started. Blast-furnace gas is its primary fuel, but distillate oil is available as an emergency stand-by fuel.

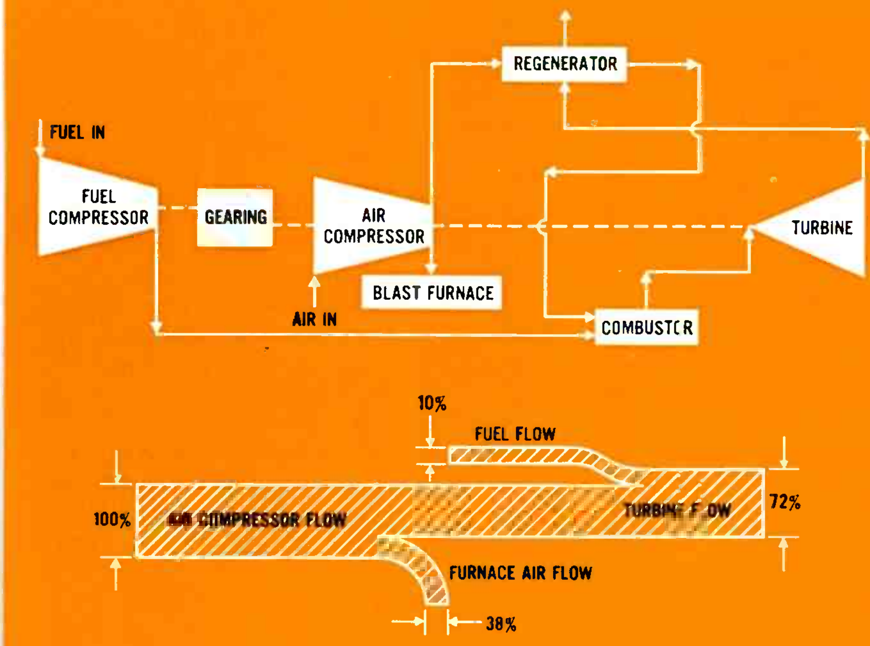
The flexibility of this machine is illustrated in Fig. 4b. Air is supplied to the process from 0 to 100 percent flow and at any pressure below the maximum speed parameter.

drives

Development of mechanical power for direct drives, or for generating electrical power, is a natural field for gas turbines because of the widespread need in industry for appreciable blocks of power with some speed range.

Here again, the gas turbine's ability to utilize the waste gases of different processes as fuel and the presence of a process heat balance that can use the exhaust energy of the gas turbine are important factors in equipment selection.

In the installation illustrated in Fig. 5, two gas turbines drive air blowers for a catalytic refinery unit. The turbine exhaust supplies preheated combustion air for two carbon-monoxide fired boilers and also heats feedwater.



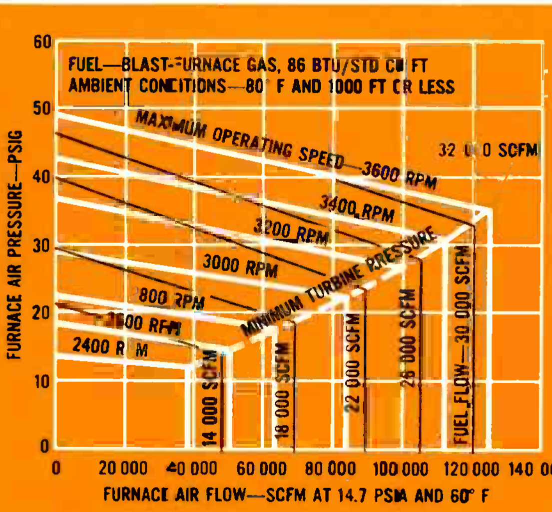


Fig. 4a (Left) Schematic diagram of an extraction unit, with flow proportions indicated. This 125 000-cfm machine supplies air for blast-furnace blowing.

Fig. 4b (Top) Performance characteristics of an extraction unit blast-furnace blower.

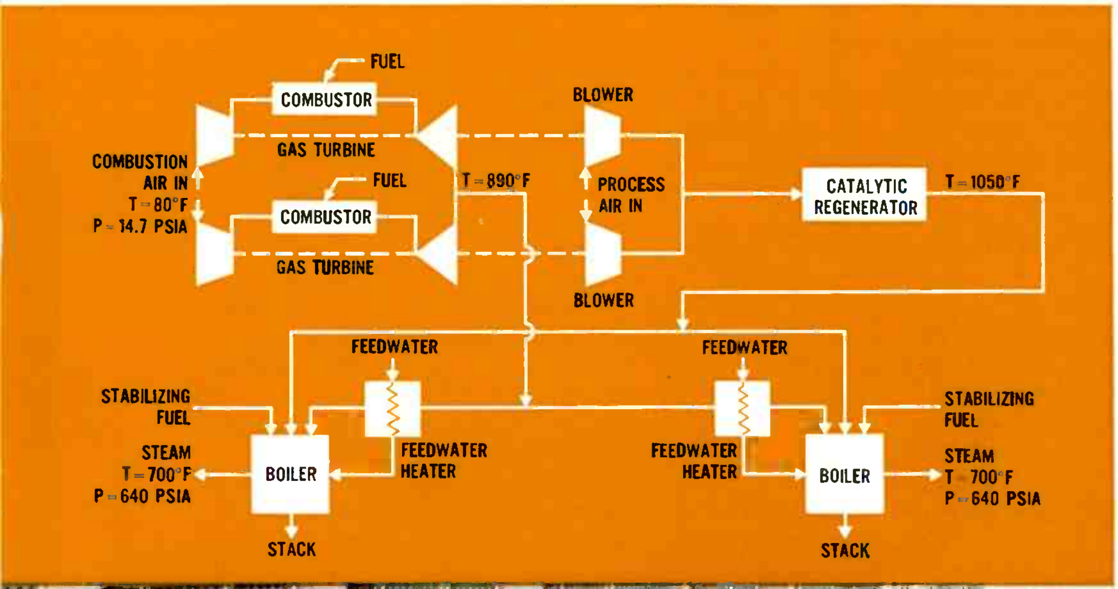


Fig. 5 Gas-turbine drive for catalytic refinery air blowing.

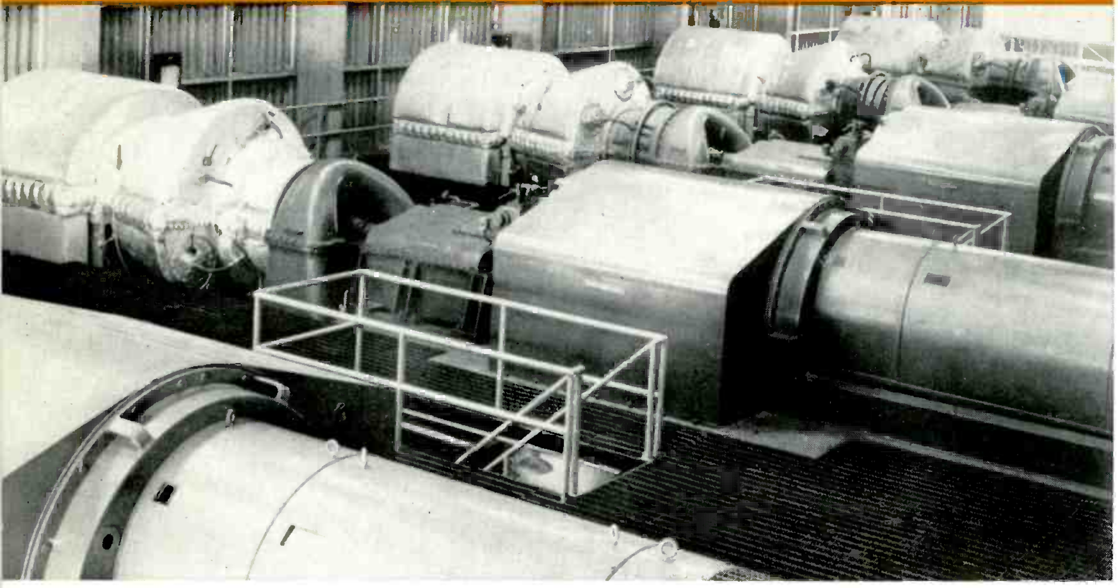


Fig 6. Five gas turbines are the prime movers in this electric power station.

Table 1 GAS-TURBINE ELECTRIC GENERATING STATION OPERATING COSTS (1958)

	Operating Costs, Gross Generation 84 050 000 kwhr		Operating Costs Adjusted to Firm Capacity of 131 140 000 kwhr	
Item	Amount ($)	Cost ($/kwhr)	Amount ($)	Cost ($/kwhr)
Labor and Transportation	97 934	0.00116	97 934	0.00074
Fuel Gas	212 519	0.00253	254 619	0.00194
Maintenance Materials and Labor	52 616	0.00063	60 000	0.00046
Overhead	5 565	0.00007	5 565	0.00004
Depreciation	323 698	0.00385	323 698	0.00247
Total	692 332	0.00824	741 816	0.00565

The turbine room of an electric power station using gas turbines as prime movers is shown in Fig. 6. The installation originally consisted of three 5000-kw gas-turbine generators; it has since been expanded to five units. Plant operating costs have proved to be lower than the estimates that led to the initial decision to use gas turbines as the prime movers. Table I presents these costs for 1958.

conclusion

Places for gas turbines definitely exist in various industrial applications. The decision as to which is better—a gas turbine or some other equipment that can accomplish the required function—rests solely with such economic considerations as comparative effects in payout periods, operating costs, and potential savings. Evaluation of many industrial applications shows that using gas turbines instead of other prime movers often results in lower installed costs, better overall operating economics and lower maintenance costs.

PERSONALITY PROFILES

W. F. DAVIS graduated from the U. S. Merchant Marine Academy in 1947 with a BS degree. He then attended Stevens Institute of Technology, where he obtained an ME degree in 1951.

From 1951 to 1953, Davis served on active duty with the U. S. Navy as operations officer aboard a destroyer, with the rank of Lieutenant, JG.

Davis joined Westinghouse as a Senior Engineer in 1957, and was placed in charge of design and development of the nuclear plant being built in Mol, Belgium in 1959.

R. M. SANDO, a graduate of the College of Engineering at New York University with a Bachelor of Aeronautical Engineering degree, was engaged in aircraft design for ten years before coming to the Air Arm Division of Westinghouse in 1952. Since that time he has held a staff position in the advanced development engineering department. In this capacity (Fellow Engineer), Sando is engaged in a wide field of engineering activities including such categories as structural design, application of heat-transfer techniques, dynamics-vibration and shock, manufacturing techniques, equipment environmental problems, and aerospace physics studies.

He has over a dozen technical disclosures resulting in four patents and has twice received the company's most meritorious disclosure award along with co-inventors for his creative efforts. Sando is a member of the Institute of Aeronautical Sciences and a registered professional engineer in Maryland.

E. J. DUCKETT joined Westinghouse at the East Pittsburgh plant in 1941, while still attending the University of Pittsburgh. In 1942, he was graduated with a BS in Physics and Engineering, and moved to the Research Laboratories. His first assignment was development work on high-power microwave tubes, resnatrons, and magnetrons.

In 1944, Duckett went on military leave to the U. S. Navy, where he served as an electronics specialist officer with the 5th Fleet staff.

Duckett returned to Westinghouse Research in 1946, and worked on microwave propagation studies, television and color television circuitry, and low-level signal measurement techniques.

He left Westinghouse for two years, but rejoined the Special Products Development Division in 1952 and was made a supervisory engineer at the New Products Department when it was formed in 1954. At New Products, Duckett has supervised efforts on power conversion equipment, ultrasonic equipment, aircraft electrical systems, fire control systems, consumer products, sensing devices, and thermoelectric generators. Duckett was made a section manager in 1957, and was recently appointed project manager of the central engineering power switch program.

Duckett obtained his MS in physics from the University of Pittsburgh in 1949, and has continued toward earning his PhD degree.

J. R. GAMBLE was graduated from West Virginia University in 1950 with a BSEE. From 1950 to 1955, he served with the Navy as a Lieutenant JG in the Civil Engineers Corps, stationed at the Public Works Department in the New York Naval Shipyard.

Gamble joined the engineering department of the Westinghouse Porcelain Department in 1955. Here, he has primarily been concerned with design and coordination of porcelain insulation for the transformer division. Gamble has been particularly active in developing uses for aluminum metals in insulator assemblies.

During his spare time, Gamble enjoys golf and woodworking.

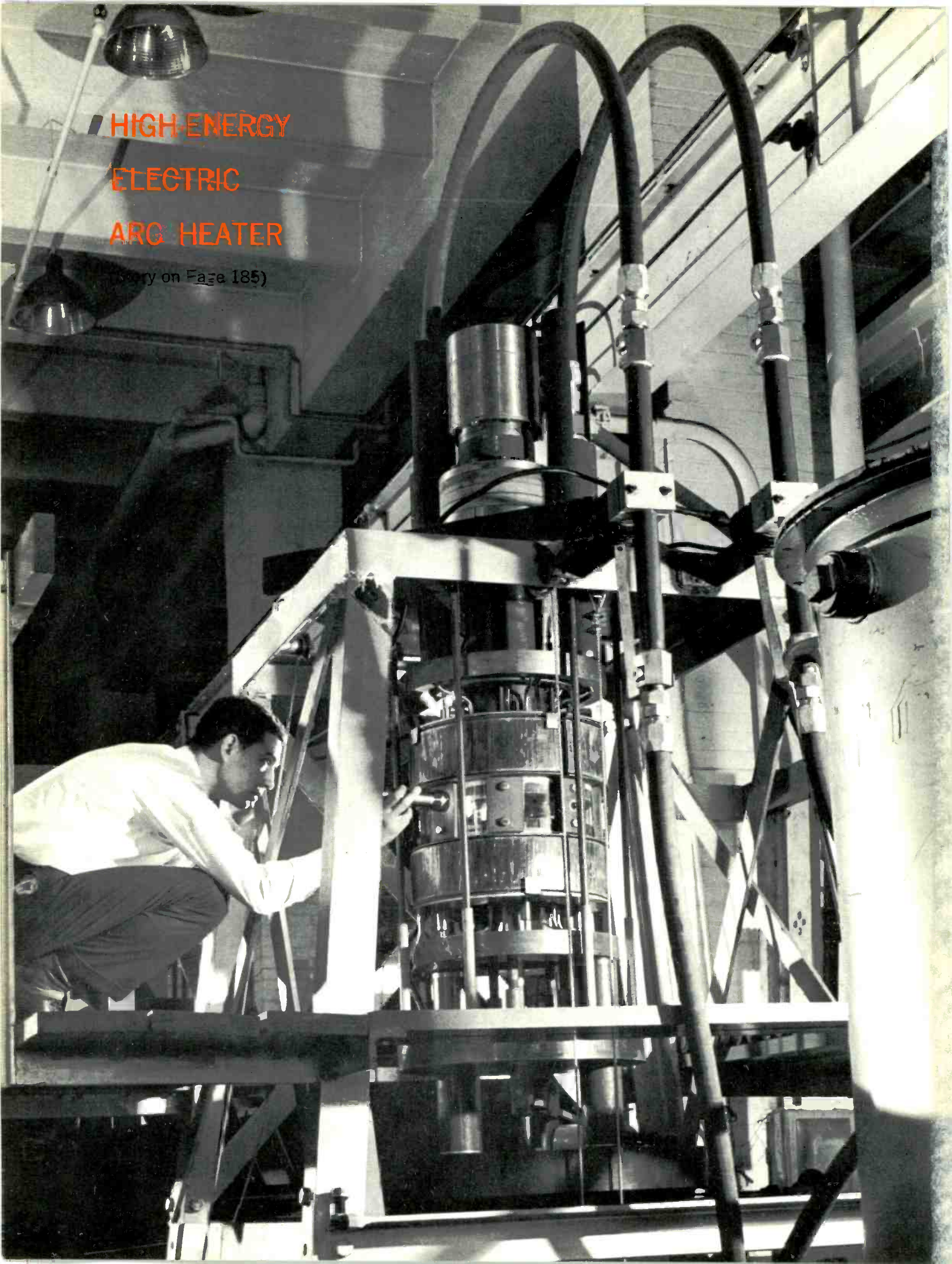
H. W. COOPER obtained his BS degree from New Mexico A & M State College in 1947, and his MS from Stanford University in 1948.

He joined the Air Arm Division of Westinghouse as an Advisory Engineer with the Electromechanical Project in 1958. Here, he has worked in the antenna and microwave fields, and also with communications systems and space systems.

The communications field was an obvious choice for Cooper. During World War II, he was with the Office of Strategic Services in charge of a communications station at the OSS headquarters in Ceylon. He helped operate communications circuits to Bangkok, Calcutta, Chungking, and other points in the Far East.

D. F. BRUCE has worked with industrial gas turbines since he joined Westinghouse in 1946. He spent about four years in shop test and control design work and then took time out for a two-year tour of Naval Reserve active duty. On his return to Westinghouse in 1952 he served as a control design engineer, customer project engineer, and facilities planning engineer. He was appointed to his present position, manager of the customer and control engineering section, industrial gas turbine engineering, in 1956.

Bruce was graduated from the University of Michigan in 1945 with a BSE (ME), and in 1950 he earned his MSME from the Towne Scientific School, University of Pennsylvania. He serves on the ASME's Technical Committee of Speed Governing for Industrial Gas Turbines.



HIGH-ENERGY ELECTRIC ARC HEATER

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