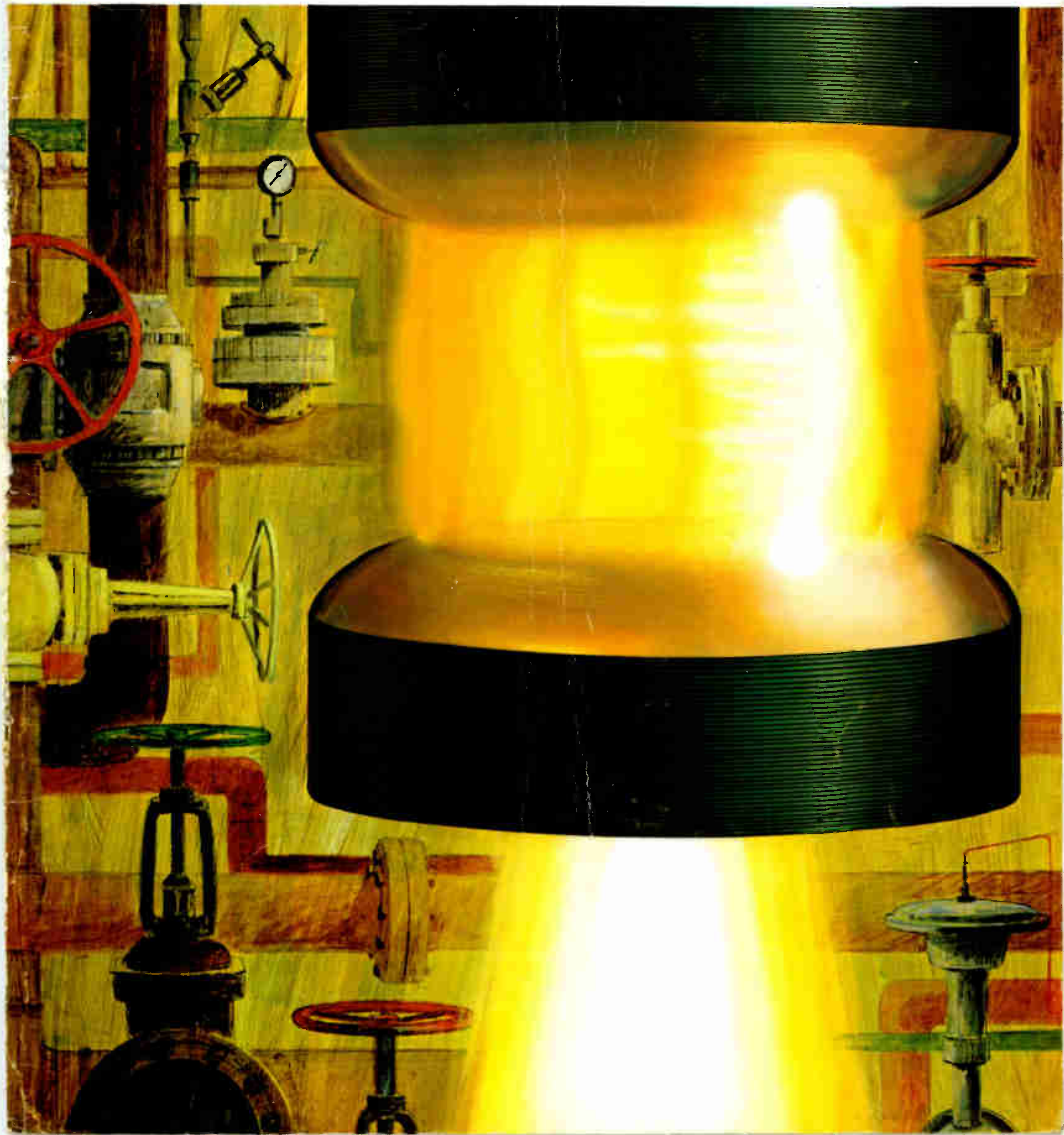
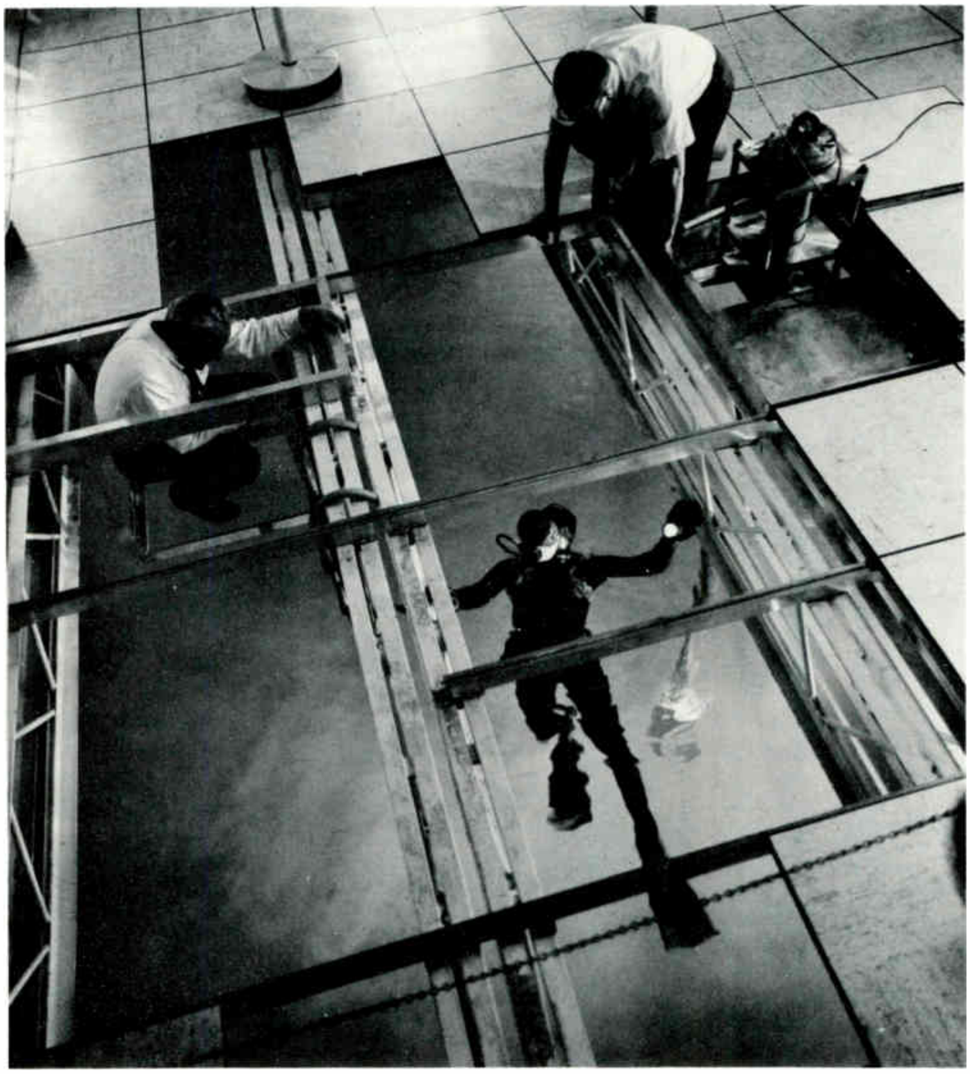
Westinghouse ENGINEER
May 1966





Underwater Research Aided by a New Facility

The oceans of the world are growing in importance as an area of scientific research; they are a frontier that is as significant as outer space and not as well understood. This new underwater facility at the Research Laboratories is designed to contribute to the continuing program of underwater research.

The facility houses a 150,000-gallon tank of water 30 feet in diameter and 30 feet deep. Within the tank are two test stations for the installation and testing of underwater sound equipment. Two-thirds of the tank lies below the ground level of the new research facility, and the laboratory that houses the electrical and electronic equipment used in underwater experiments is located above it. Access to the tank is through the laboratory floor, which can be removed in two-foot-square sections. Below-water equipment and test apparatus penetrate the tank through these openings.

The new laboratory is part of the electro-acoustics department, from which came the first successful side-looking sonar system to display clear detailed pictures of the ocean floor at depths never penetrated by light. Using sound waves to generate its pictures, the sonar scans the ocean bottom in strips up to a half-mile wide, pinpointing objects no more than two to three feet across. Sonar systems will be an important aspect of the work of this new laboratory.

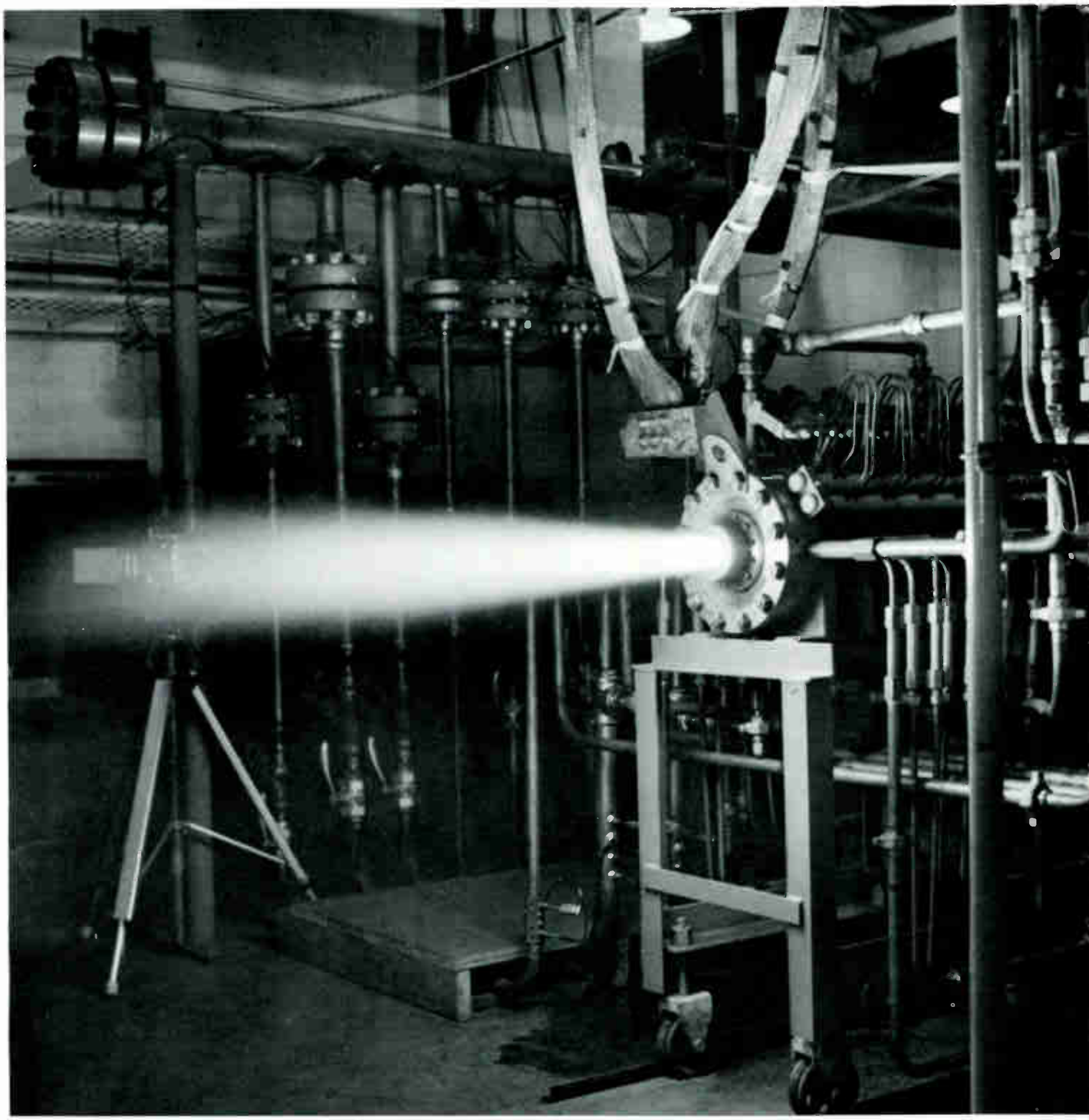
Westinghouse ENGINEER
May 1966, Volume 26, Number 3

Subscriptions: United States and possessions, $2.50 per year; all other countries, $3.00 per year. Single copies, 50¢ each.

Mailing address: Westinghouse ENGINEER, P. O. Box 2278, 3 Gateway Center, Pittsburgh, Pennsylvania 15230.

Published bimonthly by the Westinghouse Electric Corporation, Pittsburgh, Pennsylvania. Printed in the United States by The Lakeside Press, Lancaster, Pennsylvania. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 North First Street, Ann Arbor, Michigan.

Cover design: The fiery interior of an arc chamber, with an electric arc rotating between the surfaces of its toroidal electrodes, is the center of interest in this month's cover by artist Thomas Ruddy. The complex array of piping and valves in the background is meant to suggest the application of the arc heater in the chemical industry, the subject of this month's lead article.



1—The Marc 200 rotating-arc heater is a three-phase arc heater rated at 20,000 kilowatts. This is the highest power ac arc heater yet built and operated.

Electric Arc Heaters for High-Temperature Chemical Processing

D. A. Maniero
P. F. Kienast
C. Hirayama

Recent developments with rotating-arc heaters indicate real potential for the device in chemical processing applications where high temperatures are needed.

The extremely high temperature of the electric arc has long made it theoretically attractive for certain chemical and petrochemical processes, but the practical and economic feasibility has been questionable. Recent advances in high-energy, rotating-arc heaters developed by Westinghouse for wind-tunnel application indicate that arc heating may now be more practical for application to industrial processes. The arc heater designs and manufacturing techniques that have been developed are being evaluated for this purpose.

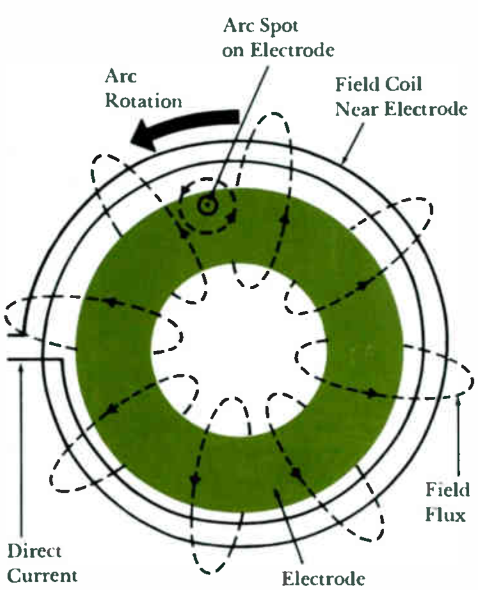
Rotating-arc heaters have been built for wind-tunnel application in ratings ranging from 2000-kw, dc or single-phase ac, to 20,000-kw, three-phase ac. To demonstrate the adaptability of these wind-tunnel heaters to chemical processes, a 3000-kw heater has been developed for conducting chemical process tests. This unit is designed for continuous operation between 100 and 3000 kw, incorporates gas-flow patterns that eliminate carbon deposition, and has provisions for multiple gas injection. Where the 3000-kw heater is not large enough for full-scale, on-line processes, these potential applications can be first investigated with this pilot plant unit, and if successful, scaled up to larger heaters. A fundamental advantage of the Westinghouse rotating-arc heater over other arc-heating approaches that have been tried in the past is the fact that as the rotating-arc heater is scaled up in size, the geometric and performance similarity can be retained. Thus, the experimental programs conducted on pilot plant models will provide meaningful engineering information that can be applied to full-scale plants.

On the other hand, 3000 kilowatts may be sufficient power for many potential chemical processes; in these instances, the 3000-kw (Marc 30) heater could become a full-scale plant device.

The largest arc heater built to date is the 20,000-kw unit (Marc 200) shown in Fig. 1. However, research and development work is continuing on extremely large arc heater facilities for the future—for example, 100,000- to 300,000-kw systems. These facilities may be needed ultimately for full-scale ground testing of aircraft, missiles and rockets, or large-scale chemical processing plants. With the rotating-arc approach, designers see no theoretical reason why heaters or multiple heater arrangements cannot eventually be built for these high ratings.

Arc Spinning and Short Gaps

All of the Westinghouse wind-tunnel heaters—dc, single-phase ac, and three-phase ac—use the basic principle of rotating an arc at high speed over toroidal electrodes. Arc rotation is produced by the interaction between the arc column and a radial magnetic field (Fig. 2). High rotational velocity of the arc prevents melting and evaporation of the current-carrying electrodes and also provides desirable mixing action. The gas being heated flows through the arcing region. The mixing action produced by arc rotation helps to provide a relatively uniform temperature profile in the heating chamber.



2—This sketch of one anode of a rotating-arc heater demonstrates the principle of operation. The arc column is caused to rotate around the toroidal anode by the radial field flux.

The techniques for moving an arc at high speed with a magnetic field have been known for some time. The principles involved were outlined by Dr. J. Slepian in 1929[1] and have been applied to circuit breakers for many years. In circuit breaker design, these principles are used to produce arc *instability*; in arc heater design, the same principles are applied to produce arc *stability*. Thus, much of the data obtained from early circuit breaker and arc interruption work could be used in developing the rotating-arc heater.

The rotating-arc approach makes possible short-arc-gap, high-current operation, which is the most stable type of operation possible. For an open-circuit voltage high enough to sustain a stable arc, arc heater power is a function of arc gap spacing and arc current. Power remains essentially constant for a given gap spacing and current and is essentially independent of the mass flow of gas through the heater. This constant power characteristic makes it possible to select temperature (by selection of gap spacing), relatively independent of gas flow, and thereby obtain good temperature control for the process. For example, the input power to a 3000-kw heater (Marc 30) can be varied over a range from 100 to 3000 kw by changing the arc gap spacing from ⅜ inch to several inches. The temperature range might be 2000 to 15,000 degrees F depending on the gap setting, power input, mass flow, and type of gas being heated.

For a given operating condition, arc heater operating efficiency is generally a function of surface area of the components forming the heating chamber. Thus, the smaller the arc heater, the higher the expected operating efficiency. With short arc-gap spacing of the rotating-arc heater, the electrodes require a relatively small chamber. For example, the heating chamber for the 3000-kw heater discussed

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above has an overall length of only 1½ feet. Efficiencies obtained with this type of heater have been as high as 86 percent when heating air and 79 percent when heating methane.

Since a short arc gap can be made to sustain either a dc or ac arc, rotating-arc heaters can be operated either way. Ac operation eliminates the need for dc rectification equipment and thus reduces system cost. This is a particularly significant factor as power ratings increase and for processes which will require continuous operation.

Water Cooling

To obtain long life for rotating-arc heater electrodes, two fundamental conditions must be satisfied: (1) Arc speed over the electrode surfaces must be fast enough to prevent instantaneous surface melting and evaporation; and (2) the temperature of all surfaces must be cooled sufficiently to prevent melting of the heater during long periods of operation.

Arc rotational speed is a function of arc current and radial magnetic field strength. Thus, for a given electrode circumference, rotational speed determines the speed of the arc spot over the electrode surface. The heater must therefore be designed and operated in such a way that these three parameters—electrode circumference, field strength, and arc current—work together to satisfy the first condition.

The second condition is primarily met by cooling the components with water. Arc heaters built and operated to date have been designed to accept surface heat fluxes up to 20 million Btu/ft²-hr. To remove this heat flux requires:

1) Water passages must be close to the surfaces exposed to heat flux;

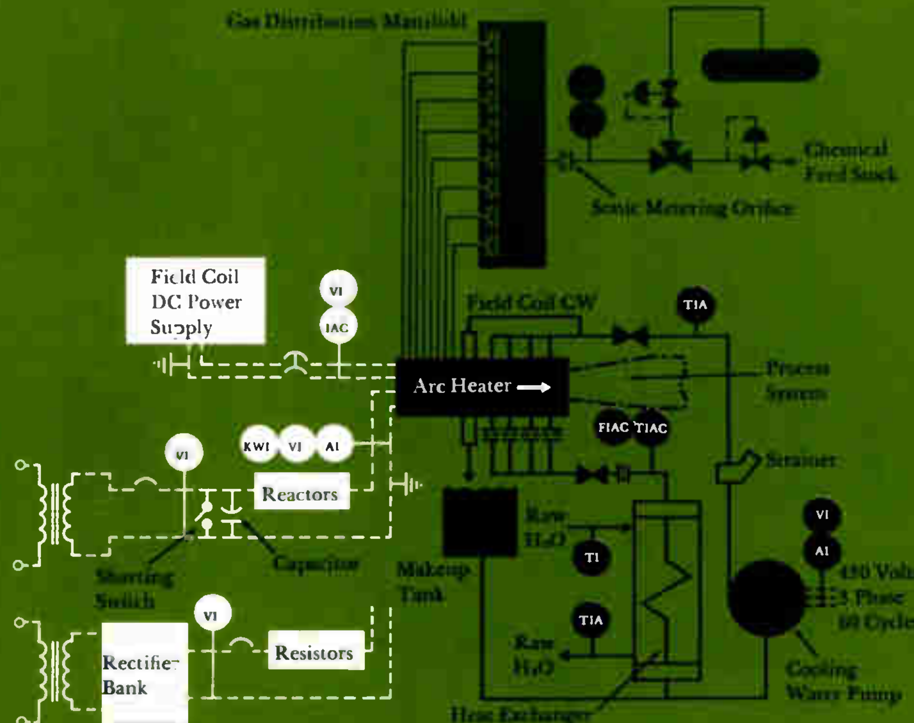
2) water passages must be uniformly spaced to avoid local hot spots;

3) cooling water must be maintained at a static pressure high enough to prevent bulk boiling in water passages; and

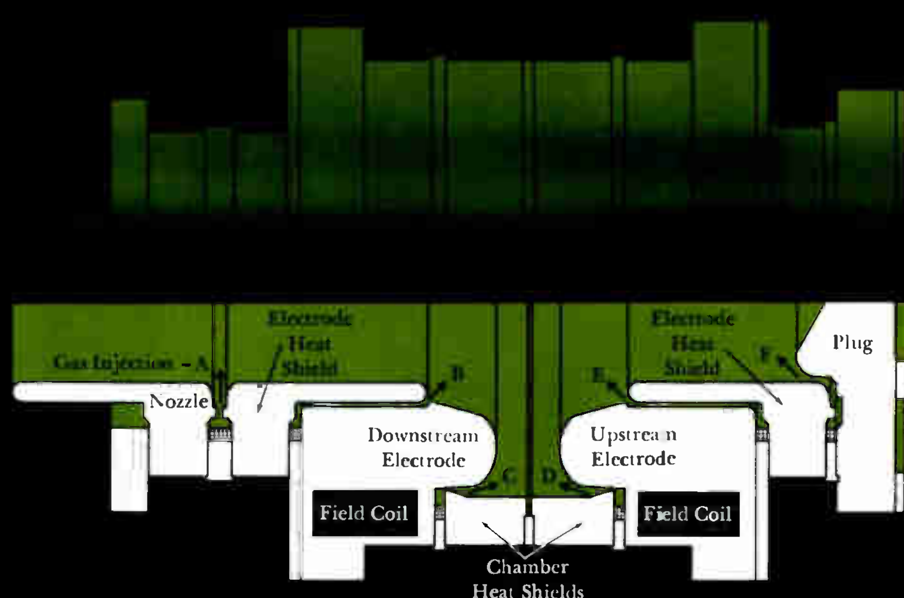
4) water velocities must be high—about 100 feet per second—for good heat transfer between metal and water.

Typical Arc-Heater System

The auxiliary equipment required to operate an arc heater is shown in Fig. 3.



3—Complete rotating-arc heater system includes electrical supply, gas supply, and cooling-water supply to the heater.



4—Cross section of the Marc 30 heater.

These auxiliaries supply, control, and protect the power, water, and gas supplies to form an integral operating system.

A single-phase or three-phase transformer drops supply voltage from the transmission line to the open-circuit value required to maintain the arc. For dc operation, the transformer is followed by a bank of rectifiers. For ac operation, air-core or saturable-core reactors are connected in series with the arc heater to displace the current waveform with respect to voltage so that a near-peak voltage will exist when arc current passes through zero, thus sustaining the arc. Capacitors are connected in parallel with the arc heater for power factor correction. For dc operation, reactors or resistors or both can be connected in series with the arc to limit arc current, but allow full open-circuit voltage to appear across the heater electrodes should the arc tend to go out.

Several thousand amperes are required by the magnetic field coils to maintain arc rotation. This current can be in series with the arc current in the case of dc operation, or it can be obtained from a separate power source such as a motor-generator set or a static type device.

A cooling-water pump furnishes several hundred gallons per minute to the heater at pressures from 300 to 1000 psi. A water filter follows the pump to prevent any solid matter from entering the arc heater. The heat exchanger cools the water in the closed-cycle cooling system. Flow restrictors in the cooling-water lines leaving the heater balance the flow rates through the individual water circuits and increase exit pressure, thereby increasing the saturation temperature.

If the heater is to be used with a condensible vapor as the feed, the cooling-water system would be operated at an increased temperature level. Cooling-water temperature entering the arc heater could be raised from an external heat source to a value greater than the saturation temperature of the vapor entering the heater.

The gas supply can be a storage type or a continuous-flow system that provides gas flow through a metering orifice into a distribution manifold. The distribution manifold divides the gas flow to the various injection locations in the heater.

All subsystems working with the arc heater are instrumented and protected so that operating conditions can be accurately determined and the system shut down quickly in case of malfunction of a component.

An Arc Heater for Chemical Processing

There have been sporadic applications of electric arc heating for chemical processing dating back to the turn of the century. However, most of these applications used long-arc, direct-current operation, which is limited in flexibility and range of operation and requires a costly high-voltage dc supply. At best, the economics and advantages of these arc systems have been marginal, which has prevented them from becoming universally accepted as a processing means. However, the extensive industries based on the cracking of natural gas, other hydrocarbons, and pure inorganic compounds such as titanium oxide and aluminum oxide provides an incentive for developing more efficient processing heaters. Since the Westinghouse rotating-arc heater can provide higher power and temperature with better control than any form of electric arc heating yet developed, an extensive investigation aimed at developing arc heaters that can be applied to chemical processing by the chemical and petrochemical industry was begun at Westinghouse.

Marc 30 Heater—The first step was the development of a heater that could withstand the severe operating conditions imposed by continuous-duty service in a processing application. A cross-section view of the Marc 30 heater developed for this purpose is shown in Fig. 4.

The first and perhaps most important feature of the Marc 30 heater is the improved high-current electrode design (Fig. 5). Two similar electrode assemblies provide the terminals for the rotating arc. Close spacing between electrodes permits the heater to be operated either ac or dc. A radial field of several thousand gauss is produced by field coils near the water-cooled electrodes. A very high arc rotation rate of about 60,000 revolutions per

5—Electrode assembly for the Marc 30 heater.

minute can be obtained, which improves electrode life and provides the mixing action needed for a chemical processing application.

Copper and copper alloys proved the most suitable material for most of the internal parts of the heater. Where high strength is not a primary requirement, oxygen-free copper is used for its high thermal and electrical conductivity. In structures where the stresses are higher, chromium and zirconium alloys of copper are used.

The copper surfaces have been operated with a number of oxidizing, reducing, and inert gases and thus far have not shown any tendency to be damaged by any particular gas.

Two types of joining were adapted and developed for the arc heater construction. One method is electron beam welding, in which a narrow beam of electrons is directed on the joint to be made. The second joining method is Rib-Bonding, in which the parts to be joined are brought together at high temperature and pressure so that the joint is formed by diffusion and crystal growth between surfaces. With both of these techniques, no additional filler material is used and the thermal conductivity of the joint is essentially the same as that of the base metal. Thus, the high heat fluxes that are imposed on these joints will not generate large temperature gradients that could cause damage during operation.

Another basic design feature incorporated in the Marc 30 arc heater to make it more suitable for chemical processing is the multiplicity of gas injection positions. As shown in Fig. 4, the heater configuration has six locations for gas injection. One or more process gases can be injected and mixed before or after passing through the arc region. The arrangement can also be adapted to provide quenching of a chemical reaction in the arc chamber.

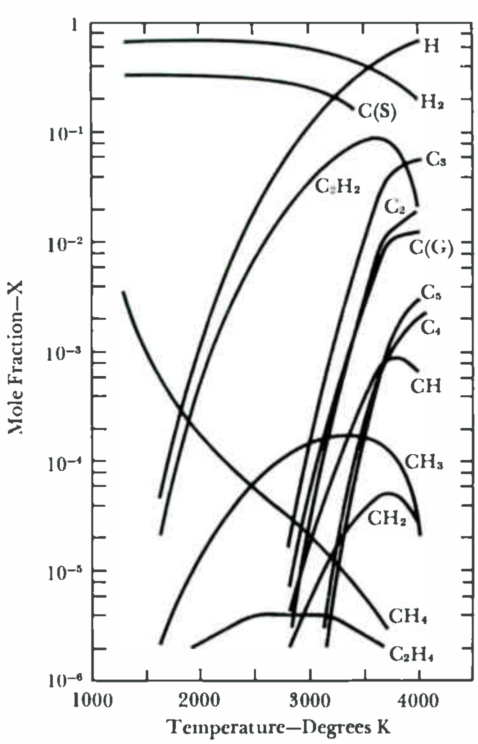
Acetylene from Methane

The second step in the investigation was the demonstration of the feasibility of applying the rotating-arc heater to a chemical process. A number of processes seem to be logical applications for an arc heater. Some typical examples are the production of acetylene, ethylene, hydrogen cyanide, carbon, and cyanogen. Other possibilities are the gasification of coal, reduction of metal oxides, nitrogen fixation from air, oxygen heating, and steam superheating.

Of the above processes, acetylene and ethylene production are of particular interest because of their economic potential; acetylene and ethylene are fundamental building blocks for the expanding plastics and rubber industries.

Some indication of the feasibility of applying the rotating-arc heater to acetylene production can be obtained by considering the high-temperature characteristics of the system, $C+2H_2$. The composition of the equilibrium mixture of this system as a function of temperature is shown in Fig. 6.

The maximum acetylene (C_2H_2) concentration (9 mole percent) appears at 3600 degrees K. Note that at this same temperature, methane (CH_4) is quite unstable. The kinetics of formation of acetylene is much faster than its decomposition, so that if the gas at 3600 degrees K is quenched at a rate of 10^5 degrees per second, the acetylene can be essentially frozen, and there will be precipitation of carbon and recombination of H and the other radicals. Under these circumstances, the gas phase should contain about 15 mole percent acetylene, the remainder being H_2, C_2H_4 (ethylene), and C_4H_2 (diacetylene). The amount of solid carbon frozen from an equilibrium mixture should be about 40 percent of the total carbon.



6—Calculated equilibrium for the $C + 2H_2$ system as a function of temperature (total pressure equals one atmosphere).

The equilibrium for the $C+2H_2$ system shows that the 3600-degree temperature should be significant in a methane-to-acetylene process. However, when methane passes through the electrode gap of the heater, that volume which sees the arc is heated to temperatures in excess of 7000 degrees K. This volume of gas is therefore completely dissociated because of the extremely high heat energy. Part of the gas, the proportion depending on the rate of arc rotation and on the gas flow velocity, will not be arced, but will mix with the hot arced gas downstream from the heater in the plenum chamber. Thus, in view of the above considerations, this should be the critical period of the chemical process. However, the difficulty of predicting just exactly how the process will behave stems from the fact that the kinetics of the reaction in an electric arc and in the following plenum chamber are not necessarily the same as an equilibrium thermal process wherein methane is passed through a hot reactor of relatively uniform temperature. Both extremely hot and relatively cool regions coexist in the arc heater. The kinetics of the reaction under these microscopically heterogeneous conditions are not known.

Thus, the experimental program objectives were to demonstrate the feasibility of using the rotating arc heater for direct processing of natural gas, and also to obtain important operating parameters such as voltage, current, efficiencies and their interrelation and dependence on arc gap, mass flow, and type of gas heated. The test data would help determine to what extent the known thermodynamic and kinetic mechanisms could be extrapolated to predict rotating-arc-heater performance.

Testing Program

The arc heater test programs are performed at the Westinghouse High Power Laboratory, where both dc and ac power are available. Resistors or air-core reactors or both are connected in series with the arc heater to stabilize the arc and match the power supply to the heater for a given test.

Feed gas is provided from gas cylinders attached to a common manifold. A pressure regulator maintains pressure upstream from a sonic orifice.

Temperature of the cooling water leaving the heater varies as a function of power loss. Thus, overall efficiency of the arc heater can be calculated on the basis of the electrical power input measured at the arc heater terminals less the heat removed by the cooling water.

Gas samples are collected at the nozzle exit with a water-cooled probe. At appropriate time intervals after the test starts, the product gas is sampled by closing off the set of solenoid valves on bottles attached to the copper tube. Thus, for any given run it is possible to obtain one or more samples at different periods during the run.

Tests conducted to date with the Marc 30 have utilized both dc and ac power ranging from 90 to 2360 kw. Electrode gaps of 0.38 to 1.5 inches have carried currents ranging from 780 to 3830 amperes for methane tests. The same arc heater has also operated at currents as high as 9200 amperes in another application where hot nitrogen was desired.

A maximum methane flow rate of 16½ pounds per minute has been tested to date in the Marc 30 heater. The unit is suitable for flow rates as high as 30 pounds per minute.

Heat addition to the process gas has varied from 2000 to 20,000 Btu per pound of methane flowing through the arc heater.

Test Results

Ideally, the methane-to-acetylene reaction would be:

$$2CH_4 + HEAT \rightarrow C_2H_2 + 3H_2$$

The heat of reaction would be about 5000 Btu per pound of methane (or 2.4 kwhr/lb C_2H_2). Additional sensible heat must be added to heat the methane to the reaction temperature. For example, to heat from 300 to 1500 degrees K, 2100 Btu/lb (or 0.59 kwhr/lb C_2H_2) of methane would be required.

Actually, the reaction can be more accurately represented by:

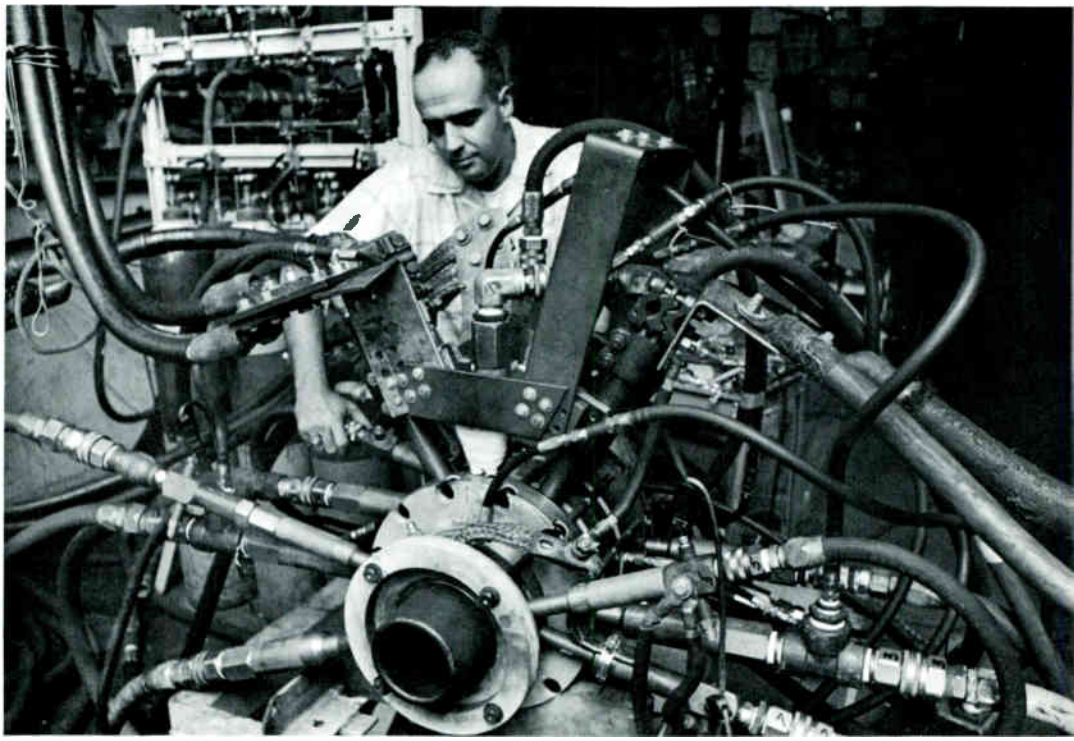
$$2CH_4 + HEAT \rightarrow (1-n)\ C_2H_2 + (3+n)\ H_2 + 2nC$$

where $1 \geq n \geq 0$. Ideally n should equal zero.

The gas analysis of a typical run with methane as the feed gas is shown in Table I; the material balance for this same run is shown in Table II. From this data, a methane conversion of 46.7 percent has been obtained. Although not yet optimized, methane conversions of 80 percent and even higher have been achieved at conditions where good mixing between the arc and the gas occurred. The energy conversion rate of the run shown in Tables I and II is 6.8 kwhr/lb acetylene. However, in other runs, energy conversion rates as low as 2.64 kwhr/lb acetylene have been obtained.

An energy conversion of 2.64 kwhr/lb acetylene is significantly lower than the 4.5 to 6.0 kwhr/lb rate reported for other electric arc processes. An examination of the enthalpy requirement indicates that 2.4 kwhr is required just for the heat of reaction; since sensible heat must also be supplied, the value of 2.64 kwhr/lb appears too low. This determination obviously needs reconfirmation by further testing. On the other hand, the kinetics of conversion in the arc heater may favor a high conversion to acetylene, so that the low energy conversion rate may be possible.

Depending on operating conditions, the acetylene concentration in the product



7—The Marc 30 heater in the High Power Laboratory being prepared for test.

gas has ranged from about 7 to 13 mole percent, the other major constituents always being hydrogen, carbon, and unreacted methane. From a theoretical standpoint, the maximum acetylene in quenched gas from 3600 degrees K should be about 15 mole percent when the product gas analysis is normalized by subtracting the unreacted methane. The acetylene concentration based on the reacted methane remains at about 15 mole percent over the wide range of enthalpy levels. It is apparent then, from test results, that thermodynamic equilibrium is not attained, particularly at low enthalpies. If equilibrium were attained, the acetylene concentration would be dependent on enthalpy (or temperature). At low flow rates and high enthalpies, however, the gas probably attains equilibrium and the average temperature is in the region of 3600 degrees K as shown by the product composition. Since temperature measurements have not as yet been made at low enthalpy levels, the average gas temperature can only be estimated to have been about 1500 degrees K.

The carbon content and its properties have varied with operating conditions. For example, the conversion to carbon has varied from a few percent to about 40 percent of the total carbon input. With ac power, the carbon was generally of an amorphous nature, whereas with dc power the properties approached those of pyrolytic graphite. Carbon surface areas varied over almost one order of magnitude from about 20 to over 100 m^2/g. The purity of some samples, determined by a spark source mass spectrometer, showed extremely low contamination (at least an order of magnitude more pure than spectrographic carbon).

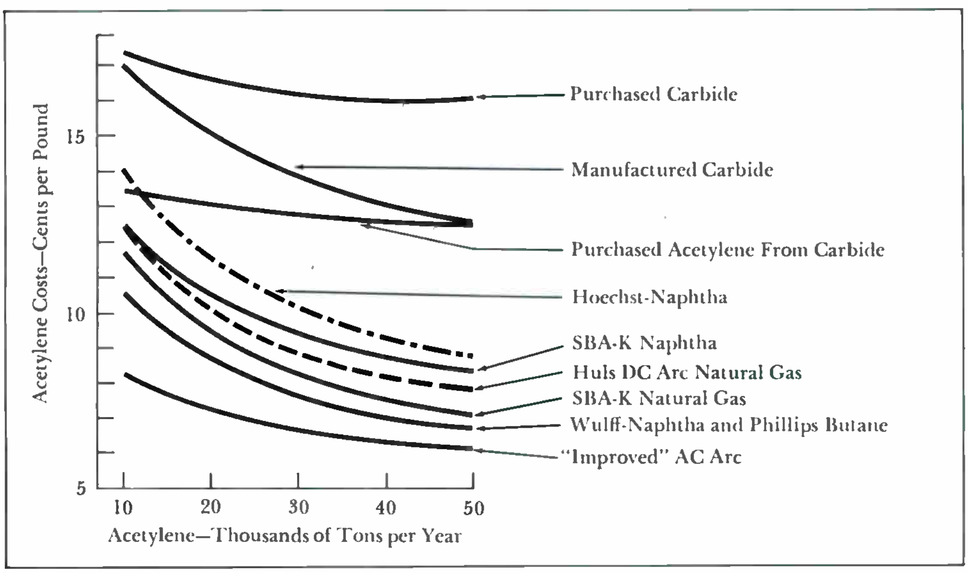
The efficiency of the arc heater, calculated on the basis of electrical power to the arc heater less heat lost to the cooling water, has been as high as 79 percent for methane input.

Table I—Product Gas Analysis in Mole Percent For Methane Run

H_2 Hydrogen	CH_4 Methane	C_2H_2 Acetylene	C_2H_4 Ethylene	C_4H_2 Diacetylene	Other Hydrocarbons
50.98	38.17	9.52	0.88	0.21	0.25

Table II—Composition of Products in Mole Percent

H_2 Hydrogen	CH_4 Methane	C_2H_2 Acetylene	C_2H_4 Ethylene	C_4H_2 Diacetylene	C Carbon	Other Hydrocarbons
46.3	34.7	8.7	0.8	0.2	9.1	0.2



8—Comparison of costs for making acetylene by various methods, calculated in 1962[2], indicate that an "improved" ac arc method could be potentially the lowest cost method.

The Future of Arc Heating

It is important to note that the engineering data obtained in the tests to date do not include the processing of the gas beyond the heater nozzle. However, in a process with high gas flow velocity, a considerable mixing action would occur downstream from the arc in the plenum chamber. Thus, for more conclusive results, a more complete pilot-plant setup would be desirable. This step will be left to the chemical and petrochemical companies to explore.

Although natural gas is presently less expensive than electricity as a fuel for many processes, only electric arcs can provide higher process temperatures; furthermore, electric power offers better control and more process flexibility. Thus, as electric power continues to become less expensive, natural gas may become more valuable as feedstock for the process itself, rather than as a fuel to heat the process.

Walter E. Lobo, chemical economist and consultant to the chemical and petrochemical industries, has compared the costs of making acetylene by various methods.[2] The comparison shown in Fig. 8, reported in 1962, is based on his calculations. It shows that the ac arc-heating process may be potentially the lowest-cost method.

Other types of chemical reactions could have similar economic potential, and test programs and evaluations are presently under way to demonstrate the potential of high-temperature processing with high-current rotating-arc heaters.

References:
[1]Slepian, J., "Theory of the Deion Circuit Breaker," presented at the winter convention of the AIEE, New York, January 28 - February 1, 1929.
[2]Midwest Research Institute, *Arc Tunnel Heaters Report*, 1962.

Air-Conditioning System Innovations Improve Operation and Extend Application Range

J. R. Harnish

A new concept in refrigerant control increases air-conditioning system reliability, operating range, and efficiency. The Hi/Re/Li system is applicable to cooling and reverse-cycle heating systems, of all sizes, that employ the compression refrigeration cycle.

Despite their widespread and successful use, conventional compression refrigeration systems for air conditioning have serious inherent application limitations; so have the reversible compression cooling and heating systems commonly called "heat pumps." Essentially, these limitations prevent reliable and effective service from the basic cooling or heating cycle below certain outdoor temperatures—about 60 degrees F for cooling and about 0 to 15 degrees F for heating.

Until now, system designers have had to add auxiliary equipment to the basic system to extend the application range below those minimum outdoor-ambient temperatures. That approach, however, is a cumbersome and expensive solution, and it introduces additional reliability problems. Now a new design approach called the Hi/Re/Li system virtually removes the limitations, permitting effective and reliable operation down to much lower outdoor temperatures. It also increases efficiency.

The system is based on a new concept that consists essentially of better control of the refrigerant to permit the heat exchangers to operate efficiently at all times and to ease stresses on the compressor. It is applicable to central air-conditioning and heating installations from the smallest residential package to the largest commercial systems. The new system is called "Hi/Re/Li" because it has all the necessary protection and operating characteristics for high reliability. Equipment and installation costs are comparable to those for basic conventional equipment; operating costs over a wide range of operation are less because of the greater efficiency.

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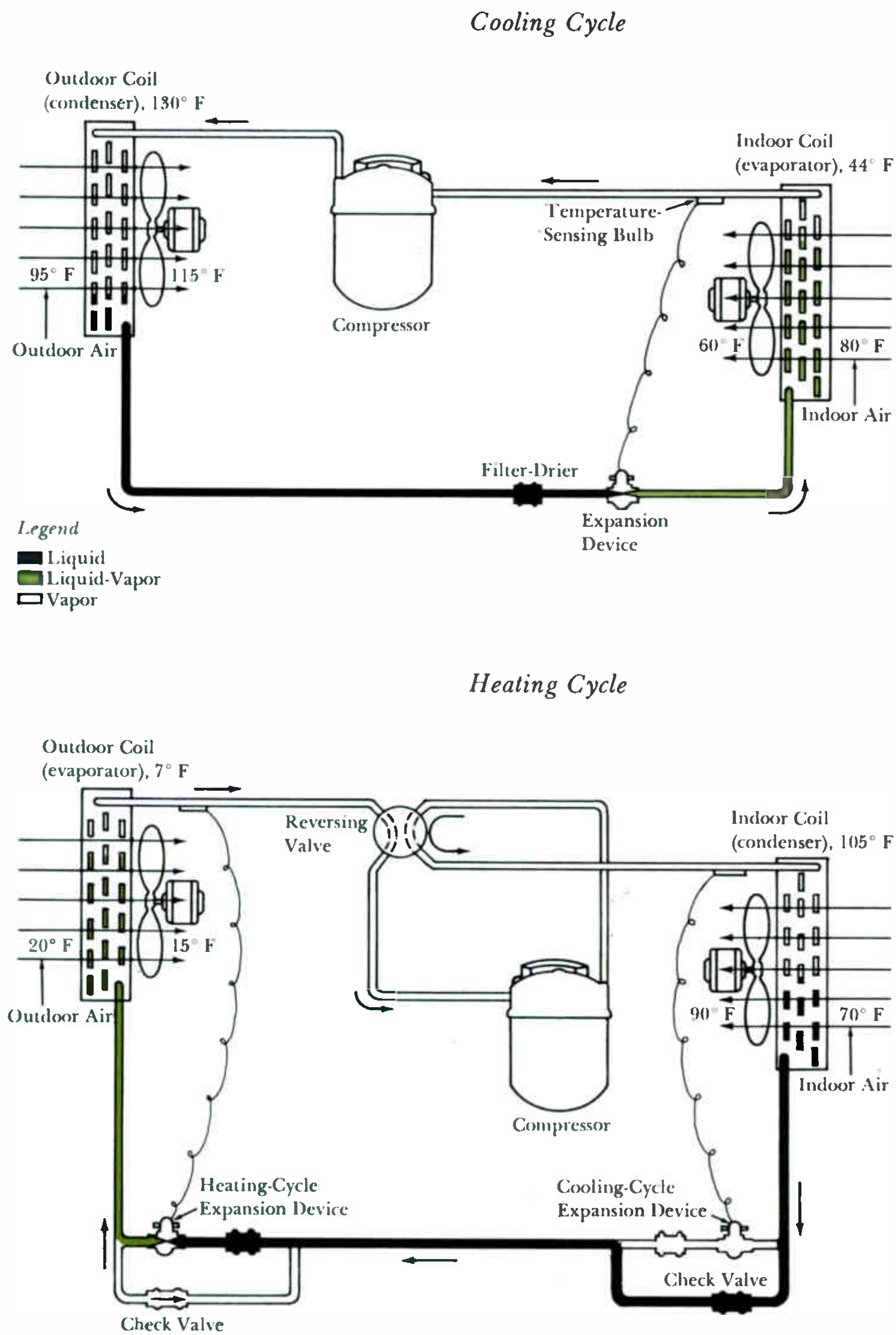


1—Conventional air-to-air nonreversible cooling cycle *(upper)* and a conventional reversible heat pump operating in the heating cycle *(lower)*. Typical air and refrigerant temperatures are included. The refrigerant expansion device in both cycles is a thermal expansion valve or a capillary tube, neither of which can control refrigerant flow throughout a wide range of operating conditions with complete reliability.

In *cooling*, the inability of conventional equipment to operate with low outdoor temperatures is an increasingly serious limitation as people come more and more to expect comfortable surroundings; places where people gather, such as restaurants and office buildings, often need interior cooling (no matter how cold it is outdoors) because of heat given off by lighting, by other electrical equipment, and by the people themselves. Moreover, many modern electrical installations such as computer facilities require critical control of temperature and air flow. (Using cool outdoor air for interior cooling usually is not practical because of the cost and space required for the ducting, blowers, and controls that would be needed to bring in outside air and to exhaust the same amount of air.)

This inability to operate a conventional cooling system when outdoor temperature is low is paradoxical at first glance; one would think that the lower the outside temperature, the more readily heat could be transferred from an interior space to the outside. In practice, though, it is not so, for reasons that will be discussed later. Briefly, conventional expansion controls lose control of refrigerant flow at low outdoor temperature, starving the evaporator and thereby causing frost buildup on the evaporator coil. If operation continues in this condition, the coil can become completely blocked with ice, resulting in compressor damage through flooding with liquid refrigerant. The new system, on the other hand, maintains control of refrigerant flow at all times.

In *heating*, the restriction of many conventional heat pumps to operation down to about 15 degrees outside temperature also stems from inability of the conventional expansion device to operate effectively over a wide temperature range. Selection and adjustment of the expansion device has to be a compromise, and at low outdoor temperature the resulting high compressor discharge temperatures may break down the refrigerant and the lubricating oil and thereby contaminate the system. The new system practically eliminates this restriction, heating at outside temperatures down to −20 degrees and thus making heat pumps practical in colder climates for the first time. (Some supplemental heating is generally required, of course, to satisfy the total heating load.)

Heat-Pump Principles

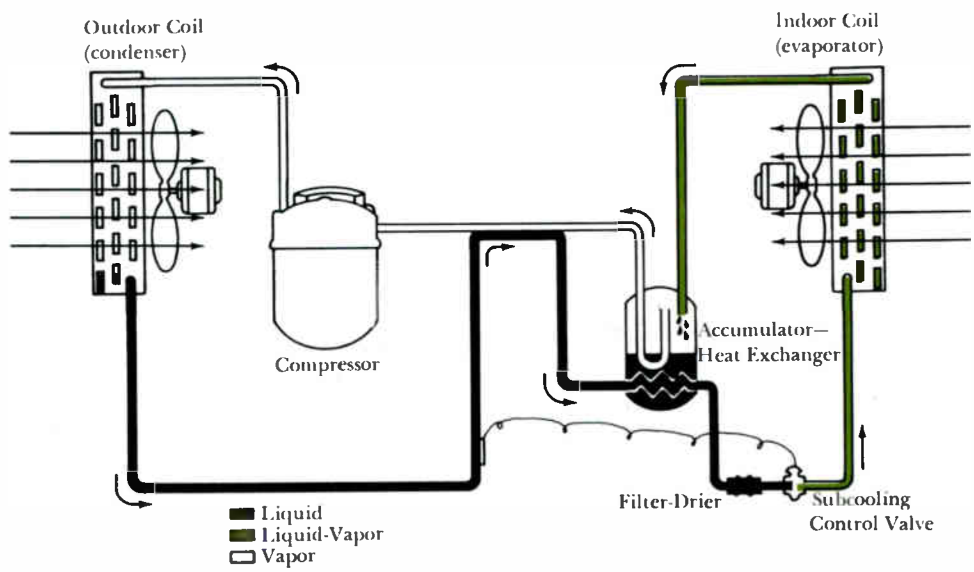
A heat pump, as the name implies, is a device for removing heat from one area and transporting it to another. Although the term is usually applied to *reversible* systems that can transport heat in either direction, an ordinary cooling unit also is really a heat pump—a nonreversible one.

Since heat flows from a warmer medium to a cooler one, heat pumps are designed to keep a circulating heat-exchange medium (refrigerant) at a lower temperature than the air it absorbs heat from in one part of the system and at a higher temperature than the air it releases heat to in another part. For cooling, the refrigerant absorbs heat from indoor air and releases it to outdoor air. For heating, it absorbs heat from outdoor air (which contains heat energy no matter how cold it is) and releases it to the indoor air.

Conventional Cooling Cycle—When the thermostat calls for cooling, the compressor drive motor starts (Fig. 1). Refrigerant gas leaving the compressor (which imparts energy to it in the form of heat) goes to the outdoor coil where it condenses to a liquid, giving up heat to the air as it does so. The liquid refrigerant flows on through an expansion device into the indoor coil; because its pressure has been reduced by expansion, the liquid evaporates in the indoor coil and in doing so absorbs heat from the indoor air. The refrigerant gas is then drawn into the compressor, and the cycle repeats.

Since reciprocating compressors pump out some of their lubricating oil, a mixture of oil and refrigerant circulates in the system; the oil has to be continuously returned to keep the compressor lubricated. A filter-drier in the system removes moisture and other contaminants.

Conventional Heating Cycle—A reversing valve controlled by a thermostat controls the direction of refrigerant flow through the two coils of a heat pump and through one of two expansion devices—one for cooling and one for heating (Fig. 1). Operation in the cooling cycle is similar to that of the nonreversible system just described. For heating, refrigerant flow in the circuit external to the compressor is reversed. The outdoor coil is now the evaporator, so the refrigerant picks up



2—Hi/Re/Li system cooling cycle, illustrated in a nonreversible system, replaces the conventional expansion device with a liquid subcooling control valve and an accumulator-heat exchanger. These components greatly improve reliability by preventing liquid refrigerant from reaching the compressor. They also extend operating range and improve efficiency.

heat there from outdoor air. The indoor coil is the condenser, so the refrigerant gives up heat there to indoor air.

Limitations of Conventional Systems

Cooling—In the conventional cycle, the expansion device is either a capillary tube or a thermal expansion valve. Its function is principally to regulate refrigerant flow to the evaporator in such a way as to wet the evaporator's surfaces (for good heat transfer) while preventing liquid from reaching the compressor.

Both devices require superheating of the gas in the evaporator; that is, heating it above the refrigerant's boiling point at a given pressure to make sure it remains free of suspended droplets. This superheating is accomplished by restricting refrigerant flow, with the expansion device, to the amount that can be superheated by the air drawn through the evaporator coil. It is done to insure that no liquid refrigerant reaches the compressor, because liquid in the compressor can damage the valves and also dilute the oil, resulting in inadequate lubrication. Part of the evaporator coil has to be used for superheating, but since the dry coil surfaces conduct heat less efficiently than wet surfaces would, heat transfer is reduced and therefore system efficiency is lowered. Also, evaporator superheat causes higher compressor discharge temperatures than would result if saturated gas were returned to the compressor.

Moreover, as outdoor temperatures drop, there is a corresponding drop in condensing pressure until, at about 60 degrees F, the pressure differential across the expansion device is insufficient to feed enough refrigerant to the evaporator. (It collects in the condenser.) As the evaporator becomes increasingly starved, the cooling capacity of the coil is drastically reduced and so the compressor has to rebalance at a lower evaporator pressure and temperature. As the coil surface temperature falls below 32 degrees F, frost accumulates on the coil. Continued operation can completely block the coil with ice, shutting off air flow through it and resulting in compressor failure from insufficient motor cooling, liquid flooding, or inadequate oil return.

Comparison of Conventional and Hi/Re/Li System Cooling Operation

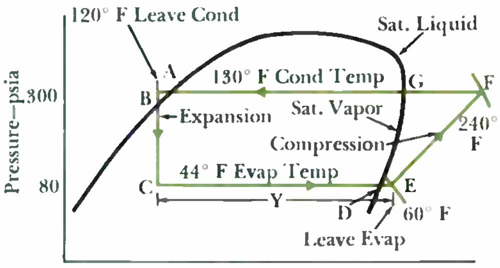
A conventional air-conditioning cooling system is represented by the upper pressure-enthalpy diagram, and the Hi/Re/Li system by the lower diagram.

In the conventional system, as the compressed refrigerant gives up its heat in the condenser, the pressure remains basically constant and there is a reduction in enthalpy (heat content) of each pound of refrigerant. Where this line intersects the diagonal line to the left (*A*), all the refrigerant has condensed to a liquid; the refrigerant is said to be saturated in the liquid state. With 10 degrees subcooling obtained in the condenser, the saturated liquid is further cooled to 120 degrees (*B*), at which point it leaves the condenser and enters the expansion valve. Flow through the expansion valve causes a reduction in pressure (*BC*). This large reduction in pressure causes formation of a considerable amount of flash gas, which can be seen from the spreading of the vertical line away from the liquid saturation line as the pressure becomes lower. Evaporator pressure and temperature are relatively constant as the refrigerant absorbs heat; therefore, the enthalpy increases. As enthalpy increases toward the right, the horizontal line intersects the saturated vapor line (*D*). This means that all the liquid has been evaporated but there is no superheat.

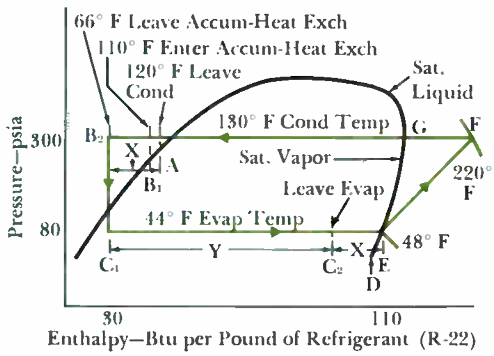
Since the conventional system controlled by a thermal expansion valve or capillary tube requires superheat leaving the evaporator, the enthalpy pickup continues beyond the saturated line to provide 16 degrees superheat to the compressor suction (*DE*). At this point, the compressor adds enthalpy to the refrigerant by raising its pressure and temperature to approximately 312 psia and 240 degrees F, a highly superheated condition. This gas enters the condenser (*F*), where it is first desuperheated to the saturation line (*G*) and then condensed and subcooled.

The Hi/Re/Li system is illustrated in the lower diagram at the same evaporator and condenser temperatures to simplify the comparison. Refrigerant leaves the condenser (*A*) at the same 120 degrees F with 10 degrees subcooling, but then enters the suction-line heat exchanger and is further subcooled to 110 degrees (AB_1). It then enters the accumulator-heat exchanger (B_1) and is subcooled to 66 degrees, at which point it enters the expansion valve (B_2) and is expanded to the lower pressure as it enters the evaporater (C_1). Now the heat-absorbing capability of the refrigerant introduced to the evaporator is far greater than it was in the conventional system, since it can absorb a quantity of heat equal to $Y + X$ rather than only *Y*. However, the compressor can only pump a given volume of gas when balanced with the evaporator and condenser. And, since it can only provide the heat removal value of *Y*, the refrigerant leaving the evaporator coil (C_2) is not fully evaporated but contains a considerable amount of liquid with vapor. This excess liquid returns to the accumulator where it, along with the small liquid flow into the suction line through the oil bleed, is evaporated. The source of heat to provide this final evaporation is the high-temperature refrigerant liquid leaving the condenser. Therefore, the system is completely in balance with the same work *Y* achieved in the evaporator, and only the interchange of heat *X* provided in the two heat exchangers. The vapor entering the compressor (*E*) is now superheated only a few degrees, so the discharge temperature (*F*) is lower than in the conventional system.

Conventional System

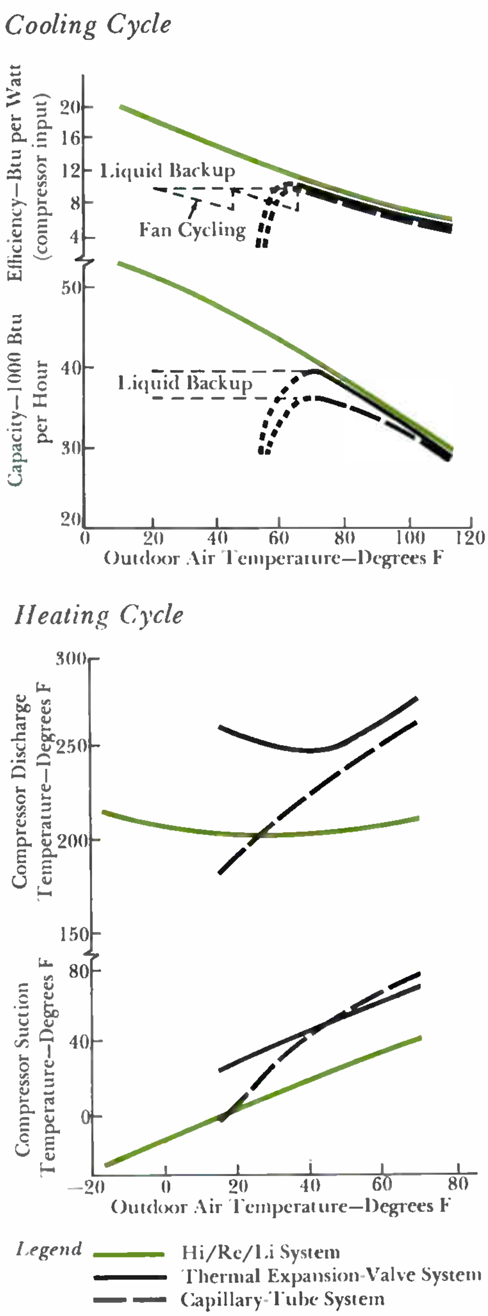


Hi/Re/Li System



X = Heat Exchange in Suction-Line and Accumulator Heat Exchangers

Y = Heat Absorbed in Evaporator Coil



3—Compressor efficiency and system capacity in the cooling cycle *(upper)* are higher at lower outdoor ambients in the Hi/Re/Li system than in conventional systems, even though auxiliary equipment is applied with the latter. Light dashed portions of the curves show performance with auxiliary equipment; heavier dashed portions show what it would be without auxiliaries. In the heating cycle *(lower)*, suction and discharge temperatures are significantly lower than in conventional systems.

The use of auxiliary equipment, such as condenser air dampers, refrigerant liquid backup controls, and condenser-fan cycling controls to reduce condenser capacity, can raise compressor discharge pressures and permit low-ambient cooling, but only at the expense of reducing capacity and efficiency. Also, liquid backup requires some means of storage to accommodate the extra liquid during conditions when part of the refrigerant is not in use. Damper mechanisms sometimes require provision for ice removal should precipitation and freezing temperatures be encountered. In addition to the cost penalties, such auxiliary equipment complicates a system and increases the amount of maintenance required.

Heating—Only 50 to 60 percent of the refrigerant is used at times during the conventional heating cycle, because the amount charged into the system is based on cooling-cycle requirements. (In heating, the amount used varies with outdoor temperature.) The remainder must be stored elsewhere in the system. Since the refrigerant is metered to the evaporator to achieve superheating, it cannot be stored there; consequently, in most conventional systems the excess refrigerant collects in the condenser, occupying as much as half of the coil. This reduces the heat-transfer efficiency of the indoor coil (condenser), raising compressor discharge pressure and temperature.

If a reversal from heating to cooling is required, to defrost the outdoor coil, the rapid change in pressure drives liquid over to the compressor. Also, the vapor collapses rapidly in the cold outdoor coil under this condition, and the sudden condensation can cause a momentary reversal in discharge and suction pressures at the compressor. As a result, expansion rather than compression takes place momentarily through the compressor. This expansion may drive oil out of the compressor, leaving it running without adequate lubrication until the oil can be returned through the system.

Some conventional systems have suction-line accumulators (vapor-liquid separation devices) to bar liquid from the compressor, but they have no means of rapidly returning the refrigerant to the system where it may be needed. Instead, it must slowly return through an oil-return bleed. Furthermore, the liquid refrigerant returned with the oil dilutes the oil.

Extremely high compressor discharge temperatures may be encountered with heat pumps during low-temperature heating operation because of high evaporator superheat and high compressor discharge pressure. This high temperature can cause refrigerant and oil to break down and form harmful acids, a factor that has often necessitated a compressor operating limit or a limitation of heat-pump application to milder climates. System inefficiencies and oil-return problems are also more prevalent at low outdoor temperature because of the low refrigerant flows involved and the problems of refrigerant distribution.

Hi/Re/Li System

Cooling—The Hi/Re/Li system employs three of the same basic components as conventional systems: compressor, condenser, and evaporator. But instead of a capillary tube or thermal expansion valve, it has a new type of metering device called a liquid subcooling control valve which is used in combination with an accumulator-heat exchanger (Fig. 2). The subcooling control valve responds to the temperature and pressure of the liquid leaving the condenser. That is, if there is too much refrigerant in the condenser coil, the temperature-sensing bulb senses that the liquid is colder and opens the valve wider to drain more liquid from the coil; if there is too little, the bulb senses that the liquid is warmer and throttles the valve to hold more liquid in the coil. This action maintains approximately 10 degrees of subcooling in the liquid leaving the condenser. ("Subcooling" means keeping the liquid temperature below the boiling point at a given pressure.) For example, if condenser operating temperature is 130 degrees, the liquid leaves it at 120 degrees.

The liquid then flows in contact with the cool suction gas line, which lowers the temperature another 10 degrees (to 110 degrees in this example.) Finally, about 45 degrees of additional subcooling occurs as the liquid passes through the accumulator-heat exchanger just before expansion by the subcooling control valve. The increased refrigeration effect given each pound of refrigerant through subcooling causes refrigerant to be introduced into the evaporator beyond the evaporation rate. This is an inherent characteristic of the system: since the refrigerant is highly subcooled, less flow is required to the evaporator. However, the compressor is circulating the same amount of refrigerant, which is in excess of the gas flow leaving the evaporator. Therefore, excess liquid is fed to the evaporator, wetting the entire coil surfaces. A mixture of liquid and vapor leaves the evaporator, but the vapor is separated from the liquid in the accumulator and the liquid is evaporated there by heat exchange with the condenser liquid. Consequently, the evaporator doesn't have to use surface for superheat just to keep liquid droplets out of the compressor. Also, overfeeding the evaporator makes refrigerant distribution through parallel circuits in the evaporator much less critical.

The saturated gas in the upper section of the accumulator-heat exchanger is drawn into a suction U tube and returned to the compressor. This U tube has a small oil-return bleed that allows a mixture of refrigerant liquid and oil to be drawn into the suction gas. The warm condenser liquid in contact with the suction line boils off the refrigerant liquid, at no thermodynamic loss, and the oil returns to the compressor.

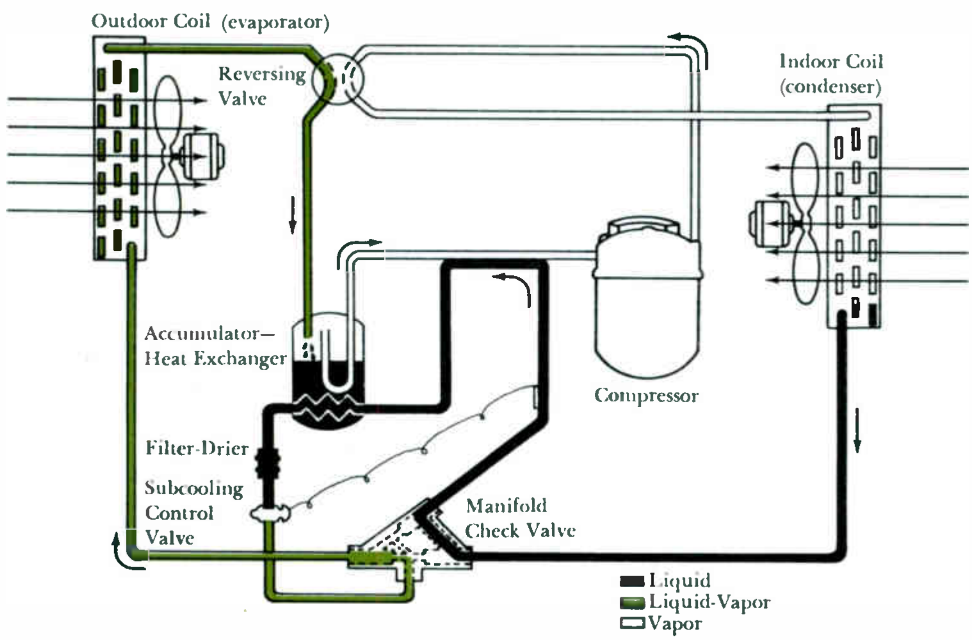
Liquid subcooling gives the refrigerant much more heat-absorbing capability in the evaporator. Pressure-enthalpy diagrams illustrate this effect and also show how the system functions to overfeed the evaporator under all conditions. (See *Comparison of Conventional and Hi/Re/Li System Cooling Operation*, page 75.)

Performance, unlike that of conventional systems, improves at lower outdoor temperatures because condensing pressure is permitted to fall with decreasing outdoor temperatures. Capacity increases and power input decreases (Fig. 3).

Heating—Heating operation with the reversible Hi/Re/Li system also involves basic differences from conventional systems (Fig. 4). An important aspect is the absence of liquid storage in the condenser, since the subcooling control valve keeps it adequately drained. Excess liquid refrigerant is stored in the accumulator, permitting lower compressor discharge pressures and temperatures. The accumulator is sized to handle the excess refrigerant, precluding the possibility of liquid flooding the compressor during a reversal from heating to cooling for defrosting. Furthermore, the gas formed from the small quantity of liquid in the indoor coil first flows to the accumulator-heat exchanger, where it quickly changes state due to contact with the large volume of stored cold liquid. Therefore, there is no prolonged expansion through the compressor, which could wash out the compressor oil.

Effective condenser drainage and low suction superheat also result in significantly lower discharge temperatures (Fig. 3). Conventional system operation is shown cut off at about 15 degrees F outdoor temperature to indicate that, with the thermal expansion system, increasingly high discharge temperatures may limit operation. The new system has lower and almost constant discharge temperatures over its entire range of operation. The lower suction temperatures shown result from the lower superheat. Compressor discharge pressures also are lower, but suction pressure is high for optimum compressor efficiency. In Fig. 3, the capillary-tube system seems to have the lowest discharge temperatures over the lower portion of its range. This would be significant if it weren't for the fact that compressor flooding is occurring in this region; it is the effect of motor and compressor cooling by liquid refrigerant that causes the apparent decrease in discharge temperatures.

Application Advantages—The new system permits more flexibility in the relative positioning of indoor and outdoor sections of split systems because many of the oil-return problems are eliminated. The amount of refrigerant charged into the system is less critical, and feeding excess refrigerant to the evaporator eliminates the possibility of one or more parallel circuits becoming starved.



4—Hi/Re/Li system heating cycle, like the conventional heating cycle, requires less refrigerant than does the cooling cycle. However, the system has an accumulator-heat exchanger so the excess doesn't have to collect in the condenser and reduce effective condensing area there.

Shaft Alignment Analysis Prevents Shaft and Bearing Failures

C. T. Yarbrough

Large rotating machines such as flywheel m-g sets are subject to shaft misalignment. This dangerous condition can be detected and measured accurately by an economical optical analysis method, and the misalignment is then readily corrected.

Proper shaft and bearing alignment is necessary when large rotating machines are installed, but, unfortunately, correct alignment at installation is no guarantee the equipment will remain aligned. As soon as the units are placed on the foundation, their weight can produce settling, and foundations rarely settle evenly. Also, torque forces tend to twist and tilt the bedplates. In time, some bearings are thrown out of alignment. Consequently, the shafts of heavy rotating equipment should be checked periodically for proper alignment. If they are not, shaft or bearing failures can easily result.

The shaft center line of heavy rotating equipment is not a straight line; instead, the shaft sags slightly between its supporting bearings because of its weight and the weight of the armatures and other components on it. Consequently, the proper bearing elevations are not necessarily in a horizontal plane. Determining and achieving these proper bearing elevations is important, because then the entire rotating assembly is cradled by the oil films in the bearings; moreover, shaft stresses then are only the bending moments between supports due to weight and the torques imposed by the function of the assembly.

For example, a typical large assembly—a multiunit flywheel m-g set—comprises a central driving motor, a flywheel, and three dc generators on each side of the motor. The bearings at the center of such an assembly are at the same elevation, but the shaft center line runs uphill toward each end (Fig. 1). (The correct alignment curve is exaggerated in the simplified elevation illustrations in this article; actually, center-line elevation at each end of a typical large multiunit assembly is approximately 0.02 inch in 40 feet.) In plan view, the shaft center line should be a true straight line.

The nature of the failures that can result from misalignment depends on the manner in which the bearings are misaligned. For example, if a foundation has settled more on one side of a unit than on the other, some bearings are overloaded. The overloaded bearings will be damaged by melting of the babbitt liner, eventually causing bearing failure. In one 12,000-horsepower flywheel m-g set, measurement of bedplate and shaft elevations showed that the bedplate had settled excessively near the right end (Fig. 2). This settling put an extra load on one bearing, which had not settled as much as adjacent bearings. However, even though this *bearing* had not settled as much, the *shaft* center-line plot showed a severe drop there (0.132 inch). Inspection revealed that from 0.012 to 0.095 inch of babbitt had been melted out across the 18-inch length of the self-aligning bearing! The operators were unaware of the bearing failure because there had not yet been any external evidence of trouble. The bearing was replaced and temporary elevation corrections were made at some of the pedestals to keep the set running safely until a longer shutdown could be scheduled for complete realignment.

Shaft misalignment also causes bending strains in the shaft. The larger the misalignment, the larger the amplitude of strain and the earlier the endurance limit of the material is reached. Cracks then develop in the shaft surface, usually at points of stress concentration such as keyways and fillets. A crack can progress unnoticed until the shaft breaks without warning. In one 10,500-horsepower flywheel m-g set supplying power for a large blooming mill, an undetected foundation settling had forced the 80-foot shaft assembly severely out of alignment. As the 30-ton motor armature spun six 7-ton generator armatures and a 64-ton flywheel, the shaft flexed excessively at each revolution to absorb the misalignment. A fatigue crack developed in a keyway and, suddenly, the shaft broke. The ragged faces of the break forced the two parts of the shaft axially, bending the other generator shafts on that side of the set, destroying three bearing pedestals, and forcing the commutator risers into the brush holders. Even though major damage was confined to one side of the m-g set, the breakdown cost the company millions in lost production time and in repairs.

Alignment Methods

Four methods of alignment have been developed over the years—tight wire, bore-sight optical, level and feeler gage, and external optical. Only the external optical method is really satisfactory.

Only new installations can be aligned by the *tight-wire* technique, because alignment is performed before any of the rotors or shafts are in place. A wire is stretched the length of the assembly, down the center of the bore, and radial dimensions between the wire and the bearing surfaces are measured accurately. The analysis must be done by a highly skilled operator; even then different operators may get different readings, and a single operator often has trouble duplicating his own readings. Temperature changes and air movement also may cause inaccurate readings. Moreover, all the weight ought to be in place before testing a new assembly for final alignment.

Bore-sighting also must be accomplished before rotors are in place. The operator places a centered target in each bearing and sights down the bore with a telescope. The bearings can then be set at the elevations corresponding to a correct alignment curve. Again, this method cannot reveal initial distortion induced by the weight of the rotor and shaft, and it cannot be applied to a unit already in service.

To make a check with *level and feeler gage*, all bearing pedestal caps are removed, all couplings loosened, and the shafts checked with a shaft level. A feeler gage is then inserted between the coupling mating faces at top, bottom, and each side to see if the faces are parallel. This technique makes in-service alignment analysis possible, but it is time-consuming—an analysis of a nine-bearing flywheel m-g set cannot be accomplished during an eight-hour shutdown. It also

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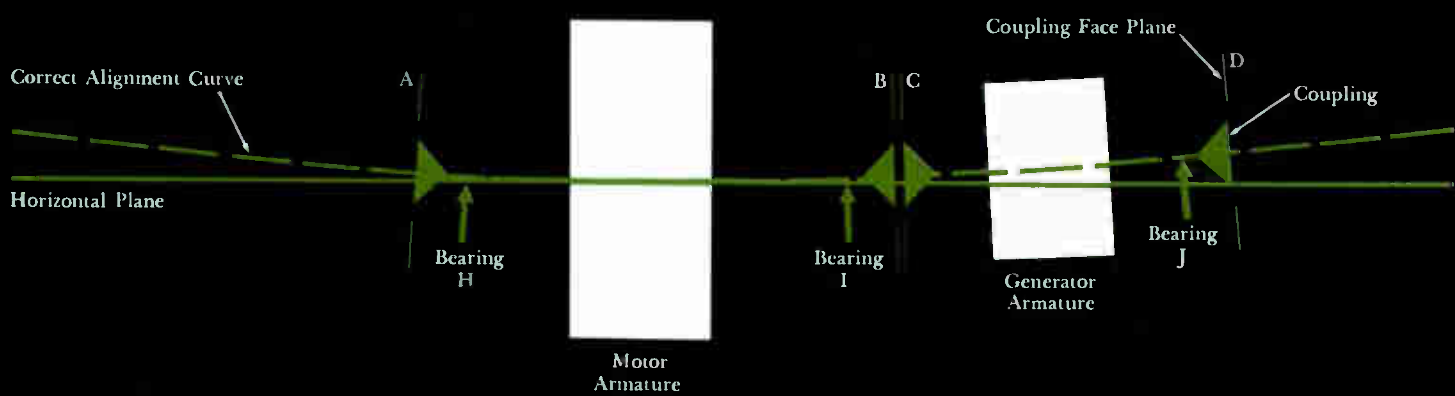
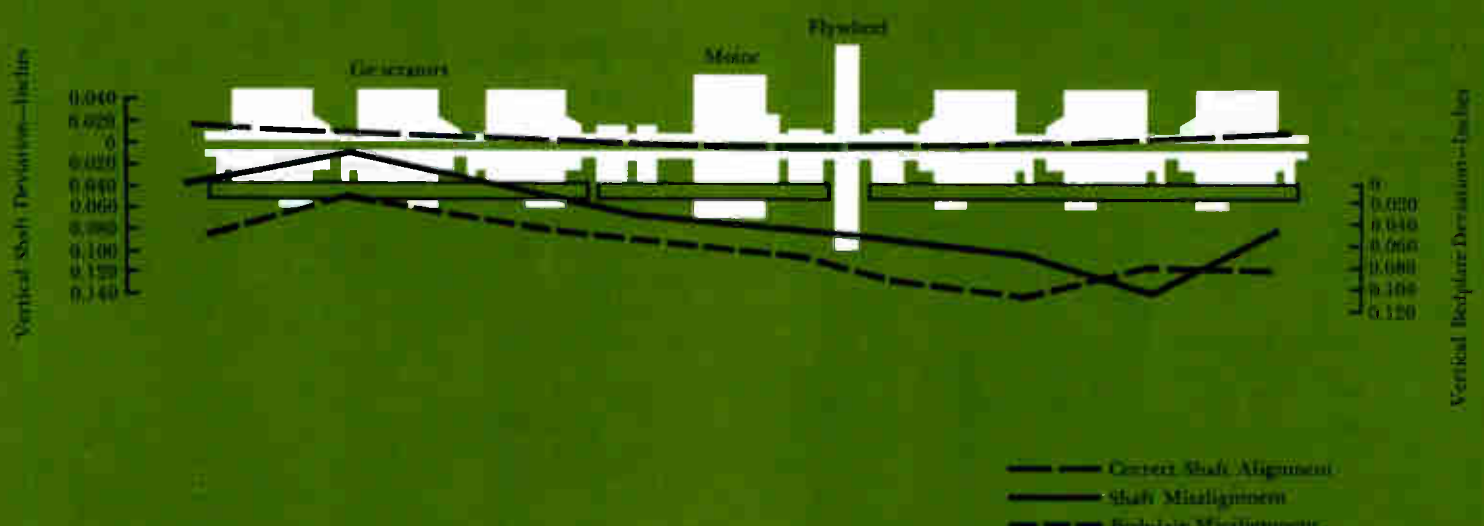


1—A shaft center line, in elevation view, is not a straight line because the weight of heavy elements makes it sag between bearings. In this simplified diagram, the sag between bearings *H* and *I* tilts the coupling faces *A* and *B* at the ends of the motor shaft so that they are not vertical. Because the planes of mating coupling faces must be matched accurately to prevent flexing strains on couplings and shafts, the outboard bearing (*J*) of the adjacent unit must be elevated as indicated.



2—Bedplate settling near right end of one large m-g set caused severe overloading of the second bearing from the right, and measurements of vertical shaft alignment showed that this bearing was badly damaged. Besides bearing damage, such misalignment can cause the shaft to break. Shims are calculated and inserted under bearing pedestals to correct the shaft alignment.

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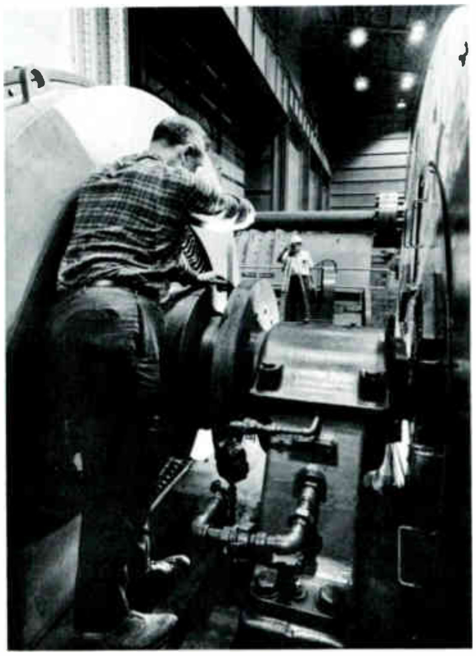

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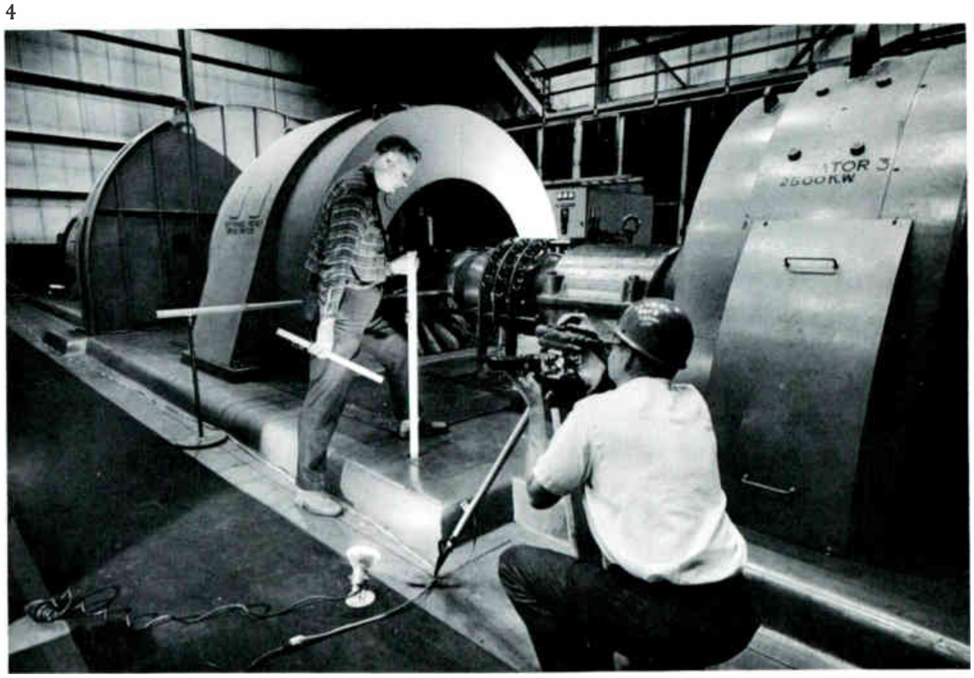

3—Vertical shaft alignment is determined with a sighting telescope. The readings are taken on a sighting scale (foreground) held vertically with one end touching the top of the shaft or coupling. (Photos courtesy of Jones & Laughlin Steel Corporation.)

4—Vertical bedplate alignment is determined in much the same way as shaft alignment—by sighting on a calibrated scale held vertically on the bedplate.

5—Lateral shaft alignment is checked by establishing a vertical reference plane with the telescope. Distances from this plane to the shaft are measured with calibrated fixtures.

can be misleading in some units due to the sag of a shaft that extends beyond a bearing. In Fig. 1, for example, the generator armature is supported by bearings *I* and *J*. Proper support requires a tight coupling at *B-C*; if these coupling bolts are loosened, the shaft center line drops at the overhanging coupling. The coupling faces part under the shaft, and a feeler gage would read this as a misalignment. Obviously, a shaft center-line analysis should be performed with all couplings bolted so that the rotating assembly is measured intact.

In the Westinghouse *external optical* alignment service, the couplings do remain bolted together. Moreover, a complete vertical and lateral alignment analysis is accomplished without dismantling any bearings; the excessive time previously required with level and feeler gage is a thing of the past. This optical alignment analysis is faster, more accurate, and more economical than other alignment methods. It can be accomplished during one or two eight-hour shutdown periods.

The technique relies on the ability of a sighting telescope to establish accurate horizontal and vertical reference planes. To establish a horizontal reference plane, the telescope is leveled and swung in a horizontal arc. Distances from this reference plane to the shaft are measured at many points along the assembly to obtain the elevation view of the shaft center line. Similarly, the plan view is obtained by establishing a vertical reference plane and measuring from it to the shaft. Measurements are made at exposed shafting, on journals, and at couplings.

Optical Analysis Procedure

The engineers conducting the alignment survey first establish the horizontal reference plane. They set up a transit to one side of the middle portion of the machine and swing it through a horizontal arc, keeping the bubble centered. On a large set it usually is necessary to take sights from several positions. In each move, the engineer cross-checks with at least two points to calibrate the difference in elevation of the transit at the new position. That is, sighting arcs overlap at the shaft to maintain continuity of the horizontal reference plane and the elevation readings. Accuracy is within 0.003 inch at 100 feet, and most vertical readings are taken from within 20 feet. Readings are taken from as many points as possible along the top of the shaft, from the center out toward the ends of the unit.

A scale held vertically is used as the sighting target (Fig. 3). This scale is calibrated accurately in tenths of an inch, and the sighting telescope has an optical vernier to read between the 0.1-inch marks to 0.001 inch. Special fixtures pass through oil-ring inspection holes so that readings can be taken right off the top surfaces of the journals. These readings establish the elevations of the top surfaces of the shaft, journals, and couplings.

Shaft and coupling diameters are then found with a "pi tape." The pi tape is easier to use than a large micrometer; it is simply wrapped around the clean shaft. Although it actually measures the periphery, it is calibrated to read diameter directly in thousandths of an inch. (This

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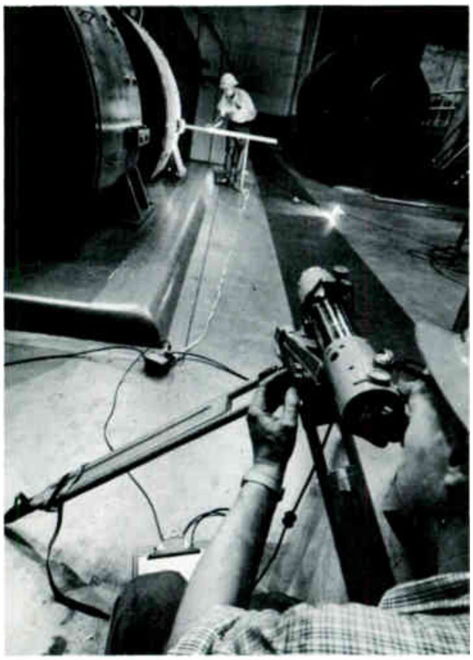


reading is accurate to within 0.002 inch.) On covered journals, the diameter is taken from the manufacturer's drawing. (Westinghouse manufacturing tolerance is +0.000, −0.003 inch on large journals.) Radius dimensions (one-half the diameters) are then added to the shaft contact readings taken with the telescope to find the shaft center line.

In addition to the shaft measurements, an elevation check also is run on the bedplate by measuring from both sides of the bedplate on the center line of the bearing pedestals (Fig. 4). Large assemblies are supported by up to three bedplate structures resting on a common foundation. The bedplates should follow the correct alignment curve—level in the center under the motor and flywheel, and rising a small amount toward the generators. However, after a large assembly has been in service, weight and torque forces usually have caused considerable movement and change in the elevation of the bedplates.

A certified elevation drawing of the shaft center line and bedplate is then made for the customer, with the elevation curves superimposed on it (Fig. 2). The locations and amounts of misalignment are determined from these plots of actual measured shaft and bedplate elevations.

To measure lateral shaft alignment, the telescope is set up near one end and to one side of the m-g set, and at the same height as the shaft center line (Fig. 5). Vertical cross hairs establish the vertical plane, which is the optical alignment reference.

A special fixture is used to transmit the lateral dimensions from the shaft surfaces out to the line of sight. This fixture is carefully aligned so that it is horizontal and also perpendicular to the shaft. Again, half of the shaft diameter must be added for plotting the lateral center-line alignment curve.

Correcting Misalignment

After the plot of plan and elevation misalignment of shaft center line is made, the next step is to observe any sharp changes in direction and decide where shims should be inserted under the bearing pedestals to correct the misalignment.

To raise the shaft, shims are added on both sides of the bearing pedestal. To shift the shaft sideways, the desired amount of shim is added to one side of the bearing pedestal while subtracting shims from the other side; this rotates the pedestal about a pivot point between the hold-down bolts and shifts the shaft center line laterally.

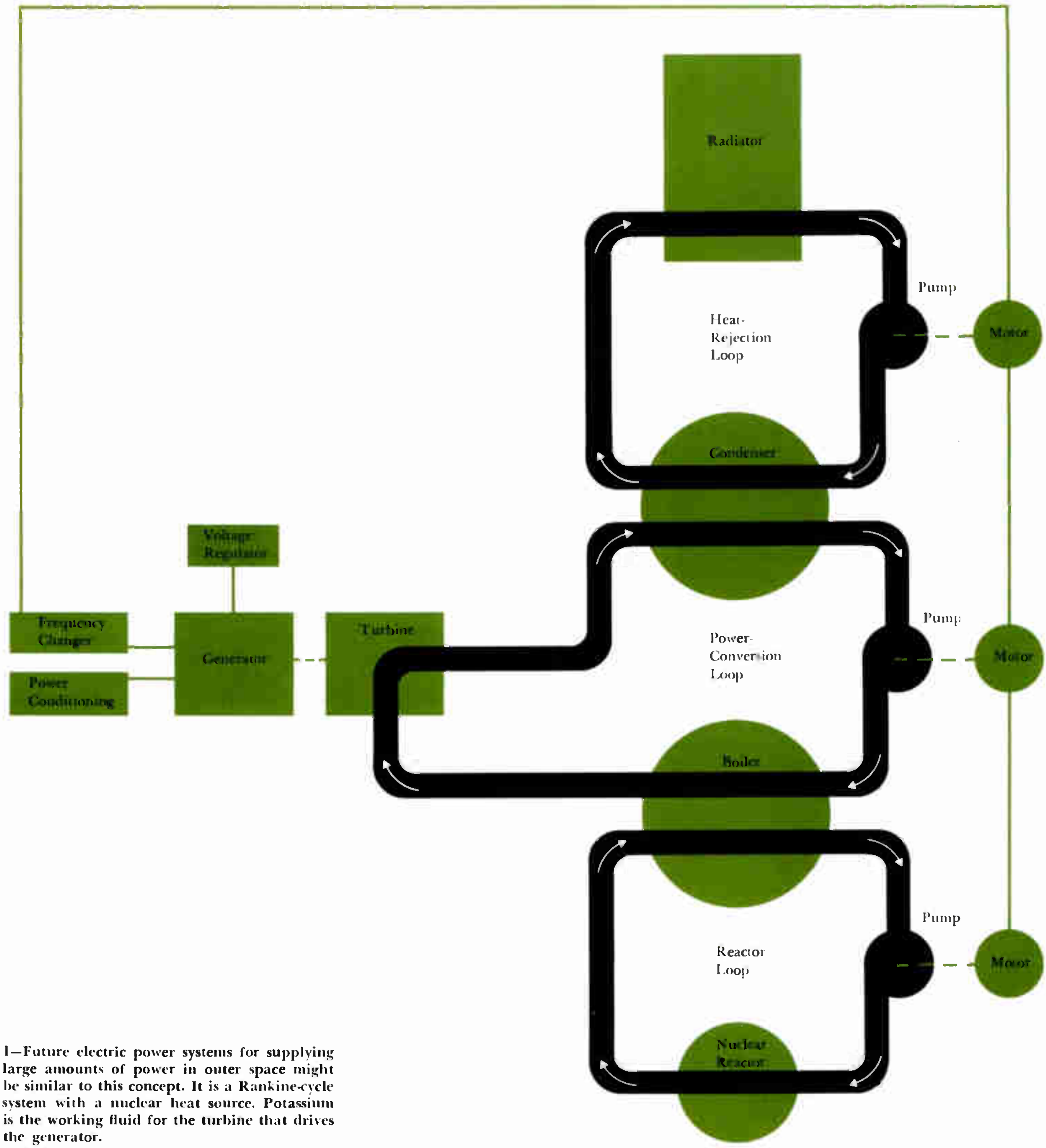
This lateral correction method is a Westinghouse innovation that saves much time and expense. The conventional method has been to slide the pedestal laterally, drill and ream the pedestal and bedplate holes for the alignment dowels oversize, and then make and install new oversize dowels; sometimes bolt holes have to be drilled oversize also. In the new method, dowels need not be changed nor bolt holes bored out. The dowels are pulled and the hold-down bolts are loosened only. Jacks raise the shaft, which raises the pedestal, and shims are slid under the pedestal according to the calculated schedule to correct all misalignment. Dowels are reinserted and bolts tightened, and alignment is given a final check.

Conclusion

The Westinghouse optical alignment service assures correct shaft alignment to within a few mils, and it is fast and economical. An alignment check increases the safety of those working around the machine and can prevent catastrophic loss of the service of a vital assembly. It also can detect excessive bearing wear and thus prevent unscheduled outages. The service should be used at installation and at yearly intervals thereafter.

The LMCD-II Generator: An Experimental Tool to Evaluate Space Electric Power System Problems

P. H. Scheffler



1—Future electric power systems for supplying large amounts of power in outer space might be similar to this concept. It is a Rankine-cycle system with a nuclear heat source. Potassium is the working fluid for the turbine that drives the generator.

Nuclear-heated Rankine-cycle power systems will be needed to provide large amounts of electric power for long space missions. A rotating inductor generator has been built and tested to define operating characteristics and to evaluate problem areas.

Orbiting space stations, manned interplanetary probes, lunar exploration craft, and other vehicles planned for carrying men and instruments in the hostile environment of outer space require highly reliable electric generating equipment to power their instruments, communications equipment, life-support systems, and other essential loads. Without electric power, any spacecraft except such passive objects as radio signal reflectors are useless.

Present-day space vehicles have generally been able to use solar cells and batteries for their power needs because their missions have been short, power requirements low, or both. Future vehicles, however, will carry larger instrument or personnel loads, will be sent on longer missions, and may have electric propulsion systems; they will require much larger amounts of electric power—hundreds or thousands of kilowatts. When manned bases are established on the moon, they too will require large amounts of power. Moreover, the power will have to be generated with equipment of high reliability, long life, and low specific weight.

The concept that shows greatest promise for meeting these requirements in the foreseeable future is a system consisting of a compact nuclear reactor heating the working fluid for a turbine generator (Fig. 1). A nuclear reactor is necessary because it is the only energy source with a specific weight consistent with the payload capabilities of proposed launch vehicles.

The choice of the turbine working fluid is dictated by the need for high system temperatures. Unused heat from the turbine exhaust must be removed, and the only way to do so in outer space is by radiation. Since the heat flow from a radiator is proportional to the fourth power of its absolute temperature, a high turbine exhaust temperature is necessary to keep radiator size and weight within practical bounds. For good power plant efficiency, turbine inlet temperature (absolute) must be about a third higher than exhaust temperature. These temperature levels dictate the use of a turbine working fluid with a high boiling point so that the desired temperature can be obtained at an acceptable pressure level. The alkali metals, especially potassium, best meet this requirement.

Such a system imposes several stringent operating conditions on the generator. First, because of its close proximity to the turbine, the generator will be exposed to the turbine working fluid—alkali-metal vapor. (It is not considered feasible to provide a zero-leakage seal between turbine and generator.) Therefore, to prevent contamination of the working fluid, generator cooling and lubrication must be accomplished with the power-system condensate. System studies indicate that a portion of the condensate could be cooled to 600 degrees F for this purpose. Second, turbine speed has to be high to achieve the required high ratio of power output to size.

The radial-gap solid-rotor inductor generator was found to be best suited for such high rotor speeds and temperatures, primarily because of its simple rotor. The rotor contains no electrical windings: it is constructed from a solid forging of a material that resists corrosion from potassium and that can be heat-treated for an optimum combination of magnetic and mechanical properties. All electrical windings and other components with inherently low mechanical strength are in the stator and thus are not subjected to rotational stresses. This construction also allows the windings to be isolated from the potassium working fluid and thus protected from corrosion.

As the concept of the generator evolved and analytical considerations were completed, the need for an experimental device increased. This device was needed to define such basic design data as generator temperature distribution, stator internal pressure requirements, variation of electrical losses with operating temperature, variation of mechanical and fluid losses with coolant flow rate, and dynamic compatibility of the bearing, shaft seal, and rotor arrangement. Further, the manufacturing and fabrication problems inherent in such generators needed to be brought to light and evaluated. The first experimental generator built was designated LMCD-I (*L*iquid *M*etal *C*ooled *D*emonstration generator, version I). Its primary purposes were to evaluate the performance of the stator conductor insulation system at 1000 degrees F and to determine the effects of a ceramic bore seal on electrical characteristics. This generator was tested only in an air environment, rather than in a potassium environment.

LMCD-II Generator

Success of the LMCD-I led to the design of the LMCD-II generator. Its design criterion was that it incorporate all of the features known to be required in a nuclear space system electric generator, but that smaller more economic components be used. Accordingly, it incorporated liquid-metal bearing lubrication and generator cooling, and it was designed to produce 50 kva of electric power at 24,000 rpm.

The generator rotor, machined from a solid bar of alloy steel, consists basically of two sets of poles separated axially by a cylindrical core section (Figs. 2 and 3). Drilled passages provide a continuous coolant flow path through each pole.

The rotor is supported at each end by a hydrodynamic type of journal bearing developed at the Aerospace Electrical Division (Fig. 4). These bearings employ the pivoted-pad concept for good stability at high speed; each contains four pads, with each pad consisting of a titanium-carbide insert held in a titanium shoe. Each pad pivots on a tungsten-carbide ball, which seats in a hardened stainless-steel socket in the bearing housing and in a titanium-carbide socket on the pad. The journal surface is a tungsten-carbide sleeve mounted on the rotor shaft with a spring mount that compensates for diff-

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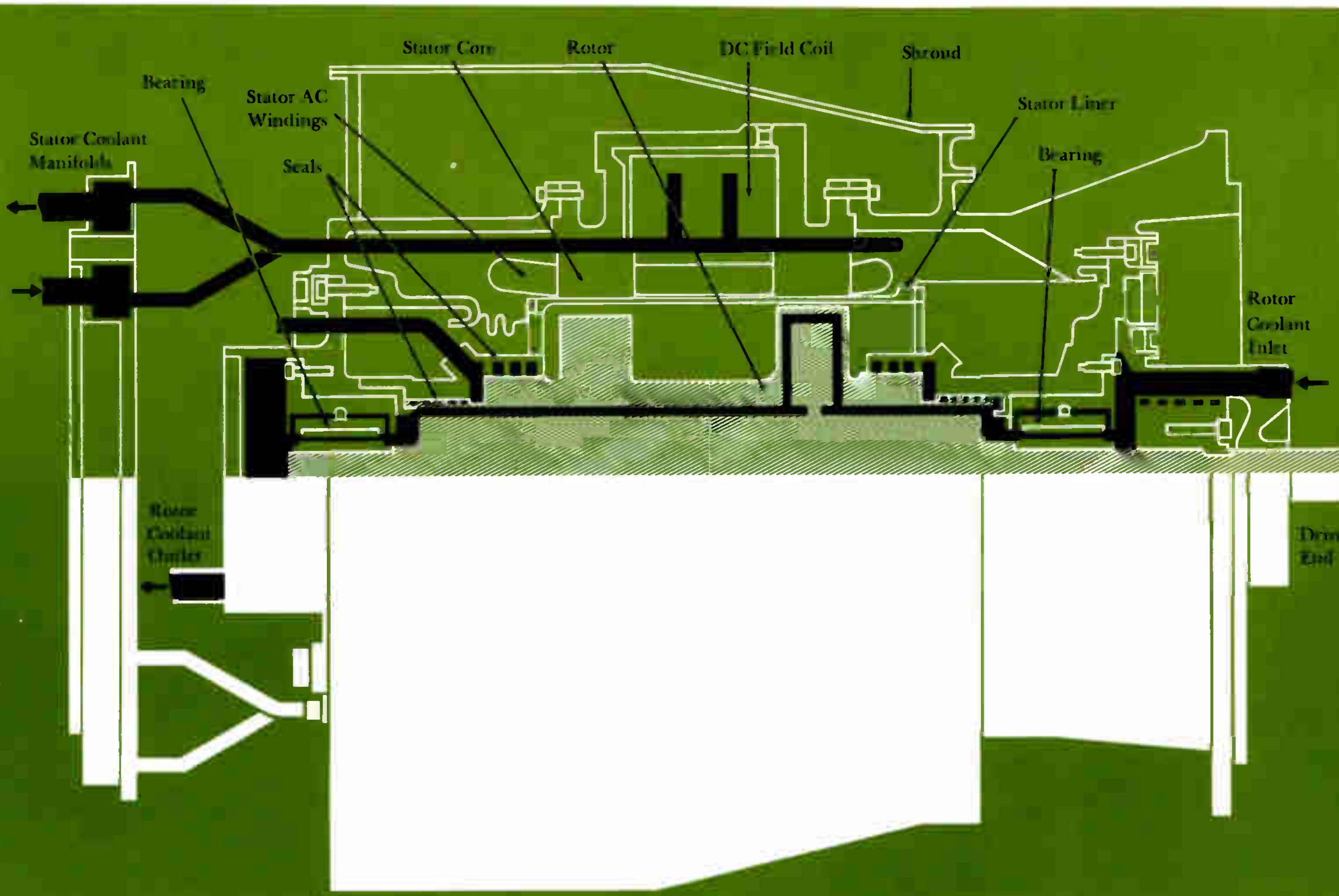


2—LMCD-II generator is a 50-kva inductor type built and tested to gather design and manufacturing data. It has a one-piece rotor for long life at high operating temperatures and rotational speeds. The generator is cooled and lubricated with liquid potassium.

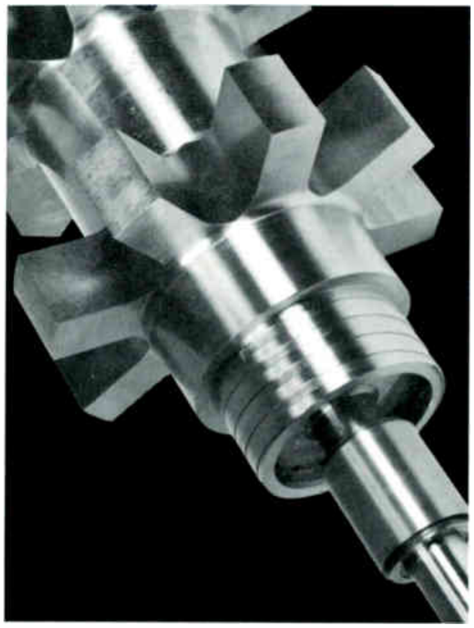
erential thermal expansion between rotor and sleeve.

The liquid-potassium lubricant is contained within the bearing housing by viscoseal shaft seals. These seals are essentially screw-type pumps, similar to the Archimedes pump, that continuously force leakage flow back into the bearing (Fig. 3). Holweck pumps are provided in parallel with these shaft seals at each end of the rotor. They are screw-thread mechanical molecular pumps with the threads on the stator, and they reduce the pressure in the rotor cavity to a value lower than that of the viscoseal discharge. This pressure reduction assures that the potassium within the rotor cavity will be in the form of superheated vapor, a necessary precaution to avoid the severe erosion of the stator bore seal that would result from liquid potassium being thrown from the high-speed rotor surfaces. These seals also were developed at the Aerospace Electrical Division.

The LMCD-II stator consists essentially of the magnetic frame, two stator cores, three-phase stator ac windings, and a toroidal dc field coil. The magnetic frame is made up of three forged rings of Hiperco 27 magnetic alloy brazed to 18 U-shaped stainless-steel cooling tubes, which are connected to inlet and outlet manifolds.

The stator cores are made of Hiperco 27 punchings and are located within the magnetic frame in the same planes as the rotor poles. Stator ac windings are formed from insulated nickel-clad copper wire. Insulation between phases and from the stator iron is provided by U-shaped aluminum-oxide channels of 0.020-inch wall thickness, and aluminum-oxide slot wedges secure the winding coils in the stator slots. Aluminum oxide was chosen because it combines good electrical resistance at the operating temperature with the relatively high thermal conductivity required to minimize the temperature gradient between coils and stator iron.

The field coil, located between the two stator cores, consists of 318 turns of rectangular wire similar to that used for the ac windings. It is separated into three sections by copper fins brazed directly to



3—LMCD-II generator rotor is machined from a solid steel forging. The bearing journal of the drive end is in the foreground; just beyond it are the rotating elements of the bearing seals, and beyond them the two sets of poles.

4—Rotor bearings are of pivoted-pad type designed for use with liquid potassium as the lubricant. Pads can be adjusted individually to control clearances and concentricity.

the stator cooling tubes, an arrangement needed to limit the temperature of the center turns to 1000 degrees F.

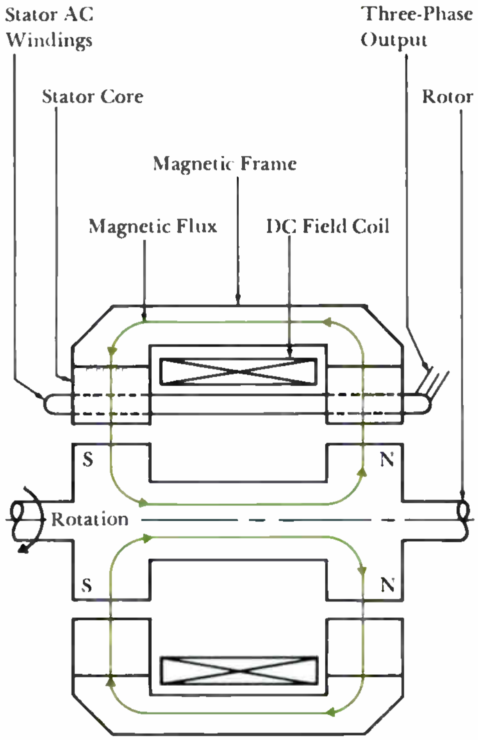
The generator is excited by energizing the field coil with direct current from an external source (Fig. 5). Magnetic flux goes through the magnetic frame and the rotor, with the circumferential space between rotor poles causing a concentration of flux in the area of the pole tips. Rotation of the rotor poles produces cyclic variations in the flux linking the individual stator coils and thereby generates ac voltage in the stator windings.

Since potassium is corrosive to the stator materials, a stator bore liner is included to isolate the stator from the potassium in the rotor cavity. It consists of an aluminum-oxide cylinder to which are brazed end pieces of iron-nickel alloy. At assembly, these end pieces are welded to the generator end bells to effect a hermetic seal. Aluminum oxide was chosen for the liner material because its high electrical resistivity minimizes the induced eddy-current losses in the liner resulting from the pulsating magnetic flux. Bearing and seal housings are bolted through piloted fits to the end bells, then seal-welded to prevent even traces of air from reaching the rotor cavity. (Potassium reacts violently with oxygen, producing much heat and forming potassium oxide; potassium oxide could clog passages, and it increases the corrosion of most materials by liquid potassium.)

The stator is enclosed by a stainless-steel external shroud, hermetically sealed to allow the stator to be pumped free of air to prevent the severe oxidation that otherwise would occur at operating temperatures.

LMCD-II Operation

Testing of the original LMCD-II configuration included three tests to 8000 rpm with Stoddard solvent as the test fluid, one test to 8500 rpm with liquid potassium, and one test to 16,000 rpm with a light petroleum-base oil. The Stoddard-solvent tests were made only to verify the mechanical alignment of the generator and to gain some indication of its dynamic characteristics; generator



5—Magnetic flux in the LMCD-II generator circulates through the magnetic frame and a stator core to the rotor and then back through the other stator core to close on itself through the frame. Rotation of the rotor poles causes cyclic variations in the flux, generating ac voltage in the stator windings.

speed was purposely restricted because of the marginal thermal properties of the solvent. The generator ran with almost no detectable vibration; measured coolant pressure drop agreed well with calculated values, and open-terminal voltage agreed closely with the calculated no-load saturation curve.

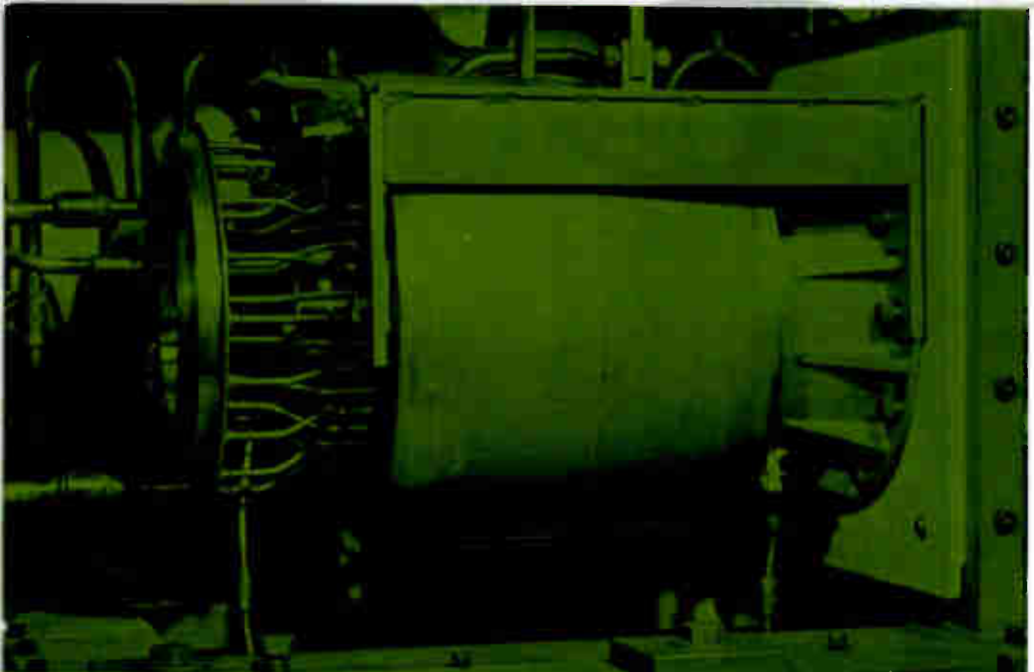
For the test with liquid potassium, the generator was welded into the Aerospace Electrical Division's liquid-metal test facility (Fig. 6). After all welds had been leak tested, the generator was enclosed in an ambient box and the test loop activated. Generator temperature was stabilized by controlling the temperature of its ambient box for 48 hours and by supplying 70 amperes of 400-cps current to all three phases of the windings. Liquid-potassium flow was stabilized without incident, first to the stator cooling circuit and then to the rotor cooling circuit. A smooth start was made, and the generator was accelerated to 8500 rpm in approximately three minutes. At this point, the potassium-loop instrumentation indicated that rotor flow had dropped to zero, so acceleration was stopped and the speed maintained at 8500 rpm. Attempts were made to reestablish rotor flow by decreasing discharge pressure and increasing inlet pressure, but without success. However, operation of the generator continued to be smooth and stable. Finally, a rather sharp inlet pressure pulse forced a small quantity of potassium past the generator drive-shaft seal. This contaminated an antifriction bearing in the drive stand to such an extent that further running was not feasible, so the test was terminated. Rundown of the generator was normal and gave no indication of distress.

The generator was removed to an argon-atmosphere glove box and disassembled. Examination showed all components to be in essentially new condition; no reason for the stoppage of the rotor flow could be seen.

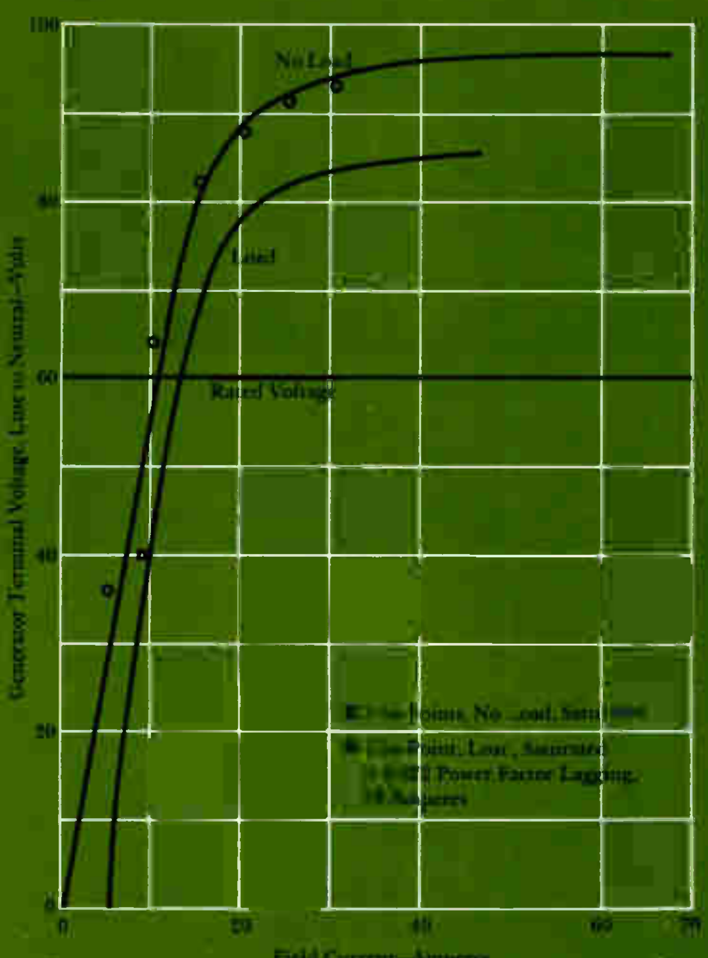
A second generator was then tested, using a light petroleum oil as the rotor coolant. Operation up to 8000 rpm was uneventful, exactly as in the tests with Stoddard solvent and liquid potassium. At higher speeds, however, the rotor inlet pressure required to maintain flow increased with speed until, at 16,000 rpm, flow became unstable. Speed was reduced to 12,000 rpm, and electrical performance was measured at that speed. Because the thermal conductivity of the test oil is much lower than that of liquid potassium, full-load test of the generator could not be approached. However, a current of 70 amperes per phase at a terminal voltage of 40 volts was attained with a field current of 8.5 amperes (Fig. 7).

After analysis of the flow data from these tests, it was concluded that the amount of rotating surface in the rotor flow path, which adds velocity to the fluid, was large compared with the stationary surfaces that "spoiled" this velocity. To maintain axial flow as speed was increased, pressure had to be applied to overcome the kinetic energy in the fluid. To avoid this necessity, the rotor flow passage was redesigned to incorporate a diffuser in both the inlet and discharge sections. These diffusers first convert rotor work into fluid kinetic energy at the inlet and then efficiently convert this energy back to rotor work at the discharge. Thus, rotor flow is maintained by rotation of the rotor and is essentially independent of inlet pressure. This rotor flow-path configuration has been simulated in a test rig and tested with Stoddard solvent over the entire generator speed range at flow rates up to 225 percent of that required by the LMCD-II generator. Stable flow was maintained at all speeds and flow rates. Inlet pressure requirements were low, being only that needed to deliver the flow to the center of the rotor; from that point, the diffusers pumped the flow through the rotor even at minimum rotor speed. Measurement of the shaft power required to drive the rotor indicated very little turbulence in the rotor flow path, even at maximum speed and flow.

The LMCD-II generators have recently been modified to incorporate this rotor configuration, and tests totaling about four hours have verified rotor flow stability. Specifically, bearing flows were shown to be entirely stable and free of any vapor or gas entrainment at all test speeds. Shaft seal performance was some-



6—Testing with liquid-potassium coolant and lubricant was performed in the Aerospace Electrical Division's liquid-metal test facility.



7—Electrical performance was measured at 12,000 rpm with oil as the rotor coolant and lubricant. A current of 70 amperes per phase at a terminal voltage of 40 volts was attained with a field current of 8.5 amperes. This performance agreed well with calculated values indicated by the curves.

what better than had been calculated previously, and rotor flow remained stable over a wide range of flow rates, discharge pressures, and rotor speeds. Electrical performance was not affected by the rotor modifications.

Conclusions

Although operating experience to date with the LMCD-II generator has not been extensive, it has provided a significant amount of knowledge and background information that will be of value in developing generators for the nuclear electric power systems required in the future. For example, the LMCD-II has yielded manufacturing and fabrication techniques, especially in the areas of assembly and alignment, that are expected to be applicable to future space generators. Similarly, it has provided a good understanding of the requirements and interrelationships of the rotor coolant flow path, bearing system, and shaft seals; the further development required can rest on the knowledge base provided by the LMCD-II.

In electrical performance and heat transfer, agreement between calculated values and test data has been good. This agreement increases confidence in liquid-metal-cooled machinery and should reduce future development requirements.

Finally, the techniques developed and the experience gained in the liquid-potassium tests made on the LMCD-II are expected to be invaluable in development tests of future generators. The handling of liquid alkali metal, and particularly the operation of a liquid-metal flow loop, requires development of precise operating procedures and painstaking attention to detail. Proficiency in this art can be approached through study but can only be achieved through operating experience.

Thus, the LMCD-II program has provided design data and background information that will increase the feasibility of future space generator initial designs, and it has provided a firm technical base for development of generator manufacturing techniques, ancillary test equipment, and operating procedures.

More Complex Integrated Circuits for Digital Systems

E. A. Sack

The multigate array—many individual integrated circuits interconnected on a single block of silicon—is the next step in the development of more complex digital systems.

Digital systems tend to grow in complexity and capability until rising costs and diminishing reliability negate the advantages of further increases in size. This practical limit on system size is pushed back by each technological development that reduces the number of *individual components* required in digital circuitry. Thus, increases in digital system complexity have been made possible by the development of integrated circuits that can provide gate-level functions, such as NAND, flip-flop, etc. As many as 50 conventional electronic components—resistors, capacitors, transistors, and diodes—can be replaced with a single silicon block, mounted in a transistor-type header.[1] Now, developmental work with multigate arrays—an interconnected group of gate-level functions on a single silicon block—suggests that even further improvements in the cost and reliability bounds can be made practical.

The potential of the multigate array approach can be demonstrated with the silicon wafer shown in Fig. 1. This wafer contains approximately 600 diode-transistor logic NAND circuits (incomplete patterns around the edge excluded). Present practice is to cut this array into individual gates (or "chips"), mount these gates in individual headers, and then reassemble these packaged gates into the configuration required to perform the desired logic functions. The inefficiency of this procedure (or conversely, the potential efficiency of the multigate array) is demonstrated by the fact that this wafer could contain all of the gates necessary to perform the arithmetic functions for a small computer.

Although complete digital systems may never be fabricated on single slices (or webs) of silicon, it is quite reasonable to expect that substantially complex subfunctions will be. However, the multigate array will not reach the level of useful hardware until integrated circuit manufacturers can (1) achieve high processing yield and a practical multilayer interconnection technology, (2) develop a package with several times the number of leads of present integrated-circuit headers, and (3) identify multigate interconnections that will be generally useful to the logic designer.

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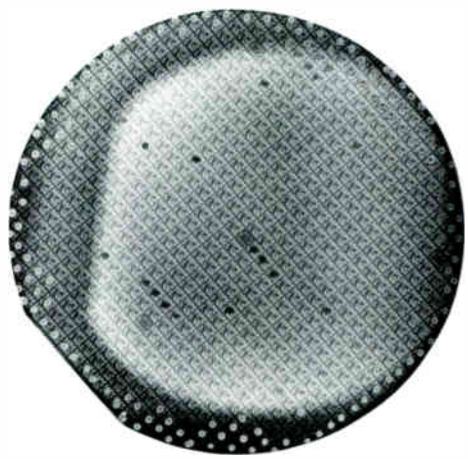
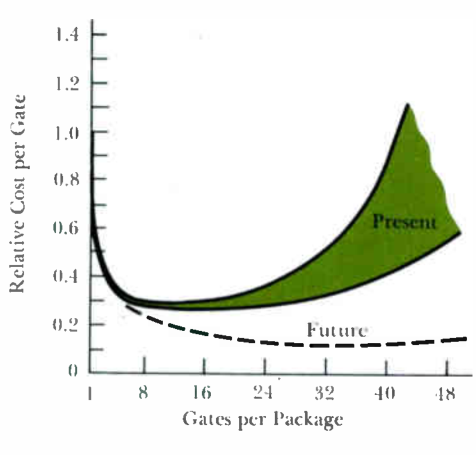


1—This silicon wafer contains some 600 digital NAND circuits (or gates). Those gates which are not electrically functional, as determined by a probe test, have been spotted.



2—The relative cost per gate of a multigate array will be a function of the number of gates per package.

Some progress has been made in each of these areas, but much remains to be done before multigate digital arrays will realize their full potential.

Multigate Array Cost

The potential cost advantage of the multigate array is illustrated by the curve in Fig. 2, which predicts the relative cost per gate as a function of the number of gates in the packaged array. The curve is based on statistically known or estimated relationships[2] between the number of gates per array and array yield before assembly-test, array yield after assembly-test, and assembly-test costs. Optimistic and pessimistic bounds to these relationships provide the upper and lower limit for the estimated cost function in Fig. 2.

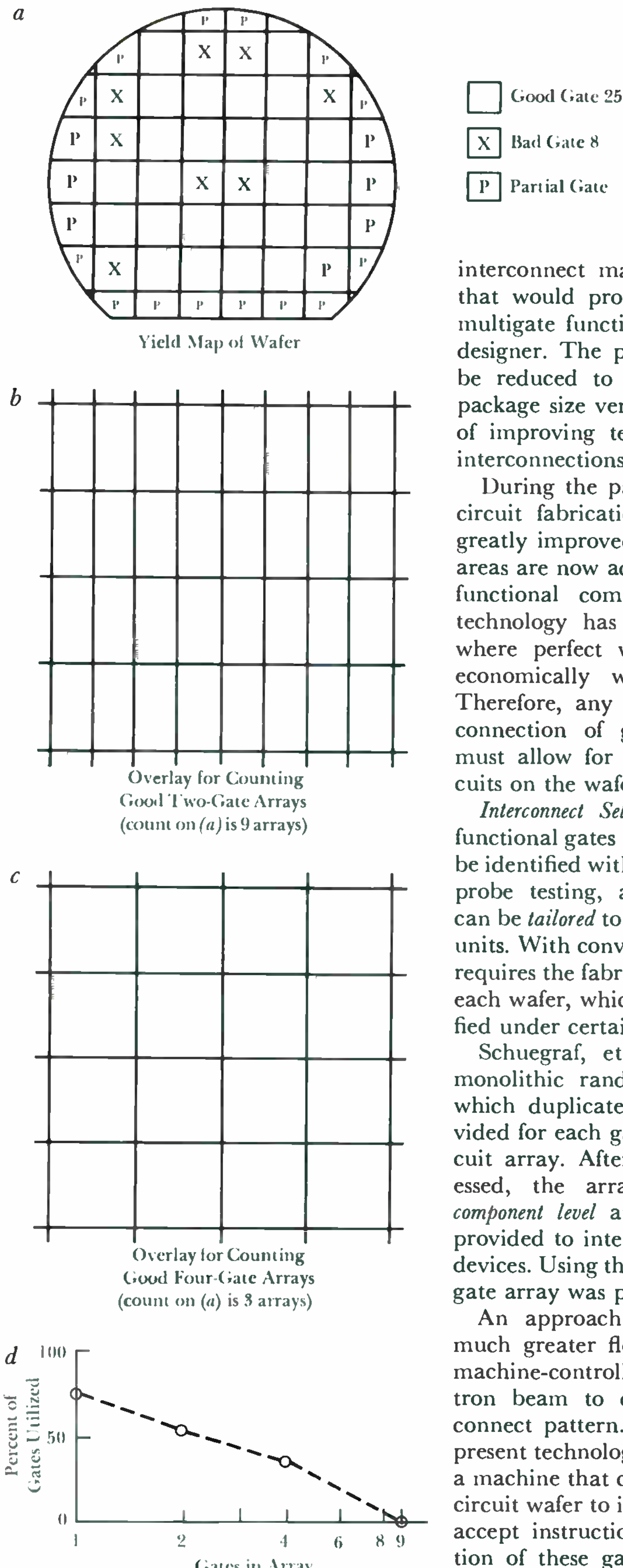
The initial sharp drop in the curve has been confirmed already by integrated circuit price quotations. Three to six gates can be purchased in a single package at little increase over single- and dual-gate prices. The curve indicates a broad minimum over which cost-per-gate is relatively constant. When the number of gates per array exceeds this minimum region, cost either rises gradually or abruptly, depending on the assumptions made concerning assembly-test yield.

The data on which Fig. 2 is based presumes contemporary practice and does not factor in certain techniques and safeguards which are now being employed in order to produce large arrays. The location of the future minimum in the curve is actually well beyond and below its present position.

Approaches to Multigate Arrays

The interconnection concept that is adopted to form multigate arrays must be attractive to both the integrated circuit and the systems manufacturers. For example, an interconnection scheme that lacks flexibility may not meet changing systems requirements; on the other hand, a scheme that is instantly variable may be too costly from the integrated circuit manufacturing standpoint. Following are some of the approaches that have been considered:

Achieve 100 Percent Yield—If all gates on every wafer were operational, a family of



3—The optimum multiple-gate array size for a production wafer *(a)* is determined by using multiple-gate overlays *(b & c)* to count operational arrays. An array-yield curve for wafer *(a)* is illustrated by *(d)*.

interconnect masks could be generated that would provide all of the complex multigate functions desired by the logic designer. The problems involved would be reduced to questions of optimizing package size versus number of pins, and of improving techniques for multilayer interconnections.

During the past few years, integrated circuit fabrication processes have been greatly improved and ever-larger silicon areas are now achieved with 100 percent functional components. However, the technology has not reached the point where perfect wafers can be obtained economically with certain regularity. Therefore, any technique for the interconnection of gates into large arrays must allow for some nonfunctional circuits on the wafer.

Interconnect Selectivity—Since the nonfunctional gates (or areas) on a wafer can be identified with reasonable certainty by probe testing, an interconnect pattern can be *tailored* to employ only operational units. With conventional technology, this requires the fabrication of a new mask for each wafer, which might indeed be justified under certain circumstances.

Schuegraf, et al,[3] have described a monolithic random pulse generator in which duplicate components were provided for each gate in the integrated circuit array. After the wafers were processed, the array was probed *at the component level* and tailored masks were provided to interconnect only functional devices. Using this approach, a seventeen-gate array was produced.

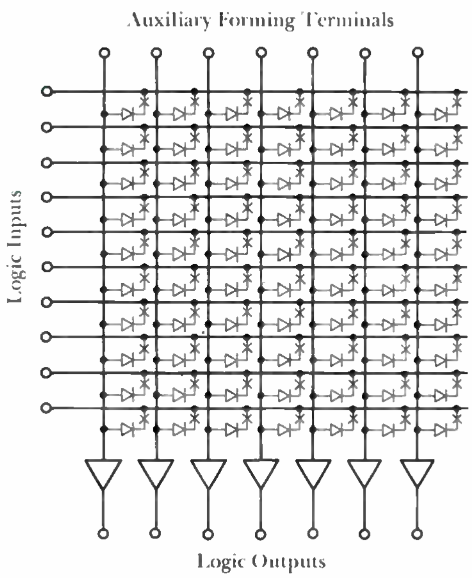
An approach that appears to offer much greater flexibility is the use of a machine-controlled light beam or electron beam to create a tailored interconnect pattern. Little extrapolation on present technology is required to envision a machine that could scan the integrated circuit wafer to identify functional gates,[4] accept instructions for the interconnection of these gates into a given digital function, decide on an optimum topology against criteria of speed, minimum area, etc., and then delineate the interconnection pattern on the wafer.[5] Parts of such a system are already under test in a number of laboratories and the ultimate development of such apparatus in one form or another seems close at hand.

Yield-Optimum Subarrays—By observing the output of a given wafer-processing line, it is possible to determine the largest array of gates that is reproducibly achieved by that line with economic yield. One technique for determining the optimum gate-array size is illustrated in Fig. 3. Once the optimum economic yield is selected, interconnect masks can be developed to connect subarrays of the gates on each wafer into useful digital functions. These masks are applicable to all of the wafers coming from the line as long as yield holds at the level established during the test period. If no preference is given to the relative position of the templet grid and the good and bad regions of the wafer in the test process, the predicted yield of multiple-gate arrays can be achieved with no optimum placement decision required of the masking operator. This optimum subarray technique has been employed in the construction of a four-stage (thirty-two gate) shift register.

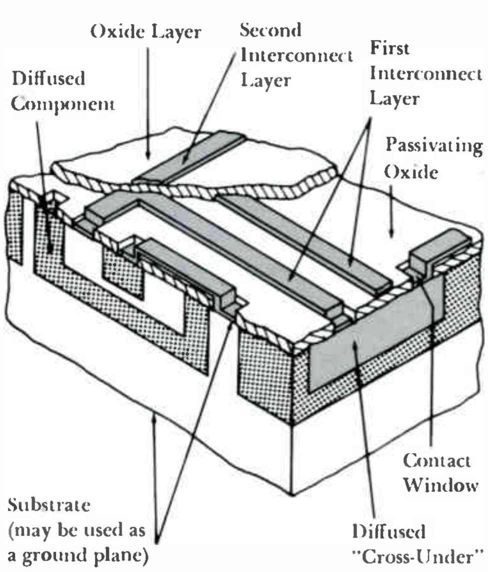
The Formable Array—Another possibility is the forming of intergate associations on the multigate array *after* the wafer is encapsulated. In this concept, the wafer is overlaid with a matrix of conductors, each connected to a package pin. The specific interconnections between the conductor matrix and the functional gates is then established by externally applied "forming" stimuli.

The formable array concept can be illustrated by the special case of a "formable fan-in" diode array, shown in Fig. 4. An array of logic diodes is fabricated on a wafer along with a conductor matrix and inverter gates. Means are provided for connecting (or disconnecting) selected diodes to (or from) the matrix. For example, a thin "neck" could be delineated in the interconnect film at each diode; this neck could be vaporized by applying a "forming" pulse to appropriate matrix terminals. In this way, diodes that were not required to perform a given logic function could be eliminated from the array.

Each of these interconnection concepts offers certain advantages; however, at the present time, only the yield-optimum sub-



4—Diodes can be disconnected from this formable fan-in diode array by applying a "forming" pulse to appropriate matrix terminals. The pulse vaporizes the thin "neck" that connects the diode to the matrix.



5—The three conventional levels of interconnection for an integrated circuit are the first interconnect layer, the diffused cross-under, and the substrate; when a second interconnect layer is used, it becomes the fourth level of interconnection.

array approach seems ready for immediate application.

Multilayer Interconnections

A conventional integrated circuit (Fig. 5) employs three levels of interconnection: (1) The metal layer deposited on the passivating oxide layer provides the majority of intercomponent interconnections; (2) the substrate serves as a satisfactory ground plane, particularly if the silicon die is well bonded to a conducting header pad; and (3) the diffused components themselves, or intentionally placed "diffused cross-unders," provide a third interconnection plane.

Although remarkably complex arrays can be developed with only these three layers, a really flexible approach to multigate arrays requires one or more additional interconnect planes. After the first metal layer has been deposited and delineated, another oxide layer is deposited on the surface of the wafer. Contact windows are opened and a second metal layer is deposited and delineated. Unfortunately, although the concept is simple, its execution is difficult.

For example, if aluminum is used as the interconnection metal, as in conventional planar technology, aluminum oxide frequently prevents suitable contact between the first and second metal layers. Furthermore, the dielectric layer that separates the metallic layers must be formed or deposited at a temperature that will not damage the first interconnection layer. The dielectric so formed is often a thermal mismatch to the oxide layer so that cracking occurs, and eventually causes the first and second metal layers to become shorted.

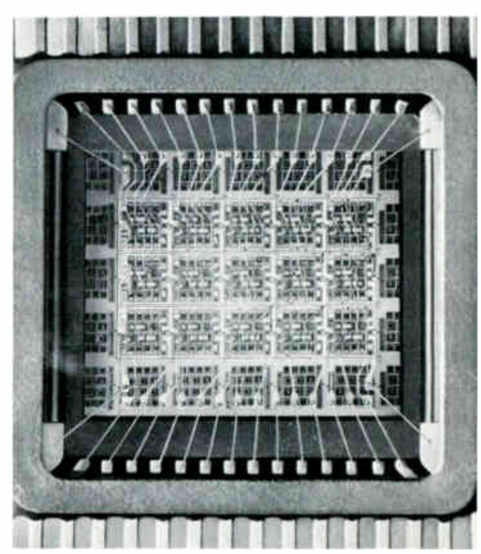
Some progress in solving this problem has been demonstrated in the new two-metal interconnect systems. These systems employ a gold or platinum conducting layer on top of a material such as chromium, molybdenum or titanium that provides adherence to the substrate dielectric. These two- (or three-) metal systems generally allow higher formation temperatures for the dielectric layer and do not readily develop surface oxides that block good contact between the first and second interconnecting layers. The 30-gate array shown in Fig. 6 uses two-metal interconnects to provide two independent layers of evaporated interconnections.

Functions for the Multigate Array

The multigate technology is too new for there to be a clear picture of which complex functions are most likely to become accepted standards. One interim approach is to simply provide a multiplicity of simple functions such as NAND gates or flip-flops in a single package. As shown in Fig. 7, from two to six gates are now available in 14-pin flat packs. An extension of this approach is shown in Fig. 8 where 30 gates are interconnected in groups of six to provide five dc coupled flip-flop gates in a 32-pin header.

On the other hand, a few complex functions have been identified as logical candidates for integration into multigate arrays. Some of the functions now under consideration are listed in Table I.

The examination of potential functions for multigate integration is facilitated through use of the diagram of Fig. 9. This is a plot of the number of terminals required to communicate with a given complex function versus the number of gates in the functional array. Superimposed on the diagram are boundaries



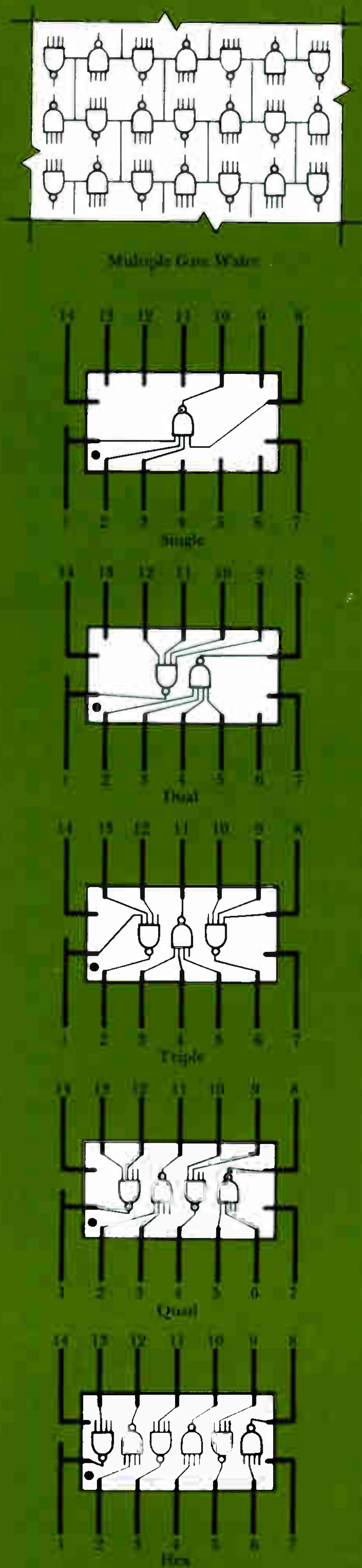
6—This 30-gate array uses two-metal interconnects to provide two independent layers of evaporated interconnections.

showing the number of pins and number of gates that can be accommodated by various flat packages.

The functions listed in Table I are plotted as solid points on the pin/gate diagram. Also shown, as open circles, are points for certain arrays from a typical data processor where no attempt had been made to optimize the interconnections for application of complex arrays.

With today's technology, it is probably less costly to provide additional gates in integrated circuits than to form additional pins on the packages. Thus, it is often desirable to reduce the pin count for a given function by generating signal complements with additional gates in the package rather than transmit complements from other stages as is done in more conventional equipment.

The two empirical curves in Fig. 9 show the relationship between the number of pins and number of gates required for complex arrays: The upper curve is more representative of present systems where, for economic reasons, emphasis has been placed on minimizing the number of gates required. However, the lower curve would be a more desirable condition for systems of the near future, where less emphasis is placed on reducing the number of gates per array, and more emphasis is placed on minimizing the number of pins required per package.

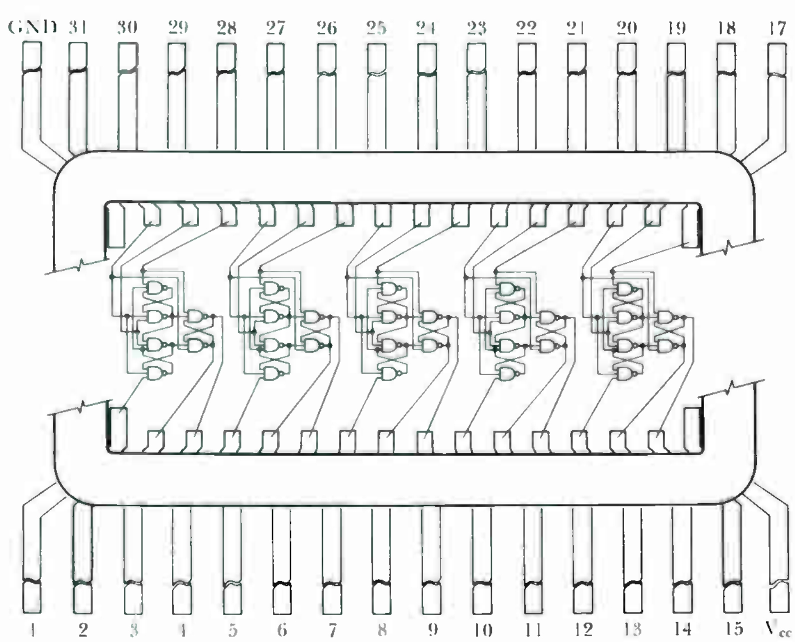


7—A multiplicity of simple functions *(left)*, such as NAND gates or flip-flops, can be provided in a 14-pin flat pack.

New Packages

Full exploitation of the multigate concept will require packages with several times the 14 leads now available in conventional integrated-circuit headers. From Fig. 9, packages with 32, 40 or 48 pins would seem to be useful objectives.

Aside from its function as a hermetic encapsulation, the integrated circuit header is essentially a "dimension transformer." On the silicon die, bonding pads can be located on centers no more than 5 to 10 mils apart around the periphery. Thus, a die 250 mils square can easily accommodate 100 connection points. However, the technology that is now used to interconnect packaged integrated circuits on the circuit board is far less tolerant. Fifty-mil pin centers are often



8—Thirty gates *(below)*, interconnected in groups of six, provide five dc coupled flip-flop gates in a 32-pin header.

considered to be the minimum that can be accommodated with present techniques. Thus, a package with 100 pins about its edge on 50-mil centers measures 1¼ by 1¼ inches. The "spacial impedance mismatch" between the integrated circuit and the printed-circuit board results in ponderous and expensive packages for dimension transformation.

Although it may not be reasonable to look to board technologies that can accommodate a 10-mil pin spacing, development of ability to use 25-mil spacing is expected.

Conclusions

Solid economic benefits can be gained by taking advantage of multigate integrated circuit arrays. At present, 25 to 50 gates in each package would appear to be optimum objectives, but further improvements in yield and package technology may ultimately make possible systems with several hundred gates in each integrated array.

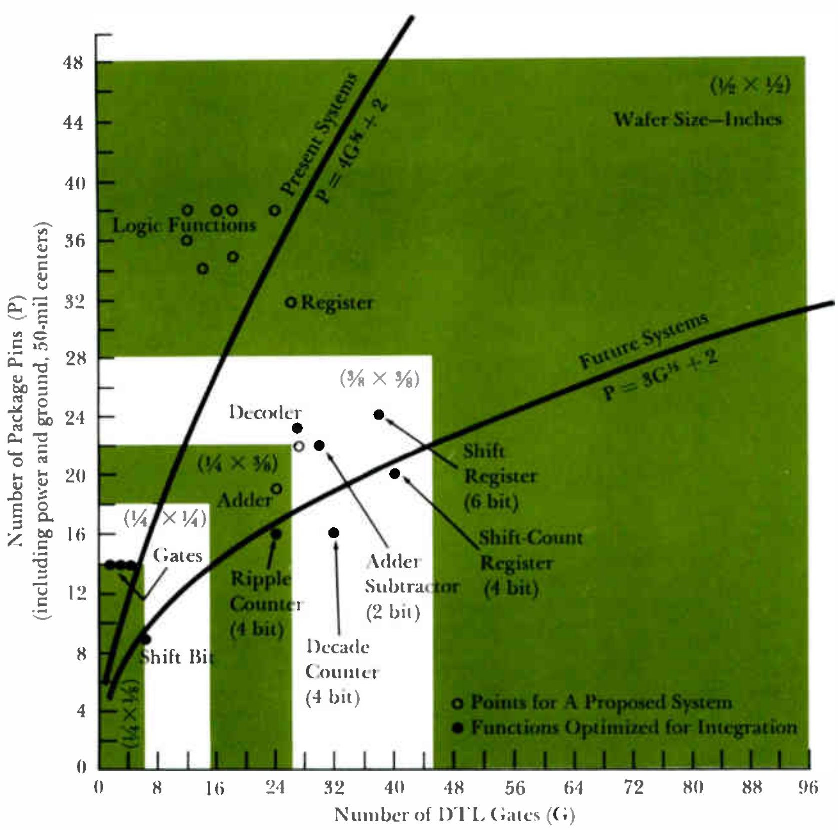
Of the various approaches to multiple-gate interconnections on the wafer, the yield-optimum subarray concept is most attractive at present. However, systems are under development that may make it practical to tailor the interconnect pattern to each array.

Techniques are now available to provide more than one layer of metallic interconnections on the silicon wafer so that complex multigate topologies can be integrated. A study of a number of 25-50 gate digital functions indicates that appropriate packages should have 32 to 48 pins. One package for this application, a ⅜-by-⅜ inch flat pack with 25-mil pin spacing, has already been developed.

The digital system engineer is not necessarily overly enthusiastic about designing with prefabricated complex functions. He argues convincingly that there is insufficient complex function generality in typical systems to justify such use and his design flexibility is too much impaired. Counter to these valid objections is a sizable cost saving per gate if the multigate integrated circuit can be efficiently employed. As usual, economics and sound engineering will eventually provide the answer.

Table I—These functions are under consideration for integration into multigate arrays.

Function	*Complexity*	*Gates*	*Pins*
Adder-Subtractor	2 bit	30	22
Ripple Counter	4 bit	24	16
Decade Counter (Synchronous)	4 bit	32	16
Shift Register	6 bit	38	24
Decoder	16 state	27	23
Shift-Count Register	4 bit	40	20
Binary Counter	1 bit	6	9
Shift Bit	1 bit	6	9



9—For a given combination of digital transistorized logic gates, some number of pins will be required. Typical relationships are illustrated.

References:

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[5]MacIntosh, I. M., "Programmed Interconnections—A Release from Tyranny," *Proceedings of the IEEE*, Volume 52, Number 12, December 1964.

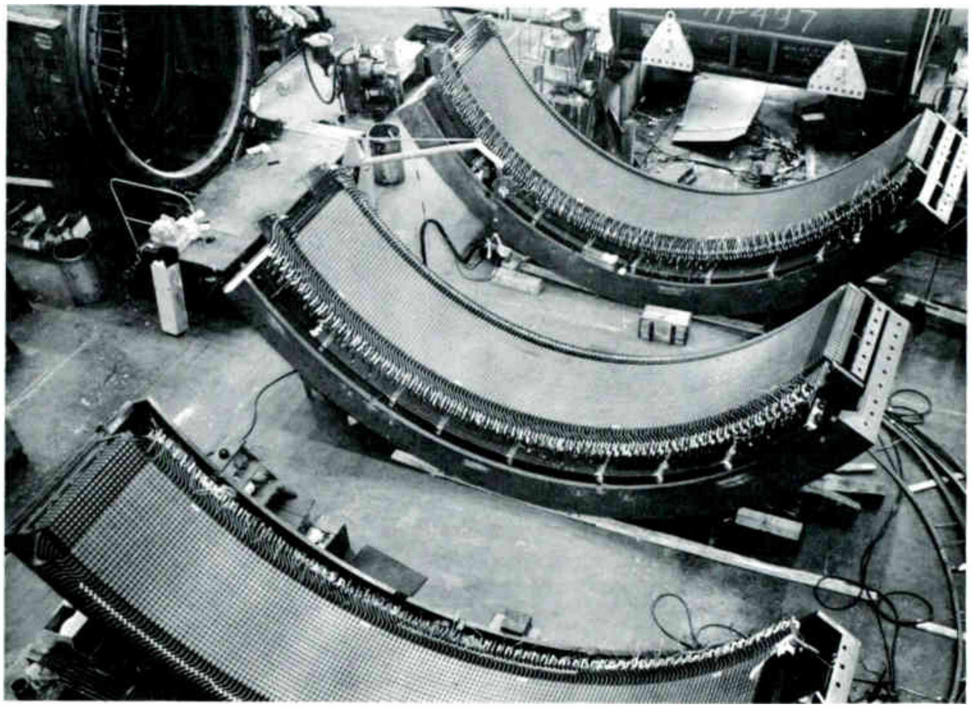
Acknowledgement:

The author is indebted to a number of his colleagues for advice and assistance in this work. Specific mention is due for the contributions of Mr. C. H. Knowles, Dr. R. C. Lyman, Mr. Paul Shearman, Mr. Tom Sikina, and Mr. Ivan Sarda.

TVA Generators Modernized

Four 25,000-kva vertical waterwheel generators installed at the Tennessee Valley Authority's Wilson Dam some 45 years ago are being modernized by installation of new factory-wound stators (*right*). When the new stators are installed, full-load rating of the generators will be 25,555 kva at 12,000 volts, with an overload capability of 29,388 kva.

The new stators will have Thermalastic winding insulation. They will also incorporate air housings of new design, with coolers to provide recirculation of ventilating air for clean operation and lower maintenance costs. The air housings will be approximately 35 feet in diameter and 13½ feet high. Brake and jack assemblies and some related equipment will also be added. All new components have been designed to fit with the existing foundations, and many existing components are being used.



Plutonium Being Evaluated As Power Reactor Fuel

Enriched uranium is the fuel most commonly used in nuclear power plants operating in the United States. Plutonium is produced as a by-product in these reactors, and it has been estimated that a billion dollars worth of it will have been produced by 1980. Success in finding practical ways to use this plutonium as reactor fuel would create a market for it, would help reduce electric generating costs, and would greatly expand the amount of power obtainable from the original uranium fuel.

To determine the value of plutonium as a fuel in nuclear power plants, a major research program is being conducted by the Saxton Nuclear Experimental Corporation (SNEC) and Westinghouse. The Saxton experimental reactor has attained its full power rating on a core containing plutonium fuel, marking the beginning of an extended program of plutonium operation being carried out for the Joint United States-Euratom Research and Development Board under a contract administered by the United States Atomic Energy Commission. (The Saxton reactor is owned and operated by SNEC, a subsidiary of General Public Utilities. Westinghouse and SNEC are engaged in a mutual five-year program of reactor development.)

Of the 21 fuel assemblies in the reactor core, the central 9 contain natural uranium oxide enriched with plutonium oxide; the peripheral 12 contain enriched uranium oxide. Selected fuel samples will be examined at the end of the operating period. From these examinations, the performance of the plutonium fuel will be analyzed and compared with predicted performance. The resulting information will then be made available for improving the present design and calculation methods employed to evaluate uses of plutonium as a commercial fuel.

Investor-owned utilities involved in the Saxton Project are Pennsylvania Electric Company, Metropolitan Edison Company, New Jersey Power and Light Company, and Jersey Central Power and Light Company. Pennsylvania State University and Rutgers University also are participating members. The Saxton reactor, which is located near Altoona, Pennsylvania, began operation in 1962. The experimental program since then has produced successful demonstrations of new and advanced fuel-assembly designs and also of the ability to control commercial water reactors with a soluble neutron absorber (boric acid) dissolved in the reactor coolant.

Fluorescent Lamp Performance Improved

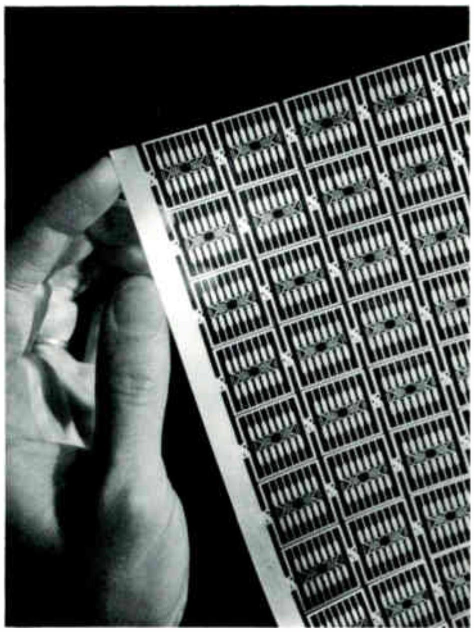
The light ouput of ordinary fluorescent lamps fluctuates widely with changes in air temperature; maximum output is obtained only within a narrow temperature range, and the lamps can lose up to 30 percent of their light output over normal temperature changes. This fluctuation is caused by changes in mercury pressure—too low when cold, too high when hot.

Now, however, a fluorescent lamp has been developed to provide almost constant light output over a temperature range of 32 degrees to 132 degrees F. Mercury pressure inside the new lamp is controlled by the addition of a small amount of the rare metal indium, which attracts and releases mercury atoms inside the lamp according to temperature. In this way, the mercury pressure is held virtually constant over a wide range of operating temperatures.

The new lamp is named the SHO-II since it retains features of the earlier Super-Hi Output fluorescent lamps and is interchangeable with them. New ballasts are not required.

Etching-Grade Kovar Alloy Forms Tiny Electrical Connections

As integrated-circuit applications and production capability increase, the number of elements included on the tiny chips of semiconductor material also increases—a dime-size chip now may have a hundred or more resistors, capacitors, transistors, and other circuit elements formed in it. This complexity, along with the small size of the circuits, presents problems in making the external connections for each element. Leads for some standard integrated circuits have been die-stamped from thin sheet metal in a pattern that brings the end of each lead to the proper section of the chip, there to be wired in place. However, the space for leads in some of the newer circuits is so crowded that leads as tiny as 0.005 inch across are needed. Such delicate parts cannot be stamped, and no suitable material has been available that could be chemically etched so precisely. (The choice of metals for leads is restricted by the need to use a material that can be sealed to the glass or ceramic package that ultimately encloses the circuit.)



External connections for complex integrated circuits are formed by precise chemical etching from the new etching-grade Kovar alloy. The typical wiring networks illustrated were etched in a sheet of alloy 0.010 inch thick, and the smallest leads are about 0.005 inch across. The networks will be separated from each other and each used to form the connections for an integrated circuit in a "flatpack" enclosure—in this case, a computer information circuit.

Now, however, a new etching-grade Kovar alloy has been developed for chemical etching of these tiny intricate lead assemblies. Uniform etching to close tolerance is made possible by small and uniform grain size, which is attained by precise annealing. Close gauge control, achieved by cold-rolling to final thickness in a Sendzimir mill, permits precise pattern registry on both sides of the sheet so that it can be etched from both sides. Also, the sheet surfaces are made flat and free from flaws and scratches so the etch-pattern negatives will conform closely to the surfaces for precise reproduction of the pattern.

Etching-grade Kovar alloy is supplied from stock as sheet or strip in standard gauges up to 0.010 inch and in widths up to 13 inches. Besides the integrated-circuit application, etched Kovar-alloy parts can be used as formed leads in other electronic applications to replace fine wires that are difficult to handle.

Submarine Oxygen Generator Control Made Smaller and More Capable

Equipment on board submarines has to be as compact as possible and also as capable as possible to conserve precious space and to perform vital functions properly. A new control unit for oxygen generators in nuclear attack submarines meets both requirements by being 10 percent smaller than the control it replaces and also being able to monitor more functions with more reliability. The wired-logic control unit regulates oxygen generators that produce oxygen for the submarine crews by electrolysis of seawater.

The control unit provides for safe and unattended operation of an oxygen generator by regulating the pressure of the generated gases, by controlling the liquid level of the 16 generating cells, and by monitoring 63 generator operating parameters. Among these parameters are wall temperature of the generating cells, purity of the generated gases, pressure levels of the various gas subsystems, purity of the distillate, and performance of the various power supplies.

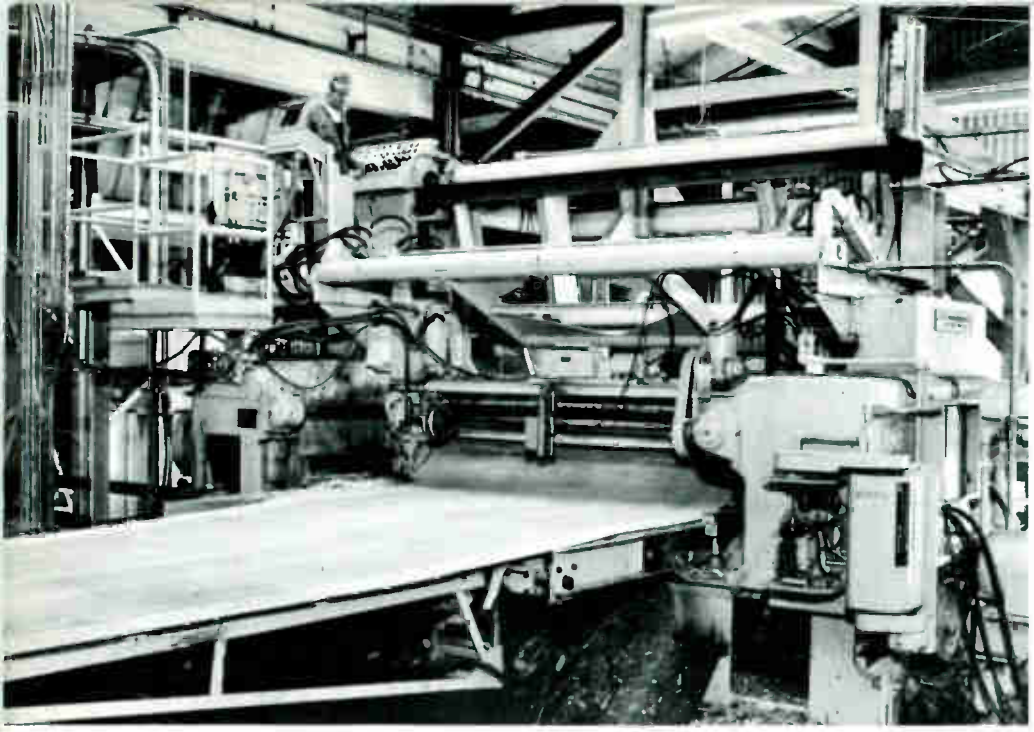
If any one of the monitored parameters goes outside preset limits, a redundant mechanism automatically shuts down the system and sounds an alarm. Also, if a failure occurs within its own monitoring circuitry, the control senses the trouble through its continuous self-checking system and shuts the generator down. In either case, one or more indicator lamps on the front panel light up to show the source of trouble.

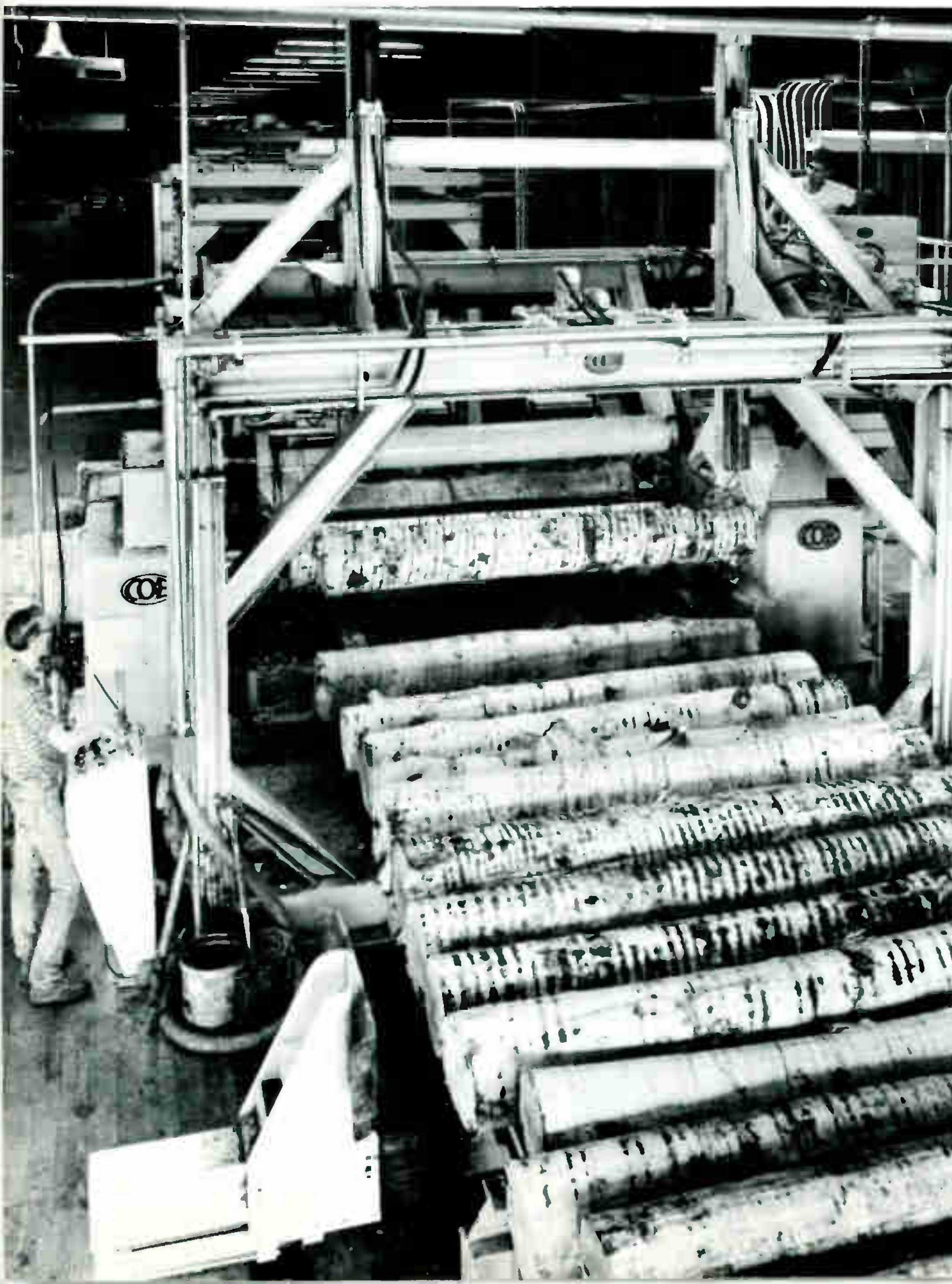
High-Grade Plywood Now Produced From Southern Pine

Recent development of successful techniques for making plywood from southern pine trees has tapped a vast new source of supply for plywood. Moreover, it has brought a new industry to the South and has brought part of the plywood industry closer to many of its markets by permitting plywood production outside the Douglas fir areas of the West Coast.

One of the pioneers in the new industry is Kirby Lumber Corporation, which started experimenting with production of pine plywood in 1962. Its plant at Silsbee, Texas, now produces 40,000,000 square feet of plywood annually from Texas and Louisiana pine forests.

Production begins with the stripping of bark from the logs with jets of high-pressure water. The logs are cut into 8-foot "bolts" and transferred to steam-heated chambers that soften them for smooth cutting. A conveyor then delivers the hot bolts to the lathe charger. The bolts, av-





eraging 15 inches in diameter, are fed into the high-speed automatic veneer lathe at the rate of two a minute.

The lathe rotates the bolt and slices from it a continuous sheet of veneer eight feet wide and one-eighth or one-tenth inch thick at the rate of 800 linear feet a minute. This sheet is fed into a six-level conveyor tray system, which provides storage and a steady supply of material for high-speed clippers that cut the veneer into sheets of various lengths. Ovens dry the sheets, and graders then determine which sheets will be used for faces, cores, and backs in the plywood panels. Sheets are coated with phenolic glue and then cold-pressed to provide the temporary bond needed for handling. Cold-pressed panels are fed into individual compartments with steam-heated steel faces that press and bake the panels under great force for the final bond. Trimming, finishing, inspection, grading, sorting, and bundling complete the process.

The heart of this modern plant, the veneer lathe, is controlled by a T-100 solid-state control system that regulates lathe rpm for constant log surface speed. Constant surface speed is achieved by use of an exponential reference to the motor control. This reference is the output of an operational amplifier whose gain potentiometer is driven by a remote knife position servo. (Sensing the knife position indicates the log diameter continuously.) This method automatically converts the operator's linear control setting of feet-per-minute cutting speed to the proper lathe speed regulator reference as a function of log diameter.

The control arrangement provides constant system gain for all log diameters with the use of standard components, a capability that previous regulators have not had. Previous methods of maintaining constant surface speed were by use of a knife-driven rheostat that proportionally

Automatic veneer lathe slices a continuous sheet of plywood veneer from a log at 800 feet a minute *(upper)*. A feedback control system regulates lathe rpm to keep log surface speed constant. The lathe is fed by a conveyor *(lower)* that delivers southern pine logs at the rate of two a minute.

reduced the tachometer feedback as a function of log diameter, or by use of a voltage regulator along with a special tapered field rheostat driven by the knife position.

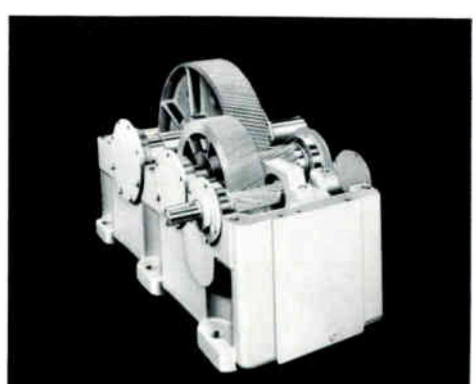
Products for Industry

Compensated ion chamber measures radiation levels at temperatures as high as 200 degrees C and is suitable for use in nuclear reactors. The WL-23084 chamber is similar in geometry to the Electronic Industry Association Type 6377 and is interchangeable with it. High-purity aluminum-oxide insulation is used throughout. *Westinghouse Electronic Tube Division, P. O. Box 284, Elmira, New York 14902.*

Solid-state on-delay timing relay rated 2 amperes continuous, 120 volts ac, can initiate operation of motor starters up to size 4. Repeatability is within ± 1 percent of time setting. The relay can be used in circuit design in exactly the same ways as electromechanical relays. To adjust timing, one of four ranges of time delay is first selected by placing a jumper wire between specified terminals; then a potentiometer is adjusted with a screwdriver for fine control within that range. Provision for remote adjustment also is available. *Westinghouse Standard Control Division, Beaver, Pennsylvania 15009.*

Flexible copper-clad materials for printed circuits meet broad range of design requirements. The new family includes copper-clad glass-reinforced polyester, copper-clad glass-reinforced epoxy, copper-clad Mylar, and a low-cost paper-reinforced copper-clad material. All have high bond strength, solderability, and dimensional stability after etching. (The insulating materials alone, without copper, are also supplied; they are bondable on one or both sides for use as binder and cover sheets in construction of multilayer circuitry.) The materials are supplied as sheets or rolls. Sheets are 18 or 36 inches square; rolls are up to 36 inches wide, slit to order. *Westinghouse Insulating Materials Division, Trafford, Pennsylvania 15085.*

TDS parallel-shaft speed reducers have a bearing for the high-speed pinion in the center of the housing. This reduces length of the pinion and gives it firm support, features that are especially important when pinion diameter is made small to obtain high gear ratio. Bearings for the low-speed gear train have been widened to reduce loads and thereby prolong bearing life. A large inspection window in the cover gives a wide view of interior. Housings are cast iron or steel, and speed ratios range from 1.84:1 to 292:1 in ratings from 1 through 5000 horsepower. *Westinghouse Motor and Gearing Division, 4454 Genesee Street, P. O. Box 225, Buffalo, New York 14240.*



Services for Industry

A Fast Reference for Engineering Drawings service (known as "FRED") applies microfilm and data-processing cards to solve the costly problem of engineering-drawing storage and reference for users of electromechanical systems. It can be applied to an existing system (converting existing drawings) or it can be specified in new systems contracts. The service is offered by the Westinghouse Industrial Systems Division, P.O. Box 225, Buffalo, New York 14240.

In the past, a set of linen originals of the drawings for a system usually was supplied with the equipment, but these drawings were easily mislaid, misfiled, or damaged in the user's plant. Maintaining a duplicate file for security was expensive, and even one set required a large amount of space for storage and reproduction. (A typical 80-inch hot strip mill, for example, requires approximately 3000 drawings that the user must store and have access to.) Moreover, production of prints from large linen originals is relatively expensive.

In the FRED system, all drawings are put on microfilm and each film is mounted in a standard data-processing card. The user's master file of drawings then fits into one card-file drawer, and he can locate a drawing and make a print from it in about half the time required to retrieve a linen original and make a white-print. Any reproduction equipment that handles card-mounted microfilm or aperture cards can be used to make prints. A master set of films is maintained by the Industrial Systems Division so that any of the user's films that are lost or destroyed can be quickly replaced.

About the Authors

D. A. Maniero, Peter F. Kienast, and **C. Hirayama** join forces in this issue to write about the arc heater and its potential application to chemical processes. Maniero and Kienast are engineers in the Arc Heater Department of the Power Circuit Breaker Division, while Hirayama is a scientist at the Research Laboratories.

Maniero joined Westinghouse in 1951 after earning his BS in Mechanical Engineering from Carnegie Institute of Technology. Later that year he was given a leave of absence to work with the Department of the Navy, Bureau of Ships, Naval Reactors Branch, where he served as liaison engineer responsible for electrical generation and propulsion equipment.

In 1953 he attended the Oak Ridge School of Reactor Technology and then rejoined Westinghouse in the Atomic Equipment Department, where his principal responsibility was canned motor pumps. In 1955 he transferred to the Atomic Power Division, where he worked on the design of various elements of nuclear reactor systems. In 1956, he was awarded an MS in Mechanical Engineering by Carnegie Institute of Technology.

In 1963 he transferred to the Arc Heater Department, where he has been primarily concerned with the development of arc heaters designed for chemical processing applications.

Kienast is product engineer of the Arc Heater Department. After graduation from the University of Wisconsin in 1960 with a BS in Electrical Engineering, he came to Westinghouse on the Graduate Student Course. In 1961 he joined the Power Circuit Breaker Division and was largely involved with negotiations on power circuit breakers and arc heaters. Since March 1962, his responsibilities have been centered on arc heater application and sales.

Hirayama earned his BS and MS degrees in chemistry from the University of Hawaii, and a PhD in chemistry from the University of Minnesota in 1957. He joined the Research Laboratories staff that same year in the Insulation and Chemical Technology Department. Since the first of this year, he has been in the Inorganic Materials Science and Technology Department. At the Laboratories his work has centered largely on fundamental studies and development of inorganic materials. Most recently he has worked on high-temperature chemical processes using the arc heater and on the development of more efficient glass lasers.

James R. Harnish earned his BS in mechanical engineering at the University of Oklahoma in 1951. He joined the York Corporation on its graduate student course in 1951 and worked there as a design and application engineer before coming to Westinghouse in 1962.

Harnish's responsibilities in the Air Conditioning Division include design and application of heat pumps and air-conditioning equipment. He has also contributed to development of refrigerant piping codes, standards, and recommended practices, and he has published about 25 technical papers. In 1964, Harnish won the Division's award for the outstanding patent disclosure of the year; it was the basic disclosure for the Hi/Re/Li heat-pump cycle described in this issue.

C. T. Yarbrough's travels as an electric service specialist have taken him to the far side of the world twice—India and Thailand—and throughout the western hemisphere. Besides directing the installation of heavy equipment, he has been called on to analyze electrical and mechanical problems on many large rotating assemblies such as waterwheel generators, turbine-generators, and m-g sets. When his analysis has located the problem, he directs the dynamic balancing, shaft alignment, shaft straightening, or whatever else is needed to correct it. Out of this experience, he developed the optical shaft-alignment method described in this issue.

Yarbrough graduated from Pasadena Junior College with an associate of arts degree in 1933 and joined Westinghouse as a winder and electrical tester in the Los Angeles service shop. He then worked as an engineer with the Los Angeles Bureau of Power and Light from 1936 to 1941, continuing his education through night-school work at the University of Southern California (and later, the University of Pittsburgh). Yarbrough returned to Westinghouse in 1941 to work in service engineering and supervision in Seattle and San Francisco. He became Headquarters Electric Service Manager in 1947 and, in 1953, was named to his present post on the manager's staff in the Electric Service Division. One of his recent tasks was as consultant to the Atomic Power Division for the transportation handling of a large nuclear pressure vessel from Chattanooga, Tennessee, to San Onofre, California.

Paul H. Scheffler has been deeply involved in the design of high-speed rotating equipment all of his career. He joined Westinghouse on the graduate student course in 1949 (after graduating from Drexel Institute of Technology with a BSME) and was assigned to the Aviation Gas Turbine Division in the development engineering department. There he helped develop the accessory gearboxes, main bearings, shaft seals, and lubrication systems of the J34, J46, and J40 turbojet engines and eventually headed the engineering section responsible for those areas.

Scheffler was transferred to the Aerospace Electrical Division in 1960 to direct a group engaged in analytical evaluation of unconventional dynamic electric power systems and in design and development of electrical apparatus cooled by liquid metals. He is now in the Systems Research and Development Department, providing consultation and coordination services in mechanical development areas of liquid-metal-cooled apparatus. He has contributed extensively to the generator development that he describes in this issue.

Dr. E. A. Sack appeared on these pages a little over a year ago, with an article describing the "state of the art" in molecular electronics. In this issue he sheds some new light on the subject, including current developments in the field.

Sack is manager of engineering for the Molecular Electronics Division, a position he has held since 196[illegible]. He came to that position from the Research Laboratories, where he had served as manager of the Electronics Department and the Solid State Devices Department between 1960 and 1962. He first joined the Laboratories in 1954, after earning his PhD degree in electrical engineering from Carnegie Institute of Technology. In 1959 he was given the Outstanding Young Electrical Engineer Award by Eta Kappa Nu.

The Impact of Molecular Electronics

For those readers who can manage to center their attention on the electronic components in this photograph, the handful of conventional components at left is equaled in microminiature form by the single element at right. In fact, the integrated circuit is but a portion of the entire package shown at right in the photo; actually it is no bigger than the pupil of your eye, yet it is capable of performing the same job as many dozens of conventional components much larger in size.