Westinghouse ENGINEER
September 1966

Calculations of the lightning flashover performance of transmission lines can be no better than the accuracy of the lightning-stroke characteristics used in the calculations. To learn more about these characteristics, Westinghouse engineers, collaborating with several utility companies, conducted a five-year field investigation that began with the 1960 lightning season. Most of the new data was accumulated with two types of devices, both of which operate on the principle of the klydonograph. (See "Results from Five Years of Lightning Study with Klydonograph Recorders," pp. 148-153.)

Shown here is the klydonograph used to measure electric field intensities in the vicinity of lightning strokes. Briefly, a record is produced on a sheet of photographic film that has been placed between a probe electrode and a grounded plate—the greater the field intensity, the larger the figure. This klydonograph record indicates that an electric field intensity of approximately 120 kv per meter existed just prior to a nearby lightning stroke.

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Cover design: One of the mainstays of an industrial society, a blast furnace, is featured in this issue's cover design by Thomas Ruddy. An article on modern programmed charging systems for blast furnaces begins on page 130.

Programmed Blast-Furnace Charging Increases Production and Improves Product

M. J. Greaves
W. A. Munson
J. C. Ponstingl

Recent advances in automatic programmed control of blast-furnace charging systems are improving furnace operation. They also are long steps toward eventual complete automation of the entire blast-furnace complex with a closed-loop control system.

The introduction of the basic oxygen steelmaking process has created a need for larger quantities of consistent-quality iron as raw material. Although the process can make a heat of steel in less than an hour, it can never realize the cost-reduction potential inherent in such capability unless the iron-making operation is geared to a similar speed and efficiency.

Therefore, steel producers are pushing for larger and more consistent blast-furnace production and lower operating costs by enlarging the furnaces, improving operating practices, and modernizing raw-material handling and charging facilities. Recent advances in furnace designs and practices, combined with innovations in solid-state electrical control equipment for material-handling and charging, have made possible individual furnace production potentials of 5000 net tons a day, compared with the maximum production of 3000 tons a day just three years ago.

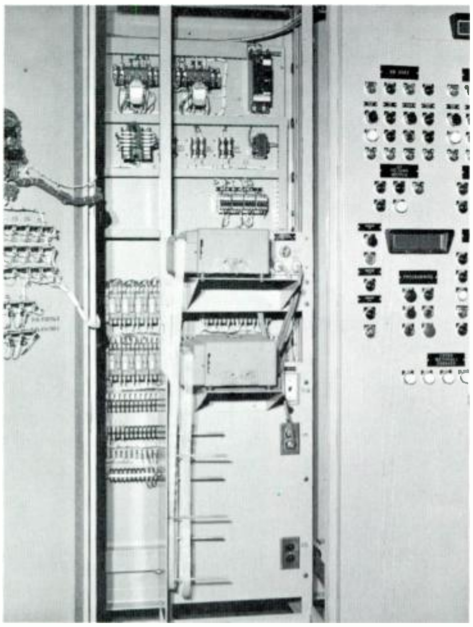
In operating practices, significant advances have been made through better handling of the hot metal, use of hotter blasts, and injection of supplementary fuel with the blast. The most significant advance, though, is the use of beneficiated iron-bearing materials in place of ore as it comes from the mine. These materials, mainly pellets and sinter, are made from ore fines and concentrates, which are either formed into pellets or fused into lumps to facilitate handling and to permit free movement of gases up through the furnace charge. Sinter, in addition, contains some of the needed flux.

Raw-material handling and charging facilities include means for screening, sizing, and blending the materials, because those operations constitute the primary control of the process. (Secondary controls include quantity, temperature, and composition of hot blast; furnace-top pressure; and raw-material distribution in the furnace.) Experience has shown that quality and uniformity of raw material result in a better product and also increase production of iron.

Since the charging control plays an important role in maintaining uniform charging and represents a small percentage of the total cost of a furnace installation, a handsome return on investment can be had through sufficient and proper application of automatic controls to the raw-material charging system. Therefore, furnace charging has received the greatest attention in the evolutionary steps toward an automated blast furnace.

Charging Facilities and Controls

Stockhouse and charging facilities vary because each is designed to suit the physical arrangement of the installation. Certain patterns have evolved, however, in revising existing facilities and designing new ones.



1—Charging of all raw materials is programmed with this solid-state control unit. Instructions are programmed on punched tape and read into the unit with the tape readers; they provide automatic charging of coke and tell the scale-car operator in the stockhouse when to charge the other materials.

A conventional stockhouse consists of a series of bins for each material. Coke, because it is free-flowing and is used in large quantities, has been handled automatically for years by means of scales, feeders, and conveyor belts to keep holding hoppers filled. (The skips are filled from the holding hoppers.) The other materials, however, usually are still weighed in a scale car by an operator as they are drawn from their bins and then delivered by the scale car to the skips.

Originally, the "charging programs" were given to the scale-car operators verbally as instructions regarding the sequence in which materials were to be charged, and the operators kept track of them with pegboards. Increased production capacities demanded a more systematic approach, however. Cam-type controllers and then relay systems were employed to energize indicating sequence lights and to provide proper interlocking to keep the scale-car operator informed of and fixed to the charging sequence established by the blast-furnace operator.

Recently, however, the number of control devices required to achieve the potential improvements in operating practices that can result from the greater selection of charge materials now available has become so great that mechanical control systems have had to give way to systems built with static solid-state control devices (mainly diodes and transistors). Such systems can easily perform the required logic within the space and time permitted. In addition, the demand for greater flexibility in choosing charging cycles and providing more information for operators and maintenance personnel requires a more capable system than relays and cam controllers can provide. Consequently, various static logic systems are supplanting the mechanical control systems in new furnaces and in furnace modernization programs.

The simplest approach is to replace existing mechanical programmers directly with solid-state programmers. The

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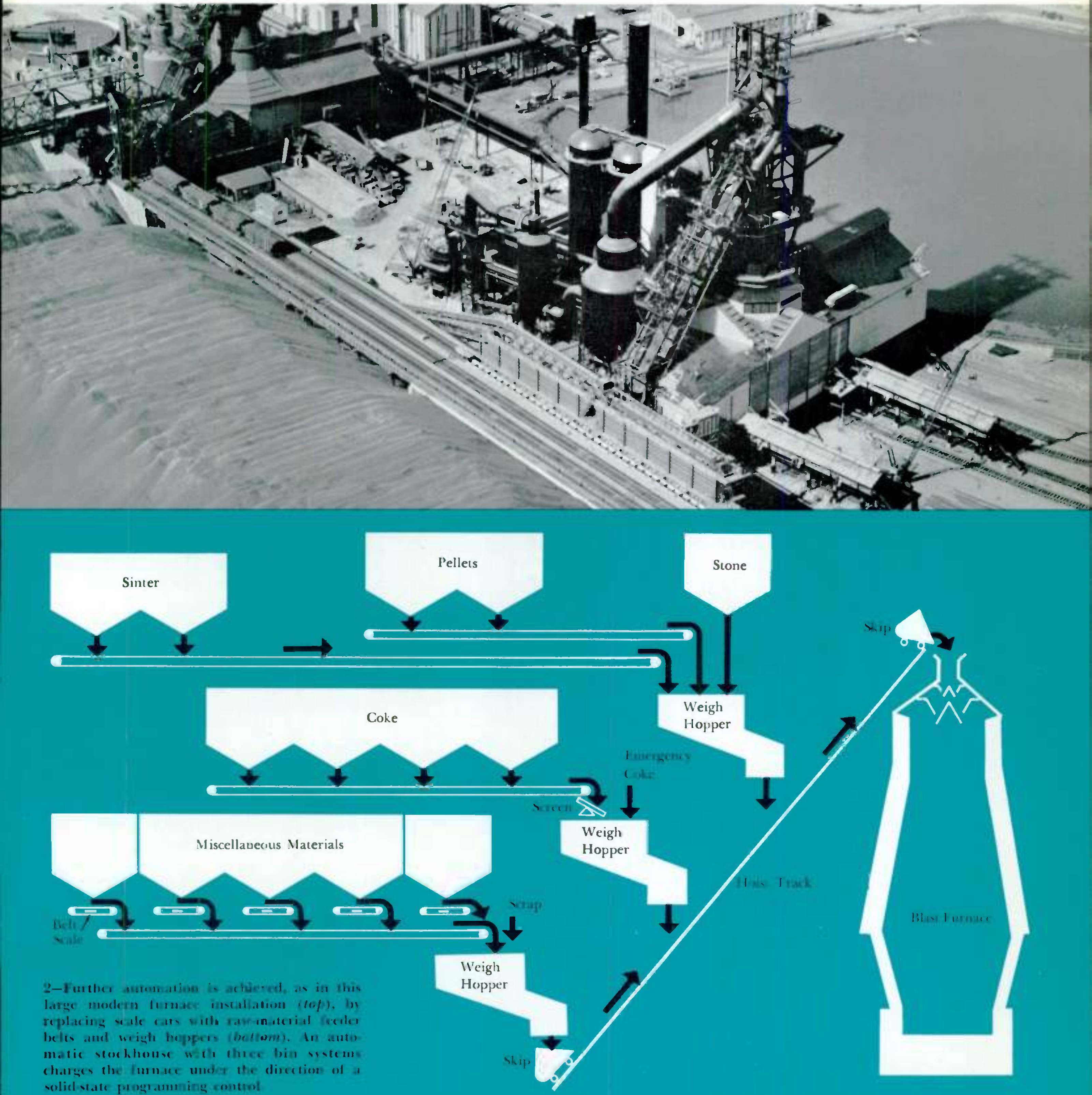


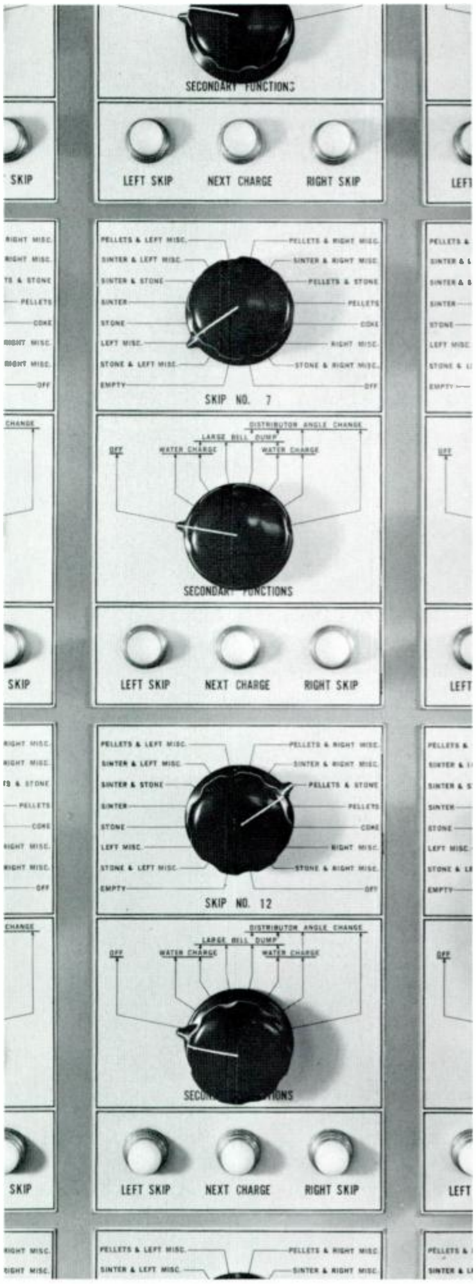
2—Further automation is achieved, as in this large modern furnace installation *(top)*, **by replacing scale cars with raw-material feeder belts and weigh hoppers** *(bottom)*. **An automatic stockhouse with three bin systems charges the furnace under the direction of a solid-state programming control.**

programming is set up by means of selector switches on a control panel, although actual filling of scale cars with fluxes and ores is still done by an operator. Such systems provide more flexibility in program selection. A typical Prodac unit can set up a pattern of 20 different skip loads.

A further improvement in material handling, with more assurance of uniformity, has been obtained recently by adding holding hoppers for materials other than coke and presenting information to the scale-car operator by means of a display panel in the stockhouse. The main control panel includes solid-state Prodac programming and manual controls as well as trouble-shooting indicating lights; it is contained in a factory-assembled cabinet mounted in the hoist house (Fig. 1). This design permitted considerable advance interconnection and control pretesting in the factory. The use of punched tape for programming (to be discussed later) was pioneered in such an installation.

For the largest furnace presently installed in the United States, the scale car was eliminated by installing a completely automatic stockhouse with feeder belts conveying all of the charge materials directly to weigh hoppers (Fig. 2). The result is faster charging, better weight control, greater uniformity of operation, and, consequently, more and better iron. Selector switches are used to establish the furnace charge program (Fig. 3). A data logger records the weights, the time the skip is charged, and other significant information.

Prodac solid-state digital controls in this system program the filling of weigh hoppers with instructions on which material is required, what quantity is required, and when the respective hopper filling is to start. The control receives digital signals from the weigh hoppers proportional to weight, and, when the correct weight is reached, the control automatically stops filling and acknowledges that the hopper is full. When the proper skip enters the pit, the weigh hopper is emptied into it. Then, when all of the other skip and furnace requirements are met (water needed, furnace level low enough, and so on), the skip is automatically started up to the furnace top. Solid-state control logic systems also are employed to sequence the furnace top equipment properly. This sequencing permits effective introduction of material to maintain the furnace level.



3—The control for the furnace installation illustrated in Fig. 2 has selector switches that permit individual assignment of 20 different skip loads. Automation enables the furnace to produce more iron of better quality.

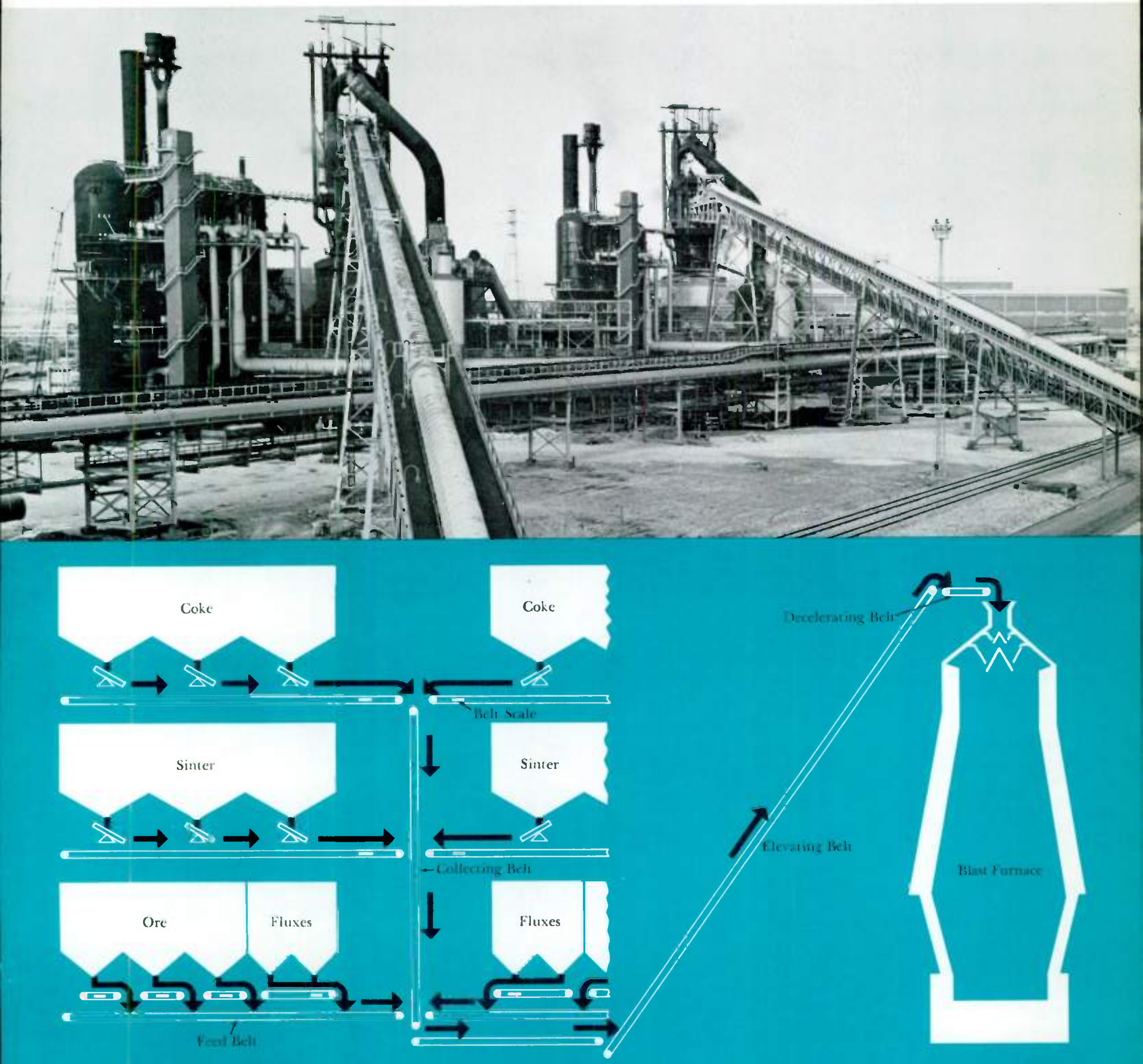
Further automation of material handling has been achieved in an installation in Europe that has a belt conveyor system in place of a skip hoist (Fig. 4). In addition to complete programming by means of switches (including weight values), the Prodac control system employs data logging, closed-circuit television, and graphic panels for continuous monitoring of the blast-furnace complex (Fig. 5). This is the first digital control system for belt-fed furnaces.

To assure a successful start-up of the complex system, cables between cabinets were preassembled with plug-in ends to permit a complete wired test in the factory. Once the cabinets were mounted in the field, the connecting cables were simply plugged in to complete the control installation.

These new control systems have not proved to be as radical a departure as the industry originally assumed they would be. Since many plants had employed automatic coke-handling systems successfully for years, the projection to other materials was a logical well-prepared step. Once sized metal-bearing materials were available and reliable scales with acceptable accuracy were obtainable (either belt scales or hopper scales), automated control systems became practical. An acceptable degree of scale accuracy has been defined within the industry as ±0.5 percent of total scale capacity for belt scales and 0.1 percent for hopper scales.

Solid-State Automatic Controls

Many years of experience with solid-state control elements in allied industries have helped produce compact and reliable assemblies of the elements and have shown that certain circuit configurations provide basic building blocks for making up a wide variety of control systems. It is not uncommon to find a particular series of control boards combined to produce a



4—Belt feeding, in place of skip charging, offers the best possibility for high production. Duplicate conveyor systems (*top*) serve two furnaces in this installation. The desired charging sequence is set with selector switches, and then the automatic materials-handling system weighs and conveys the raw materials from bins to furnace top in the desired proportions and sequences (*bottom*). Bins and feed belts are arranged on both sides of the collecting belt that conveys the materials to the long elevating belt.

blast-furnace charging panel while, in another area of the steel mill, the same boards are regrouped to perform control functions for rolling mills. This standardization of assemblies helps reduce unit costs and also permits a high degree of parts interchangeability, with consequent simplification of spare-parts inventory and maintenance procedures.

Many advanced solid-state control systems have been installed and are successfully operating. They provide programming and fully automatic charging of all raw materials as well as complete interlocking and sequencing of all material-handling facilities and the furnace top system. Most of them have several different modes of operation that can be classified as automatic, semiautomatic, manual, and maintenance.

In the *automatic* mode of operation, the control system performs all functions within its ability whenever required conditions have been met. For example, when a contact closure in the coke scale indicates that the coke hopper is empty and information from a limit switch indicates that the hopper gate is closed, operation of the coke-filling system is initiated to fill the hopper. As coke is introduced into the hopper, the scale system provides pulse signals to the programmer, with each signal indicating that a specific amount of material has been added. When the weight accumulation reaches a certain value, the coke feeders and associated conveyor are stopped. (The screen, however, is permitted to run until all coke is unloaded from it.) The control then knows that the coke hopper is full and, when the proper skip enters the pit, it dumps the hopper. When the hopper is empty, its gate is closed and a signal is given to initiate skip movement.

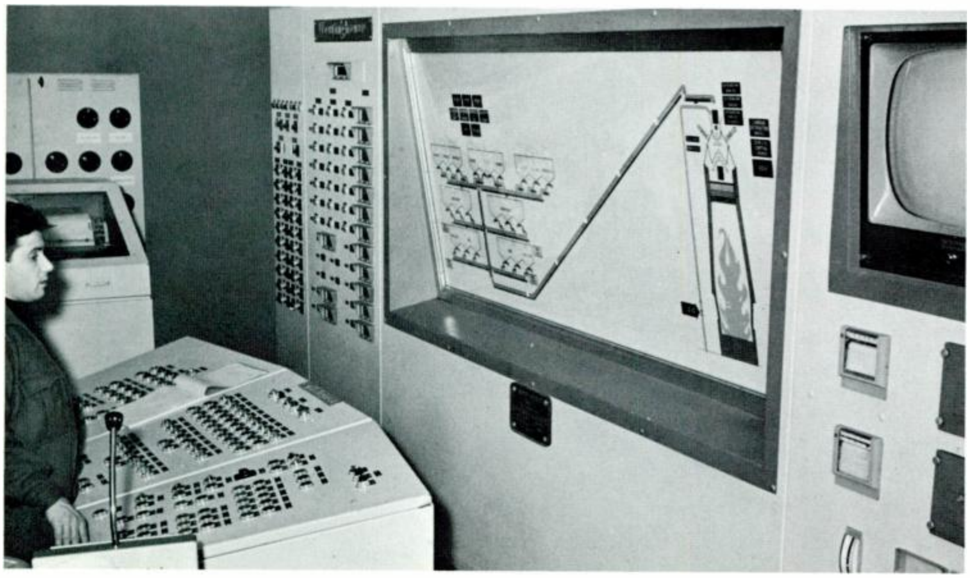
The *semiautomatic* mode is some form of sequence-by-sequence operation, with the sequences initiated by the operator. With the coke example, again, semiautomatic operation probably would go like this: When a skip enters the pit, a light indicates its presence; the operator presses a *Load Coke* pushbutton, which automatically dumps the coke hopper and then closes its gate; the operator presses a *Coke Hopper Refill* pushbutton, which refills the empty coke hopper; the operator presses a *Skip Start* pushbutton that initiates skip motion, with acceleration and deceleration controlled by drum cam limit switches. All conditions are checked as in the automatic mode, but actual initiation depends on the operator once all other requirements have been met. This semiautomatic mode is used when the automatic programmer is being maintained.

The *manual* mode of operation bypasses the programmed control as well as the directed sequences so that the furnace can be charged even with the automatic systems inoperative. If a scale system is lost, for example, the operator could both start and stop coke-hopper filling. Only minimal interlocking is in effect, and operation and sequencing are under the operator's direct command.

In the *maintenance* mode of operation, all protective interlocks are bypassed so devices can be operated for inspection. As in manual operation, all functions are initiated by the operator; the prime difference is that unsafe conditions can be created, so extreme caution is required. This mode is used only when scheduled in advance or in emergencies such as a mechanical failure in the furnace top equipment.

Experience has shown that, as the automatic systems become more efficient, operators tend to rely more heavily on them. Differences in results between automatic and manual operation will some day become so apparent that operators will constantly try to stay on automatic. Also, it is conceivable that two automatic control systems (one on standby) may be more economical than a mode-selectable system.

5—Animated graphic panels in the control room permit continuous monitoring of the furnaces illustrated in Fig. 4. Selector switches on the panel at the extreme left of the graphic panel are used to assign raw-material loads and other functions; the panel just to the right of that includes switches to set desired weights and readouts to show actual weights.



Programming Systems

Solid-state logic control systems for charging operations and furnace-top functions are presently being programmed with selector switches, punched cards, or punched tape. The two most common methods are selector-switch and punched-tape programming. Each method has certain inherent features.

Selector-Switch Programming—In this method, the number of material loads that can be included in a round is determined by the number of selector switches available. (A "round" is any number of skip loads of different materials fed to the furnace in a prearranged sequence; it is complete when the sequence starts to repeat.) In most installations, the maximum number of different loads that can be programmed before it is necessary to repeat the charge sequence is 20. The pattern is normally arranged so that a pattern of 10 loads maximum can be repeated indefinitely, and a different charging pattern is established on the other set of 10 switches. When a different fill pattern is required, it is only necessary to instruct the control to transfer at the end of the round in progress. The advantage of selector-switch programming is that the program can be readily modified by merely changing switch settings.

The latest selector-switch systems can select the number of times one pattern is to be repeated before transferring to the other pattern. A typical programming control cabinet of this type is shown in Fig. 5. Although these refinements provide more flexibility in programming, the program is still limited to a maximum of 10 loads of a given pattern before it must repeat or transfer to a different pattern of 10 loads. Additional selector switches would increase the flexibility, but they would also increase the size of the panel.

Punched-Tape Programming—This method employs a paper or mylar tape, perforated with coded charging instructions for transmittal to the control system. The instructions usually specify the basic charging pattern to be followed, the number of the round in process, the number of loads within the round, and the same information presented by the other systems (such as type of material, whether water is required, if a large-bell dump is required, and if a distributor angle change is needed). This information usually is programmed on the tape with each load separated by space codes. The beginning of each round is identified by a unique character for proper identification in the control logic.

This system permits a relatively unlimited number of loads to be programmed individually without increasing the size of the operator's panel or the control itself. Although units presently in use

The Blast-Furnace Process

A blast furnace consists essentially of a cylindrical structure with a hearth at the bottom and an opening at the top. Auxiliary equipment generates a blast of hot air, supplies raw material to the furnace, and carries away the molten iron, slag, and gas produced.

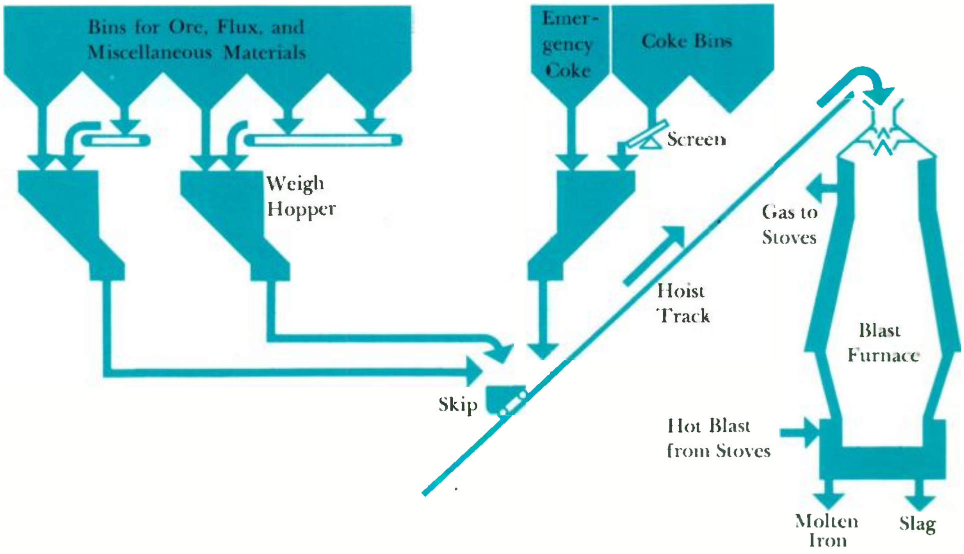
Raw materials, consisting mainly of ore, flux (limestone or dolomite), coke, and sometimes scrap, are charged through the furnace top by means of a system of gas locks called bells that confines the gases and maintains pressure in the furnace. Water may be charged also, to cool the furnace top. Hot air (the "blast") is blown in above the hearth to support continuous combustion of the coke.

Carbon monoxide formed by partial oxidation of the coke reduces the iron oxides in the ore to molten metallic iron, which collects on the hearth. (Since more carbon monoxide is formed than is used, it makes the gas mixture that collects in the furnace top combustible; this mixture is piped off and burned in "stoves" to heat the air blast.) The flux melts and combines with the nonmetallic part of the ore to form a molten slag that floats on top of the iron. Periodically, the furnace is tapped to remove slag and iron. The iron is usually charged, still molten, into a steelmaking furnace as the basic ingredient in the steelmaking process.

Most blast furnaces are charged by hauling the materials in cars (called skips) up an inclined track and dumping them into the furnace top, where the loads are located radially by a distributor and admitted to the furnace by the small and large bells. The sequence and proportions in which materials are charged help control the process. They determine the chemical analysis of the iron, slag, and gas produced and, along with the quantity and temperature of blast air, they also determine production rate.

The blast-furnace process is presently characterized by batch inputs and outputs, even though the reduction process itself is continuous. Retention time in the furnace is six to eight hours.

High volume capability is another characteristic. A typical furnace receives about 1000 skip loads a day, containing 9000 tons of material, and produces about six 500-ton casts—3000 tons of iron a day. It operates continuously for at least four years before it is shut down for major repairs. In that time, about 13,000,000 tons of raw materials are weighed and charged in controlled proportions and sequences to produce about 5,000,000 tons of iron, 2,000,000 tons of slag, and 16,000,000 tons of gas.



have been limited to 200 different loads, this limitation was imposed primarily by the selected readouts; there is no reason why 1000 or more different loads could not be programmed through the use of different readouts.

The information for a new load is advanced into the control from tape storage as the last programmed load is moved out of the loading area and started on its journey to the furnace top. Since this information is presented to the control as a sequence of pulses, electronic storage capability is required in the control to retain the tape information until it is used. Thus, the increased flexibility of perforated tape programming introduces control complexity, a need for additional control components, and more operating restrictions than are found in a switch-programmed unit.

The operating restrictions occur because, with the large number of loads that can be programmed, changing the program becomes more complex than with switch programming. First, a new tape must be prepared and loaded into a standby tape reader, which is put into operation after completion of the round in progress. The new tape is then run around until it is at the desired starting point. The control is then initiated and everything started up again with the new tape commanding furnace charging.

Punched-Card Programming—A conventional punched card specifies the program the control is to follow. Although as many as 160 different skips can be programmed per card, this system has not received great acceptance because it requires storage space for cards and a special machine to enable the operator to "read" the program vehicle (the punched card). To obtain maximum use of the card, information is presented only as yes-no decisions and, accordingly, requires deciphering if the program is to be checked. Since this code is a foreign language to many furnace personnel, there has been a natural reluctance to install punched-card programming control.

In summary, this type can provide more loads than the selector-switch control and accomplishes similar results with fewer components than the perforated-tape control (since the card reader provides its own electronic storage). The major drawback is its difficult language. There is also the necessity to prepare a new card or set of cards to change the program for an extended period of time. (All three systems have provisions for the operator to make program modifications of short duration.)

Data Accumulation

Furnace automation, employing weigh transducers and solid-state logic, has made it convenient to add data accumulation and logging equipment in a number of the newer furnace installations. The compilation of information has shown that the loads being sent to a furnace are more consistent than originally anticipated and that the established charging patterns are more strictly adhered to. This type of operation has resulted in more uniform hot metal.

Maintenance Considerations

Although the solid-state logic technologies have been but recently adapted to blast-furnace controls, they have accumulated much experience in such other areas of the steel mill as blooming-slabbing mills, which have employed punched-card techniques for years, and the newer hot strip mills, which make use of digital computer controls. Therefore, maintenance departments are equipped with the necessary tools to test solid-state devices and the circuit boards made up of those devices.

Troubles that do occur are usually in the physical equipment rather than in the solid-state controls. Even though a system may have several thousand diodes, transistors, and other solid-state devices, maintenance and operating personnel have had little trouble in adapting to the systems. Indeed, there is far more pride of achievement associated with maintenance of the new systems.

Conclusion

Automatic programming makes it possible to deliver a more uniform flow of raw materials to a blast furnace, and, as a direct result, a more consistent and predictable output of hot metal has been achieved. An unexpected result is that operating personnel are accepting the control systems better than was anticipated. This is attributed to the fact that the control relieves the humdrum existence that used to be the operator's lot by placing him more directly in command of charging operations. Because the operator can now keep better watch on furnace performance and can give it attention as required, more preventive maintenance is being practiced today than ever before; this results in better furnace performance with less downtime.

Due to the increase in furnace capacity and the resultant larger material requirements, material-holding hoppers for skip loading are becoming larger. Since a limited area is available for skip loading, the increased size of the holding hoppers is beginning to create problems. These problems are stimulating more interest in continuous charging by conveyor belts in place of skip charging.

Considerable experience with the modern control techniques has led to improvements and centralization in the design of systems and control rooms. At some plants, instrumentation and controls associated with the stoves and hot-blast equipment are being drawn closer to the area where the furnace charging control is located. In new designs, a single supervision center, housing all logic and command systems for the complete blast furnace including many of the auxiliary facilities, is being evaluated.

In the past, automatic charging controls were designed around the furnace mechanical system. In the future, the mechanical system may be designed around an automatic control system, with the ultimate goal being complete automation employing a closed-loop control system. This will require instrumented knowledge of all essential furnace operating variables. The time required to obtain and analyze furnace performance data is now a serious bottleneck to production, and is, in fact, the major barrier to closed-loop control. Development of improved instrumentation and practical sensing devices must be accelerated to make such control a reality.

Carbon-Steel Tube-to-Tube-Sheet Joints for High-Pressure Feedwater Heaters

A. Lohmeier
S. D. Reynolds, Jr.

Improved fabrication and handling techniques have been developed for welding carbon-steel tubes to the tube sheet. The early problems of welded-joint failure have been eliminated.

The tube-to-tube-sheet juncture is probably the most crucial part of the structural design of high-pressure feedwater heaters. The joint must be sufficiently strong to sustain the axial tube load created by the pressure differential across the tube sheet, which may be as high as 5000 psi in modern plant cycles. The joint must remain impervious to water under this high pressure differential while sustaining the cyclic stresses due to tube-sheet flexure, thermal variations between the tube and tube sheet caused by such operating conditions as start-up and shutdown, and possible abnormal transient operations that cause sudden changes in feedwater temperatures. These flexural and thermal stresses can be sufficiently large to propagate leakage paths from weld metal flaws. Any minute leak paths that do develop in the tube-to-tube-sheet joint at the high pressures employed can rapidly erode to dimensions that require removal of the heat exchanger from service. Such outages of power-plant regenerative heat-exchange equipment result in losses in efficiency and capability, and severely affect power-plant economics.

Fortunately, improved fabrication and handling techniques have been developed over the past few years to eliminate the juncture problems that occurred in the earlier high-pressure heaters built with carbon-steel tubes. In fact, the problem has been reduced in the present Westinghouse design to the point where a five-year warranty can be given on the integrity of the tube-to-tube-sheet juncture.

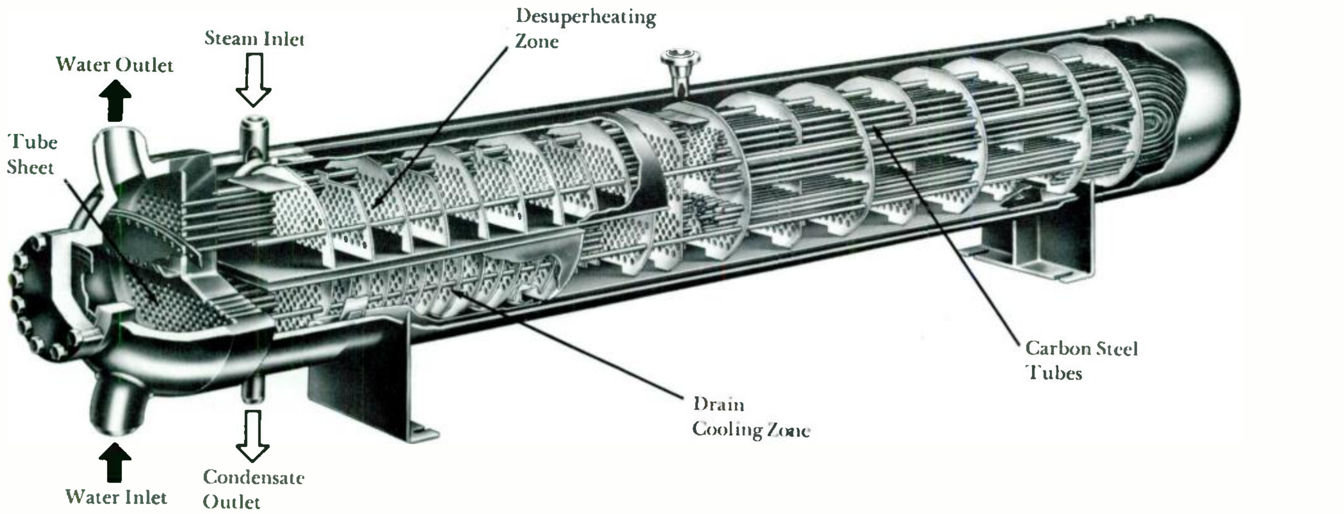
Although not developed for nuclear applications, these tube welds meet all of the requirements of *ASME Boiler and Pressure Vessel Code for Nuclear Vessels.*

Carbon-Steel Tubes

The tube-to-tube-sheet juncture was not a serious problem until a few years ago when manufacturers were forced to abandon nonferrous materials for high-pressure feedwater heater tubing. At the elevated feedwater temperatures used in modern power-plant cycles, copper can be removed by solution of the tubes and deposited elsewhere in the cycle—in boilers and in turbine blading—to the extent that steam passage through the blading is restricted. Copper-nickel tubing can also exhibit scaling corrosion and in some cases can fail through stress-corrosion cracking mechanisms. Thus, the commonly used nonferrous tube materials, such as arsenical copper, admiralty metal, copper-nickel, or Monel metal, were no longer desirable tube materials for use with high-pressure boiler designs. During the search for tube materials that did not contain copper, it was found that the general corrosion and pitting problems with carbon-steel tubes could be minimized with improved handling and fabrication techniques, controlled water conditions, and proper shutdown practices. Since these steps overcome the fundamental deficiency of carbon-steel tubing, this material soon became the choice of many designers.

Service Difficulties With Carbon-Steel Tubes

Shortly after the construction of the first high-pressure feedwater heaters with carbon-steel tubes, many manufacturers experienced trouble with welded tube-joint leakage in service. Leakage was not restricted to those feedwater heaters having a particular type of tube-weld geometry or welding process; it occurred in heat exchangers having simple fusion gas-shielded tungsten-arc (TIG) welds, shielded metal-arc (stick-electrode) welds,



1—High pressure feedwater heater for modern plant cycles raises the temperature of inlet water to the boiler at pressures up to 5000 psi. All-welded construction assures trouble-free operation and minimum maintenance.

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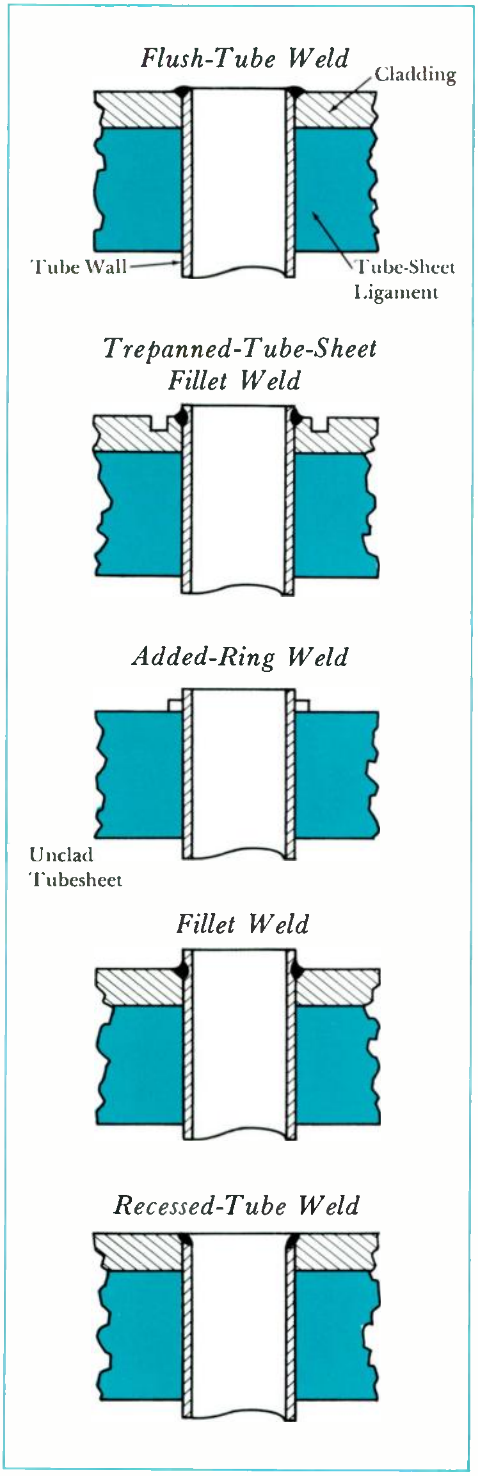
ring welds using the TIG process, and recessed TIG tube welds with carbon-steel-clad tube sheet. All applications had carbon-steel tubes with varying carbon contents up to 0.28 percent.

Examination of the tube-weld failures in the field and at the factory indicated that the leak path was generated from porosity within the weld, caused by gas formation during the welding process. Such defects could have resulted from the presence of moisture, iron oxide (rust), oil, or other foreign material in the interface between the tube and the tube sheet. Subsequent investigation indicated that the propagation of leak paths through the weld from the porosity cavity could be attributed to the limited ductility of the carbon-steel weld material and adjacent heat-affected zone. The porosity may not have completely penetrated the joint during manufacture and therefore was not detected during various quality-control tests. However, subsequent operation (pressurization, heating, or combination of both) provided the stress mechanism to complete a leakage path after a few cycles. Once penetration was achieved, flow through the inclusion rapidly enlarged the leakage path.

Concurrent with the investigation of field failures, an extensive welding development program was undertaken to evaluate various welding processes, tube-joint configurations, and possible tube-sheet cladding materials. Although designers believed that a suitable carbon-steel weld could be made using only improved welding techniques, this would not eliminate the problem of chemical heterogenity in tube-sheet forgings made of carbon steel. Alloy segregation, including carbon, can lead to localized spots in the ingot where the chemical composition is completely unsatisfactory for tube welding. For example, localized regions of high carbon content are normal problems with heavy-section carbon-steel forgings. To eliminate this problem, Westinghouse development effort was concentrated on the use of a ductile, erosion-resistant cladding material for the tube plate. The cladding material, applied by a welding process to the tube sheet, would provide a welding surface with the desired homogenity.



2—Of these possible tube-to-tube-sheet weld configurations, the recessed-tube weld has proved most simple and reliable for carbon-steel-tubed heaters.

Three possible materials considered suitable for cladding were low-carbon steel, austenitic stainless steel, and a high-nickel alloy. Each of these materials would increase the weldability of the tube sheet by providing deoxidizers for the tube weld to minimize atmospheric gassing and improve the properties of the tube weld. However, for reasons that will be discussed, only high-nickel alloy cladding has been found satisfactory.

Metallurgical Considerations

The tube weld is a fused juncture between the tube and tube sheet, and the joint design may be one of several different configurations as shown in Fig. 2. The essential requirement of the weld is that it fuse the tube and tube-sheet material without undesirable mechanical or metallurgical properties as a result of the mixing of the two materials. Thus, the weld and heat-affected area should be resistant to cracking and free from porosity. The weld metal should also have good corrosion resistance because the weld is of small dimensions so that the leakage path distance through the weld is short. Good erosion resistance is desirable so that small leaks that do develop will not enlarge at a catastrophic rate. The coefficient of thermal expansion of the weld should also be similar to that of the tube and tube sheet to minimize thermal stress. And finally, the tube, tube sheet, and filler metal used for the weld should have similar melting points to minimize defects due to lack of fusion during welding.

The high-pressure feedwater heater tube sheet is usually a carbon-steel forging (SA 266, Grade II) with carbon content ranging from 0.27 to 0.35 percent. In high-pressure designs, the tube is usually a carbon steel of 60,000 to 70,000 psi tensile strength and carbon content of 0.25 to 0.30 percent.

Simple fusion welding of these two materials results in a weld with carbon content of 0.26-0.33 percent. However, the weld and the attendant heat-affected zone may not have the good mechanical or metallurgical properties of the original materials because carbon steel is allotropic, i.e., subject to solid-state crystallographic change. When phase changes occur, the desirable austenitic crystal structure (all carbon present is soluble so that the material is homogeneous) changes to the brittle martensitic structure in which the carbon atoms exist in a state of supersaturated solid solution. This crystal structure change can leave high restraint stresses in the material, which may cause delayed cracking in the brittle heat-affected zone.

When tube welds are made directly to the tube sheet with a filler metal, the weld metal may have the desired low carbon content, but because of the fast cooling rate caused by the mass of the tube sheet, the heat-affected zone forms a martensitic area. Similarly, a low-carbon-steel cladding will improve the weld by keeping the carbon content low, but again, the heat-affected zone can cool rapidly to form a brittle area. It is therefore preferable to apply a cladding material that does not have the undesirable metallurgical properties of carbon steel so that neither the weld nor the heat-affected zone will be susceptible to brittle martensite formation upon cooling.

Certain alloy systems, when cooled rapidly to room temperature, will retain their ductility and crack resistance, and are generally free of allotropic transformation. Both of the other cladding possibilities mentioned—austenitic stainless steel and some high-nickel alloys—possess these desirable characteristics.

Stainless-steel tube sheet cladding has been used extensively for many stainless-steel tubed nuclear power heat exchanger applications. With proper control of the weld deposit analysis, desirable mechanical properties can be produced. When austenitic stainless-steel tube sheet cladding is further diluted with variable amounts of carbon steel, it becomes difficult to produce the desired properties.

The coefficient of thermal expansion of stainless steel is 50 percent higher than that of carbon steel. Thus, the feedwater temperatures of today's fossil-fuel plants can produce severe stresses at the fusion zone.

The third possible cladding material, Inconel, a high-nickel alloy (Ni-Cr-Fe), has been found to have all of the desired mechanical, metallurgical, and physical properties. The major characteristics that make Inconel desirable for tube-sheet cladding can be summarized as follows:

1) The coefficient of thermal expansion is similar to that of steel.

2) As deposited on the tube sheet, Inconel has higher tensile strength, yield strength, ductility, and notch toughness than the carbon steel forging.

3) Corrosion resistance of Inconel is equal to or better than that of austenitic stainless steel because of the high chromium and nickel content.

4) The erosion resistance of Inconel is equal to or better than that of austenitic materials normally used for erosion resistance in power-plant practice.

5) Since Inconel is not allotropic, the heat-affected zone of a tube weld has mechanical properties equal to those of the cladding in all respects.

6) The melting point of Inconel is similar to that of carbon steel.

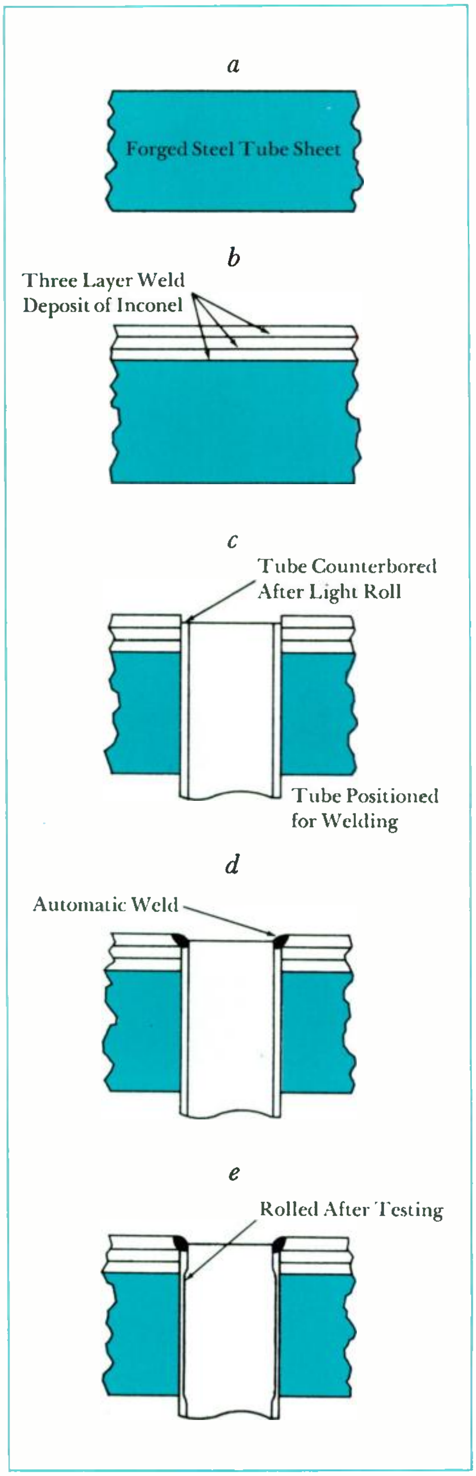
7) Inconel is metallurgically compatible with carbon steel over a wide range of dilution. For a simple fusion weld on an Inconel-clad tube sheet, all cladding layers and the tube weld fall well within the stable austenite region. (The ability of Inconel to form solid-solution alloys with many other alloy systems is the characteristic that makes this alloy one of the most commonly used filler metals for dissimilar metal welds). Because of the high solubility of carbon steel in Inconel, Inconel cladding can be used as a filler metal by the simple fusion technique.

8) Inconel cladding can be applied to the tube sheet with the reliable inert-gas metal-arc (MIG) process. A similar high-nickel-alloy process has been used for nickel-Monel overlays on feedwater heaters and for Inconel nuclear steam generators and has produced tube-sheet overlays with excellent chemical and mechanical properties.

Tube-Welding Process

Although many welding processes can be used to join the tube to the Inconel-clad tube sheet, most high-quality tube-to-tube-sheet welds are made by the TIG process. The joint geometry of the tube weld must be designed for mechanical,

continued page 143



3—Summary of the tube-welding procedure for carbon-steel-tubed feedwater heaters.

Tube-to-Tube-Sheet Welds

Three-hundred thousand welds in service without a leak have resulted from the tube-to-tube sheet welding procedure highlighted in the following photographs. Although many other steps are involved, the eight operations illustrated here play key roles in providing the high reliability record of the carbon-steel-tubed feedwater heater.

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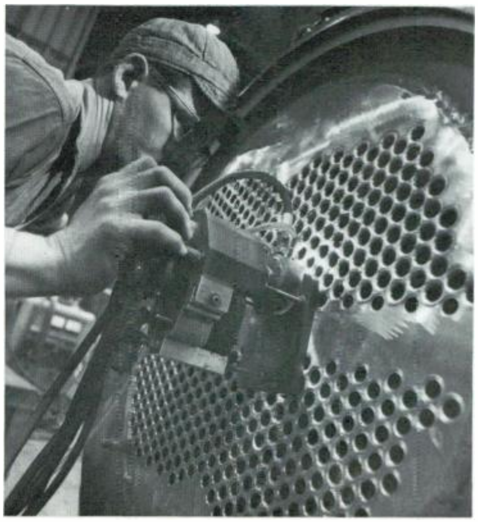
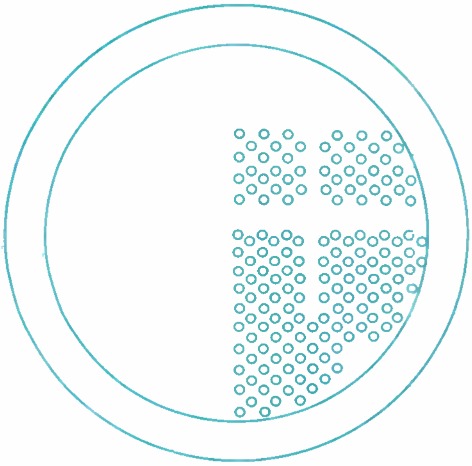




1—Three layers of Inconel weld-deposit cladding are applied to the face of the tube sheet, providing an ideal filler metal for fusing to carbon-steel tubes.

2—After finish machining, the integrity of the Inconel cladding is tested ultrasonically.

3—Tube-sheet holes are drilled with an automatic tape-controlled machine, insuring accurate spacing of the holes.

4—Tubes are inserted and, after light rolling to hold the tubes in place during the welding sequence, each tube and tube hole is counterbored. This step provides mechanical cleaning of welding surface prior to welding.

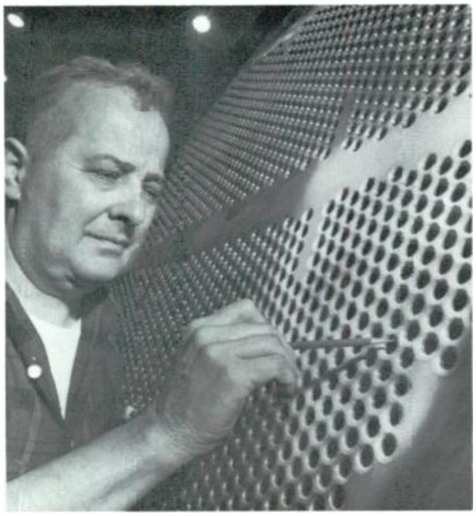
5—The recessed weld is made by the automatic TIG process, fusing the Inconel cladding to the carbon-steel tube.

6—The dye penetrant test is the first of several quality-control checks on the tube-to-tube-sheet weld. This test detects surface defects in the cladding and the tube weld.

7—Carbon-steel tubes are deep rolled, starting ½ inch below the weld, to provide another seal against leakage and to minimize stresses on the tube weld.

8—After the hemi-head is welded to the tube sheet, the weld is stress relieved with a carefully controlled heating cycle which maintains the necessary level of temperature for the required time and minimizes thermal stress during heating and cooling.

6



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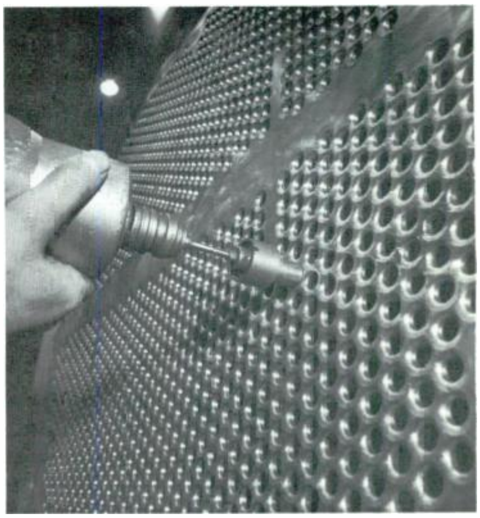

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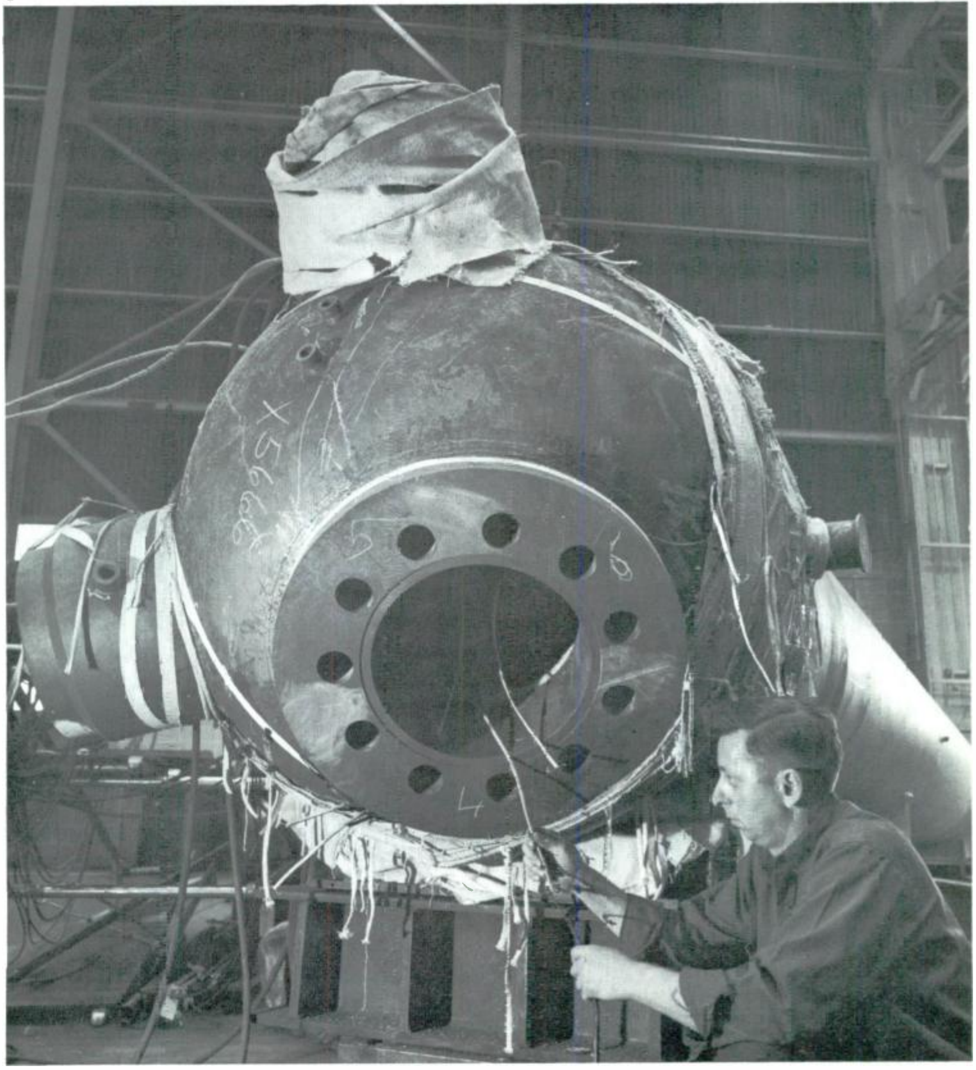
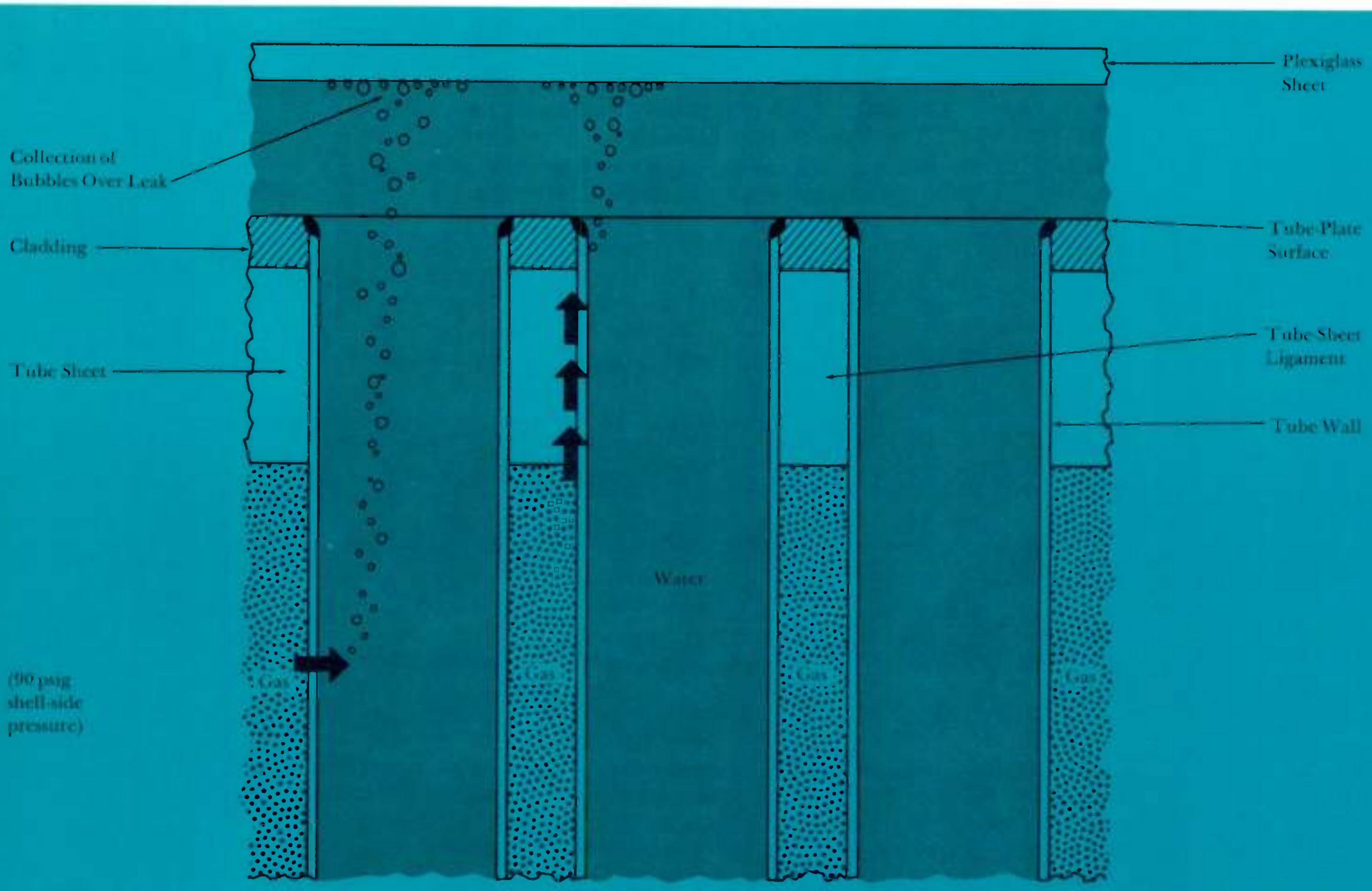




4—One of the inspection tests for tube-sheet weld quality is the lake bubble test. Air pressure is applied to the steam side of the feedwater heater prior to final tube expanding. Leaks in either the tubes or welds are detected by the bubbles that form in the pool of water covering the tube-sheet surface.

metallurgical, and dimensional reproducibility. This is accomplished best in an automatic process, with a joint that is both mechanically and metallurgically simple. The tube-welding process now employed utilizes a fully automatic TIG tube-welding gun with primary and auxiliary argon gas shielding. The control circuit automatically starts, stops, and adjusts the rotation, high-frequency arc ignition, amperage, and gas shielding.

Provided the proper tube-weld chemistry, cladding material, and manufacturing techniques are used, many different weld geometries should provide a successful tube weld. However, experience gained from developmental tests or in-service operation with all of the various joint designs shown in Fig. 2 indicates that the most reliable joint is the simplest one, the recessed-tube weld joint.

The recessed-tube cladding-fusion technique makes possible mechanical cleaning of all surfaces to be fused; the tube is first lightly expanded to provide a tight mechanical fit, and then the tube and tube hole are cut with a counterbore cutter immediately before welding, thus insuring welding surface cleanliness. The recessed-tube technique requires no addition of filler metal because the Inconel cladding provides the filler. This technique melts only the corner of the clad hole and fuses only to the top of the tube. This is an advantage because the less surface to be melted, the less chance for porosity defects. Finally, since any mass-produced weld is statistically subject to conditions causing some defects, the recessed weld provides a joint that can be repaired by simple techniques.

Tube-weld porosity is the defect that most often produces tube-sheet leakage. In view of the excellent metallurgical properties of Inconel cladding, it was believed that the Inconel tube weld would also have inherent mechanical properties that would deter propagation of porosity defects. A test program was developed to demonstrate, by comparison with carbon steel, the ability of Inconel welds manufactured under adverse conditions to sustain cyclic operation.

Two carbon-steel tube sheets were constructed to dimensions that under hydrostatic pressure would give stress intensities comparable to those experienced on actual heat-exchanger tube sheets. One tube sheet contained tubes welded to a tube sheet clad with low-carbon steel; the other had tubes welded to an Inconel-clad tube sheet. Each tube sheet contained various combinations of weld-process cleanness. Prior to the initiation of the cyclic tests, the model tube sheets were thoroughly leak tested and no leaks were detected.

The tube sheets were then subjected to cyclic testing, which consisted of pressurizing the tube side with steam at 1000 psig and 550 degrees F; pressure was released when tube-sheet temperature reached 500 degrees F, and reapplied when tube-sheet temperature fell below 300 degrees F.

The test conclusively verified the ability of Inconel tube welds to withstand propagation of porosity defects. Whereas the carbon-steel-clad sheet with purposely introduced subsurface porosity defects developed leak paths after about 200 cycles, the Inconel-clad sheet with similar weld porosity did not develop leak paths after 1000 cycles.

Weld Quality Control

Since the reliability of a feedwater heater is a function of the total reliability of thousands of tube welds acting in parallel, it can be seen that for a suitably reliable heat exchanger, the reliability for each tube weld must approach unity.

Although automatic welding techniques minimize the number of defects, the probability of defects being present in a few welds still remains high. Unfortunately, there are few, if any, techniques available that can economically seek out subsurface welding defects. X-ray and ultrasonic flaw detection methods show promise, but to date they are difficult to interpret and costly to perform.

Normal inspection of tube-sheet weld quality is done by hydrotest and gas pressure testing techniques. The simplest technique is to pressurize with water (hydrotest) alternately from each side of the tube sheet and observe for leakage. A more effective procedure is air-pressure testing from the feedwater heater steam side, prior to final tube expanding, and observing for bubbles emanating from the tube welds in a pool of water covering the tube-sheet surface (lake bubble test).

The basic limitations in these tests are that they reveal only those defects that provide, at the time of testing, a flow path completely through the weld. Experience with carbon-steel tube-sheet welds has shown that the leaks that can occur after service operation give no indication of leakage during factory leak testing.

One method that has been successful in detecting subsurface defects is cyclic testing of the tube-sheet weld at the factory. This test has been attempted in two forms: cycling the tube sheet to hydrotest pressure a number of times, and providing a thermal shock to the tube-sheet weld surface. The pressure-cycling test has been particularly successful in locating potential leakage paths. The principle is, of course, that if the defect is of the type that will require a short propagation distance to complete the leak path, then the high tube-joint stresses during hydrotesting applied for several cycles will be sufficient to complete the path.

Conclusions

Early in the welding investigation, it was suspected that the Inconel tube weld would be less sensitive to variations in welding conditions and would have the inherent properties that deter propagation defects. Comparative tests of Inconel with other cladding materials have demonstrated this to be true. Even when Inconel cladding with intentional porosity was tested, the porosity did not propagate to provide a leakage path. Service experience has likewise demonstrated the superiority of the Inconel cladding approach. No tube-to-tube-sheet joint leaks have been experienced with the high-nickel alloy cladding process in many years of field experience with over 300,000 tube welds. The recessed tube-to-tube-sheet weld process, employing fusion of the tube with Inconel cladding, is believed to be the most reliable tube-to-tube-sheet joint yet developed for high-pressure feedwater heaters with carbon steel tubes.

Long Metal Boom Structures Unrolled from Compact Storage

Tubular booms that can be stored as spools of flat strip metal and unrolled where needed are being developed. As the material is unrolled, it curls into a straight tubular structure that is much more rigid than the flat strip. Results indicate that booms 10,000 feet long are feasible.

The technique is being developed primarily for applications in outer space, such as antennas and stabilizing booms for spacecraft. Other uses foreseen include deployment of instruments from spacecraft and underwater craft, and coupling of spacecraft in flight. Since the booms can be made tapered if desired, they also should be useful as structural elements strong enough to serve as columns for erectable structures on the moon, under water, and probably even on the earth's surface.

The flat metal strip is formed and heat-treated in such a way that its normal form is tubular. Even though it is rolled up flat for storage, it returns to the tubular shape when unrolled. The forming and heat-treating processes are continuous, so the strip can be made to the desired length. Most of the work so far has been on booms half an inch in diameter, but the process is applicable to larger or smaller diameters. The development work is being done under a contract with the National Aeronautics and Space Administration's Goddard Space Flight Center.

The engineers on the project have solved two problems that have heretofore limited the potential of this type of extendable support. First, they have achieved a high strength-to-weight ratio by applying special heat-treating processes, by forming interlocking seams on the edges of the strip, and by putting many small holes in the strip. Second, they have prevented the distortion that occurs in space when the side of a structure facing the sun is heated to high temperatures while the side away from the sun is cold. The special patterns of holes in the strips allow sunlight to pass through the boom and thereby heat the side away from the sun; since the entire boom remains at the same temperature, distortion of the structure is prevented.

Light slender booms primarily for space applications are fabricated from flat strip metal. The strip is perforated and given a permanent tubular set, but then is wound flat on a spool for compact storage. The strip is unwound by a small motor-driven device through guides that reform the tubular shape.

About 15 percent of the metal usually is removed by the holes, but more than 50 percent can be removed when the application requires. Each square inch of strip has about 100 holes, which are formed in the desired patterns by a photochemical etching process.

Linear Particle Accelerator in Operation at Stanford

A giant linear particle accelerator that has recently gone into operation at Stanford University might be called the world's longest small-bore shooting gallery. The largest linear accelerator yet built, and the nation's newest "atom smasher," it accelerates electrons down a straight two-mile tube to collide with target atoms. It was built by Stanford for high-energy physics research under a contract with the U.S. Atomic Energy Commission.

The linear type of electron accelerator has an important place among particle accelerators because it can produce more beam energy than the more common circular type, which is limited by radiation losses to an energy output of about 10 billion electron volts (bev). (Circular proton accelerators can greatly exceed this energy, but data analysis is much more complex.) The Stanford accelerator was first turned on fully in May this year at reduced power, with a beam energy of 10 bev. Shortly thereafter, it was operated at 18.4 bev and peak current of 15 milliamperes.

When the accelerator goes into full operation early next year, it will produce up to 20 bev with peak beam currents as high as 30 milliamperes. At present, there are only two accelerators in the world producing particles having energies greater than this; both are circular proton machines operating in the neighborhood of 30 bev. Even that rating will be exceeded in the Stanford accelerator's Phase II, when modifications will increase the beam energy to 40 bev.

The high energy of the beam is produced by accelerating electrons through the tube with pulses of microwave energy generated by 240 klystrons spaced along the tube. The tube is in a tunnel, separated from the klystron gallery above it by 25 feet of earth and concrete to shield personnel in the gallery against radiation. Waveguides carry energy from the klystrons down to the tube.

The klystrons receive power from pulse modulators—250 kilovolts in 2.5-microsecond pulses. This voltage, and the resultant output power, must be closely regulated to maintain a narrow energy spectrum in the electron beam. Regulation is accomplished by controlling the voltage to which the pulse-forming networks in the modulators are charged; it is performed by a circuit designed around high-power thyristors.

The latter circuit is an innovation. Previous electron accelerators have employed a thyratron circuit to regulate the pulse-forming network voltage. Thyristors

Accelerator tube stretches two miles down a tunnel. Waveguides, one of which is seen at upper left, bring microwave energy from 240 klystrons to accelerate electrons through the tube for high-energy physics research.

were chosen for this accelerator because they do not burn out, as thyratrons do, thus adding an important degree of reliability in a facility that is expected to be used around the clock.

The Phase-II modifications of the accelerator, to increase the beam energy, will consist essentially of increasing the number of modulators and klystrons from 240 to 960.

Equipment in Progress for High-Speed Ground Transportation Program

Advanced electrical propulsion equipment and auxiliary systems are being produced for self-propelled railway passenger cars capable of speeds of 160 miles an hour. The streamlined new cars are being built by the Budd Company for the Pennsylvania Railroad, which will operate them under contract to the U.S. Department of Commerce between New York City and Washington, D. C., during a two-year passenger-service test.

The cars are expected to travel this highly populated Northeast Corridor in an elapsed time of less than three hours, with at least four stops included. The chief aim of the demonstration is to discover whether the public will be attracted to the service in sufficient volume to make it economically practical.

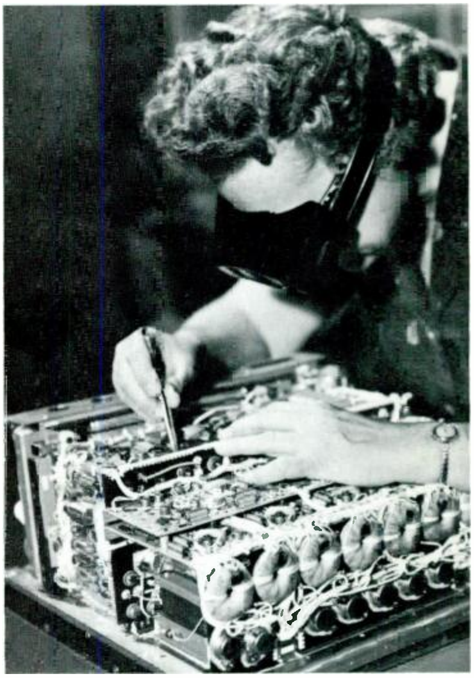
The electrical equipment includes four 300-horsepower Tracpak motor-gear units for each car; a speed-maintaining control system; and an auxiliary power supply for operation of air-conditioning, lighting, heating, ventilating, and food facilities. Delivery of the equipment is scheduled for the middle of next year, and the new cars are expected to go into operation in the fall.

Central Inverter Will Supply Apollo AC Power Needs

A single electric power inverter will provide central power conversion in the Apollo spacecraft, in contrast to the use of a number of small local inverters in previous spacecraft electrical systems. Use of this high-power central static inverter will provide lighter weight, lower cost, capacity for load growth, flexibility in load selection, and improved maintainability.

The Apollo spacecraft will consist of a command module, a service module and, for lunar exploration missions, a lunar excursion module. Its command module is designed to permit three men to work, sleep, and eat without wearing pressure suits. The service module will contain fuel, rocket engines, and the fuel cells that provide the electric power.

In developing the new inverter, engineers had to devise new components, materials, and methods. Among these developments were special printed circuits with metal cores for cooling, new high-power transistors, a foam encapsulant that provides hermetic sealing and vibration damping, and transformers using new materials for weight saving and low acoustic noise levels. The inverter was developed under contract to the Space and Information Systems Division of North American Aviation Corporation.



Inverter for central electric power conversion in Apollo spacecraft is inspected at the factory. It provides three-phase 400-cps power.

All of the ac power in the spacecraft will be supplied by the new inverter. Some of the electrical and electronic functions that will rely on this power are instrumentation, environmental control, service propulsion gauging, communications and data handling, guidance and navigation, lighting and data viewing, fuel-cell control, fuel-cell gas and water separation, and management of waste materials.

The inverter will provide ac power at 1250 volt-amperes, 115/200 volts, three phases, and 400 cps. Primary power will be supplied to the inverter by the fuel cells, which also power other functions that use low-voltage dc. Batteries in the command module will provide input power for the inverter during reentry into the earth's atmosphere after the service module is jettisoned.

The inverter is built to demodulate transients and dc ripple voltages of 10 to 1000 cps on the primary-power dc bus, caused by the dc loads. The demodulation approach was selected because conventional filter networks for attenuation of the dc voltage fluctuations would be prohibitively large and heavy.

Stronger Red Output Improves Fluorescent-Lamp Color Balance

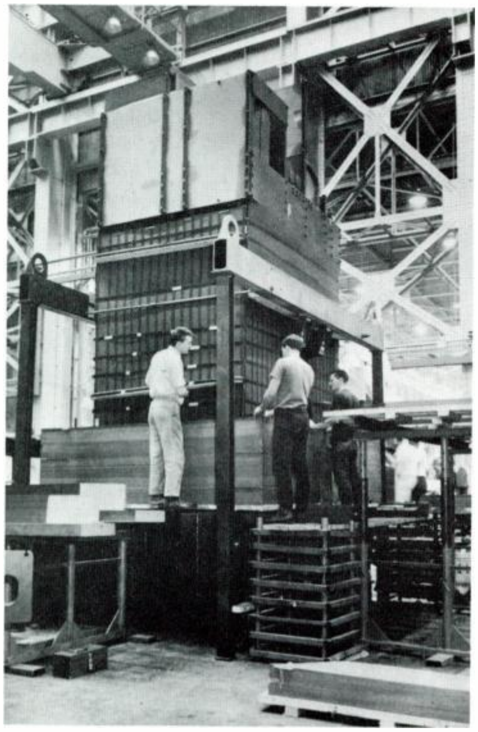
The red phosphors that have been used in fluorescent lamps provide far less brightness than the green and blue ones, so it has been necessary either to limit the brightness of the green and blue (so they don't outweigh the red) or to accept a light output lacking in the red area of the spectrum. The latter approach produces a light that tends to be unflattering to complexion and to interior furnishings. Now, however, a new lamp provides both greater brightness and a marked improvement in color balance.

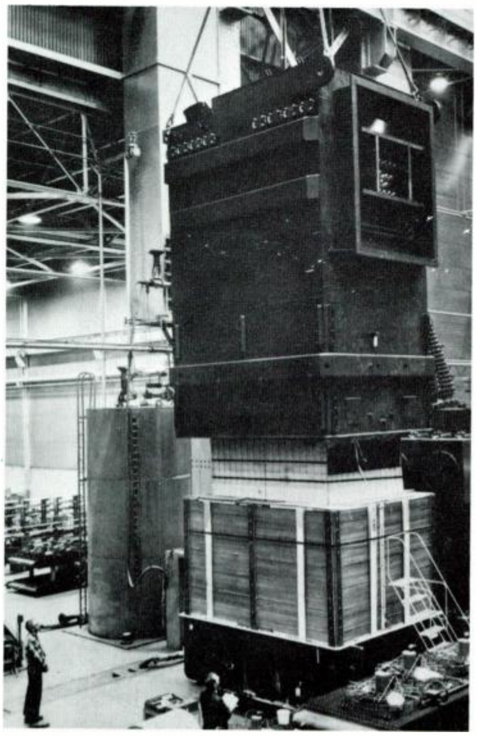
The Living White fluorescent lamp, as it is called, produces light that is rich in the orange-red end of the color spectrum, so it has a greatly improved color balance at full output. Its light output is 10 percent higher than that of present Cool White Deluxe lamps. This increased light output and better balance were made possible by supplementing the other phosphors in the lamp with the rare-earth materials yttrium oxide and europium.

EHV Transformers Built for Keystone Project

Nineteen EHV transformers for the Keystone mine-mouth power generating project are being shipped from the manufacturing facility in Muncie, Indiana. They will tie the generating plant through a 500-kv transmission line to the project's various systems. The project is one of the largest coordinated EHV transmission and power-plant programs ever undertaken by electric utility companies of the Pennsylvania - New Jersey - Maryland Interconnection.

In manufacture, grain-oriented electrical steel punchings for the transformers are meticulously placed (see photos). While work is progressing on the phase and bottom section assembly, the top section of the tank is also made ready. The top section is then lowered over the core and coil assembly. The transformer is then sealed, dried, and tested.





Electrical-steel punchings for EHV transformer are put into place *(top)*. Then the top section of the transformer is lowered over the core and coil assembly *(bottom)*.

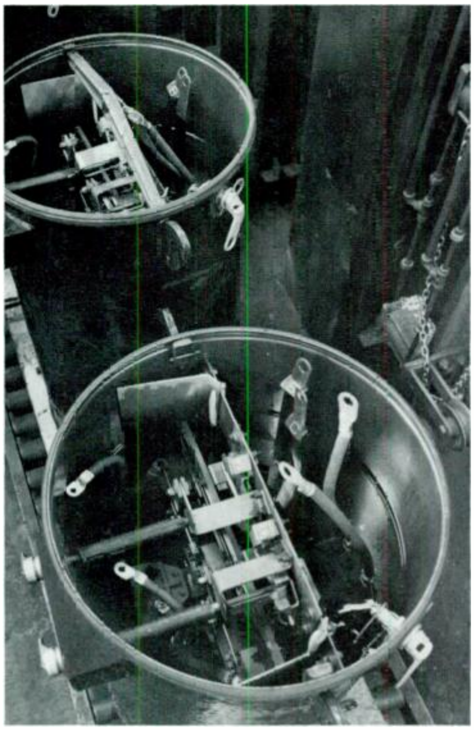
These units are rated 217,000 kva, 500/230 kv, and the top rating for all 19 can be increased 20 percent by the addition of extra cooling equipment. All units also have load tap changing of plus or minus 10 percent.

Products for Industry

WC-161 operational amplifier is a commercial integrated circuit with both single-ended and differential outputs. Applications include general-purpose instrumentation, integration, and summation. With feedback, it can be used as a transducer amplifier, preamplifier, voltage comparator, and bandpass or buffer amplifier. Differential gain is 2200 volts per volt, input impedance is 300,000 ohms, output impedance is 40 ohms, and drift is 10 microvolts and one nanoampere per degree C. *Westinghouse Molecular Electronics Division, Box 7377, Elkridge, Maryland 21227.*

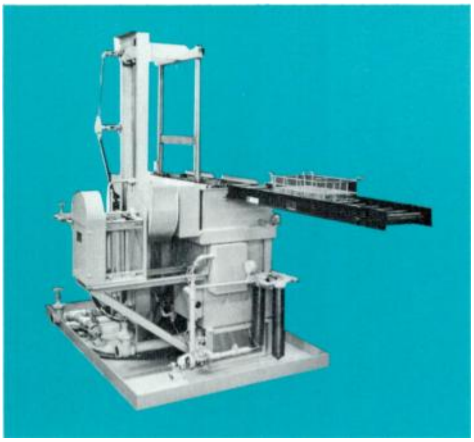
Model 30 numerical control system employs integrated circuitry for dependability, compactness, and cool operation. Reliability of the integrated circuitry permits a five-year warranty on the logic cards, and cool operation eliminates the requirement for air conditioning or ventilation. The model 30 can control a variety of three-axis machines. Basic positioning functions are contained on plug-in logic cards; optional auxiliary functions or provisions for new accessories are provided by additional plug-in logic cards. *Westinghouse Systems Control Division, Box 225, Buffalo, New York 14240.*

Oil load-break switch (LBO) for loop-feed applications is an accessory for the vault-type distribution transformer (SPB). It is used for sectionalizing or as a disconnect for the SPB unit. It is rated for 200 amperes continuous current and load-break, 125-kv BIL, 10,000 amperes



momentary current, and 10,000 amperes closing current. The four-position, single-phase, two-pole switch is mounted within the SPB transformer tank under oil to protect it from moisture and to simplify installation. Its four switching positions enable personnel to isolate a line fault quickly while maintaining full service, or to disconnect a transformer quickly for maintenance or change-out without disrupting the service of remaining transformers on the loop. *Westinghouse Distribution Transformer Division, Sharpsville Avenue, Sharon, Pennsylvania 16146.*

Hi-Torque Speed Control *(top right)* is a thyristor control of new design for fractional-horsepower dc motors. It provides an even change of motor speed from low to high and maintains it through full range. The unit comes in three models (901, 902, 903) that cover the complete range of motors up to one horsepower. Basic speed control is accomplished by varying the voltage to the armature from a full-wave silicon-rectifier bridge. Typical applications are in drives for small conveyors, process machines, machine tools, and laboratory apparatus; electronic experimentation; lamp dimming; and resistance heating control. *Westinghouse Specialty Motor Plant, Box 1611, Springfield, Massachusetts 01101.*



Ultrasonic vapor degreaser *(above)* cleans parts for assemblies requiring unusually clean components. Baskets of parts are conveyed into the semiautomatic two-position unit and pass successively through a vapor zone for precleaning and an ultrasonic cleaning tank. The time cycle can be varied to match the application. A one-kw magnetostrictive transducer is bottom-mounted on the tank to provide 20-kc ultrasonic energy to the cleaning bath; it is powered by a thyristor power supply. *Westinghouse Industrial Equipment Division, 2519 Wilkens Avenue, Baltimore, Maryland 21203.*

Load-O-Matic reactor control system for crane drives has been redesigned to incorporate a new thyristor static amplifier. The amplifier supplies and controls excitation current for the system's saturable reactors; it has two channels to handle both hoist and lower control. The system is designed for ac-motor crane drives from 5 to 400 hp. It is smaller and lighter than the older unit, with its two magnetic amplifiers and associated parts. System performance has been improved by minimizing the effect on speed of voltage variations commonly found in crane power supplies. The new amplifier is common to all drive ratings, reducing spare-parts inventories and simplifying maintenance procedures. Although designed for hoist drives, variations can be used for control of other crane motions. *Westinghouse Systems Control Division, Box 225, Buffalo, New York 14240.*

New Literature

Lasers, a 24-page illustrated booklet, describes recent advances and techniques in systems engineering, directed research, and basic studies. In systems engineering, the booklet goes into laser tracking, ranging, and illuminating; light modulation; high-power lasers; and welding. Under directed research, laser crystal and laser glass are covered along with high-energy coaxial laser pumping, spectral additive lamps, and pulse-shaping techniques. The basic-studies section presents information on liquid laser research, argon lasers, plasma generation by laser pulse, holography, electron-pumping mechanisms, high-energy electron-beam pumping, and cathodoluminescent pumping. Copies available from Director, Westinghouse Corporate Laser Program, Box 1693, Baltimore, Maryland 21203.

A Modern View of Out-Of-Step Relaying (Silent Sentinels RPL 66-1) is an illustrated 18-page booklet. It reviews the nature of out-of-step conditions, discusses their effects, relates the philosophy of sound out-of-step relaying, and describes new apparatus for satisfying the required relaying functions. Copies available from Westinghouse Relay-Instrument Division, Plane and Orange Streets, Newark, New Jersey 07101.

Results from Five Years of Lightning Study with Klydonograph Recorders

Edward Beck
D. F. Shankle
S. B. Griscom

Two recording devices that use an old principle of measurement in new configurations have provided valuable new data on the characteristics of lightning.

The information gathered from a five-year field investigation of lightning effects on transmission lines[1] has disclosed that lightning stroke characteristics differ from today's popularly accepted concepts in at least two major respects:

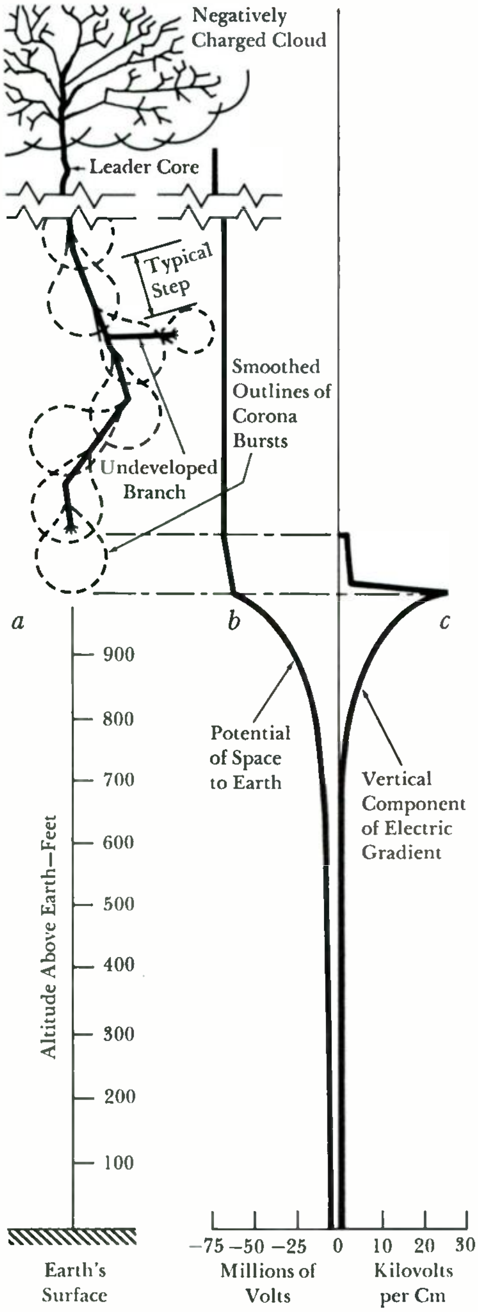
First, the electric field intensities in the vicinity of lightning strokes are much greater than previously thought, which means that high voltages can be induced in open-wire conductors without actual stroke contact—a hazard to transmission and distribution systems that has been considered harmless for many years.

And second, the initial rate of rise of lightning stroke current is much steeper than has been generally assumed, so that the inductive components of tower top potential produced by stroke current ($L\ di/dt$) are higher than the values calculated with present techniques that use a slower rate-of-rise for stroke current.

Both of these characteristics were predicted by a theoretical model of the lightning stroke, called the *prestrike* concept,[2] which was originally developed in 1958. Each of these effects would cause higher voltages across the insulator string, thus increasing the possibility of arc-over. Since a higher than predicted number of line flashovers *have occurred* on some extra-high-voltage lines, investigators hope that application of this new information will permit a more accurate determination of the effects of lightning on various transmission tower configurations.

The Prestrike Concept

Most investigators agree that lightning strokes develop from cloud to earth except for high pointed objects, and that the stroke consists essentially of two parts: a *leader*, which bridges the gap from cloud to ground and establishes an ionized path; and a *return stroke*, which reilluminates the leader path with all its zigs and zags, starting at the struck point and traveling upward to the cloud at a velocity of about 0.3 to 0.1 times the velocity of light. The leader is rather weak (500 amperes average) compared to the return stroke, which may have a peak of 10,000 to 250,000 amperes. The average duration of the high-energy portion of the return stroke is about 50 microseconds to half value with a time to crest of about 10 microseconds.



1—The prestrike theory predicts that the leader (*a*) progresses step-by-step, as a series of corona bursts, from thundercloud to earth. Air space potential (*b*) is shown for a typical leader head poised 1000 feet above earth. The vertical component of electric gradient (*c*) is shown for this same leader head. Note that the gradient is greatest external to the head and least near the tip of the leader core.

However, one of the most fundamental aspects of lightning—the physical mechanism by which the leader advances toward earth—is as yet unproven although the field research is gradually uncovering the facts. Most conventional theories have generally assumed the leader to be a column of uniformly distributed charge, which progresses in some step-by-step fashion as the air breaks down from the leader core outward. In contrast, the *prestrike* theory (Fig. 1) predicts that the leader progresses as a series of large corona bursts (or leader heads), each of which consists of a large air space charge volume, perhaps 100 feet in diameter, with most of the charge concentrated on its outer boundary. The potential gradient at the surface of this corona burst is not uniform because the surface is not uniform. At some point or points, the gradient becomes sufficient to start a burst which propels charge farther and creates a new burst. The breakdown in the leader head itself progresses from its surface back to the leader core rather than from the leader core outward.

This model of a large leader head with charge (usually negative) concentrated on its outer boundary produces two effects that differ significantly from conventional theory:

1) The charged leader head causes high electric field gradients as it approaches earth. In most generally accepted methods for calculating the lightning performance of transmission lines, the component of voltage due to the leader field has been minimized because of its relatively small diameter.

2) The large leader head carries several times more charge per unit length

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than the leader channel; thus, the prestrike theory concludes that when the leader head contacts earth, a short, steep-fronted spike of current must precede the return stroke current.

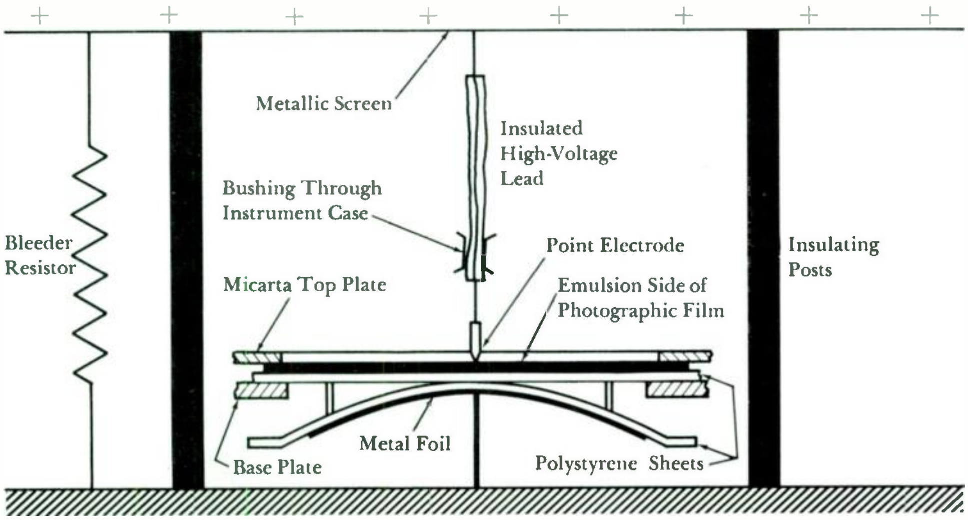
Since the existence of these characteristics—higher field gradients and steeper rates of rise of stroke current than considered heretofore—can explain some of the discrepancies between the predicted and actual outage rates of some 345-kv transmission lines, a major part of the investigation has been devoted to gathering information on field gradients and stroke currents.

Klydonograph Recorders

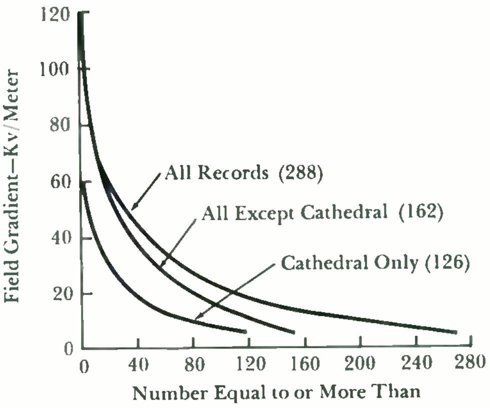
Most of the new data has been accumulated on two types of devices, both of which operate on the principle of the klydonograph. Both instruments are adaptations of the original klydonograph invented by J. F. Peters of Westinghouse in 1923. The klydonograph registers voltages on photographic film in the form of Lichtenberg figures. This figure is named after Dr. Lichtenberg, who discovered (about 1777) that when a Leyden jar was discharged to a glass plate—which had been sprinkled with powder and held between a pointed and a flat electrode—the powder would instantly arrange itself into a pattern (see inside front cover), with a radius roughly proportional to discharge voltage. Peters used photographic film instead of powder, thereby providing a permanent record. Since the time for pattern formation is less than 0.01 microsecond, extremely fast momentary voltage crests can be measured.

A cross-sectional view of the klydonograph used in the field-gradient research is shown in Fig. 2. A wire screen, which acts as the pickup, is supported by four insulating posts. The screen is grounded through a high resistance. The lead to the pointed electrode is also connected to the screen. The film, pointed electrode and ground electrode are housed in a light-proof metal container that serves as a base for the device. In the field-gradient-measuring klydonograph, the plate electrode is spherical in shape, curving away from the pointed electrode. This serves to reduce the electric field intensity at a faster rate as the radial distance from the pointed electrode increases, so that the instrument has a range of 3 to 60 kilovolts, approximately three times greater than a klydonograph with a flat-plate electrode.

2—Simplified cross-sectional view of the klydonograph gradient recorder. Bound charges on metallic screen appear as high voltage at the point electrode when the field from an overhead leader collapses.



In the field of an advancing leader head, the screen becomes charged. If the potential of the leader head is negative (as it is in over 90 percent of the strokes), a positive charge is induced on the top surface of the screen and a negative charge on the undersurface. The negative charge drains off to ground through the bleeder resistor, and the positive charge is held on the screen by the charged leader head. When the stroke contacts earth, the field collapses, and a positive voltage proportional to the field change appears on the screen. This voltage is impressed on the klydonograph electrode and produces the Lichtenberg figure on the film. The radius of the figure is also a measure of the field change. The device is calibrated in terms of kilovolts per meter of field change. Actually, the field just before stroke contact is somewhat higher than the indicated field change, but since the accuracy accorded to the klydonograph is only ± 25 percent, the field can be assumed to have been as recorded.



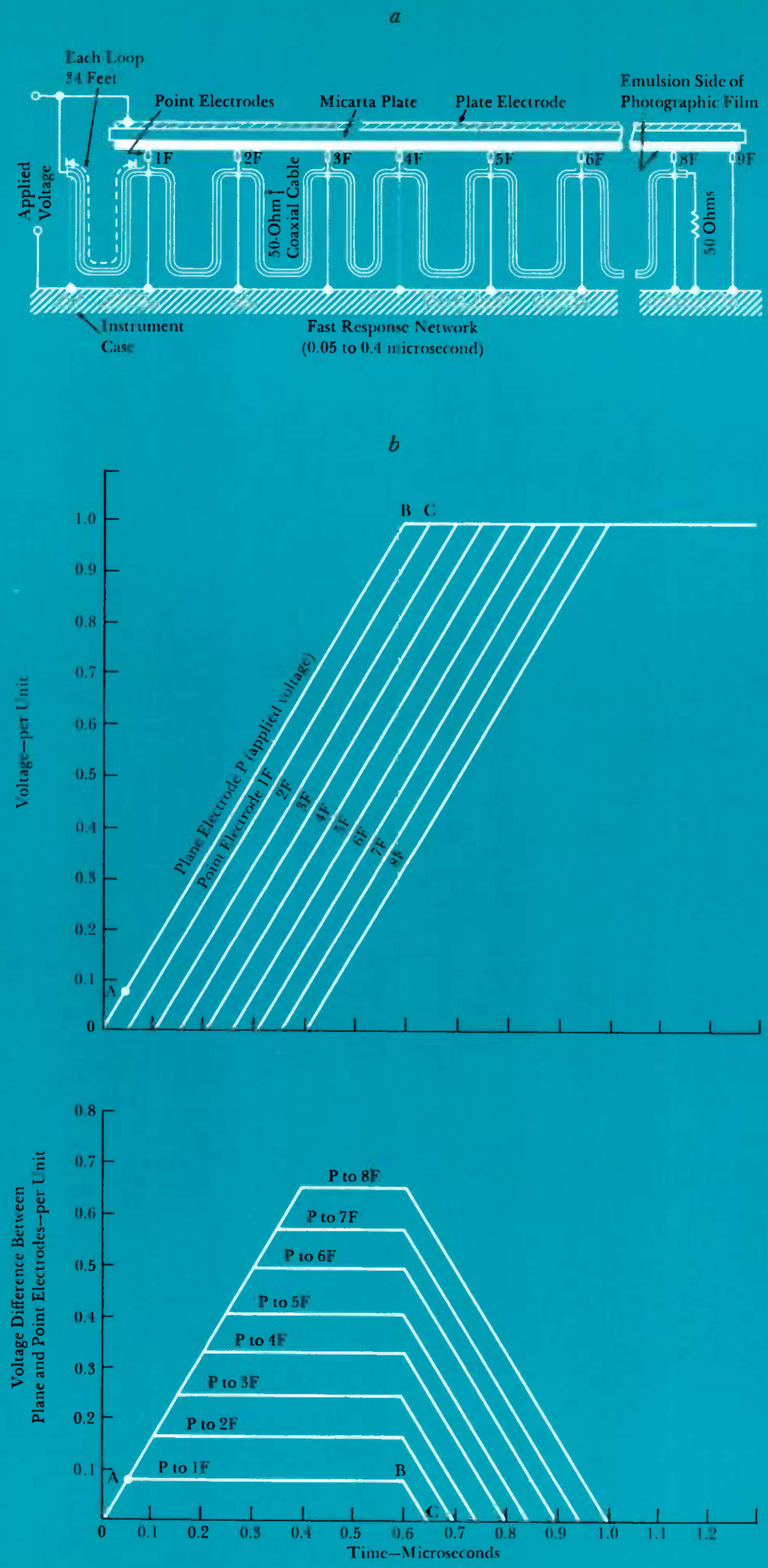
3—Electric gradients recorded by eight kine-klydonographs during the five-year investigation are summarized.

The second type of klydonograph recorder, the *kine-klydonograph*, was developed to record the current-time characteristics of the lightning stroke. This instrument records a series of Lichtenberg figures in a manner similar to the field-gradient recorder. However, instead of merely giving a measurement of the maximum voltage between the point electrodes and a grounded-plate electrode, the kine-klydonograph measures in addition the difference of voltage between the plate electrode and a series of point electrodes as a function of time. (The prefix "kine" denotes the time-variation of magnitude.)

The operating principle of the device is shown in Fig. 4a. For ideal conditions of no distortion or attenuation, an applied voltage waveform to the lead-in would appear with no delay on the plate electrode; at point electrodes *1F*, *2F*, . . . *8F*, the voltage-time curves are replicas of the applied voltage waveform, but displaced in time by the delay of the cable—in this instance, about 0.05 microsecond per section. Thus, a total accumulated delay of 0.4 microsecond exists between the plate and the *8F* electrode. There is no delay associated with point electrode *9F*. It measures the maximum potential difference between the lead-in wire and the instrument case.

A "slow network" was also included in the original version of the instrument, in deference to then-existing theories. It did confirm rise times in the range of 5 to 10 microseconds for the high-energy component of the stroke current. Had it been used alone, the extremely high initial rise of the prestrike current would have escaped detection.

To illustrate the operation of the device, assume an applied-voltage waveform shown in Fig. 4b, which is also the voltage on plate electrode *P*. The voltages between the instrument case and the point electrodes are obtained by repositioning curve *P* at successive intervals of 0.05 microsecond. Thus, the voltage difference between the plate electrode and a point electrode is the maximum instantaneous voltage difference between the point electrode and the plate electrode. For example, the difference voltage between the plate electrode and electrode *1F* follows the applied voltage up to time (*A*) when the delayed voltage wave reaches the point electrode. The difference voltage then remains constant until the applied voltage wave reaches its crest (*B*),



4—Schematic diagram is shown for the fast-response network of the kine-klydonograph (*a*). Voltage to instrument case is delayed 0.05 microsecond (*b*) by each coaxial-cable section, to produce corresponding voltages (below) between plate and point electrodes.

whereupon the difference voltage falls back to zero (*C*) and remains at zero. Each successive point electrode from *1F* to *8F* attains successively greater voltage differences between itself and the plate electrode because a greater part of the wavefront of the applied voltage is subtended by the coaxial cable. Therefore, the Lichtenberg figures recorded by the device for this simple input waveform would consist of a series of Lichtenberg figures of increasing diameter, from electrode *1F* to *8F*. Thus, by analyzing the relative sizes of these figures, investigators can deduce information on both magnitude and rate-of-rise of the lightning-current stroke. Actually, the interpretation of Lichtenberg figures is considerably more difficult when the input waveform is more complex,[3] but this simplified example serves to illustrate the application of the device.

Both the klydonograph and the kine-klydonograph are well suited to this type of investigation because they are triggered and powered by the lightning stroke itself and thus respond instantaneously, require no operating power, and are relatively simple to install and maintain. The instrument recordings are not significantly affected by the intense magnetic field of a lightning stroke. They require no attendance except for periodic film change. Klydonograph records can be assumed to be no better than ± 25 percent accurate, but in view of the vagaries of lightning, this is not a handicap.

The Laboratory

During the investigation, 80 kine-klydonographs were installed on transmission towers of five electric utility systems[1] in Pennsylvania, Ohio, Illinois and New York. Eight field-gradient klydonographs were installed on building roofs in Pittsburgh and vicinity, and in Chicago, Akron, Ohio, and Greensburg and Washington, Pennsylvania. Klydonograph and kine-klydonograph locations were chosen to cover a reasonably large area where lightning storms are relatively frequent, and which are accessible for periodic film changes.

A 535-foot building in Pittsburgh (Cathedral of Learning, University of Pittsburgh), surmounted by a 50-foot insulated mast, was equipped with all of the recording devices used in the investigation. Because of its height, this installation produced a greater number of records than other installations. However, the results have been treated separately because the conditions differ considerably from those of a transmission line.

Electric Field Gradients

All klydonograph gradient recorders except the one on the Cathedral of Learning are placed near the center of buildings which have considerable roof area and are not significantly higher than their surroundings.

A total of 116 films from all stations produced 288 Lichtenberg figures. The records varied from 5 kv/m, the threshold of recording, to 120 kv/m. The highest gradients were recorded at Greensburg which produced 100 and 120 kv/m in 1962; and at East Pittsburgh which produced gradients of 120, 120, 112 and 100 kv/m. The East Pittsburgh recorder is located on the roof of a building located in a valley with ground higher than the building some 1500 feet away on both sides. Evidently the building's location in the valley does not preclude the probability of strokes.

Of the 288 Lichtenberg figures, not all can be considered companions of separate strokes. Superimposed figures on films with multiple records can be caused by electric field changes when the leader head changes positions as it approaches earth, or by leader heads that pass overhead to strike at points more remote.[1] Since the sizes of the Lichtenberg figures are a function of both field intensity and the distance of the stroke from the instrument, the strokes accompanying particularly high gradients must have hit nearby. Thus, when gradients of 100 kilovolts per meter or more were measured, there can be little doubt that the stroke terminated near the recorder.

The klydonograph results are plotted in probability form in Fig. 3. The threshold of recording was about 5 kv/m; five of the 288 records showed electric fields of 100 kv/m or more. Based on experience, the range of the klydonograph recorders is estimated to be about 1500 feet, although the recording range is dependent on the intensity of the stroke.

It might be assumed that the gradient recorder installed atop the Cathedral of Learning would be exposed to high gradients because of its height of 535 feet. However, the 50-foot mast, only 25 feet away, militates against this. This appears to be the case because during the five years of measurement, much higher gradients were recorded elsewhere; the highest gradient recorded at the Cathedral was 59 kv/m.

Gradients of 120 kv per meter, which are undoubtedly greatly exceeded at times, mean that on a conductor suspended 100 feet (30 meters) above earth, a voltage of more than 3600 kilovolts can be induced. The observations confirmed that high voltages can be induced by leader heads passing overhead without necessarily striking close by. This fact was demonstrated by the kine-klydonograph installations on transmission towers. Thirteen records of ground-wire current are believed to have been obtained without direct lightning stroke contact—the result of induction from nearby strokes or strokes passing over the line. Potentials as high as 1000 kv were indicated for these nonhits, which is comparable to voltages caused by direct strokes. Thus, it appears that induced voltages on high-voltage lines, once believed innocuous, require further study.

While there is still insufficient data to claim absolute proof, the existence of very high field gradients close to downward strokes does substantiate the *prestrike* concept of stroke development. To demonstrate this argument, the effects of the lowermost 80 feet of the leader have been calculated for a conventional leader stroke and the prestrike concept (Fig. 5). Although a complete analysis should presumably require separate determination and summations of effects due to the leader head, segments of the leader up to the cloud cell, the cloud cell, and their respective images, it can be shown that the major contribution to field gradient, because of its relative proximity to the conductor, is only the lowermost portion of the leader.

The constants for this calculation are based on an earlier work,[1] with a bulbous prestrike leader head 80 feet in diameter, and containing a charge of 0.053 coulombs. The conventional leader concept is represented by 80 feet of leader having 0.0225 coulombs of uniformly distributed charge. Theoretically, both of these models should produce return stroke currents of 50,000 amperes, about twice the current of a typical stroke.

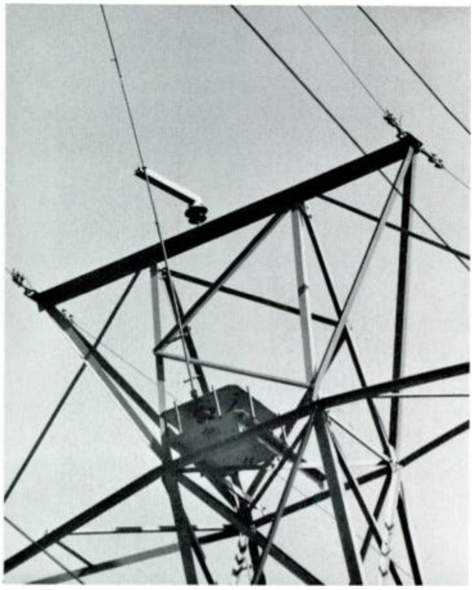
The leader head shown in Fig. 5 is in its penultimate position. A short length of conductor would have a potential as shown as a function of distance of leader from the conductor. A long length of conductor (several miles) grounded through transformers would have bound charges in the vicinity of the leader, just as in the case of the gradient recorder screen. Thus, when the leader makes its final jump to earth, the charges are no longer bound and the section of conductor opposite the leader takes a potential as shown by the curves. This assumes an instantaneous discharge of the leader. The actual potential will be somewhat less for finite rates of discharge. The prestrike model predicts that substantial voltages can be induced on transmission line conductors, even for strokes to ground as much as 200 feet away. These predicted effects are being observed in field measurements.

Stroke Current Characteristics

Thirteen stroke currents were recorded with kine-klydonographs on 138- and 345-kv transmission line towers. All were of negative polarity, and ranged from 11 to 50 kiloamperes, for a median of about 25 ka. Four negative strokes and one positive stroke were recorded at the Cathedral of Learning during this period. The positive stroke had the highest current so far recorded, 80 ka.

Within the two years that upward strokes from the Cathedral of Learning could be detected, six *upward* strokes were found. The threshold of stroke recording with kine-klydonographs is about 7 ka, but approximate amplitudes of these long-duration surges were obtained by the progressive breakdown of spark gaps at current intervals of 600 amperes. Generally the upward strokes were in the range of 600 to 1200 amperes. This confirms the results of other investigators, who have found that only high structures are apt to initiate upward leaders. It is unlikely that upward strokes are initiated from towers of usual heights. They may develop occasionally from very high towers, such as those at river crossings, but it seems unlikely that they are a significant cause of flashover because they generally are low in current amplitude.

As records came in it soon became obvious that the kine-klydonograph was detecting rates of rise of current that had not been evident in earlier investigations. The average rate of rise in strokes to transmission towers was 40 kiloamperes per microsecond during a 0.25-microsecond period. This figure was corroborated by records of strokes to the Cathedral. The 0.25-microsecond period was selected because this is the reflection or down and back time for the traveling wave in a transmission tower of average height. After this period of time, the reflected voltage of opposite polarity erases tower top potential. The highest rate of rise recorded was 230 ka per microsecond in an interval of 0.05 microsecond.



Typical kine-klydonograph installation atop a transmission line tower. Mast is visible at upper left. The instrument is located between the two parallel plates.

These findings indicate that the rate-of-rise of lightning current is much faster than the four-microsecond-to-crest waveform on which the AIEE calculation procedure is based. A generalized waveform of stroke current, as postulated from kine-klydonograph data, is a swiftly rising initial spike, followed by a slower rising peak, as shown in Fig. 6.

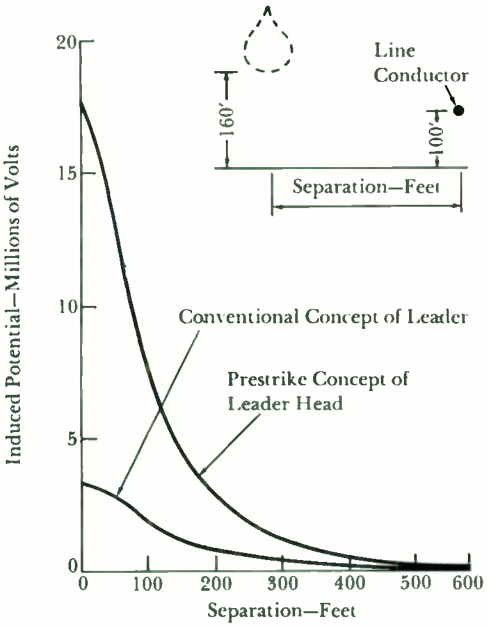
As originally installed, the purpose of the kine-klydonograph was to determine crest amplitudes and rates of change of current when towers were struck. Later, installations were made to record ground-wire currents to and from the tower simultaneously with the lightning stroke current. Thus, ground-wire current records, taken in conjunction with lightning current records, revealed the electrical response characteristics of the transmission system.

Records of current into the shield wires when the tower is struck enabled the determination of tower top potential produced by the steeply rising portion of the stroke current. The potentials found to date have ranged from 280 to 700 kv. These values were found on a relatively limited number of installations on well-designed transmission lines. Much higher tower top potentials could be expected upon a greater accumulation of data.

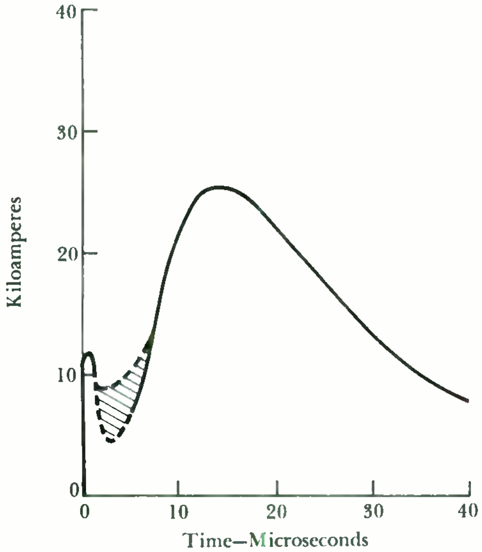
Measured values of tower top potential caused by natural lightning strokes have not been available heretofore. For the towers involved in this research, the average tower footing resistance ranged from 1.7 to 2.8 ohms. These resistances are so low that the IR drop produced by the highest current recorded, 50 kiloamperes, is at the most about 150 kv, assuming a 3-ohm footing. To produce a tower top potential of 700 kv, as noted from the steep rise, the current required through 3 ohms would be 233 ka. This provides further evidence of the significance of the high-rate-of-rise component in the stroke current.

Time for Another Look

The results of the study have indicated that lightning characteristics and effects are more complicated than thought heretofore. The newly discovered characteristics suggest that a new analysis is in order,



5—Calculated comparison of the induced potential in a line conductor produced by the conventional concept of a lightning leader and the prestrike concept of a leader head.



6—Concept of waveform of lightning stroke as constructed from kine-klydonograph records. The initial component contains the prestrike spike; subsequent return stroke components are similar to the initial component but do not contain the prestrike spike.

particularly for lines operating at 345 kv and higher.

The indications are that the presently accepted guide lines for the protection of transmission systems, particularly extra-high-voltage, should be reexamined and that there may be more than the two modes of transmission line flashover that presently are considered. The two modes that are now accepted are a stroke to a conductor, and a stroke to a tower or to the overhead ground wire with a backflash to a conductor. In addition to these, it now appears likely that the voltage induced by a nearby stroke to earth or by a leader passing over the line may be sufficient to cause flashover, or that flashover may be promoted by corona around an insulator string as a result of the high field gradient.

The information from the five-year field investigation should be helpful in the design of new lines with low lightning outage rates. A calculation routine to remedy the deficiencies in the AIEE-accepted procedures for economic optimization of transmission-line designs cannot be offered at this time. However, the two fundamental characteristics of lightning that were observed—steep initial rates of rise of stroke current, and high field gradients—lead to some tenable suggestions for securing better lightning protection for transmission systems.

A lightning stroke impinging on a tower produces a tower-top potential dependent upon the rate of change of current, the tower surge impedance, and the surge travel time from tower top to earth and back. Since the rates of change of current were found to be steeper than previously suspected, it may be desirable to limit tower top potentials by minimizing tower surge impedance and surge travel time from tower top to earth and back. For example, low-height, single-circuit towers with widely spaced tower legs will lower the effective inductance of the tower; several radial buried counterpoise wires, about 50 feet long at each tower leg, are preferable to driven rods because they reduce the effective tower height and thus shorten surge travel time; tower footing resistances of 20 ohms or less for ehv and 10 ohms or less for hv lines appear to be acceptable values.

Increased coupling between crossarms and phase conductors will help reduce the potentials across insulator strings produced by the steep short-duration spike of tower potential.

Two shield wires with small shielding angle and with as little height above the conductors as is consistent with good mechanical design are preferable to a single ground wire because they will reduce electrically induced voltage on phase conductors; also, the surge impedance of two ground wires in each direction is commensurate with the tower surge impedance and thus materially reduces tower-top potentials.

Two masts or "whips" on each tower, about 20 feet long, projecting upward and outward from the tower top should intercept a large percentage of the strokes that would otherwise strike towers or nearby ground wires. This would produce two beneficial results: The leader head would be discharged at a greater height above the phase conductor, thereby reducing the electrically induced voltage; and the mast would interpose a relatively high surge impedance between the leader head and the tower, thus lessening the rate of change of current into the tower.

The steps suggested above should result in better lightning performances of transmission lines. However, at this stage of the work it is not feasible to ascribe factors to be used in actually predicting lightning performance. Further data study to reassess methods of estimating the lightning performance of high-voltage lines and their economical construction are required.

Westinghouse ENGINEER **September 1966**

Acknowledgement:
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Thyristor-Power DC Drive Systems

L. F. Stringer
L. R. Tresino

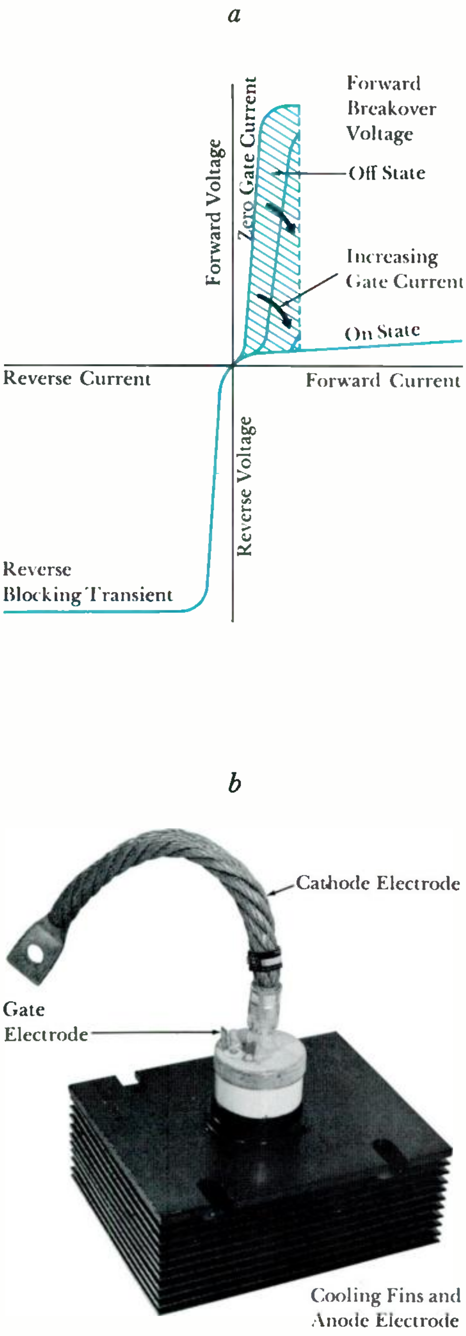
Static power supplies based on thyristors are replacing m-g sets in dc drive systems because they are more efficient, cost less to install and maintain, respond faster, and are more reliable.

The motor-generator set has been used almost exclusively for many years to convert ac power to dc power for industrial adjustable-speed drives. Within the past two years, however, the use of static conversion equipment employing thyristors (silicon controlled rectifiers) has become so extensive that the m-g set is no longer the standard of industry.

This static thyristor conversion equipment can be used for almost any adjustable-speed constant-torque or constant-horsepower drive application. It has been supplied in place of m-g sets for main drives on hot strip mills having ratings greater than 10,000 hp; it is just as suitable for a 50-hp drive on a metal-processing machine or a paper machine requiring precise control over a wide speed range.

Orders for the M4 line of thyristor drive systems for 50 main drives on eight separate rolling mills have been received by Westinghouse to date. These drives have a combined nominal rating of 160,000 kw. The mills include a 10,000-hp reversing mill and a 25,600-hp six-stand continuous mill in an aluminum hot line that has been in successful operation for a year. Other main-drive applications include continuous hot strip mills, cold reversing mills, and sectional paper machines. An additional 240 drives have been applied for such auxiliaries as screwdowns, sideguards, slitters, pinch rolls, shears, scrap choppers, and coilers.

Several basic reasons account for such rapid and widespread acceptance of thyristor drive systems. Briefly, the advantages of m-g sets, such as inherently matching the characteristics of dc motors and providing power-factor correction, are offset in many applications by the higher efficiency, lower installation cost, faster response, greater reliability, and lower maintenance cost of thyristor conversion equipment. In addition, thyristor equipment does not contribute to ac system faults, an important consideration for high-power drive systems.



1—Thyristor characteristics (*a*) depend essentially on ability to block voltage in both directions until, when turned on by a gate signal, it conducts in the forward direction. This ability is used to rectify ac supply power in such a way as to produce adjustable-voltage dc power for drive motors. Practical realization of the advantages of static power conversion has been made possible by reliable thyristors of high voltage and high current rating (*b*).

These advantages could also be cited (though to a lesser degree) for ignitron rectifier drives, which have been used successfully for continuous hot strip mills and rod and bar mills. The thyristor, however, cannot arc back, so expensive power transformers with extra bracing to withstand the stresses imposed by arc-back faults are not required, and derating for reduced-voltage operation to avoid increasing the frequency of arc-backs is not necessary. Furthermore, the lower losses of thyristors makes it possible to cool them directly with air and eliminates the need for the troublesome cooling-water systems required by ignitron rectifiers. More important, the thyristor has made it possible to build standard modular integrated drive systems that include not only the power-conversion equipment but the adjustable-voltage control equipment as well—all factory-assembled, wired, and tested. This facilitates field erection, interconnection, start-up, and maintenance and also reduces the time and cost involved.

For these reasons, thyristor power-conversion equipment has almost completely replaced ignitron rectifiers in industrial uses, and, by 1970, it probably will be used in place of m-g sets in 80 percent of new installations.

Application Considerations

Thyristor drive systems offer the following advantages:

1) Efficiency is at least five percent better than that of m-g sets at rated load.

2) Installation cost is lower because the much lower weight and absence of rotating elements (except for small cooling fans) permit use of minimum foundations. Also, the integrated systems approach requires fewer interconnections and reduces start-up time.

3) Flexibility is inherent, since a system can be designed to suit reversing or nonreversing applications, at low or high

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power levels, with standard modular control and power-supply units.

4) Response is fast because the inherent time delay associated with the fields of rotating machines is eliminated; system response is limited primarily by the mechanical inertia of the drive and the commutating ability of the motor.

5) Maintenance requirements are low because the brushes and bearings of m-g sets are eliminated.

There are, of course, several disadvantages as well:

1) Power factor is good at rated dc voltage but drops about in proportion to the reduction in dc voltage. This characteristic is not serious for small drives, but it can be serious for large drives operating at reduced speeds for extended periods. A system study is advisable for such drives.

2) Current ripple in the dc output increases motor heating and reduces motor commutating ability. Usually, with properly designed motors, the ripple is sufficiently limited by transformer and motor reactance to eliminate any adverse effects. It is sometimes necessary, however, especially with large drives, to further reduce the ripple by adding dc smoothing reactors or using 12-phase power-conversion circuitry.

3) The waveform of the ac supply voltage can become badly distorted (voltage ripple), and this can adversely affect operation of other static conversion equipment connected to the main line. Applying isolation transformers and minimizing common impedance coupling can prevent it from becoming a problem.

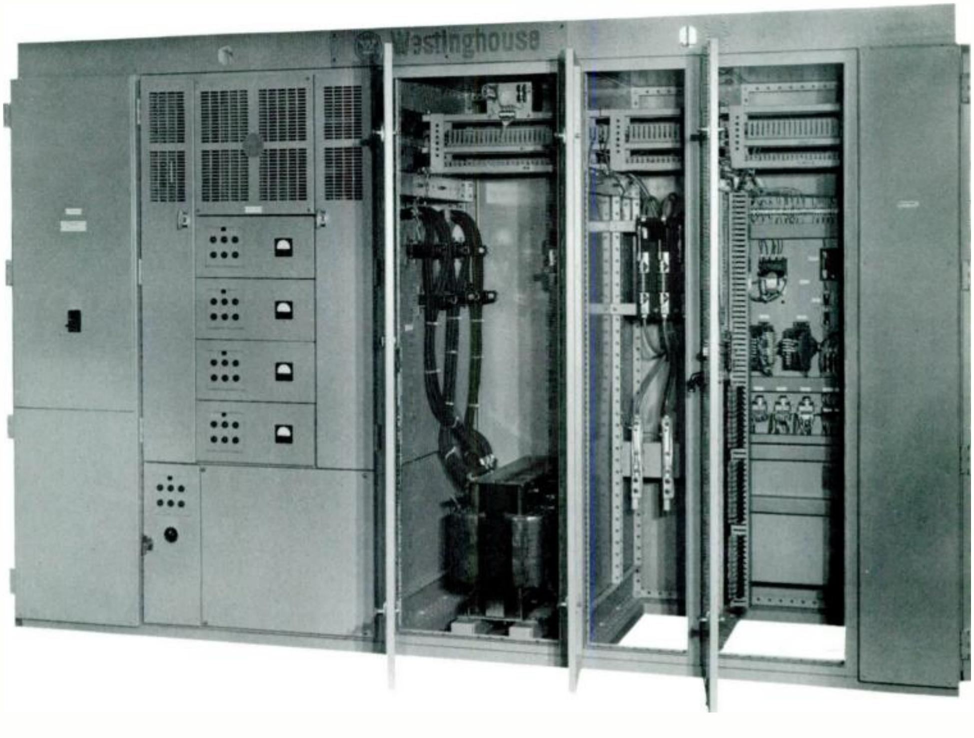
The advantages have been realized in practice, and the disadvantages have had no adverse effect.

The Thyristor

The operational capabilities of a thyristor are determined by its ability to block applied voltages in both the forward and reverse direction and, when gated, to conduct current in the forward direction with a low forward voltage drop (Fig. 1). If a voltage within the rating of the thyristor is applied to the anode and cathode terminals in either the forward direction (anode positive) or reverse direction (cathode positive) when the thyristor is in the "off" state, only a small leakage current flows. If the anode is positive, the thyristor can be switched to the "on" state by driving current through the gate and cathode terminals. In the "on" state, the thyristor can conduct a large current from the anode to the cathode terminal with a very small voltage drop. Once the anode current exceeds a low value known as the latching current and remains greater than a somewhat lower value known as the holding current, the gate current can be reduced to zero and the thyristor remains in the "on" state. Once the anode current falls below the holding value, however, the thyristor reverts to the "off" state.

In addition to these basic characteristics, the thyristor has other characteristics that must be carefully considered in its application. For one thing, it can change from the "off" to the "on" state, even though no gate pulse is applied, if the forward voltage exceeds the breakover voltage as shown in Fig. 1. This condition is known as a forward breakover; it can also occur if the rate of buildup of forward voltage becomes excessive (the dv/dt effect). If the reverse voltage exceeds the reverse blocking transient rating, a very large reverse current flows. Since the voltage does not collapse as it does in the forward direction, the power losses are quite high and, unless the reverse current is quickly limited, the thyristor fails.

Another characteristic is that, when a thyristor is gated, the complete junction area is not turned on instantaneously. Initially only a small area is turned on by the gate pulse. If the current commutated into the thyristor builds up too rapidly, an excessive current density is produced and may cause the thyristor to fail (the di/dt effect). For this reason, the thyristor has to be gated by a pulse with fast rise time and large amplitude.

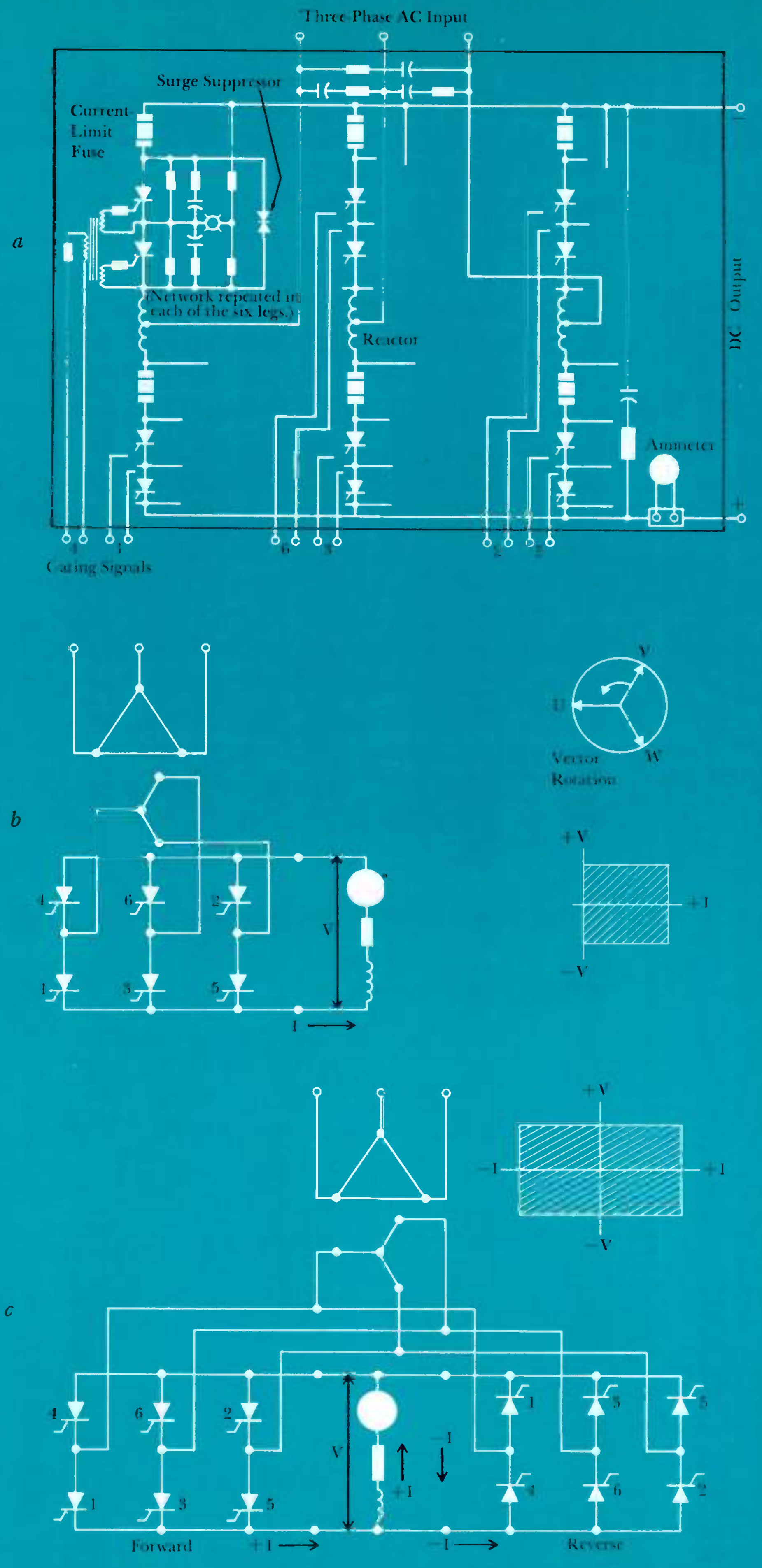


Power and control equipment for a thyristor dc drive are integrated in one structure, as in this system for a 100-hp motor with 300-percent overload capability. It includes (left to right) a dc cabinet, thyristor cabinet housing two power cases for the forward direction and two for reverse, transformer cabinet, incoming line cabinet, control cabinet, and regulator cabinet for voltage, load-balance, current-limit, and speed control. The motor can be operated under duty cycles limited only by its own capabilities.

The Type W223 thyristor used in the M4 thyristor drive systems described in this article has a continuous current rating of 475 amperes rms and is capable of blocking reverse voltages up to 1250 volts. It has two unique features that make it especially suitable for power applications. First, instead of having the semiconductor element soldered to a copper slug and a cathode lead, all electrical and mechanical contacts are established by compression bonding to eliminate the fatigue problems usually encountered when solder is used in large devices subject to temperature cycling. Second, an integral heat sink is formed by pressing copper fins on the copper slug rather than threading the slug for mounting on a separate heat sink. This design eliminates the significant thermal contact drop otherwise found between thyristor and heat sink. Heat generated in the junction region is transferred to an air stream. The maximum operating junction temperature of the Type W223 thyristor is 125 degrees C, a limit imposed by the temperature dependence of such device characteristics as static and dynamic forward voltage blocking capabilities. During normal operation under continuous or frequently repeated load conditions, the rated junction temperature cannot be exceeded. Under nonrecurrent fault conditions, however, the rated junction temperature can be exceeded until circuit protective devices act to clear the fault.

Thyristor Power Case

The basic building block for the thyristor power supply establishes the minimum unit of power conversion. This building block could be constructed for either of two means of increasing power-conversion capacity: paralleling thyristor cells directly, or paralleling complete six-



2—Thyristor power case *(a)* is the basic module in a thyristor power supply. (The numbers indicate the firing sequence of each leg.) Its circuit *(b)* is a six-phase double-way bridge, which can supply either positive or negative voltages but only positive current. Reversible current is provided by a dual converter consisting of two power cases connected back to back *(c)*. Power cases are paralleled to provide the desired power output.

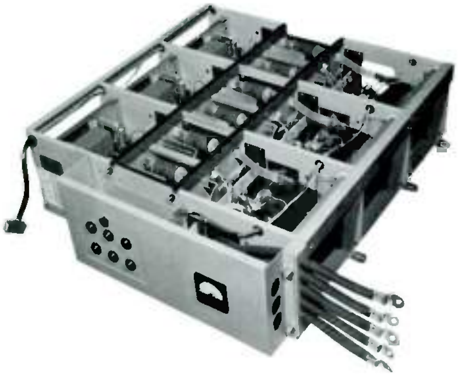
phase double-way bridges. The construction adopted for the M4 thyristor drive systems consists of a six-phase double-way circuit; it is a modular unit called the thyristor power case (Fig. 2a).

Two thyristors are always connected in series, regardless of voltage rating, for standardization and to fully use the production yield of thyristors (which includes a range of blocking voltage ratings). The basic circuit used for ac to dc power conversion is shown in Fig. 2b. Although the direction of the dc output current cannot be reversed, the polarity of the dc output voltage can be reversed by delaying the gating of the thyristors with respect to the applied ac voltages. A reversible dc output current is obtained by connecting two six-phase double-way circuits in an antiparallel circuit (Fig. 2c).

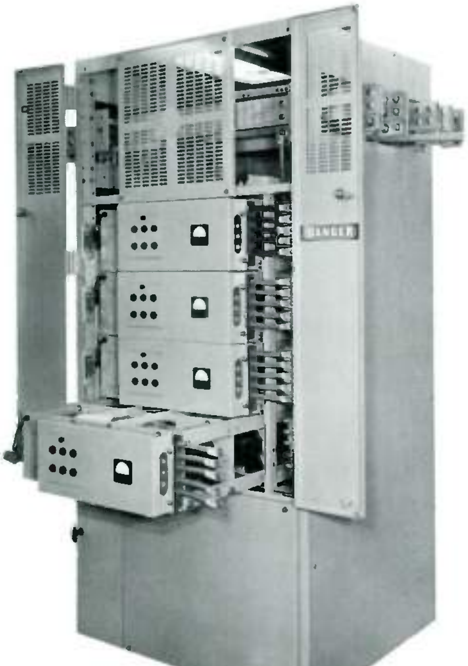
The RC networks in the power case (Fig. 2a) that are connected in parallel with each thyristor serve a dual purpose. In conjunction with air-core reactors, they control the rate of change of applied voltage produced by commutation, and they dynamically balance (within 10 percent) the division of the voltage applied to the two thyristors connected in series. Resistors are used as dc voltage dividers that compensate for small differences in the leakage currents of the two thyristors.

The RC networks that shunt the phases of the ac supply damp the oscillations that would otherwise be produced by commutation. The RC network that shunts the dc load insures that the commutated phase voltage at light loads and large delay angles becomes positive within the period of the gate pulse. Besides their use for wave shaping, the reactors enforce load balance when two or more cases are connected in parallel.

If fault conditions are not cleared by other means, current-limiting fuses protect the thyristors and isolate defective branches in drive systems with paralleled cases. Neon lamps indicate blown fuses or defective thyristors by means of a bridge circuit. Selenium surge suppressors are connected in parallel with the two thyristors in each leg to limit transient voltage peaks. The gate pulses are supplied to the thyristors through pulse transformers and attenuator resistors. An ammeter and an ammeter shunt are provided to meter output current in the positive lead to check loading and to give a partial indication of load balance between paralleled cases.



3—Thyristors and fuses are located in a vertical central duct in the power case for forced-air cooling. Continuous rating of the case is 460 amperes.



4—Thyristor cabinet includes up to four power cases and also a blower and the required number of gate-pulse amplifiers.

The 12 thyristors in a power case are mounted in a central duct through which high-velocity cooling air passes (Fig. 3). Current-limiting fuses are also mounted in the air stream, since their stud temperature should be limited. Barriers in the central duct isolate the phases. The reactors are mounted in the right side of the case; they are air-core edgewound coils braced to withstand the stresses of fault currents. The ac RC networks are mounted close to these reactors, and the dc RC network is behind the front cover. Neon fault lights are visible through lenses on a door in the front cover; opening this door exposes the lights, their bridge resistors, and test points. The ammeter also is on the front cover.

The remaining elements of each leg are on removable panels in the left side of the case. External power connections are made with flexible cable brought out at the front right, and the external gate leads are brought out in a cable at the front left of the case.

Continuous rating of each power case is 460 amperes, a rating established by fuses, conductors, and the need for overload capabilities. To match the motor capability in a main drive, for example, the 460 amperes would correspond to the 125-percent two-hour load requirement. The continuous rating would then be 368 amperes and the maximum frequently repeated rating would be 175 percent, or 644 amperes, for four minutes. Higher ratings are obtained by connecting as many as 20 power cases directly in parallel on both the ac distribution bus, which is supplied from a single thyristor transformer secondary, and the dc collector bus. Reversible operation is obtained by connecting the power cases directly in parallel and antiparallel arrangements. The arrangement need not be symmetrical if the rating requirements in the forward and reverse directions differ. Still higher ratings are achieved by 12-phase operation with multiple thyristor transformers.

Thyristor Cabinet

The basic thyristor cabinet houses up to four stack-mounted thyristor power cases, which are front-connected and front-removable (Fig. 4). Cases can be gated simultaneously for parallel operation or individually for independent operation. For parallel operation, the ac distribution and dc collector buses are mounted in the top of the cabinet. The external power cables of each case are connected to terminal blocks, which are connected to the buses by cables of equal length for equal IR drop. Gate signals are fed to each case from one or more gate-pulse amplifiers in a drawer at the bottom left of the cabinet.

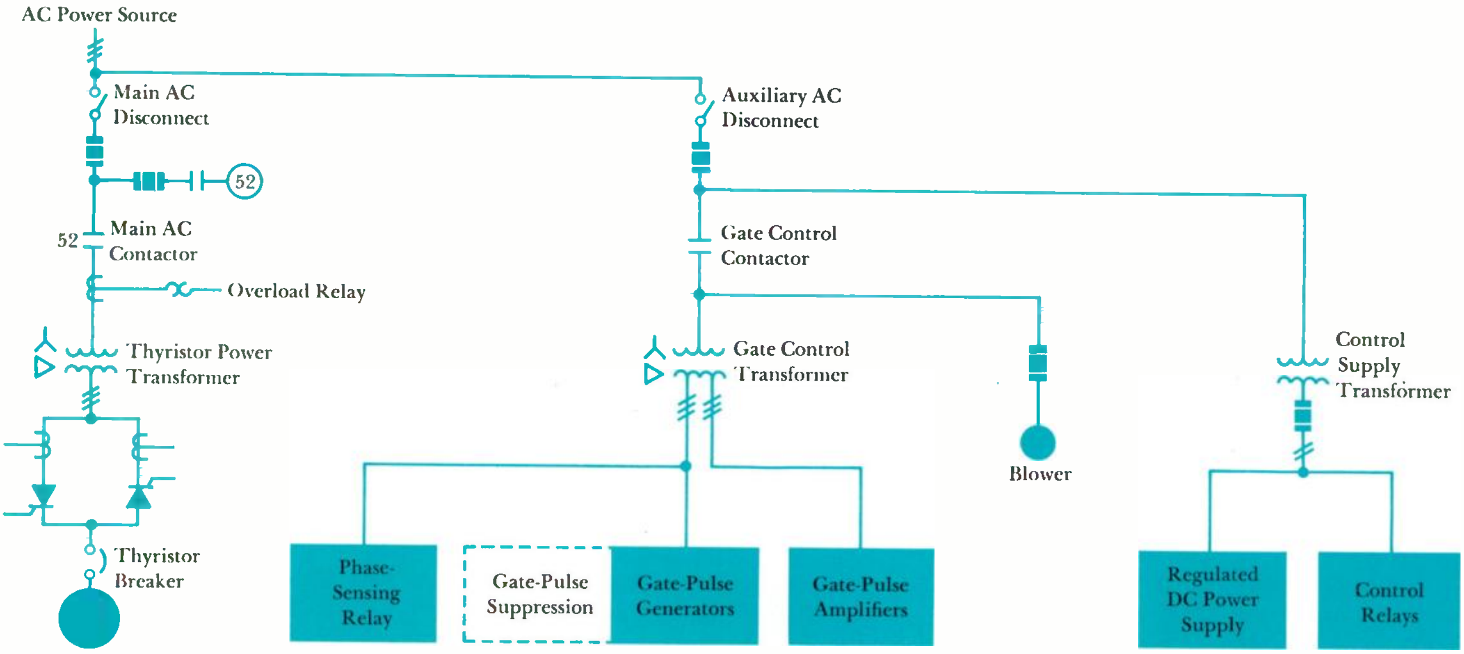
A blower for case ventilation is mounted to the right of this drawer, and a pressure switch insures that the blower is in operation when required. The blower air intake is from the top front of the cabinet. Air flows down over the load-balancing reactors and into the blower inlets. The blower outlet is connected to the central duct of the lower case, so air passes through the cases from bottom to top and removes heat from the thyristor heat sinks before being exhausted out the top of the cabinet.

Gate-Pulse Generators and Amplifiers

Since as many as 20 cases may require simultaneous gating pulses in, say, a 5000-horsepower 700-volt drive, the gating system was separated for convenience into two parts: the gate-pulse generator (GPG), which generates low-power-level pulses having a relative phase position that is responsive to a dc control signal; and the gate-pulse amplifier (GPA), which generates high-power-level pulses having a relative phase position that is responsive to and in phase with the pulses from the GPG. Each GPG drives from one to five GPA's and one GPA drives from one to four thyristor power cases. The GPG is associated physically with the adjustable feedback-control equipment, and the GPA with the thyristor power cases that it drives. Up to four GPA's can be mounted in each thyristor cabinet to allow each of the four cases in the cabinet to be independently gated when that is necessary.

In a six-phase double-way converter circuit, two legs (one in the positive half and one in the negative half) must always be able to conduct current simultaneously to complete a current path through the load. The thyristors in each leg are gated sequentially every 60 degrees, with those in the positive and negative halves of the circuit being gated alternately. To insure a conduction path, either the width of the gating pulses must exceed 60 degrees or each thyristor must be pulsed twice during each cycle—initially and 60 degrees later. Double pulsing is provided by the GPA in the M4 thyristor drives because it permits the use of relatively narrow pulses. This facilitates the generation and distribution of gate pulses having rise times less than one microsecond and peak amplitudes greater than two amperes, which are necessary conditions to insure proper thyristor turn-on. Double pulsing has the additional important advantage that gate pulses are provided if, and only if, gating is required.

The GPG is self-compensating; that is, the gate delay angle is reduced if the



5—Thyristor drive system consists of the required number of thyristor cabinets, a dc motor, a power transformer, and control equipment. The one illustrated is a typical dual-converter system for applications requiring medium power (100 to 500 kw) and low voltage (460 volts ac).

source voltage falls, and it is increased if the source voltage rises. The internal voltage of the converter remains fixed in either event. The gating circuit provides a linear relationship between the input dc control signal and the internal voltage of the power converter. The pulse delay angle responds instantly to the input dc control signal within the gating cycle to provide precise pulse timing, to allow for instantaneous pulse suppression for fault protection, and to avoid insertion of time delays in the feedback control loops.

Fault Conditions

Faults may be self-clearing if the fault current is low or if circuit voltage conditions change before the current can become abnormally high. In general, however, fault conditions require the operation of protective devices such as branch fuses, dc circuit breakers, or gate-suppression circuits.

Reverse and forward faults caused by forward breakover of a thyristor are cleared by branch fuses. The gate suppression circuit operates whenever the fault current as sensed by current transformers in the ac supply lines exceeds approximately 20 percent of the current-limit setting; suppression of gate-pulse generation confines the fault current to the last two branches gated. If a fault occurs while the converter is in the rectifier mode of operation, the fault current is forced to zero by the ac supply voltage. If a fault occurs while the converter is in the inverter mode, gate suppression is not effective for clearing it because the fault current is generated by the counter voltage of the motor. A high-speed dc circuit breaker is required for this purpose. (If the drive has a single converter, for nonreversing service, the dc breaker is not required.) Most faults are cleared by gate suppression or dc circuit breaker operation, or both.

Thyristor Power-Supply System

When the thyristor cabinets are integrated with the ac power transformer, the ac and dc control apparatus, and the feedback controllers, the assembly becomes a thyristor power-supply system for powering and controlling a dc motor

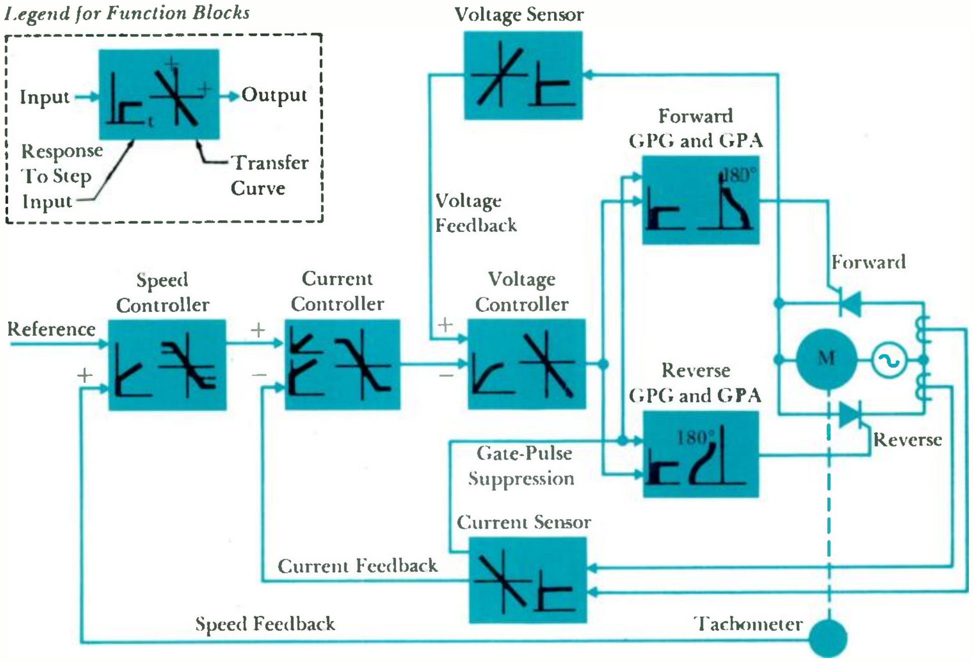
Speed Control System

In the control system for a typical dual-converter thyristor drive system, the forward and reverse thyristor converters are gated by two gate-pulse generators (GPG's) and gate-pulse amplifiers (GPA's) controlled from a common voltage source. When control voltage is zero, the phase of the gating pulses produced by each GPG is retarded by 142 degrees with respect to that required for full positive output voltage of the associated converter. This retardation is provided by independent bias sources located in each GPG and is done to prevent flow of circulating current. If, for example, the forward converter is conducting load current, the instantaneous voltage impressed on the thyristors in the reverse converter is negative when those thyristors are gated. Consequently, the reverse converter cannot conduct current. This condition does not exist during a current reversal, however, and a circulating current fault occurs unless the forward current is forced to zero before the reverse converter is phased in. This is one of the functions of the control system.

Cascaded voltage, current, and speed feedback control loops also are provided. A voltage feedback loop encloses the dead zone created by the offset bias voltage sources in the associated GPG's. The voltage control loop serves not only to linearize the nonlinearity introduced by the dead zone, but also to linearize the nonlinear behavior of the converter when the load current becomes discontinuous. Control voltage for the two GPG's associated with each power unit is supplied by a voltage controller. The voltage sensors that supply the feedback signals for the voltage controllers are push-pull magnetic amplifiers for isolation and are operated at a carrier frequency of 10,000 cps for fast response.

The reference or command signal for the voltage controller is provided by the output voltage of the current controller. Current feedback signals for the current controller, and the gate-suppression signal for the GPG's, are supplied by the current sensors. The current sensors receive their input signals from current transformers that meter the ac line current supplied to the forward and reverse converters.

The command signal for the current controller is provided by the output of the speed controller. Current limit is provided by limiting the maximum output signal of the speed controller. A tapered current limit as required by the motor can be provided by reducing the limit setting of the speed controller as a function of the voltage reference signal. Current rate control is also provided to limit the rate of change of motor armature current to a value the motor can successfully commutate.



drive (Fig. 5). The main-line ac disconnect switch in the system illustrated serves to isolate the thyristor power supply from the ac power source. Current-limiting fuses on the load side of the disconnect switch provide primary protection. The ac contactor is provided for sequencing functions, for applying power to the thyristor transformer to safely carry the high inrush currents, and for interrupting the magnetizing current of the thyristor transformer. The thyristor breaker in series with the motor armature is provided to clear inverter faults. It also serves as a manual disconnect in the motor armature circuit.

An auxiliary ac fused disconnect switch makes it possible to check the auxiliary equipment with the main disconnect switch open. Auxiliary transformers supply the gate-pulse generators and amplifiers, the ac control relays, and the regulated dc power supply for the feedback controllers.

As previously stated, one of the chief advantages of thyristor drives is the opportunity afforded for construction of standard integrated systems that include not only the power-conversion equipment but the adjustable-voltage control equipment as well. The structure in the photograph on page 155 includes all components, factory-wired and assembled, necessary for drive operation. The GPG's are mounted at the top of the regulator cabinet. Control modules are front-connected to reliable screw-type terminal blocks, and all interconnections are made in accordance with quiet-wiring principles. The basic control elements are computer-quality operational amplifiers using only silicon transistors, which can be operated at an ambient temperature of 55 degrees C.

For medium-voltage power supplies (600 volts to approximately 22 kv), the ac power system has medium-voltage switchgear apparatus on the primary side of the thyristor transformer and an auxiliary three-phase transformer connected to the same source for low-voltage auxiliary power. For 2300- and 4160-volt systems, the main ac disconnect and ac contactor can be an Ampguard 2500 or 5000 fused starter, respectively. This provides the same lineup of apparatus illustrated schematically in Fig. 5 for the low-voltage ratings in the 100- to 500-kw range; it is supplied as a complete integrated power-supply package. Above these ratings, the medium-voltage switchgear equipment and the thyristor power transformers are separately mounted. In the higher kilowatt ratings, the thyristor converter portion of the drive system becomes simply a lineup of thyristor cabinets and associated feedback controllers so as to maintain an integrated power converter with gating and feedback control elements.

Power System Considerations

Proper selection and design of the ac supply are important in applying thyristor drive systems. At reduced dc voltage, the power factor of the load placed on the ac supply by the converter is low. Static capacitors or synchronous machines can be used for power-factor correction, but the effect produced on the voltage regulation of the ac bus over the full range of operating conditions requires careful evaluation. Since the ac load current of a converter is nonsinusoidal, resonant conditions at harmonic frequencies must also be included in the evaluation.

Because of the inductance of the ac supply, the load current cannot be switched instantaneously from one phase to another in the six-phase double-way converter circuit. The ac supply is short-circuited during the switching period, which occurs six times in each cycle; in fact, this short circuit causes the switching to occur and is necessary for the operation of the converter. During the short circuit, the ac supply voltage must be absorbed by the impedance of the thyristor transformer and the ac feeder supplying the primary ac bus. Consequently, notches are produced in the waveform of the voltage on the ac bus, with the magnitude of the notches depending on the ratio of the feeder and transformer impedances. If the ac bus supplies more than one thyristor drive, the notches produced by one drive can disrupt the operation of the other drives. In such cases, the thyristor transformers should be supplied from stiff lines (high power, high voltage) to minimize adverse effects.

Voltage and Power Ratings

A standard line of lower-power thyristor drive systems, used mostly on metal-mill auxiliaries, has been designed in increments of dc kilowatts from approximately 25 through 500. These systems have current-limit ratings from 200 to 300 percent, depending on their continuous dc current ratings and the number of thyristor cases used. Standard dc voltages are 250, 375, and 460, and the corresponding nominal dc-motor horsepower for type MC mill motors at 230 armature volts ranges from 25 through 375. The mill motors are all capable of double armature voltage and would deliver approximately double horsepower at double speed and rated armature current.

The dc voltage rating for a thyristor power supply is the maximum terminal voltage at 200-percent current and 95-percent ac line voltage. On metal-mill auxiliary drives, the 460-volt dc operation is required for speeding up or slowing down auxiliary functions of the mill that may not require accurate speed regulation at 460 volts. If speed regulation is required at rated armature voltage, control range must be made available to provide it. A five-percent control margin for conditions of top speed, full load, and minimum line voltage usually suffices.

The reverse blocking voltage capability of the thyristors used permits voltage rating to 700 volts maximum. This provides a ratio of the thyristor nonrepetitive blocking voltage rating (1250 volts) to the maximum ac repetitive working voltage of approximately 2.5 to 1.

Conclusions

Thyristor power supplies will continue to replace m-g sets for dc-motor drive systems. Power factor, supply voltage distortion, fault protection, and voltage transients must be carefully considered for all large installations. In a properly designed system, however, the advantages inherent in solid-state thyristor power supplies suit them for either the general-purpose system or the most complex.

About the Authors

Alfred Lohmeier and **Samuel D. Reynolds, Jr.** are an appropriate team to coauthor the article on the welded-steel-tube feedwater heater since they both worked on this heater design.

Lohmeier joined the Westinghouse Steam Division after graduating from Polytechnic Institute of Brooklyn with a BME degree in 1951. While in the mechanical design section of the Large Turbine Engineering Department, he worked on the design of steam turbines, axial-flow compressors, forced-draft blowers, and condensate and circulating water pumps. By 1955, he had also found time to earn an MME degree from the University of Delaware. In 1956, Lohmeier moved to the Heat Transfer Apparatus Engineering Department to work on the design of heat-transfer equipment. Now an Advisory Engineer in the Heat Transfer Engineering Department, Lohmeier provides consultation in structural design, analysis, and evaluation of pressure vessels, heat-exchange equipment, and rotating machinery for power generation.

Reynolds is a graduate of Lehigh University with a BS degree in Metallurgical Engineering. His first contact with Westinghouse came during the summer of 1952 between his junior and senior year, when he worked as a technician in the nondestructive testing laboratory of the Steam Division. Upon graduation the following year, Reynolds joined the Division's Metallurgical Department. He left Westinghouse late in 1953 for a military leave of absence, during which he earned a commission in the Navy and served in a classified electronics program. Reynolds returned to the Steam Division's Welding Laboratory in 1957 and a year later moved to the Heat Transfer Division. As a Senior Metallurgical Engineer, he is responsible for material selection, corrosion analysis, and welding process development. He also serves as a project engineer on special manufacturing and field welding problems.

The seeds for the lightning article were cast in 1958 when **S. B. Griscom** first proposed his prestrike theory (*Westinghouse ENGINEER*, Nov. 1963). We have since heard many lively discussions regarding the pros and cons of "Sam's Theory." Two of the engineers on the "pro" side, **Edward Beck** and **Derrill F. Shankle**, have joined Griscom to discuss the results of the five-year field investigation.

For Edward Beck, this article marks his tenth appearance in the *ENGINEER* and certainly keeps him at the head of our "most published author" list. All but one of his articles have been on some aspect of lightning or lightning protection, which is understandable, since he has been involved with lightning protective devices since coming with Westinghouse in 1922 (except for two years spent with the X-Ray Division). When Beck retired in 1960, he was manager of lightning arrester engineering in the Distribution Apparatus Division. He has continued his work in lightning and high-voltage research as a consultant to the Electric Utility Engineering Department.

Beck is a graduate of Columbia University with an EE degree (1917).

Griscom joined Westinghouse on the graduate student program after obtaining his EE degree from Cornell University (1922). Although he has been involved in almost every phase of electric utility engineering, Griscom has been particularly active in high-voltage transmission work. His attention was focused on lightning stroke characteristics when the standard methods for predicting lightning performance of transmission lines began going awry on 345-kv lines. This led to his development of the prestrike theory, and also to the development of the two klydonograph devices used to measure stroke characteristics in the five-year study. Although Griscom retired in 1965, he has continued his work on lightning research and other utility problems as an engineering consultant to Westinghouse.

D. F. Shankle joined Westinghouse on the graduate student course after graduating from the University of Pittsburgh in 1943 with a BSEE degree. He soon went to work in the Electric Utility Engineering Department and has progressed through a variety of assignments. In 1947, Shankle became Sponsor Engineer for the Midwestern Region and assisted utilities in system planning studies and application of utility apparatus. In 1956, he assumed responsibility for directing the Advanced Development Section and supervised special studies in the analysis of power system problems and the application of power equipment outside the electric utility industry.

Shankle was made manager of the Transmission Section in 1960. This group conducted analytical studies and field investigations on lightning and its effects on high-voltage transmission lines, power system switching surges, and radio interference and corona loss performance of ehv transmission lines.

In 1964 he assumed his present position of Manager of the Field Research Section. There, much of his time is spent on special field investigations of transmission lines, such as the Apple Grove 750-kv project, the Leadville high-altitude ehv project, and the five-year study of lightning stroke characteristics.

Dr. L. F. Stringer joined Westinghouse on the graduate student course in 1947. He was assigned to the Metal Working Section of the Industry Engineering Department in East Pittsburgh, and in 1956 he was transferred to the Systems Control Division in Buffalo as manager of the Mill Systems Development Section. In 1963, he was given the special assignment of directing and coordinating the corporate effort involved in the development of high-power thyristor dc drive systems.

Dr. Stringer is now Consulting Engineer and Director of Advanced Development, Systems Control Division. He holds a BS in electrical engineering from the University of Texas, an MS from California Institute of Technology, and a PhD from the University of Pittsburgh.

L. R. Tresino graduated from West Virginia University in 1952 with a BSEE and joined Westinghouse on the graduate student course. He was assigned to the Systems Control Division in Buffalo, where he worked on design of dc drive systems. He found time to take courses at the State University of New York at Buffalo, earning his MSEE there in 1963.

Tresino is now Supervisor of Product Development in the division's Industry Control Product Group, responsible for development of product standards for dc drive systems and regulators. Before his appointment to that post, he had served a year as supervisory engineer in packaged-drive applications and a year as associate manager of the division's OEM Drives Product Line Group.

Dr. M. J. Greaves, J. C. Ponstingl, and **W. A. Munson** join forces to write about blast-furnace systems as they do to design and apply them.

Dr. Greaves is Director of Engineering of the Iron and Steel Division, Arthur G. McKee and Company. He has been responsible for the design of 63 blast furnaces with a combined capacity of 42,000,000 tons annually and also for sintering and pelletizing plants with a combined capacity of 55,000,000 tons annually. He earned his BS in civil engineering at Utah State College in 1939, his MCE at Cornell University in 1940, and his PhD at Carnegie Institute of Technology in 1956.

Ponstingl's forte is improving industrial control. As a senior district engineer in the Westinghouse Cleveland office, his main interests at present are material-handling and steel-mill automation. Ponstingl graduated from Case Institute of Technology with a BS in electrical engineering in 1941. He joined Westinghouse on the graduate student course and was assigned first to the former Control Engineering department. He moved to the Cleveland office in 1949 when he switched to the Consulting and Application group, and he assumed his present position in 1961.

Munson has design responsibility in the Industrial Systems Division for blast-furnace charging systems; among the projects he has handled is the first completely automatic conveyor-fed furnace charging system. He graduated from Wayne State University in 1948 with a BS in electrical engineering and joined Westinghouse on the graduate student course. After a short design stint at the Small Motor Division, he was assigned to the Power Transformer Division to design load tap-changer transformers and large power regulators.

Munson moved to Electric Utility Engineering in 1954, where he worked on dc transmission and harmonic problems in power systems. He also earned an MS in electrical engineering at the University of Pittsburgh in 1958. In 1959, he went to Buffalo to take up his present responsibilities.

This special high-voltage dc laboratory at the Westinghouse Semiconductor Division will be used to develop new and improved solid-state devices for use in high-voltage dc transmission line terminals.