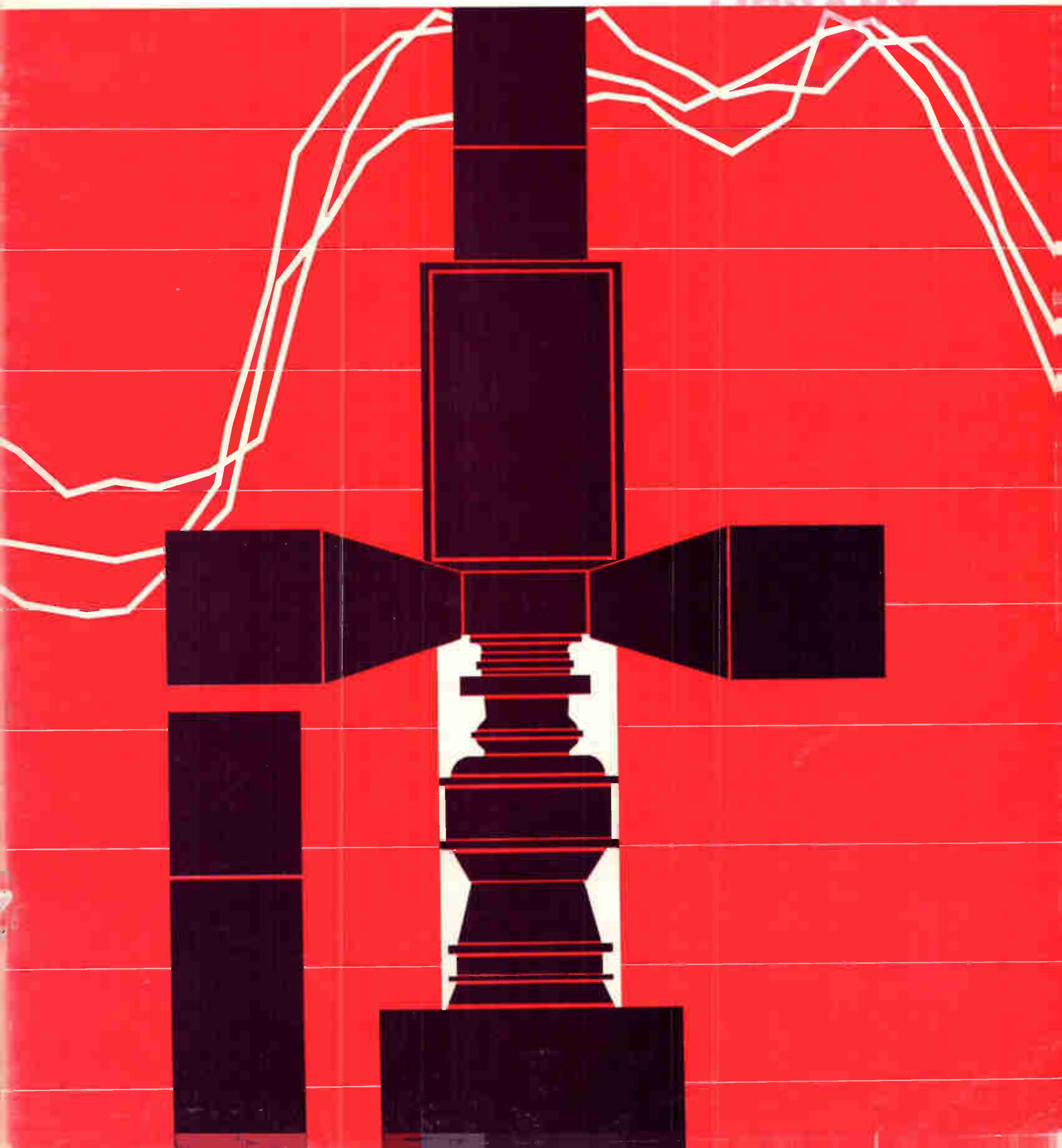
Westinghouse ENGINEER

September 1969



Transformer Production Benefits from Innovations in Manufacture and Design

The manufacturing plant and the product were designed together for the new Westinghouse facility at South Boston, Virginia, which produces small oil-insulated power transformers. Transformers made there were all redesigned to take full advantage of the advanced automation and manufacturing techniques that were provided in the plant; the result is faster production and improvements in the transformers' strength, efficiency, and quietness.

The transformers are rated at 500 to 5000 kVA, 69 kV, and are used in power-center, network, and substation applications (*photo 1*). They are of rectangular core and coil construction. The new designs were developed from research and testing to provide the short-circuit strength needed to repeatedly withstand the increasingly large short-circuit currents available in modern systems. Besides product improvement, the redesigning permits taking full advantage of parallel rather than serial assembly operations, standardization on aluminum conductors, step-lap core construction, and improvements in coil winding. (For more information about the step-lap core construction, see *Step-Lap Core Construction Improves Power Transformers,* page 158.)

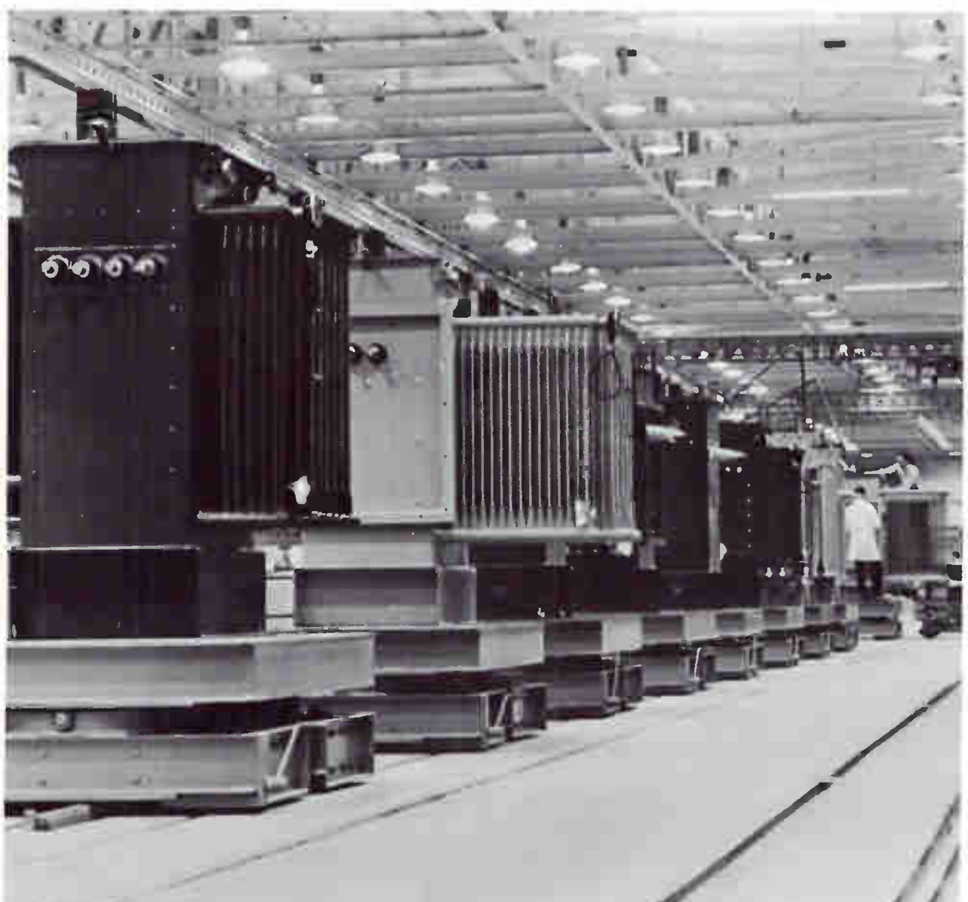
The plant's production control system is on a real-time basis, with about 20 reporting terminals placed strategically to feed the plant's central computer the status of each component, product, and order. The system measures real-time reported progress against a plan and isolates deviations for immediate corrective action.

A strip-winding machine begins the coil winding operation by building up the low-voltage section and then the insulation that separates low- and high-voltage windings (*photo 2*). Then the high-voltage winding is put on by a strap-winding machine equipped for automatic traversing and tensioning. The coil goes next to a turns-counter and test station and then is pressed to size before baking (*photo 3*).

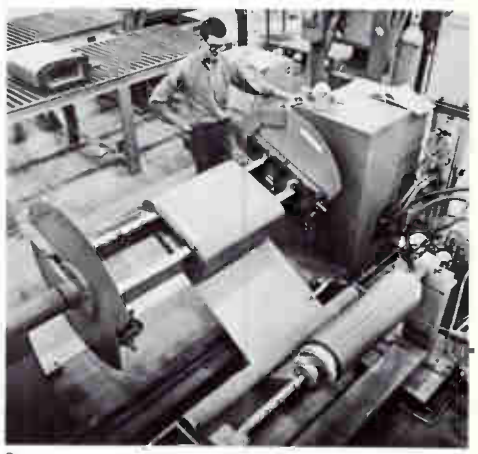
Core manufacture begins with annealed and slit Hipersil coils fed into three shear lines that produce the punchings for step-lap core construction. Punchings are stacked to form a bottom yoke, center leg, and two side legs, which are welded into the frame bottom. The coils and the top yoke of the core are added, and then the top frame is welded on with pressure on the top yoke to insure a quiet and strong unit.

An assembled and tested core is dried in an oven and a vacuum chamber before being bolted into its tank. The unit is transported along the main assembly line, where assembly is completed and the unit is filled with oil or Inerteen under vacuum. Electrical testing, leak testing, and attaching the required external components complete the manufacturing process.

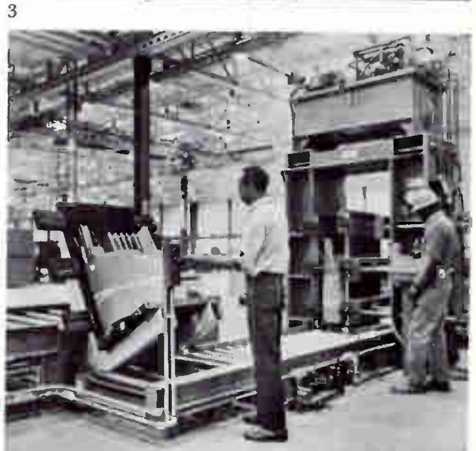
1



2



3



Westinghouse ENGINEER
September 1969, Volume 29, Number 5

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

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

Published bimonthly by the Westinghouse Electric Corporation, Pittsburgh, Pennsylvania. Printed in the United States by The Lakeside Press, Lancaster, Pennsylvania. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, Inc., 300 North Zeeb Road, Ann Arbor, Michigan 48106.

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries:
Econo-Pac; Centriline; Camp; De-ion; Inerteen; Hipersil; Insuldur.

Front cover: A large gas-turbine power plant for electric-utility peaking service is the theme of the cover by artist Tom Ruddy. The design also suggests the modular construction of the plant, which is described in the article beginning on the following page.

Back cover: The core of the Saxton Experimental Power Reactor was photographed from above immediately after it had been reconstituted as Saxton Core III. This core is expected to provide more knowledge about use of plutonium in commercial pressurized-water reactors. (More information on page 159.)

Gas-Turbine Peaking Plant Provides 58 MW in a Modular Package

V. V. Schloesser

The W-501-G Econo-Pac gas-turbine power plant combines technological advances with proven design approaches in a packaged unit that provides large single-plant economy with modular installation convenience.

The modular packaged power plant has become a most useful peaking tool for electric utilities, enabling them to balance their systems and meet emergency conditions economically. Of the various prime movers applied, combustion gas turbines have won favor over the others because they require less total capital investment per kilowatt installed or kilowatthour generated. Other advantages such as remote unattended operation, quick starting, no need for cooling water, and black-plant startup capability provide further economic incentives for choosing gas turbines.

However, one disadvantage of gas turbines has been small unit size. Most units sold by all manufacturers through 1968 were rated between 15 and 20 MW, so, to meet peaking requirements of 30 to 250 MW, utilities have had to buy many small units and group them. The result is less efficient land use than larger units would provide, more total maintenance requirements, and higher total operating expenses.

To meet the need for larger single-unit capacity, Westinghouse embarked on a program early in 1965 to develop a large gas turbine. The result is the W-501-G turbine (Fig. 1). It is the prime mover in the new Econo-Pac power plant that provides 58 MW of peaking power while retaining modular packaged construction for fast and economical installation.

Development

The initial design in the W-501 series provided a net base load rating of 37 MW and 44 MW peak. (All ratings in this article are at 80 degrees F and 1000-foot altitude and with inlet- and exhaust-duct losses commensurate with adequate silencing.) The primary objectives in the initial design were to increase performance through high turbine inlet temperature, permit rapid load transients, and maintain long life of the hot parts.

All of the features proven by successful field operation of previous designs were retained, including the two-bearing rotor with bearings easily accessible at inlet and exhaust ends. The compressor rotor is an assembly of discs held on a shaft by a shrink fit; blades are assembled in the discs by side entry and are easily removable. The turbine rotor is a bolted assembly with curvic couplings between discs, and its blades also have serrated roots for side entry and easy removal.

The first W-501 unit was shipped in September 1968 and placed in commercial operation in December after completing a comprehensive full load test. It is in base-load supercharged combined-cycle service with a net gas turbine output of 42,680 kW. Four additional units have been shipped, and another is scheduled for shipment during 1969. Total running time is about 6000 hours.

The current version of the 501 series (W-501-G) is scheduled for 1970 shipment. It will have a net plant base load rating of 51,750 kW and a peak load rating of 58,000 kW. The rating increase is the result of incorporating a larger and improved compressor.

W-501-G Turbine Design Features

Compressor—All aerodynamic parameters were kept at the same levels in the W-501-G unit as they were in the previous designs, but air flow was increased by enlarging the inlet area with a corresponding increase in cycle pressure ratio. The first two stages are of tapered-hub constant-tip-diameter design, while the rest of the compressor is of constant-hub design.

Interstage bleeds in the sixth and eleventh stages are opened during the starting cycle and through 90 percent speed to assure good starting. The variable inlet guide vane is modulated from a 50-degree closed position at ignition to its design setting at 90 percent speed to further improve acceleration during starting.

Stator—The bearing supports consist of radial struts in the compressor end and shielded tangential struts aft of the turbine. The tangential-strut design is a Westinghouse exclusive feature that effectively keeps the rear bearing centered during both transient and steady-state operation. Shields protect the struts from large transient temperature changes that occur during rapid starts or load swings.

Compressor vane assemblies have both inner and outer shrouds. They are similar in mechanical design to the compressor stationary elements that have given virtually trouble-free service in the past.

The turbine section consists of four stages, each with precision-cast segmented vanes. Each vane row is supported by individual inner cylinders (radially keyed to the turbine outer cylinder) that also support segmented liners forming the flow path outer boundary for the rotating blades. The segmented vane and liner system permits relative transient thermal growth between the segments and the inner cylinders to minimize thermal stress. Use of cooled individual inner cylinders minimizes blade tip clearances, thus maximizing turbine efficiency. Moreover, careful selection of the number of segments minimized the contribution of leakage flow harmonics to turbine-rotor blade vibration.

The system of individual inner cylinders permits easy access to any turbine row. An entire row of vane segments can be removed by a special roll-out feature with the spindle in place, so the row can be inspected, repaired, or replaced without disturbing the remaining rows or the spindle.

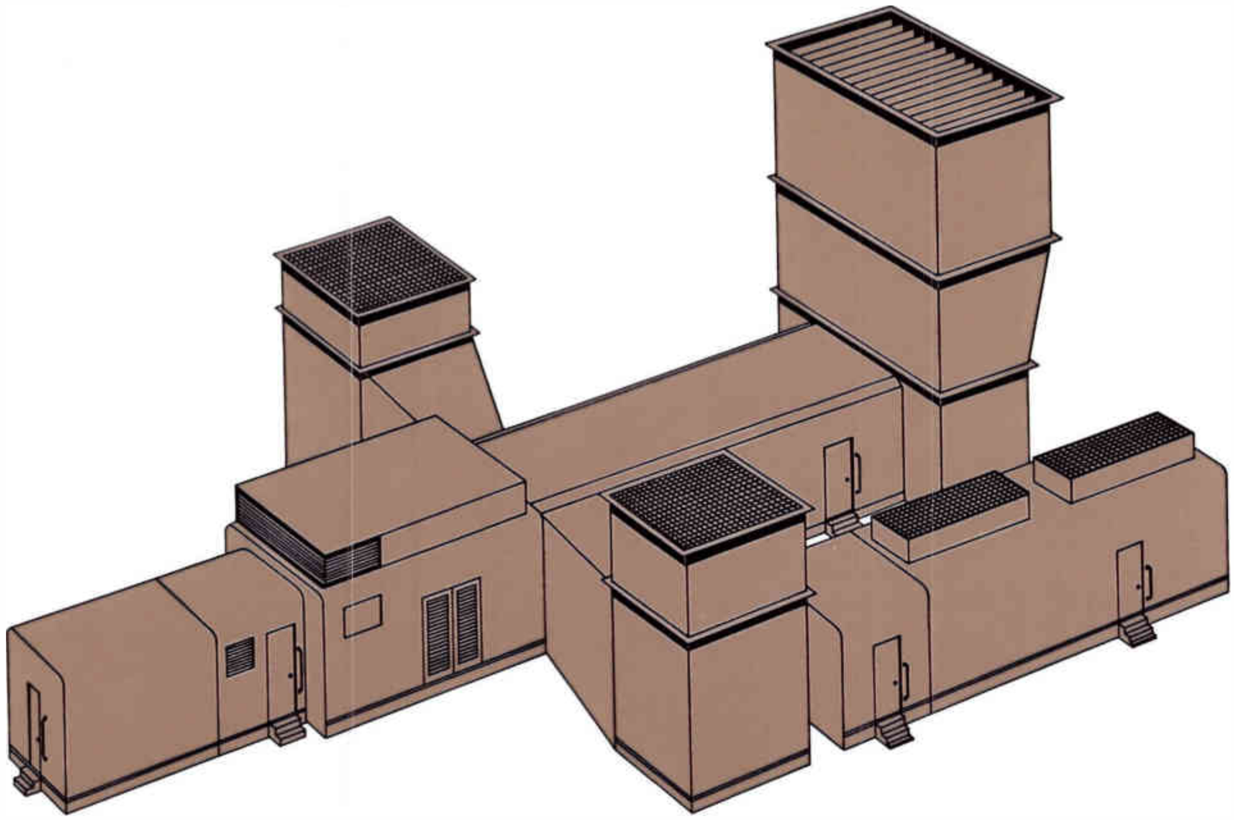
Leakage past each turbine vane row is minimized by a new seal structure con-

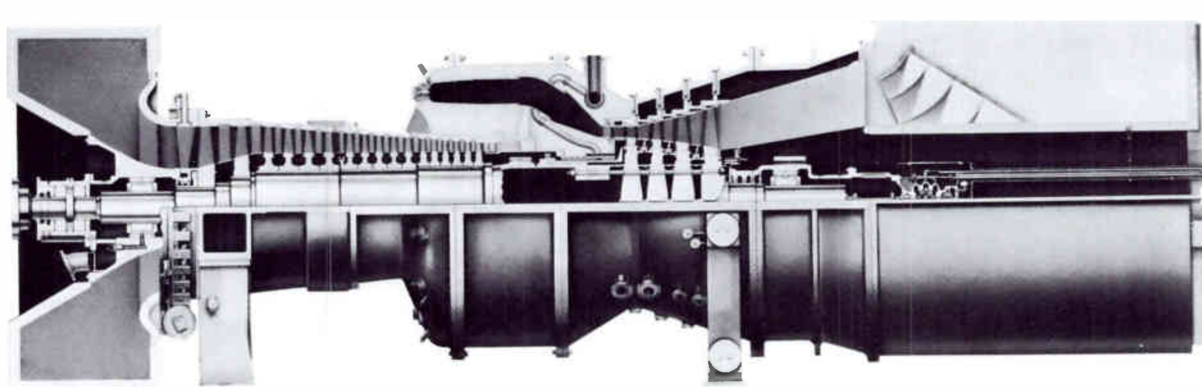
Top—Artist's concept of an installed W-501-G Econo-Pac gas turbine power plant illustrates the modular construction and the all-weather enclosures used. Although the turbine is the largest shipped as a complete assembly, its weight and dimensions are small enough to permit rail shipment to most parts of the United States.

1—(*Bottom*) W-501-G gas turbine gives the Econo-Pac power plant 58 MW of peaking power. Its rotor is supported by two pressure-lubricated journal bearings, and it has 17 compressor stages and 4 turbine stages.

V. V. Schloesser is Engineering Manager, Small Steam and Gas Turbine Division, Westinghouse Electric Corporation, Lester, Pennsylvania.

This article is adapted from a paper presented before the 31st Annual Meeting of the American Power Conference, April 22, 1969, sponsored by the Illinois Institute of Technology.





sisting of a seal support ring radially keyed to the vane segments. The seal ring is maintained at optimum temperature by cooling air. This system permits relative radial thermal growth between vane segments and seal support ring, thus permitting use of minimum radial seal clearances.

Rotor—The rotor is supported on two pressure-lubricated journal bearings. This time-proven design was retained because of its many advantages—mainly fewer alignment problems, less oil required, less oil cooler capacity required, and greater reliability since no bearing is located in a high-pressure high-temperature zone.

Because rotor dynamics are a prime design consideration in large rotating apparatus, the following proven features were incorporated to reduce spindle vibration response:

1) Large-diameter journals with spherically seated pivoted-pad bearings. These bearings are free from oil whip instability and accommodate shaft deflection or misalignment. They are operating successfully in large steam turbines and in the W-501 gas turbines.

2) Compressor spindle built up from ring-type discs shrunk on a hollow forged shaft. This construction gives a favorable weight-to-stiffness relationship, resulting in achieving the desired critical speed. The hollow shaft design has been proved in the W-501 turbines now in service.

All four rows of turbine blades are tuned to insure that they are not in resonance at operating speed. The blade frequency calculations were verified by static and rotating tests. All turbine blades are of extended-root design, which isolates the roots and disc rims from the hot gas stream and reduces the three-dimensional stress concentration that occurs when load is transferred between two cross sections of different shape.

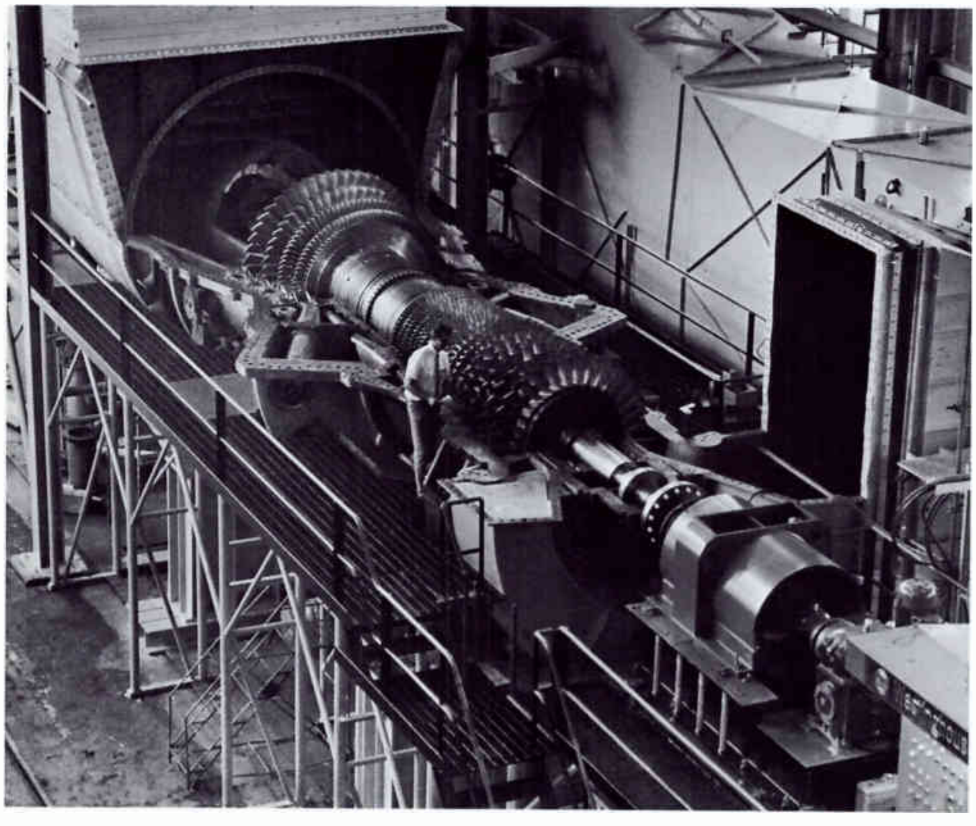
Cooling System—Protection of parts from the high-temperature gas stream during both transient and steady-state operation was a primary objective to insure reliability and long life. A three-circuit cooling system provides the desired temperature profile at the entrance to the turbine blading (Fig. 2).

The first circuit bypasses some of the compressor discharge air around the combustors and introduces it at the inner annulus of the turbine flow path, just ahead of the first stationary row, to provide a radial temperature profile that is relatively cool at the hub (regardless of combustor discharge temperature) and increases toward the tip.

The second circuit takes bleed air from the fourteenth compressor stage. Part of the flow is cooled and filtered by an inertial self-cleaning filter and then piped to the rotor to cool all the turbine discs. The air enters the root serrations of each disc to remove heat transferred by conduction from the blades to the discs and then is discharged into the gas stream through the serrations, thereby reducing the temperature of the blade root-to-disc joints. This cooling keeps disc temperatures below 600 degrees F to assure long life and reliability. The remainder of the flow is directed to cool the blade ring cavities; it then flows through the hollow second-, third-, and fourth-stage vane segments to cool the inner seal housings.

The third circuit directs compressor discharge air to the first vane segment shroud and into the first-row vane segments to cool the vanes.

Combustion System—The combustion system design is based on experience with similar components in other Westinghouse gas turbines, and laboratory testing at full flow and pressure conditions has provided additional assurance of satisfactory performance. Its general configuration is a circular array of 16 can-shaped combustors arranged around the machine axis. The combustors are enclosed in a



***Left*—W-501-G gas turbine photographed during assembly in the manufacturing plant. The exhaust and inlet ducting is for factory testing before shipment.**

2—(*Right*) Turbine cooling system protects the parts from damaging overtemperatures during transient and steady-state operation. Circuits 1 and 3 employ compressor discharge air; circuit 2 uses air bled from the compressor's fourteenth stage.

plenum chamber into which compressor discharge air flows at relatively low velocity. Hot gas flows from the combustors to the turbine inlet through transition pieces.

Air flow management has been improved to reduce smoke by eliminating fuel-rich zones in the combustor primary zone, without adversely affecting flame stability. Tests show exhaust smoke levels less than No. 5 on the ASTM D 2156-65 smoke test apparatus, equivalent in the Ringelmann system to a value much less than Ringelmann No. 1.

The fuel injector design provides both for burning gaseous or liquid fuel alone and for dual-fuel operation, when automatic switchover under load from one fuel to another is desired. The liquid fuel injection system has single-orifice pressure-atomizing fuel nozzles with no moving parts. Air atomizing assist is used for starting. The system is easy to maintain and tolerant of foreign particles in the fuel stream. Ignition is by spark and cross-firing between combustors.

Combustors are of stepped-wall construction for efficient film cooling of the refractory metal, a construction that prolongs the combustor's life and enables it to tolerate considerable abuse. The combination of fuel management, combustor design, and fuel injector design produces a gas outlet temperature pattern that is uniform within 100 degrees F.

Performance

The accompanying table shows performance of the W-501-G unit with natural-gas and distillate-oil fuels for three modes of operation—base, peak, and system-reserve loads. The initial recommended inspection interval for base-load operation is 9000 hours; for peak-load operation, 2500 hours; and for system-reserve operation, 500 hours.

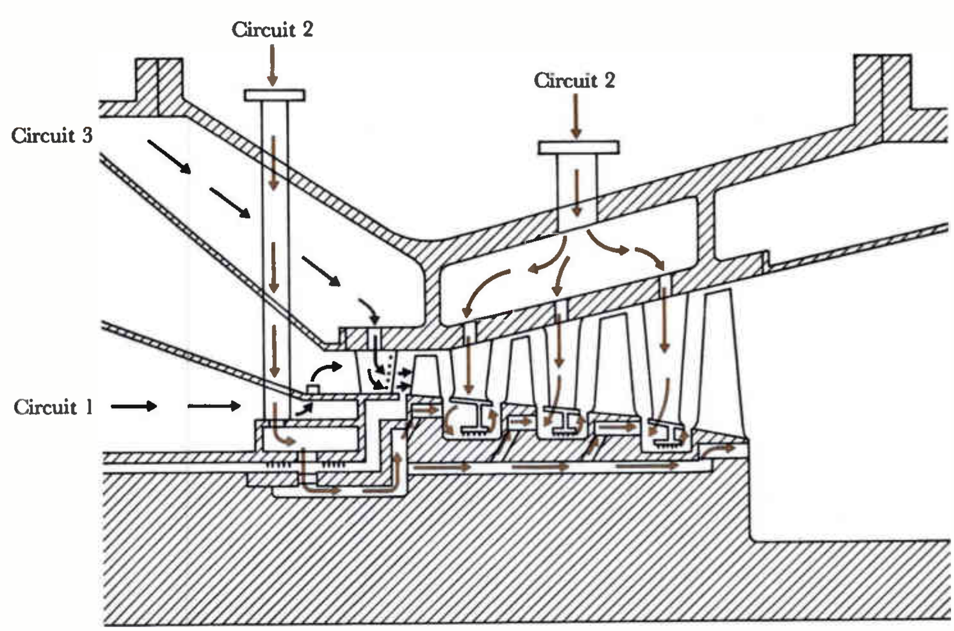
Generator Design

A new air-cooled generator rated 62,500 kVA at 13,800 volts has been designed to match the output of the W-501-G turbine over the full ambient temperature range. Its maximum capability is 77,400 kW at −10 degrees F and 0.90 power factor.

The generator has brushless excitation with rotating diode rectifiers, eliminating the requirement for generator or exciter brushes. The diodes are in bridge circuits on a diode wheel. Excess capacity is provided so that, if a diode fails, the unit can continue operating until the diode can be replaced at a convenient or normal shutdown period.

Power Plant Packaging

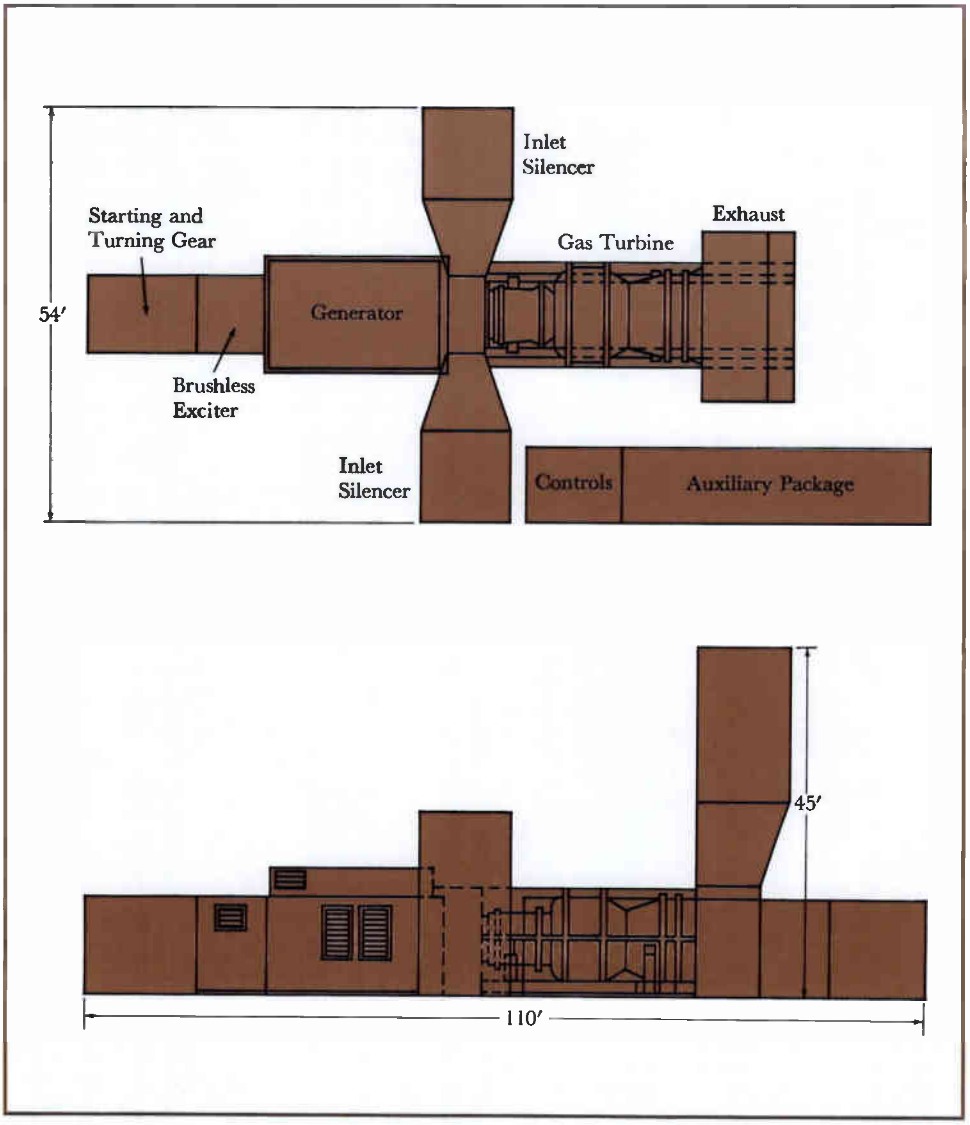
The W-501-G Econo-Pac power plant is divided into six major equipment packages: gas turbine, auxiliaries, control, generator, starting, and inlet and exhaust (Fig. 3). These packages are housed in all-weather enclosures. The enclosures are designed for maintenance accessibility and include thermal and acoustical insulation where applicable; lighting and heating are provided in en-



Performance of W-501-G Econo-Pac Gas-Turbine Power Plant

	Gas Fuel	*Oil Fuel*
Base Load		
Power (kW)	51,780	50,600
Heat Rate (Btu/kWh)	12,220	12,630
Peak Load		
Power (kW)	58,000	56,600
Heat Rate (Btu/kWh)	11,930	12,330
System Reserve Load		
Power (kW)	61,500	60,000
Heat Rate (Btu/kWh)	11,830	12,210

Note: Performance is based on ambient temperature of 80 degrees F, pressure of 14.17 psia barometric (1000 feet), use of standard inlet and exhaust systems (sound level "A"), and use of lower heating value natural gas and distillate oil fuels.



3—Plant arrangement requires little land. The major components are packaged assemblies for fast economical installation.

closures where routine maintenance is to be performed.

Gas-Turbine Package—This consists of the gas turbine mounted on a shipping skid, which is an integral part of the assembly. It is the largest gas turbine shipped by rail as a complete assembly, but total weight of the package and envelope dimensions were controlled to permit rail shipment to most parts of the United States.

Inlet and Exhaust Systems—These are manufactured as modules and shipped to the field for assembly. They include silencing provisions.

Generator Package—The generator package, including the brushless exciter, is mounted on a common base and shipped as an assembly. Its cooling air system includes an air cleaner and a silencer.

Auxiliary Package—This consists of equipment necessary for operating the plant, such as the fuel system, lubrication system, motor controls, and oil coolers. All heat exchangers are air cooled to allow dry-plant operation.

Starting Package—An ac squirrel-cage motor with torque convertor, turning gear, and automatic disengagement clutch are mounted on a common base to make up the starting package.

Control Package—A walk-in enclosure with heating, ventilation, lighting, and air conditioning houses the consoles, controller, and optional control equipment.

Conclusion

The W-501-G Econo-Pac gas-turbine power plant makes 58 MW of peaking power available in a single unit while retaining modular package features, quick installation, and low capital investment. Because of its relatively low heat rate, it also provides economical power for intermediate power generation requirements (1500 to 2500 hours per year). Moreover, it is well suited for relatively large base load combined-cycle applications where total energy systems are desired.

Combination Motor Starter Now Provides Complete Circuit Protection

J. M. Michaelson

A fast-acting magnetic current sensing device protects motor circuits by interrupting low-level faults while they are still low. A current limiter backs up the magnetic device for positive protection in applications where higher fault current may appear.

For years, the "combination" in combination starters has been motor starting and circuit protection. Now the concept has been carried farther with a combination of adjustable low-level fault protection and, when needed, high-level fault protection—all with circuit-breaker convenience.

Since most motor circuit faults are initially only 20 to 100 times the motor's full-load current, low-level fault protection is an essential feature of a true combination starter. To provide motor users with that important protection, Westinghouse engineers developed a unique current sensing device known as the motor circuit protector (MCP). It reacts immediately to any current above a preselected safe level in any of the three legs of the motor circuit, tripping the unit to open the circuit before the motor, the starter, or any other circuit components can be damaged.

The MCP provides the fastest low-level fault clearing presently possible—faster even than a correctly applied fuse. It gives the A/206 combination starter interrupting capacities as high as 50,000 amperes. (See table on page 136.) For applications where available fault currents can exceed the A/206 ratings, a special current limiter is included with the MCP in the A/207 combination starter to provide complete circuit protection at up to 100,000 amperes of fault current. The current limiter guards against high-level faults, while the MCP quickly clears low-level faults without affecting the current limiter. The limiter is a sealed unit so that its elements cannot be replaced with improper fuses.

In addition to their low-level fault protection and high interrupting capacity, the Westinghouse combination starters have all of the safety and convenience features of conventional molded-case circuit breakers, including quick-make quick-break action, dead-front safety, straight-through wiring, compact size, protection against single phasing, and reduction of fuse inventories. These advantages usually reduce overall motor down time for greater system productivity and profitability.

Because the MCP was designed specifically for motor circuit protection, the protection is easily tailored to fit the specific needs of every electric motor manufactured. (Each motor needs a protective device with precisely the right tripping point, since each has a different locked-rotor current value.) The user simply obtains the motor's full-load current rating from its nameplate, determines the correct trip point setting from a table supplied with the starter, and sets the exact trip point needed for his particular motor with a single adjustment. If the motor is replaced by another motor with different electrical characteristics, another simple adjustment of the MCP provides complete protection for it.

Breaker-type accessories such as auxiliary switches, shunt trips, and undervoltage releases can be added to the MCP for special applications, if necessary. The new combination starters are available in a wide variety of enclosures to meet the requirements of any installation. A tamperproof interlock mechanism assures dependable performance and maximum safety to operating personnel.

Publication of the 1968 National Electrical Code, which recognized the use of instantaneous-trip circuit breakers as integral parts of combination starters, was an important factor in the decision to develop the A/206 and A/207 starters. Before, the policy universally accepted was inclusion of components listed by Underwriters' Laboratories, Inc. This occasionally presented problems in motor controller protection, especially for motors with full-load currents of six amperes or less. Another factor was the need for a device of circuit breaker type specifically designed for the needs of motor circuits.

A/206 combination motor starter *(top)* includes a motor circuit protector (near the top of the cabinet) to open the circuit immediately on low-level faults. The A/207 starter *(bottom)* also has the motor circuit protector and, in addition, a current limiter (just beneath the protector) to interrupt high fault current.

J. M. Michaelson is a design engineer at the Control Products Division, Westinghouse Electric Corporation, Beaver, Pennsylvania.

Moreover, continually increasing transformer ratings along with more and more industry specifications requiring higher short-circuit capacities had created a need for a current limiter package that could be added to a circuit breaker.

Fault Conditions

Fault current is a complex and varying phenomenon of electrical circuits. As the name implies, it is a direct result of some faulty circuit condition that reduces the resistance and allows current flow in excess of the design value. For this discussion, any current that exceeds the locked-rotor current (approximately six times full load) of the motor being protected is considered a fault current. Faults can be categorized into two basic types: normal (low current level), and extremely high current level.

Normal faults make up most of the overcurrent conditions ever encountered by combination starters. The usual situation is an insulation breakdown in the motor windings or feeder wiring. The fault current that results depends on many factors. All theory of insulation points to the fact that when flashover occurs, the current almost instantaneously rises to a value determined by the available current less the resistance value of the arc and the total impedance to the point of fault. Available current depends on fault location, since the impedance of all the components between power source and point of fault have to be considered.

To illustrate, consider a typical 480-volt installation with 18,000 amperes available at the line leads of a combination starter. The added impedance of the breaker, starter, and overload relay heaters reduces available current at the load leads to approximately 10,000 amperes (depending on the choice of components). A 25-foot run of No. 10 wire between starter and motor reduces the available current to approximately 6000 amperes. Finally, internal impedance within the motor windings brings the available current at any point down to 100 amperes or less. Thus, depending on the point of failure, the current that must be safely interrupted by the combination starter can vary anywhere from 10,000 amperes to 100 amperes.

Most faults occur within the motor windings due to an insulation breakdown, so the initial level of fault current is normally extremely low in relation to system capacity. However, the initial fault causes arcing that, if not arrested, cascades and broadens the physical area of the fault, shorting out more and more turns and cancelling impedance in the process. In a matter of cycles, the fault current can reach the full potential available at the motor line terminals if not interrupted immediately. Thus, while most faults are initially only 10 to 20 times full load, they quickly avalanche to 600 to 1000 times full load. The lower currents, if removed from the line immediately, cause no appreciable damage to the contactor or the overload relay heaters; however, if they are allowed to remain for a period of time, the resulting higher currents can damage those devices.

Extremely high initial fault currents are the exception. As just explained, high available fault current is present only from the combination starter load terminals to the motor line leads. There is little reason for an insulation breakdown in that path, so the likelihood of short circuit is reduced to an accidental severing of the conduit and resultant phase-to-phase or phase-to ground short circuit and to inadvertant installation of the equipment with a built-in fault condition. A fault at full system capacity occurs only with a bolted fault condition such as might be caused by an obvious wiring error; in practice, that is almost impossible because shorted conductors normally part, creating an arcing fault rather than a bolted condition. Furthermore, adequate checks before applying power disclose that type of error. However, if it occurs, such a fault is extremely dangerous to personnel and equipment if not removed from the line very rapidly, so the disconnect must have the interrupting capacity to remove it safely.

With modern industrial plants requiring increasingly large blocks of power, larger and larger transformers are being used and available current at the point of application of a combination starter has increased considerably. While 18,000 amperes or less of available current is typical, in more and more plants the available may be 25,000 to 50,000 amperes.

Such high available current is especially likely when the combination device is a portion of a motor control center or a plug-in unit on a bus-duct run, where the impedance drop from the incoming transformer to the point of use is very small. Again, however, even though the available current is high, an actual motor winding fault is of low level and is not dangerous if opened immediately. However, if the high-level fault current passes through the combination starter, catastrophe results unless some means are present to limit the current within the capacity of the protective device. The only way now known to limit the current is to

Combination Starter Interrupting Ratings
(rms symmetrical amperes)

NEMA Size	*Starter Type*	*240 V*	*480 V*	*600 V*
0	A/206	50,000	50,000*	50,000*
	A/207	100,000	100,000	100,000
1	A/206	50,000	18,000	14,000
	A/207	100,000	100,000	100,000
2	A/206	50,000	18,000	14,000
	A/207	100,000	100,000	100,000
3 and 4	A/206	50,000	18,000	14,000
	A/207	100,000	100,000	100,000

Note: A/206 combination starters have the new motor circuit protector. A/207 starters have both motor circuit protector and current limiter.
*18,000 at 480 V and 14,000 at 600 V when using 15-A MCP.

add impedance or to open the circuit in the first ⅛ to ¼ cycle before the current can rise to its full value. Impedance coils able to reduce the current sufficiently are large and often not practical; consequently, the current limiter is included in the new combination starter to protect equipment when available fault current is high.

A circuit breaker, having a sensing device that includes a mechanical linkage system to induce opening, performs adequately when required to interrupt currents within its rating, usually within ½ to ¾ cycle. However, when applied beyond its rating in systems with high available fault current, auxiliary assistance is required to clear the circuit in ⅛ to ¼ cycle to minimize damage.

One might think that the problems can be avoided if a fusible device is used in the first place, and that is true to a certain extent. However, extensive testing has proved that an instantaneous-trip circuit breaker clears a low-level fault much faster than any correctly applied fuse. A fuse is inherently a thermal sensing device, and, for low current levels, a time delay must be built in to enable it to ride out the initial inrush peaks. The breaker is a constant-time device requiring ½ to ¾ cycle to clear low-level faults, so it clears the circuit 10 to 15 cycles faster than a fuse. And a breaker has other advantages in reduced down time, lower operational cost, lower maintenance cost, smaller size, greater reliability, and insurance against single phasing.

1—Motor circuit protector is adjusted when the starter is installed to tailor the trip setting to the individual needs of the motor being protected. It is readjusted easily if the motor or circuit components are changed.

Motor Circuit Protector

The motor circuit protector (MCP) is basically an instantaneous-trip device. However, it includes features that heretofore were not available, and, most important, it is the first breaker designed and rated specifically for use in combination starters on motor protection circuits.

Externally, the obvious difference is provision of only one screwdriver adjustment cam rather than the three on previous instantaneous-trip devices (Fig. 1). The cam provides a quick and convenient means of adjustment and reduces the likelihood of errors in setting the trip value when applying the breaker in a protection system.

Even more important is ability to set the device for a maximum trip rating. The 1968 NEC code states, "The setting of an instantaneous trip circuit breaker (without time delay) may be increased over 700 percent, but shall in no case exceed 1300 percent of the motor full load current." To comply with the new code, a locking pin is provided with the MCP to insure that the 1300-percent maximum figure is not exceeded. The user simply refers to the table of full-load current values provided with the combination starter and determines the correct pin position for the motor being used. He inserts the pin in the selected position on the periphery of the adjustment cam, where it acts as a stop for the cam to insure that the breaker is properly applied.

The frame size of the MCP is exactly the same as that of the EB, EHB, and FB thermal-magnetic circuit breakers, and the unit is interchangeable with them. There are seven ratings, required to cover the complete range of continuous full-load current that size 0 to 4 combination starters encompass: 3, 7, 15, 30, 50, 100, and 150 amperes. The 3-, 7-, and 15-ampere units are required to properly protect size 0 starters and their overload relay heaters. However, the 30-ampere unit is used with the size 1 starter, 50 with size 2, 100 with size 3, and 150 with size 4. The advantage of this arrangement is in having a particular disconnect-protective device engineered specifically to a starter size when the two are used within their designed ratings, thus eliminating the confusing method now used where two or perhaps three ratings of circuit breakers are required to adequately protect a circuit of given voltage over the full horsepower range of the starter size. This is an industry first—breakers specifically designed to correlate with starter sizes to eliminate application confusion.

Because the MCP is a current sensing device, ambient temperature does not appreciably affect its performance. That feature eliminates the need to derate because of an unusual ambient condition.

The MCP has the identical handle operational features, contact structure, and arc suppressing parts as the thermal-magnetic breakers (EB, EHB, and FB), and its terminals are approved for use with copper or aluminum wire. The difference is in the sensing mechanism that reacts to current changes to trip the breaker.

The sensing mechanism gives the MCP its ability to react quickly to any overcurrent above a preselected safe level. Its magnetic trip assemblies are three closely calibrated current sensing relays; excessive current in any one of the three poles of the breaker activates the magnetic attractive action of the stationary portion of the assembly, which pulls down the moving armature causing the latch to disengage and trip the breaker.

Current Limiter

The current limiter is essentially a fuse, but it has the unique advantages of including all three phases in one package, being easily adaptable for use with a circuit breaker, being small in size, and having fusing characteristics designed to meet the needs of the specific system of MCP, starter, heater, and motor that it will protect.

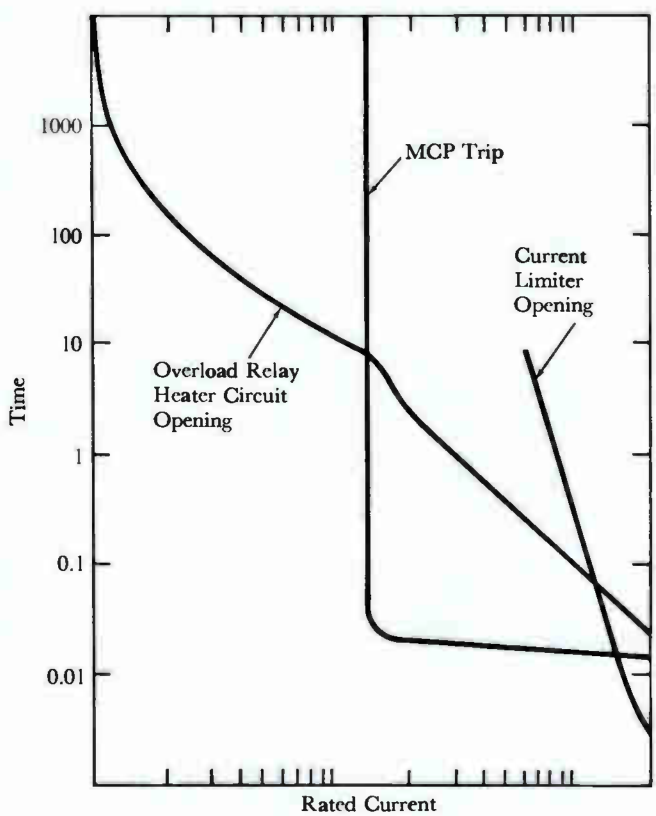
Coordination is completely compatible in all applications so that the current limiter functions only at the proper crossover point. An equivalent coordination might be made with specially designed fuses, but the design and construction of the current limiter make it extremely convenient to use because it dovetails neatly into the load end of the MCP.

The current limiter is a three-pole block that is connected directly to the MCP load terminals. One physical size is used for all current limiters, but, since the device is designed for motor circuit protection, seven ratings are available (each rated to coordinate with the seven MCP's). This feature simplifies application and provides the ultimate in circuit protection. The new A/206 combination starter has provision for incorporating the current limiter whenever a user increases his system capacity to the point where he requires the added safety assurance. The current limiter includes a spring-loaded trip indicator for each pole; when fault current blows the fusing links, the indicator is released and protrudes from the cover. A blown current limiter indicates a serious circuit problem that must be corrected before restoring service. Therefore, limiter replacement in itself is not likely to increase down time because, in the vast majority of cases, any fault great enough to cause the limiter to open is serious enough to require extensive circuit corrective measures.

However, most faults are low-level faults that the MCP senses and clears before the current reaches a level that causes the current limiter to function (Fig. 2). Any current that does cause the limiter to function also trips the breakers, eliminating any chance of single phasing.

The current limiter case is of high-strength glass-reinforced polyester material. It and the sand that encloses the current-carrying links enable the device to interrupt a fault of 100,000 amperes safely, well above most system capacities now in use in this country.

The most important feature of the current limiter is that its use increases the interrupting capacity of a breaker combination starter to 100,000 amperes symmetrical. The result is ability to exploit all the inherent advantages of breaker operation (minimum downtime, low operating cost, and low-level fault protection) in a completely coordinated system applicable to a circuit having up to 100,000 amperes available current.



2—Typical coordination curves illustrate how the combination starter protects a motor circuit. The overload-relay curve shows relay response time up to approximately six to seven times motor full-load current. The motor circuit protector (MCP) then reacts to clear the circuit on faults above those values, to approximately 150 to 200 times full load. Finally, if required, the current limiter opens any faults above that range.

Application

The first application consideration is determining available current in the system at the point of use of the combination starter. The appropriate starter is then selected from the table on page 136.

When installing an A/206 or A/207 combination starter, the user consults the full-load current chart provided on the enclosure door and correlates the information with the motor nameplate value to properly position the stop pin. All MCP's are shipped with the screwdriver adjustment cam set in the minimum position, which probably will cause tripping on motor starting if not adjusted. Instructions are included for setting the adjustment cam until the MCP trips and then selecting the final position to provide the maximum circuit protection the device affords.

Conclusion

The new combination starters provide complete protection. A motor circuit protector clears low-level faults rapidly and without affecting the current limiter. The current limiter reacts only to excessively high faults, which demand extremely rapid clearing for circuit protection.

Aircraft Window Temperature Controlled with Simple Static Tap Changer

D. E. Baker
H. H. C. Richards

An autotransformer with a static tap changer provides varying power levels for controlled gradual heating of aircraft windows to avoid thermal shock, and it does it without causing power system distortion. Little or no filtering is needed to prevent radio-frequency interference. The circuit design also is applicable to any other system requiring ac voltage control.

Window heating, needed to defog and deice windows in aircraft cockpits, is accomplished by supplying ac electric power to a transparent conducting layer that acts as a resistance heater in the laminated window. (Direct current is not used because of its tendency to cause migration of the conducting layer and consequent resistance change.) The front windows are controlled at the temperature above deicing that provides maximum strength and flexibility to prevent breakage if the aircraft hits a large bird.

To improve the heating control of aircraft windows, a simple control system based on an autotransformer controlled by a static tap changer has been developed. In addition to the basic tap changer and its control circuits, the system contains protection circuits. The new controller is packaged in a simple plug-in container. A typical design operating from 200 volts at 400 Hz provides 4000 watts at 180 volts at the window (Fig. 1).

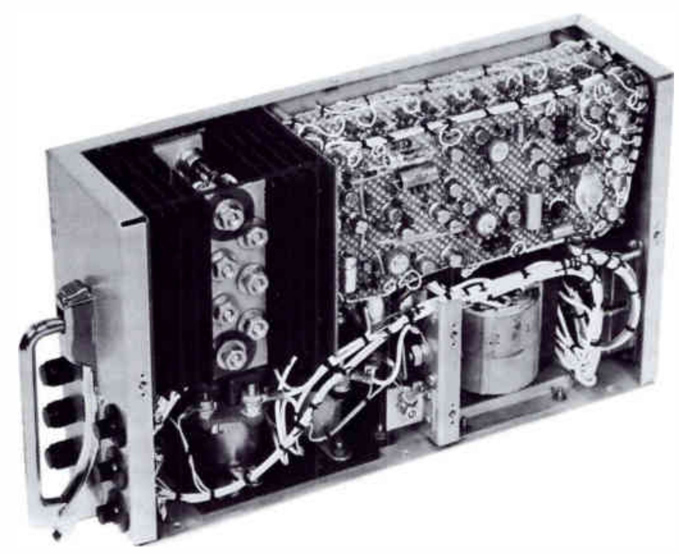
Earlier Systems

Up to now, window temperature has been controlled by on-off controllers, pulse modulation, or phase-back modulation.

An *on-off controller* applies either full power or no power to the window (one cycle every 10 to 20 seconds) to obtain an average power level (Fig. 2). Unfortunately, such operation causes large thermal stresses in the window that can lead to delamination and fatigue cracking. Moreover, on-off systems depend on relays and circuit breakers and have a

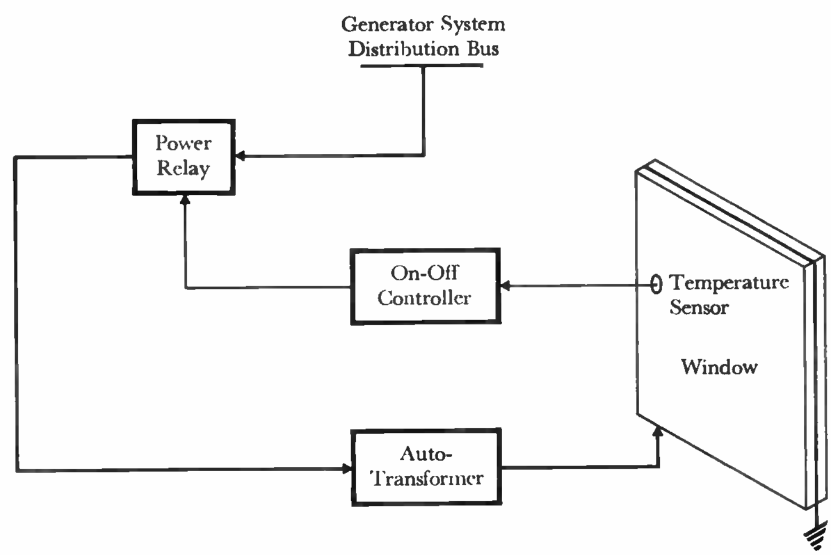
D. E. Baker and H. H. C. Richards are design engineers in the Utilization Systems Department, Aerospace Electrical Division, Westinghouse Electric Corporation, Lima, Ohio.

1



1—Engineering prototype of the static controller for aircraft window temperature is packaged in a simple plug-in container, shown here with its cover removed. This typical unit measures 3 9/16 by 7 5/8 by 12 9/16 inches and weighs 10 pounds.

2

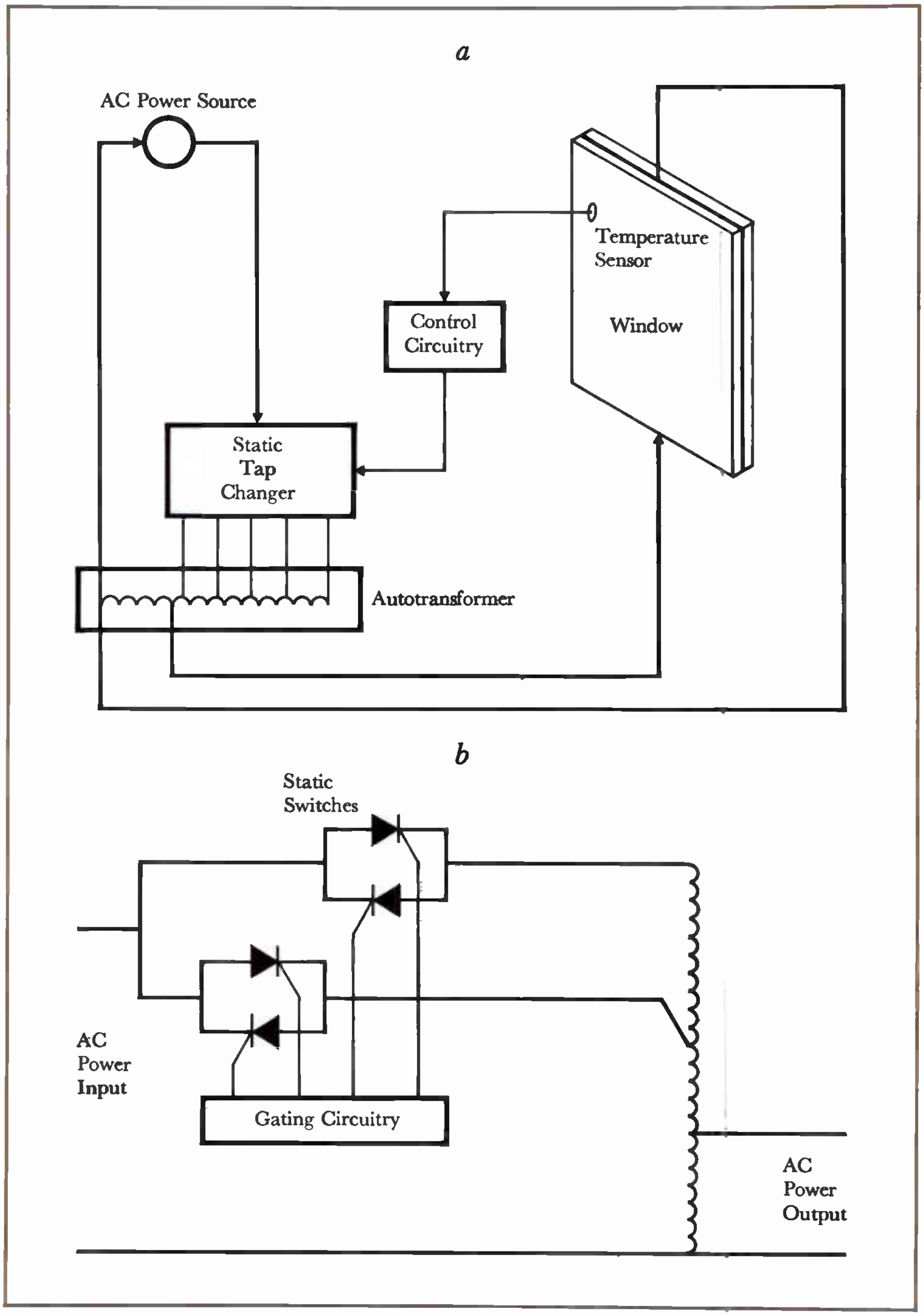


2—On-off controller has provided the simplest window temperature control, sensing temperature at the window and applying either full power or no power to keep temperature near the desired value. However, thermal cycling and overheating are likely to damage windows, so the control system is unsatisfactory for most aircraft.

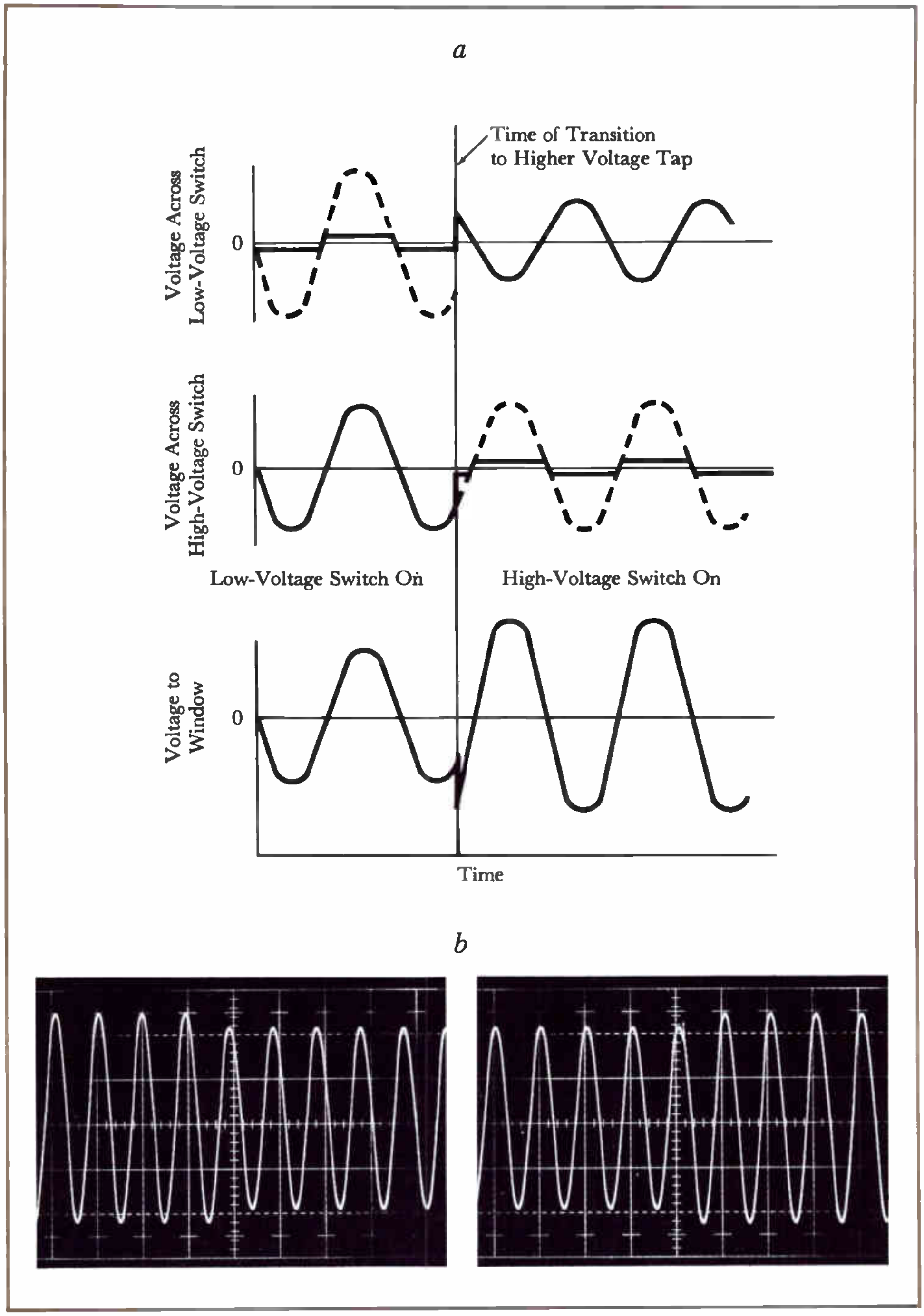
history of failures that lead to window overheating with resultant formation of bubbles in the plastic interlamination. Neither type of damage can be tolerated in the larger aircraft such as the Boeing 747, in which a single window replacement can cost $15,000.

Pulse-modulation systems are static circuits that include a thyristor switch. Although they apply and remove full power more rapidly, they are still on-off systems and have the same disadvantages. In addition, the on-off repetition rate is close to the aircraft generator system natural frequency; when repetition rate and system natural frequency coincide at about 25 hertz, voltage modulation is caused in the aircraft generator system. Consequently, the method has seen little aircraft use.

Phase-back systems also are static circuits, with temperature sensed at the window to control power by firing thyristors at various phase angles of the voltage waveform. Phase-back control eliminates the on-off power problem and the pulsing problem, but firing the thyristors at various points of the voltage waveform instead of at the zero-voltage crossover point chops up the waveform and thereby causes a wide range of harmonics in the input current. Harmonics are introduced whenever the waveform of the current drawn from the generator system distribution bus is not a true sine wave. The lower harmonics such as the third and fifth cause harmonic distortion of the voltage waveform at the distribution bus, while the higher harmonics generate radio-frequency noise. Attempts have been made to remove enough of the harmonics to make the temperature control and the electrical system mutually compatible. The third harmonic is a large part of the problem because its removal requires large heavy filters. No lightweight and electrically stable filter design was found in a computer and test program carried out at the Aerospace Electrical Division. Though phase-back designs with some harmonic and radio noise filtering have been successful in certain aircraft electrical systems, others have caused malfunction of additional loads connected to the ac bus and have had to be removed.



3—(*a*) The new tap-changer control system gives good temperature control without disturbing the aircraft electrical system. Control circuitry provides an error signal from actual and desired window temperature, and a static tap changer adjusts the autotransformer taps accordingly. (*b*) A tap changer is illustrated in simplified form (two-tap unit) to illustrate its operating principle. Tap changing is done on the primary side of an autotransformer. Two thyristors in inverse parallel connection form an ac switch for each transformer tap.



4—(*a*) Voltage waveforms from the simplified two-tap static tap changer of Fig. 3b are shown before and after transition to a higher output power level. Tap change is synchronized with ac voltage wave so that transition results in only a small discontinuity in output when going from a lower to a higher tap; it causes no discontinuity when going from a higher to a lower tap because commutation occurs naturally at the zero crossover point. (*b*) Actual waveforms of an operating unit show the pure sine-wave nature of the current drawn from the electrical system during transition from step 4 to step 5 *(left)* and step 5 to step 4 *(right)*. The point of tap change going up shows as a small discontinuity.

With this background of knowledge, the Westinghouse engineers sought a new approach to satisfy the many requirements for window heat control while guaranteeing compatibility with the electrical system. The result is the static tap-changer system.

Static Tap-Changer System

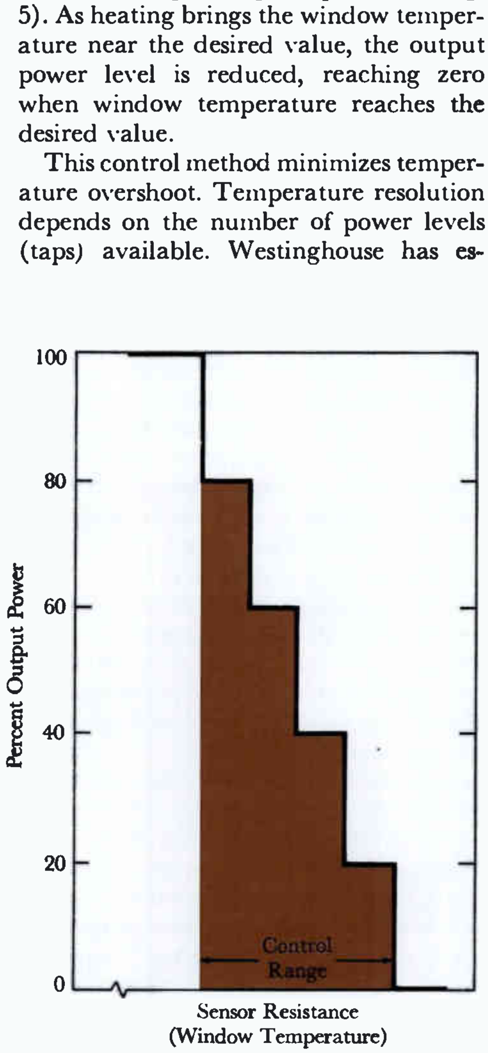
By changing taps on the primary side of the autotransformer, the new system controls power to the windshield in small steps without disturbing the aircraft power system and with little radio-frequency interference generated (Fig. 3a). Each tap is connected to two inverse-parallel-connected thyristors used as an ac switch (Fig. 3b). When a switch is gated (turned on), the autotransformer is excited by the ac system input voltage, and the output voltage is applied to the window. Since the thyristor switch is either full on (360-degree conduction) or full off, the currents drawn from the ac system are very nearly pure sine waves. When more power is required, a different thyristor switch is turned on and the ac line voltage excites the autotransformer at a higher level. When a higher power thyristor switch is turned on, the previously conducting switch is turned off.

Window temperature is sensed by a resistive sensing element embedded in the window. Its signal is used by the control circuitry to generate a dc error signal, and a simple system of error voltage level detectors operating with a single gate-drive oscillator triggers the thyristor switches as needed to keep the window at the set temperature. A synchronizing circuit insures that the tap change is made at the correct time point on the ac voltage wave. If a tap change to higher power level were made at the zero voltage crossover point, the thyristor tap being shut off would not have sufficient junction clearing time; the tap turned on would cause it to stay on, resulting in shorted turns and loss of control. The problem is prevented by making the tap change before the zero crossover point by a time slightly greater than or equal to the clearing time of the thyristor.

Transition to a higher output power level causes only a small discontinuity in output voltage and input current (Fig. 4). Switching is done at the zero crossover point at all times except during a tap change to eliminate the need for harmonic distortion filtering.

Control circuitry varies to suit the user's needs, but one feature, proportional control, is required for all practical window temperature controllers. The system is so designed that output power is inversely proportional to window temperature near the desired operating temperature (Fig. 5). As heating brings the window temperature near the desired value, the output power level is reduced, reaching zero when window temperature reaches the desired value.

This control method minimizes temperature overshoot. Temperature resolution depends on the number of power levels (taps) available. Westinghouse has established with control users that three to five taps are sufficient for good control without system disturbances.



5—Proportional temperature control reduces power output of the autotransformer as window temperature approaches the desired value. It minimizes temperature overshoot and thus safeguards the window from overheating and thermal stress. The curve is for a five-tap system. Ramp warmup also is provided.

With proportional control in the static tap changer, the tap-changing process is not a periodic function and has no definite repetition rate. As a result, no detectable voltage modulation appears in the electrical system.

A ramp warm-up function is usually provided to protect windows from breakage and delamination caused by thermal shock and temperature overshoot. When the unit is turned on, the control increases the power in steps at a predetermined rate. It does not allow full power to be applied to the window until three minutes has elapsed; the proportional control takes over if the window reaches normal operating temperature at any time during the warm-up period.

Other optional features that can be provided are windshield overheat detection and shutdown circuits, shorted- and open-sensor detection and shutdown circuits, preflight confidence tests, adjustable temperature range (internal adjustment), and adjustable output voltages for variation in windshield parameters (several output connections on the transformer).

The window temperature control can be manufactured in many ratings and configurations. The standard configuration is a 3/8 short ARINC package, which is a plug-in rack-mounting type. It can be designed for natural convection cooling or forced-air cooling. Construction is normally of modular subassemblies for easy maintenance.

Test Program

System tests have been run with a 4-kW unit on single 40- and 60-kVA generators by stepping the tap changer up and down with various preloads on the generator. No change in voltage modulation was detected on the system during tap changing. The system was loaded and unloaded and faults cleared to determine if voltage transients caused any disturbance in the tap changer; none was detected. Moreover, an ac voltage was induced in the temperature sensor leads without causing any disturbance.

In conducted and radiated radio noise tests, the requirements of stringent specifications such as Boeing Specification D6-15060 were met with only small lightweight filtering or suppression devices. Approximately 0.75 pounds of filtering is required for the tap-changer control, while 12 pounds of filtering is required for comparable performance from a phase-back unit.

More liberal requirements (about 10 dB above the upper limit in specification Mil-I-6181) could be met without any filtering or suppression.

Audio noise tests were conducted with the unit operating on the various taps. No sound power level above 54 dB was detected at any frequency range or with the broad-band spectrum measurement.

For life testing, the unit was cycled up and down through each step for 30,000 cycles without malfunction.

Some testing has been conducted for component failure analysis of the power semiconductors. No change occurs if an SCR becomes shorted on the tap in operation; when the tap is changed, however, a short circuit occurs, immediately tripping the input protective breaker. The remainder of the circuit is so designed that component failures cause the controller to go to zero output power.

Conclusion

The best way to control heating power to a window is with the static tap-changer system. It gives the following advantages: minimum electromagnetic interference and harmonic distortion with minimum weight, maximum power system stability, efficiency greater than 95 percent, minimum temperature overshoot when used with proportional control, fast response to power needs, ability to use any leading or lagging power factor, and reliability greater than 36,000 hours mean time before failure (in a five-tap unit).

In addition to its use in a window heat controller, the static tap changer can be applied anywhere ac voltage control is needed. It has been used successfully as a regulator for a three-phase regulated 100-ampere ac-to-dc converter; other potential applications include ac line regulators and motor speed controllers.

Electric Power Systems for Large Arc Furnaces

L. C. Elliott

Steelmaking arc furnaces have increased in size until they may present major problems (both to the furnace system and to the electric utility supplying power) in flicker, transient overvoltages, and instability. The problems can be prevented or corrected by proper analysis of the circuit and proper application of corrective equipment.

Just ten years ago a 100-ton arc furnace drawing about 25 MVA was considered a large furnace; today, a number of furnaces of 150- to 250-ton capacity with power inputs ranging up to 85 MVA are in use, and units twice as large are being seriously considered. Not only is size increasing rapidly, but also the *number* of arc furnaces used for steel production is increasing in the United States.

One of the two major reasons why steel companies are building more capacity in arc furnaces is that the cost of producing steel with arc furnaces has become more competitive with the costs of the other processes and, in many situations, is less. The other is that air pollution is more easily controlled with arc furnaces than with the other types.

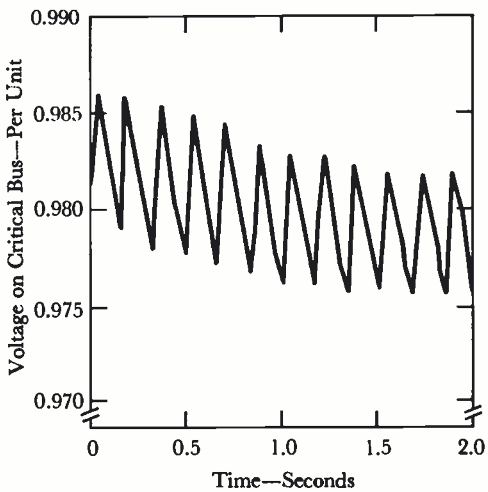
Electric utilities generally consider arc furnaces desirable loads because of the large amount of power required and the high load factor. The furnaces do, however, present a number of problems to the utility. The melt-down period is characterized by violent fluctuations of current at low power factor that, in turn, may produce large voltage fluctuations, or "flicker." (See *Furnace Operation*, page 148.) The fluctuations are random and vary in frequency and magnitude. If not corrected, the fluctuation can be objectionable to other customers on the system by causing production disruption in manufacturing processes, fluctuations in television vertical-hold circuits, and annoying lamp flicker.[1]

Moreover, overvoltages high enough to cause failures in power transformers, voltage regulating transformers, buffer reactors, and lightning arresters can appear in furnace circuits as the result of harmonic resonance. Circuits with large shunt capacitor banks (usually part of the circuitry of large arc furnaces for power factor correction) are susceptible to a harmonic resonant condition, the result of switching operations that cause the circuit to oscillate at its harmonic frequency.

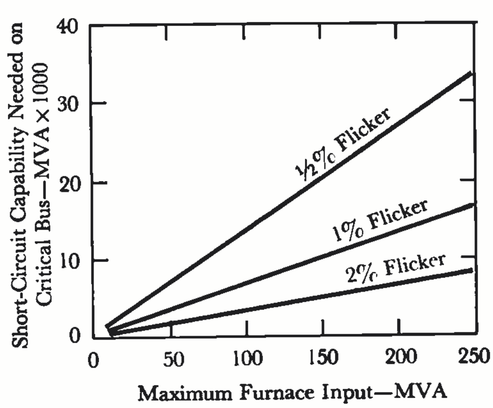
Finally, when a synchronous condenser is in the circuit, improper circuit parameters can cause hunting or instability of the condenser.

None of the problems are insurmountable. A detailed system study can determine the design parameters of an existing or proposed system and identify the corrective or preventive measures that will provide satisfactory operation.

L. C. Elliott is Transmission Consultant, Power Systems Planning, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.



1—Flicker voltage level on the utility's critical bus can be predicted with a computer dynamic stability program. The results illustrated in this example are for a furnace loaded for 0.12 second and then unloaded for 0.05 second to produce a flicker rate of six cycles per second. The resulting voltage change is about 0.8 percent. For about 1.4 seconds there is a general voltage sag of approximately 0.3 percent during this type of operation.



2—Compensation is needed in the electrical systems of practically all large arc furnaces. These curves show estimated short-circuit capacity that would be needed on the critical bus to reduce voltage change on the bus to one-half, one, and two percent for furnace load swings in various sizes of typical furnace systems if no compensating equipment were applied. (Base-load power factor is corrected to near unity, but the load swings are considered to have 75-percent power factor.)

Flicker as It Affects the Utility

The main concern of the utility supplying an arc furnace is flicker. The amount of flicker allowable is directly related to the magnitude and frequency of the voltage fluctuations; however, although a great deal of research has been done on the problem, the amount allowable from an arc furnace load is an elusive quantity because of the random nature of both the voltage and the frequency.

The severe voltage fluctuations all occur during the melt-down period, seldom at a rate of less than one per second. As a molten pool forms, a cyclic flicker occurs at a lower current magnitude. Its random frequency is usually between two and eight cycles per second with excursions up to fourteen cycles.

Permissible voltage fluctuation for eight cycles per second is about 0.5 percent; for one cycle per second it is about 1.2 percent.[2] Most utilities approach the problem conservatively because of the difficulties in making corrections after the equipment has once gone in service. They usually require that the design criteria for the flicker level on their critical bus be one percent or less for the maximum voltage excursions. That restriction is a realistic goal.

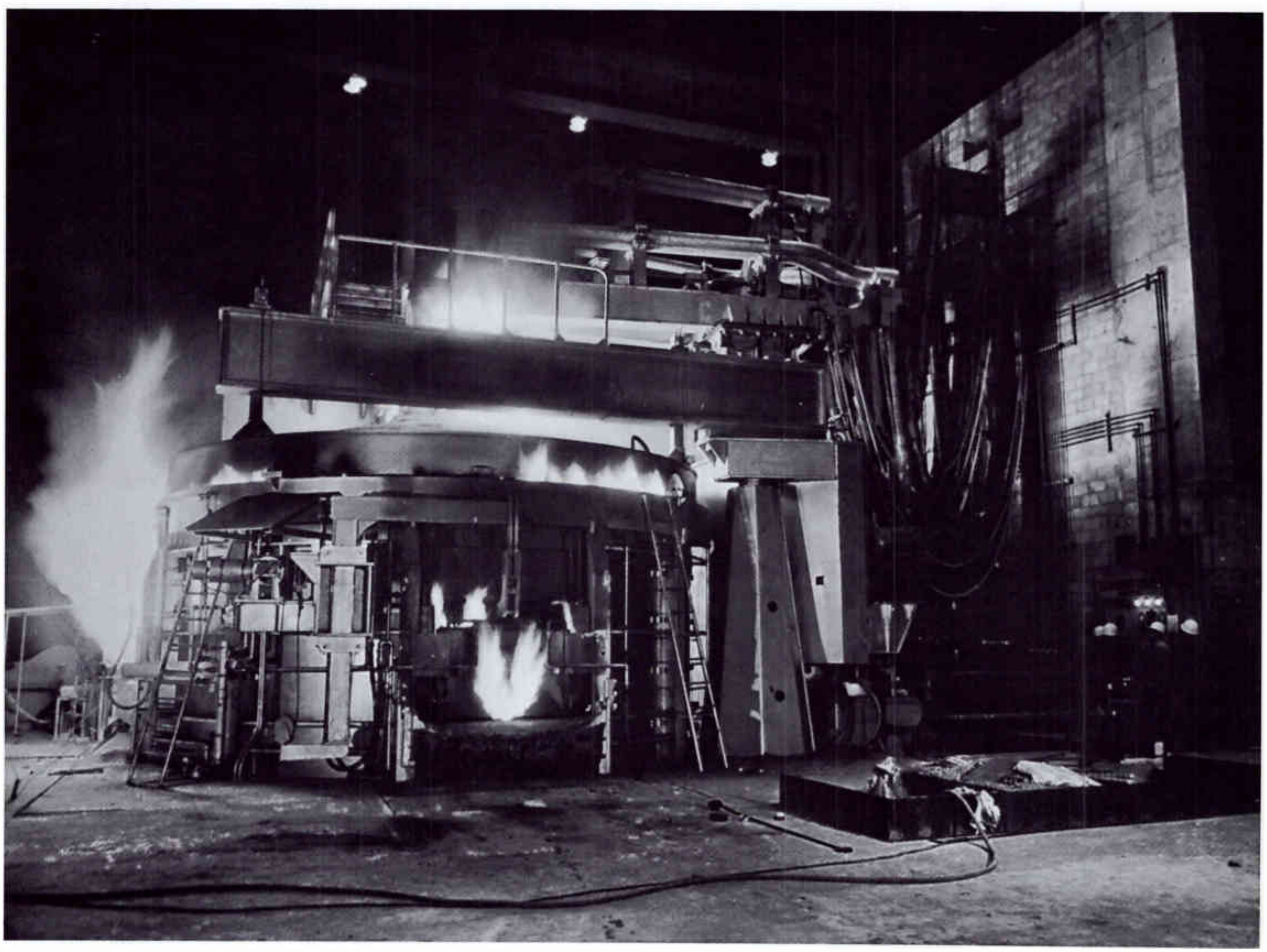
The voltage levels can be predicted for various furnace conditions with a computer dynamic stability program (Fig. 1).

Furnace Electrical Characteristics

Until a few years ago, it was common to connect the furnace electrical system directly to the utility system with little or no compensation. The utility could usually handle the loads with a minimum of problems. As furnaces have increased in size, however, it has become increasingly difficult for the utility to supply the large var requirements and to tolerate the fluctuating load; few, if any, utilities can allow a large arc furnace to be connected without some type of major compensation in the furnace electrical system. Estimated short-circuit capacity that would have to be available on the critical utility bus is shown in Fig. 2. (The critical bus is the first bus in the utility system having loads for which voltage fluctuation might pose problems.)

A typical furnace circuit with compensation is diagrammed in Fig. 3. The furnace is energized at low voltage through a furnace transformer. Since power input to the furnace is a function of the transformer's secondary voltage, the voltage is varied to vary furnace input. In the past the furnace transformer included a no-load tap changer for changing voltage, but in recent years load tap changers have been used either in the step-down transformer or in a separate regulating transformer as shown in the diagram.

The arc in an arc furnace is a nearly pure watt load, but the furnace leads, furnace transformer, regulating transformer, buffer reactor, and step-down transformers all are large blocks of reactance. Power factor is about 65 percent, so the



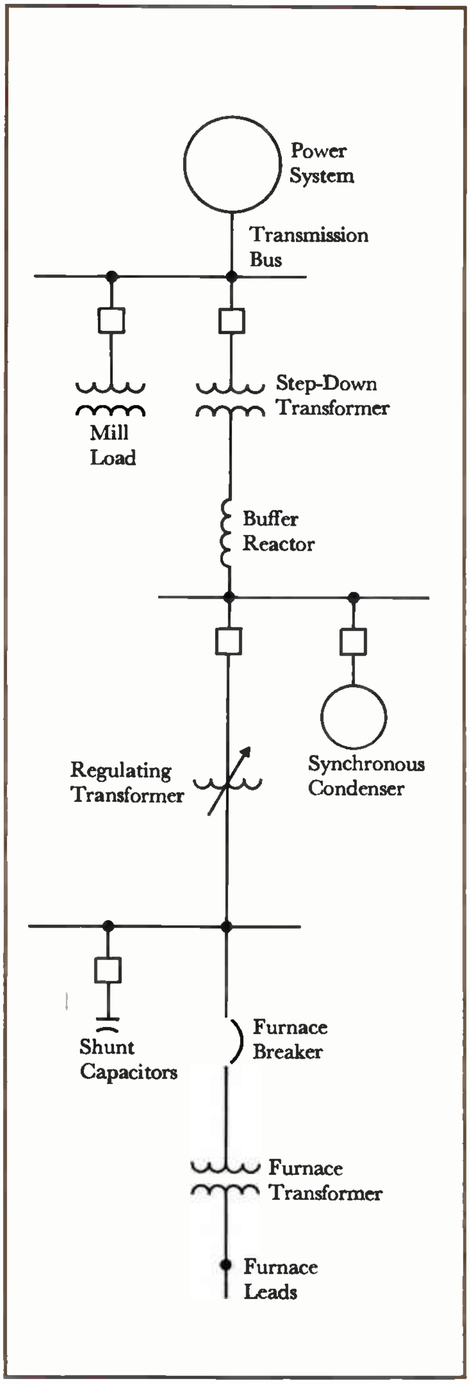
This 200-ton steelmaking arc furnace typifies the large furnaces increasingly used by the steel industry. Power requirements of such furnaces are large, and wide power demand fluctuations are inherent in their operation.

var requirements of the furnace system are greater than the watt load on the furnace. Also, the erratic furnace load fluctuations cause erratic changes in the var requirements of the system, which directly affects the flicker levels on the utility system. These large var requirements must be supplied either by the utility or in the mill. If they are supplied by the utility, the lines and transmission apparatus must have enough capacity to carry the vars. If they are supplied in the mill, switched shunt capacitors are often used to supply the greater portion of the base var load and a synchronous condenser to supply the remainder of the base var requirements and absorb the major portion of the furnace load swings. This arrangement restricts requirements on the utility to the watt base load and only a portion of the furnace load swings.

Synchronous Condenser

The base load vars carried by the synchronous condenser can be maintained by proper adjustment of the condenser terminal voltage, but the division of the var load between the utility system and the condenser on var swings is a function of the ratio of the synchronous condenser subtransient reactance and the system reactance[3] (Fig. 4). The data in the figure can be applied only for load variations of short duration (no longer than two or three cycles) because the relationship is based on the subtransient reactance. For longer var changes, the var division depends on the ratio of machine transient reactance to system reactance.

The condenser also absorbs a share of the watt swings, for during a swing there is a small change in frequency and the condenser acts as a synchronous generator. The division of watts between condenser and system is determined by the ratio of the *H* constant of the condenser and the effective *H* constant of machines in the rest of the system. Here again, the condenser can only supply watts to the furnace for swings of a very few cycles because it soon loses its ability to produce watts. For swings lasting longer that four or five cycles, the condenser initially picks up a portion of the watt swing and then drops all of the watts, with the system absorbing the complete watt change.



3—A typical method of providing compensation in an arc-furnace circuit is with switched shunt capacitors and a synchronous condenser. A buffer reactor is used to make the reactance of the utility system high compared with the condenser subtransient reactance, forcing the condenser to pick up the major portion of the var swings.

To be able to supply a load of this magnitude, the utility must have substantial capacity with low impedance. When the reactance of such a utility system is very low and approaches that of the synchronous condenser, it can be seen from Fig. 4 that the utility takes a large share of the var load. Since the flicker level on the utility bus is, to a large extent, a function of the var flow from the system, the utility will be subjected to undesirable flicker. Installation of a buffer reactor, as shown in Fig. 3, can increase the utility system reactance as seen by the furnace system and condenser, thereby forcing the condenser to take a larger share of the var swings and, in turn, reducing flicker. The magnitude of the flicker voltage level that can be tolerated, the reactance of the utility system, and the reactance of the selected condenser determine the amount of reactance needed in the reactor.

The amount of power that can be delivered to the furnace is limited by the impedance of the furnace circuit components. One method of increasing power is by raising system voltage, so some steel companies are using furnace transformers with a 34-kV primary. However, rotating machinery of that voltage is not presently available, so the synchronous condenser cannot be connected directly to the furnace transformer primary circuit. Probably the best solution is to connect the condenser to the circuit through a transformer (Fig. 5a). A disadvantage, however, is that the reactance of the combination of condenser and transformer will have increased, reducing the condenser's capability to pick up the var swings of the furnace. Reactance of the buffer reactor then must be increased to force the condenser to accept the swings. Increasing the reactor size, of course, increases the system impedance to the furnace and, in a large installation, could reduce furnace power input. Adding the transformer also increases the system's var requirements, which must be supplied by the condenser or by additional shunt capacitors.

Another method of connecting the condenser to the system is through a third winding of the step-down transformer

(Fig. 5b). Var requirements are somewhat lower than in the previous method, but there is one major disadvantage: although the high-voltage winding of the step-down transformer can act as a buffer, there is seldom enough reactance in the winding to reduce the flicker level on the utility bus to an acceptable level. If a reactor is required, it then must be in the primary circuit of the transformer and so must be an oil-filled unit at the transmission voltage.

Series Capacitor

If the circuit is such that a large buffer reactor is impractical, the reactor can be eliminated or reduced in size by installing a series capacitor in series with the synchronous condenser.[3] The capacitor reduces the effective reactance of the machine, thereby decreasing the reactance ratio. The ratio then is $(X_m-X_c)/X_s$, where X_m is condenser subtransient reactance, X_c is capacitive reactance of the capacitor, and X_s is system reactance. This arrangement enables the condenser to absorb a larger share of the reactive variations of the furnace load.

Studies performed on digital computers with dynamic stability programs can determine the magnitude of voltage fluctuations on selected critical buses during various furnace load changes. Further studies then can show the effectiveness of corrective equipment (Fig. 6).

Addition of a series capacitor to such a circuit as that in Fig. 5b can present some problems, for it causes low-frequency harmonics to flow in the system following load changes. When a series capacitor is used to partially cancel the inductive reactance of any circuit at system frequency, there will be an electrical natural frequency at something less than the system frequency. Such oscillations are referred to as "subharmonic resonance." For a circuit with a single series capacitor, as in the system under consideration, the value of the subharmonic frequency, f_n, can be determined from the following equation:

$$f_n=f_0\sqrt{X_c/X_L},$$

where f_0 is the normal system frequency, X_c is the series capacitor reactance at system frequency, and X_L is the total inductive reactance of the system in series with the capacitor.

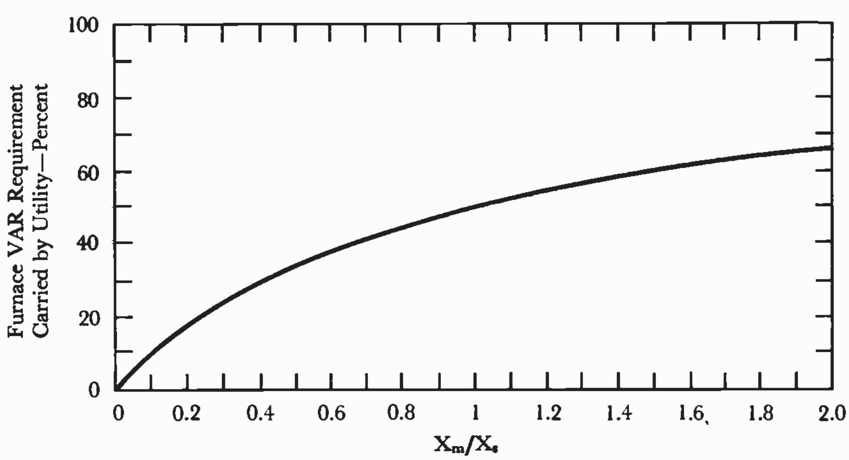
It is evident from the above equation that when the series compensation equals the inductive reactance of the system, resonance occurs at the system frequency. For this reason, it is recommended that the compensation not exceed 75 percent of the condenser subtransient reactance.

During melt-down, the rapid load changes can cause the subharmonic currents to build up until the protective gap across the series capacitor sparks over, taking the capacitor out of the circuit. If the capacitor is not automatically reinserted, the utility then absorbs the larger share of the voltage swings. If the capacitor is automatically reinserted, the gap probably will spark over again during the period of rapid load changes, aggravating the flicker problem for the utility. The currents can be neglected if the system has positive damping.[3] If the system does not have sufficient loss to provide adequate positive damping of the subharmonic transients, damping can be added by installing a resistor in parallel with the series capacitor.

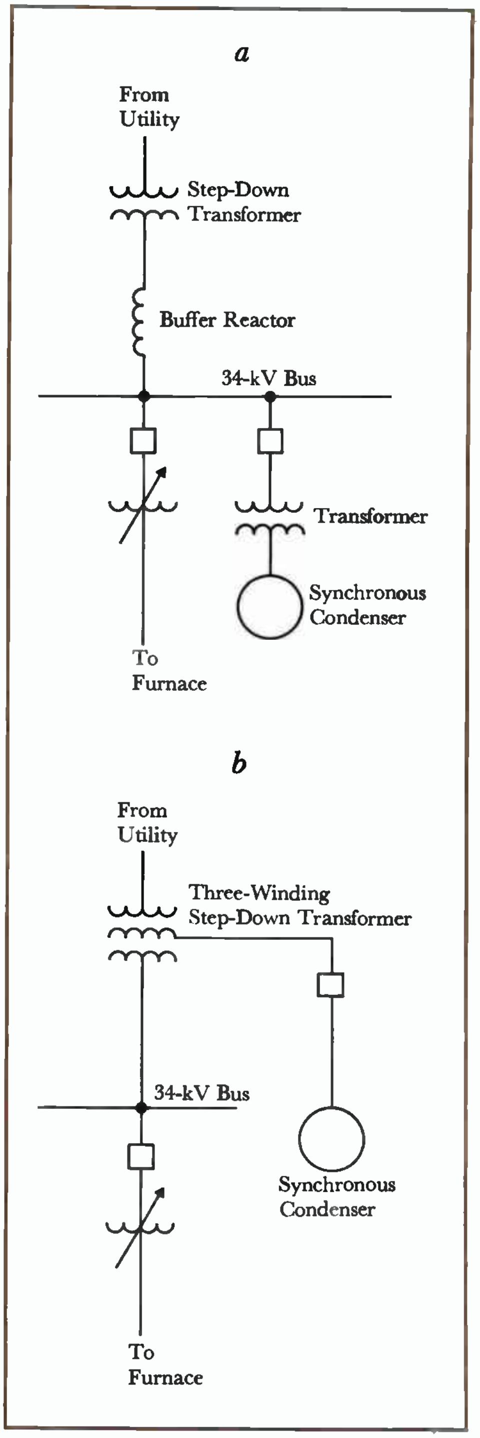
If the furnace and condenser are relatively small by today's standards, the losses in the shunt resistor are small enough that they are not of major concern to the steel company. In a large installation, however, resistor losses make the method uneconomical. To reduce the losses, a filter can be installed to pass subharmonic current and, to a large extent, block current at normal system frequency.

Shunt Capacitors

The large load swings imposed on the condenser cause machine heating, and margin for the swings should be provided. Consequently, the base load of the condenser should be limited to 75 percent of the machine rating. Moreover, it is more economical to supply the base-load vars by shunt capacitors. Normally, enough capacitors are installed to provide most of the var requirements of the system. During the melt-down period, the voltage on the furnace is usually high and the var requirements are high. During the refining period, voltage is reduced, power input to the furnace is reduced, and the var requirements go down. Therefore, the capacitors are usually installed between the regulating transformer and the furnace transformer. Since the corrective



4—Division of var load between the utility system and the synchronous condenser is a function of the ratio of the condenser subtransient reactance, X_m, to system reactance, X_s. Because flicker level on the utility bus depends mainly on var flow from the system, the utility is subjected to an undesirable amount of flicker if its reactance is so low as to approach that of the condenser. A buffer reactor can be installed in the circuit to increase the system reactance as seen by the furnace circuit and condenser.



5—When the synchronous condenser cannot be connected directly to the furnace primary circuit, it can be connected through a transformer (*a*). Another method (*b*) is connecting it through a third winding of the step-down transformer.

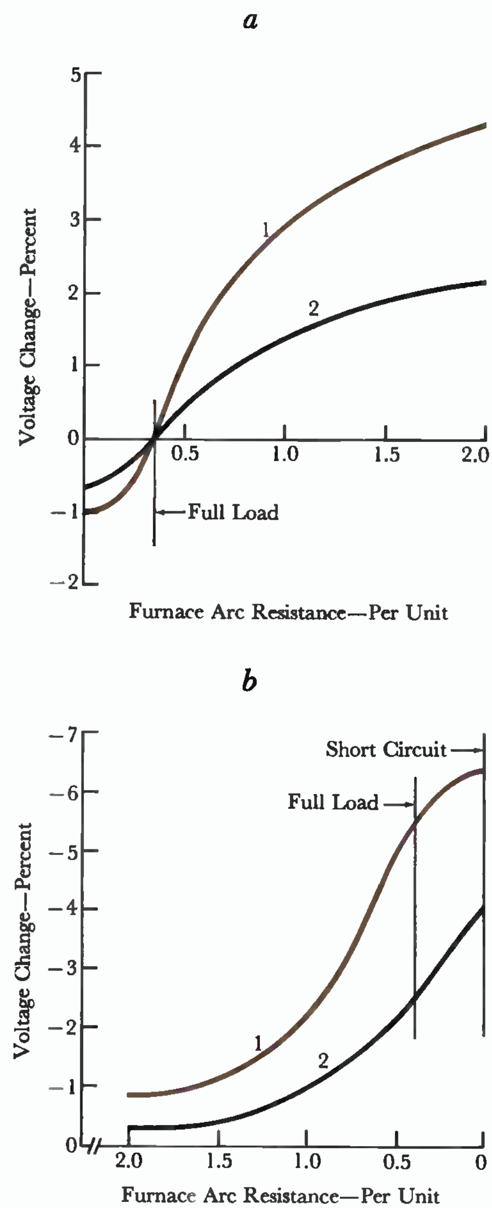
capability of a capacitor varies with the voltage, the var output varies with the requirements, with no need for switching. The tap changer is sometimes incorporated in the furnace transformer, so the capacitors must then be connected to a fixed voltage bus. That arrangement requires switching the capacitors in and out of service to vary the var input to match system requirements.

High overvoltages due to resonance at various harmonic frequencies may occur in the furnace circuit when energizing an unloaded furnace transformer. The shunt capacitors contribute to the resonant condition, and the larger the Mvar size of the capacitor bank the greater the probability of the resonant condition. The overvoltages can be reduced by placing a reactor in series with the capacitor to form a capacitor-inductor filter. Tuning the filter to reject the resonant harmonic frequency reduces harmonic voltage. Another solution is to add a resistor in series with the capacitor bank. The resistor damps the circuit and reduces the overvoltages to tolerable limits. However, that solution is somewhat impractical; since the resistor must carry the total capacitor current, it becomes excessive in size for large capacitor banks. A detailed study of the furnace system on an analog computer or similar device is necessary to determine which harmonics are resonant with high overvoltages and to determine what the characteristics of the corrective equipment should be to reduce the overvoltages.

Stability

Normally, instability of machines on the utility system is not a problem with arc furnaces because the machines are large compared with the furnace system and because there is usually considerable impedance between the furnace circuit and the machines.

If a synchronous machine is part of a furnace circuit with a large buffer reactor, however, the condenser can become unstable during severe load swings. If the swings are large and repetitive with a frequency at or near the natural frequency of the machine, there is a good possibility of the machine being forced



6—Computer studies can show the amount of voltage fluctuation during various load changes with and without corrective equipment. Here the study was to determine the effectiveness of series compensation of a synchronous condenser in a circuit similar to that of Fig. 5b. The curves in *a* show results with the furnace taken from full load to no load and from full load to short circuit: curve 1 is without a series capacitor in the condenser circuit, and curve 2 is with the capacitor. In *b* the furnace was taken from no load to short circuit, again without and with the series capacitor. Inclusion of the capacitor reduced voltage fluctuation materially.

Furnace Operation

An arc furnace for the manufacture of steel is essentially a steel shell with a spheroidal bottom, lined with refractory material. It has a tilting mechanism and lip for pouring. The diameter of large furnaces now being installed is between 22 and 26 feet.

The roof is arched and is lined with refractory material; three holes admit the graphite electrodes, one for each phase. Roof, electrodes, and superstructure can be lifted up and swung to one side so that the furnace can be charged.

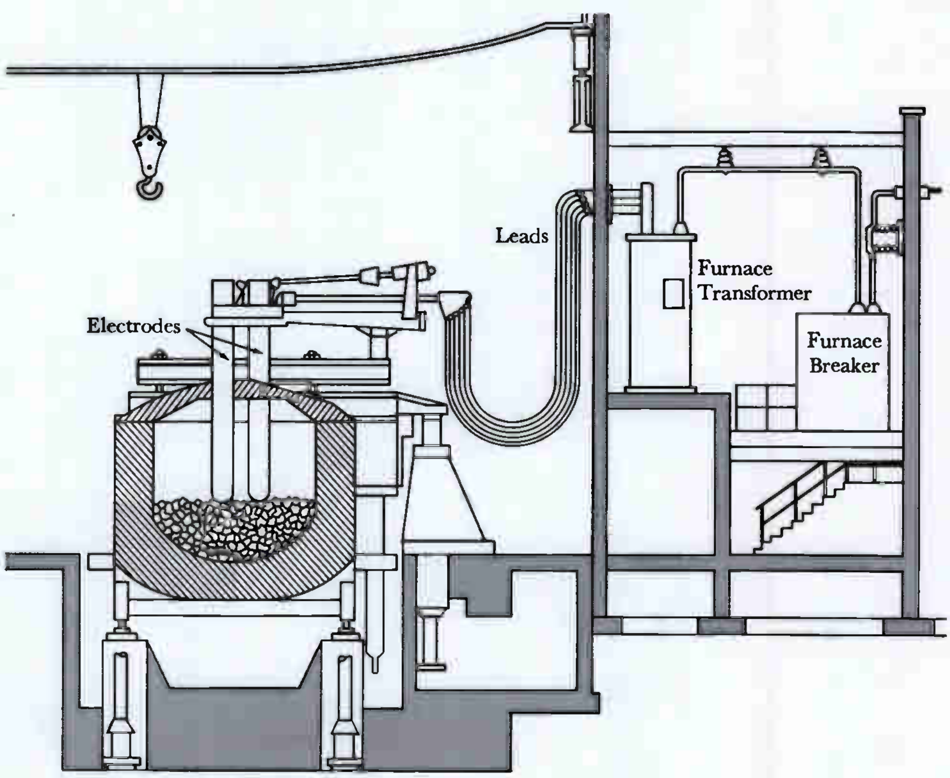
The electrodes are typically about 24 inches in diameter. They are usually molded in sections six to eight feet long and threaded at each end so that a new section can be screwed on as the other end wastes away, thus allowing the electrodes to be continuously fed to the arc. Electrodes are raised or lowered by remote automatic control that adjusts each electrode's position to hold circuit impedance constant and thus, as nearly as possible, maintain constant current.

Power is supplied by a furnace transformer connected to the electrodes by a number of conductors, which are water cooled for the largest furnaces. Transformer secondary voltage varies between 300 and 800 volts, depending on the size of the furnace and the operation being performed. Voltage change is accomplished with a load tap-changing transformer or regulator in the primary circuit or with no-load taps in the furnace transformer.

After the furnace has been charged, usually with steel scrap, the operator energizes the circuit with the electrodes in the withdrawn position. They are then lowered under automatic control until they contact the charge and an arc is ignited; the control then attempts to maintain constant impedance in the circuit. In some methods of operation, the furnace transformer secondary voltage is at a high level during the initial part of the melt-down for maximum power output. Constant current cannot be maintained until a significant quantity of the charge has been melted, because of the changing shape of the mass of scrap as it liquifies. The arc is quite irregular and the load fluctuates wildly—from short-circuit when the electrodes contact the metal to no-load when the arc is extinguished. Since scrap is usually bulky, the furnace must be recharged one or more times during melt-down.

When the charge has been partially melted, the arc becomes steadier with a fairly constant current. After complete melt-down, a refining period is carried out with a very steady arc. Voltage and, therefore, current is reduced to a low level during refining because the power requirement is little more than the loss of heat from the furnace.

The time required to make a heat of steel varies considerably, depending on the size of the furnace and the type of steel. Total time may be as short as 90 minutes for a low-grade carbon steel requiring little refining, with 60 to 65 minutes of that used for melt-down. For higher grade steels, it may be as long as eight or nine hours with a melt-down time of two and a half hours.



out of step. If the reactance of the buffer reactor is less than the reactance of the furnace transformer, regulating transformer, and furnace leads, the system usually is stable.[2] When a series capacitor is part of the condenser circuit, the machine tends to be more stable since synchronizing power into the machine is increased. It is advisable, in any case, to perform a stability study on any proposed large furnace installation to determine the possibility of instability of nearby synchronous machines.

Multiple-Furnace Operation

Only single-furnace operation has been considered so far in this article, but most steel producers have more than one furnace. With two or more furnaces operating in parallel, the magnitude of the voltage fluctuations obviously is greater than with one furnace. It is also reasonable to assume that few fluctuations occur at the same instant in all furnaces (although that may happen on occasion). Attempts have been made to arrive at a multiplying factor that can be applied to the flicker voltage level of one furnace to obtain the flicker level in multiple-furnace operation, but most of the work is inconclusive. The voltage swings are so irregular and random in magnitude and occurrence that it is difficult for the analyst to determine how much worse one condition is than another. Also, operating procedures of various companies vary. To keep electrical demand down, some operators never melt down in two furnaces at the same time; there is then only a small contribution to flicker from the refining furnace. Others pay no attention to demand and start melt-down on any furnace whenever it is ready, a practice that obviously affects magnitude of the voltage fluctuations.

Investigations have shown that the resultant rms voltage fluctuation is the square root of the sum of the squares of the individual rms voltages.[4] Moreover, when N furnaces of equal size are operated in parallel, the magnitude of the voltage fluctuation is the fluctuation produced by one furnace multiplied by a constant K_f, which is equal to $\sqrt{N}$. The investigators also found that the flicker level is reduced if one or more furnaces are on the refining cycle and that the fluctuation of a refining furnace can be considered about half that of a furnace in the melt-down cycle. Assuming, therefore, a mill with several equal sized furnaces, some of which are on the refining cycle, the multiplier becomes:

$$K_f = \sqrt{N + (0.25)N_r},$$

where N is the number of furnaces on melt-down and N_r is the number of furnaces on the refining cycle. Fig. 7 demonstrates the increase in flicker voltage level for one, two, and three furnaces, all on melt-down.

The investigation did not include the problem of flicker level of two or more furnaces of different sizes operating in parallel. However, it can be estimated with a similar routine:

$$K_f = \sqrt{N + F_1^2 + F_2^2 \cdots + F_n^2},$$

where N is the number of largest furnaces of the same size and F is the per-unit MVA of smaller furnace sizes. For any furnace on the refining cycle, one-half the per-unit size should be used in this equation.

Conclusion

Because a large arc furnace's electrical supply system presents a number of problems to the furnace system itself and to the utility, a detailed system study should be performed to determine proper design parameters. The study should include steady-state watt and var flow, flicker voltage levels, stability of the synchronous machine (if used), harmonic overvoltages, and application of the series capacitor (if used).

None of the problems are insurmountable. Proper application of corrective equipment can make the system perform to the satisfaction of the steel company and the utility.

Westinghouse ENGINEER **September 1969**

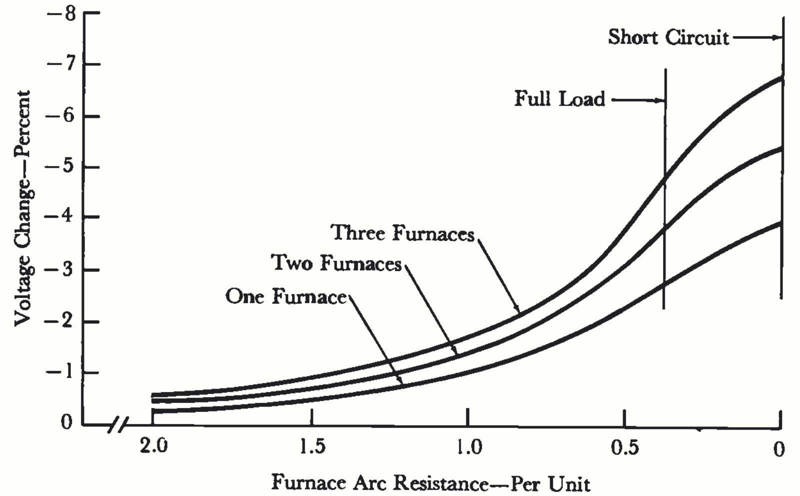
REFERENCES:

[1]AIEE System Planning Subcommittee, "Survey of Arc Furnace Installation on Power Systems and Resulting Lamp Flicker," *Transactions* 57-9, pp. 170-181, Sept. 1957.

[2]D. M. Sauter, "Voltage Fluctuations on Power Systems," *Electric Utility Engineering Reference Book, Distribution Systems*, Vol. 3, Westinghouse Electric Corporation, p. 349.

[3]R. L. Witzke and E. L. Michelson, "Technical Problems Associated with the Application of a Capacitor in Series with a Synchronous Condenser," *AIEE Transactions*, Vol. 70, pp. 519-525, 1951.

[4]J. A. S. Hilditch and I. G. Harvey, "Simulation and Summation of Supply Voltage Fluctuations Due to Arc Furnaces," *Abnormal Loads on Power Systems*, Institute of Electrical Engineers, London, p. 78.



7—Voltage fluctuation on the critical bus increases when more than one furnace is operating. It can be expected to change about as shown here for one, two, and three furnaces, all in the melt-down part of the operating cycle. The curve is that for the series-compensated furnace electrical system represented in Fig. 6b (curve 2).

Developments in Circular Core-Form Transformers

Gordon R. Monroe

Today's power transformers are built to withstand the mechanical stresses imposed by system short circuits, and to distribute impulse voltages evenly along the winding to minimize electrical stress on insulation.

Recent improvements in core-form circular-coil transformers typify the continuing efforts in development and refinement of power transformer design and construction. Core-form circular-coil transformers built by Westinghouse include the self-cooled ratings ranging from 501 through 60,000 kVA, with a maximum BIL of 900 kV. For all applications, the windings are liquid-immersed so that, with the various combinations of forced-oil and forced-air cooling, the above range of self-cooled power ratings can be extended as much as 66⅔ percent.

The main application for this medium-power range of transformers is in substations. With the growth of power system size and complexity and the increasing emphasis on continuity of service, substation transformers are subjected to more frequent and more severe short circuits. Although not all medium-power units are located on an infinite bus capable of maintaining voltage on a short circuit, the tendency in system design is certainly in that direction, so these transformers must be designed to withstand the mechanical forces that will result. The core-form transformer has kept pace with these requirements by continued improvements in the bracing of the core and coil assembly, improved processing of coils during manufacture, and the development of insulating materials with improved mechanical strength.

From an electrical standpoint, the most severe stresses on transformer insulation are the impulse voltages that result from switching surges or lightning strokes. Unless initial impulse voltages are distributed uniformly along the winding, the winding insulation is severely overstressed near the line end. New winding insulation and winding configurations with high series-capacitance characteristics have improved impulse voltage distribution.

Other improvements that have been recently introduced to the core-form transformer include new methods of drying and processing insulation to improve its dielectric strength, cast epoxy bushings, and a new load tap changer design.

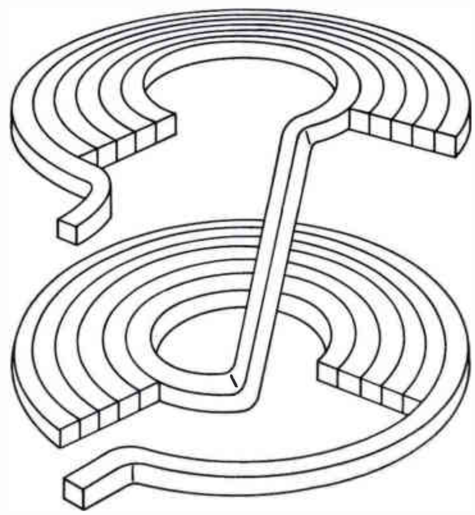
New Core and Coil Construction

Although transformer standards specify the magnitude and duration of a short circuit that a transformer must withstand, the number of short circuits has never been stated or defined. The usual practice is to verify short-circuit strength of a transformer through the successful completion of a single test. However, the real problem of providing adequate short-circuit strength for a modern power transformer is one of designing the transformer to withstand multiple system short circuits. Since it is not practical to give every transformer multiple short-circuit tests, each prototype or representative design is tested for adequacy by a complete series of short-circuit tests.

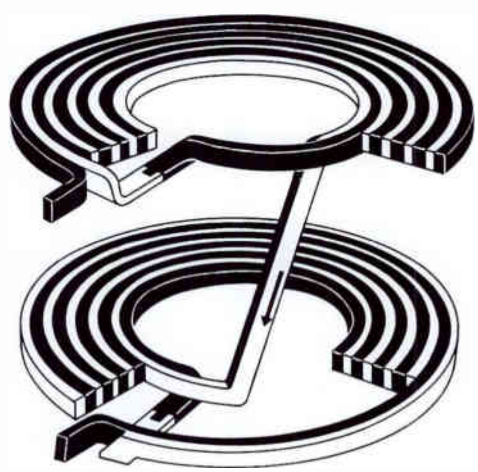
To provide adequate short-circuit performance, a method of designing and processing of thė coils for core-form transformers is now in use that, along with verification of the strength of the coils during manufacture, assures reliable and trouble-free operation:

First, the short-circuit forces are accurately calculated for each transformer. The methods of calculation have been verified by extensive tests at the Westinghouse High Power Laboratory. The coils

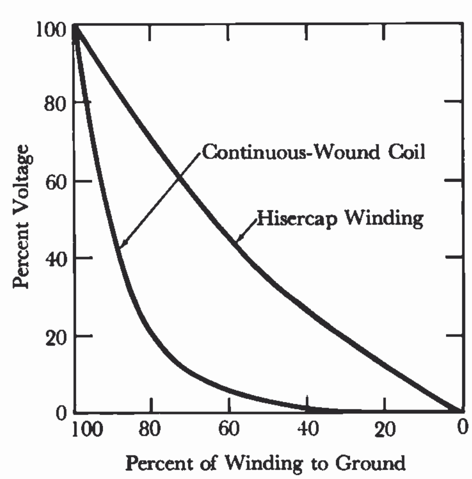
a



b



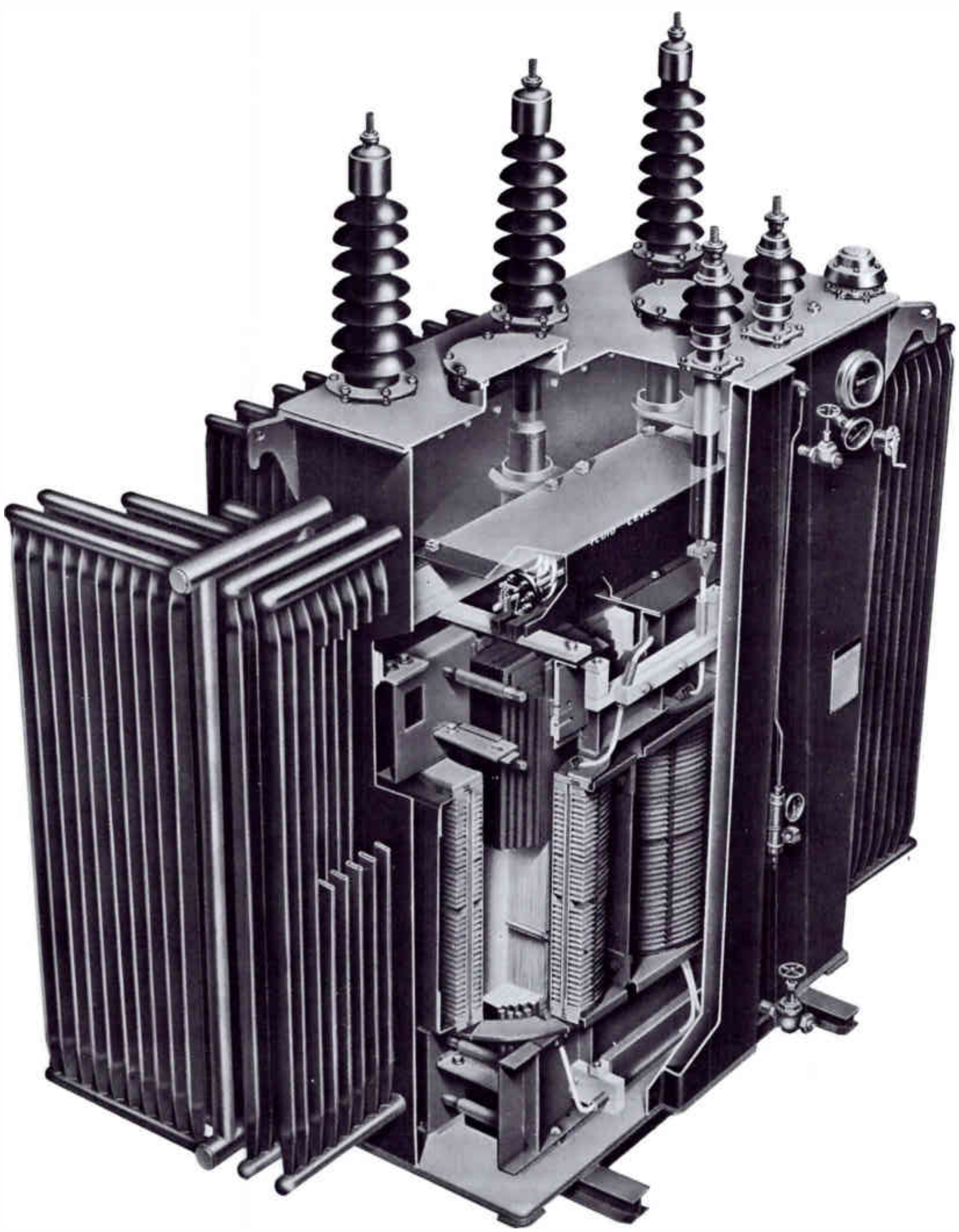
c



1—(*Left*)—Initial impulse voltage distribution is improved with Hisercap coil construction. These cutaway sketches compare the winding configuration for continuous wound coils (*a*) with interleaved construction of a Hisercap coil (*b*). The improved distribution of voltage with Hisercap construction (*c*) is shown for a typical high-voltage coil.

***Right*—Cutaway view of typical circular core-form transformer illustrates coil and core construction.**

G. R. Monroe is Section Manager, Internal Core Form Development Section, Transformer Division, Sharon, Pennsylvania.
The author wishes to acknowledge the contributions of E. P. Nason, Section Manager, Tap Changer Development Section, and C. L. Moore, Section Manager, External Core Form Development Section.



are designed and manufactured to withstand these calculated forces.

To verify the ability of the coils to withstand their own internally generated forces, they are pressed in a hydraulic press with a pressure equal to the calculated short-circuit forces.

And finally, a new method of coil clamping is used to prevent relative movements between the primary and secondary coils; pressure rings at the top and bottom of the coil assembly provide uniform pressure around the entire coil periphery.

Two new designs of pressure rings have been developed to improve coil support and reduce stray losses. One is a ring made by winding glass filaments impregnated with epoxy resin into a mold and then curing to form a solid homogeneous flat ring having a strength equivalent to steel. These rings have excellent dielectric properties and become part of the coil insulation structure. They are used on transformers with ratings up to about 10 MVA and 69 kV.

For transformers above these ratings, the ring is made by winding strips of thin low-loss silicon steel bonded with epoxy resin into a large flat ring. The high-permeability steel laminations are parallel to the leakage flux lines at the ends of the coils and provide a low-reluctance and low-loss path for the leakage flux to flow back to the main core. This tends to straighten the flux lines and reduce the eddy current losses in the coils and supporting members.

The final proof of the adequacy of a transformer design lies in its actual performance in service. Obviously, not every transformer can be short-circuit tested. However, full-size prototype units, typical of the units being manufactured, have been tested extensively. For example, a 2000-kVA transformer has been subjected to a series of over 100 short-circuit tests without failure.

Because of the difficulty of conducting tests and the complexity of the test facilities required, the number of tests on larger transformers are limited. One approach is to test one phase assembly of a large three-phase unit. Two short-circuit tests have been made recently on a single-phase assembly of a 25-MVA (self cooled) three-phase transformer. The high-voltage winding is rated at 110 kV delta with 10-percent regulating taps; the low-voltage winding is rated 20 kV wye.

The first test was made on a set of coils taken from a transformer that had been in service; the second test was conducted on one phase of a transformer of identical rating, but with new coils constructed with the latest processes and materials (see *New Core and Coil Construction*). Visual observations were made during the test and high-speed motion pictures were taken. In addition to providing transformer designers with a better understanding of the forces and their effect on coils during short circuits, the tests clearly demonstrated the desirability of recent improvements in manufacturing techniques:

1) The materials used, in addition to having good dielectric properties, must be mechanically stable. This requires drying and dimensional stabilizing at operating temperatures and pressures.

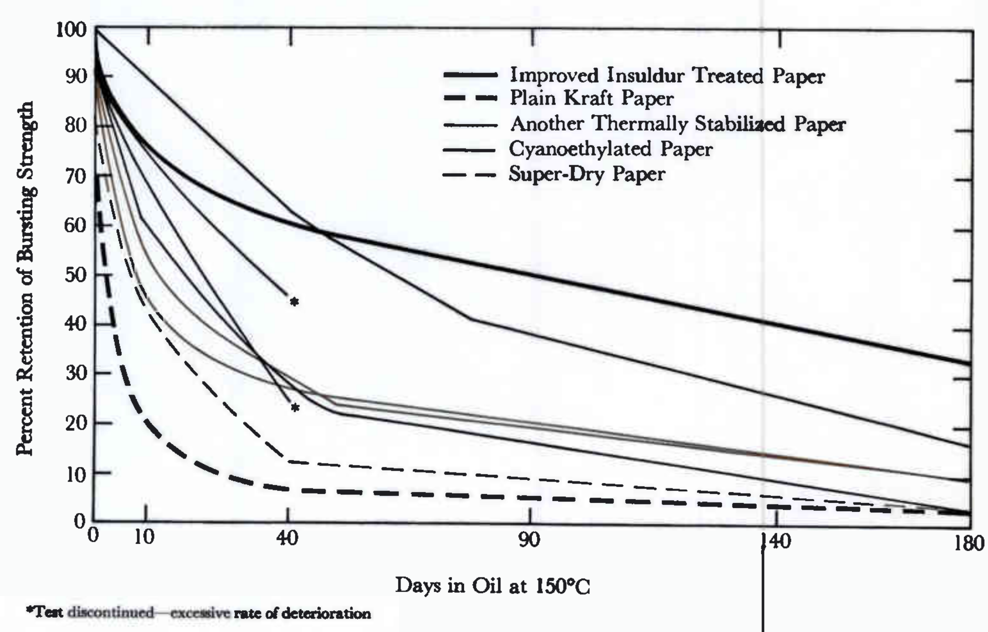
2) Sufficient pressure must be applied during manufacture to compact the coil and remove all dimensional variations which are attributable to manufacturing tolerances. This procedure makes the coil the same height at all points of support.

3) After the coils are assembled on the core, clamping pressure must be applied uniformly around the coil.

New Windings for Improved Voltage Distribution

To an impulse voltage wave, a transformer winding presents a complex combination of inductances and capacitances. The initial voltage distribution is related to the two basic capacitances involved, the winding capacitance to ground (C_g) and the series capacitance (C_s) of the winding. The lower the ratio C_g/C_s, the more uniformly the initial surge voltage is distributed throughout the winding and the lower the resulting stresses on winding insulation at the line end. Thus, anything that increases series capacitance or reduces ground capacitance improves the impulse voltage distribution.

On the lower voltage transformers, although a relatively high C_g/C_s ratio is inherent because of the physical arrangement of the windings, it is normally not necessary to reduce the ratio; but above



2—The superior strength of Insuldur treated insulation compared with plain Kraft paper and other types of stabilized papers is demonstrated by comparing bursting-strength retention in oil at 150 degrees C.

New Core and Coil Construction

For transformer coils to withstand the mechanical stresses of multiple short circuits during service life, they must be clamped with uniform pressure around the coil circumference. These key steps in manufacture ensure that all dimensional variations will be removed so that uniform clamping pressure will be maintained during transformer life:

A—After winding, each high-voltage and low-voltage coil is compacted and leveled to make the height at each column of radial spacers the same.

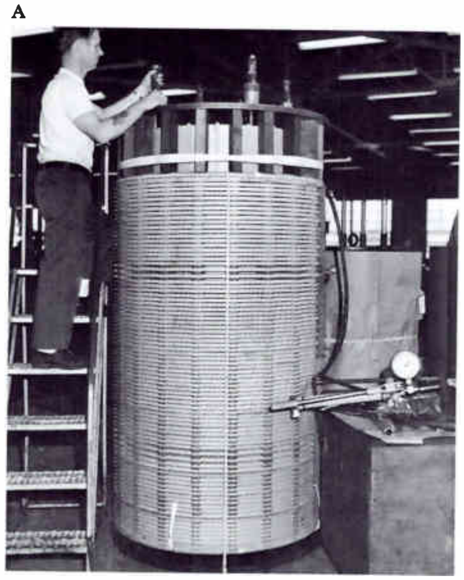
B—The leveled coil is clamped under spring tension and placed in the Vapotherm oven to remove all moisture from coil insulation and radial spacers.

C—Upon removal from Vapotherm oven, each coil is compacted in a hydraulic press to a pressure equal to short-circuit stress. The coil is sized to final coil height with radial spacers where required and repressed to be sure that coil comes to design height.

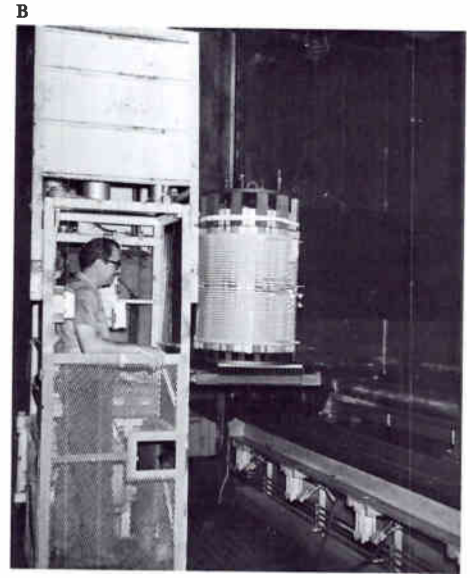
D—A pressure ring is installed on each phase, which contains high-voltage and low-voltage coil assemblies. The uniform coil height ensures that both assemblies will be held with equal clamping pressure.

E—All three phases are assembled on the transformer core and clamped to specified design pressure.

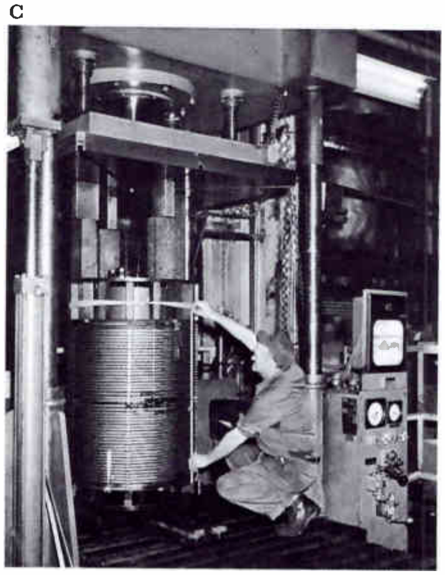
A



B

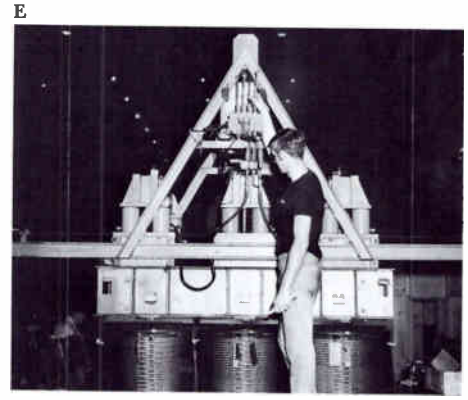


C



D

E



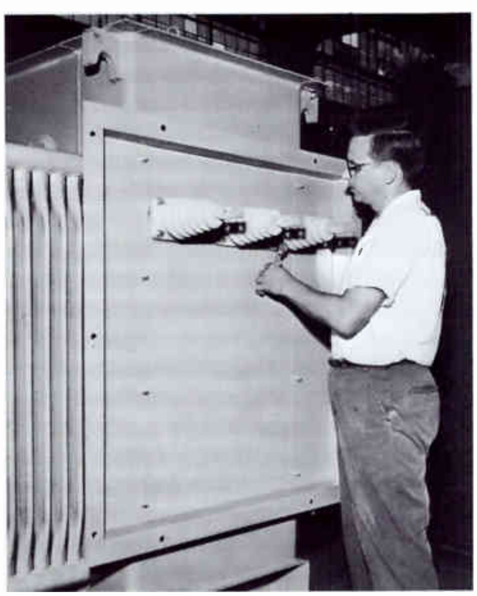
69 kV, special winding configurations are desirable to increase the series capacitance. Westinghouse transformers use Hisercap interleaved construction to accomplish this (Fig. 1b). Basically, interleaved windings consist of parallel conductors interconnected to give high series capacitance. The improvement obtained with Hisercap windings, as compared with the continuous pancake windings, is shown in Fig. 1c.

New Methods of Drying and Processing

Moisture can materially reduce the dielectric strength of transformer insulating materials and oil. Therefore, precautions are taken to remove any water that may be present in the insulation at the time of manufacture, and the complete transformer is then sealed to prevent the entrance of moisture while in service.

Westinghouse now uses a Vapotherm process for drying the coils and all pressboard or wood insulation prior to assembly into the transformer. Coils and insulation are loaded into a large tank and the pressure in the tank is reduced to 22 mm of mercury. A solvent with a boiling point higher than water is pumped into the tank and brought to a boil with steam-heated coils. Vacuum is maintained during the heating cycle. As the solvent vapor condenses on the relatively cool surfaces, it gives up its latent heat of vaporization and raises the temperature of the parts being dried above the boiling point of water. The solvent is then removed, and the pressure is reduced to 0.1 mm of mercury to remove all moisture. Without breaking vacuum, the complete tank is flooded with transformer oil so that all of the material in the tank is impregnated with oil.

After the core and coils are assembled in their own tank, the whole assembly is dried again by a hot-oil vacuum process. Each transformer is evacuated and filled with oil, which is circulated through the tank and heated until the temperature of the system reaches equilibrium. The oil is then pumped out while the transformer continues to be subjected to a high vacuum. After the vacuum cycle, the tank is filled with filtered, degassed and dehydrated oil. The transformer is now ready for test.

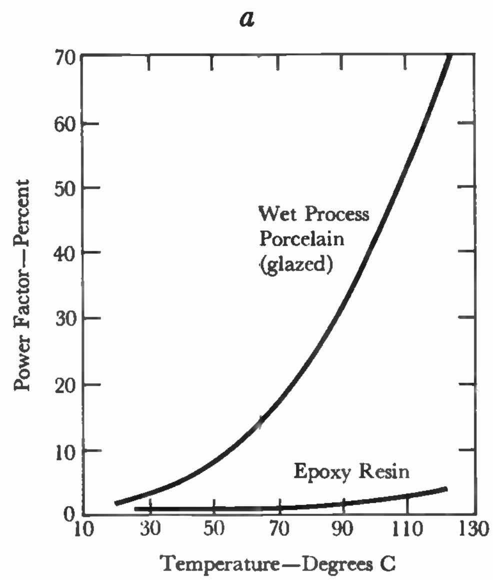


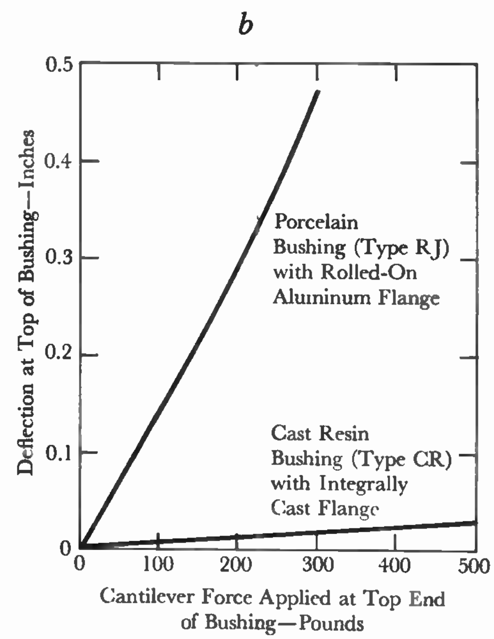
3—Wall-mounted epoxy bushings are now used on power transformers.

New Insulation Materials for Transformers

The search for and application of new insulation materials is a continuing project. Some of the new materials that are now being applied in modern transformers are high-density papers and insulating boards. A joint project with a major paper manufacturer has resulted in the development by the paper manufacturer of an improved paper for turn insulation. This high-density paper has about 35 percent higher dielectric strength and about 20 percent higher specific inductive capacitance (S.I.C.) than the previously used material. (Higher S.I.C. provides greater winding capacitance for the same thickness of paper, which helps to increase winding series capacitance.)

High-density insulating board has been developed for making the radial spacers used to separate pancake coils. These spacers provide electrical insulation be-





4—Epoxy bushings have demonstrated better performance than porcelain bushings with lower power factor (*a*) and with lower deflection under static cantilever loading (*b*).

tween sections of the coils and withstand the high short-circuit mechanical forces without deformation.

An important factor contributing to the maintenance of the initial mechanical strength built into the core and coil assembly is the Insuldur system of insulation protection, which has been in use in Westinghouse power transformers for many years. With this system, compounds of dicyandiamide, melamine, and polyacrylamide are added during paper manufacture to stabilize the cellulose (glucose) molecules. These compounds retard molecular breakdown at elevated temperature, which prevents thermal degradation of the insulation during service and prevents the insulation structure from shrinking dimensionally. Thus, coils remain tightly clamped and movement of windings during short circuits is prevented. The superior strength of Insuldur treated paper compared with other types of stabilized papers is shown in Fig. 2.

Accelerated thermal aging tests have demonstrated the superior performance of transformers using the Insuldur system. For example, in a 12-year test of 16 prototype power transformers, only the two units equipped with the Insuldur system had their coils still tightly clamped at the end of the test period. The untreated coils of the other units had all loosened.

Cast Epoxy Bushings

A cast epoxy resin system as the primary insulation in electrical bushings for indoor application is now a reality in the lower voltage classes up through 15 kV, and it shows great promise for higher voltages.

The low-voltage epoxy bushing, a simple combination of conductor embedded in solidly cast epoxy with an integrally cast flange, is the ultimate in simplicity. The ends of the stud can be flattened before the epoxy is cast to provide an ideal terminal for direct bolting to line fittings. (With porcelain, on the other hand, the bushing must be assembled from components and sealed with gasketed joints.) Typical of the new epoxy designs is a line of 15-kV wall-mounted indoor epoxy bushings now in production (Fig. 3).

From a performance standpoint, the epoxy bushing has higher corona inception voltage levels, lower power factor (Fig. 4a), and better cantilever permanent set characteristics (Fig. 4b) than the porcelain bushing. For example, typical corona inception voltages for 15-kV bushings are 26 kV for an epoxy unit and 14 kV for a porcelain unit. Cantilever forces of up to 500 pounds at the top end of the stud of an epoxy bushing have caused deflections of 30 mils and a permanent deflection with the force removed of only 3 mils; a porcelain bushing with a metal flange had a permanent deflection of 175 mils from a 300-pound force applied for one minute and removed. Thus, the danger of fatigue cracking or gasket seal failure is reduced considerably with epoxy bushings.

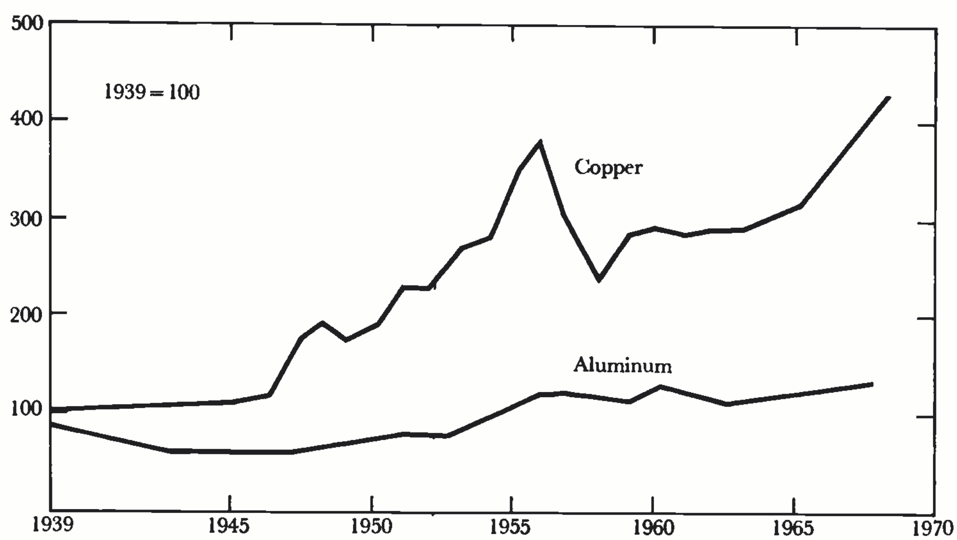
The successful application of resins to outdoor bushings involves development of both the shed contour and the resin formulation. To test these developments, many epoxy bushing designs and resin systems have been service tested on transformers installed on utility systems. Also, many tests are being conducted on customers' test racks in their most contaminated test sites to demonstrate the performance of epoxy bushings in highly contaminated areas.

In summary, epoxy resin bushings have demonstrated good arc and track resistance, good weathering characteristics, low power factor at elevated temperatures, good thermal shock properties, and high tensile strength. The resin system now in use was selected after carefully screening and testing several hundred possible systems.

Use of Aluminum

Interest in the use of aluminum for transformers has fluctuated with such factors as relative economics, copper scarcity, and certain customers' preferences.

The comparative price trends of copper and aluminum since 1939 are shown in Fig. 5. This illustrates the contributions aluminum can make to price stability in the transformer market. The fundamental cause of the copper price variation



5—The comparative price trends of copper and aluminum demonstrate the economic advantages of using aluminum in power transformer construction.

is the critical relationship between supply and demand, which is periodically aggravated by defense requirements, labor interruptions, and the unreliability of foreign sources. These factors are not expected to improve appreciably.

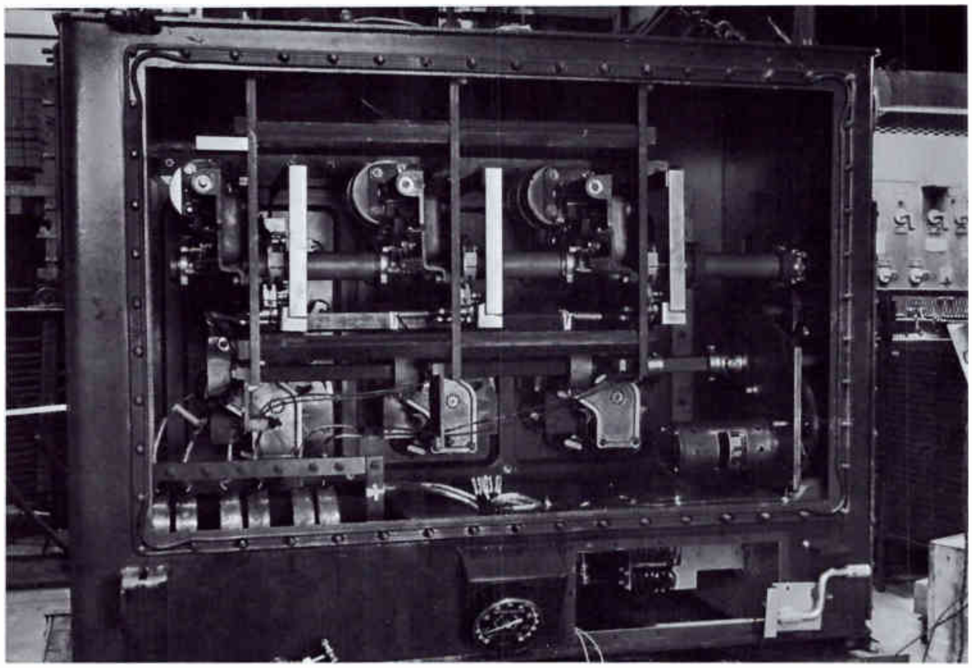
In over 15 years of experience with aluminum windings in power transformers, there has been no difference between the service records of copper- and aluminum-built transformers.

Because of the electrical properties of aluminum, aluminum conductors must always be larger than those made of copper. Thus, the windings for a circular-coil core-form transformer require a core opening that ranges from about 3 to 19 percent greater than required for copper windings. On the other hand, the greater surface area of the larger aluminum conductor per unit length increases the heat dissipation of conductor surface by about 20 percent compared to that for copper windings. From a mechanical standpoint, aluminum in the annealed condition has only one-third the strength of copper for equal cross sectional area, but since mechanical strength is proportional to conductor dimensions, the larger aluminum conductors are often as strong as their equivalent copper conductors without additional mechanical supports.

Aluminum joints and terminations can be made completely reliable. Basically, three methods of termination can be used: welding by the TIG (gas tungsten arc) or the MIG (gas metal arc) process; bolting with compression spring washers with the aluminum contact surfaces either silver or tin plated; and pressure crimping.

In the final analysis, the use of aluminum or copper must be evaluated on an economic value basis, just as are the different grades of electrical steel. The characteristic costs of each manufacturer determine which grades of core materials and conductor materials will provide the same equivalent function for the ultimate user.

6—The UVT (or Vacutap) load tap changer, using vacuum switches in place of arcing contacts, will replace the medium-capacity tap changers now in use.



New Load Tap Changers

The type UVT load tap changer, also called Vacutap load tap changer, is a three-phase tap changer utilizing the reactor (preventive auto) switching principle. This new device will replace the medium-capacity tap changers now in use. This tap changer utilizes vacuum switches (sometimes referred to as vacuum interrupters or vacuum bottles[1]) for arc interruption in place of the arcing contacts on conventional load tap changers.

The UVT tap changer (Fig. 6) is rated at 34 kV (200 BIL), 2000 volts per step, 1000 amperes, and will operate for ± 10 percent regulation up to 480,000 kVA of line capacity.

The use of vacuum switches minimizes oil contamination and reduces maintenance costs because arcing takes place in a vacuum rather than in oil. Contact life is longer than with conventional equipment, so the vacuum switch could conceivably last the life of the transformer for normal utility service. The contact is good for more than a half million operations and the mechanical life is three million or more operations. A tap change occurs in 1 to 1.5 seconds.

Molded Fiberglass Fan Blades

A new molded fiberglass fan blade is now going into production for application to transformers for delivery in late 1969. This blade will replace the cast aluminum blade that has been used in the past.

Laboratory tests and field experience have shown fiberglass to be more resistant to corrosion than aluminum. Fiberglass also lends itself to new techniques of balancing that promise further freedom from vibration. Tests have also shown that fiberglass blades will have a slightly lower sound level than aluminum blades.

Conclusion

Development and research work is being directed towards production of transformers that will be even more economical to operate and that will have an even greater degree of reliability. Those future developments in core-form transformers will continue to emphasize improved performance, reduced maintenance, and reliable trouble-free operation.

[1]R. A. Few and S. J. Cherry, "Vacuum Circuit Breaker for 15-kV Distribution Substations," *Westinghouse ENGINEER*, Jan. 1969, pp. 24-6.

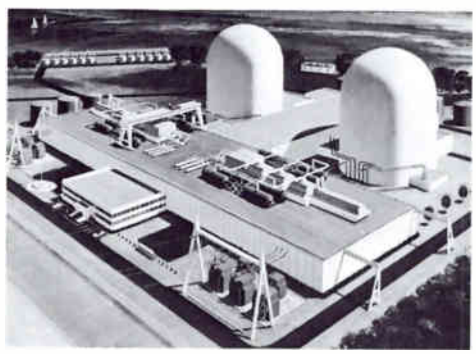
Nuclear Information Center Carries Story of Peaceful Atom

Refurbished and renamed, the former ferryboat *Elizabeth* is now serving as a floating nuclear information center for Public Service Electric and Gas Company. The 194-foot vessel, which once shuttled commuters across the Hudson River between Jersey City and New York, has been painted white, orange, and gold in its reincarnation and named *The Second Sun* in honor of the new force for life, nuclear energy.

The Second Sun carries an audiovisual show and exhibit area developed to provide better public understanding of nuclear energy, especially for generating electricity. The boat has been moored at various points along the Delaware River to enable as many as possible to see the show and exhibits. It is expected to attract at least 50,000 visitors annually.

The Second Sun is now docked at the Salem Nuclear Generating Station being built by Public Service on a 700-acre site in lower Alloways Creek, New Jersey. The station will have two pressurized-water nuclear units supplied by Westinghouse. The first unit, which will have a capacity of 1090 MW, is scheduled for completion in 1972; the second is to produce 1112 MW beginning in 1973.

Public Service is responsible for the design, construction, and operation of the Salem plant but will share ownership, costs, and electric output with Atlantic City Electric Company, Delmarva Power & Light Company, and Philadelphia Electric Company. The station will be the largest electric generating plant in New Jersey and one of the largest nuclear stations in the world.



(Top) **Floating nuclear information center, *The Second Sun*, carries exhibits and an audiovisual show to inform the populace about the peaceful uses of nuclear energy. *(Center)* The ugly duckling that was transformed into *The Second Sun* was the former Hudson River ferry *Elizabeth*. *(Bottom)* Some of the vessel's exhibits have to do with the Salem Nuclear Generating Station, shown here in an artist's concept of the finished plant. It will be the largest generating station in New Jersey when completed in 1973 by Public Service Electric and Gas Company.**

Fans Are Discreetly Quiet at the Metropolitan

At performances in the new Metropolitan Opera House, Lincoln Center, New York City, the audience is oblivious (as it should be) to the air-handling system that makes their listening environment comfortable. Yet that system moves as much as 1,300,000 cubic feet of air a minute into the building, pushed by some 80 blowers powered by 1200 horsepower. The air emanates from ornamental grillwork at the rear of the ceiling, wafts gently over the listeners, and is returned through flush-mounted grilles in the floor under the seats.

The building's designers selected Westinghouse equipment to meet the rigid sound limits prescribed for the occupied space. The equipment includes airfoil blowers, Centriline fans, ventilating sets, heating and cooling coils, and drive motors. No special equipment was required; in every part of the system, properly selected standard equipment met the specifications.

All equipment was shock and vibration mounted, and flexible ducts and pipe connections were used where necessary. For the larger pieces, the entire flooring and walls of the equipment enclosure were isolated from the main structural members to prevent vibration from being carried through the building.

Nonconsumable Electrode Developed for Vacuum Arc Melting

A nonconsumable electrode has been developed for vacuum melting of metals at high power levels. Melting is accomplished by a high-current electric arc discharge directly between the electrode tip and the molten pool. A field coil arrangement that rotates the arc, and water cooling of the copper tip, restrict the tip erosion rate and therefore provide long life.

The primary application probably will be in melting reactive metals such as titanium and zirconium, where the electrode has the advantage of eliminating the extensive electrode fabrication procedures employed for the present consumable melting process. With the nonconsumable electrode, sponge and scrap can be melted directly in any desired ratio limited only by chemistry considerations, providing melters with a new tool to improve the economic use of scrap in the melting of reactive metals. The independent control of power and material feed that is provided is equally applicable for steel melting, allowing hot topping of ingots and superheating for casting.

The electrode was developed by the Westinghouse Power Circuit Breaker Division. It has been tested in melting titanium sponge and scrap and also stainless steels. Power levels of 750 kW have been obtained with reversed polarity for extended test times, melting titanium sponge at 15,000 amperes dc and stainless steel at 19,000 amperes dc.

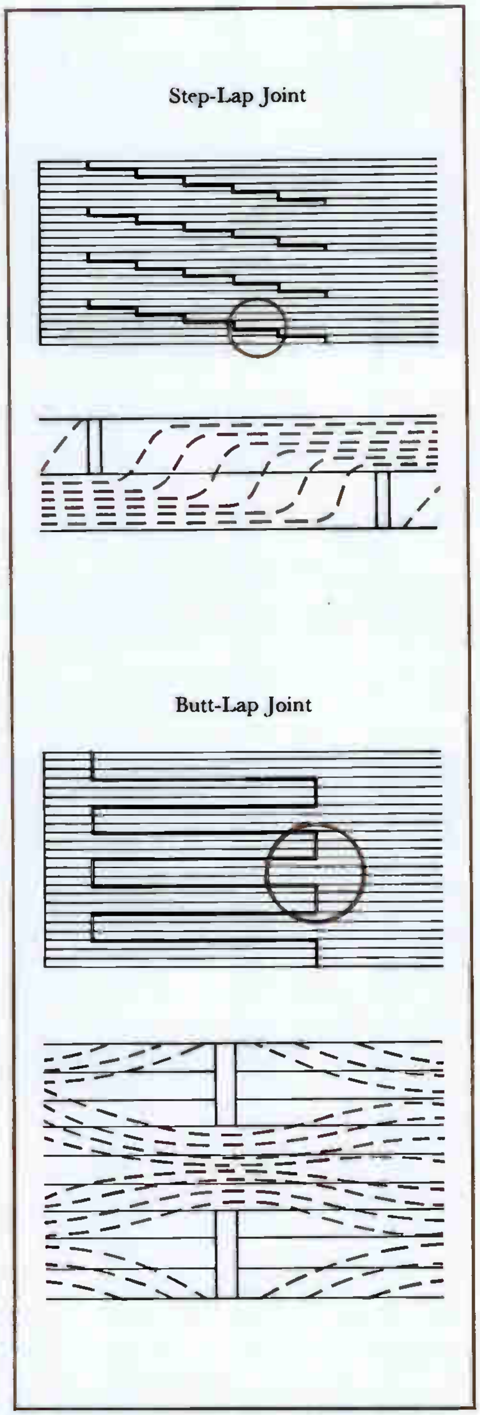
A tip used for melting stainless steel for 26½ hours (10 hours at 19,000 amperes and 15 hours at 15,000 amperes) lost only 19 grams and had a projected life of 254 hours. Typical erosion rates when melting titanium sponge have been 2 grams per hour, with projected tip life 40 hours or more. Calorimetric data indicate that power loss to the tip is directly proportional to arc current and is approximately 25 percent of the input.

Tests were made over the pressure range of 2×10^{-3} to 200 torr. Most of the arc control was performed manually, with visual observation of the pool and other critical parameters.

Acceptable operating conditions and melt rates have been obtained in 12-, 15-, 19-, and 25-inch molds. Feed rates have varied from 6 to 15 pounds per minute, and material evaluations are presently being conducted to determine operating parameters for production melting. Two furnaces specifically designed for the electrode are being installed in production facilities.

Step-Lap Core Construction Improves Power Transformers

The magnetic cores for power transformers are usually built up by stacking laminations cut in such a way as to form a combination of butt and lap joints at the corners of the core. That construction can form a good magnetic circuit, but it has disadvantages. One is the great care with which laminations must be stacked to optimize magnetic performance. Another is power loss at the joints, requiring higher excitation current than would otherwise be needed.



Step-lap joint facilitates assembly of a transformer core. The step-lap construction also reduces the amount of exciting current required, and the amount of vibration produced, because magnetic flux is not constricted as it is in the common butt-lap joint.

A new step-lap joint now in use facilitates core assembly and also minimizes losses and sound level. It is employed in the small oil-insulated power transformers produced by the Westinghouse Power Transformer Division.

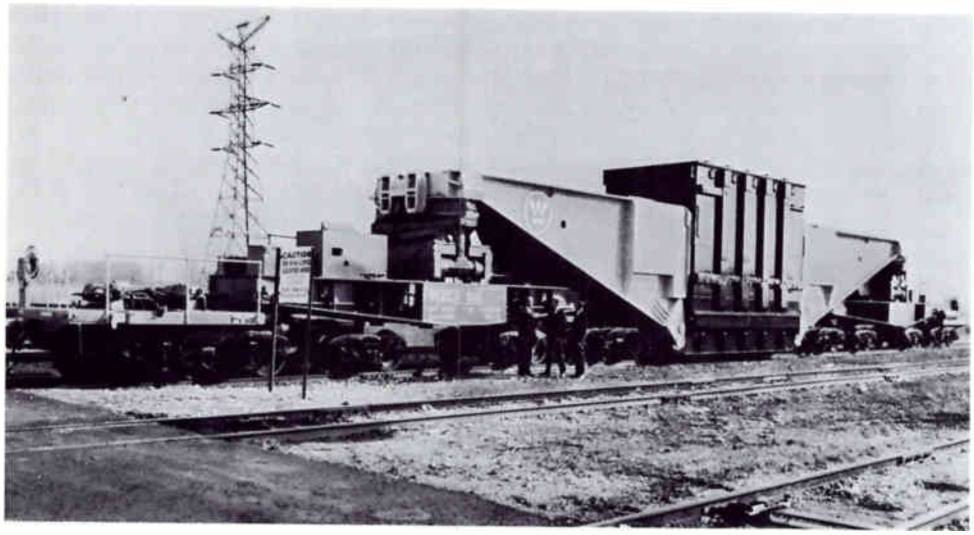
In the step-lap joint, induction (flux lines per unit area) is only a fraction of that in the laminations leading to the joint, as flux spreads out where it crosses the lap portion of the step. (See figure.) A butt-lap joint, in contrast, has about twice as much induction at the joint as in the laminations leading to the joint, as flux lines crowd where the air gaps are bridged.

Eddy currents representing lost energy are generated by flux crossing between laminations, since the currents are restricted only by the relatively large area of the plane of the steel sheets rather than by the small sheet thickness. Flux must cross over three laminations, and at a much higher induction, in the butt-lap joint. Reluctance of the step-lap joint is so much lower than that of the butt-lap joint that the no-load exciting current required for a core with step-lap joints is considerably less than that for a butt-lap core. The result is achievement of a given performance level with greater efficiency and smaller unit size. Sound level is less also because the much lower induction at the joints results in less "motor-action" vibration there.

Like Transformers, Schnabel Cars Continue to Grow

The first transformer shipped on Westinghouse's new million-pound-capacity Schnabel railroad car was a 650,000-kVA, 345-kV main generator step-up transformer for Texas Power and Light Company's Tradinghouse Creek Steam Electric Station near Waco, Texas. The car with transformer was more than 155 feet long.

The car has 20 sets of trucks for maximum distribution of load on the rails, and it is equipped with power-operated devices for raising, lowering, and transverse adjustment of the transformer to clear obstacles in the route.



The latest Schnabel car for transporting power transformers handles the really big fellows. Its capacity is a million pounds.

Since the transformer is part of the loaded car, it rides within 7 inches of the rail compared with approximately 30 inches on a standard depressed-center railroad car. This feature effectively reduces the shipping height of the transformer by approximately 24 inches.

Like its companion 500,000- and 750,000-pound-capacity Schnabel cars used in shipping large transformers, the new car has its own power and built-in jacking system that raises the transformer approximately 15 inches above the rail for unloading. The huge transformer can thus be unloaded and the car halves recoupled for return to the factory without use of external lifting facilities. Unloading usually can be completed in eight hours.

Flash Evaporator Plant to Produce Pure Water from Mine Drainage

The first facility for converting stream-polluting mine drainage into pure water will be capable of treating five million gallons daily of acid water now flowing into the Susquehanna River. A site near Wilkes-Barre, Pennsylvania, was selected for the plant because of the large quantity and extremely poor quality of the drainage water from abandoned mines in that region. The plant will be erected on a two-acre site along the east bank of the Susquehanna River.

The ultrapure water produced by the plant will be sold to help pay for plant operation. Even pharmaceutical, photographic-film, chemical, and dye manufacturers will be able to use the water directly.

The treatment plant will employ a flash evaporation process developed by Westinghouse in a research program sponsored by the Coal Research Board in the Department of Mines and Mineral Industries. The process is similar to that used in desalting plants that convert ocean or brackish water to fresh water. The plant will be built by the Water Province Department of the Westinghouse Heat Transfer Division.

To withstand the corrosive effects of the acid mine drainage, the flash evaporator system probably will have titanium tubing. A pilot demineralization plant employing titanium tubing has been operating successfully for a year with no serious corrosion; it has treated more than 50,000 gallons of mine drainage from the Wilkes-Barre area.

The start of construction is planned for next May, with initial plant operation scheduled for July 1971.

Saxton Core III

The core of the Saxton Experimental Power Reactor (back cover) has been reconstituted as Saxton Core III. Its nine central fuel assemblies were made from Core II assemblies by removing the plutonium-enriched Zircaloy-clad fuel rods and reinserting them into new assembly grids. Those assemblies are surrounded by 12 uranium-dioxide stainless-steel-clad assemblies from Cores I and II. The arrangement allows many of the fuel rods to operate at high power levels without exceeding overall thermal limits.

The Saxton reactor is a tool for developing and evaluating advanced nuclear fuel and operating technology. For example, irradiation of the uranium-dioxide rods from Core II will certify the power burnup capability and design limits of oxide fuel elements used in commercial pressurized water reactors. Other contributions expected from Core III include more knowledge about use of plutonium fuel in such reactors. Also, the fuel elements will be irradiated under load cycling conditions simulating those expected in reactors operating as load follow plants in utility systems.

The Saxton reactor is owned and operated by the Saxton Nuclear Experimental Corporation, a subsidiary of General Public Utilities. The experimental program there is the responsibility of the Westinghouse Nuclear Fuel Division.

Products for Industry

Cast-epoxy secondary bushings for pole-type distribution transformers are offered initially on 5-, 10-, 15-, 25-, 37½-, and 50-kVA single-phase units. The aluminum-spade bushing has electrical and environmental characteristics equal to or better than those of the porcelain-and-copper bushing it replaces, and it prevents dissimilar-metals problems since most utilities now use aluminum on secondaries. The epoxy is cast around the aluminum stud to form a hermetic seal, so the conductor gasket assembly is not required and a source of leakage and loose connections is thus eliminated. Also, the epoxy has considerably higher flexural strength than porcelain. *Westinghouse Distribution Transformer Division, 469 Sharpsville Avenue, Sharon, Pennsylvania 16146.*

Limit switches for industrial and machine-tool environments have double-sealed construction, which extends their life by excluding contaminants such as coolant or cutting oil. A full cover gasket with a wide flange serves as the primary seal, and the integrally molded housing of the internal switch assembly is independently sealed by contoured neoprene. The switch can be changed with a screwdriver from actuation in one direction to actuation in the other direction or to actuation in both directions. Rotating the head to permit access to terminals from front, back, or either side is just as easy. A large number of standard heads and arms are available to meet the requirements of different applications. *Westinghouse Control Products Division, Beaver, Pennsylvania 15009.*

Limit Switch

Three-Axis Numerical Control

Three-axis numerical control for drills with automatic tool selection is a standard packaged design featuring 0.0001 programming increment for x and y axes (0.001 for z), 300-character-per-second tape reader with tape rewind, fixed spindle cycles, and provision for tool-length offsets. Each axis has point-to-point positioning and straight-cut machining. Standard features of the Model 33 control provide the functions required for most turret drills; for additional requirements, plug-in option kits permit field modification. Integrated-circuit logic makes possible a totally enclosed compact cabinet that protects against outside contamination. Inputs are by EIA standard coded paper tape or manual dial-in. *Westinghouse Industrial Systems Division, 4454 Genesee Street, P.O. Box 225, Buffalo, New York 14240.*

Expulsion power fuses (Types RBA-200-400-800 and RDB) are boric-acid types for effective protection of circuits and equipment that operate on voltages from 2.4 to 34.5 kV. The De-ion fuses are applicable in electric utility and industrial power plants for indoor (RBA) and outdoor (RDB) use. The RBA fuse is available in hookstick-operated disconnect-type mounting or non-disconnect-type mounting; the complete fuse consists of a mounting bracket, fuse-holder, refill, and discharge filter or condenser. The RDB has a hookstick-operated disconnect-type dropout mounting incorporating a sleet hood, cable terminal, and dropout mechanism into a single unit at the break end. The boric-acid refill interrupts currents of short-circuit magnitude within half a cycle. RBA and RDB fuseholders are interchangeable and non-breakable. *Westinghouse Switchgear Division, 700 Braddock Avenue, East Pittsburgh, Pennsylvania 15112.*

Services for Industry

Nuclear Services Department has been created to serve the electric utility industry more effectively. It is responsible for the following services: nuclear training; plant modification, maintenance, and in-service inspection; quality assurance; engineering; and refueling (except sale of reload fuel). In addition, auxiliary equipment such as reactor-containment fan coolers, simulators, and ice-condenser containment systems and equipment will be developed and marketed by the department, as well as renewal parts for the company's pressurized-water reactors. *Westinghouse PWR Systems Division, Penn Center, P.O. Box 355, Pittsburgh, Pennsylvania 15230.*

Remote batch computer service called RITS (Remote Input Terminal System) gives businessmen, engineers, and scientists direct access to high-capacity computers through local terminals. The terminals, located in the user's plant or at a nearby Westinghouse Tele-Computer Service Center, can be used to develop new programs or execute previously written and retained programs. All compilations and calculations are carried out on an IBM 360/75 computer system, with input and output handled by an IBM 360/50. Data transmission between the two systems is done automatically at very high speeds. More than 2000 presently written computer programs are available, including engineering methods analysis, systems modeling, environmental load analysis, optimization techniques, network studies, and Camp services for numerical machine-tool programming. *Manufacturing Information Services Department, Westinghouse Information Systems Laboratory, 2040 Ardmore Boulevard, Pittsburgh, Pennsylvania 15221.*

About the Authors

V. V. Schloesser graduated from the University of Kansas in 1943 with a BSME degree. He joined Westinghouse on the graduate student training program and went to the Steam Division, where he was assigned to a group working on the first turbojet aircraft engine designed and built in the United States. He remained in the Aviation Gas Turbine Division when it was formed in 1945, becoming a section manager in 1948 and then serving in various other technical management positions. He contributed to the design and development of all Westinghouse turbojet engines, and in 1956 he was made Assistant Chief Engineer.

Schloesser transferred to the Atomic Equipment Division in 1958 as Engineering Manager. In 1963, he moved to the Small Steam and Gas Turbine Division as Project Manager for marine gas turbine study programs. He is now Engineering Manager, responsible for design and development of small steam turbines (up to approximately 25 MW) as well as peaking and industrial gas turbines of all sizes. Among the projects he has guided are the design upgrading of the division's older gas turbines and the design and development of two new frames—the W-251 (25 MW peak) and the W-501 (58 MW peak).

J. M. Michaelson, Jr., earned his BS degree in Mechanical Engineering at Pennsylvania State University in 1957 and joined Westinghouse on the graduate student training program. After short assignments at the Air Arm Division and then at the Automatic Merchandising Division, he joined the Standard Control Division to work on special customer orders. He then assumed design responsibility for the Type A enclosed control line, which includes combination and noncombination starters in a complete series of enclosure types. He also contributed to a proposed new bus duct design.

Michaelson was assigned to the new Control Products Division when it was formed earlier this year. There he has organized the design of the new combination starter described in this issue and supervised the testing of starters on various short-circuit conditions to coordinate their protection systems.

H. H. C. Richards graduated from Virginia Military Institute in 1941 with a BS degree in Electrical Engineering. He then worked in the experimental aircraft department at Fairchild Aircraft Corporation until 1944, when he joined the U.S. Army Air Forces and served at the Wright-Patterson Air Force Base fuel laboratory. He joined Westinghouse in 1946 as a tester in the former Transportation and Generation Department.

Richards transferred to the Aviation Engineering Department (now the Aerospace Electrical Division) in 1947, where he has had a variety of responsibilities in engineering design, standardization, and quality and reliability programs. He is now a Senior Engineer in the Utilization Systems Department, where he has worked on design of power supplies, temperature control systems, temperature sensing elements, transformers, motor controls, motor starters, ground detection devices, and static tap changers for power control.

Donal E. Baker graduated with a BS degree in Electrical Engineering from the University of Denver in 1966. He joined Westinghouse on the graduate student training program and was assigned to the Utilization Systems Department, Aerospace Electrical Division. There he has contributed to the design and development of control and power circuitry, including electronic temperature controllers, ac power modulators, and regulated ac to dc converters. He is a member of Tau Beta Pi and Eta Kappa Nu.

L. C. Elliott graduated from Missouri University School of Mines and Metallurgy in 1939 with a BSEE. He worked at Republic Steel Corporation until the following year, when he went into the U.S. Army. Elliott served in the European Theater, Sixth Armored Division. He was discharged in 1945 and joined Pacific Gas & Electric Company in the Distribution Engineering Department, working mainly on substation design.

Elliott came to Westinghouse in 1953. After a brief period in Electric Utility Engineering, he became District Engineer in Minneapolis. Then, in 1967, he was made Transmission Consultant in the Electric Utility Headquarters Department (now Power Systems Planning).

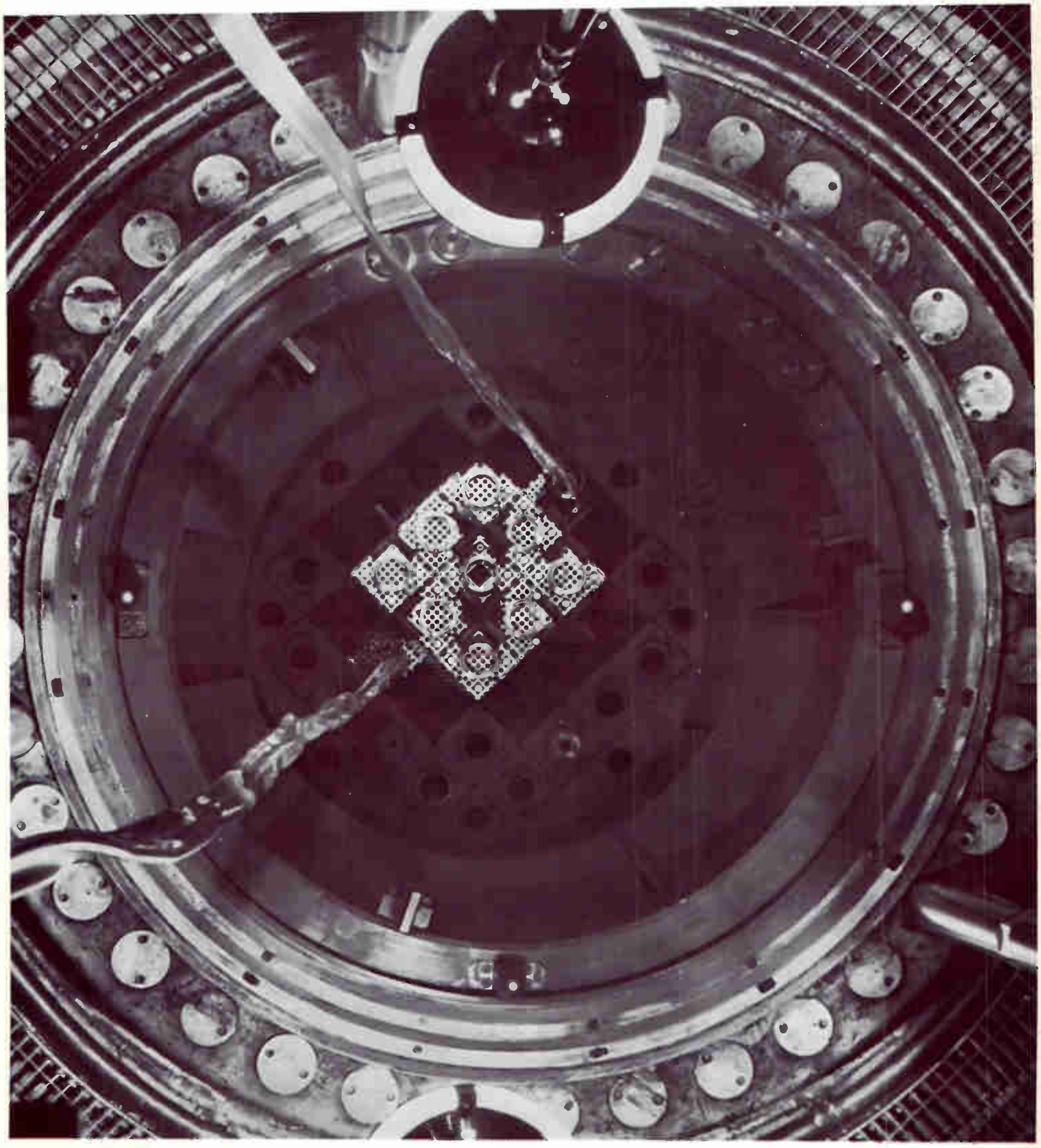
Gordon R. Monroe graduated from the University of Utah in 1928 with a BSEE. He came with Westinghouse and was assigned to the Transformer Division to work in the test area. Since this initial assignment, Monroe has worked as a development design engineer, as section manager of commercial orders, and as section manager of development. He has worked with dry-type core-form transformers, network transformers, precipitation transformers, and medium and large core-form transformers. His recent efforts have been in development of circular core-form transformers and the analysis of mechanical forces in transformers and on surge voltage distribution in windings. Monroe is presently section manager of the internal core-form development section.

Westinghouse ENGINEER

Westinghouse Electric Corporation
Gateway Center, Box 2278
Pittsburgh, Pennsylvania 15230

Address Correction Requested
Return Postage Guaranteed

Bulk Rate
U. S. Postage
PAID
Lancaster, Pa.
Permit 1582



Saxton Core III (More information on page 159)