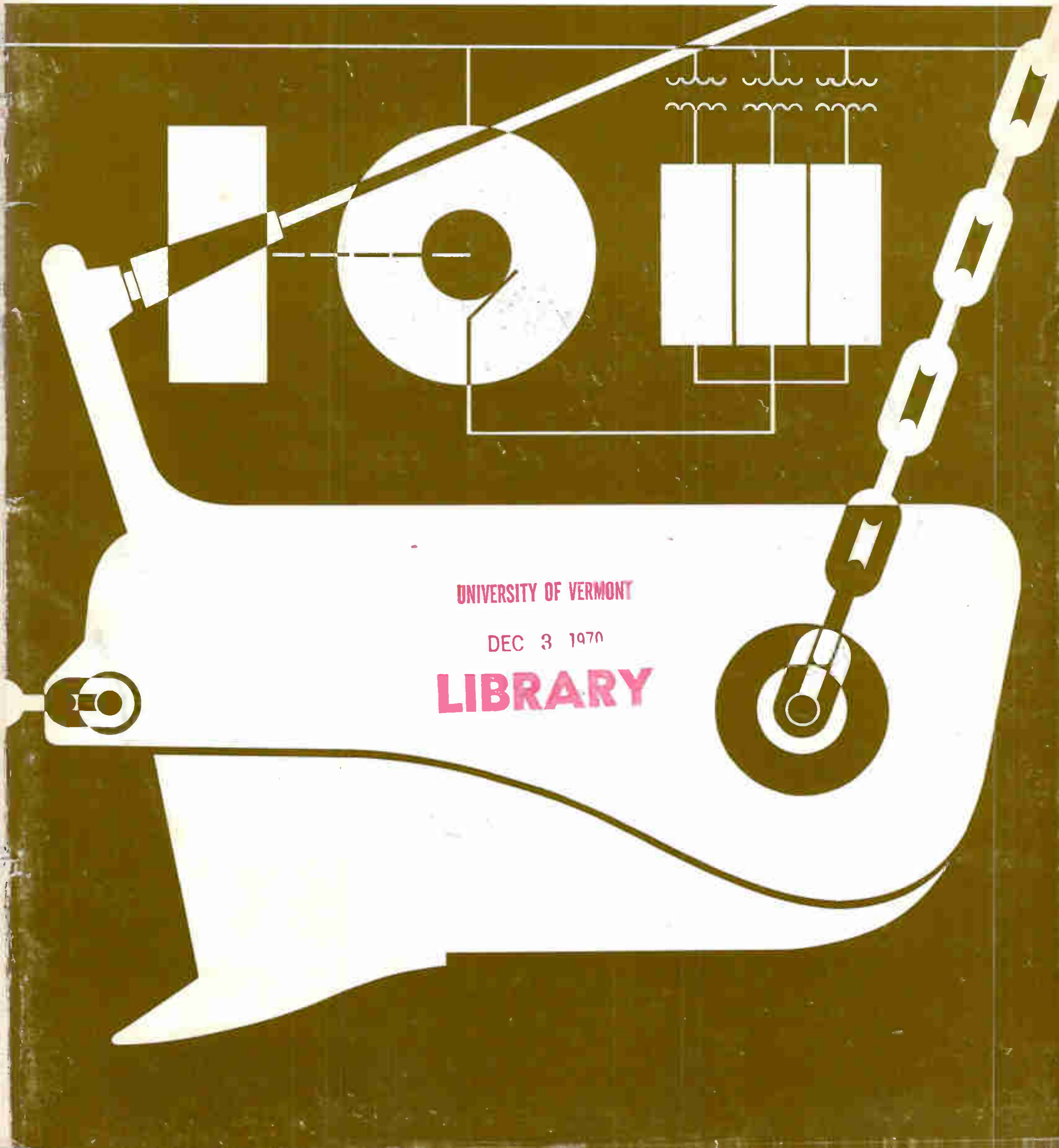
Westinghouse ENGINEER

November 1970



Modern Steam Turbine Plant Serves Electric-Utility Needs

A new manufacturing facility has greatly increased the Westinghouse Large Turbine Division's plant capacity and thereby is enabling the Division to meet the needs of electric utilities for more and larger turbines. Initial products are the 1800-r/min steam turbine elements required by nuclear plants. Those being made now have 40- or 44-inch last-row blades; in the future, turbines with 52-inch last-row blades and larger will be made. In addition, plant expansion is planned for production of low-pressure 3600-r/min turbine elements.

The plant is located near Charlotte, North Carolina. Its manufacturing area is so planned that it can readily be expanded on three sides (Fig. 1).

Both the product and the plant were designed for rapid manufacture and high product reliability. The various turbine ratings have many identical components for efficient manufacture and interchangeability. Numerically controlled machine tools are used in component manufacture to obtain the uniformity and accuracy that permit interchangeability.

Straight-line flow is used as much as possible in machining and assembling. The shop has main aisles for outer cylinders, inner cylinders, and rotating elements, with smaller parts for the main components flowing into the lines where they are needed.

In assembling an outer housing, a manipulator clamps sections for tack welding (Fig. 2), which holds the sections together for transfer to automatic and semiautomatic welding operations farther down the aisle. Inner cylinders are formed in a similar manner and the required machining is done, such as the finish boring shown in Fig. 3.

Rotor discs are machined from forgings, as are the shafts (Fig. 4). Then a shaft is upended, and bladed discs are heated and shrunk on it (Fig. 5). Rotors are tested at rated temperature, and at rated speed and overspeed, in a "heater box." Finally, the fabricating operations culminate with assembly of the components (Fig. 6).

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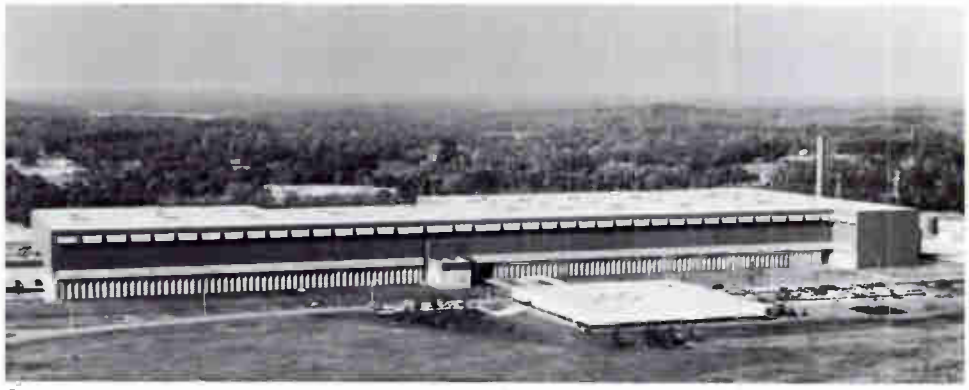

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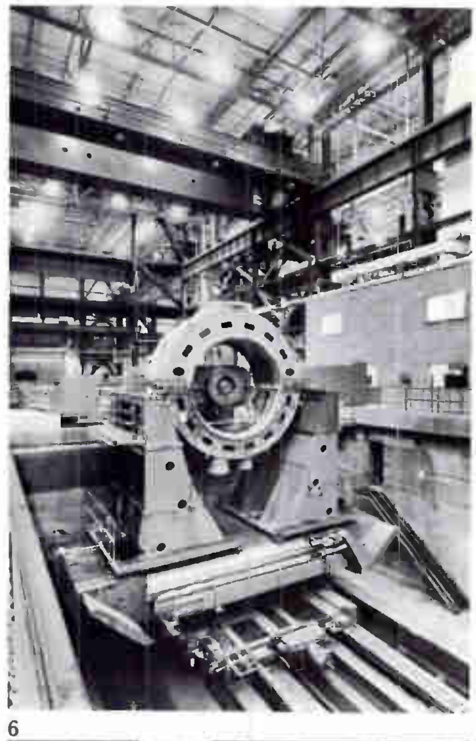

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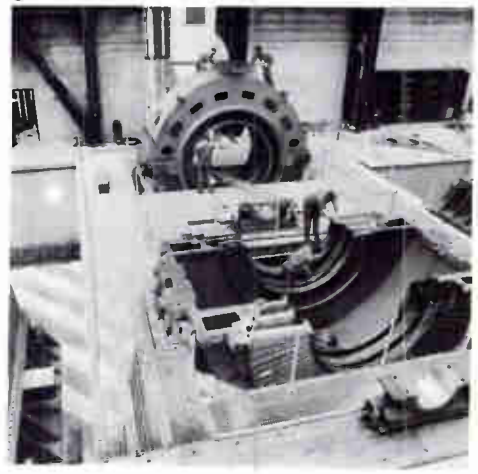

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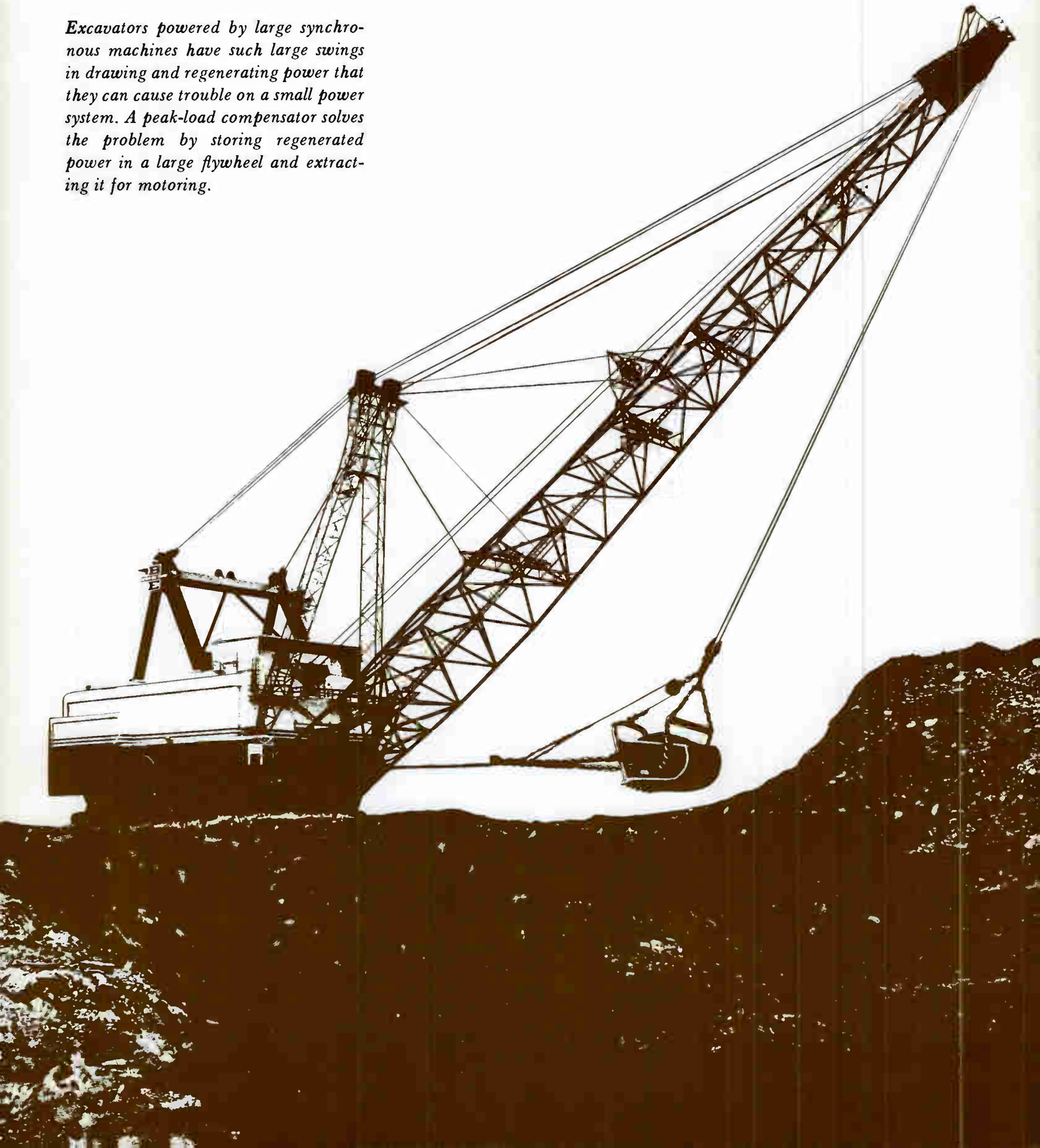
Front cover: A dragline bucket is combined with a circuit representation of a peak-load compensator in the cover design by Tom Ruddy. The compensator smooths the wide load swings otherwise inherent in the operation of large excavators; it is described in the article beginning on the following page.

Back cover: Part of Vancouver Island, including the city of Port Alberni, appears in the image made by airborne geologic reconnaissance radar through cloud cover. Some 300,000 square miles in various parts of the world have been mapped for clients since Westinghouse initiated the service about a year ago.

Energy Storage at Site Permits Use of Large Excavators on Small Power Systems

L. A. Kilgore
D. C. Washburn, Jr.

Excavators powered by large synchronous machines have such large swings in drawing and regenerating power that they can cause trouble on a small power system. A peak-load compensator solves the problem by storing regenerated power in a large flywheel and extracting it for motoring.



When large electrically powered excavating machines are used on small power systems, they can cause troublesome system voltage fluctuations and frequency disturbances because of the large (and sometimes almost periodic) load swings inherent in the operation of excavators. The problems may interfere with the economic use of large excavators for mining.

To solve them, a peak-load compensator has been devised. It is an energy storage system that has the effect of moving a new power source to the excavator site, so it can enable the largest excavators to operate on small power systems with little disturbance.

The Problems

Neither the voltage nor the frequency variations are likely to be problems on the large interconnected power systems generally typical of the United States, except perhaps near the end of a long transmission line of small capacity and high impedance. Most generation systems here can tolerate cyclic power fluctuation on the order of 5 to 10 percent of connected running steam-generating capacity, and most power lines have sufficient capacity to keep voltage swings within commonly accepted flicker limits. But the story may be vastly different on the small systems typical of developing areas.

The problems' source is in the discontinuous nature of the power system loads created by excavating equipment. (This article deals specifically with draglines, although similar if not identical statements can be made about shovels.) The basic digging cycle involves three motions—drag, hoist, and swing. A total cycle results from intermittent operation of each motion, perhaps in pairs and, more rarely, all three simultaneously.

The combined load of the three motions is a cycle of power flow that contains large peaks and valleys (Fig. 1). If the motoring peak load is called 100 percent, then the average load is about 40 percent. An excavator with peak motoring power of 15,000 kW, for example, would draw an average power of about 6000 kW. The regenerating peak loads may be anything from 60 to 100 percent of the motoring peak magnitudes.

The fluctuating load impressed by the dragline on the power system first of all causes the system voltage to vary. The power supplier attempts to hold his sending voltage constant, so the receiving voltage must vary; in severe instances the too low (or too high) voltage may cause equipment malfunctions. One partial solution is to vary reactive power flow as load power conditions change by varying the field of the synchronous machines used to power the three motions. With motoring (positive) load the power factor is forced leading, and during regeneration it is allowed to go lagging. The result is a nearly constant receiving voltage for all conditions of load. Unfortunately, this cannot be done without limit: the pullout torque restrictions of the synchronous machines must be respected, thereby limiting the amount the power factor can go lagging. Similarly, saturation of the motor iron and the thermal capabilities of the synchronous motor field restrict the amount of leading reactive power that can be caused to flow. Within these limitations, however, reactive power control is effective in handling the voltage fluctuations.

Still, nothing has been done about the flow of real power. As a matter of fact, without perhaps serious tampering with the basic load cycle, real power flow is an invariant of the system.

The variation in the real power requirements of the load is reflected into changes in the energy flow in the system generating stations. For brief energy flow changes, accommodation of generation is achieved by small speed changes in the

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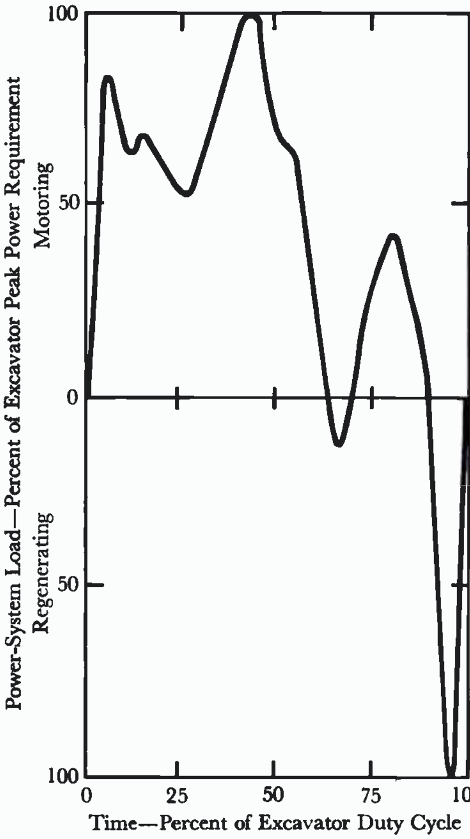
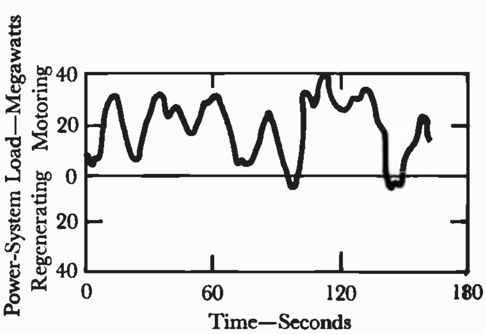
The dragline shown at left has a 275-foot boom and a bucket capacity of 90 cubic yards. Its electrical control and power equipment were supplied by Westinghouse. Even the largest excavators can be operated on small power systems when a peak-load compensator is used with them; without the compensator, the excavators' cyclic power demands can disturb system voltage and frequency.





1—*(Top)* Typical duty cycle of an excavator has widely fluctuating power demands. The curve is an idealized representation, omitting the higher-frequency fluctuations characteristic of the synchronous machines used to power the three motions on large excavators. A typical average duty-cycle time is 60 seconds.

2—*(Bottom)* System load can be smoothed somewhat by applying more than one excavator. However, peaks and valleys of several machines' loads will coincide at random times unless they are prevented from doing so.

alternator, but as the duration of each power disturbance increases, governor action occurs.

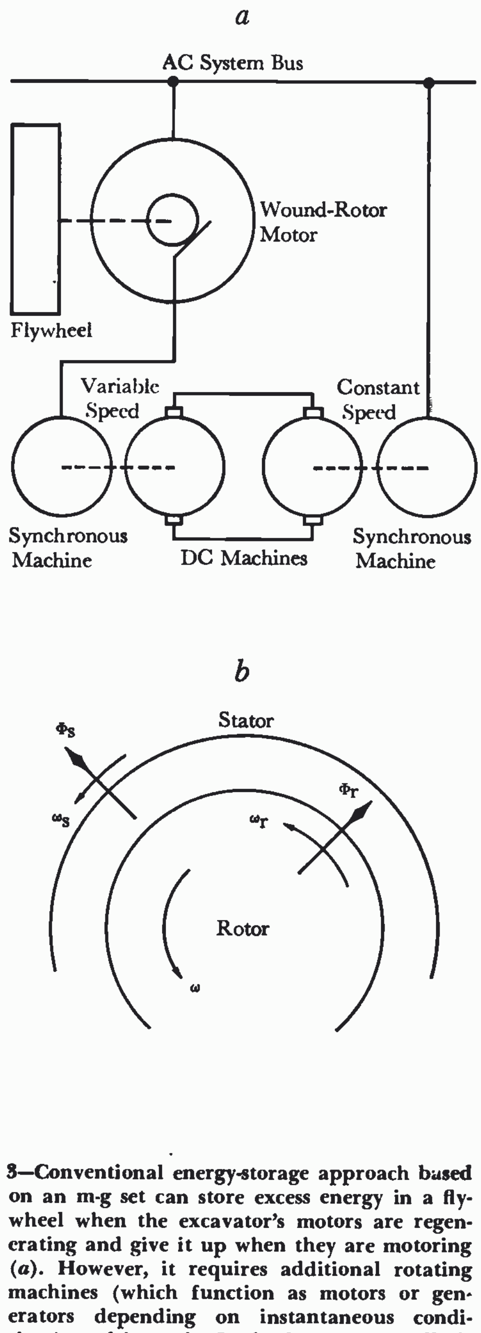
In a steam-powered station, the governor changes steam flows in an attempt to keep the speed deviations (and the consequent frequency deviations) small. However, even though the governor may be capable of following and compensating for the approximately one-minute load cycle of typical excavating equipment, the boilers may not be. The one-minute cycle tends to upset both boiler firing and boiler water-level control, and it can cause wild excursions in both.

Frequency swings may also affect other equipment, even though the average frequency is constant. For example, there may be equipment depending on the power system for a clock frequency.

The basic source of power can be improved, of course: special boiler drums, more total generation capacity, and larger-capacity lower-impedance power lines. As an area develops, some or all of these improvements occur; they may be prohibitively expensive during the early phases of operation, however, especially in remote areas such as Australia's vast "outback." In any case, they generally are beyond the control of the mine operator, so options more directly under his control are needed.

As a partial solution, more excavating machines can be put on the system to diversify the load. If the various excavators can be kept running out of phase so that no load peaks or valleys coincide, the resultant system load will be smoother (Fig. 2). Sooner or later, though, several machines will fall into step and the peaks and valleys will coincide unless the natural operation of the machines is interfered with. However, interference tends to reduce production because the faster-cycling machines must be slowed.

Even if interference to the digging cycles could be tolerated, cycle coincidence would be hard to prevent. The total system load would have to be monitored and an evaluation made as to the cycle modifications necessary to prevent excessive load swings. Probably nothing less than a computer-operated supervisory control system would be satisfactory: a computer to predict the loads for the immediate future and to generate the control strategy, and a supervisory control to put the strategy into effect. The cost would include both the capital investment for hardware and the continual effective operating cost resulting from less than maximum utilization of the excavating equipment.



3—Conventional energy-storage approach based on an m-g set can store excess energy in a flywheel when the excavator's motors are regenerating and give it up when they are motoring (*a*). However, it requires additional rotating machines (which function as motors or generators depending on instantaneous conditions), and its main flywheel m-g set usually is unable to operate above synchronous speed.

Normally, the magnetic fields in the rotor and stator of the m-g set's wound-rotor motor interact to cause the motor to operate as a synchronous machine (*b*). However, the phase of the rotor supply voltage can be adjusted to shift the rotor flux position (Φ_r) closer to or farther from alignment with the stator flux (Φ_s), resulting in less or more torque respectively. The speed changes can be controlled to cause power to flow between flywheel and power system in the amounts, and at the times, desired for compensation of load fluctuations.

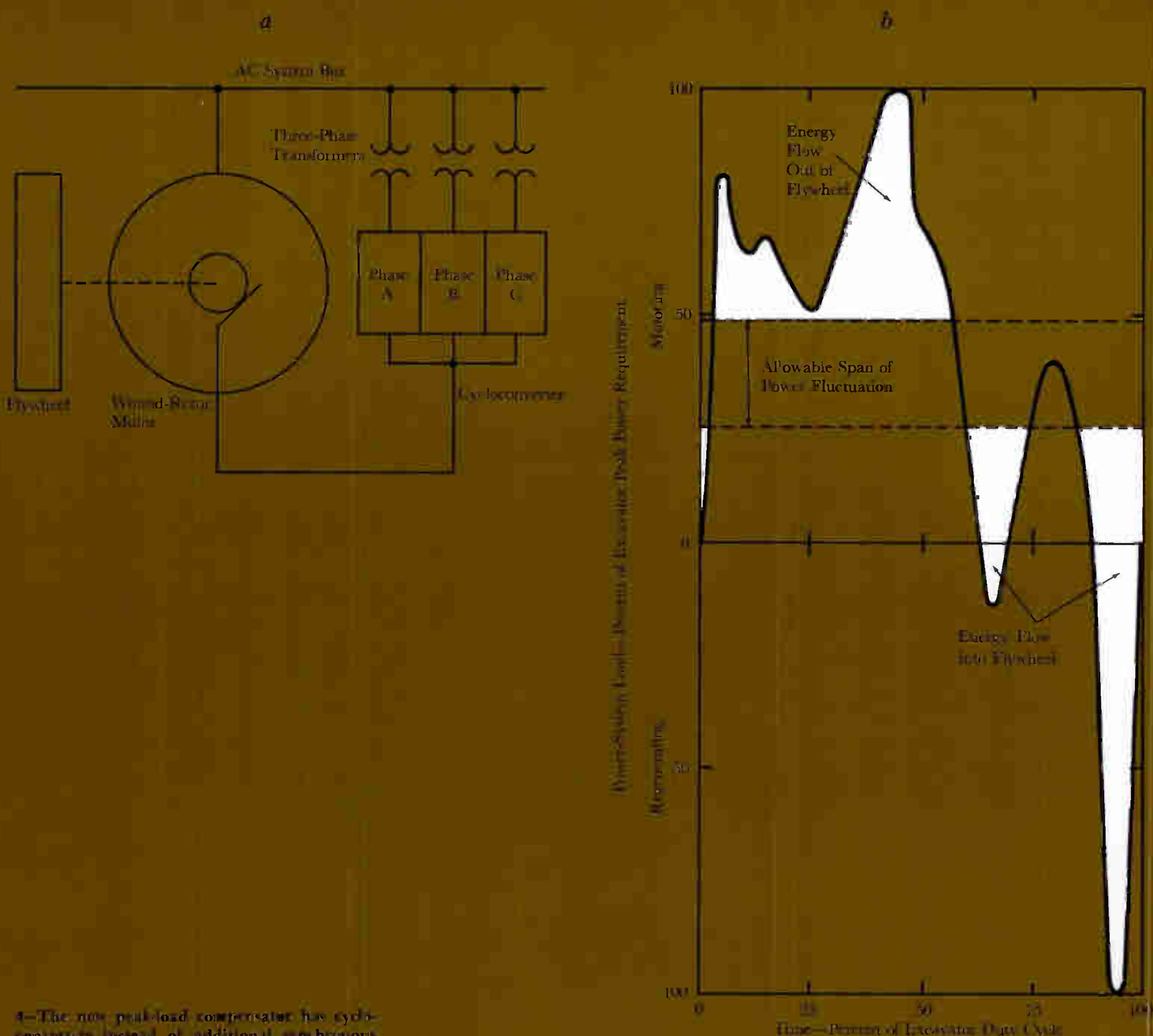
Since the fundamental problem is caused by the large cyclic swings in the power requirements of the excavating machine, the direct approach is to eliminate the swings or reduce them to an acceptable level. The reversal of power flow during the digging cycle implies that the load cycle might be smoothed if some mechanism were provided for storing the energy developed during regeneration and then using the stored energy to help supply the motoring energy requirements. A mechanism used to do this in other industries, such as metal rolling, is the m-g set driven by a wound-rotor motor and equipped with a large flywheel and a slip regulator.

That mechanism has now been applied in the new peak-load compensator for excavators. The large flywheel m-g set is mounted external to the individual excavating machines to avoid mounting problems and to incorporate diversity effects on multimachine applications into the system design.

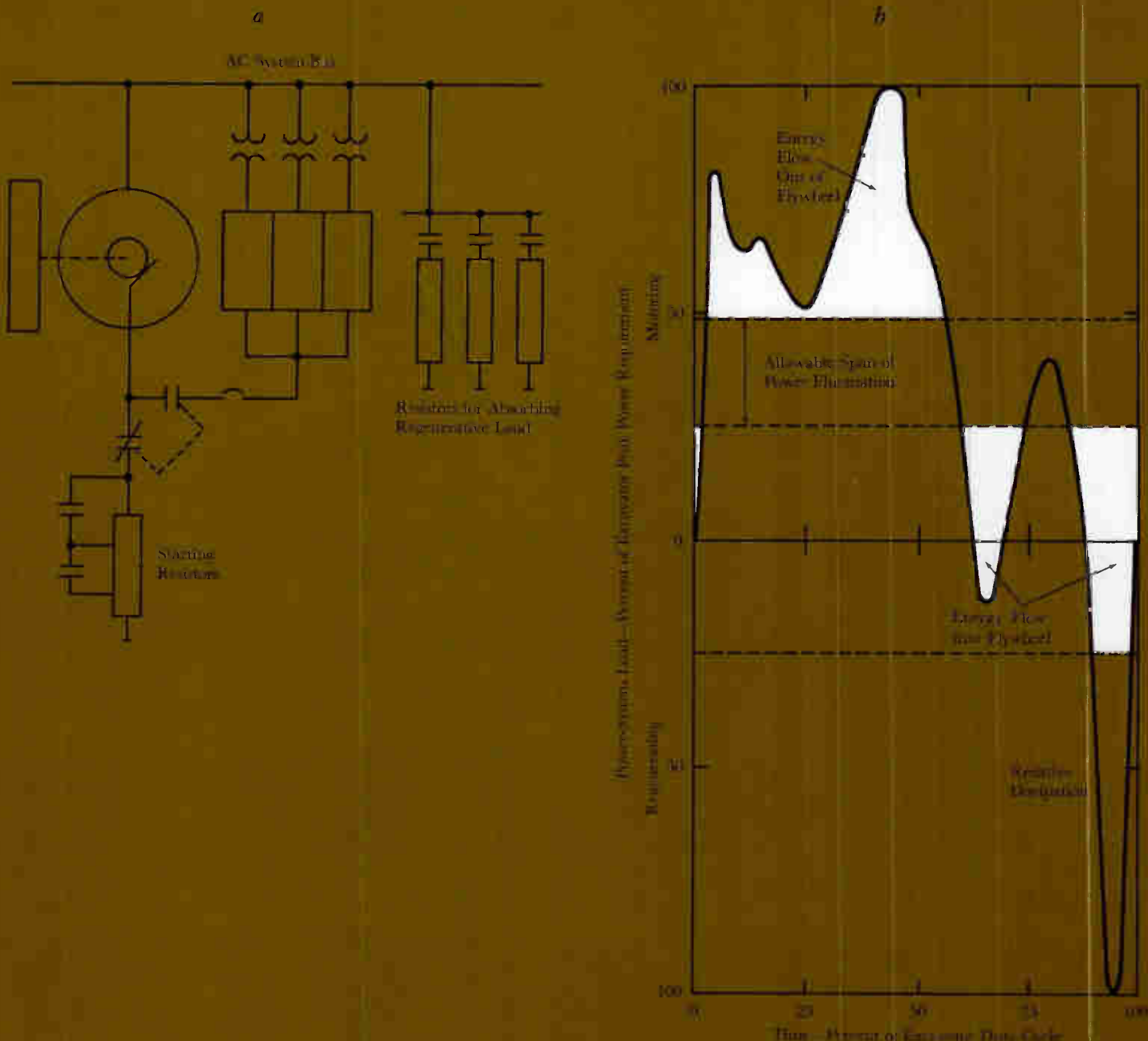
Peak-Load Compensator

The problem of using a flywheel set for energy storage is one of control, as the speed of the set must be varied to "pump" energy into and out of the flywheel. Several techniques have been used for speed control in the past, almost all of which involve pieces of rotating equipment in addition to the main flywheel set itself (Fig. 3). In essence, these approaches supply a variable-frequency voltage to the rotor of the wound-rotor motor, and, by so doing, force the angular velocity of the rotor to change. Most of the schemes have been limited to operation below the synchronous speed of the set.

In operation, a magnetic field is established by the motor stator. This field rotates in synchronism with the line supply frequency (exactly, as with any con-



4—The new peak-load compensator has cycloconverters instead of additional synchronous machines to supply the variable-frequency voltage for rotor excitation (*a*). Use of cycloconverters enables the m-g set to operate through synchronous speed, thereby minimizing its electrical power requirements and the size of its flywheel. In the power curve (*b*), the white areas show the periods when the peak-load compensator is active; that is, when both it and the power system are contributing to the net power flow.



5—In the complete peak-load compensator (a), equipment size can be further reduced by including resistors to dissipate some of the regenerated power instead of forcing it into the flywheel. The effect is to reduce the regenerative peak (b). (The dashed line between contactors indicates interlocking that prevents simultaneous closure.)

ventional three-phase motor). The rotor is excited from a variable-frequency three-phase source through its slip rings, establishing a rotating magnetic field that rotates in synchronism with the variable-frequency supply. Since the rotor is mechanically free to rotate, under normal operating conditions it moves at such a velocity and in such a direction as to lock the rotor field and stator field together. For instance, if ω_s is the angular velocity of the stator field with respect to the stator and ω_r is the angular velocity of the rotor field with respect to the rotor, then

$$\omega_s = \omega_r + \omega, \quad (1)$$

where ω is the angular velocity of the rotor. With this condition satisfied, the wound-rotor motor operates as a synchronous machine.

By advancing or retarding the phase of the rotor supply, the rotor field can be made to advance or retard slightly from its normal steady-state condition. The resulting interaction with the stator field causes decelerating or accelerating torque to be developed and the rotor to change speed.

As with the more conventional form of wound-rotor motor operation, several components of torque or power can be identified. Neglecting losses, the power flow as seen by the system is the power crossing the air gap (P_{ag}). This divides into the mechanical power (P_m) applied to the rotating masses and the electrical power (P_e) flowing in the rotor circuit. The division of power is related to slip (s),

$$s = \frac{\omega_s - \omega}{\omega}, \quad (2)$$

such that with $P_{ag} = P_m + P_e$,

$$P_m = (1-s)P_{ag} \text{ and } P_e = P_{ag}. \quad (3)$$

When operating near synchronous speed (with s about 0), a relatively small amount of power flows in the rotor circuit compared with that going into the flywheel. If the set were able to operate through synchronous speed, the rotor electrical power requirement could be minimized. At the same time, the flywheel size could be reduced, since the higher average speed would require less inertia to store a given amount of energy.

The new peak-load compensator achieves these benefits by permitting operation of the flywheel m-g set through synchronous speed. Its source of variable-frequency power for the rotor circuit is the cycloconverter, a piece of apparatus made feasible by solid-state technology (Fig. 4). The three-phase cycloconverter can generate low-frequency alternating currents of either phase rotation, or direct current. Therefore, ω_r in Equation 1 can be either positive, negative, or zero and thus ω_s will be below, above, or at synchronous speed.

The cycloconverter can be likened most simply to three voltage-regulated thyristor dual converters, one for each phase. As reference, each dual converter receives a low-frequency (occasionally dc) voltage, with the three references synchronized and maintained in exact 120-degree phase relationship with each other. By very slowly changing the reference frequency with an external control system, the output frequency of the cycloconverter is caused to vary, and hence the rotor field angular velocity is changed. Rotor torque develops and the rotor speed changes. As the speed changes, power flows between the flywheel and the power system.

This power flow is from the flywheel during periods of high excavator motoring load and into the flywheel during periods of low motoring or regenerative load (Fig. 4b). In the figure, it is assumed that the power system can absorb the power fluctuations represented by the span between the two boundary lines. The energy-storage requirements of the compensation system (cycloconverter, wound-rotor motor, and flywheel) are proportional to the white area. The necessary peak power capability is proportional to the maximum absolute value of the difference between the base of a white area and its associated load peak; for the system illustrated, it occurs during maximum regeneration and is more than twice the power flow occuring during maximum motoring. The exact positioning of the white areas is set by the requirement that net energy flow over the whole cycle must be zero.

To reduce the size of the equipment (which is determined by peak power capability) without appreciable change in the energy flow, the regenerative peak can be reduced by dissipating a portion of the regenerative power in resistors instead of forcing it to flow into the flywheel via the wound-rotor motor. Such a scheme is illustrated in Fig. 5. With only one machine, the resistor losses can be reasonably large; however, with several machines operating on a power system, simultaneous peak regeneration of all machines occurs infrequently and total power dissipated in the resistors is small.

Design considerations for such a system are that the positive and negative flow of energy (in and out) to the flywheel must be zero, the positive peak power requirements should approximately equal the negative peak requirements to minimize motor size, and acceptable levels of power swing must be determined from an evaluation of the penalties imposed by the power supplier versus the capital and operating costs of a compensating system. Digital computer studies aid in the choice of operating parameters, such as flywheel energy capability and peak-power motor capability; from these choices, costs can be determined to permit the final evaluation.

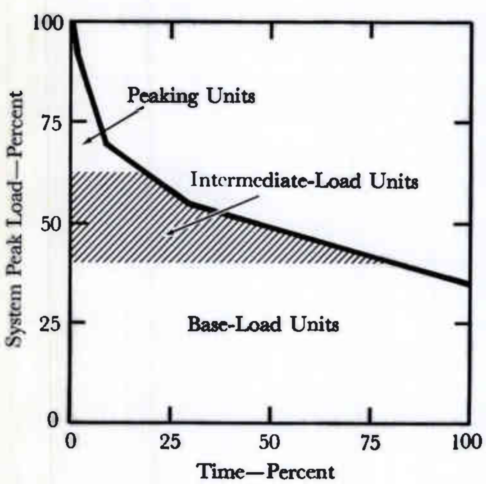
Conclusion

The peak-load compensator not only corrects for real power fluctuations but also reduces voltage flicker problems by making the load on the power system itself more nearly constant. It has the effect of moving a new power source to the excavating site. Used in conjunction with suitable reactive power control, it should enable the largest excavators to operate on small power systems with a minimum of disturbance.

Combined-Cycle Plant Serves Intermediate System Loads Economically

P. A. Berman
F. A. Lebonette

A combined-cycle plant—in which gas turbines, heat-recovery boilers, and a steam turbine are matched to provide an optimum plant—provides a power level of 230 MW at a heat rate less than 9400 Btu/kWh. Installed capital cost is kept low by use of pre-engineered components and packaging techniques.



1—System peak load duration curve shows service of intermediate-load units.

In recent years, the electric utility industry has been installing two basic types of power generating stations to provide for the base load and peak loads on their systems. The main source of base-load power has been steam turbines, and through the years the technological improvements in base-load steam turbine design has provided improved heat rates due to increasing temperature, increasing pressure, and using regenerative and reheat steam cycles. Gas-turbine plants purchased for the past several years have been used primarily to handle the peak loads.

Over the years, the *intermediate load area* between base load and peak load on the system (Fig. 1) has been supplied from the older, less efficient base-load units. However, the relatively small technological gains in recent years have been offset by increased costs in other areas, such as construction costs. Heat-rate gains in steam plants have slowed and new units are now not much more efficient than their predecessors. There is no longer any real economic advantage in purchasing new base-load units to improve overall system heat rate and moving older, but nearly as efficient, units into the intermediate load region. Therefore, Westinghouse turbine designers have been investigating power plants expressly designed to handle intermediate duty. These plants would provide high levels of power, but they would have short delivery times and capital costs somewhere between the simple gas-turbine peaking plant and the central-station steam plant. The duty would be from 2000 to 7000 hours per year, and the plant would be designed to start up daily in one hour or less.

Studies have shown that a combined-cycle system using gas turbines and steam turbines could provide an optimum plant for this duty.

Combined Cycle

The combined-cycle plant proposed for intermediate-load duty is composed of gas turbines, heat recovery equipment, and steam turbines. These components can be combined in many ways, so it is necessary to define a particular combined-cycle plant to make specific statements and draw conclusions.

The Westinghouse combined cycle, shown in Fig. 2, consists of two gas turbines, two heat-recovery boilers, and one steam turbine. Each gas turbine is a completely packaged power generating plant operating at 3600 r/min. Each exhausts to a heat recovery boiler.

To accomplish the match between the gas turbines and the steam turbine, the heat recovery boilers utilize the exhaust heat from the gas turbines and provide additional energy by burning fuel in burner elements to produce the steam flow required by the steam turbine.

Each heat recovery boiler consists of five basic components: a burner element provides additional heat energy through combustion of fuel in the gas-turbine exhaust gases; a superheat section and an evaporative section together provide superheated steam for the steam turbine; and an economizer and a low-pressure coil provide feedwater heating to the evaporative section.

The steam turbine is a single-cylinder nonreheat condensing unit operating at 3600 r/min and driving its own 3600-r/min electrical generator. The steam exhausts axially to the condenser.

Selection of Components

Basic economics favor a combination of the largest gas turbine, heat-recovery boiler, and steam turbine possible where these components can be prepackaged so that they can be installed in a minimum time. Key to matching the components for a specific plant is the relative sizes of the steam turbine and gas turbines. These components are unique designs that are not available in an infinite number of sizes, but they should be combined in an optimum manner.

The largest Westinghouse gas turbine available on a production basis is the W-501 frame,[1] which has a rating of approximately 60 MW.

The large low-pressure 3600-r/min steam turbines that can be packaged are the 23-, 25-, or 28.5-inch low-pressure

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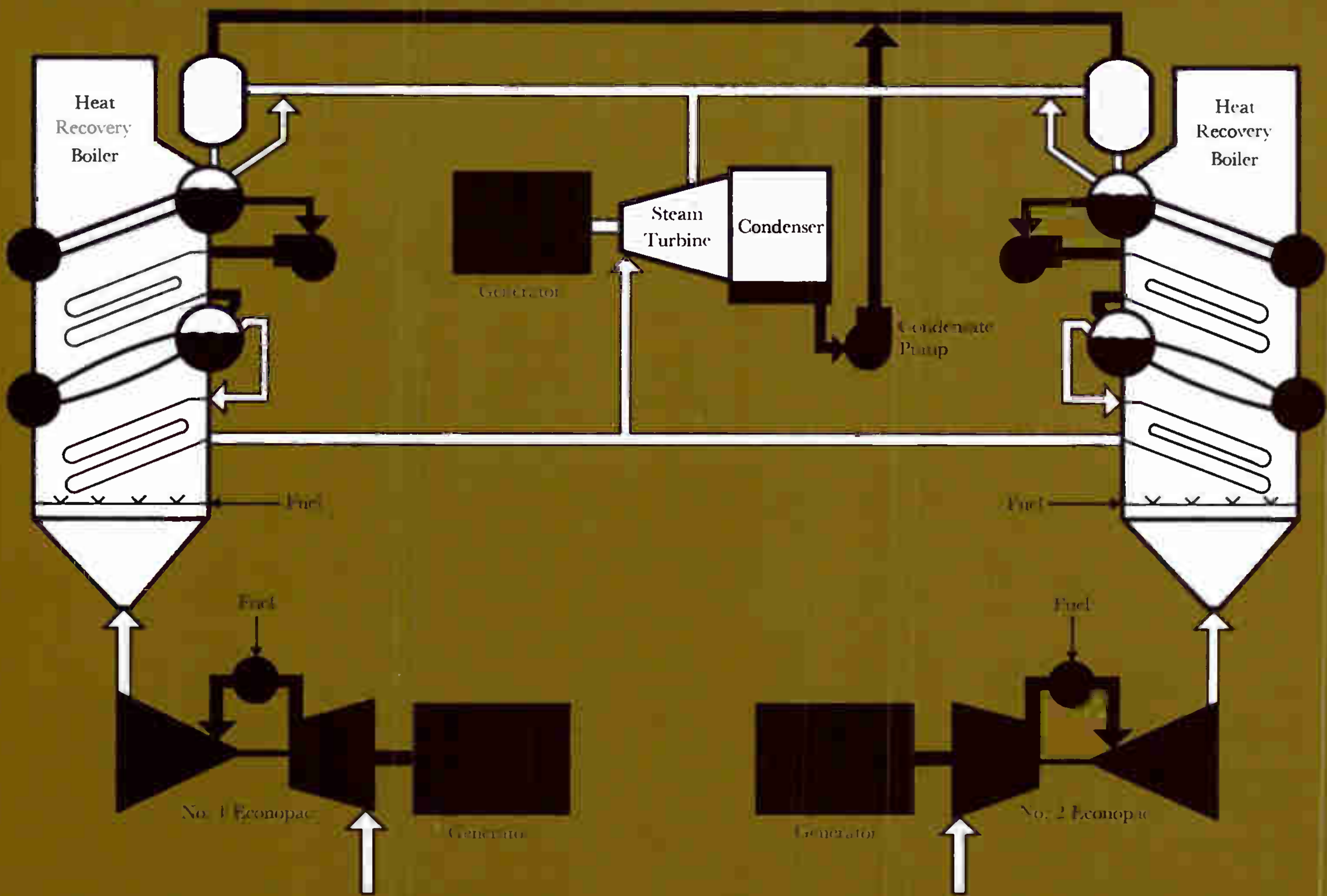
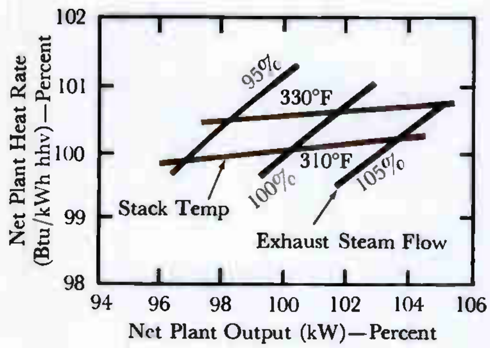
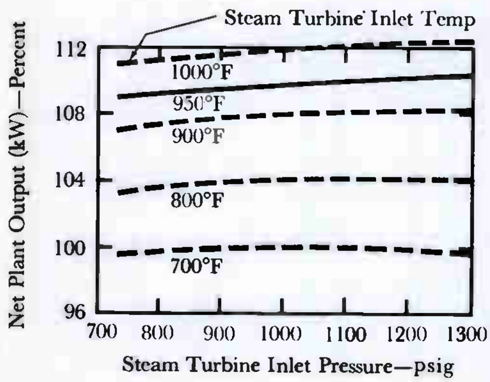
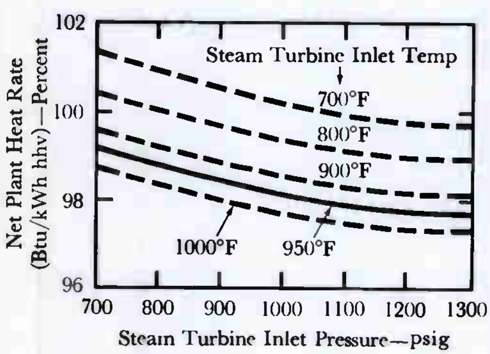


2–Combined-cycle schematic arrangement.







3—(*Top*) Effect of exhaust steam flow on net plant performance.

4—(*Center*) Effect of steam conditions on net plant power output.

5—(*Bottom*) Effect of steam conditions on net plant heat rate.

ends. (These values refer to the last-row blade heights of the steam turbines and are indicative of their flow capacities.) These ends are normally the exhaust elements in central station tandem-component units; they were investigated as single-cylinder units that could be shipped fully assembled with rotors in place to minimize field erection costs.

The most logical components available for combining into a combined-cycle plant, the W-501 gas turbine and a 23-, 25-, or 28.5-inch low-pressure steam turbine, must be matched in the cycle with a heat recovery boiler. The heat recovery boiler should also be a packaged unit so that it can be installed in a minimum time. Packaged heat-recovery boilers designed for high gas flows at relatively low temperatures normally incorporate extended heat-transfer surfaces in the form of finned tubes. This limits the size of the boiler and places restrictions on boiler construction, leading to systems having relatively little firing.

For optimum plant performance, steam flow through the turbine element should be maximized. The effect of steam flow on the net power and heat rate of a combined-cycle plant for a given selection of stack temperatures is shown in Fig. 3. For example, as flow increases from 95 to 100 percent (at a given stack temperature) the net gain in power is about 3½ percent with an accompanying increase in heat rate of less than 0.2 percent. Thus, it is desirable to choose a gas turbine and recovery boiler combination that can provide the maximum allowable steam flow for the low-pressure-end size selected.

A single W-501 gas turbine would reach the limit on allowable firing temperature for a packaged heat-recovery boiler utilizing finned tubes before the boiler could produce the maximum allowable steam flow for a single-flow 23-inch end. Furthermore, the resultant power level with a single gas turbine would be approximately 125 MW, which is small for most utility intermediate peaking applications.

Two W-501 gas turbines in parallel can produce sufficient steam with suitable heat recovery boilers to reach the maximum allowable exhaust steam flow for both the 25-inch and 28.5-inch ends. The heat recovery boiler firing temperature required is about 1100 to 1200 degrees F, which is a reasonable value for finned tubes. Therefore, two W-501 gas turbines were applied to the cycle and the 28.5-inch turbine end was chosen to maximize power production in the steam turbine portion of the cycle.

The steam conditions chosen for the steam turbine inlet are 1200 psig at 950 degrees F. The effect of temperature on plant performance for a given pressure level is significant, as shown by the curves in Figs. 4 and 5. Increasing temperature 100 degrees produces approximately 4 percent more power, with a heat rate improvement of approximately 0.8 percent. Steam temperature was limited to 950 degrees F to avoid the need for more expensive materials for the steam turbine.

Performance also improves slightly as pressure is increased, as shown in Figs. 4 and 5 for two gas turbines and maximum allowable steam flow on a 28.5-inch end. Steam pressure was chosen at 1200 psig to avoid mechanical design problems, to avoid excessive water treatment, and to limit steam turbine back-end moisture.

The condenser pressure chosen is 2.5 inches Hg abs, which is a reasonable attainable value with cooling towers in most parts of the United States.

In summary, two W-501 gas turbines exhausting to two heat recovery boilers can produce the maximum allowable steam flow for a 28.5-inch-end steam turbine with inlet steam conditions of 1200 psig/950 degrees F and a condenser pressure of 2.5 inches Hg abs.

Boiler Pinch Point

A critical item in exhaust heat recovery is the boiler *pinch point*. (See *Heat-Recovery Boiler Cycle*.) The heat transfer distribution through the boiler is illustrated schematically in Fig. 6b, and the term pinch point is defined.

The effect of boiler pinch point on the overall plant performance, for a maximum allowable exhaust steam flow, is shown in Fig. 7. If the pinch point is increased by 10 degrees F, for a given stack temperature, power decreases 0.8 percent and heat rate increases 0.3 per-

Heat-Recovery Boiler Cycle

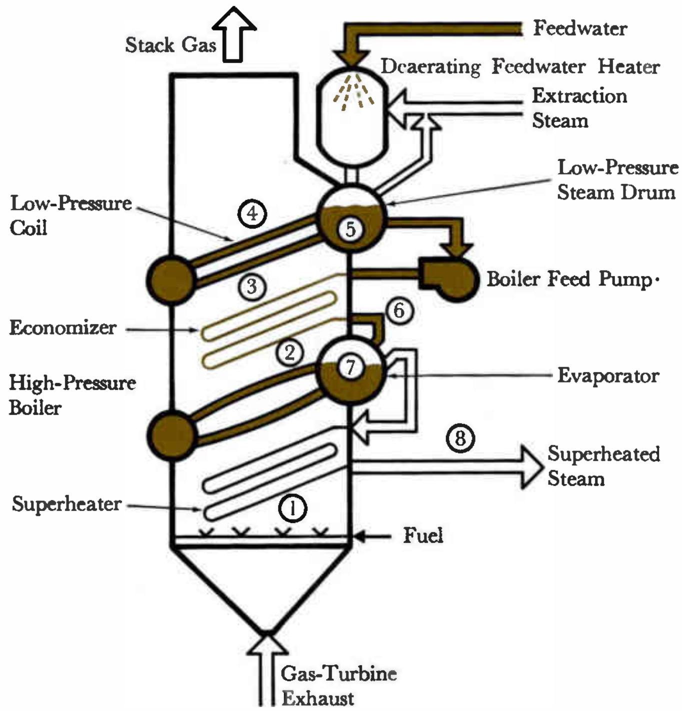
Selection of the basic cycle parameters for a heat-recovery boiler begins with the choice of steam turbine inlet conditions: Inlet steam ***pressure*** determines what the saturated steam temperature in the evaporator (*7*) must be; inlet steam ***temperature*** (*8*) determines how much energy must be added to the saturated steam as superheat; and the ***approach temperature*** selected (normally 5 to 20 degrees F) determines how much energy must be added to water coming into the evaporator (*6*) to bring it up to saturation temperature (*7*). The sum of those energy requirements is the energy required for each pound of steam flow through the turbine.

The steam turbine end selected sets steam flow, so the product of steam flow and energy per pound of steam is the total energy that must be extracted from the gas between the burner outlet (*1*) and the exit from the high-pressure boiler (*2*).

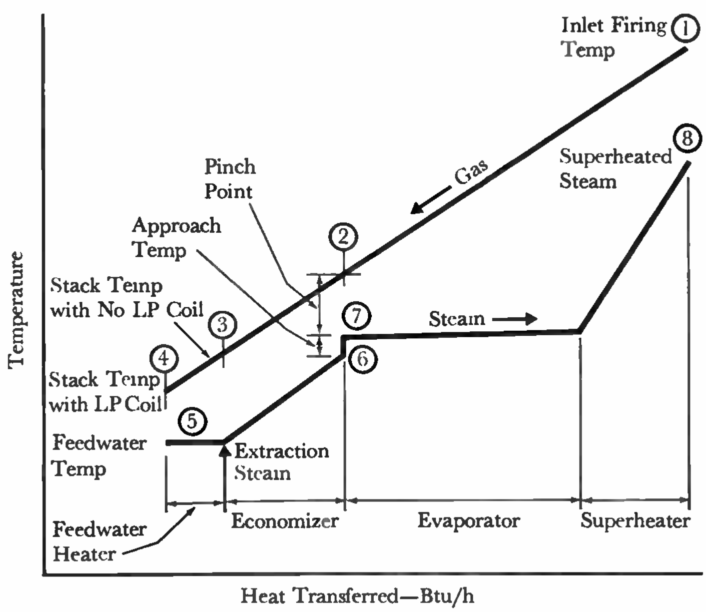
The gas temperature required at the exit from the high-pressure boiler (*2*) is found by adding the ***pinch point*** (the differential temperature between saturated steam and gas at the high-pressure boiler exit, usually 30 to 50 degrees) to the steam saturation temperature (*7*). Since gas flow is fixed by the gas turbine exhaust, firing temperature (*1*) can be found by dividing the total energy required from the gas by the gas flow to determine the gas temperature drop from the burner outlet (*1*) to the boiler exit (*2*). Once firing temperature (*1*) is set, the energy that will be available in the gas from the high-pressure boiler exit (*2*) to the stack (*4*) is also set.

Some of that remaining energy is recovered in the economizer (*2* to *3*), the amount determined by feedwater temperature (*5*). Beyond that, the only way further heat can be recovered is through the low-pressure coil, which uses recovered stack energy (*3* to *4*) to make low-pressure steam for the deaerating feedwater heater. The deaerating feedwater heater also has another source of energy, extraction steam from the turbine. The relative amount of steam used from these two sources becomes an economic tradeoff of first cost versus efficiency. For a fixed turbine end, more extraction steam will produce a larger throttle flow for a fixed exhaust flow so that more power can be taken from the turbine. On the other hand, the use of more low-pressure coil steam means that more heat can be recovered from the stack, which improves cycle efficiency. In other words, more extraction steam results in greater capacity (lower capital cost per kW), whereas more low-pressure coil steam provides better cycle efficiency (lower operating cost). The basic limitation to feedwater heating by recovery in the stack is the dew point (*4*). If stack temperatures were allowed to fall below this value, and if there is sulfur in the fuel, acid corrosion would result.

6a



6b



cent. For the combined cycle under discussion, the pinch point was chosen at 40 degrees F, a reasonably attainable value for boiler design.

For a given pinch point and the steam generating system depicted in Fig. 6a, the range of stack temperatures is limited to a minimum value of 280 degrees F to avoid corrosion in the boiler, and a maximum value of 345 degrees F, at which point no low-pressure steam is generated in the low-pressure coil of the boiler and all feed heating is done by extraction steam.

Plant Arrangement

The design parameters and the reasons for particular choices have been discussed. A plan view illustrating the physical plant arrangement is shown in Fig. 8. The components are arranged to permit grouping of electrical generators and steam generators. Adequate setdown space is provided for maintenance. The overall plant encloses an area 200 feet by 210 feet.

Plant Performance

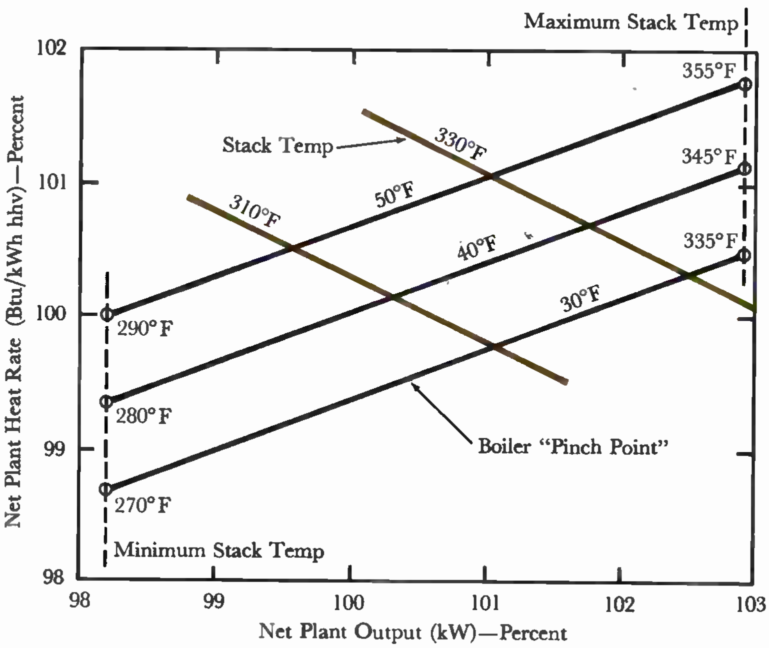
The plant is designed for dual fuel operation, burning either distillate oil or natural gas. With natural gas, the plant will produce 230,000 kW at a heat rate of less than 9400 Btu/kWh based on the fuel's higher heating value. This rating assumes an altitude of 1000 feet, an ambient air temperature of 80 degrees F, and a condenser pressure of 2.5 inches Hg abs.

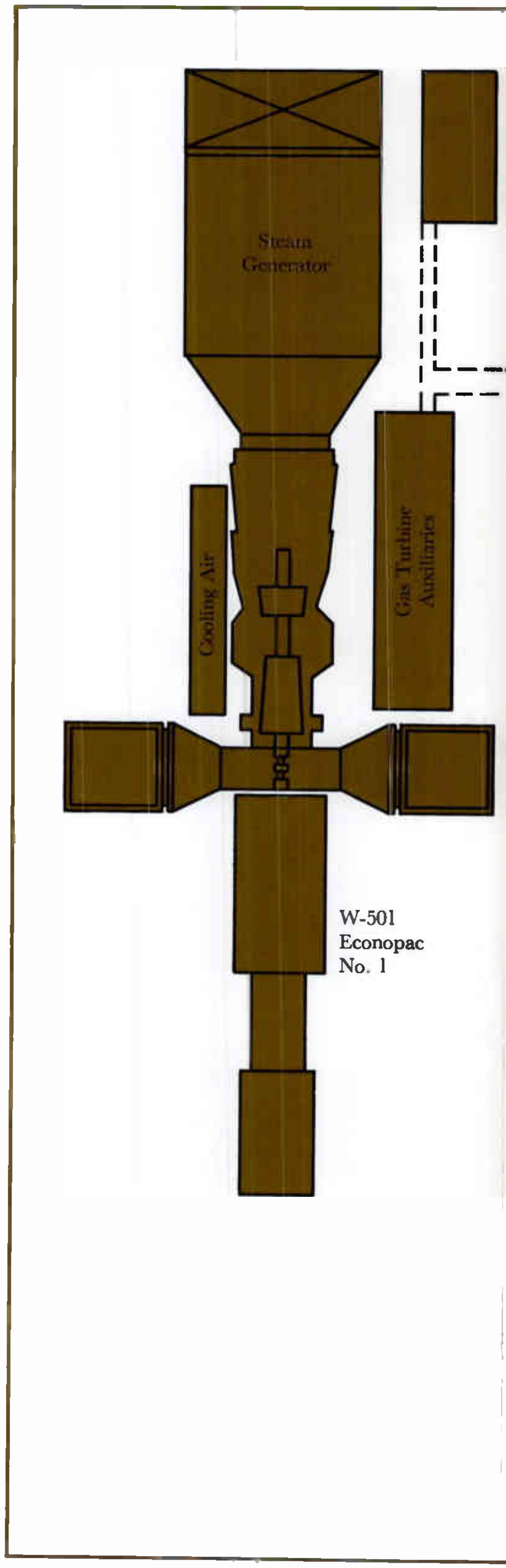
Conclusion

A power plant designed to cover the intermediate range of electrical demand combines two gas turbines with a steam turbine and retains the advantages of both. The combined cycle provides a power plant that has the following characteristics:

1) Power level of 230 MW at 9400 Btu/kWh (based on natural gas fuel, higher heating value);

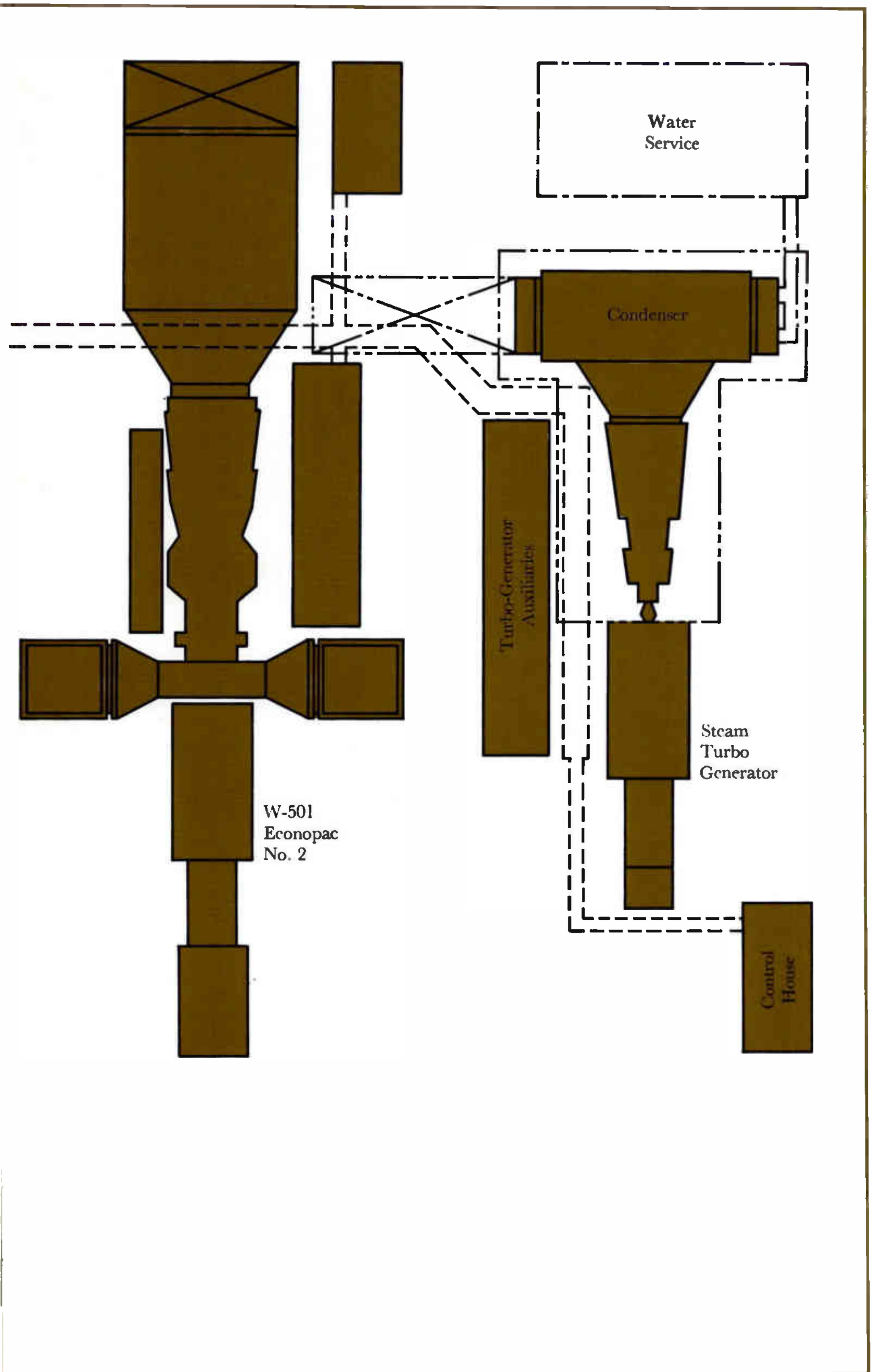
2) Availability of full-load power in one hour from "hot standby" conditions, and half-load in about 30 minutes;





7—(*Above*) Effect of boiler pinch point on net plant performance.

8—(*Right*) Plot plan of physical plant arrangement.



3) Installed at a \$/kW value less than that of central station steam plants due to pre-engineered packaging techniques;

4) Shorter installation time, again due to pre-engineering and packaging; and

5) Since 50 percent of the plant is gas-turbine power, less heat is rejected to cooling water (on the basis of pounds of water per kilowatt) than in a conventional steam turbine plant of similar size. For some locations, this could simplify or eliminate siting problems.

REFERENCES:

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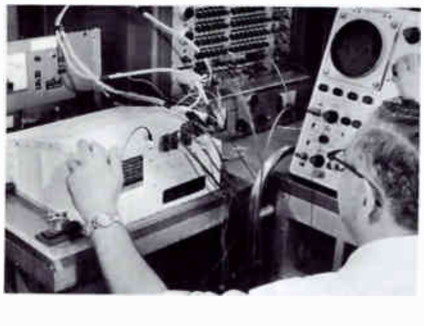
Apollo Inverter

Back from 10 orbits around the moon, one of the inverters from the *Apollo 8* command module is being given a postflight test in the photograph. Three of these solid-state inverters are used, two normally in service and one in reserve. They invert 28-volt dc power from the spacecraft's fuel cells and batteries to provide three-phase 400-cycle 115/200-volt ac power for the various ac loads. They have operated without failure in all of the Apollo missions to date, logging some 100,000 hours of operation by the end of the *Apollo 13* mission in qualification tests, unmanned flight, and manned flight.

The time-tested Apollo command-module inverter consists essentially of a dc buck-boost voltage regulator and eight ac power stages. Eight equally phase-displaced voltage square waves from the power stages are synthesized into three-phase stepped waves that are nearly sinusoidal. The secondary windings of an "octadic" power transformer are interconnected in a unique harmonic-neutralization combination. Little dc and ac filtering is required because the interconnection neutralizes harmonics up to the fifteenth.

The inverter was designed and built by the Aerospace Electrical Division under subcontract to North American Rockwell's Space Division, which built the Apollo command module for the NASA Manned Spacecraft Center.



verters might provide isolation of the disruptive loads.) The other is unbalanced phase loading (both real and reactive), which upsets individual phase voltage magnitude and phase position integrity on a phase-coupled three-phase inverter.

The trend is toward such disruptive ac loads in aerospace power systems because of the increasing use of single-phase devices. It can be countered by applying the new inverter in single-phase modules that can be paralleled to build up a large single-phase load capability. The modules are universal in that they can also be connected easily in three-phase arrays to provide high-power three-phase systems.

The New Inverter

The ability of a universal single-phase inverter module to serve effectively as either a central or a local static inverter is measured by how well it can compensate for line disturbance at its dc and ac ends. The new time-optimal-response single-phase inverter operates by feedback synthesis of its output to produce precision power even when all disruptive influences at both the input and output are acting in concert. The secret is use of a closed-loop control that accomplishes high transient response, as a high-fidelity linear amplifier does, to make the inverter output comply with a sinusoidal prototype waveform.

The voltage level of a variable-voltage sinewave oscillator (used to generate the prototype waveform) is controlled in response to a sampling of output voltage (Fig. 1). A separate high-frequency sampling of the filtered ac output is made for the master comparator, which has a hysteresis established by positive feedback (resistor *R1*). Various compensation and protective networks produce a continuously oscillatory mode of operation with output always in the close vicinity of the prototype waveform.

A single center-tapped power stage drives the power transformer. It obeys the simple two-state commands from the master comparator, which monitors the comparison of the prototype waveform with the output (Fig. 2).

The di/dt feedback (which is capacitor-voltage "jerk" feedback) of capacitor *C1* current provides this inverter approach with anticipatory information that is new to the bang-bang feedback art. The hysteresis of the master comparator is modified by the jerk feedback voltage to anticipate changes in the ac output voltage.

Classical bang-bang theory employs drive that is exclusively either +1 or −1.[3] In the new inverter, however, balance in drive magnitudes (+1 or −1) exists only at crossover of the output sinusoid (Fig. 3). At all other times, the classical theory must be modified by a sine function that makes "boost" drive weaker near peak output voltage while "buck" drive is augmented.

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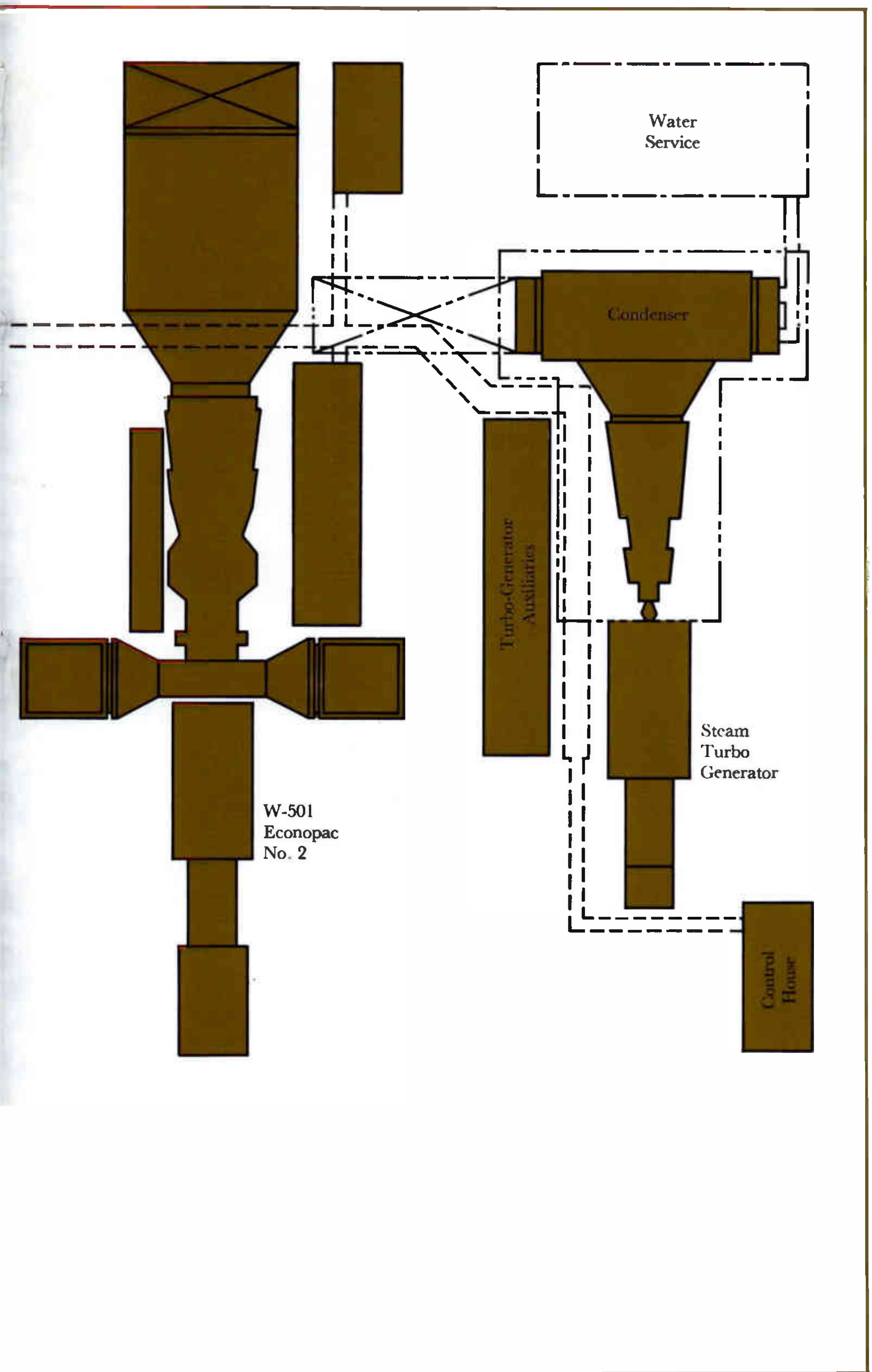
The most apparent difference between the new bang-bang inverter and advanced open-loop waveform inverters[4,5,6] is in the control of the output filter: at no time is the filter allowed uncontrolled resonance. A positive or negative battery potential is always applied to it, thus overcoming the effects of any disturbances caused by load changes or power-source variation.

The new inverter can have any of several kinds of power stage. The full-bridge stage, with its four power-switching elements, is by far the best kind when input voltage is 56 volts or higher. It is able to expand the bang-bang approach and some other advanced inverter approaches to commutated waveforms,[5] which can achieve lower harmonic distortion because the drive selection of zero volts is available in addition to plus and minus battery potential.

A center-tap power stage was included in Fig. 2 because the earliest applications



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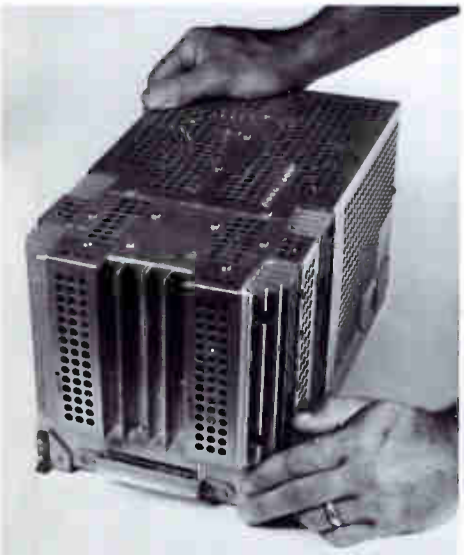
Static Inverter for Aerospace Applications Provides High-Quality AC Power Despite Disruptive Influences



Photo—**Inverter for the Lockheed L-1011 aircraft is of the new type—the "bang-bang" time-optimal-response inverter. Feedback control enables it to synthesize an ac output that is insensitive in voltage and frequency to input voltage ripple and to load variations. The inverter is made in single-phase modules; for a spacecraft, modules can be combined to provide the level of single-phase or three-phase power required.**

Wave-form synthesis in a new aerospace inverter is by feedback rather than by the feed-forward techniques normally used in static inverters. As a result, voltage and frequency of the ac output are inherently insensitive to input voltage ripple and to load variations.

The inverter developed for the Apollo Command Module was based on an advanced circuit concept for 1960, and the concept is still a strong candidate for aerospace applications wherever phase loads are reasonably well balanced and linear. However, spacecraft and aircraft ac electrical loads no longer tend to be so restricted.

For today's needs, a more advanced static inverter has been developed; it synthesizes a voltage wave form by a time-optimal-response closed-loop technique. The result is inherent demodulation of input voltage ripple and provision of output voltage that is transient-free despite nonlinear load variations as great as 100 percent instantaneous change—all without complex circuitry.

The new inverter's output is driven in a "bang-bang" mode, which means that the alternate switching from negative to positive battery polarity (to construct the ac output waveform) is done at full positive and full negative voltage. A nonlinear feedback control system determines optimum switching times to force the waveform of the output voltage to comply with that of a prototype sinewave.

Inverters are needed for spacecraft because many ac loads have to be supplied even though all the power is presently provided by inherently dc devices such as batteries and fuel cells; they are needed in large commercial and military aircraft to serve with batteries as standby ac power supplies. The first application of the new inverter is in a single-phase 750-VA rating for the Lockheed L-1011 commercial aircraft. For spacecraft, it would be packaged as a 500-VA single-phase module. Modules would be paralleled when more power is needed and connected in three-phase arrays when three-phase systems are desired.

Andress Kernick is a Fellow Design Engineer at the Aerospace Electrical Division, Westinghouse Electric Corporation, Lima, Ohio.

Harmonic neutralization[1] was the basic approach used in the reliable Apollo command-module inverter. (See *Apollo Inverter*, p. 176.) It continues its hold in the field of large industrial static inverters such as the Accur-Con line of inverters, but development of fast-switching power transistors and gate-controlled switches has challenged designers of superior static inverters in smaller ratings (15 kVA and below) to maintain high efficiency while achieving waveform quality and response that approaches what has been provided in the past by linear feedback amplifiers. The result was the development of the new inverter.

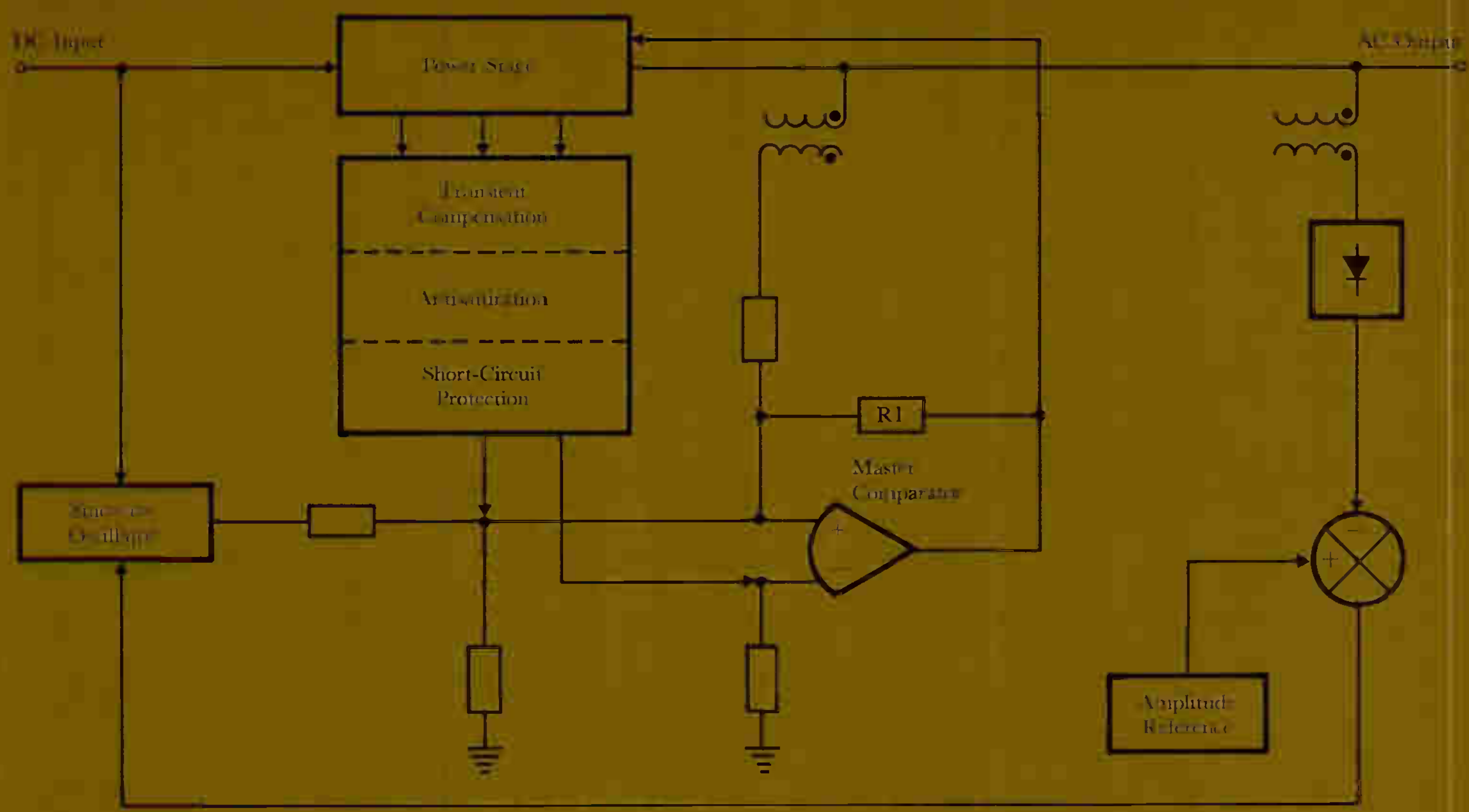
Besides inverter improvement, the development has advanced time-optimal-response nonlinear servomechanism practice in general. Its concepts can improve performance of many types of static power conditioning equipment.

Central versus Local Inverters

An aerospace power system starts with a basic energy converter or battery that produces dc power, some of which is used directly and some inverted to ac power. If one inverter is connected to several ac buses, it is known as a central inverter; if several inverters are each connected to separate buses, they are called local inverters.

When the dc input voltage is modulated by many nonlinear loads, centralizing the inverter as in the Apollo command module may save weight by requiring only one electronic filtering network.[2] There is no such advantage, however, if electronic active filtering can be done in the inverter inherently, without added circuit complexity, as it is in the new bang-bang time-optimal-response inverter; such an inverter can be used just as well as a local inverter.

One of the many disruptive interactions that could thwart the Apollo inverter in delivering precision power as a central inverter is the interaction of aperiodic and nonlinear distorting ac loads with the other inverter loads. (Separate local in-



1—Bang-bang time-optimal-response inverter, diagrammed in block form here, employs feedback to anticipate changes in ac output voltage and modifies the sum with output of a reference sinewave oscillator accordingly. The resulting summation is used by the master comparator to vary the power switching times to keep the waveform of the inverter output close to sinusoidal. (Dots indicate instantaneous like polarity.)

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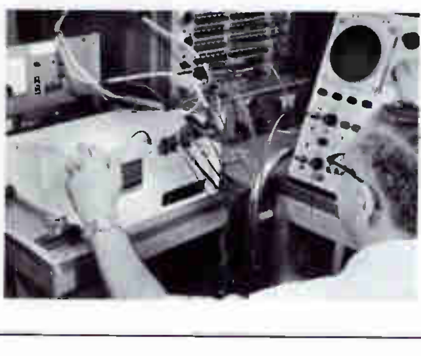

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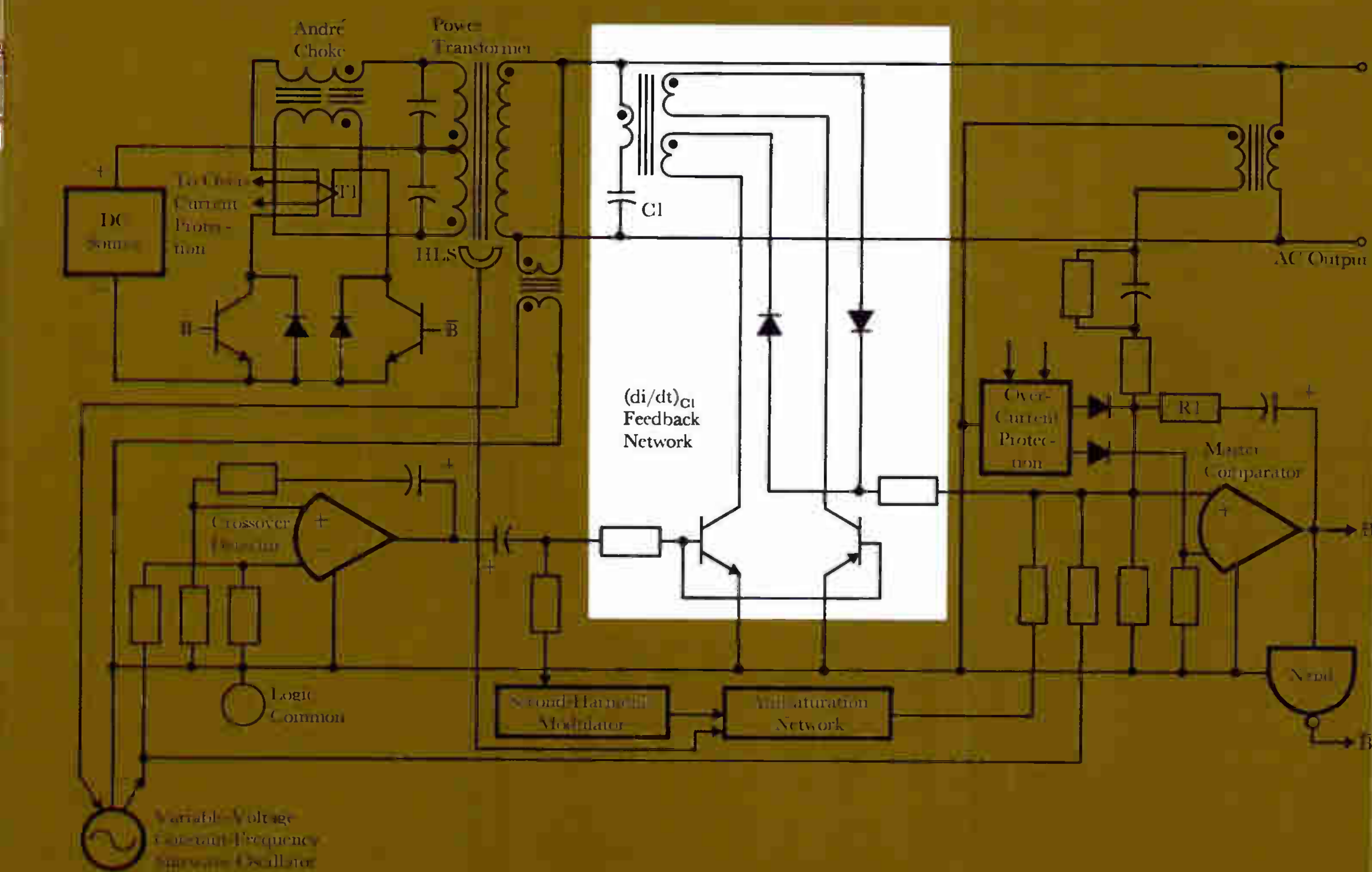
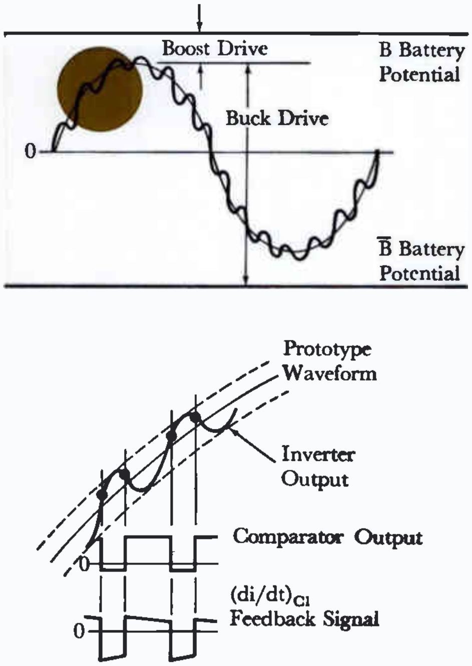
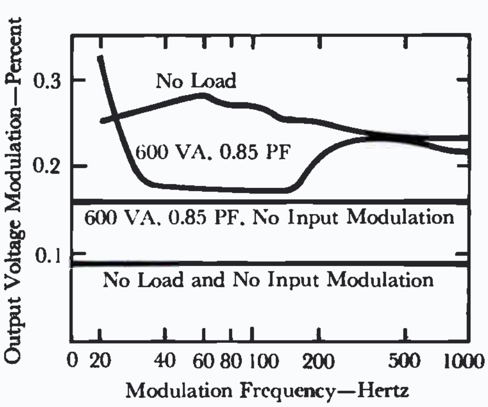


2—The inverter is diagrammed in greater detail here. A center-tapped power stage (upper left) is shown; other types also can be used.



3—Anticipatory control keeps the output voltage within desired limits around the prototype waveform. The control drive is not linear; instead, boost drive is made weaker near peak output voltage as shown while buck drive is made stronger. The dots on the enlarged output wave indicate switching times.



4—The negligible output voltage modulation due to input voltage ripple is illustrated for the new inverter at various conditions of input modulation and load. Modulation on the dc bus was one volt peak to peak on input voltage of 24 volts dc. This relative insensitivity to input voltage ripple is comparable to that of the Apollo command-module inverter. It suits the new unit for use as a local inverter as well as a central inverter.

of this inverter have been with batteries and fuel cells that provide only 20 to 30 volts dc power. The André choke used must be a "swinging" choke to accomodate wide load range; that is, its inductance must vary as a function of current. This nonlinear requirement, which normally applies only to André chokes, is important also in the design of single-winding filter chokes for the bang-bang power circuit. Nonlinearity provides high efficiency at low power outputs without seriously limiting the upper power levels.

The output filter choke swings such that the master comparator commands always maintain a minimum spacing in excess of the storage time of the power-switching devices, thus allowing for the storage time without waveform distortion. This advantage of the bang-bang inverter over those advanced inverters requiring operation of the power-switching devices at the edge of saturation permits efficient direct power conversion of a low-voltage power source with the simplest possible circuit.

When a low-frequency output voltage is required, the bang-bang inverter could have a transformerless high-voltage dc-link power stage to avoid a large fundamental-frequency transformer.

Transient Response

In attenuation of input voltage ripple, the new inverter duplicates the ability of the Apollo inverter (Fig. 4). It is, therefore, suited as a *local* inverter. Moreover, the inner feedback loop acting through its time-optimal power stage maintains output voltage close to that of the prototype sinewave in spite of disruptive load, as an ideal *central* inverter should (Fig. 5).

Overcurrent protection circuitry senses instantaneous current in the power-switching devices and commutating diodes of each power branch as shown in Fig. 2. Overriding inputs are exerted to reverse the master comparator when a dangerous level of current is approached. Retreat from the excessive current level to approximately 60 percent within a half period of output short-circuit current is carried by the commutating diode of the opposite branch. The short-circuit mode of operation is also "bang-bang" in that the nonlinear output filter choke delays buildup and decay of power-branch current between hysteresis limits. Trapezoidal short-circuit current in the power branch induces a similar voltage waveform on the burden of current transformer *T1*. Peak-to-rms ratio of power-transistor current in the trapezoidal waveform approaches 1.25 instead of the more severe 1.414 normally encountered with sinewave operation. Current limiting ceases with an immediate return to normal operation when the overcurrent is no longer approached.

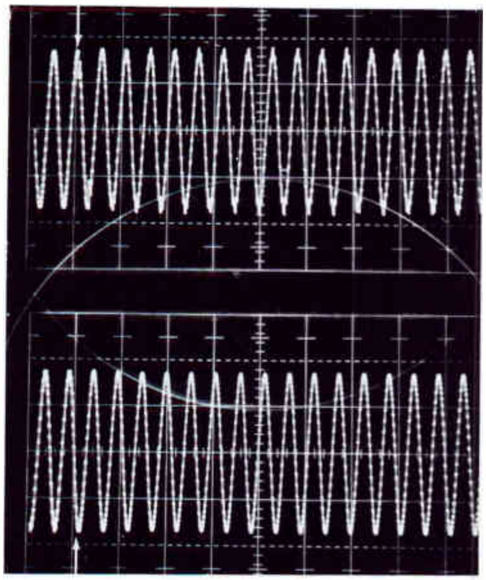
A 750-VA bang-bang inverter has been connected in parallel with one phase of a 90-kVA aircraft generator at a slip frequency of 12 hertz without damage, since the instantaneous overcurrent protection treats this condition just as it would any ordinary short circuit.

Control of DC Component

A small dc component of unbalance between the volt-seconds of alternate half cycles in the operation of the power transformer can result in eventual saturation of the magnetic core on one end of its unsymmetrical hysteresis loop. The intensity of the exciting current under saturated-core conditions can exceed the highest instantaneous load current on the inverter several times over unless some preventive measure is taken.

The saturation problem requires a new solution in advanced static inverters, where previous approaches such as core gapping and early termination of power-switch half-cycle conduction are inadequate. These inverters produce a prescribed fundamental-frequency waveform (usually a sinewave) by numerous discrete switching cycles per period, and the integrity of the waveform depends on each of the controlled segments per half period remaining intact; therefore, the inverters cannot allow half-period balance control, which would tamper only with the latter segment or segments of the waveform. Whatever corrective action is to be taken must be distributed evenly among the discrete segments generated per half cycle.

One of the major causes of dc component in inverters is switching-time *a*



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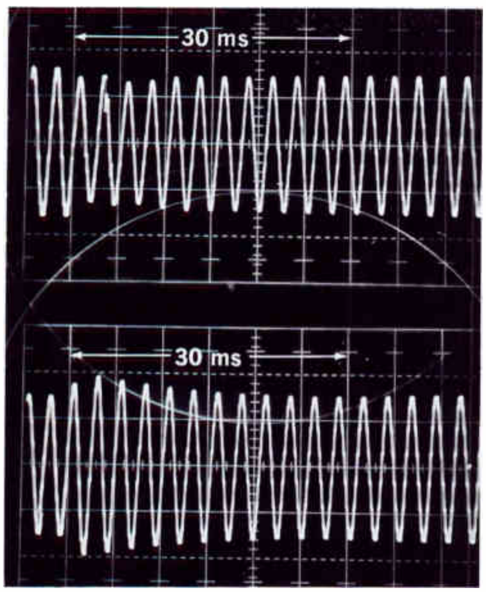

5—(*a*) Lack of output voltage transient when going directly from no load to full load (upper), and from full load to no load (lower), is illustrated by oscillograms for the new inverter. The arrows point out where load changes occurred; scale divisions are 5 milliseconds and 100 volts. For comparison (*b*), the response of the Apollo command-module inverter to the same conditions of single-phase load is illustrated. The disturbances lasted 30 milliseconds, as indicated by the arrows. Insensitivity to disruptive loads makes the new unit better suited for use as a central inverter in a spacecraft.

error. In the advanced inverter approaches, the problem worsens considerably because the errors accumulate from the generation of multiple segments, whereas in conventional square-wave or quasisquare-wave approaches there is but one controlled segment per half period.

Once saturation is impending in the power transformer, the increase in exciting current tends to reduce volt-seconds delivered through the driving-source internal impedance (the conventional way of controlling saturation); however, an independent sensing device might choose to make up those lost volt-seconds and thereby lose stability. The pitfall is avoided in the new inverter by sensing the condition of the power transformer rather than attempting to balance volt-seconds by means of an independent device.

This potential instability plagues the transformerless high-voltage dc link power circuit, for the saturable magnetic core is located somewhere in the ac load. Use of series capacitors to block dc component, as is done in the staggered-phase carrier-cancellation approach, may well be the only infallible solution for the various dc-link circuits.[4]

For transformer-type power stages, a hysteresis-loop sensor (half of a small "C" core) bridges a stepped gap in the main power transformer core (Fig. 2). The gap is relatively free of flux except when saturation at one end of the hysteresis loop is impending.

To correct the unbalanced flux condition, an antisaturation network interprets the signal from the hysteresis-loop sensor. The result is a negative dc-level correction for mixing with the output of the sinewave oscillator to form the prototype waveform at the input to the master comparator. The antisaturation network functions by means of a ring demodulator biased by a second-harmonic modulator that is inherently synchronized to the fundamental of the sinewave reference signal. When the hysteresis-loop sensor is properly phased to the second-harmonic modulator, the dc-level correction signal is polarized such as to neutralize dc component in the inverter's output by its effect on the prototype waveform.

Summary

Wherever phase loads are not reasonably well balanced and linear, a more advanced static inverter than the Apollo command-module type is essential. Such a device is the new bang-bang time-optimal-response inverter. In addition to single-phase and three-phase paralleling capabilities, its universal single-phase modules have inherent dc input ripple demodulation and elimination of nonlinear ac load distortion on the output. This capability suits the new unit for use as either a central or a local inverter.

Feedback of output filter-capacitor current provides the unique anticipatory feedback control that enables the inverter to maintain time-optimal response and its attendant low waveform distortion over a wide load range.

In parallel arrays, load is divided continuously by an instantaneous differential current sensor loop with error input to the individual master comparators. Accurate phase and frequency control are accomplished at the level of the prototype waveforms. Finally, even though the new inverter has a 400-Hz power transformer, its circuit simplicity keeps its size, weight, and efficiency comparable to those of more complex inverter approaches.

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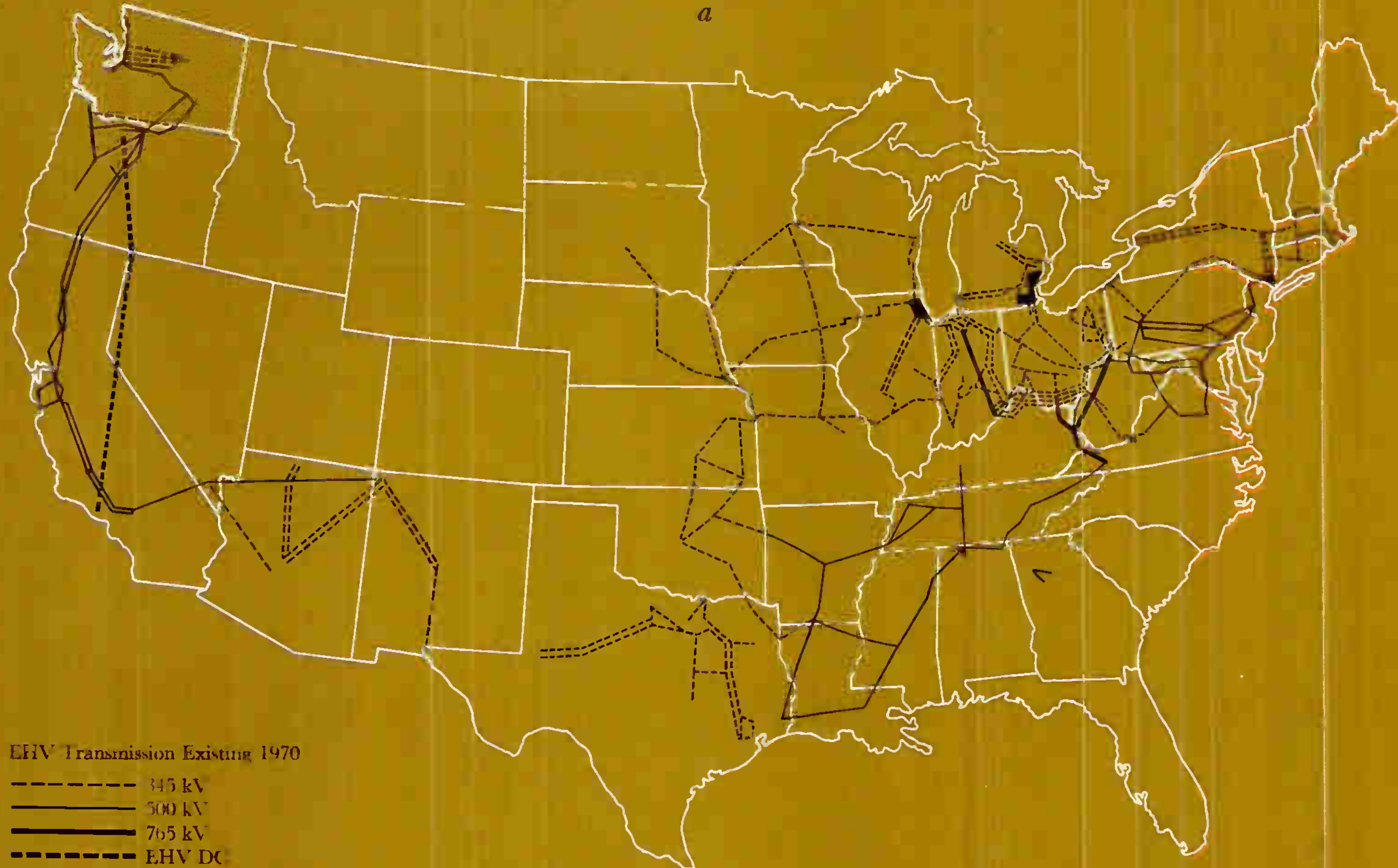
a


EHV Transmission Existing 1970
345 kV
500 kV
765 kV
EHV DC

b


EHV Transmission FPC 1990
345 or 315 kV
500 kV
765 or 735 kV
EHV DC

Transmission in the 70's

R. F. Lawrence

Decisions made in the 1970's about kinds and voltage levels of power transmission will establish the patterns for several decades beyond. Surveys and industry reports show no plans for transmission voltage levels above 765 kV. However, it is not too early to think about building transmission lines now for operation at higher UHV voltages in the future.

An overall view of transmission in the United States today reveals a complex of transmission voltage lines from 115 kV up through 765 kV. However, an indication of the expected growth for the 70's can be obtained by considering only EHV.

The EHV lines that were in service at the beginning of 1970 are shown in Fig. 1a, and the dramatic change expected by 1980 is shown in Fig. 1b. (This pictorial view of transmission growth is from the FPC Regional Advisory Committee Reports.[1]) Note the expansion of 765-kV transmission in the Midwest and the planned introduction of it in the Pacific Northwest.

Beyond 1980, additional 765-kV transmission is expected in the New York–New England area and in the Twin Cities area in Minneapolis.

The tremendous population growth in the southeastern United States, particularly Florida, represents a heavy load growth but relatively little increase in EHV transmission.

According to these plans there are no interties to the Southern Company or Florida power pool at EHV, nor is the Texas interconnected system tied to the rest of the country by 1980. The western U.S. transmission "doughnut" is still not interconnected at EHV voltages. The eastern two-thirds of the U.S. and the western third are interconnected at a voltage level above 230 kV.

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1—(*a*) EHV transmission lines in service at the beginning of 1970 included 345-, 500-, and 765-kV ac lines and a dc line on the West Coast. (*b*) For comparison, the added lines expected by 1980 are shown.

While the maps do not show use of any voltage above 1100 kV, the FPC Regional Advisory Committee Reports reflect the consideration of use of voltage in the 1100-kV range. The increase of circuits in parallel not only on the 345-kV systems but also on the 500-kV systems implies increased transmission requirements in the next decade.

The underlay of 230-kV transmission is extensive, but it would be difficult to illustrate on a small chart. In summary, though, there will be over 60,000 miles of 230-kV transmission by 1980 and nearly 200,000 miles of 115- and 161-kV transmission.

Transmission Growth

The capability of a transmission line is a function of several factors. Regardless of voltage, there is a thermal limit on continuous current flow (Fig. 2). Depending on external factors such as temperature, weather, wind velocity, etc., higher short-time ratings (30 minutes to 2 hours) may be used during emergencies. Intersecting this thermal limit, and reducing the capability for longer line lengths, is the circuit rating based on certain stability criteria. Surge impedance ratings and line loadings, such that transient stability and steady-state stability margins would be indicative of operations near the limit, were the criteria used for developing the curves in Fig. 2. Normal or typical design loadings for transmission circuits are shown by dotted lines below the indicated thermal limits. These more nearly indicate the loadings acceptable and economical for continued utility use, with the margin between this level and thermal limits available for emergencies. Typical circuit loadings, as shown in the NEMA Survey of Power Equipment Requirements, are listed for several voltages in Table I.

For understanding the growth of transmission capability, and the actual level of this growth, the term "megawatt-miles" has been developed. The use of this term implies two facts: (1) lines of each voltage can be assigned megawatt ratings (Table I), and (2) transmission system capability is related to the distance power is transferred.

An analysis of the lengths of lines between terminals on U.S. systems at 345 kV is shown in Fig. 3. The average line length is 67 miles and the median length is 57 miles. Analyses of the lengths of lines for other transmission voltages reveal similar histograms. Average and median line lengths are summarized in Table II for 115 through 765 kV.

As may be observed by studying Fig. 2, the maximum megawatt capability of a transmission line is the thermal rating for short lines, and it becomes nonlinear with reduced values for long distances. The point of nonlinearity occurs above 75 miles for the lowest voltage shown, and at about 150 miles for the highest voltage shown. The nonlinearity occurs at much further distances when the typical loadings are used. As Table II indicates, most line lengths are below 100 miles, so megawatt-miles provides a meaningful way to evaluate transmission capability. (The product of circuit loading and circuit length provides the megawatt-mile capability.) The megawatt-mile

*Table I. Typical Line Capabilites**

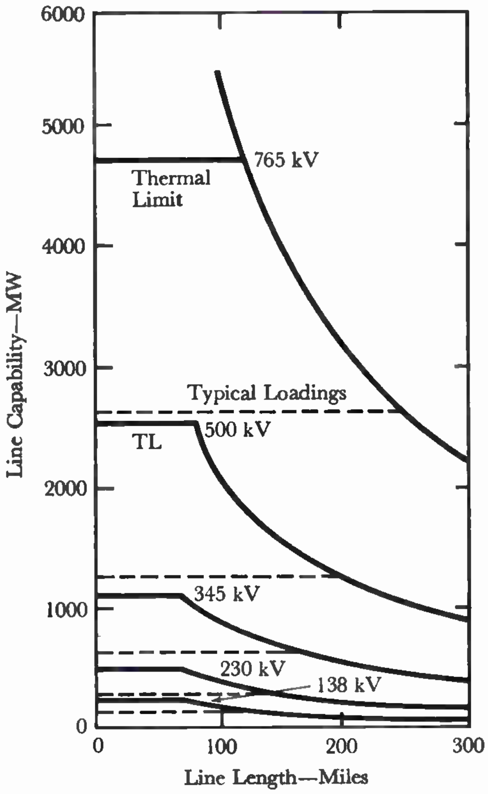
Voltage (kV)	*Capability (MW)*
115-161	100
230	250
345	600
500	1200
765	2500

*As used in the NEMA Power Equipment Survey.

*Table II. Lengths of Transmission Lines in Service in the U.S. in 1969**

Voltage (kV)	*Length (miles)* Average Length	Median Length
115	21	15
230	46	26
345	67	57
500	67	50
765	73.5	70.5

*From FPC data reported by utilities.



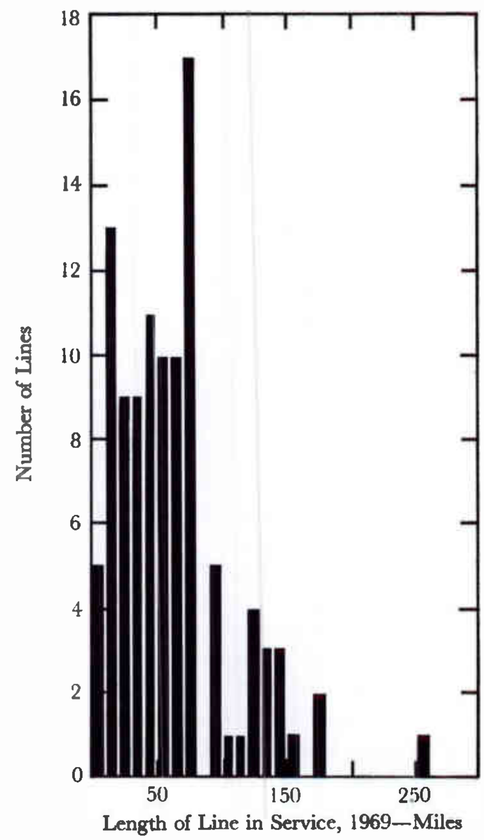
2—Thermal limit and circuit stability are factors in determining the capability of a transmission line. Typical actual loadings are considerably lower than the thermal limits, with the difference available for emergencies.

figure is a simple convenient measure of gross capability, obviously better than miles or circuit miles of lines. For example, the circuit miles of 500-kV transmission added in the next decade would not reflect the large increase in gross capability that this voltage class will provide (Fig. 4).

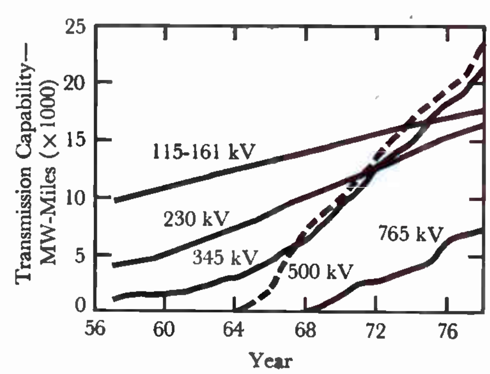
For a comprehensive treatment and study of statistical information concerning transmission growth, the NEMA Survey of Power Equipment Requirements[2] should be studied in detail. However, it is possible to summarize the most significant characteristics of transmission growth for the next decade.

Total growth of transmission capability in gigawatt-miles through 1978 is compared with generating capability in Fig. 5. The transmission and generating capability curves are plotted with an ordinate relationship of 100 to 1; that is, transmission capability is 100 gigawatt-miles for one gigawatt of generation. As the two curves plotted together show, generation and transmission capability followed almost the same pattern until 1965; the curves then diverged, with transmission capability increasing at a more rapid pace.

This comparison of transmission and generation capability reveals an interesting fact. In the period up to 1965, there were 100 gigawatt-miles of transmission installed for each gigawatt of generation in service. However, by 1970 the transmission capability growth had increased to a new ratio of 140 gigawatt-miles per gigawatt of generation. The reason for this transient movement between 1965 and 1970 is that the utility industry changed from one mode of interconnected system operation to another—the large growth in EHV and the move to pooling of systems is a rational explanation for the excursion. The pattern of annual additions confirms this explanation. Fig. 6 shows the annual transmission capability additions for 115-230 kV and for EHV. The annual additions are essentially constant for non-EHV transmission. From the period 1964 to 1968, the EHV annual additions show a sharp rate of rise, which occurred when pooling and EHV were growing rapidly.



3—Lengths of lines in 345-kV service in the United States in 1969. The lengths are terminal-to-terminal.



Source: NEMA Publication PE-2

4—Transmission capability by voltage class shows the important role of EHV in moving bulk power.

Reliability

Transmission provides economic interchange of power between generation units, sharing of generation reserve, point-to-point transmission from mine-mouth or hydro generation to load centers, and utilization of seasonal diversity. But since the Northeast Power Failure of 1965, much greater emphasis has been placed on transmission for interconnecting systems and pools together as a means of improving *reliability*.

System reliability actually consists of two parts—*availability* and *security*. Availability is the probability that a power system will supply the load despite line and equipment outages. It is measured statistically to reflect outages in a quantitative way with such terms as mean time to failure, number of outages, and duration of outages.

System security expresses a system's ability to withstand stresses imposed, for example, loss of generation. Consider generation losses in terms of two large power system pools with sizes from 20 to 80 GW. The transmission interconnection between the pools depends upon the distance between the pools, the number of lines in parallel, and the voltage of the lines. Distance can be defined electrically in terms of the reactance of the interties between the two pools (Fig. 7). Curves are shown for 10, 15, 20, and 25 percent permissible loss of generation in one pool while maintaining stability after the loss.

For example, consider two 40-GW pools and a 10-percent permissible loss of generation. The maximum permissible intertie reactance is 0.46 per unit. One way to reduce the intertie reactance is to double the number of intertie circuits or to halve the distance. In this case, the intertie reactance would then be 0.23 per unit and, for this improvement, an 18-percent permissible loss in generation (almost a two-fold increase in system security) could be tolerated.

Stronger interties between pools and systems will improve system security, i.e., the ability of systems to stay together in the event of loss of generation or transmission or other major stress. Since impedance is a basic parameter of transmission between systems, it is apparent that low impedance resulting from higher voltages or more lines in parallel improves system security. A higher level of system security can be obtained with more lines at lower voltage but not as economically. Fewer lines at higher voltage would also alleviate right-of-way problems.

The costs relating to transmission capability, including equivalent transformation requirements, are shown in Fig. 8. For equal capability, twelve 345-kV lines are required to carry the same power as one 1100-kV line. The figure shows total cost for 8000-MW capability as a function of the distance. The crossover point of approximately 100 miles, at which 1100 kV becomes less costly, is quite speculative today because actual costs are not known.

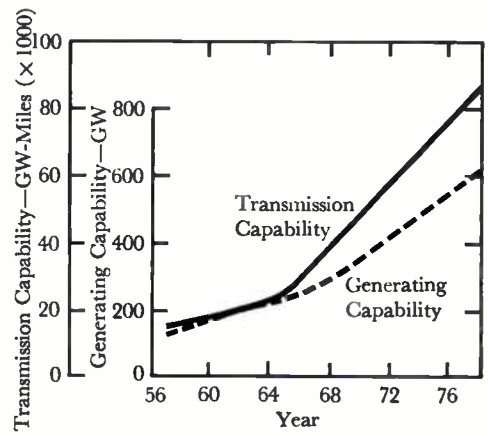
Underground Transmission

There are situations now, and there are going to be more of them, where there is just no alternative to underground transmission. These will be short runs, perhaps 10 to 20 miles, from a generating plant to a load center or for segments of transmission interconnections in suburban areas. The runs could be only a few thousand feet, under water, or under a highway.

It is a rule of thumb that the underground-to-overhead transmission cost ratios, when including the cost of fabricated materials, installations, right of way, etc., produce actual figures well in excess of 15 to 1.

Thus, while it seems impractical to expect long underground transmission lines through open country, it is not difficult to visualize short sections transmitting power in large quantities under highways, rivers, or in urban areas where right-of-way will no longer be obtainable. Today's requirements probably do not demand technologies beyond the conventional paper-insulated, oil-impregnated, pipe-type cable. But looking to the future, it is not hard to visualize the necessity for carrying the output of 3000- to 5000-MW generating plants or 5000- to 10,000-MVA-capacity intertie circuits between systems, particularly under emergency conditions.

There seems to be little basis for ex-



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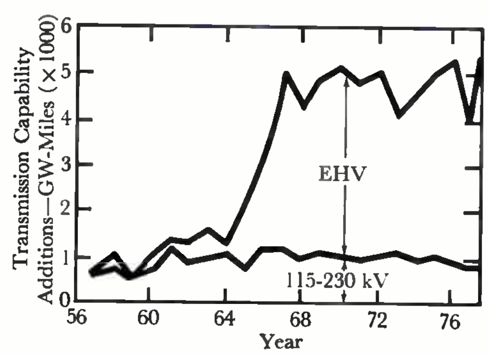

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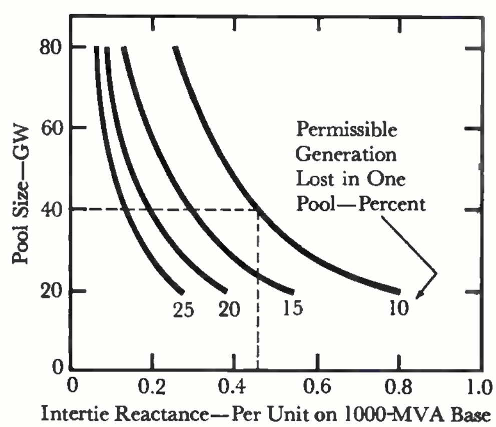
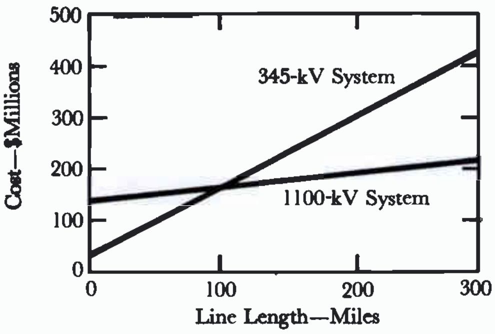
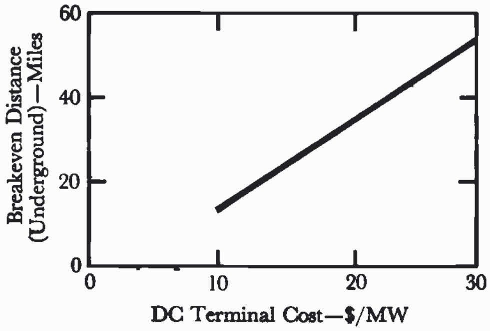


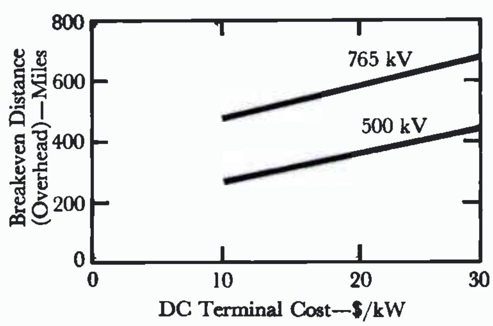
5—Growth of transmission capability (in gigawatt-miles) is compared with generating capability through 1978.

6—Additions in transmission capability, EHV and non-EHV.

7—Pool-to-pool transmission requirements for system security depend on pool size, intertie reactance, and permissible generation loss in one of the pools.







8—Costs are compared for 345-kV and 1100-kV systems that are equal in transmission capability.

9—The distances at which the cost of underground transmission for dc power is equal to that for ac power vary with the cost of dc terminal equipment.

10—Breakeven distance is shown as a function of dc terminal cost for ac or dc overhead transmission.

pecting a significant cost reduction with today's conventional underground transmission. Real cost reductions would seem to necessitate a new technology. Advances such as high-pressure gas-insulated systems, in addition to cryogenic superconducting systems, appear to hold considerable promise for the future.

DC Transmission

The problem with dc transmission is that dc lines, underground or overhead, require extensive terminal conversion equipment. The cost of solid-state dc terminal equipment is estimated at $33 per kilowatt. The effect of cost on the economics of dc is reflected in Fig. 9. The curve shows the distances at which the cost of underground transmission by ac or dc are equal in terms of various prices for the terminal equipment.

For today's costs, an underground transmission segment must be more than 50 miles long before dc transmission becomes competitive with ac transmission. Since the majority of undérground installations won't exceed 10 to 20 miles, there appears to be little use for dc in underground transmission at the present time.

In all probability, millions of dollars of development would be required to reduce those costs even by a third. And even if terminal equipment could be reduced to $20 a kilowatt, dc would be competitive only for underground segments of around 35 miles or longer. Hence, there still wouldn't be many installations for underground dc.

For overhead applications, the problem is the same—the high cost of terminal equipment (Fig. 10). Even if terminal equipment costs were only $20 per kilowatt, line lengths must exceed 300 miles to be more economical than 500-kV ac. The longest 500-kV line in the country today is less than 300 miles.

Summary

The picture of what the 70's hold for transmission seems clear in terms of "conventional wisdom." As this decade begins, transmission capability is growing steadily although the *additions* per year show a flat characteristic through 1978. Surveys and industry planning show no growth in transmission voltage levels above 765 kV, a surprise perhaps in view of the strong influence that environmental considerations will have in the coming decade.

There is plenty of evidence today to indicate the magnitude of the problems that the industry will face in the siting of generating plants and locating of transmission lines. The larger size generating units that will be installed to take advantage of the economy of scale in generation can be expected to be followed by more and stronger transmission interconnections. These transmission interconnections, not only between plants, systems, and pools but also for the bulk power transmission required to serve the load, will require rights-of-way across the countryside and in urban areas that will be more difficult to obtain. Thus, transmission voltages above EHV levels must be seriously considered for the best utilization of rights-of-way and for improvement in the reliability of power systems.

Use of 1100 kV is a possibility that should be considered for the 70's. UHV can well be one of the opportunities that could prepare the industry to meet the decades beyond the 70's.

REFERENCES:

[1] 1970 Reports to the Federal Power Commission of the Regional Advisory Committees.

[2] *Second Biennial NEMA Survey of Power Equipment Requirements of the United States Electric Utility Industry 1969-1978*, NEMA Publication PE-2.

Research Sub and Mother Ship Matched to Each Other

One of the latest deep-diving ocean research vessels is *Deepstar-2000*, a three-man electric submersible that normally will dive as far as 2000 feet below the surface but is capable of diving 2500 feet. Its mother ship is *Midwife*, a diesel-powered aluminum catamaran that carries the submersible nestled between its hulls for surface transport and also provides the necessary support functions during dives.

The submersible's propulsion system employs hydraulic pumps and motors so that propeller speed can be varied continuously from near zero to full. Bouyancy can be finely adjusted by transferring oil from hard tanks to inflatable bladders instead of by the usual method of dropping weights. Together with the small size of the submersible, these features impart exceptional maneuverability.

Deepstar-2000, the new three-man research submersible, will be used with its catamaran support vessel for scientific investigation of oceans, lakes, and estuaries down to 2000 feet below the surface.

In fact, the novelty of the *Deepstar-Midwife* system lies mainly in its maneuverability on and in the water and from one body of water to another. *Midwife* is easily disassembled for shipment, so the *Deepstar-Midwife* combination can be transported anywhere in the world by truck, rail, ship, or plane.

Unlike any other submersible and support ship, the two are designed to be "in tune" on the surface, moving up and down together with the waves. Thus, they avoid the hazards inherent in launch and retrieval if one is going down and the other up.

Other features of *Deepstar-2000* include flexible photographic equipment and a data-logging system that automatically records signals from measuring instruments directly on computer tape for analysis. The vessel has lighting booms extendable to 16 feet in front.

The submersible is 20 feet long, 5½ feet high, 7 feet wide, and weighs less than nine tons. Maximum speed is three knots. It is designed to carry a pilot and two observers for dives up to 12 hours, with reserve life-support equipment for 36 more hours. Passengers and pilot work in a cylindrical steel pressure hull 10 feet long and five feet in diameter, with hemispherical closures at the ends. This shape gives a more convenient working space than the spherical hulls generally used in submersibles. A fiber-glass fairing has external equipment and instruments attached to it.

Midwife is 45 feet long and has a 21½-foot beam. It has an elevator between the hulls to let *Deepstar* into and out of the water. Maximum speed is six knots and range 180 miles. For long crusies, it is towed by another ship. Although it has sophisticated controls and instrumentation for maneuvering and dive monitoring, it can be operated by two men.

The two vessels will be used for scientific research—to investigate the biology, geology, physics, and chemistry of oceans, lakes, and estuaries—and as test beds for experimenting with such marine equipment as sonar. *Deepstar-2000* can reach all continental shelves (the submerged fringes of the continents) and most lake bottoms. Its first use was in a project to study the deep scattering layer—a drifting cloud of marine organisms that obscures sonar signals.

Deepstar-2000 is the second in a family of Westinghouse submersibles. *Deepstar-4000*, currently undergoing modification after some 500 dives, can also be used with *Midwife;* both submersibles are operated by the Westinghouse Ocean Research Laboratory, San Diego. *Deepstar-20,000* is under construction at the Westinghouse Ocean Research and Engineering Center in Annapolis, Maryland. *Midwife* was designed and constructed by Ocean Science and Engineering, Inc., Long Beach, California.

Walky-Mappy Position Locator Tells User Where He Is

A man-carried land navigation system electronically measures and accumulates the distance and direction of every step the man takes. The result is continuous provision of accurate position data—even at night, in heavy foliage, or in varied terrain.

Originally conceived by the U. S. Army Land Warfare Laboratory for military use, the system also has commercial applications as in rescue missions, forestry, and mineral exploration, where it could be used in conjunction with existing maps or as a preliminary mapping device. It was designed and is built by the Aerospace and Electronic Systems Division, Westinghouse Defense and Space Center.

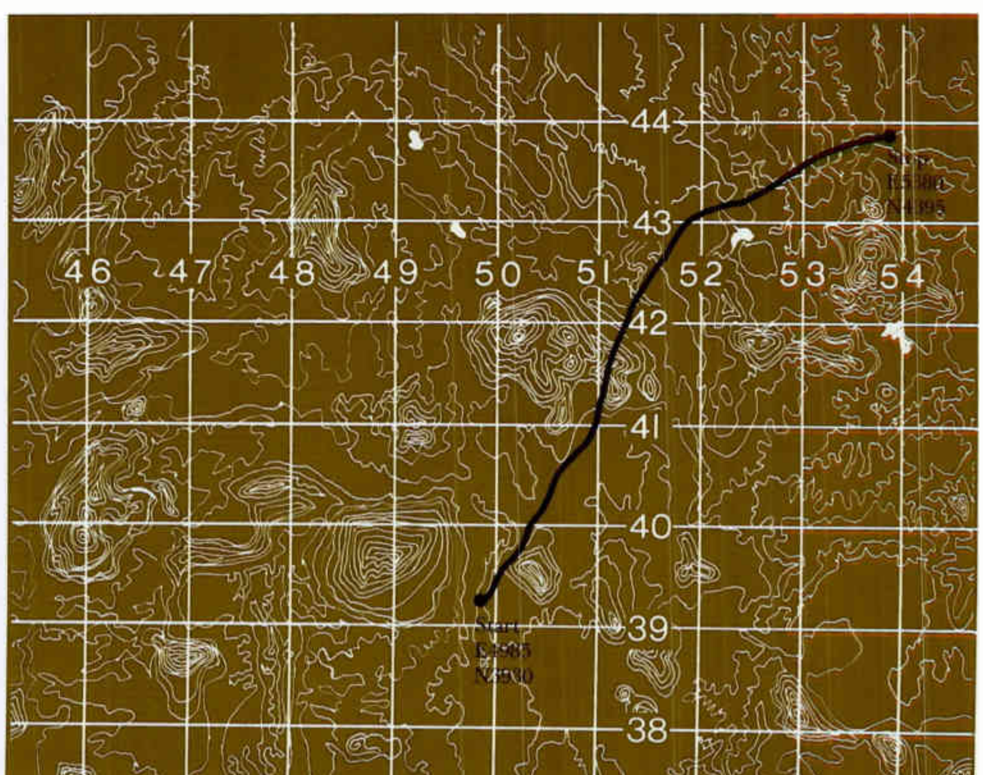
The Position Locator consists of a pair of boot antennas that measure the length of each step, a backpack computer, and a display and control unit. The backpack computer includes a compass that resolves a unit heading vector into rectangular coordinates. These coordinate vectors are then multiplied by the length of each step, and the results are accumulated in an up-down logic counter. The display and control unit has a pair of odometer-like counters that indicate "easting" and "northing" coordinates in meters, compatible with standard Universal Transverse Mercator (UTM) maps. Known coordinates are set into the counters at the start of a walk; thereafter, the counters indicate the current position of the operator in map coordinates. A calibrated dial on the backpack is set to the declination angle of the geographic area where the system is being used, thus referencing the two readout counters to UTM grid north.

One antenna is a transmitter and the other a receiver; they are mounted on the boots and connected to automatic step-length circuitry in the backpack by a three-conductor cable. The circuitry deduces the length of each step from the minimum received signal during the step. This signal is inversely proportional to the third power of distance, so a cube-root circuit following the receiver generates a voltage linearly proportional to actual step length.

A resolver multiplies the step-length information by the two heading vectors generated by the compass in the backpack. Multiplying the heading vectors by the length of the step resolves the step into a rectangular coordinate system (i.e., north and east components). The compass outputs are scaled so that the vector sum of the two heading vectors is a unit vector. This prevents the compass from affecting the "distance traveled" computation when its outputs are multiplied by the step length. The compass is operated for one millisecond each time the operator's feet pass one another. (That part of the stride was chosen because the man's body is then most likely to be facing his actual direction of travel; at other times, his body may be swinging or twisting.)

The logic pulses from each channel of the resolver are accumulated with the appropriate sign (+ for north and east, − for south and west), and, after dividing by an appropriate scaling factor, are used to drive a stepper motor in each channel. The motors, in turn, drive the readout counters.

The hand-held display and control unit contains the stepper motors, the readout counters, and a number of controls. A slew switch for each channel enables the operator to set in his initial



starting coordinates. A battery-condition indicator and a system self-test switch and readout are also included on the display and control unit. A calibration control on the display and control units is initially used by the operator to adapt the unit to any peculiarities in his walking pattern. He puts the Position Locator in the *calibrate* mode, walks a measured 100-meter course (in any direction), and then adjusts the control to a setting equal to the error in the distance reading.

Distance-measuring accuracy of the automatic step-length circuitry, after calibration, is within one percent of the distance traveled. With normal walking, little or no reduction in accuracy has been observed for travel through swamps, dense foliage, or even directly through water.

Extensive travel in hilly terrain poses some problem because the system measures the distance between two points along the surface of the terrain, whereas map coordinates are planar projections that do not account for vertical variation of the terrain. However, error is easily held to about 2 percent by categorizing hilly terrains into three types and superimposing an appropriate correction factor on the calibration dial of the display and control unit. Some reduction in accuracy also occurs when the operator runs.

Static accuracy of the compass is within approximately one percent. Dynamic accuracy depends somewhat on the characteristics of an operator's walk; extensive field data show it to be within 1 to 2 percent for most operators.

Left—Position Locator is an electronic navigation system carried by one man. It accumulates the number and length of the user's steps and coordinates that information with compass indications to calculate the distance and direction traveled from a known point. The user determines his position by reading map coordinates on the display and control unit (held in his hand) and comparing them with map grid lines such as those on the simplified map illustrated.

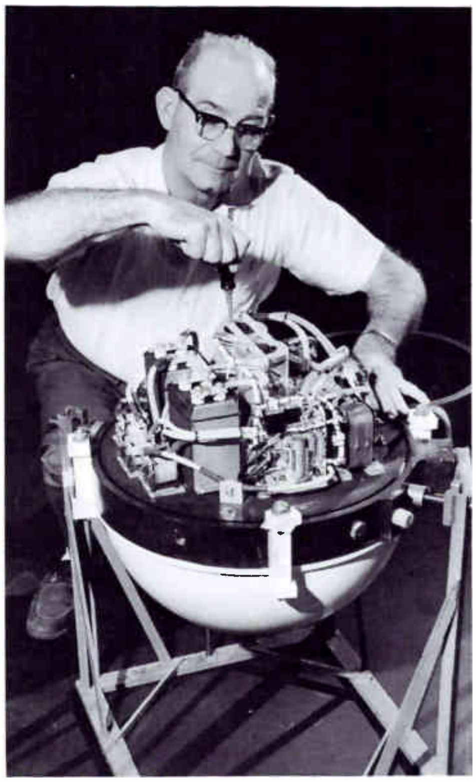
Right—One of the motor controllers for the second deep-submergence rescue vehicle is being readied for shipment here. Its spherical housing will protect it from crushing water pressure at operating depths to 5000 feet.

Second Deep Submergence Rescue Vehicle Gets Electrical Systems

Electrical systems for the U. S. Navy's second Deep-Submergence Rescue Vehicle (DSRV-2) have been supplied to Lockheed Missiles and Space Company, builder of the vehicle. The battery-powered ac drive systems for propulsion, maneuvering, and hydraulic equipment will provide precise positioning ability, needed in a submarine rescue operation because position must be controlled within inches even in strong water currents.

A DSRV has seven drive systems, each consisting of a controller and an ac motor. They are a 15-hp main propulsion drive, four 7½-hp thruster drives for maneuvering, and two 7½-hp hydraulic pump drives.* They were made by Westinghouse Aerospace Electrical Division.

*Robert C. Fear, Robert R. Madson, and Joseph M. Urish, "AC Power Provides Flexible Maneuvering for Deep-Submergence Rescue Vehicle," *Westinghouse ENGINEER*, March 1969, pp. 41-45.



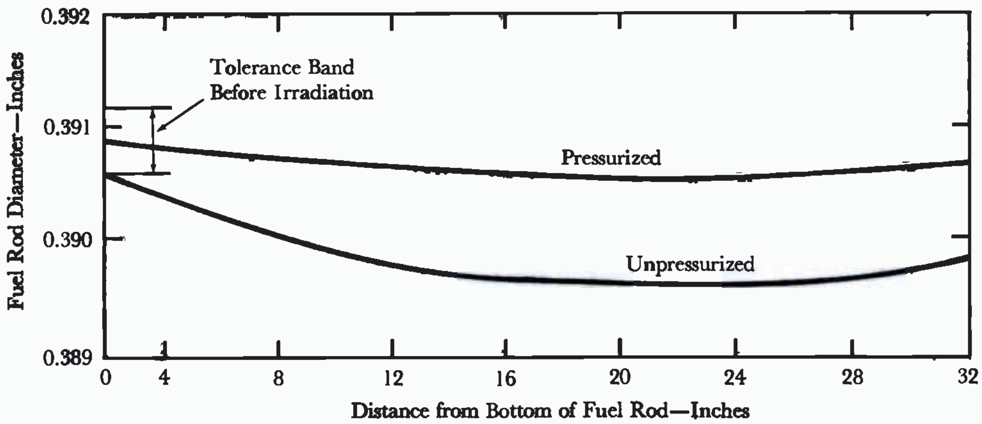
Controllers and motors are built for operation at depths to 5000 feet. The controllers, one of which is shown in the photograph, are solid-state dc-to-ac adjustable-frequency three-phase inverters. They are housed in spherical housings that resist water pressure and also transfer heat from electrical components to the surrounding seawater; components are mounted on a heat-conductive plate sandwiched between the hemispheres.

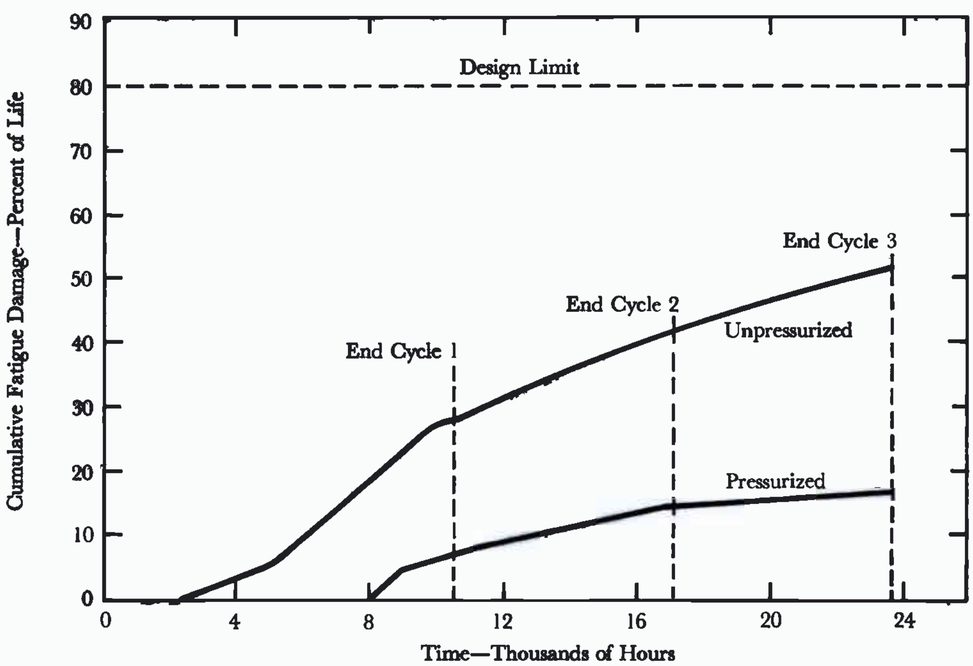
Nuclear Reactor Fuel Rods Improved by Pressurizing

Both the reliability and the operational capability of fuel rods for water-moderated nuclear reactors have been found to be improved by pressurizing the rods internally. The benefits were demonstrated by a four-year development program and, as a result, all of the reactor cores built by the Westinghouse Nuclear Fuel Division now have fuel rods pressurized with helium.

A water-reactor fuel rod consists of pressed and sintered uranium-dioxide pellets sealed in a Zircaloy sheath called the "cladding." The cylindrical pellets are ground to accurate diameter for a controlled clearance between pellets and cladding to accommodate pellet growth due to thermal expansion and swelling. The rods are sealed by welding a plug into each end. Before development of pressurizing, the sealed rods normally contained air at one atmosphere pressure.

During operation in a reactor vessel, the fuel rods are subjected to external pressure (about 2250 psig in pressurized-water reactors). The high compressive stress, in conjunction with the high operating temperature, deforms the cladding gradually by creep, reducing the internal clearance. When the cladding contacts the fuel pellets, significant stresses and strains are produced in it by the thermal expansion of the pellets resulting whenever power level is increased. The interaction is especially significant in reactors that must meet variable load requirements, because the load changes subject the cladding to cyclic stresses and strains that can cause fatigue failure.





1—*(Top)* Diameter reduction due to creep in fuel-rod cladding was much less for a pressurized rod than for an unpressurized rod in a typical test. Reduction in amount of creep delays or prevents contact between cladding and fuel, thus sparing the cladding the stresses it otherwise would receive as the fuel pellets expanded and swelled in contact with the cladding. The 36-inch rods were irradiated for 400 hours in a pressurized-water reactor at external coolant pressure of 2000 psi and mean temperature of 700 degrees F across the cladding walls at the midpoints of the rods. The pressurized rod was filled with helium under initial 500-psi pressure at room temperature. Creep was greater at rod midpoints than at ends because of the higher temperatures there.

2—*(Bottom)* Pressurizing greatly reduces fatigue damage of the cladding even when fuel temperature varies cyclically as it does in a load-follow power generating plant. Only moderate internal pressure—250 psi—was assumed in this example.

The primary reason for internal rod pressurization is to partially offset the external coolant pressure and thereby reduce the rate of cladding creep and delay or prevent contact with the fuel pellets. The consequent reduction of stresses and strains to which the cladding is subjected improves reliability. At operating temperatures, the compressive stress in an internally pressurized fuel rod is about half that in an unpressurized rod. Since creep is proportional to stress raised to a power (values between 2 and 4 are indicated by experiment), the creep rate in a pressurized fuel rod is reduced by a factor of 3 to 10.

Typical test results are shown in Fig. 1. The two rods had nominally identical initial dimensions, within the tolerance band shown, before irradiation in the Saxton reactor. Such tests confirmed that an initial pressurization significantly reduced the rate of creep and so delayed contact between cladding and fuel. Moreover, the fuel pellets actually densified slightly due to the hydrostatic gas pressure, whereas pellets in an unpressurized rod would have swelled; that factor also increases the time before contact occurs.

A large number of internally pressurized rods are being irradiated in the Saxton and Zorita reactors. Burnups exceeding 10,000 megawatt days per metric ton of metallic uranium have been achieved at high linear power ratings without signs of problems.

Studies have shown that cladding fatigue life improves as internal gas pressure is increased. The reasons are greater delay in contact with fuel and reduced cyclic stresses and strains after contact. Even a moderate level of internal pressure (such as 250 psig) results in a severalfold increase in time to contact and a threefold reduction in fatigue damage (Fig. 2). Depending on plant load cycling characteristics and the level of internal pressurization, the improvement in cladding fatigue life can vary from a factor of 2 to 10. Thus, the ability of internally pressurized fuel rods to operate in a power plant under load-follow conditions promises to far exceed that of unpressurized fuel.

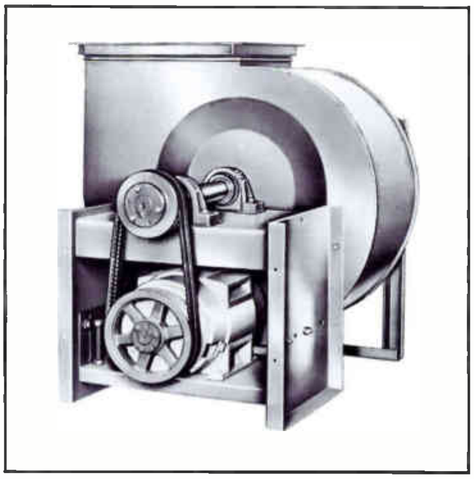
Moreover, internal pressurization reduces cladding failures caused by mechanisms other than strain fatigue. Essentially all the major cladding failure mechanisms (with the notable exception of pure corrosion) are highly stress-dependent.

Fuel temperatures in pressurized rods are roughly 150 degrees F lower at the beginning of service than those in unpressurized rods because of the thermal conductivity of the high-pressure helium in the gap. Lower fuel temperatures can be used to improve reliability and safety margins, or greater power output can be provided at the same fuel temperature found in unpressurized rods. Lower fuel temperature also results in somewhat lower uranium 235 requirements since fuel reactivity varies inversely with temperature.

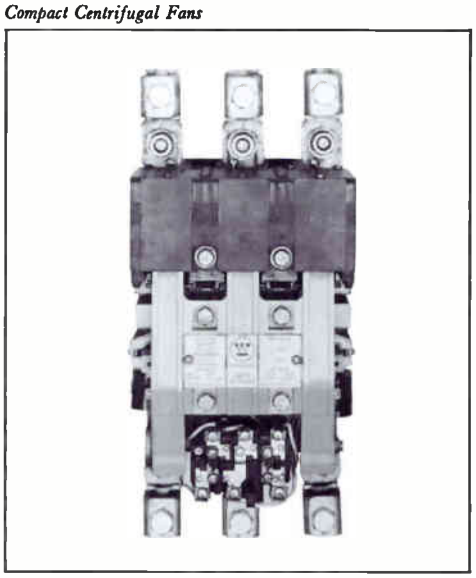
In summary, internal pressurization significantly reduces the stresses and strains to which fuel-rod cladding is subjected and thereby appreciably enhances reliability for a given set of operational parameters. Where enhanced reliability is unnecessary, as it may be in moderately rated base-load plants, internal pressurization can improve plant capability in the form of higher power, higher burnup (lifetime), or greater load cycling ability.

Products for Industry

High-voltage capacitor assemblies, type HWP, are compact units with a Dyna-Vac low-loss film dielectric system. Their small size usually makes it feasible to install them directly at the load—for example, at the terminals of large motors to increase power factor. Ratings are 25 through 150 kVAc in single-unit assemblies and 175 through 300 kVAc in two-unit assemblies. *Westinghouse Distribution Apparatus Division, Box 341, Bloomington, Indiana 47402.*



Compact Centrifugal Fans



Contactor

Semiautomatic Welding System

Compact centrifugal fans in airfoil-bladed Series 8000 or flat-bladed Series 3000, Classes 1 and 2, are now available in Arrangement 10 for use in incinerators, high-pressure cooling systems, industrial furnaces, and standardized boilers. The Silentvane packaged fans allow users to meet a wide variety of industrial requirements at minimum cost. The motor is located inside the bearing pedestal to save floor space. Moreover, plant assembly of motor and drive minimizes field installation costs. Wheel diameters ranging from 12 to 37 inches provide air volumes from 1000 to 30,000 ft^3/min at operating temperatures to 650 degrees F. Accessories include inlet vane control. *Westinghouse Sturtevant Division, Damon Street, Boston, Massachusetts 02136.*

Two ac-operated contactors utilize new materials—especially molded glass polyester—to minimize size and weight. They are Type GCA, NEMA Size 5 and 6. Size 5 achieves further size and weight reductions when used in starter applications because encapsulated current transformers and three-pole overload protection can be mounted integrally. Features include front-removable parts for easy maintenance, straight-through wiring for reduced installation time and cost, block-type three-pole overload relays to provide motor overload protection, and mechanical interlocks for linking (vertically or horizontally) to other contactors of the same or different sizes. Size 5 has continuous rating of 600 volts, 60 Hz, 300 amperes open, 270 amperes closed; Size 6, 600 volts, 60 Hz, 600 amperes open, 540 amperes closed. Both are available in either two- or three-pole designs. *Westinghouse General Control Division, 4454 Genesee Street, Box 225, Buffalo, New York 14240.*

Semiautomatic welding system, Type RS-250, is a 250-ampere constant-voltage dc system for gas-shielded consumable-electrode welding. It is a general-purpose system having a power supply with open-circuit voltage ranging from 44.5 volts down to 9.0 volts. Continuous vernier control of voltage allows adjustment under load. The power supply operates on 230- or 460-volt 60-hertz three-phase power. Wire feed speeds can be selected over the range of 50 to 500 inches per minute. *Westinghouse Welding Department, P.O. Box 300, Sykesville, Maryland 21784.*

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Author Index

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About the Authors

L. A. Kilgore's byline first appeared in the *Westinghouse ENGINEER* in our third issue—November 1941—with an article on large wind-tunnel drives. Since then he has contributed at least seven articles on subjects ranging from power supplies for nuclear particle accelerators to human relations.

Kilgore came to Westinghouse in 1927 from the University of Nebraska, where he had earned his BSEE. He was assigned from the graduate student training program to the turbine-generator division at East Pittsburgh to work with large motors, generators, electric couplings, and rectifiers. He progressed from engineering supervisory to management positions, along the way adding an MS from the University of Pittsburgh in 1929 and an EE degree from the University of Nebraska in 1934. In 1956, Nebraska awarded him the honorary degree of Doctor of Engineering. He also attended the Harvard advanced management course.

Kilgore was made Assistant Manager of the ac generator engineering department in 1946, and in 1953 he became Director of Engineering for the East Pittsburgh Divisions. He became Consulting Engineer for the East Pittsburgh Divisions in 1964 and is presently Consulting Engineer with Power Systems Planning.

Besides being a designer and inventor with some 30 patents to his credit, Kilgore is also an educator. He started teaching in the Westinghouse Design School from 1928 to 1931. Then he taught a course in advanced machine design at the University of Pittsburgh graduate school from 1936 to 1949 and has continued to act as a thesis advisor there. He has aided and guided young engineers in other ways also, including organizing and conducting seminars.

D. C. Washburn, Jr., received his BS degree in electrical engineering from the University of Colorado in 1949. He worked first as a field engineer with a consulting engineering and contracting firm and then served in the Army. In 1953, he joined Westinghouse as a field service engineer in El Paso, Texas.

Washburn transferred in 1956 to the former Industry Engineering Department, where he worked on application of electrical equipment to pipelines and later on the engineering of other advanced electrical equipment. He became a part of the Industrial Systems Division when it was formed in 1965. There he has worked on design and application of various industrial drive systems. Always willing to undertake a new technology, Washburn earned his soaring pilot's license during his vacation last summer.

Paul A. Berman graduated from the University of Pennsylvania with a BSME in 1953 and obtained his MSME there in 1956. He joined the Westinghouse Gas Turbine Division (now the Small Steam and Gas Turbine Division) in 1953, where he worked first on cycle analysis and compressor and turbine design in the thermodynamics section. He then moved to the special project section to design nuclear gas turbines, marine gas turbines, and circulators for gas-cooled reactors. Berman has also worked in the Division's application engineering and product engineering sections, contributing to the design of the COSAG marine gas-turbine plant, gas-turbine exhaust-heat boiler systems, and the 25-MW Econo-Pac gas-turbine generator package plant. Berman served as supervisor of Value Engineering for 2 years and is presently Manager of Combined Systems Engineering, where he works on combined-cycle power systems such as the new PACE plant described in this issue.

Frank A. Lebonette came with Westinghouse in 1952 to work as a design engineer in the Small Steam and Gas Turbine Division's engineering department. Since 1964, he has worked in the applications area, which has included many gas-turbine installations involving waste-heat energy conversions. He is presently a project engineer in the Combined Systems Engineering Department.

Lebonette earned his ME degree from Stevens Institute of Technology (1951) and his MME from the University of Delaware (1958). He has been an instructor in mathematics and engineering at PMC College's evening division for the past five years.

Andress Kernick graduated with a BSEE degree in 1946 and then a BSME degree in 1947, both from the University of Kansas. He joined Westinghouse on the graduate student training program, and his subsequent career as primarily an electrical rather than mechanical engineer was determined by his being selected for electrical design school.

Kernick went to the Electric Engineering and Service Department in 1949 at its Chicago district and moved in 1953 to its Des Moines district. In 1955 he joined the Director Systems Department, where he became a senior design engineer on Cypak static control components and systems. He received his MSEE degree from the University of Pittsburgh in 1956.

Kernick went to the Aerospace Electrical Division in 1960, and there he was coinventor (with Theodore Heinrich) of harmonic neutralization in sinewave static inverters such as the Apollo command-module inverter and the Accur-Con line of industrial inverters developed by the General Control Division. (The two men recently shared a special patent award for that invention.) In 1962, he became a fellow engineer and project engineer for the Apollo inverter. He holds 10 patents, has written eight technical papers in the fields of static control and static inverters, and is a registered professional engineer. Off the job, Kernick is an accomplished violinist and violist and an advanced senior master in bridge and chess.

R. F. Lawrence graduated from Pratt Institute with a BEE degree in 1943 and joined Westinghouse on the graduate student training program. His first permanent assignment was in the former Electric Utility Engineering group, where he was made a Sponsor Engineer in 1947 and served as a consultant to utility companies and Westinghouse district engineers on many power problems. Lawrence became Manager of the group's distribution engineering section in 1956, responsible for long-range development, apparatus application, and general analysis of distribution problems. That section is now the Transmission part of Power Systems Planning, and Lawrence is its manager.

Lawrence is a Fellow member of IEEE and a registered professional engineer. He has authored more than 60 published technical articles and papers. He has also been active on many industry committees and is now general chairman of the IEEE Conference on Underground Transmission to be held in Pittsburgh in May 1972.

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Radar imagery of Vancouver Island. (Information on contents page.)