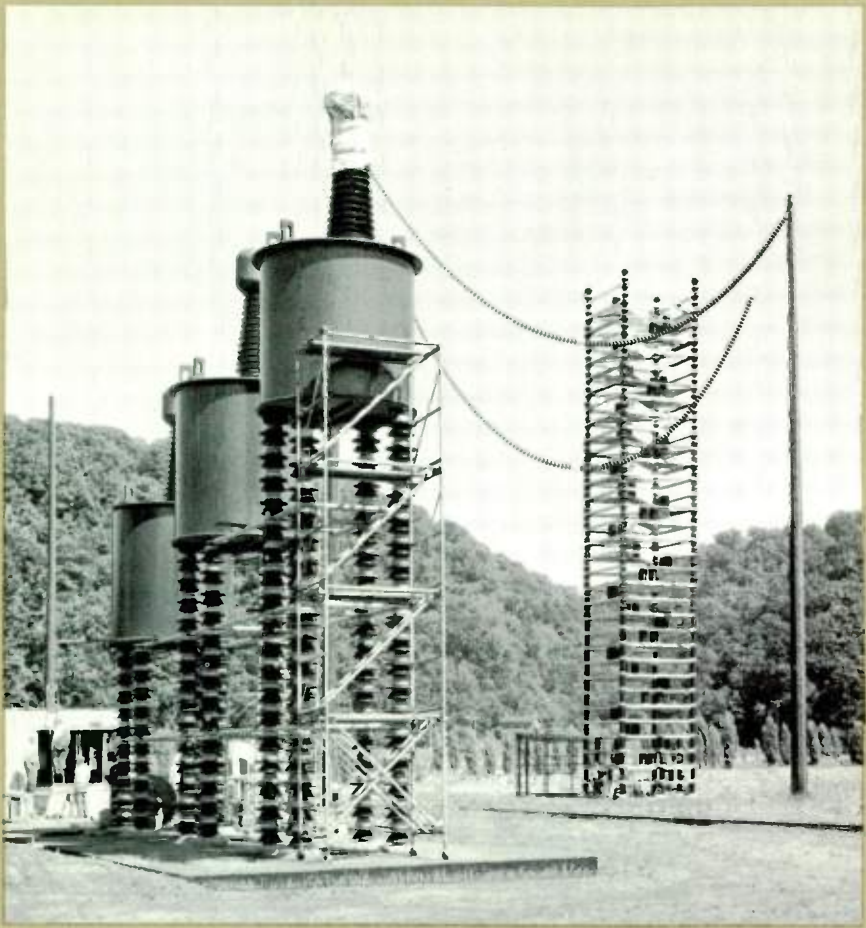
Westinghouse ENGINEER

NOVEMBER 1964



Surge Generator for New EHV Test Center

This 85-foot, tower-type, 6400-kv surge generator has been installed at the new Westinghouse EHV Center to test present and future circuit breaker designs. The surge generator has provisions for an ultimate rating of 10 000 kv, and switching surge circuitry.

Initially, the power transformers will be energized through a 500-kv transmission line from the Westinghouse high-voltage laboratory, providing an output of 1600 kv with provisions for later increasing this voltage to 2100 kv.

The rail siding leading into the area will permit many items to be tested without unloading. The new center has sufficient land area for constructing and testing full-scale towers and transmission line sections.

Westinghouse
ENGINEER

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries:

CYPAK, Micarta, Prodac

Cover Design: An improved hydrogen gas cooling system for steam-turbine generators has resulted from modifications in both rotor and stator cooling. These modifications are featured in this month's cover design by Thomas Ruddy of Town Studios, Pittsburgh.

Published bimonthly by the Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.
Subscriptions: United States and Possessions, $2.50 per year; all other countries, $3.00 per year; single copies, 50¢ each.
Mailing address: Westinghouse ENGINEER, P.O. Box 2278, 3 Gateway Center, Pittsburgh, Pennsylvania 15230.
Microfilm: Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 North First Street, Ann Arbor, Michigan.

Printed in the United States by The Lakeside Press, Lancaster, Pennsylvania.

NOVEMBER 1964 VOLUME 24 / NUMBER 6

Improved Cooling Increases Generator Capabilities

R. A. **Baudry,** *Consultant, Large Rotating Apparatus Division, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.*

E. I. **King,** *Development Engineer, Large Rotating Apparatus Division, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.*

Modifications in the hydrogen inner-cooling system make possible increased generator ratings within present space and material limitations.

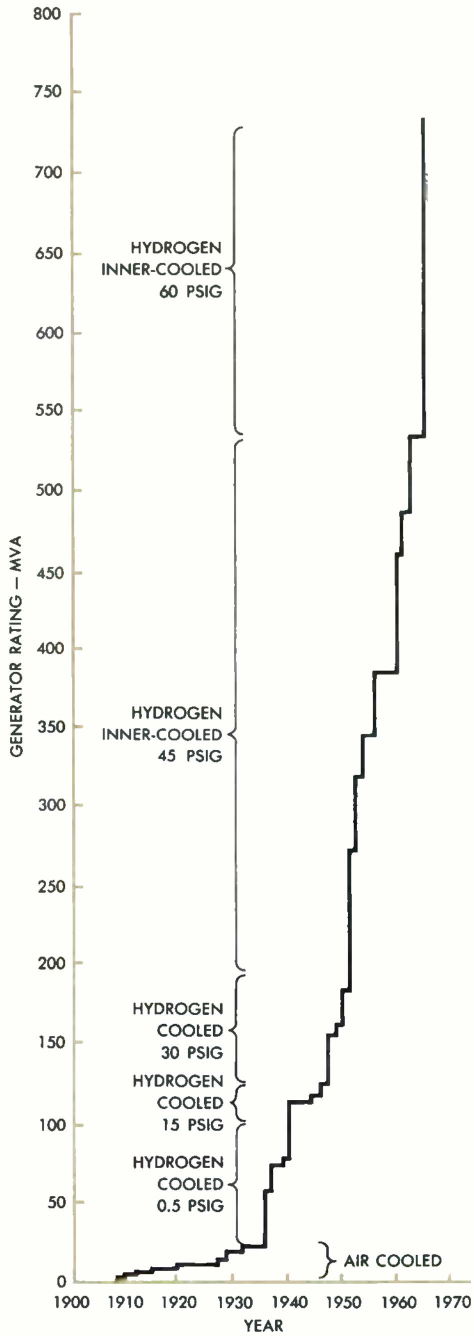
New developments in the hydrogen gas cooling system for steam-turbine generators make possible significant increases in generator capability. In a situation similar to that of the late forties, the maximum capacity of generators has been approaching a practical limit within present design techniques; and as before, an improvement in cooling, so that existing materials can be used more effectively, is the key to advancement. Rotor cooling has been improved by dividing the winding inner-cooling system into a series of zones and introducing essentially full blower pressure at each zone, so that cooling effectiveness is independent of rotor length. Stator cooling has been improved by increasing the number and revising the arrangement of cooling ducts, and by adding an external high-pressure compressor and heat exchanger. Thus, the already proven hydrogen gas cooling system with these modifications has extended machine ratings beyond past space and material limitations.

Inner-Cooling

The inner-cooling principle, in which hydrogen gas is forced through hollow conductors, was introduced in 1951[1] and permitted generator sizes to increase in an orderly fashion. The first Westinghouse generator to use the inner-cooling principle in both rotor and stator windings was placed in service in 1954[2]. Since that time, 28 600 mva of Westinghouse hydrogen inner-cooled generators have been shipped, the largest with a capability of 535 mva. But turbine generator ratings are again approaching the capabilities practical within present space and material limitations.

Operating experience with the inner-cooled machines has proved the reliability of the hydrogen inner-cooling system. Thus, the retention of hydrogen gas cooling for both rotor and stator windings is a desirable goal in the development of advanced designs. However, a cooling

1

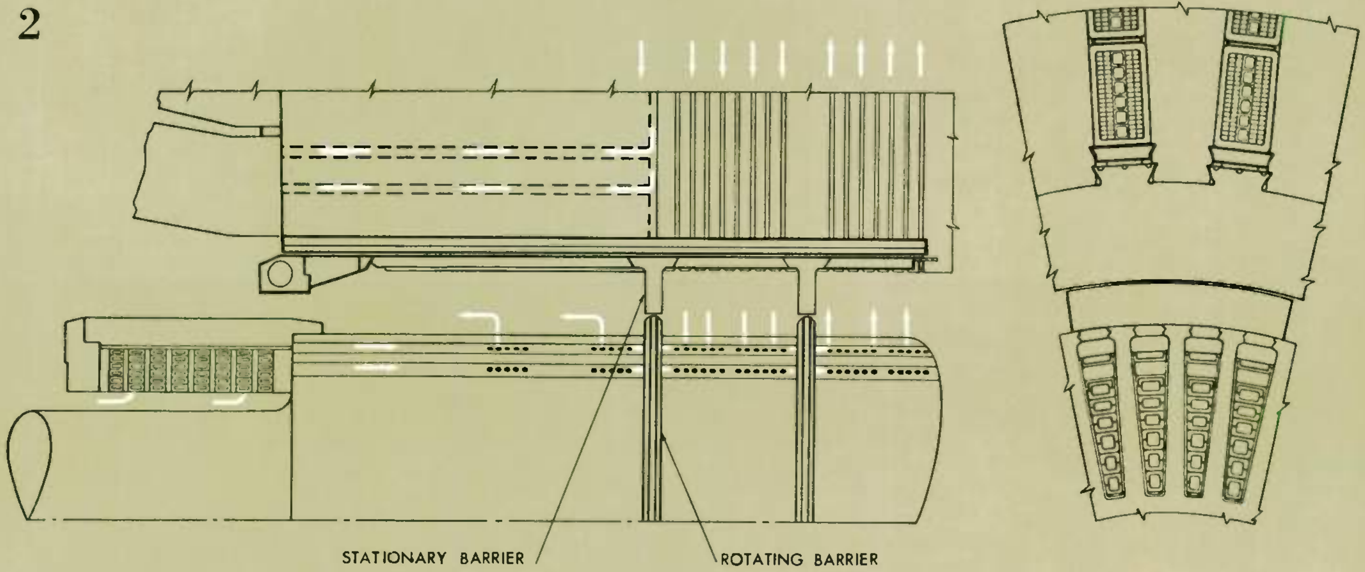


MAXIMUM KVA RATING is shown for 3600-rpm tandem generators now in service or on order.

[1] "Generator Coils Cooled Internally—Rating Increased by One Half," C. M. Laffoon, *Westinghouse ENGINEER*, November 1951, p. 170-2.

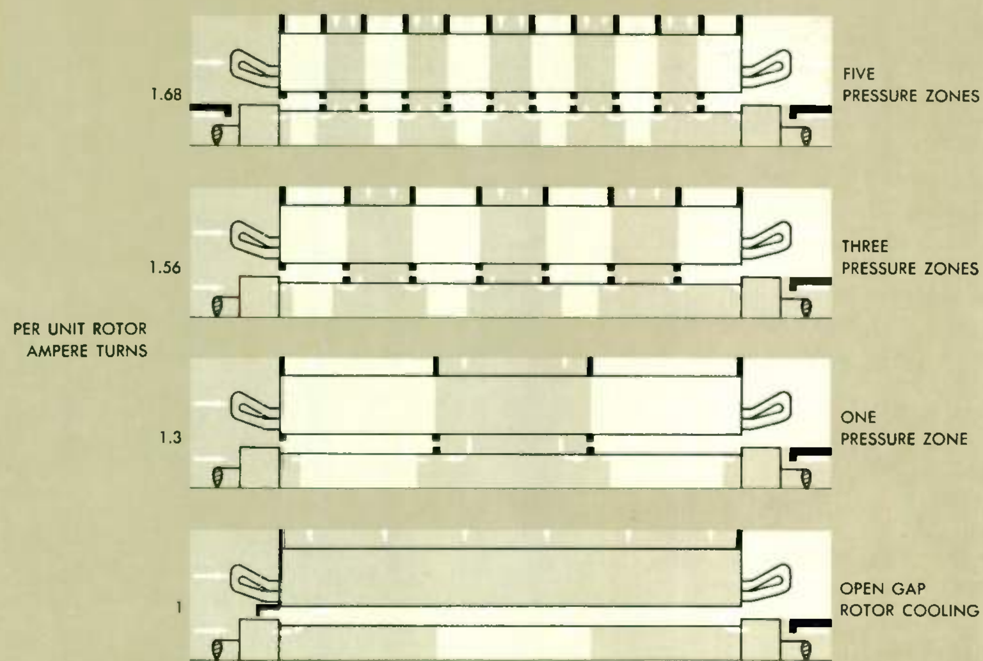
[2] "Inner-Cooled Generators—A Progress Report," C. M. Laffoon, *Westinghouse ENGINEER*, July 1954, p. 157-160.

2



GAP BARRIER ARRANGEMENT consists of rotating and stationary barriers, which control the flow of cooling gas from a high-pressure inlet zone to a low-pressure exhaust zone.

3



PRESSURIZED GAP ROTOR CAPABILITY is a function of the number of pressure zones.

system was needed that could materially increase the hydrogen mass flow through both rotor and stator windings.

The effectiveness of any cooling system is fundamentally a function of the mass flow of the coolant, in which the power consumption for moving the coolant is compatible with the efficiency of the machine. The power requirements for larger mass flow increase as the first power of the static pressure and the second power of the velocity of the cooling fluid. It is, therefore, much more economical to increase the static pressure of the gas in the machine than to increase the blower pressure. However, the permissible increase in static pressure of the gas is limited by the rotor windage losses. The first inner-cooled generator was tested in the shop at a pressure of 95 psig, and could have been operated continuously at that pressure if required. Thus, as larger generator ratings are required, a gradual increase in the static pressure of the gas can be utilized for the benefit of both stator and rotor winding cooling. However, an increase in static pressure alone is not enough. For future requirements of large capacities, the flow rate of the cooling fluid must also be increased.

Rotor Cooling

With the present inner-cooled rotor ventilation system, cooling gas enters the windings at each end of the rotor and is discharged through outlets at the mid position of the rotor. To minimize the length of the cooling ducts and the required gas-pumping power, the winding extensions at each end are cooled separately. This system has proven effective. The use of an efficient high-pressure axial-flow blower has made it possible to build rotors of the required capacity with a very simple ventilating system.

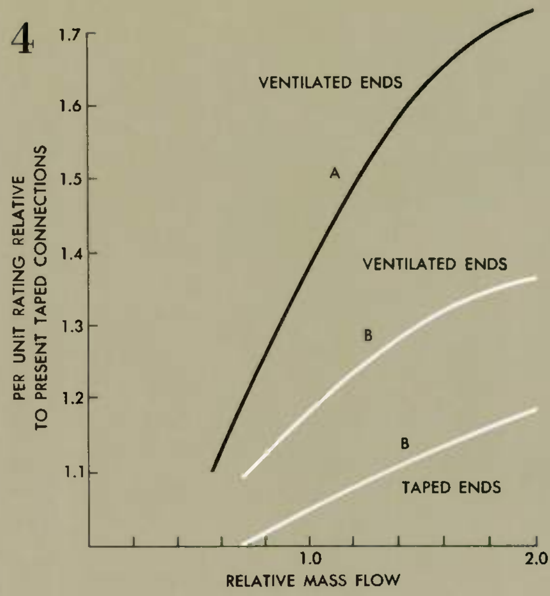
But today, on the longer machines, a further improvement in the mass flow of the cooling gas is needed to increase the ampere-turn capacity of the rotor for a given gas-pumping power. This has been accomplished with a new system of air-gap barriers, placed so that almost full blower pressure can be developed across each of several short axial sections of the rotor windings.

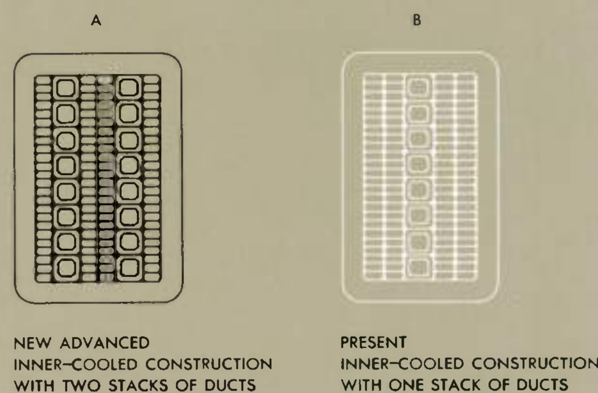
The air-gap barriers, shown in Fig. 2, consist of two parts—a nonmagnetic ring shrunk on the rotor, and a barrier of wedge sections made of Micarta, fastened to the bore of the stator. The wedge sections are engaged in a groove provided in each stator slot above the coil wedge. In each slot, the complete assembly is tightly wedged against the core by glass tape stretched to the desired tension by a special pushbutton-operated jack. The complete installation of each barrier requires only a few minutes. A radial clearance of approximately 1/8 inch between the stator and rotor barriers minimizes gas leakage from the pressure zones, and provides a control for the gas necessary to ventilate the gap for load and windage losses.

In a conventional inner-cooled rotor employing open gap cooling, the axial blower builds up gas pressure at each end of the rotor. Gas is forced into the hollow winding at each end, and exhausted at the outlets at the midpoint of the rotor.

With the new pressurized zone cooling system, the blower forces gas into the inlets at the ends, and also at pressurized inlet zones positioned along the rotor. The gas is exhausted at low-pressure zones between the pressurized

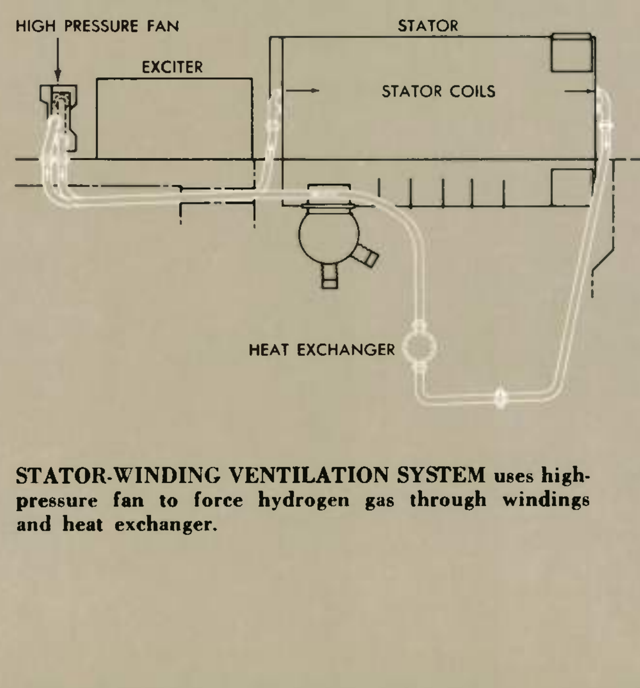
4





THERMAL CAPABILITIES for stator coils of one and two stacks of vent ducts with hydrogen inner cooling.

5



STATOR-WINDING VENTILATION SYSTEM uses high-pressure fan to force hydrogen gas through windings and heat exchanger.

zones. With this pressurized zone cooling system, the cooling ability of the system responds directly to the pressure produced by the blower, and the efficacy of the ventilation system is thus independent of rotor length.

The increase in rotor ampere-turn rating obtained with the pressurized gap system with one, three, or five pressure zones is shown in Fig. 3. Thus, a rotor ampere-turn rating with five pressure zones will be 1.68 times as great as the conventional open-gap-cooled rotor presently used on inner-cooled machines.

Stator Coil Cooling

The present inner-cooled stator coil, used since 1954, consists of four stacks of insulated conductor strands, separated by a center stack of nonmagnetic high-resistivity metal ducts, as shown at the bottom of Fig. 4. Cooling gas is forced through the ducts by the pressure differential produced between the ends of the coils by the shaft-mounted axial blower. The basic simplicity of this system and its low eddy losses resulting from the use of thin strands makes an extension of this system desirable for the larger generator ratings now required.

For a given accepted temperature rise at the end of the coil, the conductor losses that can be removed by the cooling gas can be increased by using two stacks of cooling ducts, one at the center of each pair of stacks of stranded conductors as shown at bottom of Fig. 4. Thus, with a given conductor having four stacks of strands, which is generally used, the heat flow density and the total thickness of the insulation in the heat path can be reduced to approximately one-half, while the cooling surface of the duct is much larger. Thus, with the same gas velocity, the heat removal capacity from the duct surface is nearly doubled. Further improvement in cooling the ends of the coils can be obtained by omitting the taping on the connections between coils, thus exposing them completely to the gas inside the casing. Adequate dielectric strength is obtained between phase groups by nonuniform spacing of the coil ends.

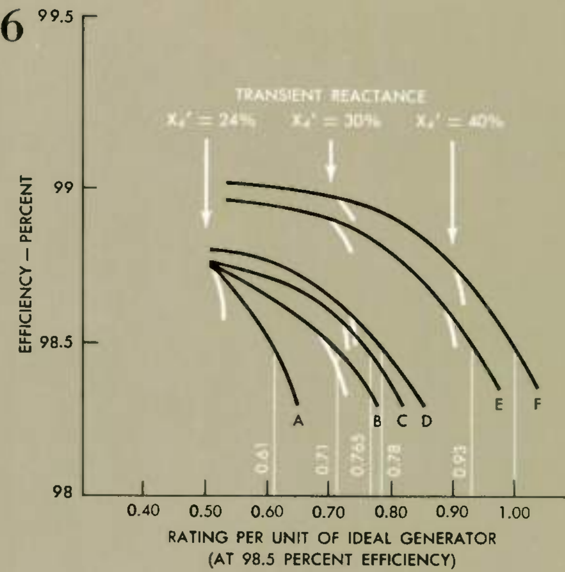
A major increase in hydrogen mass flow and cooling ability with low power consumption can be obtained by circulating hydrogen inside the stator coils at high pressure, 225 psi above the ambient stator pressure. This pressure is entirely independent of the normal hydrogen pressure inside the stator housing and is localized within a relatively small system consisting of a small external axial compressor and cooler, connected to the stator coil cooling ducts. Using the new stator coil construction with two stacks of ducts, tubular connections are used to connect each end of the coil to a header located at each end of the machine. Hydrogen gas is circulated by the external compressor through the coils and through an external hydrogen-to-water cooler (Fig. 5). Hydrogen pressure inside the coil-cooling system is maintained automatically, and any leakage from the connections will flow harmlessly into the surrounding hydrogen in the stator housing. This makes the system relatively easy to maintain.

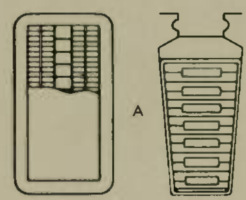
The increase in stator coil rating made possible with increased coolant mass flow is shown in Fig. 4.

Prototype Generator in Production

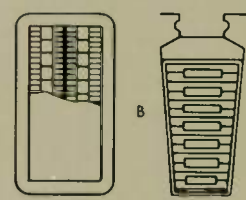
A 256-mva generator is now being built with pressurized, two-duct-stack stator cooling and pressurized

6

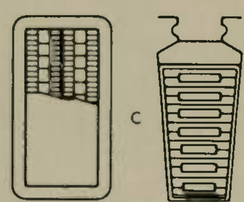




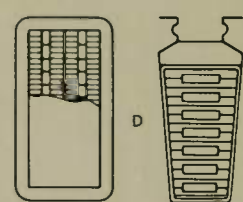
INNER COOLED; ONE STACK OF DUCTS STATOR COILS; OPEN GAP ROTOR COOLING



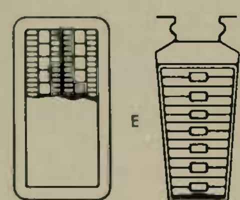
ADVANCED INNER COOLING; TWO STACKS OF DUCTS STATOR COILS; PRESSURE ZONES ROTOR COOLING



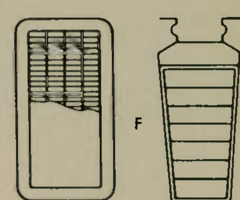
PRESSURIZED STATOR COILS; PRESSURE GAP ZONES ROTOR COILS



WATER COOLED STATOR COILS; PRESSURE GAP ZONES ROTOR COOLING



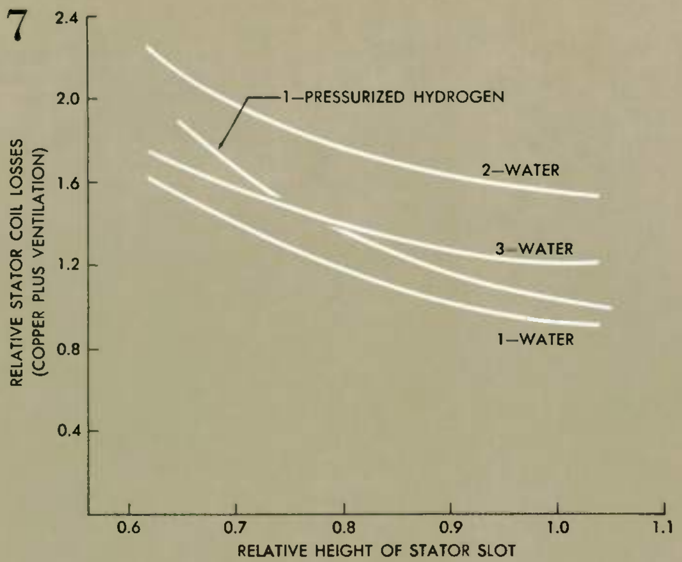
WATER COOLED ROTOR; WATER COOLED STATOR COILS; 0.5 PSIG HYDROGEN

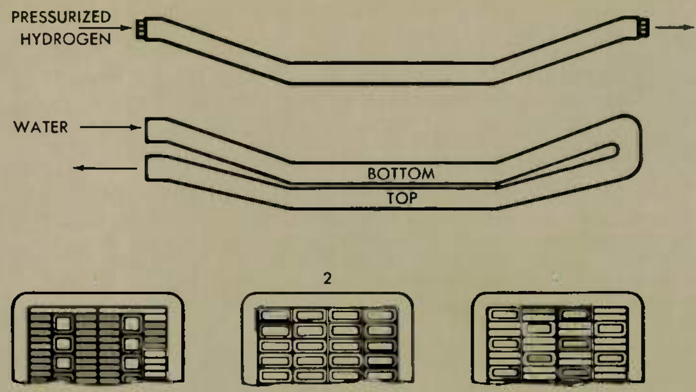


IDEAL GENERATOR; ALL COPPER WITH PERFECT COOLANT; 0.5 PSIG HYDROGEN

SUMMARY OF EFFICIENCIES for various machine cooling arrangements demonstrates the effectiveness of the new hydrogen inner-cooling system. Curves branching downward from the lettered curves show restrictions on ratings imposed by three values of transient reactance. If an attempt is made to maintain a constant transient reactance by shortening the stator slot, thus reducing the stator copper, the higher losses would cause the efficiency to drop sharply as shown.

7





RELATIVE PERFORMANCE of stator coil constructions for water and pressurized hydrogen cooling.

gap zone rotor cooling. In this machine, the small circulating blower for the high-pressure gas is placed at the end of the main shaft, and connected to the stator winding header by means of two 6-inch-diameter steel pipes.

The small compressor impeller is supported by two bearings combined with gland seals supplied from the generator gland seal oil system, which is provided with an adequate number of emergency back-ups.

This pressurized stator-coil cooling system permits the large capacity generator ratings that will be required in the foreseeable future, yet it maintains the fundamentally simple, rugged and reliable stator coil construction that has been used so successfully in the inner-cooled generators now in service.

Maximum Rating of Generators

With these improvements in cooling methods for rotor and stator coils, the maximum generator rating is no longer limited by thermal conditions, but rather, by other performance requirements such as efficiency and transient reactance. This situation is illustrated in Fig. 6, where the maximum rating of machines with several types of rotor and stator cooling systems is shown as a function of generator efficiency and transient reactance. The lettered curves show the efficiency as a function of rating with no regard for transient reactance. The curves branching downward from the lettered curves show the limitations imposed by three values of transient reactance.

For the stated requirements and efficiency, but with 60 psig hydrogen pressure with a 40-inch-diameter rotor, the ideal generator (Curve F on Fig. 6) could develop a maximum rating slightly over 1000 mva. The maximum ratings that could be obtained with the other types of machines may be estimated from the factors given in Fig. 6. In all the machines in Fig. 6, the rotors have the same body dimensions but the stator outer diameter would vary with the type of stator coil cooling and the air gap dimension. Higher ratings can be obtained with lower voltage, lower short-circuit ratio, higher power factor, or higher stator hydrogen pressure.

The maximum rating of a generator is limited by the efficacy of the cooling of both the rotor and the stator windings, which must be matched for optimum design. For example, the generator of Curve C has a rotor effectively cooled with pressurized gap zones, and a pressurized stator winding. In this case, the use of water-cooled stator coils, as shown on Curve D, results in only a relatively small increase in rating. This is based on the stator coil design with two stacks of ducts, which permits the use of thin strands with resulting lower eddy losses and improved performance as shown on Fig. 7.

Whereas the Curve C unit employs a pressurized stator winding with coil connections and external blower, the improved gas-cooling system shown by Curve B of Fig. 6 has made it possible to obtain single-shaft-generator ratings up to about 750 mva at 60 psig hydrogen pressure with no external stator cooling system and without increasing the rotor size beyond that already in service. Five machines are now on order with this construction, the largest having a rating of 733 mva.

Still larger ratings can be obtained with the improved gas-cooling system by using increased rotor diameter, increased length, increased gas pressure in the casing, or pressurized stator coils as shown by Curve C of Fig. 6. With these methods, a single-shaft rating of 1100 mva can be obtained.

The foregoing estimates apply to 2-pole, 3600-rpm generators. The same principles can be applied to the 4-pole, 1800-rpm generators, which can be built with ratings even greater than those for 2-pole generators.

With the newly developed rotor and stator winding and cooling system, the large turbine generator ratings required in the foreseeable future can be designed and built with fundamentally the same components that have been proved by ten years of reliable service.

Westinghouse ENGINEER Nov. 1964

The Economic Development of Mine-Mouth Power Plants, EHV Transmission, and Nuclear Generation in the United States

J. K. Dillard, Manager, Electric Utility Engineering Department,
C. J. Baldwin, Manager, Advanced Development,
Electric Utility Engineering Department,
Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.

Major improvements in electric utility economics will probably come from one of the three areas mentioned above.

Some of the greatest opportunities for improvement in electric energy economics in the foreseeable future lie in three different developments: mine-mouth power plants, 500-kv transmission grids, and very large nuclear plants.

The trend in these directions is already under way. Three large mine-mouth plants of capacities between 1000 and 1800 mw are under construction at locations of 150 to 400 miles from their major load centers; about 2000 circuit miles of 500 kv transmission are either under construction or in the advanced planning stage; and six large nuclear reactors in the size range of 395 to 515 mw are on order, and a 1000-mw plant has been proposed.

This is a change from the historical pattern of improving energy economics by reducing the heat rate of conventional plants and reducing their installed costs relative to the construction cost index. Results in this area have been good; in the 25-year period from 1937 to 1961, the *average* station heat rate has been reduced from a little over 17 000 Btu/kwh to about 10 500. During the same period, steam plant investment has risen from $110/kw to $130/kw, as opposed to a more than three-fold increase in the construction cost index for labor and material costs for steam plants.

Further improvements in the traditional pattern are still possible, such as the application of steam-gas turbine combined cycles, but nevertheless greater potential for economic improvement now lies in mine-mouth plants, EHV transmission, and large nuclear plants.

Energy Transportation Systems

Energy transportation is a key factor in the economic selection of a mine-mouth plant over a conventional plant or a nuclear plant. The primary energy resources of the United States are not located in the areas of highest population density. Consequently, some bulk transportation is required for most of the energy consumed.

Competition between the various fuel sources and energy transportation systems accounts for some of the substantial improvements in energy economics in the United States today. The construction of exceedingly large mine-mouth plants with 500-kv transmission has had the effect of forcing down the transportation costs of coal by rail. Similarly, the application of nuclear power in the high-fuel-cost areas has helped reduce the cost levels of fossil fuels and their transportation media. As the costs of fossil fuel come down, increased efforts are applied to reduce the cost of EHV transmission and nuclear power.

The salutary effects of competition between energy transportation systems and fuel sources is already being felt by individual utilities. For example, one utility has estimated it will save about $20 million per year in fuel transportation costs from the application of the integral train concept.

The recent substantial reductions in rail rates because of the integral train concept have narrowed the spread of fuel costs between sites in the United States. The reduction in the delivered cost of fossil fuel makes it harder to justify mine-mouth plants or atomic power. Nevertheless, there is still a substantial transportation cost involved in moving energy, and sizable fuel cost differentials still exist between the energy source and use areas of the United States. The geographical distribution of delivered fuel costs is illustrated in Fig. 1. It is in this framework and its long-range trend that mine-mouth power plants, 500-kv transmission, and nuclear power must be justified.

Status of EHV Transmission

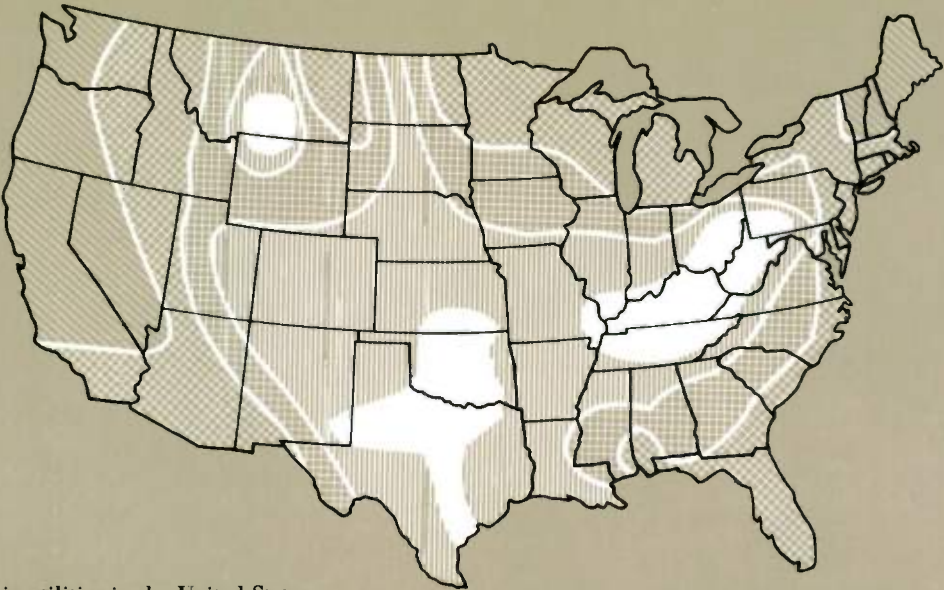
Transmission expansion in the United States has been careful and measured. Instead of being a goal in itself, each move to a higher EHV level has derived from economic need.

Technology for moving to 500 kv has existed for many years as a result of field testing programs carried on continuously since 1946 at this voltage level. Tests today are being made at the 775-kv level and are providing the basic engineering data required for any voltage requirements of the next 20 years in the United States.

If a transmission system is to be developed most economically, the voltage level selected must be compatible with the blocks of power to be transferred. The surge impedance loading (SIL) concept defines the permissible power transfer capability of any circuit for various transmission distance.* Thus at 200 miles, for example, a 345-kv circuit can transfer nearly 500 mw, a 500-kv circuit can transfer nearly 1300 mw, and a 700-kv circuit about 2800 mw. The long-range need for capability as well as

*SIL= 2.5 kv^2 for single conductor lines and 3.0 kv^2 to 3.9 kv^2 for bundled conductor lines. Capability, in kilowatts, for a 100-mile line is 2.0 SIL, a 200-mile line is 1.5 SIL, and a 300-mile line is 1.0 SIL. Lines less than 100 miles long are usually thermally limited and may be loaded as high as 4.0 SIL.

1



DELIVERED COST OF FUEL to electric utilities in the United States.

Table I—NEW UNIT CHARACTERISTICS

Unit Capacity MW	Forced Outage Rate Per Cent		4-Year Maintenance Cycle Weeks per Year	Fixed Operation and Maintenance Cost Dollars per Year	Full-Load Heat Rate Btu/kwh	
	Immature	Mature			System A	System B
400	3.5	2.7	3-3-3-6	510,000	8930	8570
600	4.0	3.0	3-3-3-6	840,000	8870	8520
800	4.5	3.3	3-3-3-6	1,040,000	8780	8430
1000	5.0	3.6	3-3-3-6	1,160,000	8660	8320

the immediate need for the project under study must be carefully considered. Changes to a higher voltage level are rarely justified by short-term projections.

Some economic studies of energy transportation systems have looked at the relative costs on a simple mills/kwh basis for point-to-point energy transportation. Taken at face value, these mills/kwh comparisons make the economic justification of EHV transmission difficult unless the distances are extremely short or the energy source is hydroelectric.

The fallacy in this type of comparison is the neglect of the operating benefits of an electrical grid. The electrical grid permits transfer of large blocks of reserve power and blocks of economy interchange energy in both directions between power systems. These two factors have played a key role in justifying the expansion of electrical transmission in the United States.

Power Pooling in the United States

As recently as 1955, the electric utility industry in the United States consisted of over 3000 independent operating systems. About 370 of these are investor-owned, but they account for about 76 percent of the total installed capacity, and the rest are cooperative, municipal, or other governmental systems. In the period 1960-1963, the investor-owned group of 370 utilities coalesced into about 20 large planning and operating power pools. Some of these investor-owned groups, by negotiating firm interchange agreements with some of the larger governmental systems, have extended the pooling to about 90 percent of the nation's installed capacity. While the bulk of the industry has operated in parallel for many years, this recent pooling marks the first extensive coordinated effort at planning major new facilities as joint ventures, and it offers new opportunities to make best use of energy resources.

Electrical transmission can be used effectively by power pools to share installed reserve and thus delay new capacity installations. The delays in new capacity requirements can be attributed to the sharing of peak load diversities, outage diversities, and maintenance requirements between systems. The net result is a lower installed reserve. The exact amount of reserve saving can be determined by probability methods.

Furthermore, larger generating plants can be installed at their lower $/kw cost without increasing reserve requirements. Neither of these benefits can be obtained with nonelectrical energy transportation systems.

An electrical transmission system also allows the exchange of economy energy in both directions between power systems or pools. In this case also, a simple mills/kwh evaluation of energy transportation methods fails to give a complete economic evaluation. When systems are tied electrically in pools, common economic dispatching of all units reduces the total production expense. Another fuel saving comes from the use of the larger pool units with their improved heat rates. Thus a detailed simulation of the future operation of the interconnected systems is necessary to identify the potential savings from economy interchange. In some studies of the economics of pooling, the savings from common economic dispatch and two-way energy transfer have amounted to nearly one-third of the total savings. Total savings from pooling have totaled up to 10 percent of the total fuel bill and investment charges on the bulk power systems of the pooling utilities.

Cost Trends of Nuclear Power

Nuclear power is also improving energy economics. The move to pooling and larger plant sizes has helped establish a competitive advantage for nuclear power in those areas where fuel costs exceed about 25¢ per million Btu. This is because nuclear plants enjoy an economy of scale beyond that of conventional plants, as shown by the relative slopes of the curves of Fig. 2, caused by the presence of relatively more components in a nuclear plant that are not strictly a function of plant size. Fossil-fuel plant installed costs vary widely because of differences in design practices, cooling water requirements, fuel sources, and labor costs. Thus they are shown as a wide band. The nuclear plant curve is for standard designs in average labor cost areas, based on guaranteed ratings. Besides illustrating the economy of scale inherent in nuclear plants, the curves show that the *capital cost* of nuclear plants is only slightly above average-cost fossil-fuel plants being built today.

In competing with mine-mouth plants and EHV transmission, the nuclear plant has a definite advantage in fuel-transportation and fuel-cycle costs. Nuclear fuel can be transportable cheaply to almost any site, favoring plant location near the load center. The only limitation at present is siting restrictions imposed for public safety reasons. However, engineered safeguards have been devised to make siting feasible even in large metropolitan areas. For such a plant, extra containment and shielding can add five to six percent to the nuclear plant costs shown in Fig. 2. Even so, such a plant can be economical.

The nuclear plant compensates for its slightly higher first cost by very favorable fuel-cycle costs. Economic comparisons made in this article assume nuclear plants to have an average full-load fuel cost of the first six years of life of 2.3 mills/kwh. This fuel cost decreases with time, and plants have a fuel cost of 1.95 mills/kwh the second six years of life, eventually reaching 1.7 mills. These values represent very conservative forecasts. Values quoted in recent negotiations are somewhat lower.

Economic Justification

The economic justification of mine-mouth power plants, EHV tranmission, or nuclear generation generally requires long-range projections of system growth, pooling arrangements, and plant usage. Until recently, the calculations necessary for accurate long-range projections were so laborious that only superficial economic analyses were possible. However, automatic planning techniques using digital computers now permit accurate and rapid economic analyses of expansion alternatives for a long future period. Twenty-year studies are usually recommended. These new methods of planning are by now well documented.

Table II—EXPANSION PATTERNS

Unit Capacity, mw		
Base Pattern Single System	Pooled Pattern P1	Pooled Large Unit Patterns P2, P3, P4
400	400	600*
	400	600
400	400	600
	400	600
400	400	600
	400	600
400	400	600
	400	600
400	400	800
	400	800
600	600	800
	600	800
600	600	800
	600	800
600	600	800
	600	800
600	600	800
	600	800
800	800	1000
	800	1000
800	800	1000
	800	1000
800	800	1000
	800	1000
800	800	
	800	
800	800	
	800	
1000	1000	
1000		

**This unit is mine mouth for pattern P3 and nuclear for pattern P4.*

Pooling and Mine-Mouth Generation

Up to this point, changes in energy economics in the United States have been discussed qualitatively. The exact nature of the savings available is shown best by a quantitative analysis of typical utility situations. To do this, two hypothetical utility systems will be compared and their potential savings computed. The systems are typical of today's individual companies or medium-sized pools.

The two systems and their primary characteristics are shown in Fig. 3. While identical in many respects, the systems are geographically separated, with one having a summer peak load and the other a winter peak load. If the two systems operate as a pool, the pool will have a winter peak. Seasonal patterns are different; consequently, maintenance coordination is desirable.

The geographical separation of the two systems results in a fuel cost differential of 10¢/million Btu. Because of this historical difference in fuel costs, System B has been purchasing installations with heat rates 4 percent below those of System A.

If System B were to continue expansion separately, it would continue to purchase the better heat rate equipment at about a 2 percent premium on installed plant costs. Installed costs for conventional units on System A follow the dashed curve of Fig. 2. Outage rates, maintenance rates, full-load heat rates, and fixed operation and maintenance costs for new units are shown in Table I.

Fixed charges on conventional plants are 12 percent; transmission fixed charges are 10 percent. The proposed base load expansion pattern for individual expansion of the two systems is shown in Table II. The next unit for installation on each of the individual systems expanding alone is of 400 mw size.

The first two columns of Table III show the installation dates for new units on each of the two systems if they were to plan expansion *separately*. These dates are selected on the basis of a design service reliability as calculated by probability methods. Sufficient installed reserve is planned to maintain a risk of insufficient installed capacity no worse than one day in ten years. Columns 3 and 4 of Table III show the installation dates for new units on the two systems with the assumptions they *merge into a pool* and plan joint use of installed reserve. Columns 5 and 6 show the yearly capacity savings under the *pooled arrangement*, which is designated pattern Plan 1. System A averages 710 mw less capacity yearly, while System B averages 840 mw less than with separate expansion. To accomplish the reserve savings, tie lines must be built between the two systems in the amounts of firm capacity shown in columns 7 and 8.

The cost of the EHV transmission to accomplish the pooling must be balanced against the savings in reserve and the savings from possible economy interchange of energy. The voltage level selected for the tie depends on the blocks of power to be transferred, not only in the earlier years but in the later years as well. It also depends on the relative cost of EHV transmission at different voltage levels. Table IV, using data from a recent Federal Power Commission document, shows the cost assumptions for installed EHV transmission at 345 and 500 kv. Both voltage levels were investigated as being reasonable selections based on the blocks of power to be transferred. Transmission system design dictated that enough circuits be installed to allow transfer of Table III values with one line out of service.

The annual revenue requirements of the necessary EHV transmission system were balanced against the savings shown in the first column of Table V to determine the net economy of the pooling arrangement. Results are plotted in Fig. 4 for various separation distances of the two power systems. This figure shows that for a 10¢/million Btu fuel cost differential, it is economical to reach as far as 550 miles to accomplish the pooling if 345 kv is used. Selection of 500 kv permits an economical 650-mile reach. If the distance between the systems is short, below 125 miles, 345 kv is the more economical voltage level.

Most savings from pooling come from the sharing of diversities and reserve reductions. Some additional savings, however, are available from the use of larger generating units sized for the entire pool. The evaluation of Systems A and B was repeated for a modified expansion pattern (Plan 2) using larger units. The pattern of Table II was used, except expansion began with the first 600-mw unit; the first five 400-mw units were omitted. The net effect of using the larger units is to slightly increase the savings with pooling, as indicated in the second column of Table V. Also, the economical separation distance is slightly increased. This is illustrated for 500 kv in Fig. 5 by the curve labeled Plan 2.

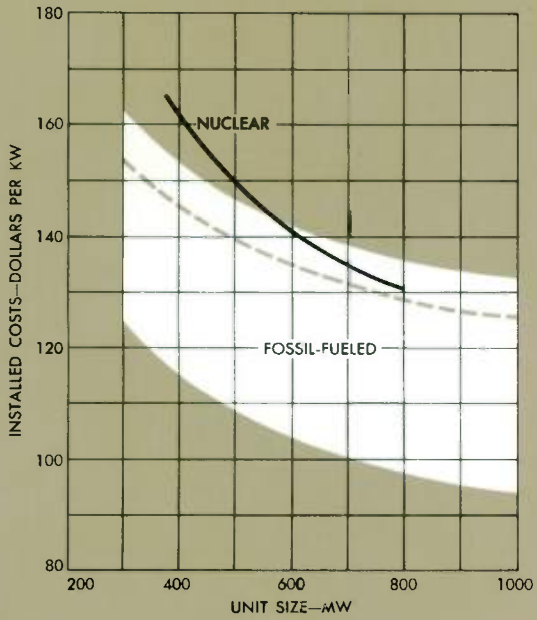
Mine-Mouth Plants

The required transmission ties, as shown in Table III, are sufficient to accomplish complete sharing of diversities and reserves. They are, of course, available for the economy interchange of energy. The two systems were dispatched for maximum economy, and tie flows were permitted up to the limits of the tie capacity between the pools. However, no additional ties were installed strictly for the interchange of energy. Since there is a substantial fuel cost differential between the two systems, it is natural to inquire into the economics of locating one of the System

Table III—NEW-UNIT INSTALLATIONS, SAVINGS, AND TIE REQUIREMENTS FOR EXPANSION ALONE AND POOLED

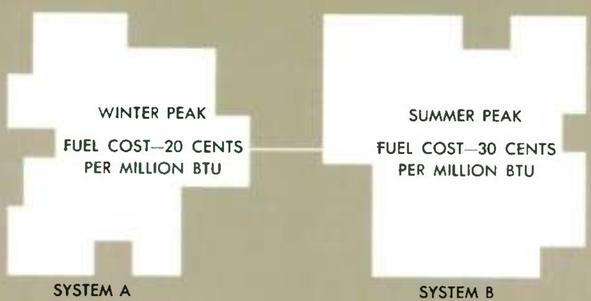
	Expansion Alone				Expansion Pooled, Pattern P1			
	Unit Requirements, mw		Unit Requirements, mw		Savings, mw		Import Tie, mw	
Column Number Year	1 System A	2 System B	3 System A	4 System B	5 System A	6 System B	7 System A	8 System B
1	400	400	—	—	400	400	500	300
2	400	400	400	400	400	400	300	300
3	—	—	—	—	400	400	800	600
4	2-400	400	400	400	800	400	400	500
5	—	400	400	400	400	400	500	600
6	400	400	400	—	400	800	400	700
7	600	600	400	400	600	1000	600	800
8	—	—	600	400	—	600	600	400
9	2-600	600	—	600	1200	600	600	400
10	—	600	600	600	600	600	600	800
11	600, 800	600	600	—	1400	1200	600	1000
12	—	—	600	600	800	600	700	500
13	—	800	—	600	800	800	700	400
14	800	800	800	800	800	800	700	900
15	800	800	800	—	800	1600	800	1300
16	—	—	800	800	—	800	1000	600
17	2-800	800	—	800	1600	800	1000	700
18	—	800	800	800	800	800	900	1200
19	1000	1000	800	—	1000	1800	1100	1900
20	1000	1000	1000	800	1000	2000	1100	1000

2



CONVENTIONAL AND NUCLEAR PLANT CONSTRUCTION COSTS, including site development, interest during construction, and utility's general overhead expense. Dashed curve shows conventional plant assumptions for sample system study.

3



IDENTICAL CHARACTERISTICS FOR SYSTEM A & SYSTEM B

***System Size*—4300 mw**
Average Unit Size—103 mw
Maximum Unit Size—350 mw
***System Peak Load*—3710 First Year, 6% Annual Growth**
Summer Diversity—300 mw
Winter Diversity—130 mw
Existing Units
Forced Outage Rates—2%
Maintenance Rates—6%
Total Availability—92%
Fixed Charges
Plant—12%
Transmission—10%

***Plan 1*—Pooled Systems With Conventional Unit Size**
***Plan 2*—Pooled Systems Using Larger Units**
***Plan 3*—Pooled Systems With Mine-Mouth Generation**
***Plan 4*—Pooled Systems With Nuclear Generation**

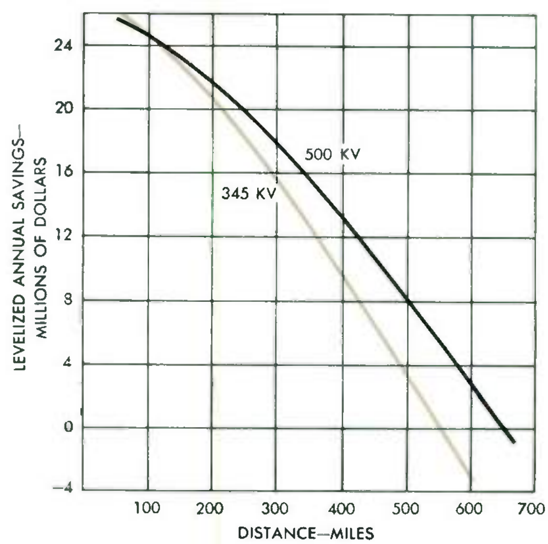
B units in lower fuel cost area A as a mine-mouth plant. This may or may not be economical, depending on the separation distances of the two areas and whether or not the two systems are pooled.

If System B expansion is considered alone, and if its first 400-mw plant is located in area A, the breakeven distances for a mine-mouth plant are those shown in Fig. 6. Here enough firm transmission has been installed to permit transportation of the mine-mouth plant energy to the load area with one line out of service. This transmission is used simply on a point-to-point energy transfer basis for a 400-mw block of power. For this limited use of the energy transportation system, the economical reach is 150 miles with 345-kv transmission, and 345 kv is obviously the correct voltage choice for fuel cost differences greater than 8 cents. The economical reach for a 400-mw hydro plant (at $200/kw) is only 270 miles. The economical separation distances are not greater because only a 400-mw block of power is being transmitted for a single system. Point-to-point transmission can be economical for dis-

Table IV—EHV TRANSMISSION FACILITY INSTALLED COSTS

	Line Voltage	
	500 kv	345 kv
Terminal Equipment		
Termination with Breaker	$ 550,000	$350,000
Transformer	50,000	33,000
Autotransformer		
600 MVA	$1,220,000	$970,000
500 MVA	1,130,000	855,000
400 MVA	1,030,000	765,000
300 MVA	920,000	660,000
Line Cost per Mile	$ 99,000	$ 77,000
per km	$ 61,516	47,845

4



SAVINGS BY POOLING with merged pattern P1. This pattern uses the individual system unit sizes given in Table II. Savings are shown for various system separation distances with connecting transmission at 345 or 500 kv.

Table V—PRESENT WORTH OF REVENUE REQUIREMENTS AND EQUIVALENT ANNUAL SAVINGS FROM POOLING (IN THOUSANDS OF DOLLARS)

	Merged Pattern P1	Large Unit Pattern P2
	Generating Plant Investment	
System A alone	$1,448,741	$1,448,741
System B alone	1,512,061	1,512,061
Sum	$2,960,802	$2,960,802
Pooled	2,539,020	2,514,709
Savings (by difference)	$ 421,782	$ 446,093
Levelized annual savings	$ 24,767	$ 26,766
	Production Expense	
System A alone	$1,535,507	$1,535,507
System B alone	1,900,961	1,900,961
Sum	$3,436,468	$3,436,468
Pooled	3,389,873	3,366,640
Savings (by difference)	$ 46,595	$ 69,828
Levelized annual savings	$ 2,796	$ 4,190
	Total Savings	
Generating Plant Investment	$ 421,782	$ 446,093
Production Expense	46,595	69,828
Sum of savings	$ 468,377	$ 515,921
Levelized annual savings	$ 27,563	$ 30,956

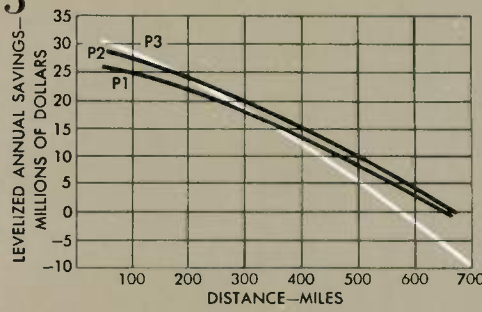
Table VI—PRESENT WORTH OF REVENUE REQUIREMENTS FOR POOL EXPANSION WITH LARGE UNITS AND WITH ONE MINE-MOUTH UNIT (IN THOUSANDS OF DOLLARS)

	Generating Plant Investment	Production Expense	Additional 500-kv Transmission Investment	Total Present Worth of Revenue Requirements
Large-Unit P2	$2,514,709	$3,366,640	—	$5,881,349
Mine-Mouth P3				
50 miles (80 km)	$2,511,876	$3,331,456	$ 9,886	$5,853,218
300 miles (483 km)	2,511,876	3,331,456	53,073	5,896,405
600 miles (966 km)	2,511,876	3,331,456	116,573	5,959,905

Table VII—SYSTEM B EXPANSION ALONE WITH THE FIRST PLANT NUCLEAR

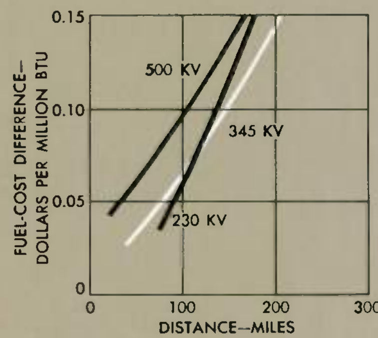
	Present Worth of Revenue Requirements Thousands of Dollars		
	No Nuclear Plant	400-mw Nuclear Plant	600-mw Nuclear Plant
Generating Plant Investment	$1,512,061	$1,523,199	$1,556,140
Production Expense	1,900,961	1,869,787	1,820,710
Total Revenue Requirements	$3,413,022	$3,392,986	$3,376,850
Savings Over Base Plan			
Present Worth	—	$ 20,036	$ 36,172
Levelized Annual Savings	—	1,202	2,170

5



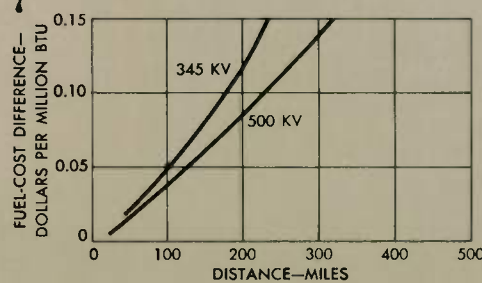
SAVINGS BY POOLING with 500-kv interconnection for various patterns:
P1: merged pattern (from Fig. 10)
P2: large-unit pattern
P3: mine-mouth pattern

6



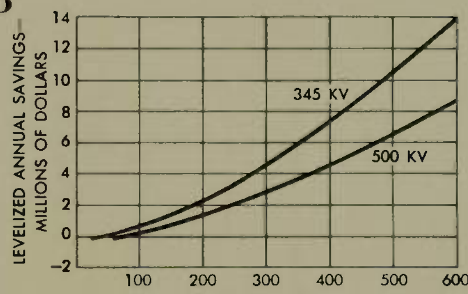
BREAKEVEN DISTANCES for a System-B 400-mw unit as a mine-mouth plant located in area A with no pooling of Systems A and B.

7



BREAKEVEN DISTANCES for a System-B 600-mw unit as a mine mouth plant located in area A when System A and B are pooled.

8



SAVINGS of the pool nuclear plan over the pool mine-mouth plan.

tances up to 400 miles if the block of power is 1200 mw and the fuel cost differential is 15 cents. However, plants this large would not be economical on a single 4300-mw system at this stage of growth.

The decision of locating a System B plant in area A is quite a different matter in the environment of the power pool of A and B. To study this, the first B unit in large-unit pattern Plan 2 was purposely located in area A instead of area B. This might be thought of as a unit which System B is obligated to provide for reserve, but which it chooses to locate in area A close to the source of fuel. The transmission needed between the systems will be increased. The dollar effect of this mine-mouth location is shown in Table VI for various separation distances between the systems. The dashed curve in Fig. 5 shows that a mine-mouth plant is economical in the pooled environment if the systems are located 225 miles apart or less for a fuel cost difference of 10¢/million Btu.

The economical distance for a mine-mouth plant based on various fuel cost differentials between the two areas and for both 345 kv and 500 kv is shown in Fig. 7. Whereas 345 kv was the economic choice when a mine-mouth plant was considered for the single system, 500 kv is obviously the choice in the pooled environment for all fuel cost differentials. It permits the maximum reaching distance between systems for the mine-mouth plant.

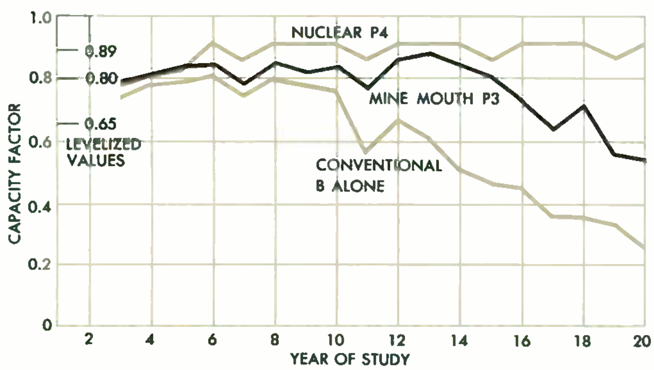
Nuclear Units

While nuclear plants can be justified on single systems alone in 25¢ fuel cost areas or above, the savings are greater when they are applied in a pooled environment. To study this aspect of energy economics, System B was expanded alone: (1) with the first unit of column 1, Table II as a 400-mw nuclear unit; then (2) with the first unit as a 600-mw nuclear unit instead of 400 followed by four 400-mw conventional units and the rest of the column 1, Table II patterns. Table VII shows that the 400-mw nuclear unit saves $1.2 million a year on System B alone, compared with the all-fossil-fuel pattern. Savings with a 600-mw nuclear unit are nearly double those with a 400-mw unit. Finally, a 600-mw nuclear unit was studied on System B in a pooled situation without any 400-mw units at all, pattern Plan 4 of Table II. When studied in the pooled environment, the plan with the 600-mw nuclear unit produced lower revenue requirements than even the mine-mouth plan, Plan 3, if the separation distances of the systems exceeded 75 miles with 500-kv transmission, or 50 miles with 345-kv transmission (see Fig. 8).

There are several effects making the nuclear plan more economical at system separation distances greater than 75 miles. One obvious saving is the elimination of the transmission associated with the mine-mouth Plan 3. Another less obvious effect is the improved loading of the nuclear plant over the 20-year study period compared with either the mine-mouth plant or a conventional plant in one of the individual system expansion plans. This effect is illustrated in Fig. 9. After reaching maturity in its outage performance, the nuclear plant remains at an equivalent level 20-year capacity factor of nearly 0.9, while the mine-mouth plant gradually is unloaded over the years by newer base load units installed on the pool. A conventional unit installed in System B expanding alone is unloaded even more quickly. The effective level 20-year capacity factor of the mine-mouth plant is only 0.8 and that of the conventional unit in System B only 0.65.

Examination of Figs. 5 and 8 shows that the mine-mouth plant is favored over the nuclear plant for separation distances below 75 miles, while the nuclear plant has greater savings for greater separations (for 500-kv transmission). In fact, the nuclear plant shows savings at the large separation distances even when compared with the large-unit pattern Plan 2. This is indicative of the present economy of atomic power in a pooled environment.

9



CAPACITY FACTORS for units installed in the early years. After reaching maturity (year 6), the nuclear plant is limited only by outages, while the fossil-fueled plants are unloaded by newer base load units.

Conclusion

The scope of the justification studies described has necessarily been limited. Economic analyses justifying mine-mouth plants, EHV transmission, and nuclear plants in the United States naturally involve the investigation of many expansion plans and many more alternatives than discussed here. Additional studies are needed to optimize the exact size of plants, to determine the limiting amount of mine-mouth generation that can be justified, and to find the amount of nuclear capacity that can be kept at a suitably high capacity factor over its entire life. The illustrations presented are indicative only of the type of long range analyses that are undertaken in the economic development of these new generation sources. However, the results are indicative of savings for utilities.

Present trends indicate that there will be increased usage of mine-mouth plants, EHV transmission, and nuclear generation. However, transmission will not be built to move large blocks of power from hydro or low-grade fossil-fuel sources that are too remote. Five to seven hundred miles is probably an upper limit considering even the most favorable circumstances with regional pools and 1000 to 2000-mw plants. Pooling will take place on a regional basis and not on a national scale. Economies will be realized by locating at least a large portion of the installed capacity relatively near the load centers. Plants will be sized to match regional requirements. Large nuclear plants will be applied in fuel cost areas of 25¢/million Btu and above. Competition from nuclear plants and regional mine-mouth plants will exert continued downward pressure on coal costs and rail rates. The benefits of this competition will be substantial.

Small Control Computers . . . A New Concept

F. G. Willard, Advisory Engineer, Computer Systems Division, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

The effective and economic process control afforded by computer control systems has heretofore been limited, by cost, to large complex processes. A new smaller system now extends the advantages of on-line computer control to many more industries.

Many process operators who really need more advanced process control have not been able to justify the cost of large computing control systems; for economic justification, they would have to extend computer control to additional functions other than the primary control function or even to most of the plant. Such broad use is not always feasible, so the economic difficulty has effectively prevented use of computer control for thousands of the smaller process applications.

Even for these relatively small processes, the large wired-logic control systems often are no longer big enough. Moreover, they offer little if any flexibility to accommodate process changes, and they may not be able to provide the required reliability. The result has been a void in industrial process control between practical wired-logic systems and computing control systems. Needed to fill this gap was a relatively small and simple, yet powerful, computing control system, one that would be widely applicable to keep equipment and programming costs low. Such a system has now been developed to bring effective and economic control to relatively small processes.

Advantages of Computer Control

Operators of large processes have had no difficulty justifying well-planned computer control economically through improved product uniformity, thriftier use of raw materials, better productivity, and other process improvements. The advantages of computer control that bring these improvements also apply to smaller processes.

One of these advantages is the capacity for feed-forward regulation: programmed with a "model," or set of equations describing the process, a computer can process available data to predict other values that are not directly measurable. These anticipated values then provide a basis for taking control action at the appropriate time.

The speed of a computer is such that it can keep watch on thousands of points in a plant constantly, giving closer supervision than is economical with conventional systems. Once available, the computer also proves capable of performing other control tasks—often minor in themselves and not, individually, justifying a computer.

A computer system also communicates with the process operator much better than conventional control systems can. This is partly because it digests process information and correlates the *significant* data instead of overwhelming the operator with raw data. Moreover, it communicates with the operator at one convenient location and in well-understood terms and concise form.

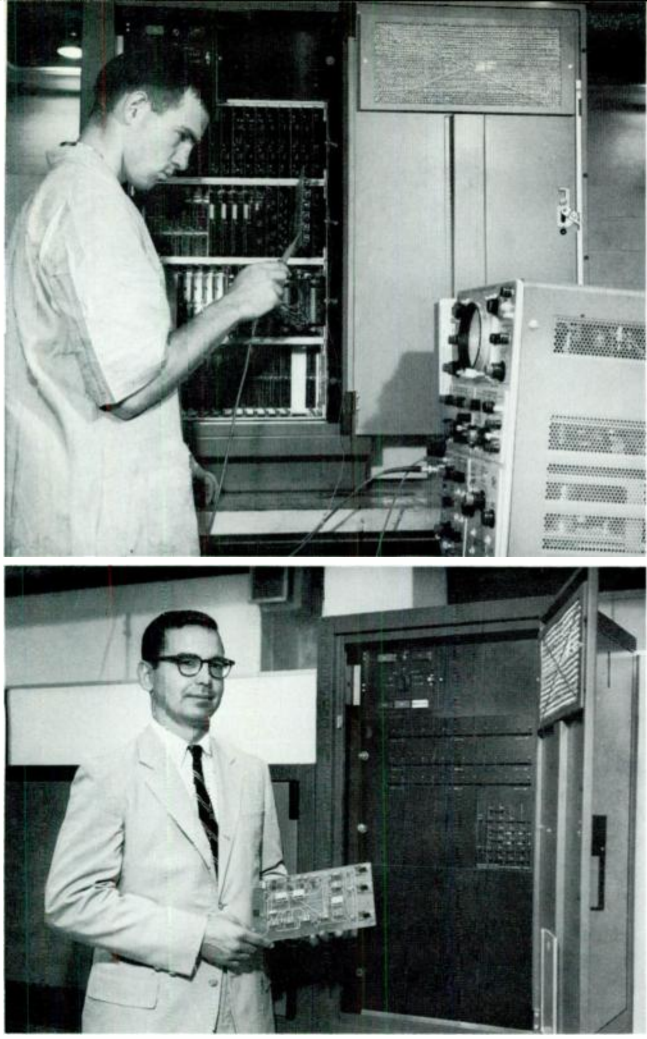
Unlike other control systems, a computer installation can be started step by step. One way of doing this is by incorporating a few control functions at a time. Another is by evolution of the control mode: start with data-logging only, add monitoring and alarming, close the control loops, and then activate fully automatic sequencing. Such flexibility also enables the operator to try a new control strategy ("program") without upsetting the wiring of the system. If it works better, fine; if not, he can return to the original program.

Finally, control equipment can be standardized. This is a most important advantage of the new small general-purpose control computer, which will be made in large numbers because of its wide applicability. Much more design effort can be put into a system that is to be produced in comparatively large numbers. The same is true for the program and the engineering that produces it ("software") and for the written description of, and instructions for using, the equipment and software ("documentation"). Both can be more thorough, for a given system price, because their cost will be spread over a large number of systems. Moreover, mass production of standard computer equipment ("hardware") lowers equipment cost and improves quality.

Standardization also makes installation and start-up more routine. Maintenance and trouble-shooting procedures are simplified as well, partly because of the more thorough documentation and partly because the procedures do not need to be intimately related to the process under control. A computer fault is best located by a test procedure that does not vary with the application.

Training of maintenance personnel can be more comprehensive and thorough when the control system and maintenance procedures are standardized. Refresher courses with standard paperwork problems are practical.

In sum, the advantages of computer process control over conventional control methods are mainly economic. The control computer permits the user to enlarge the degree of control exercised over the process; it improves communication between control system and operator; installation of the control is simpler, faster, and more



MODULAR CONSTRUCTION facilitates assembly of a Prodac 50 computing control system to fit each need. The taller cabinet houses the main frame in this grouping, and two smaller cabinets house input-output equipment and a multiplexer. Logic circuits are checked by standard trouble-shooting routines (top). Each computer circuit card (bottom) contains elements that are functionally related.

error-free; and standardization contributes substantially to control efficiency and economy. Where there is a sufficiently large task or group of tasks to justify investment in a computer control system, it can provide a greater amount of control capability dollar-for-dollar than any conventional control system.

When to Apply Computer Control

Electromechanical systems (relays), wired logic (such as the Westinghouse CYPAK system), and digital computers are all capable of performing similar control functions. However, each has certain economic limitations.

A good basis for comparison is control complexity (Fig. 1). With relays, the cost of a minimum system is small. However, increases in the volume of data to be processed (and, therefore, in the number of relays needed) cause directly proportional increases in the cost of the system, until system engineering complexity begins to increase the cost at a rate faster than the rise in capability. In addition, since every large relay control system is different from every other, the costs of drafting, wiring, testing, installation, and checkout increase disproportionately to the control function. The shape of the curve makes it evident that there is a point beyond which electromechanical systems become impractical, if not impossible. Some monumental systems have been built with relays, but at great risk for both the user and the manufacturer.

Static switching devices substantially increase the amount of control information—and therefore the amount of control—that a system can handle. Wired-logic systems composed of these devices cost more, in small sizes, than relay systems, but as size increases they cost less.

In short, some applications are most economically handled by relay systems and others by wired-logic systems. The latter can be more complex than the former, but even so the application engineering, custom manufacturing, and resulting complexities of large systems can again create great risk for both user and manufacturer.

PRODAC 50 COMPUTER CONTROL SYSTEM

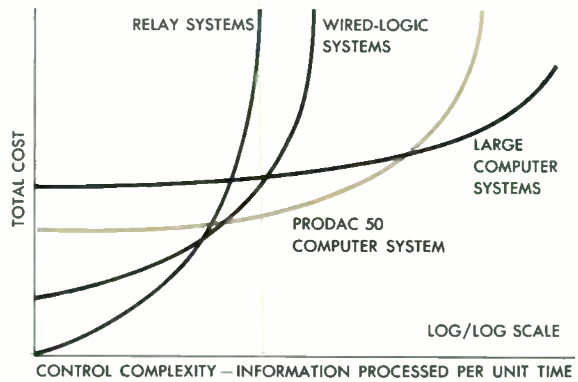
The new small general-purpose control system operates with 14-bit binary words and has 25 instructions, each with indirect addressing option. Its add instruction running time is 18 microseconds. The memory is guarded; that is, words in memory are not lost if power fails.

For flexibility, core memories of 4096 to 16 384 words are available, along with 16, 32, 48, or 64 external interrupts. Up to 64 input-output channels can be used, with up to 64 addresses per input-output channel. The number of analog inputs per second can be 40, 80, 120, or 160. Analog signal levels are 0 to 50 millivolts, 0 to 5 volts, or both. Paper-tape systems of 10 or 60 characters per second can be used, as can multiple logging and alarm printers.

All of the semiconductor devices are silicon types, and they operate reliably up to 50 degrees C ambient temperature. Functional packaging of components on large circuit cards facilitates maintenance.

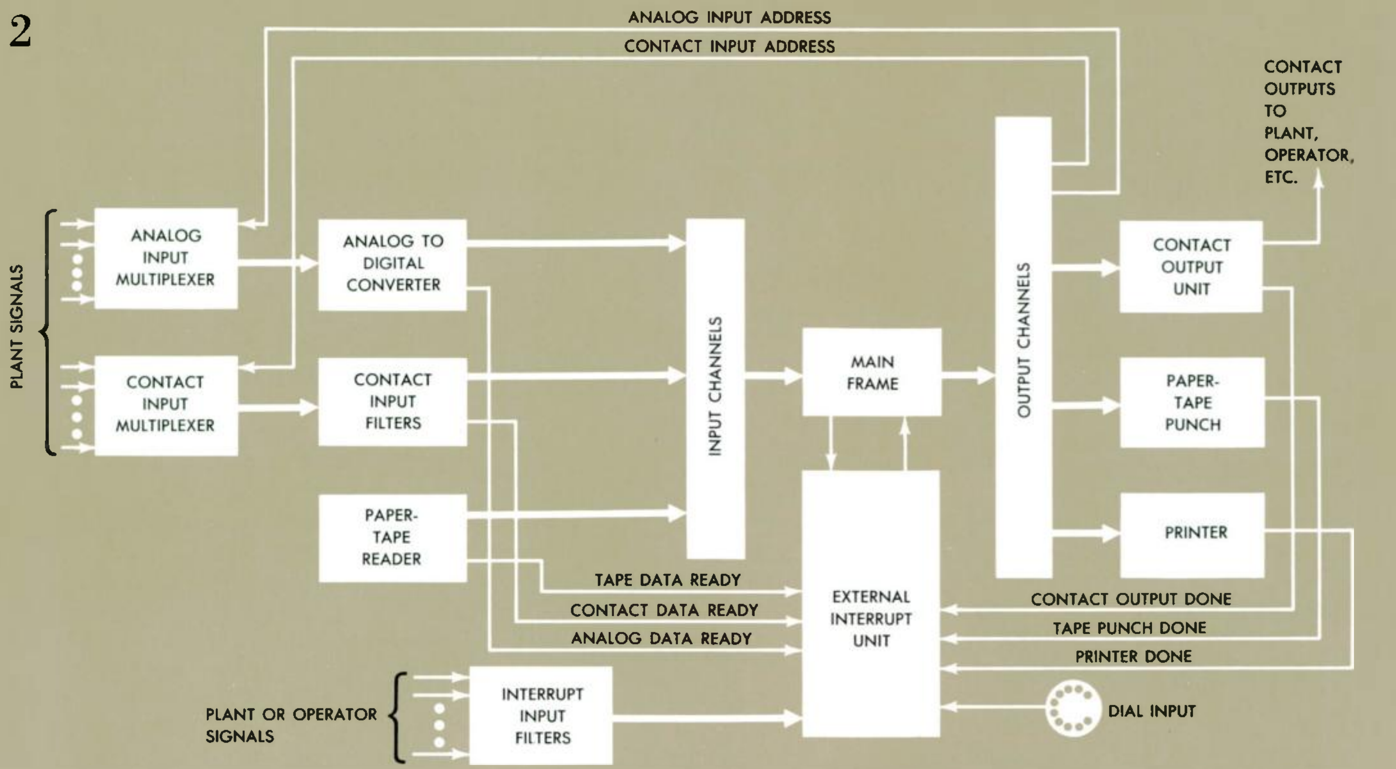
The pre-engineered programs available include interrupt and input-output executives, library routines (such as arithmetic and trigonometric), and standard application routines (such as scan, monitor, alarm, three-mode control, engineering units conversion, and digital blending).

1

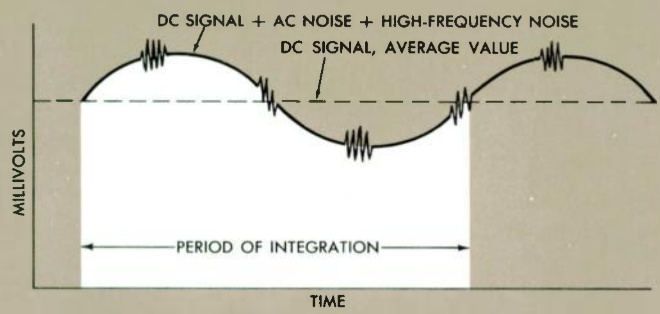


CONTROL SYSTEMS CAN BE COMPARED on the basis of control complexity and total system cost. ("Control complexity" is the capability of a system expressed as the number of logical decisions it can make per unit time.) Both relay systems and wired-logic systems are economical for control of relatively simple processes, but the more capable computer control systems are needed for more complex processes. The new Prodac 50 computer control system fills the former gap between wired-logic systems and large computer systems.

2



3

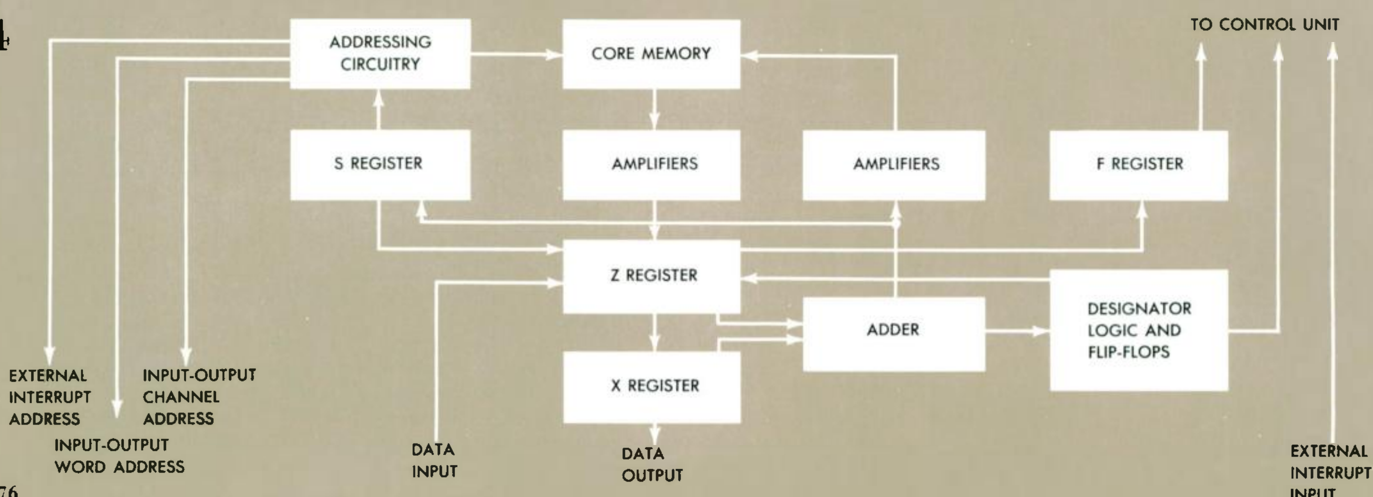


2) **PRODAC 50 COMPUTING CONTROL SYSTEM** consists of a main frame, or central processor, and various input-output facilities specifically designed for communication with industrial plant equipment and with human operators. As many as 64 input and output channels can be used.

3) **ANALOG INPUT SIGNALS**, such as those from plant thermocouples, are integrated within the analog-to-digital input converter to reject electrical noise. The integration is performed for one cycle of the ac supply power to cancel noise induced by line frequency. High-frequency noise also integrates out, leaving a signal value equal to the thermocouple voltage.

4) **PRODAC 50 MAIN FRAME** is a stored-program, random-access, parallel, binary computer. It is a general-purpose machine designed for low cost, high reliability, and adequate performance for use as a process controller. The size of the core memory is selected to suit the control application.

4



It is at this point that computers enter the picture, because the processing of large amounts of information is the forte of digital computers. The minimum installed price for any computer is considerably higher than the cost of a minimum wired-logic system, *but a major increase in the amount of control information to be processed adds relatively little to the system cost* (Fig. 1). Equally important, the capability of the system is so great that it considerably extends the limits of automatic control. The ease with which additional functions can be added to a computer control system stems from the computer's inherent ability to perform logical and mathematical operations; the only additional cost involved is that of getting the information into the computer and selecting the series of operations to use it meaningfully.

Just as there is a "crossover" of the relay and wired-logic curves in Fig. 1, so there is a crossover of the wired-logic and computer curves—a point beyond which it becomes more sound, economically, to use the more capable system. This crossover, for most computers, occurs near the practical complexity limits for static control systems. The successful large control systems now operating, such as those for electric-utility systems, steel rolling mills, and a large pulp mill, might not have been possible at all without control computers. Maintenance alone would have made wired-logic systems prohibitively costly; in contrast, such control is relatively simple for a computer.

The systems just cited are all large systems, necessarily high in initial cost. Between them and wired-logic systems has been a large gap. The new Prodac 50 system is small enough to fill this gap while retaining the important computer characteristics that permit major increases in function without corresponding increase in cost (Fig. 1). It was especially designed for small or subfunction control applications, but it is expandable by adding more input-output and memory equipment and expanding programs as the need arises.

Requirements of a Small Control Computer

The foremost design requirement is low cost, and an important factor in total cost is system availability. In a plant with a large throughput, lost production due to control-system failure is serious or even catastrophic. Availability consists of reliability (the inherent freedom from failure in a system) and maintainability (the inherent ease with which a malfunction can be diagnosed, located, and corrected). The chief determinant of *reliability* is the number of components involved. Quality control, derating of components, and system testing are important, of course, but for comparable systems the one with fewer parts has greater freedom from failure. Because such a system has a long mean time between failures, the maintenance man has little opportunity to practice. *Maintenance* procedures, then, must be kept as simple as possible and documentation must be thorough.

In the large systems, the cost of application engineering is sometimes greater than the cost of the computer itself. For most control applications, however, a large fixed cost for application engineering is intolerable. One solution is for the people most familiar with the process—the users—to do the application engineering. Since this work entails having all the necessary information about the equipment, the control-system supplier must make the information available in readily understood terms. This is feasible only if the supplier has preengineered much of the work and made standard packages of hardware and software.

Expandability is essential so that the system can be simple at first and then enlarged as it becomes economically feasible to add to the degree and scope of control exercised over the process. Many industries have little detailed information about what goes on in their processes; they require a considerable amount of data-logging and study before the computer can be given direct control.

The Prodac 50

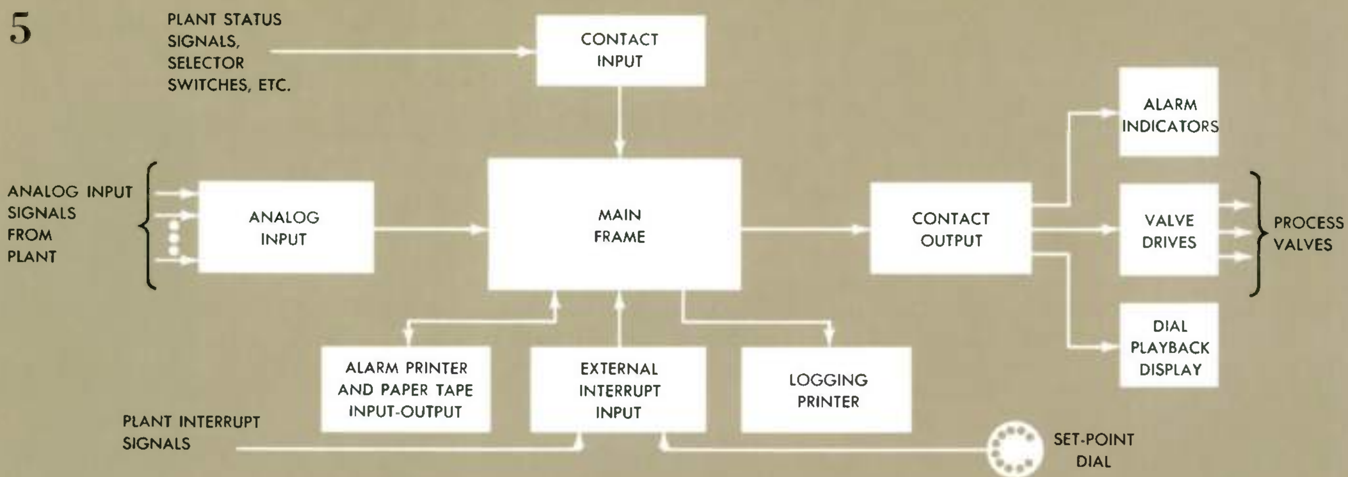
The Prodac 50 computing control system is a stored-program general-purpose controller (Fig. 2). Input to the main frame, and output from it, consists of two types of information: variable data and address. Data communication is provided by up to 64 input and output channels, each consisting of a 14-bit parallel path into or out of the main frame. Address communication, used to select and control the input-output channels and any associated multiplexing units, is output by the main frame at the same time that data is either input or output. The addressing capability is sufficient to permit selection of any of the 64 possible channels and, at the same time, any of the 64 multiplexed devices for each channel.

External interrupt input is also provided, with up to 64 independent inputs available. For a signal applied to any of the 64 interrupt inputs, a separate and unique response is caused directly within the main frame without need for additional input operations. Such direct response allows interrupt input signals to be processed with little main-frame duty cycle, making it practical to use these inputs as control and timing means for other input-output communications—for example, the "Data Ready" and "Done" signals indicated in Fig. 2.

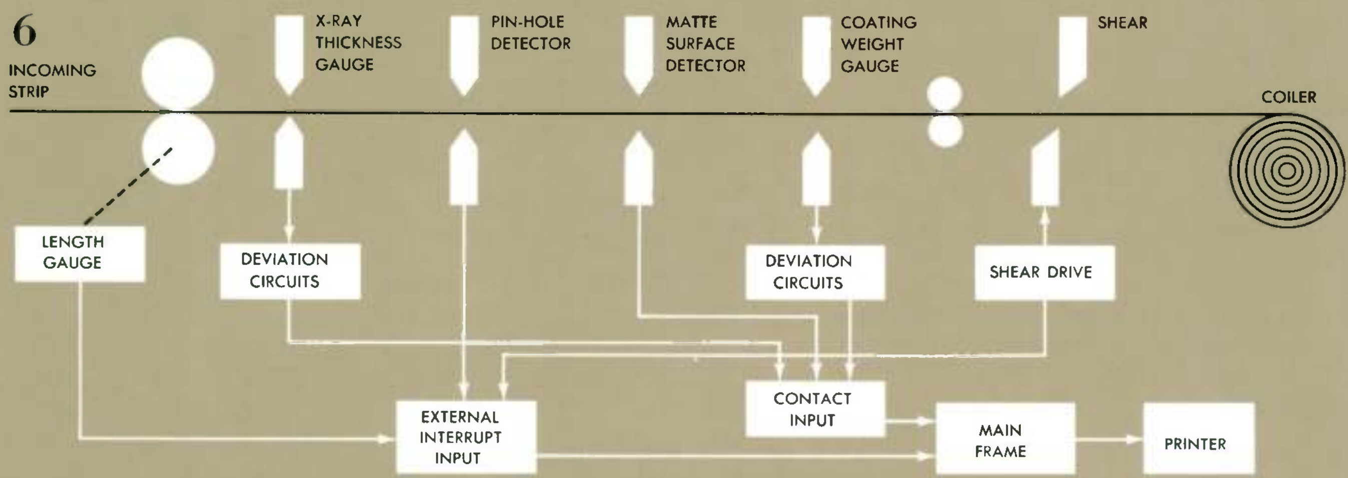
Analog input, contact input, contact output, and interrupt input units provide the connections between the plant and the main frame, as well as the noise-rejection filtering and isolation required in most industrial environments. Noise is rejected from analog signals by integration within the analog-to-digital converter (Fig. 3). Contact and interrupt inputs have RC filtering and transformer coupling to reject noise. Contact output is performed by mercury-wetted relays. Telephone-dial inputs, paper-tape readers and punches, and typewriters also can be provided.

The Prodac 50 main frame is a stored-program, random-access, parallel, binary computer (Fig. 4). It has been designed around the requirements of low cost, high reliability, and adequate performance for use as a small process controller.

Core memory, which is available in capacities of 4096, 8192, 12 288, or 16 384 words, forms the heart of the main frame. The accumulator and the program location counter, as well as the 64 external-interrupt program-origin control words, are kept in core memory to reduce the number of flip-flops required. Cycle time for the memory is 4.5 microseconds, and memory contents are protected against loss in the event of power failure.



DIRECT DIGITAL CONTROL, one application of the Prodac 50 system, is the controlling of a number of process devices directly with the computing control system. This arrangement centralizes the control functions by eliminating the conventional individual device controllers. (The controlled devices are process valves in this example.)



INSPECTION DATA ACCUMULATING, another application, produces reports on the quality of tinplate. The computer calculates the number of feet with and without defects in each finished coil.

Functional time-sharing is used extensively, with the Z and X data registers and the address, or S, register used both to process data and to perform internal control functions as directed by the instruction or function code held in the F register. These are all single-level registers; shifting, counting, and adding operations are performed by transfer of data between the registers and through the adder.

Twenty-five instructions have been included, providing the conventional add, subtract, load, store, input, output, and various jump and jump-test operations. In addition, several instructions affecting any location in memory are used: right and left shift, decrement, and set and clear most significant bit. Addressing of instructions is in either direct or indirect mode, selectable by one bit of the function code, for each instruction.

System reliability has been achieved by careful selection of components, wide-tolerance circuit design, and minimization of the number of components. In addition, exclusive use of silicon semiconductors, widely separated circuit cards, and forced ventilation keep temperature rise down and thereby extend component lifetimes.

The large printed circuit cards contain most of the logical interconnections, and circuits on any given card are functionally related to make trouble-shooting simple. For instance, one bit of each register, data path, and adder are all on a single card. If trouble develops in the processing of data, the maintenance man need only identify which bit is in error to be able to replace the defective circuit. In addition, all flip-flops have indicators at the ends of their cards to aid symptom checking.

This design for reliability and maintainability gives the system a calculated on-line availability of 99.9 percent.

Several characteristics of the Prodac 50 equipment keep cost low. First, the general-purpose nature of the system and its high degree of standardization and flexibility permit volume manufacture of identical equipment. Second, the modularity of the system makes for little waste of capacity for small tasks while retaining good capability for complex tasks. In fact, plug-in expandability of inputs, outputs, external interrupts, and memory permits accurate system sizing with no need for spare capacity. Third, extensive time-sharing results in an unusually small number of components. Fourth, careful signal treatment in the computer helps keep installed cost low by eliminating the need for additional special signal treatment and special plant wiring.

Application engineering cost is kept low by an extensive library of preengineered preprogrammed typical control functions. Priority, input-output, and format-control executive programs have been devised, as have various arithmetic packages such as trigonometric and exponential routines. In addition, application functions such as scan, monitor, alarm, and three-mode control are available. Programming of sequence-control logic generally requires more custom work than the other examples cited; therefore, a standard decision-table technique has been devised for straightforward creation of such logic programs as may be required.

Application

Although *design* emphasis with the Prodac 50 has been dual (minimum cost and maximum reliability), the main *application* consideration with a small computer control system is cost. The user can help keep cost low.

First, engineering content must be kept low; that is, specialty console devices, unusual instrumentation, or unusually stringent environment should be avoided if possible. The preprogrammed software packages should be used in conjunction with the various pre-engineered equipment subsystems provided.

Second, manufacturing cost should be kept low by using the standard equipment without modification and by avoiding unusual performance or test specifications.

Third, the application should be carefully defined. Each feature added to the control system will increase hardware, programming, or engineering cost (or all three); each feature should be justified economically.

Fourth, the source of application know-how must be selected intelligently. Often, it is less expensive for the user to train his people to perform most of the application engineering than to teach the system vendor enough about the process. Perhaps the best plan is with the user serving as application engineer and the vendor as consultant, providing back-up service.

Two typical applications for which the Prodac 50 computing control system is suitable are illustrated for example purposes in Figs. 5 and 6.

Direct digital control (Fig. 5) is simply the controlling of a number of plant devices (valves, for example) directly in a digital, time-shared, sampled-data fashion. The control computer system handles the same task conventionally performed by a number of electronic or pneumatic three-mode controllers. Therefore, it has provision for measuring pressures, temperatures, flows, levels, and other variables as analog feedback signals; for accepting set-point signals (by dial); and for driving the process valves (by stepping motors). Calculation for each control loop is performed within the main frame; it consists of summing terms proportional to the difference between set-point and feedback (proportional term), the integral of this difference (reset term), and the derivative of this difference (rate term) and transmitting the sum to the valve controller. This calculation is repeated from once per second to once per 20 seconds, depending on the dynamic properties of the quantity controlled by the valve.

In addition to the direct digital control task, limit checking and interlock checking of the plant variable signals are usually required. An alarm printer and various alarm indicators warn the operator of variables out of limits. One or more logging printers are provided for data-logging and trend indication. Paper-tape reading and punching equipment permits convenient entry of program and mass data and output of data for analysis by other, off-line, computing facilities.

Prodac 50 systems can be readily justified economically for direct digital control in plants of about 50 to 150 control loops, depending on the nature of the loops.

The other example is a much simpler application, since few inputs and no control output are used (Fig. 6). The required task is to produce quality reports for completed inspected coils of tin-plated steel, the raw material for "tin" cans. Can manufacturers purchase tinplate by the coil, paying one price per foot for prime grade, a different price for mender grade, and nothing for scrap grade. (Prime grade is entirely within specifications; mender grade can be salvaged by reflowing; and scrap has such defects as pinholes in the plating, off-gauge steel, and incorrect coating thickness.)

To account for defects in a coil, the data-gathering procedure must recognize that the various gauges and detectors monitor material considerably ahead of the shear, which defines the end of a coil. The system shifts all data to model the progress of material through the inspection stations, correlating it spatially to the location of the shear. Otherwise, defects apparently at the end of a coil would in fact be in the first part of the subsequent coil. Furthermore, the system makes the accounting in integral feet so that multiple defects within a particular foot will be charged as a single defect foot. The printout for each coil usually includes total footage, prime footage, and mender footage; it forms the basis for billing.

Summary

Most controlled processes are fairly simple, so the availability of a small computing control system can extend the benefits of computer control to a great many plants of all sizes. To keep the cost of such a system low, it must be widely applicable to permit volume manufacture and consequent economies. The system also must be powerful yet simple, and its installation and use must be simple and economical. Reliability must be high, and maintenance procedures easy.

Such a system has been developed in the Prodac 50 computing control system. Because its functional modules can be assembled as needed in preengineered packages, the control engineer can give his attention to the control function rather than to the control hardware. The task of selecting and installing a computer system no longer need be monumental.

A Comprehensive Approach to Product Reliability

T. A. Daly, Director of Reliability, Headquarters Engineering Staff, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

P. H. Ockerman, Director, Reliability Control, Headquarters Manufacturing Controls, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

Achieving high reliability of industrial products requires a comprehensive look at all the elements that affect reliability. At Westinghouse a corporate-wide program has been instituted to assure continued improvement in reliability.

Today, industrial products are continually being called upon to perform a wider variety of functions, and perform them faster and more efficiently. At the same time, because of increased costs, especially in downtime, higher reliability is an economic "must." These two factors, complexity and reliability, do not naturally go together, but the inherent conflict must be solved.

This situation has led many companies to a critical look at reliability and all the methods formerly used to ensure reliable product performance. At Westinghouse this has resulted in the development of a more integrated approach to the broad question of reliability and how it is achieved; in 1963 a corporate-wide program was initiated to assure the continued growth of product reliability in its broadest sense.

The program takes advantage of all the pertinent work done in the defense and space areas, where many useful new concepts and techniques have been developed during the past decade; however, it also recognizes that the requirements and the economics of industry are often quite different, and therefore require different approaches.

What is "Reliability?"

The word reliability, in itself, is unspecific and subject to different interpretations. Therefore, the starting point for any reliability program is a meaningful definition.

The most common definition is: "Reliability is the probability that a product will satisfactorily perform its functions under the specified environmental conditions for a specified period of time."

This is a perfectly valid definition; however, it is purely quantitative, and for industrial purposes Westinghouse felt that its definition should be more comprehensive, i.e., it should be qualitative as well as quantitative. This led to the following definition:

Reliability is the measure of customer satisfaction, evaluated by how well products and services fulfill a customer's needs, for a useful life in the customer's environment.

This definition serves as the basis for the Westinghouse Reliability Program. The most distinctive fact about the program is its comprehensiveness. The basic elements are outlined in Table 1.

In considering reliability methods, several other definitions are useful:

Reliability control is defined* as "the coordination and direction of *technical* reliability activities through scientific planning from a systems point of view."

Reliability engineering is defined* as "a design adjunct which assists in establishing a product design with high *inherent reliability*."

Lastly, *inherent reliability* is* "the reliability designed into the product. It can be lowered, but never increased, by manufacturing and control methods."

A second distinctive element is the reliability control methods used in the program. Much has been written about mathematical techniques for predicting and determining the probability that a given product will perform its function throughout its intended life. However, the aspect of reliability control by management has frequently been slighted or overlooked.

In the Westinghouse Reliability Program, line functions such as marketing, engineering, manufacturing, purchasing, and service retain their conventional responsibilities for maintaining and improving reliability. The salient features are: (1) the degree of formality of systems for improving and controlling reliability; (2) the manner in which product performance data is used; and (3) the degree of management supervision of functions affecting reliability.

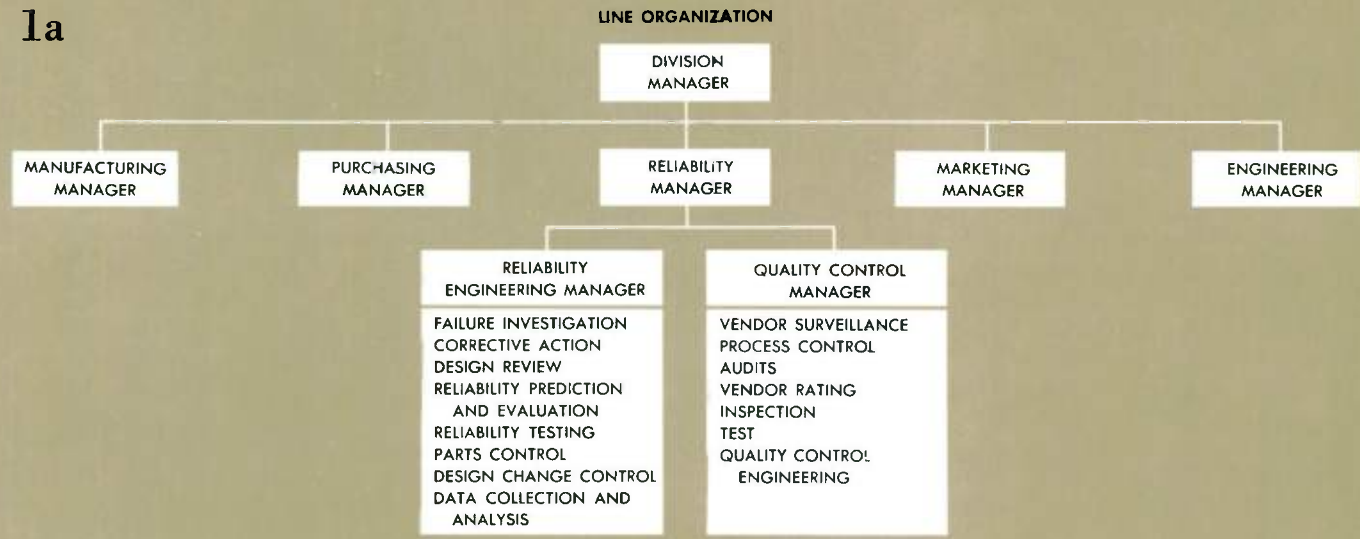
Reliability Organizations

Generally, reliability management takes one of two forms: line or staff, depending primarily on the company's customers, type of product, and existing organization.

In the line organization (Fig. 1a), the Reliability Manager, reporting to the General Manager, has directly under him such functions as Reliability Engineering, Quality Control Engineering, Inspection, Test, and, in some instances, the Field Service functions. This organization is most prevalent in companies having a heavy mix of government contracts and is used in a few Westinghouse locations. In addition to its prime objective of exercising control over the quality and reliability of products, this

*Definitions from *Reliability Training Text*, 2nd Edition IEEE-ASQC, March 1960.

1a



b

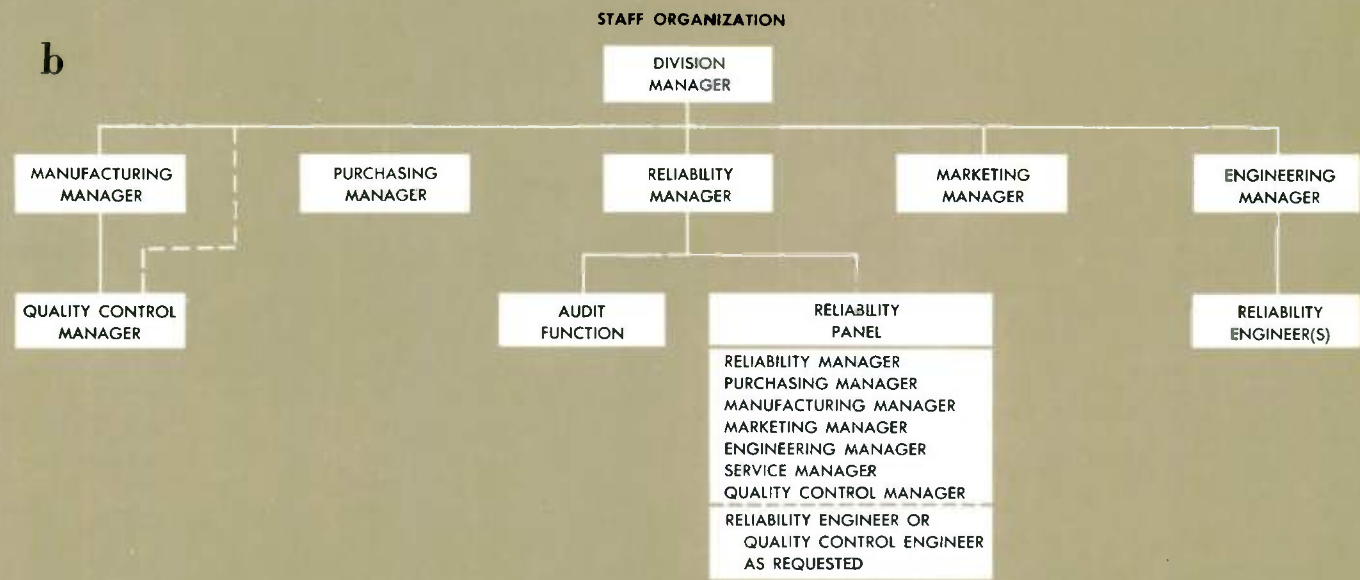


Table I—RELIABILITY PROGRAM

1. Institute and maintain in each Division an aggressive program to improve and control reliability, coordinated at the Division Manager's staff level.
2. Assign responsibilities to each functional department for product reliability.
3. Establish reliability goals with measurable values assigned to elements affecting customer satisfaction: life, service, and ease of installation and maintenance.
4. Develop and formally review conceptual product designs to insure that they accurately reflect and incorporate:
   a. Customer reliability requirements.
   b. Standardized components and simplicity of design.
   c. Results of performance data from factory and field.
5. Verify, through formalized procedures, before releasing for volume manufacturing, the design and performance of products and processes:
   a. Considering conditions of installation, use, and service.
   b. Including accurate and understandable instructions on installation, operation, and servicing of the product.
6. Control specifications and drawings to assure manufacture to current design information.
7. Establish and operate quality control procedures to assure conformance with engineering specifications, utilizing scientific test equipment whenever practical.
8. Encourage suppliers to participate in the Westinghouse reliability effort and purchase from suppliers who consistently provide reliable material or components.
9. Audit the reliability program by:
   a. Conducting the reliability testing on each product to substantiate continued conformance with original verification programs.
   b. Evaluating the effectiveness of the reliability programs in each management function.
   c. Gathering, interpreting and transmitting to responsible personnel in each functional department significant product performance data from factory and field.
10. Train each employe in the reliability control technique important to his job.
11. Maintain at the corporate level a reliability research and advisory function to increase the reliability potential of the Corporation.

organization is also charged with responsibility for providing documentary assurance to the customer that all contractual requirements have been met.

This line organization tends to centralize responsibility for providing customer assurance and reduces the amount of coordination between functions necessary in controlling the documentation. Usual objections to this organization are two-fold. One is possible duplication of effort; and the other that this parallel organization tends to dilute the responsibilities of the engineering and manufacturing organization for designing and building reliable products.

The second form of reliability management—and the type most commonly used at Westinghouse—places the Reliability Manager in a staff capacity (Fig. 1b). His efforts are directed toward planning, implementing, and coordinating a reliability program to (1) formalize the activities of the line functions that affect reliability; and (2) check the performance of line functions in improving and controlling reliability. In this organizational concept, reliability engineers are appointed in the design engineering sections to perform the functions shown in Fig. 1a, and to train design engineers in the same techniques. Quality control engineering, inspection, and test are in the Quality Control Department and may be part of the manufacturing organization. The reliability manager exercises his coordinating function through a *reliability panel* composed of the managers of marketing, engineering, manufacturing, purchasing, and field service. He also may have reporting to him one or more reliability engineers who assist in the reliability audit function discussed later.

Advantages of this type of organization are: (1) It is more efficient in that duplication of effort is eliminated, and (2) it places full product reliability responsibility on those functions best able to control it. However, for this type organization to be successful in promoting an effective program, strong support must be provided by the general manager and his staff.

Frequently, modifications of these two forms of reliability management are used. For example, in some instances field service is included as part of the Reliability Manager's responsibility. However, the control techniques described are applicable to any type of organization.

Establishment of Reliability Goals

No reliability effort can be successfully controlled and monitored without establishing targets, toward which progress can be periodically assessed. These goals cannot be of value unless they are stated in measurable units—for example, in percent reliability, or in mean-time-between-failures (MTBF). "Percent reliability" is a statement of probability. For example, a statement that a given model motor is 99 percent reliable means that on the average 99 of every 100 motors of that model produced will *perform* without failure in the manner specified over a stated period of *time* in the *environment* specified. "Mean-time-between-failures" is the inverse of rate-of-failure for repairable equipment. For instance, to state that a television set is to have a reliability goal of 1000 hours MTBF means that the average operating time between failures requiring service would be 1000 hours throughout the design life of the set.

Establishing reliability goals is an extremely difficult task, and certainly no hard and fast rules apply equally to such dissimilar products as turbines and toasters. Marketing considerations, such as customer expectations, competitive status of products, and pricing must be considered. Process capabilities, materials availability and cost, design state-of-the-art, and other design trade-off considerations affect the goals. The goals established have significant implications for the manufacturing organization. Acceptance test programs and Acceptable Quality Levels (AQL's) of parts must be compatible with the goals established.

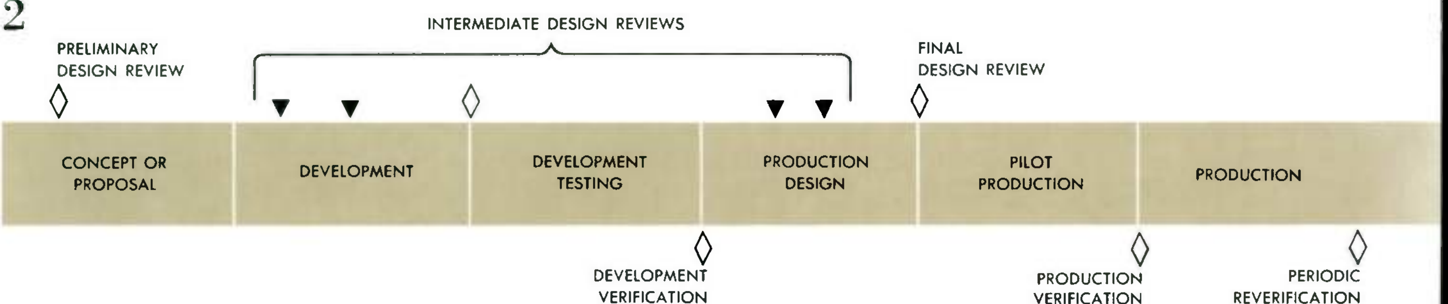
In any statement of reliability, the elements of probability, time (or cycles), satisfactory performance, and operating environment *must* be specified if the statement is to be meaningful.

A high degree of subjective judgment is involved in establishing initial reliability goals. Commonly, they are based on engineering judgment, historical knowledge of product performance, and the best available information on customer acceptance. As data from test and field performance is obtained, and knowledge of customer acceptance is accumulated, the goals can be further refined.

This situation is not unlike that of setting target dates for completion of new development projects. This is also a difficult task, but is done every day on the basis of past experience and engineering judgment. Some of these target dates are missed, but progress of the project is far better than if no goals had been set up.

The Polaris missile launching system is a case in point. No reliable historical failure rate data was available on

2



DESIGN REVIEWS AND VERIFICATION MEETINGS are held at various intervals during the progress of a product from concept to production. Solid triangles indicate additional design reviews required, dependent upon product complexity.

3a AREAS ANALYZED AND DISCUSSED IN A DESIGN REVIEW

Performance requirements
Environmental conditions
Design assumptions
Reliability goals
Failure rates and failure mode analyses
Parts and materials selection
Stress analysis
Manufacturability
Development, verification and reliability test criteria and specifications
Operability (human engineering)
Safety
Function vs. cost (value engineering)
Standardization
Ease of installation and maintenance
Vendor selection and control
Other items such as locking devices, finishes, complexity, compatibility with other systems and equipment, etc.

b SECTION OF TYPICAL DESIGN REVIEW CHECK LIST

	Yes	No	Not Appl.
1. Does the design *specification* include all customer requirements?			
2. Does the design meet all functional requirements?			
a. Are maximum stresses within limits through full range of travel, load, voltage, etc.?			
b. Is derating utilized, wherever possible, to increase reliability?			
c. Does design represent optimum in simplicity?			
d. Have failure modes of critical elements been considered?			
e. Are proper locking devices utilized?			
3. Is the design satisfactory for all environmental conditions?			
a. Temperature (operating, transportation, and storage)?			
b. Humidity (operating, transportation, and storage)?			
c. Vibration (operating and transportation)?			
d. Shock (operating and transportation)?			
e. Corrosive ambients (salt air, sea water, acids, etc.)?			
f. Foreign materials (dirt, oil, sand, grit, etc.)?			
g. Immersion (water, oil, inerteen, etc.)?			
h. Pressure and/or vacuum?			
i. Magnetic fields?			
j. Sound ambients?			
k. Weather?			
l. Radio interference?			
m. Nuclear radiation?			
4. Has available data on similar designs been reviewed, including:			
a. Factory test malfunction reports?			
b. Field service trouble and failure reports?			
c. Customer complaints?			
5. Have standard, time-tried parts been used wherever possible?			
6. Are drawing and specification tolerances achievable in production?			
7. Does the design minimize installation problems?			
8. Does the design minimize maintenance problems?			
9. Has a thorough value engineering or MATS analysis been made?			
10. Have all provisions for personnel safety been included?			
11. Has a study of product appearance been made?			

many of the new pneumatic, hydraulic, and electromechanical elements, nor was there time to perform complete reliability tests on all items. Yet a very high reliability objective was established for the system, and equipment goals were allocated. Early field testing indicated that the goals established were in fact attainable, and subsequent in-service trials demonstrated reliability surpassing the objective.

In the instances where it is not feasible or practical to set a percent reliability or MTBF goal, other objectives can be established, such as:

(a) Design margin (design strength/maximum stress)
(b) Total maintenance cost over a specified life
(c) Average annual cost to own (first cost plus operating and maintenance costs)
(d) Number of service calls over a specified life
(e) Warranty (e.g., 5 years or 50 000 miles)

Regardless of the terms in which the goal is specified, progress toward its achievement must be assessed periodically during development, production acceptance testing, and after the product is in service. Such checking uncovers weak elements and permits additional effort to be concentrated on them.

Design Review

The review of designs to ensure maximum inherent reliability is basically an analytical rather than a control procedure. However, the use of formal procedures and schedules is an important control technique. This provides a positive method for ensuring that all aspects of the design are considered at the concept stage, and at selected points throughout the design cycle (Fig. 2).

The timing of design reviews varies with the product and the sequence of events in the design plan. If the design is being prepared in response to a customer invitation to quote, the first review should be held prior to submission of bids. A second review should be held after the contract is firm. The design should be reviewed again after completion of a development model, and finally when design work is complete, prior to release for production.

If the design involves developing and marketing a new product, or modification of an existing product, the cycle is somewhat different. Here the first review should be held when the design is in the conceptual stage, before performance and physical configuration are firmly established. A second review should be held when development models have been completed and process and test specifications have been drafted. A final review should be held when the design is ready for release for manufacturing.

Sometimes, it may be desirable to subdivide the design review activity into separate reviews for various components or subsystems of the complete product, depending on the complexity of the design and the duration of the design cycle.

The review committee should include designers of high competence and extensive experience in the engineering fields involved, as well as experts in the areas of marketing, manufacturing (including quality control), and field service. The group should be given the agenda, drawings, specifications, and check lists at least ten days in advance of the meeting, to allow advance preparation and shorten the formal review.

The purpose of the design review is to find flaws in the design at a stage where changes can be made easily; criticism must, of course, be constructive.

Design review check lists are extremely useful; these are an expansion of the topics shown in Fig. 3a, and ensure that no important details are overlooked. A section of a typical check list is shown in Fig. 3b.

The review committee recommendations are subject to acceptance or rejection by Design Engineering, since this department is responsible for the design. Should serious differences of opinion arise, the Reliability Manager is obligated to present the matter to higher levels of authority.

The value of the formal design review has been demonstrated for many years in defense projects. In the industrial product area, one recent review produced 23 significant improvements, eliminating design, manufacturing, and installation problems which would have cost an estimated $100 000 to correct after the equipment had been assembled.

Verification

Product verification is a formal procedure for establishing by actual test that (a) the design meets all performance and marketing objectives, and (b) manufacturing planning, tooling, and methods will satisfactorily produce the product.

Product reliability is frequently compromised by incomplete verification of design, manufacturing processes, and tooling. Verification procedures should not be reduced or eliminated because of testing cost or the pressure of production release dates.

Verification procedures—in various forms—have been common for years in many companies. However, the elements of control introduced by the Westinghouse Reliability Program can ensure that (a) all verification procedures are formalized, (b) they are complete and technically correct, (c) all involved departments are represented, and (d) all products *and processes* are verified prior to release for production.

The *development verification* (after testing of prototypes) and *production verification* (after tests of a pilot run made with production tools and processing facilities) should be incorporated in the overall development, design, and production plans and schedules. Check lists (Fig. 4) should be developed for use in the verification meetings to ensure that all requirements of performance, environment and installation are considered. Periodic reverification is also recommended, using units taken off the production line at regular intervals (see Fig. 2).

The design review and the verification procedure are *distinct sequential steps* in the assurance of a reliable product. Neither is a substitute for the other—both are essential.

A newly developed technique called Verification of Installation of Products (VIP)* takes this program beyond the manufacturing aisles to the customer's location. The objective of this technique is to develop better installation methods and to determine design modifications for improving the installability of equipment. A similar technique has been developed for verifying the serviceability of products. These two techniques are powerful adjuncts to reliability programs.

Quality Control

A frequently asked question is: What is the difference between reliability and quality control? The primary difference is in the time realm. Quality control is concerned with the *conformance* to drawings and workmanship quality of the product at a given point in time, while reliability is concerned with satisfactory *performance* of the product throughout its useful life.

Thus, most quality control is concentrated in manufacturing and procurement of hardware, while reliability extends beyond this in both directions, including marketing considerations, design, and field service.

In the Westinghouse Reliability Program, emphasis is placed on evaluating and upgrading quality control programs and fitting them properly in the overall program. Quality control has two main tasks: To preserve the reliability of the design by assuring that products consistently conform to specifications, and to provide management with information needed to keep unacceptable products to a minimum. Both of these tasks depend on collection and analysis of data. For maximum effectiveness in preventing deterioration of product quality and for optimum balance in control vs. cost, the quality control effort should concentrate on preventing the purchase or manufacture of defective material. This means that inspection and test activities should be on a planned basis with the continuous objective of determining and correcting *causes* of quality deterioration. For instance, emphasis should be placed on process control instead of depending only on final parts inspection. Supplier quality control should concentrate on supplier rating and selection based on receiving inspection results and supplier surveys rather than merely sorting bad lots from good lots on receipt.

The quality control group should issue procedures affecting each stage of quality control operation. The procedures should define the specific action to be taken in all functional areas and operating situations of the department. They normally are accumulated into a manual.

Auditing for Reliability

The word "audit" has financial connotations to most people. Financial auditors check financial controls to assure that procedures are adequate and that they are being followed. The reliability auditor has the same relationship to reliability functions.

In addition to auditing their own functions, some quality control departments conduct audits of suppliers' quality systems and procedures, and their manufacturing performance. In the Westinghouse Reliability Program, this technique is expanded in scope to include *all functions having responsibilities affecting the reliability of products.*

The audit team consists of two to six members selected on the basis of ability to analyze and evaluate the procedures of the department being audited. The Reliability Manager is generally permanent chairman of the team.

As examples of functions that are audited and areas of interest to the audit team, consider the following:

1. Does marketing have an adequate formal procedure for supplying the engineering department with such necessary information as customers' use of products, environ-

*See "*Verifying the Installation of Products*," by R. L. Finch, *Westinghouse ENGINEER*, July 1964.

mental conditions at installation points, installation restrictions, etc? Are these procedures rigidly complied with?

2. In purchasing, are reliability and quality performance used as criteria in selecting suppliers? Are there provisions in the purchasing procedures for follow-up action in instances of poor supplier performance?

3. In engineering, is there a formal design review procedure? Is there a procedure for establishing reliability goals? Is there a formal step-by-step design and process verification program? Are all of these procedures followed?

Where this technique is used, a check list is prepared to assure that all pertinent areas are investigated. Fig. 5 is a typical check list for auditing a purchasing function.

Maintaining an attitude of objectivity on the part of the audit team is one of the most difficult aspects of reliability auditing. The team should look at the documented procedures and at actual compliance from a customer point of view. This question should be continually in mind, "If I were a customer of this company, would these procedures give me confidence in the reliability of its products?" The purpose of the audit is to determine areas for improvement—not to place blame for past mistakes.

A possible objection to the audit technique is that the line manager should be responsible for reviewing his procedures and performance to determine their adequacy. However, two factors must be considered here. Practically everyone has difficulty in making an objective self-assessment. The other is that one department's procedures may well affect the operation of several other departments. Actually, the audit function does not change the line manager's basic responsibility; any corrective action must still be taken by him.

4 SECTION OF TYPICAL DEVELOPMENT VERIFICATION CHECK LIST

	Yes	No	Not Appl.
1. Is the design specification complete?			
2. Does the product meet all specification requirements?			
a. Operational requirements?			
b. Environmental requirements?			
c. Reliability requirements?			
d. Size limitations?			
e. Weight limitations?			
f. Installation requirements?			
g. Maintenance requirements?			
h. Appearance?			
3. Were all development tests completed?			
a. Test equipment accuracy verified?			
b. Tests not limited by test equipment?			
c. Tests covered range of operating tolerances?			
4. Are test prototypes true copy of production units?			
5. Detail cost breakdown available?			
6. New Production tooling required?			
7. New facilities required?			
8. Factory rearrangements required?			
9. New Process specifications required?			
10. Special inspection procedures required?			
11. Legal questions resolved? Patents, trademarks?			
12. Applicable IEEE, NEMA, ASA standards, etc., met?			
13. Applicable UL, NEC, pressure vessel codes, etc., met?			

5 SECTION OF TYPICAL RELIABILITY AUDIT CHECK LIST

	Yes	No	Not Appl.
Purchasing			
1. Are suppliers encouraged to establish reliability programs?			
2. Are suppliers impressed with the need for reliable products?			
3. Are bids evaluated on a *total* value basis, considering past performance and actual capabilities?			
4. Is supplier asked to include Westinghouse representative in his Design Review?			
5. Are surveys made on all prospective suppliers?			
6. Are the results of vendor surveys used in evaluating suppliers?			
7. Are vendor rating system reports used in evaluating suppliers?			
8. Do Purchasing representatives participate in Design Reviews?			
9. Do Purchasing representatives have up-to-date knowledge of the Reliability Program?			
10. Are all defective item reports fed back promptly to suppliers?			
11. Is there an effective follow-up system to get corrective action from suppliers?			

Other Aspects of the Reliability Program

The reliability techniques outlined here are some of the major methods as they apply to the broad spectrum of products manufactured by Westinghouse. A complete reliability program for a single division usually encompasses all of these, plus additional ones applicable to the division products.

Conversely, in the case of certain types of products a formal reliability organization may be unnecessary, and a simpler approach and simpler technique may suffice. The nature of any effort to constantly improve reliability obviously depends on the starting point, the type of product, and the needs of the customer. Therefore, in application, this corporate program usually must be modified.

No mention has been made of data collection and analysis. This is a broad field and is beyond the scope of this paper. The entire field of reliability is based on the ability to predict and measure the performance of a product over its life span. This prediction and measurement must be based on information drawn from factory testing and field experience. This implies a comprehensive system for collecting, tabulating, and analyzing the information as well as communicating the information to those groups who must take action.

As with any new management technique, there is a real danger that the establishment of procedures may be confused with or interfere with the achievement of actual results. It is conceivable, although unlikely, that each of the techniques reviewed here could be exercised to perfection and still result in no real control of the reliability of products. These are the tools. For real control, full management commitment to a systematized, *active* program is the vital ingredient.

Most importantly, however, the various groups involved in the reliability program must never let the system for achieving reliability make them lose sight of the ultimate purpose—customer satisfaction with a well-designed and manufactured product.

A New Microscope for Microelectronics Research

*I. M. Mackintosh, Elliott-Automation, Ltd., Boreham Wood, England.**
J. W. Thornhill, Manager, Information Devices Department, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.

The scanning electron microscope produces a composite view of physical topography and surface potential.

The period at the end of this sentence is less than a thousandth of a square inch in area, but it will cover a considerable portion of a microelectronic circuit. With the aid of a new scanning electron microscope, scientists at the Westinghouse research laboratories are mapping, in the finest detail, areas no larger than this on the surfaces of microelectronic devices. The microscope's resolution and depth of focus, which provide clarity and detail to the pictures it produces, are better than can be achieved with the finest optical microscopes.

Of particular importance in microelectronic applications, the scanning electron microscope can also provide basic information on the electrical performance of the electronic devices under study. The combined structural and electrical detail in scanning electron beam photographs have provided information about complex device structures that could not be obtained with standard visual inspection techniques. Furthermore, the instrument offers a new technique for fabricating very minute devices believed capable of extremely high-frequency performance.

Knoll in Germany, and later, scientists at Cambridge University in England have worked on the scanning electron microscope. The device functions somewhat like a closed-circuit TV system, with a camera inside the instrument and a display tube outside for viewing. Pictures can be displayed at magnifications as high as 10 000 times, which is about ten times better than is possible with conventional optical microscopes. In fact, this is the highest magnification that can be achieved directly on a solid specimen, without drastically thinning the specimen for inspection in a transmission electron microscope or using replication techniques.

Microscope Operation

A block diagram of the Westinghouse scanning electron microscope and its associated pattern generator is shown in Fig. 1. The main body of the instrument is a vacuum chamber, which houses the electron gun and magnetic lenses. The two magnetic lenses can focus the electron beam on the specimen with a spot size as small as 0.1 micron. Scanning coils, also located in the column, move the beam in a TV-like raster, adjustable from 250 to 1000 lines, over the specimen. The scanning coils are driven by the scanning generator. This same scanning signal is fed to the cathode ray tubes, one of which is for viewing and the other for pattern generation. Thus, the CRT tubes are scanned in synchronism with the primary beam scanning the specimen.

With a 0.1-micron spot and a 1000-line raster, an area as small as 100 by 100 microns can be scanned. The area scanned can be increased up to two millimeters square with an accompanying increase in beam spot size.

An aperture is located between the electron gun and the first lens. Pulse-controlled coils near this aperture can deflect the beam away from the aperture, thus turning the beam on and off with respect to the specimen. This arrangement prevents voltage transient effects in the power supply and is more satisfactory than actually turning the beam on and off during the various scanning operations.

As the primary electron beam scans the specimen, secondary electrons are emitted from the specimen surface. These low-energy electrons are collected, amplified, and fed as a control signal to modulate the brightness of the viewing cathode ray tube.

In the amplifying process, the secondary electrons are actually converted to pulses of light by a scintillating crystal, and then back into electrical pulses by a photomultiplier tube. This two-step process provides the required noise-free amplification.

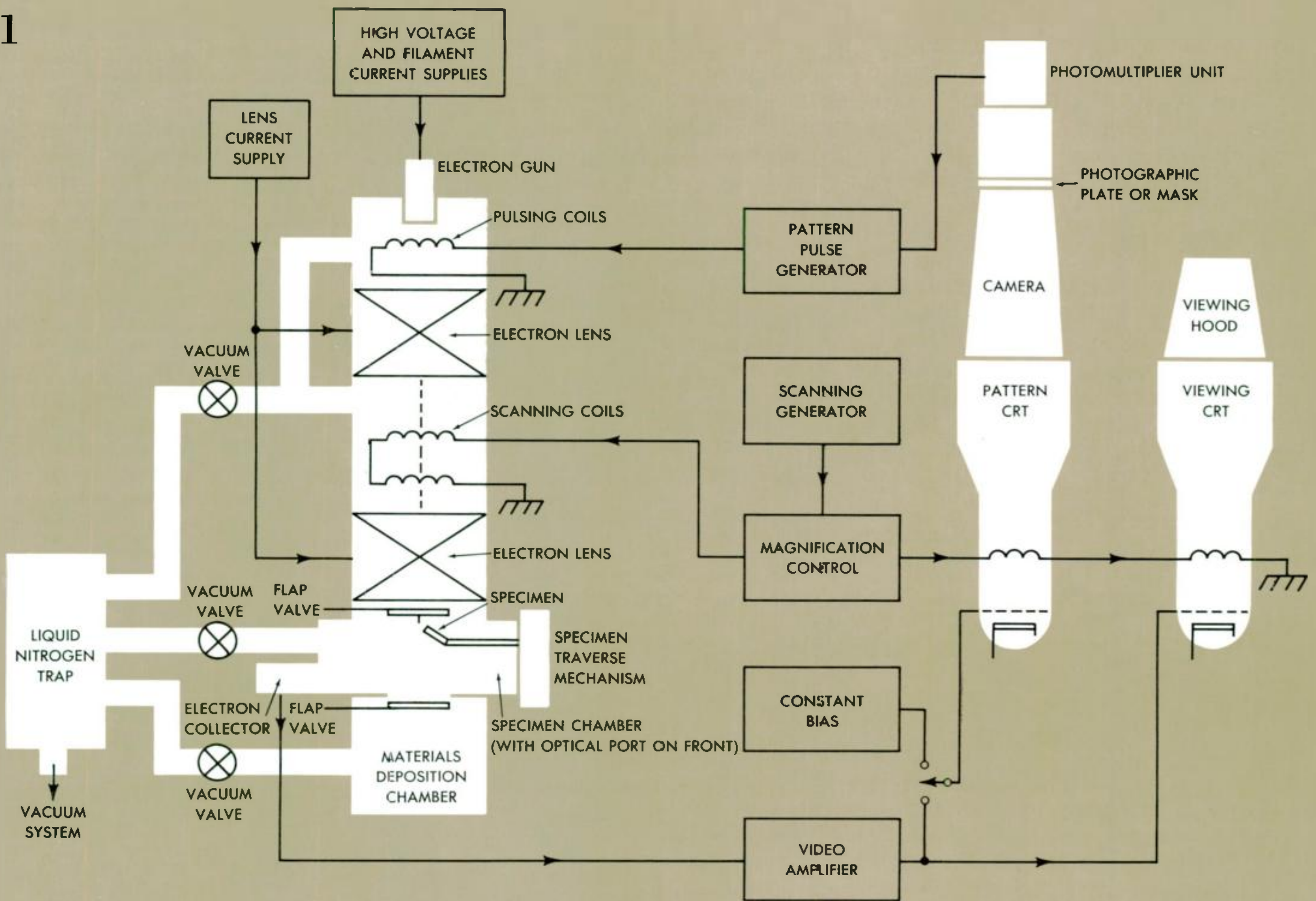
Ignoring obvious factors such as mechanical vibration and imperfect power supplies, the resolution of the display image is determined by attainable beam current, scattering effects in the specimen, and by the signal-to-noise ratio of the secondary electron collection system. Optimization of these factors has led to resolutions that are limited mainly by the beam spot size to values of about 0.1 micron, since anything smaller than roughly 0.6 times the spot diameter cannot be resolved.

Scanning Electron Micrographs

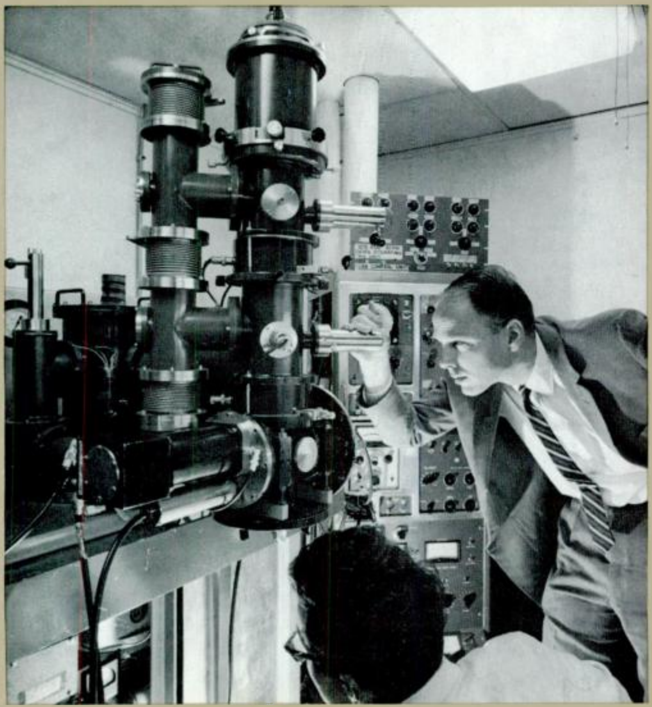
As the primary electron beam scans the specimen surface, the number of secondary electrons emitted is a function of specimen material, surface topography, and the angle of incidence of the primary beam. Thus, when secondary emission from the specimen is optimized, the image obtained on the cathode ray tube is easily interpreted in terms of the physical structure of the specimen surface. A characteristic of scanning electron micrographs

Previously Manager, Techniques R&D Section, Information Devices Department, Westinghouse Research Laboratories.

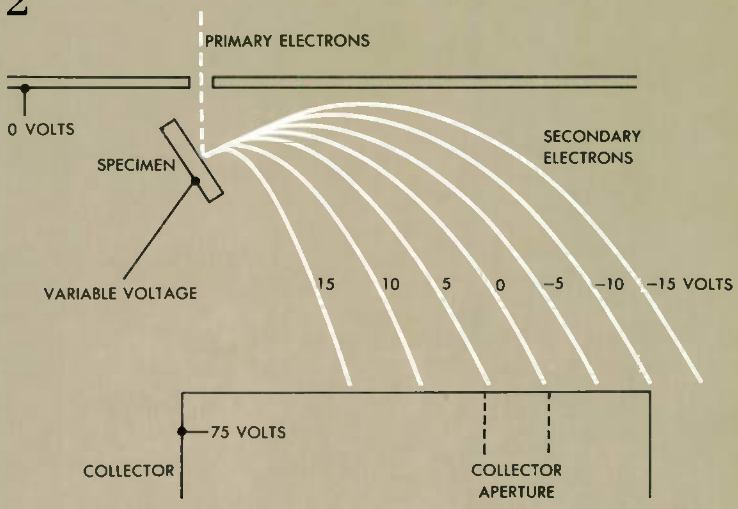
1



SCANNING ELECTRON MICROSCOPE and its associated pattern generator function like a closed-circuit television system.



2



SECONDARY ELECTRON TRAJECTORY is a function of specimen surface potential, as shown here for surface potentials of +15 to −15 volts.

SCANNING ELECTRON MICROSCOPE, a new type of electron microscope, forms detailed images of tiny surface areas by scanning them with a fine electron beam.

is the enormous depth of field, as can be seen in Fig. 4.

One of the unique features of the scanning electron microscope is its ability to detect potential differences between adjacent areas of the specimen surface. How this effect is obtained can be explained briefly as follows. Upon leaving the specimen surface, the trajectories of the slow secondary electrons are determined primarily by the potentials existing between the specimen and final lens, and between the specimen and collector, as shown schematically in Fig. 2. For this particular arrangement, the variation in a typical secondary electron path is shown for specimen potentials ranging from +15 to −15 volts. Therefore, if the effective width of the collector aperture is made small, the secondary electron current collected becomes a sensitive function of specimen potential at the particular point of incidence of the scanning electron beam.

With a suitable geometrical arrangement of the sample surface, collector and other electrodes in the specimen chamber, the scanning beam image produced will be a superposition of the physical topography of the specimen and the potential differences across its surface.

Under special conditions, potential differences as small as 0.1 volt should be detectable with this technique. The present instrument has detected potential differences down to 0.2 volt with no difficulty.

In the Westinghouse instrument, the scanning beam has an energy of from 5 to 50 kev, with current ranging from 0.001 to 1 nanoampere (one nanoampere = 10^{-9} ampere). Thus, the beam is nondestructive (no lattice damage occurs at these energies), but because the probe current is so small, a scanning electron micrograph must be recorded over a period of time to avoid shot-noise effects. The scanning time can be varied from one-half second to about four and a half hours, but the usual scanning periods are one to three minutes.

A scanning electron micrograph of an NPN silicon power transistor viewed at an angle of about 45 degrees is shown in Fig. 3. The thermocompression bonded leads are clearly in focus, thus demonstrating the great depth of focus of the instrument. Considerable information about the device can be obtained even without the application of external biases (Fig. 3a); with biases applied (Fig. 3b), an essentially complete picture of device performance is obtained. The topography of, and voltage variations in, the device surface show clearly, even though much of the surface is covered with a passivating (insulating) layer of silicon oxide. The improvement over an optical micrograph (Fig. 3c) is clearly evident.

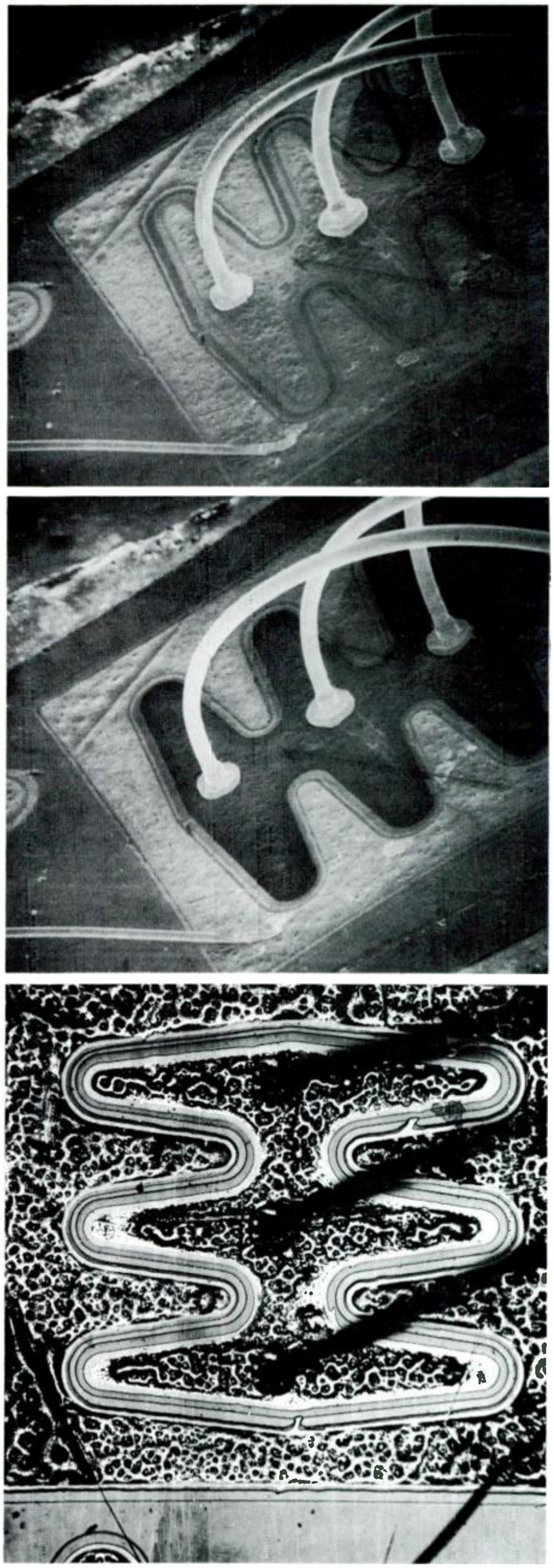
One of the interesting possibilities emerging from this work is the possible correlation of device failures (in actual use or in reliability studies) with marginal faults detected by this instrument. For example, aberrations in PN junctions that were previously undetectable by optical means but can be located with the scanning electron microscope may have no adverse effect on the initial device characteristics, but might lead to hot spots and hence to early failure.

The scanning electron microscope also can be used in the same way that optical devices are used for detecting imperfections or contamination in processing. For example, a common process used in the fabrication of in-

3a

b

c



NPN SILICON POWER TRANSISTOR is viewed at an angle of about 45 degrees (a); with biases applied (b), the picture becomes a composite of topography and surface potential. Optical micrograph (c) of the same device demonstrates the superiority of the scanning electron micrograph.

tegrated circuits is the etching of oxide diffusion windows; any residual oxide left in the windows may drastically affect the subsequent diffusion and yield an incorrect impurity profile. There are indications that the scanning electron microscope can provide positive and rapid detection of any residual oxide film because the secondary electron emission from a silicon dioxide surface is larger than from bare silicon. At the same time, the instrument can be used to examine the oxide pattern by comparing the window locations and boundaries with a standard pattern.

Fabricating Semiconductor Devices

The scanning electron beam can produce another effect that suggests an application to the fabrication of extremely minute devices. The electron beam can replace the light normally used to expose the photosensitive emulsion that is used to coat the surface of a semiconductor material during some of the processing. The beam produces chemical changes in the emulsion, which is then treated in a standard fashion to produce an etch mask. Because of the limited energy in the electron beam, back-scattering of high-energy secondary electrons is limited, especially in ultra-thin photosensitive films. Thus, with 0.2 micron photoresist films now being perfected, edge sharpness of the image should be about 0.14 micron.

By way of comparison, the resolution obtainable from optical systems is limited by the diffraction of light to about 0.5 micron; further losses of resolution arise from the slight blurring of the edges of the pattern in the original optical mask and from scattering effects in the photosensitive emulsion, so that the practical edge sharpness obtainable from optical exposure is about 1 or 2 microns.

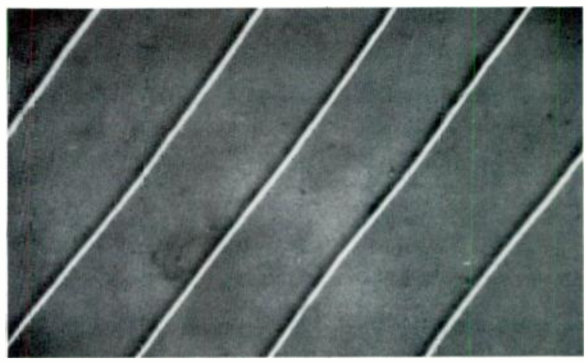
In making an electron beam exposure, the pattern generation system (Fig. 1) can be used to make the primary beam scan the specimen in a predetermined pattern. An optical mask of the desired shape is placed between the screen of the pattern generation oscilloscope and a photomultiplier unit, the output of which is connected to the pulse generator, which actuates the "off-on" coils in the scanning electron microscope column. The system is arranged so that a transparent region in the mask leaves the beam on, while an opaque region turns the beam off. An image of the mask can thus be transposed in minified form to the specimen, to cover an area determined by the particular raster size used.

An example of the definition possible with this scanning beam exposure of photoresist is shown in Fig. 5. These aluminum lines on an oxidized silicon substrate are about 1.0 micron wide with an edge sharpness of about 0.2 micron. They were made by exposing a photosensitive etch resist film of about 0.5 micron thickness with a scanning electron beam of about 0.5 micron diameter, developing the resist layer, and then etching the aluminum. Thus, it is evident that polymerization of a photosensitive etch resist film by high-resolution electron beam can provide a significant increase in edge sharpness over optical exposures. The development of thinner films or of other materials that undergo chemical change under electron bombardment may increase the superiority of the electron beam method even further.

4

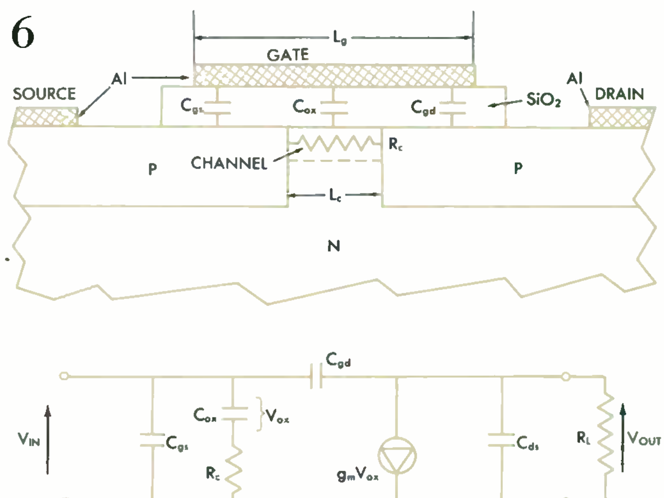
SCANNING ELECTRON MICROGRAPH of a 500-mesh nickel microscope grid viewed at 45-degree angle.

5



ALUMINUM LINES about 1.0 micron wide with an edge sharpness of about 0.2 microns were made with a scanning electron beam.

6



SCOUT (Surface-Controlled Oxide Unipolar Transistor) and its equivalent circuit.

The one limitation of electron-beam film polymerization is the time consumed in making the exposure. Exposure time is determined by the charge density required for effective polymerization of the film and the current density available in the beam. For example, with present techniques and photosensitive resists, a one square inch slice would require an exposure time of about 60 hours. This is obviously enormous in comparison with present optical techniques, although in some cases the tremendous increase in recording detail may compensate for the extra time required. As the technology advances, improvements in scanning techniques, electron optics, and photosensitive materials could improve this situation.

The potential benefits that could come from the use of high-resolution electron-beam techniques can be demonstrated for a typical device, the surface-controlled oxide unipolar transistor (SCOUT) shown in Fig. 6. The theoretical frequency response of this relatively simple device can be calculated, but it is difficult to achieve because of dimensional variations during manufacture. With optical techniques, the channel length (L_c), a critical dimension, is subject to variations of about ± 1.7 microns. Thus, if reproducibility of 10 percent in total channel length is a realistic requirement for quantity production, optical techniques cannot be used for channel lengths of less than about 17 microns. However, with electron beam polymerization techniques, variation in total channel length should be reduced to ± 0.35 micron, so that channel lengths could be as low as 3.5 microns. Since frequency response in this instance is approximately proportional to the square of this dimensional ratio, frequency response with a smaller device could be increased by a factor of about 25.

Another motive for reducing the size of solid-state devices is the need for higher packing densities in microelectronic systems. Of course, other limitations, such as power dissipation, may offset or prevent the benefits of reduced size. Considerable attention has been paid to the packing density problem, and it has recently been suggested by some that a linear dimension of about 10 microns is the practical limit imposed on any device that must be made in large numbers and at high yield. As the foregoing discussions indicate, even this limit is not yet practical with conventional optical techniques; however, it is well within the reach of electron-beam techniques.

Conclusions

The experimental work with the scanning-beam electron microscope is still new, but the instrument has already demonstrated its capability for conventional microscopic applications.

In studies carried out for the U. S. Air Force under contract with the Electronic Technology Division, Aeronautical Systems Division, Wright-Patterson Air Force Base, high-resolution scanning electron beams have demonstrated several effects applicable to solid-state device technology. Additional interesting implications for future solid-state device applications can be extrapolated from present work. There have been enough encouraging results to suggest that these new techniques are likely to become important and that the scanning electron microscope will become a valuable tool in solid-state device technology.

Westinghouse ENGINEER Nov. 1964

Technology in Progress

Ultrasonic Energy Improves Iron-Ore Beneficiation

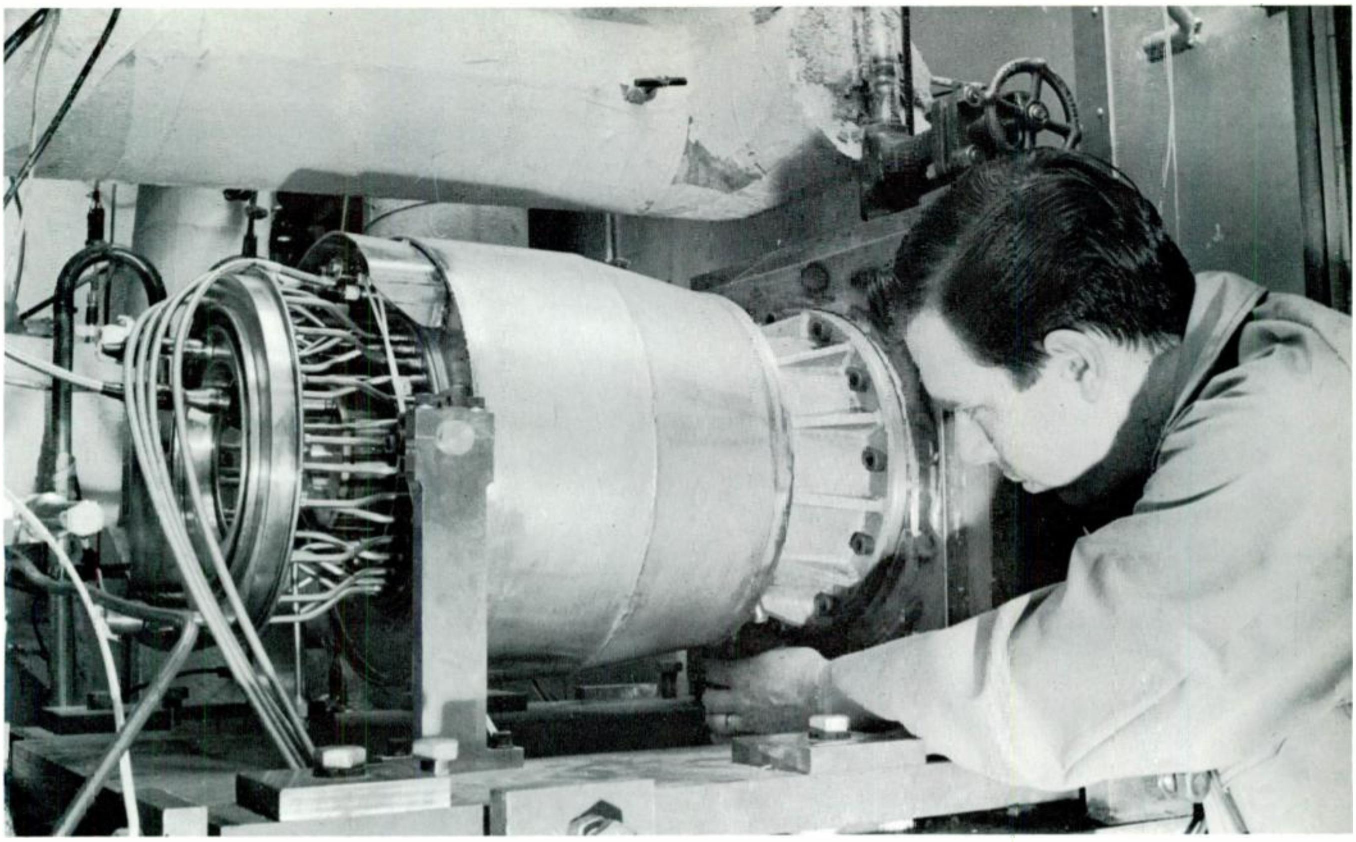
Taconite, a hard rocky iron ore, requires considerable processing to concentrate its iron content sufficiently for blast-furnace use. The processing, or beneficiating, consists essentially of crushing the ore and then increasing the ratio of iron oxides to waste material ("gangue") by a series of magnetic-separation treatments. Unfortunately, the iron oxides, because they are magnetic, tend to form clumps that trap gangue and carry it through the separators.

Recent investigations in the application of ultrasonic energy to taconite beneficiation have resulted in an improvement to the process that reduces the amount of gangue carried over and thereby increases the value of the processed material. The improvement, worked out by the Westinghouse General Industries Systems Department, consists of adding powerful ultrasonic transducers to the processing line between magnetic-separation stages. Intense ultrasonic energy directed into the flowing material induces violent forces in the clumps that break them up, releasing trapped gangue for separation at the next stage. The transducers could either be added to present beneficiation lines or included in new lines.

In the laboratory, the use of ultrasonic energy has reduced the gangue content more than ½ of one percent. This would be a significant improvement in an actual plant, since the unwanted gangue in the processed material reduces the material's value an estimated 35 cents per ton for each percent of gangue content. In a plant producing ten million tons of beneficiated taconite a year, for example, such an improvement could save almost two million dollars a year.

Liquid Potassium Cools and Lubricates Space Generator

A 50-kilowatt working model of a space-vehicle electric generator that is cooled and lubricated by liquid potassium has been built and is being tested. (See photograph.) Because it operates at temperatures and speeds higher than any attempted before for such a generator, it represents significant steps forward in materials and design technology. The generator, designated LMCD-II, is part of the SNAP-50/SPUR program for development of space power plants. (Planned rating of the SNAP-50/SPUR generator is 350 kilowatts.) The work is being done by the Westinghouse Aerospace Electrical Division for the Atomic Energy Commission through the U. S. Air Force, in cooperation with AiResearch Manufacturing Company.



Rotating electric generators are promising power sources for many projected space missions because they appear to be the most practical type for applications that need large amounts of power. (Such applications might include unmanned planetary probes propelled electrically, lunar-base power, and military space vehicles.) Studies have indicated that a rotating generator driven by a high-temperature turbine using potassium as its working fluid would have a high power-to-weight ratio and a long operating life. Design requirements in the SNAP-50/SPUR program include operating life of 10 000 continuous hours and specific weight of about 20 pounds per kilowatt of output power.

The LMCD-II is an inductor generator, a type that has a solid rotor to eliminate the problems that would be encountered with rotating windings at high speeds and temperatures. Its coolant temperature is about 600 degrees F, it operates at 24 000 rpm, and it produces power at 3200 cps, 120/208 volts. Power factor is 0.75 lagging.

A ceramic winding insulation was developed to help achieve long life at high temperature. In addition, a ceramic rotor-cavity seal protects the stator insulation from potassium vapor. It is an alumina cylinder brazed to metal end pieces, which are welded to the generator frame.

In operation, liquid potassium passes through the generator's cooling system to carry heat away. The metal also lubricates the two tungsten-carbide pivoted-pad bearings. This type of bearing was selected for its stability at high speed and at the loads anticipated in zero gravity. A special seal system keeps liquid metal out of the rotor cavity; at the speed the rotor travels, it would be damaged by impact with a droplet of metal.

Data-Logging and Computing Equipment for Enrico Fermi Nuclear Plant

An automatic data-logging and computation system has been installed at the Enrico Fermi nuclear power station of the Societa Elettronucleare Italiana (SELNI) in Italy. The power station includes a pressurized-water reactor (primary system) and two turbine-generator units (secondary system). It will supply 270 mw of electric power. The data-logging and computation equipment serves both the primary and secondary systems.

The computer automatically performs any computations necessary to present all variables in engineering units. This includes linearization, scale factoring, zero suppression, ranging, span and zero adjustments or both, and averaging as required. The computer is programmed to compare analog input signals, in digital form, with stored low and high alarm settings. If an off-normal condition is encountered, the computer initiates an alarm printout, giving time, location, and value, and an audible alarm.

For the primary system, the equipment furnishes logs of all analog inputs and selected calculated values every 60 minutes or on demand. Perturbographic logging (post-mortem review) is initiated automatically by the closure of external contacts or manually from the operator's console. Forty-two analog inputs are scanned every 10 seconds, and the last six values of these readings for each point are stored and continuously updated in the computer memory. A scram signal or contact closure from the operator's console "freezes" the updating of selected analog inputs and initiates the storing of 18 additional readings.

Sequence-of-events recording is initiated by the closure of one or more of 13 interrupt inputs. The sequence of the first 10 contact closures or of the contacts closed within 60 seconds after the first contact closure, whichever occurs first, is recorded on the perturbographic-log typewriter. Time interval between each recorded contact closure is printed in multiples of cycles.

Calculations are performed on line for reduction and analysis of reactor temperature data and for determination of total thermal power and gross efficiency. Calculations for thermal calibration of the steam generators are performed on demand.

Secondary-system performance calculations are being developed and programmed by the operating organization.

The basic element in the data-logging and computing system is a Prodac 510 digital computer with an 8192-word core working memory and a drum auxiliary memory of 65 536 words. Input-output peripheral equipment provides for 464 analog inputs, 163 contact-closure inputs, 24 process-interrupt inputs, and 100 contact-closure outputs. The computer's memory contents are protected against loss during turnon, turnoff, or power loss in the primary (ac) or internal (dc) circuits regardless of sequence.

Thin-Film Transducers Vibrate at Ultrahigh Frequencies

Piezoelectric transducers, which convert electrical pulsations into mechanical vibrations, ordinarily consist of a thin wafer of a crystalline material such as quartz. To achieve high frequencies, these ordinary piezoelectric crystals must be made so thin that they shatter under the vibrations they generate; they are so fragile, in fact, that it is nearly impossible to handle them without breakage.

A new way of making crystal wafers produces transducers that are much more durable. These transducers have been operated at frequencies up to 75 000 megacycles, and the technique should eventually provide frequencies approaching a million megacycles.

The transducers are thin films of cadmium sulfide deposited on a substrate from vapor in a vacuum chamber. Conditions are controlled so that the atoms of cadmium and sulfur build up in an orderly fashion to form nearly perfect single-crystal films. The transducers that operate at 75 000 megacycles are only 300 angstroms thick.

Because the transducers are being used to study the structure of such crystalline materials as ruby and sapphire, they are deposited directly on the surface of a block of one of those materials. The technique replaces the former method of cementing a conventional thin fragile transducer to the block.

In use, a short pulse of high-frequency microwaves is fed to the thin-film transducer. Mechanical vibrations of the same frequency are set up in the transducer, which transfers them to the entire block of material. These vibrations reflect back and forth inside the block and eventually die away; their velocity and lifetime yield basic information on the physical perfection of the material under study.

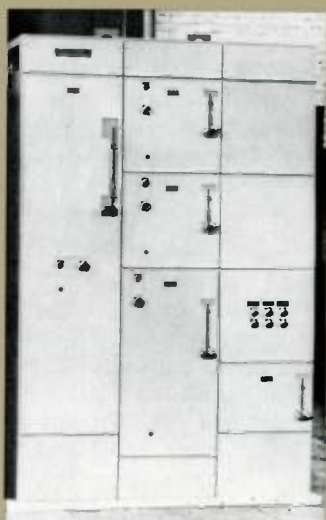
The thin-film transducers were developed at the Westinghouse Research Laboratories in a cooperative project under contract with the U. S. Air Force's Cambridge Research Laboratories, Cambridge, Massachusetts.

Products for Industry

Power-line carrier test set aids in checking the performance of power-line carrier or audio-tone equipment. Type TCT set is three rack units high in a 19-inch rack mounting, but it can also be used as a portable unit. The set contains two 4½-inch foundation instruments. One measures r-f milliamperes with a thermocouple, range-changing switch, and non-inductive shunts. The other instrument measures ac and dc volts, dc currents, ohms, and dbm with a range-changing switch, shunts, and resistors. *Westinghouse Relay-Instrument Division, Plane and Orange Streets, Newark, N. J. 07101.*

Unit-design safety control center is made for 110, 220, 440, and 660 volts and up to 200-hp capacities. The units have complete metal enclosures and draw-out components for safety. (See photograph, lower left.) Each load feeder is protected by a starting contactor and by a circuit breaker or fused safety switch. Mechanical interlocks prevent operating and inspection mistakes. The centers are 90 inches high and 20 inches deep, the widths varying according to the number of distribution units assembled together. *Westinghouse Low-Voltage Distribution Equipment Division, P. O. Box 868, Pittsburgh, Pa. 15230*

Magnetic-tape demand recorder (Type WR-2) provides dependable accurate recording for customer revenue billing, system and substation load monitoring, and load-survey data collection. (Photograph, lower right.) The unit records, on magnetic tape, time-interval pulses and impulses proportional to the load being metered. Magnetic tape eliminates inking and printing problems and results in mechanical simplicity. Tape is reuseable. Optional features are battery carry-over and register that displays kilowatt-hours and kilowatt demand. *Westinghouse Meter Division, P. O. Box 9533, Raleigh, N. C. 27603.*



ABOUT THE AUTHORS

René A. Baudry is a Graduate Mechanical Engineer (1919) of Ecole Nationale D'Arts et Metiers, France. He joined Westinghouse in 1925 as a draftsman in the Large Rotating Apparatus Department. He has progressed through positions of mechanical engineer, development engineer, manager of the mechanical development section, and manager of the development engineering department. He retired in June 1964, but has continued his association with Westinghouse as a consultant to the large rotating apparatus department.

Baudry has accumulated 60 patents in his development work on waterwheel generators, hydrogen-cooled machines, and inner-cooled turbine generators. He has received two separate $5000 patent awards from the company for his development of spring mounting for turbine generator stators and the inner-cooling system for turbine generators.

Edward I. King, Jr., who coauthored the article on inner-cooled generators in this issue with Baudry, is a Fellow Engineer in the large rotating apparatus development section. He specializes in rotating machinery design and development and has integrated the use of the digital computer in the analysis of computer problems. His most recent efforts have been concentrated on the development of the advanced inner-cooling system described in this issue. King holds a BSEE degree from the Polytechnic Institute of Brooklyn (1950), and obtained his MSEE from the University of Pittsburgh (1958).

J. K. Dillard, a regular contributor to these pages, joins another regular contributor, **C. J. Baldwin,** to discuss developments in mine-mouth power plants, EHV transmission, and nuclear power generation. Dillard, manager of the electric utility engineering department, is an EE graduate of Georgia Tech and has an MS degree from MIT. He joined Westinghouse in 1950, after three years on the Electrical Engineering Department staff at MIT.

Baldwin, manager of the advanced development section of the electric utility engineering department, is responsible for investigations in power system generation, transmission, and distribution. Baldwin is a graduate of the University of Texas (MS in EE) and holds a professional EE degree from MIT.

F. G. Willard earned his AB at Dartmouth in 1953 and his MSEE there the following year. He joined Westinghouse on the graduate student course in 1954, and in 1955 he was assigned to the systems control division as a development engineer. This was at the inception of the Prodac line of industrial control equipment, and Willard contributed to the design and application of such milestones as the first card-programmed steel-mill control and the first fully automatic blooming-mill control. He was responsible, in 1960, for development of the computer required for the first computer-automated plate-mill control, and in 1962 for the input-output system of the Prodac 580 and 510 control computers.

Willard is now an advisory engineer in the Computer Systems Division, in charge of equipment development for computing systems. His most recent concern has been development of the central processor and input-output equipment for the Prodac 50 control system that he describes in this issue.

Both **Thomas A. Daly** and **Paul H. Ockerman** have backgrounds in reliability engineering in naval programs performed by Westinghouse, and therefore have an excellent base from which to help build the type of program needed for nonmilitary products. This program is described in the article on page 180.

Daly received his degree in electrical engineering "with distinction" from Purdue University in 1934. His experience as a design engineer with Westinghouse encompasses such diversified fields as industrial control, distribution transformers, and naval weapons. During the past twenty years as a manager, Daly has, among other assignments, served as engineering manager of the Ordnance (now Underseas) Division, where he developed the Navy's present acoustic service torpedo and other military equipment, an area in which he holds twelve patents. Since that time, he has served as factory planning manager for the Distribution Transformer Division, where he guided plant layout, equipment development, and facilities procurement for the coil winding, core manufacture, and automatic test areas of the new Athens, Georgia, transformer plant.

He then became manager of reliability engineering for the Sunnyvale (California) Divisions, where he planned and administered reliability and quality assurance programs for the Polaris Launching and Handling System. His present assignment is Director of Reliability for Westinghouse, in which job he is responsible for the implementation and coordination of the corporation's Reliability Program.

Ockerman attended both the University of Kentucky and Morehead State College, and earned his BS degree in mathematics and physics from the latter in 1950.

He soon became a laboratory supervisor in mass spectroscopy and isotopic analysis for the Union Carbide Nuclear Corporation at Oak Ridge, Tennessee, and Paducah, Kentucky. Ockerman joined Westinghouse in 1955 at the Bettis Atomic Power Laboratory. He became manager of quality control at Bettis in 1960. In 1963, he moved to the Headquarters Manufacturing Control Department, as director of reliability control, his present assignment.

Ian M. Mackintosh and **Jay W. Thornhill** are coauthors of the scanning electron microscope article in this issue.

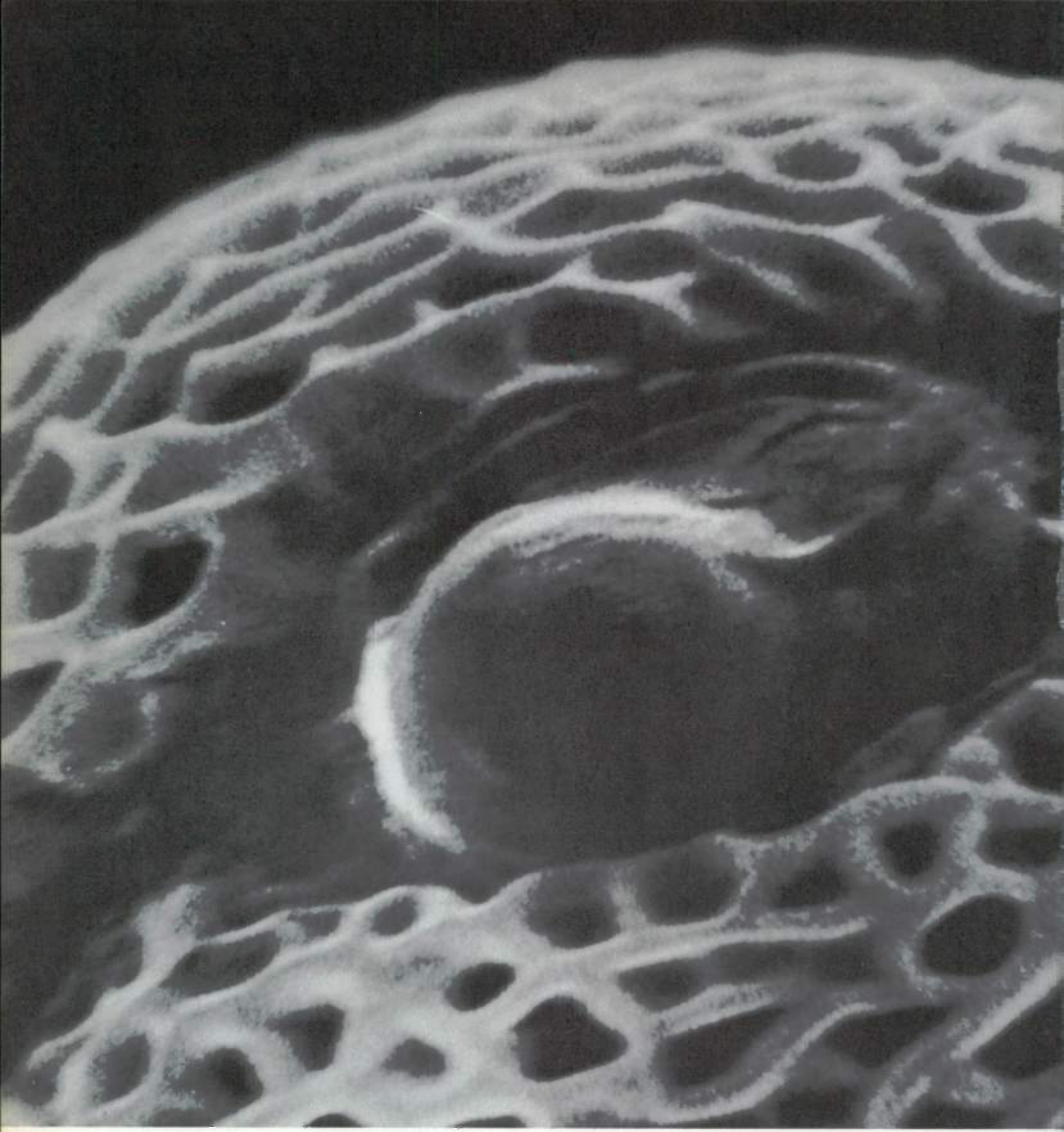
Mackintosh received his B.Sc. and Ph.D. degrees from the University of Nottingham in 1953 and 1956. He joined the Bell Telephone Laboratories at Murray Hill, N. J., to do research primarily in the fields of silicon switching devices and solid state diffusion techniques.

Mackintosh came with the Westinghouse Research Laboratories in 1962 to be manager of the integrated devices laboratories. Here, he was responsible for research programs on new device concepts and phenomena, and for development of integrated devices and new solid state techniques and processes. Later in 1962, Mackintosh was appointed manager of the information devices department where he was responsible for research and development of semiconductor and dielectric devices, and for device fabrication and measurement techniques.

In July 1964, Mackintosh resigned his position with Westinghouse to return to England, where he joined Elliott-Automation, Ltd.

Thornhill graduated from Penn State in 1942 with a B.S. in physics. After military service, he did graduate work at Purdue University, and obtained his M.S. in physics in 1950. Thornhill came to the Westinghouse Research Laboratories in 1963 as manager of the techniques R & D section. He is presently manager of the information devices department.

Prior to joining Westinghouse, Thornhill held supervisory positions with Texas Instruments and Sylvania Electric Products, Inc. Thornhill has done research and development on a variety of new semiconductor devices and techniques, including germanium thin films, germanium diodes and transistors, silicon diodes, silicon rectifiers, silicon transistors, photosensitive devices, silicon functional and integrated structures, and piezoresistive devices.



Not the surface of the moon, but a germ's-eye view of a pollen grain (nutmeg geranium), magnified some 5000 times. The unusual photograph was made with a scanning electron microscope, a new type of electron microscope that forms detailed images of tiny surface areas by scanning them with a fine electron beam. The beam causes the specimen to emit secondary electrons in numbers determined by the shape and nature of the surface. The resolution and depth of focus possible with the new microscope provide much better detail than can be obtained with conventional optical microscopes.

Westinghouse

ENGINEER

INDEX

SUBJECT • AUTHOR • BIOGRAPHY

VOLUME 23 • 1963
VOLUME 24 • 1964

subject index (PI . . . Products for Industry; R&D . . . Research and Development; TP . . . Technology in Progress)

T

U

V

W

X

Z

author index

biography index (Biographies appear on the inside back covers.)

Published by the Westinghouse ENGINEER
Box 2278, Pittsburgh, Pa. 15230