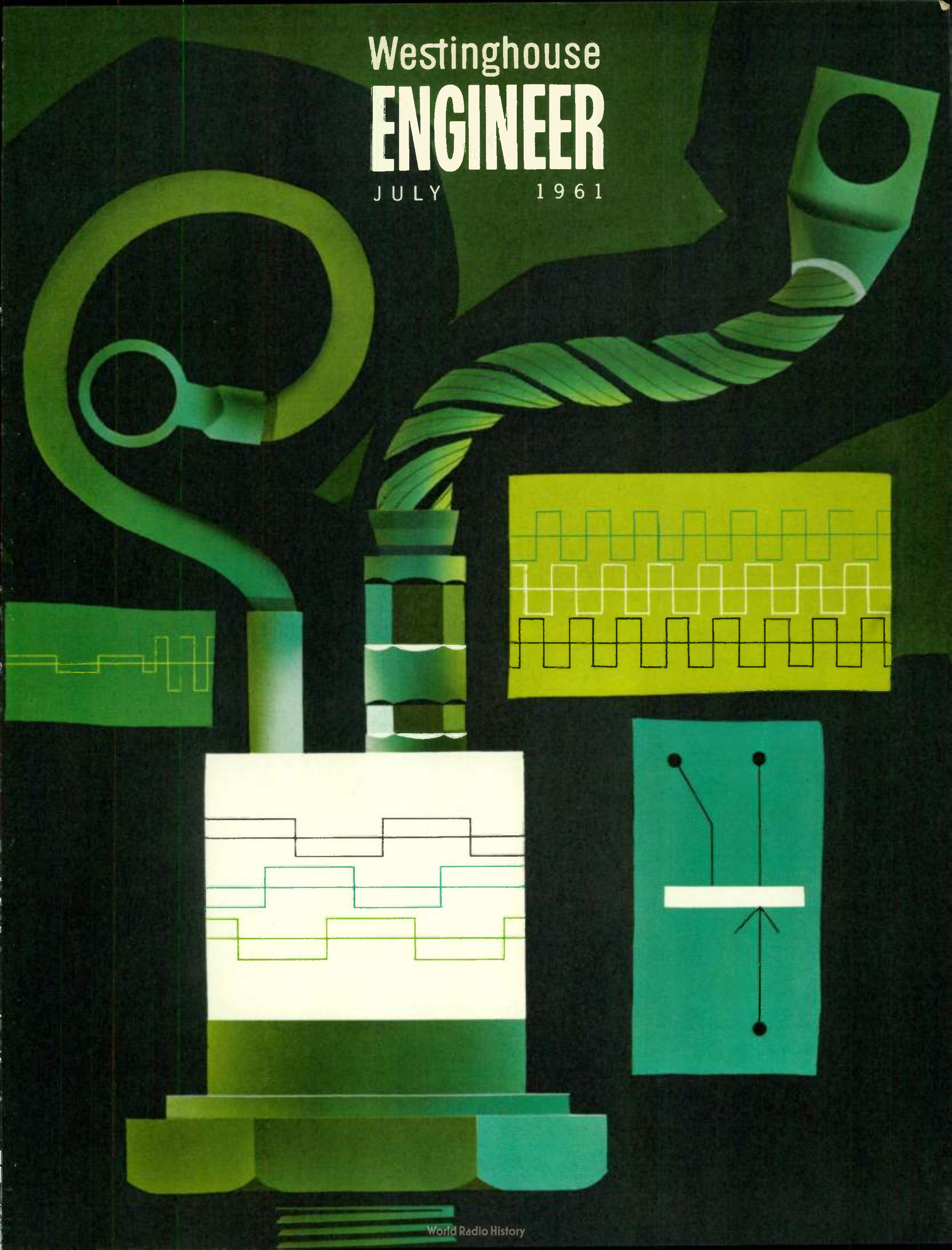
Westinghouse ENGINEER

JULY 1961

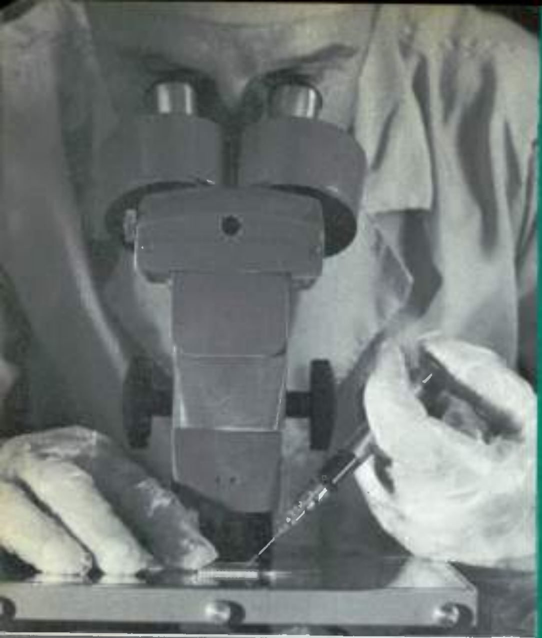


ELECTRONIC SURGERY

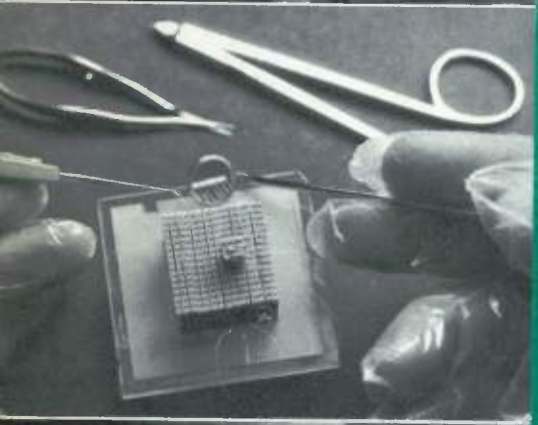
Electronic devices — tiny, precise, and highly complicated — are the brain and nerves of modern machines. In some respects they even outdo human performance: They see with rays invisible to the unaided eye; they feel the heat of a distant star; they hear and speak across millions of miles from vehicles deep in outer space; some make decisions based upon their own experience.

Such devices are even beginning to receive human-like treatment as scientists of the Westinghouse Research Laboratories adopt surgical techniques to "operate" upon research models of electronic circuits. In immaculate surroundings, surgical tools are used for assembling precision circuitry and for correcting any defects that may exist among wire as thin as human hair and electronic components smaller than a pin head.

The techniques shown were devised to assist in the development of the ELF screen—a new electronic device for displaying television-type information on a flat, solid, glowing panel. The research, supported by the U.S. Navy's Bureau of Ships, is considered the forerunner of vital military display systems and, perhaps eventually, television-on-the-wall for the home.



With the aid of a microscope, a hypodermic syringe is used to apply a plastic glue that binds together a continuous line of electronic ionic switches.



A surgical mirror and dissecting probe are put to work on a complex matrix of electronic circuits.

A surgeon's scalpel trims an experimental ionic switch gap, made to an accuracy of better than one-thousandth of an inch.

In this ultra-clean electronics laboratory, "surgeons" use a special type of welding machine to join the glass and metal parts of experimental electronic tubes.

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Cover Design The Trinistor controlled rectifier is the subject of this month's cover by artist Dick Marsh. This semiconductor device can be used as a converter, an inverter, a frequency changer, a variable frequency generator, a motor controller, or a voltage regulator. In this issue its use in TAFI, a new adjustable frequency inverter, is described.

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TABLE OF CONTENTS

CVTR . . . A Pressure-Tube Reactor The pressure-containing element in this design is a U-tube rather than a large vessel.

P. G. DEHUFF, Manager, CVTR Project
Atomic Power Department
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Editor's Note In 1956, four utility companies in the Southeast formed the Carolinas Virginia Nuclear Power Associates, Inc. (CVNPA), with the objectives of discovering and studying economic ways of producing and utilizing nuclear power. The companies are: Carolina Power & Light Company, Duke Power Company, South Carolina Electric & Gas Company, and Virginia Electric & Power Company.

Westinghouse is designing and furnishing the nuclear reactor plant and Stone and Webster is in charge of plant engineering design and construction. CVNPA submitted a proposal to the Atomic Energy Commission in 1957, under the third round of the Power Demonstration Program. The proposal was accepted, with research and development cost to be borne by the AEC, and the cost of plant construction and operation by CVNPA.

The heavy water pressure tube reactor plant is now being constructed in Parr, South Carolina, with completion scheduled for mid-1962. When completed, the reactor will feed steam into an existing turbine generator. See sketch below.

Several years ago, nuclear designers foresaw the possibility that the physical size of pressure vessels for closed-cycle reactors might eventually become a limiting factor in nuclear plant design. Since calculations at that time indicated that reactors of 300 mw or larger would be necessary for economic power, the difficulty of designing, manufacturing, and shipping the large vessels necessary for these ratings loomed as a major obstacle.

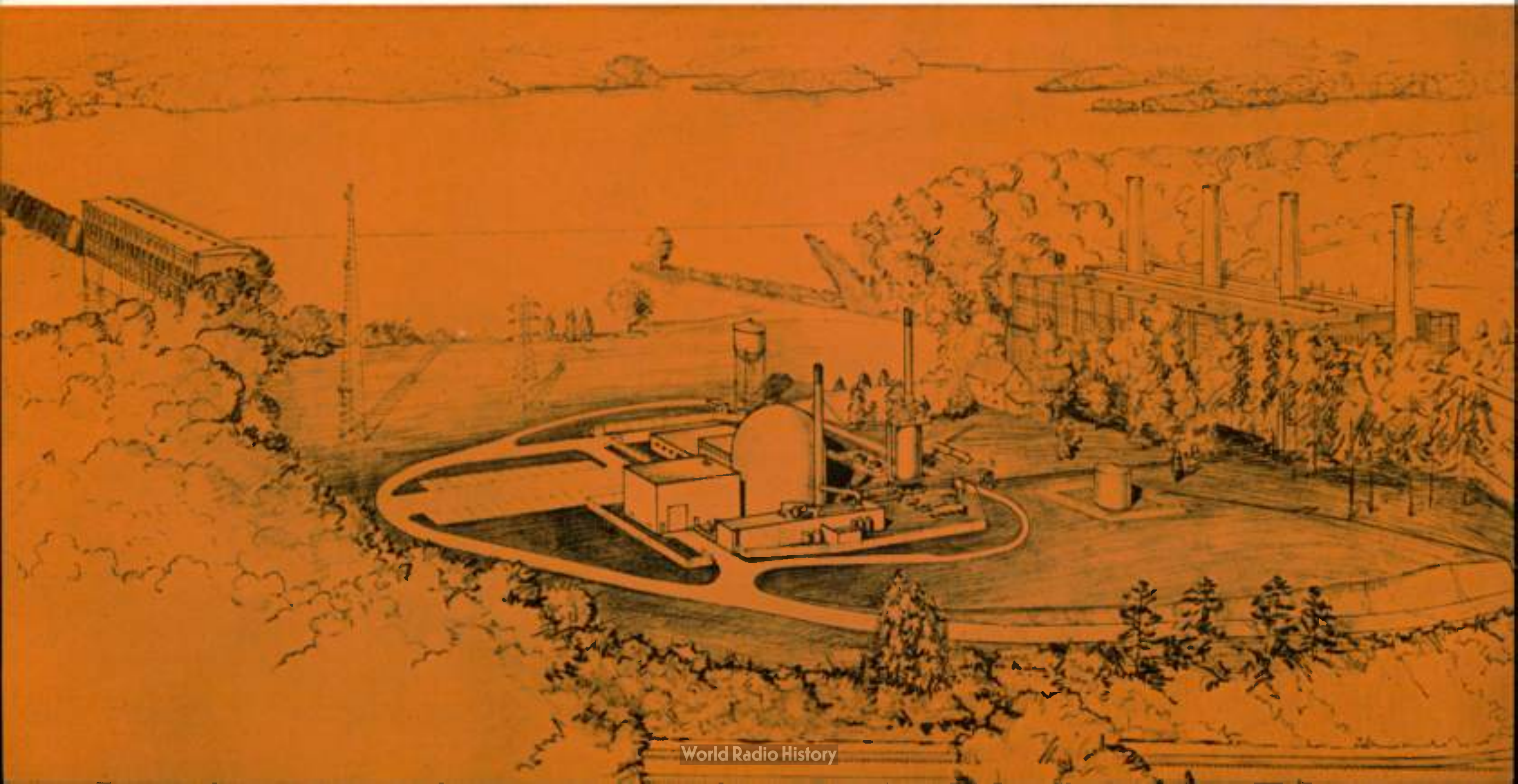
The alternative of using many smaller diameter vessels, or tubes, seemed attractive. In such a design, each tube could contain one or several fuel elements, and could have much thinner walls because of the small diameter of the tube (about four inches) compared to that of a large pressure vessel (about 100 inches). If many such pressure tubes were connected together in a parallel flow arrangement, the capacity of the reactor could be increased without incurring the corresponding increased stresses that would accompany such an enlargement of a single pressure vessel.

This possibility led to the CVTR (Carolinas-Virginia Tube Reactor) Project, in which the pressure tube concept is being used in a prototype power reactor. This reactor, with a net electrical output of 17 mw, will serve as a prototype for a large scale plant of 200 mw or more.

During the past few years, considerable progress has been made in the construction of pressure vessels, so that their size has not become a limitation for reactors. However, this has not dimmed the prospects of the pressure tube reactor, because vessel size may still remain a problem for very large reactors of the future.

description of the plant

Unlike most contemporary power reactors, the CVTR will use heavy water as both a coolant and a moderator with the coolant loop separate from the moderator (Fig. 1). This nuclear steam generator is capable of producing approximately 60 mw thermal in the core. About 18 000 lbs. of heavy water at an average temperature of 530 degrees F and 1500 psia are circulated in the primary coolant loop by two canned motor pumps at a rate of 3.3×10^6 lb/hr. Dry saturated steam at 605 psia steam temperature 487



degrees F and 201 000 lb/hr is produced in the Inconel tubed steam generator and fed to an oil-fired superheater where the temperature is raised to 725 degrees F to meet the operating conditions of the existing turbine generator.

pressure tubes and fuel assemblies

Each pressure tube consists of two vertical, straight tubes joined at the bottom by a U-shaped connection. Each leg of the pressure tube contains a fuel assembly, a neutron shield plug above the fuel assembly, and thermal baffling, which insulates the relatively cold pressure tube and moderator from the hot primary coolant.

The details of the pressure tube, arrangement of the fuel assembly, and other internal features are shown in Fig. 2. The pressure tube section in the core and reflector regions will be made of Zircaloy for neutron economy. However, the remainder of the pressure tube will be made of stainless steel because of the high cost of Zircaloy. A mechanical joint is used because no acceptable method of metallurgically joining these two metals is now known.

A total of 84 fuel assemblies are used, two in each of the 42 U-tubes. Each fuel assembly consists of a 19-rod cluster of Zircaloy clad fuel rods, each 0.5 inch outside diameter, with the rods contained in a hexagonal flow baffle of 0.03 inch wall thickness. The rods are hung from a grid attached to the upper end of the hexagonal flow baffle, allowing independent axial expansion of each rod eliminating thermal bowing. All rods except the center one have a spiral fin, which spaces the rods and improves coolant mixing.

The fuel rods contain a total of 8200 pounds of uranium dioxide pellets. The complete core has an effective diameter of 83 inches and an effective height of 96 inches. To improve power distribution, the core is designed to utilize at least two regions of fuel enrichment.

The thermal insulating barrier in the CVTR pressure tube is formed by alternate layers of Zircaloy and stagnant

Fig. 1 The nuclear steam generator for the CVTR uses heavy water as both a coolant and moderator.

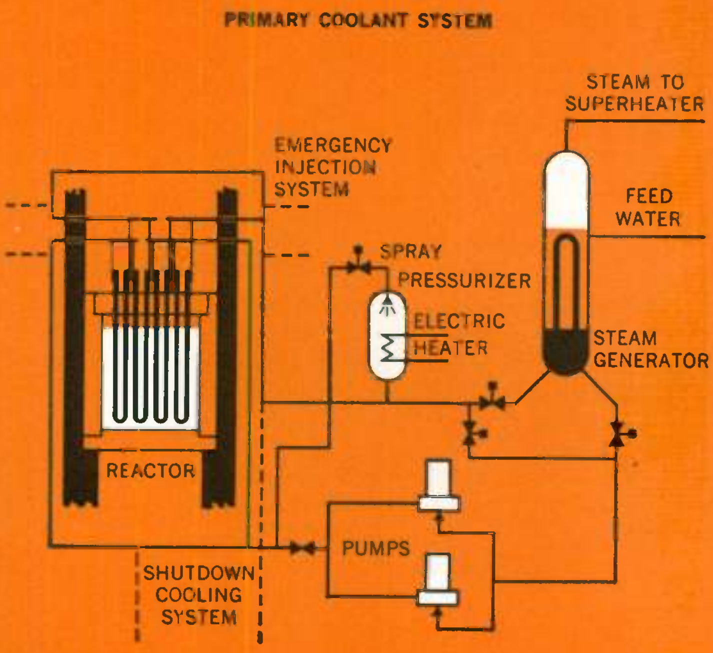
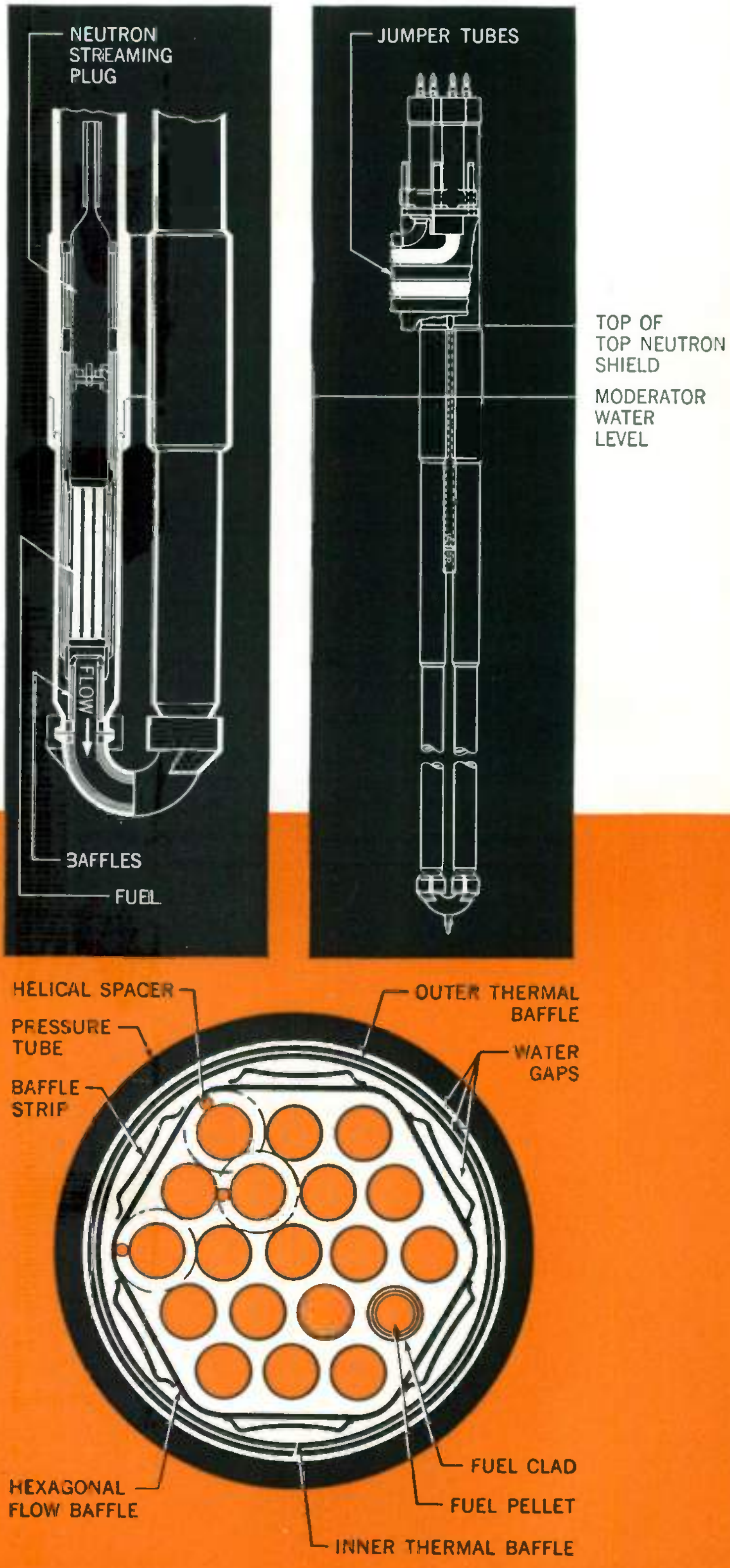
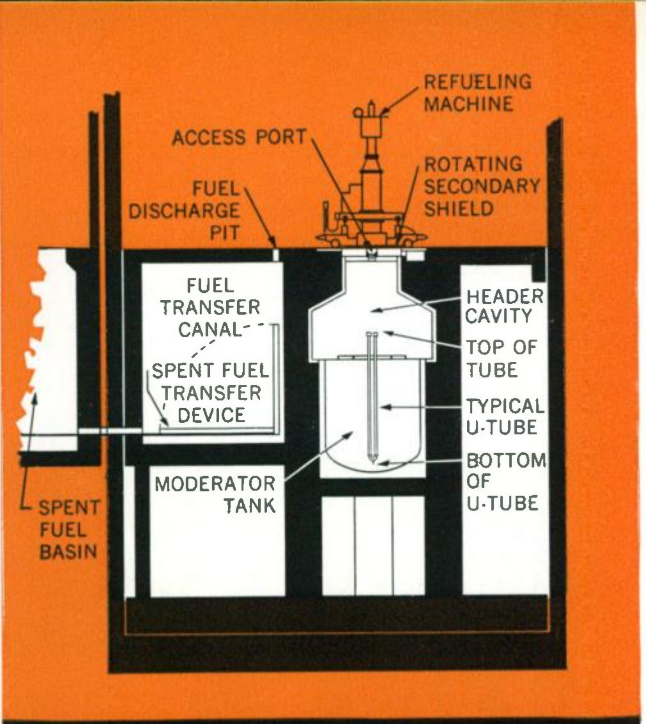


Fig. 2 Fuel for the CVTR is contained in pressure tubes, through which the coolant flows. View at left, which is foreshortened, shows the fuel assembly. Bottom view shows a cross section of the tube, and the arrangement of fuel.





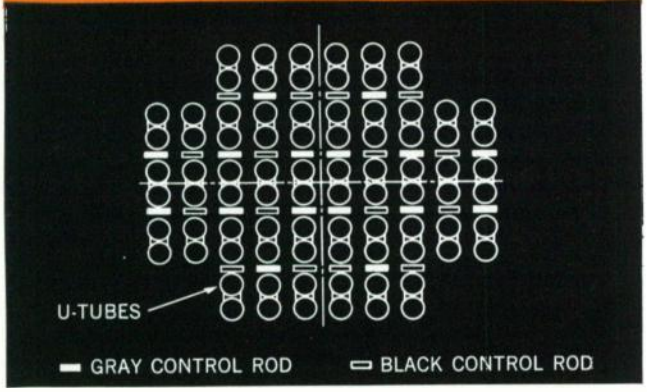


Fig. 3 This elevation view shows the position of the reactor and access equipment.

Fig. 4 Thirty-two control rods are positioned in the core as shown above. Two different types are used.

heavy water surrounding the fuel assembly. Several layers of heavy water are provided, rather than a single layer. This minimizes convective currents which would increase the heat losses. The Zircaloy required to separate the water into layers increases the losses by conduction; therefore, the baffle design lends itself to optimization.

The present fuel cycling concept calls for replacement of only four fuel assemblies at each refueling. Depleted fuel assemblies are transported by the refueling machine to a fuel transfer canal. The spent fuel is then transferred through a specially provided penetration in the vapor container wall to the storage racks in the spent fuel basin. Refueling can be accomplished by removing either the entire U-tube or only the fuel element and the thermal baffles.

reactor control

Thirty-two control rods of a simple slab configuration are provided (Fig. 4), with drive mechanisms mounted above the core transmitting motion through a shaft and gear arrangement. Sixteen of these rods (black rods) will be fabricated from high neutron cross section boronated stainless steel. These rods, normally positioned above the core, will compensate for xenon fluctuations, hot-to-cold change in reactivity, and shutdown. The remaining sixteen control rods (gray rods) are much lower in absorption cross section and act, in effect, as shim rods. They will be used in steady state operation to compensate for fuel burnup, samarium poisoning and moderator degradation.

reactor compartment

The main reactor components are contained by a primary biological shield within the plant in a compartment roughly 35 feet high by 17 feet in diameter (see Fig. 3). The core is suspended in the moderator tank which, in turn, is suspended from the walls of the primary biological shield. The U-tubes pass through a top neutron shield consisting of heavy water and stainless steel in alternate layers. This heavy water is also a part of the moderator liquid volume. Thermal shields consisting of water-cooled plates surround the moderator tank. These shields absorb a great deal of heat generated by gamma particles which would otherwise overheat the outer concrete shield.

moderator tank

As shown in Fig. 3, the moderator tank is a cylindrical stainless steel tank approximately 16 feet high by 9 feet 3 inches in diameter, which will contain about 700 cubic feet of heavy water. The moderator is pumped into the bottom of the tank, through the flow distribution plate, past the U-tubes and the top shield, then out through an overflow. With an inlet temperature of 130 degrees F and an outlet of 180 degrees F, the average temperature of the moderator is maintained at 155 degrees F.

support structure

The U-tubes are hung from a support structure that rests on the moderator tank. This structure establishes lattice spacing in the core and bears the weight of the U-tubes; it also provides a means of attaching the U-tubes to jumper tubes that carry the primary coolant to and from the core. The large eight-inch headers combine the flow from all the jumper tubes.

header cavity

The upper portion of the U-tubes, the support structure, the control-rod drive train, the jumper tubes, and the headers are all contained within the header cavity. The temperature in this cavity is maintained at about 500 degrees F to reduce heat losses from the various radiating bodies. A moderator sweep gas system maintains a constant sweep of helium gas, introduced at 180 degrees F into this cavity (and also across the liquid surface of the moderator) to remove any potentially explosive mixtures of deuterium and oxygen. The header cavity is closed by a secondary rotating shield designed to permit refueling machine access to each fuel position in the core.

vapor container

The vapor container is designed primarily to contain any products released as a result of a maximum credible accident, and also provides adequate biological shielding for post-accident conditions. The container is constructed of reinforced concrete for structural strength with a steel liner for vapor containment. The structure proper is a domed right circular cylinder of 58 feet inside diameter and overall inside height of 119 feet. The vapor container design pressure is 21 psig.

auxiliary systems

The CVTR design includes such conventional auxiliary systems as the moderator and primary coolant purification systems, component cooling water, waste disposal, and fuel handling equipment. However, the use of heavy water necessitates additional special equipment. Instruments for detecting heavy water leaks into light water systems alert the operator so that he may act to avoid possible radioactive contamination in these light water systems. The instrument systems also reduce the irrecoverable loss of heavy water through early detection of leaks so that repairs can be made. Conversely, other instruments are provided to detect light water leakage into the heavy water, thus avoiding degradation of the heavy water.

Despite the best preventative efforts, some leakage and degradation are to be expected. Therefore, careful consideration has been given to the collection of these liquids, and to the holdup, analysis and proper segregation of the various qualities of degraded liquids. The objective here is to preserve leakage containing a high percentage of D_2O and to dispose economically of other leakage.

pros and cons of the pressure tube design

Although improvements are being made in the methods required for refueling power reactors of the pressure vessel type, the length of time is still measured in weeks. Obviously, this represents a costly proposition to an electric utility. One advantage of a pressure tube reactor is the relative ease of local refueling or relocating of fuel.

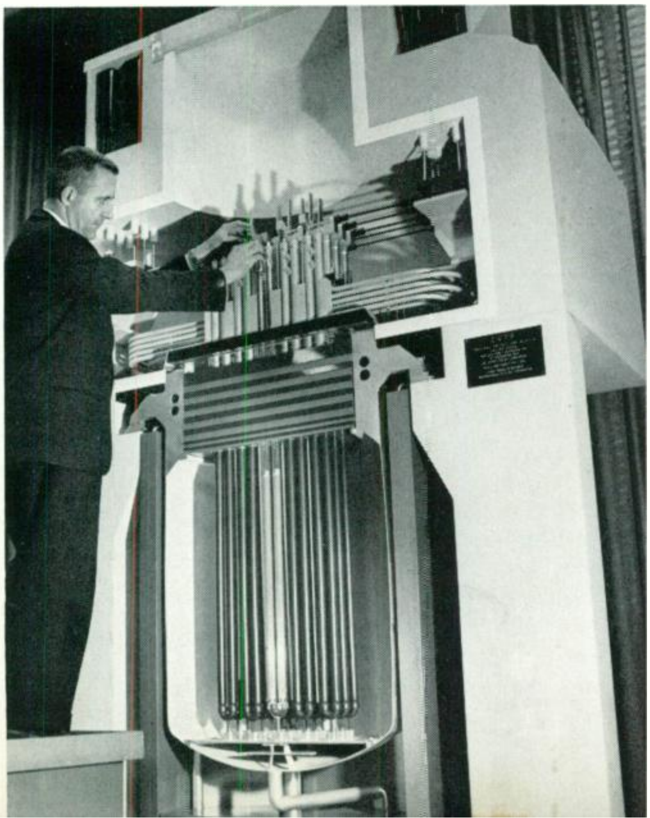


Fig. 5 A scale model of the CVTR. The author is holding one end of a U-tube; horizontal piping at top is for coolant flow.

With burnup of fuel in a reactor, certain regions of the core will operate at higher flux levels than other regions. This will result in a more rapid depletion of fuel in the high burnup region and a local reduction in power output. If the overall core is to produce the rated power, then other regions must produce relatively more power, or fuel elements must be shifted from a high to a low flux area and vice versa. This is particularly important in a large heavy water reactor where there is the possibility of using natural uranium (which contains only 0.7 percent U-235) and where easy fuel cycling is mandatory if the life of the fuel is to be prolonged and power costs are to be decreased.

The pressure tube provides refueling advantages in several ways: first, because of the smaller diameter of the tube as compared to a large pressure vessel, threaded caps can be used to seal the end of the tube through which refueling takes place. Removing several of these caps, shifting or replacing fuel or U-tubes, and resetting the caps then requires a relatively short time and the refueling operation is in terms of days rather than weeks.

Another advantage of pressure tube reactors lies in the control rods and drive mechanisms. In a power reactor the control rods must be located within the core to furnish proper control and shutdown characteristics. In a large pressure vessel this means that the mechanism which raises and lowers the control rod must be a part of the pressure containing system. A mechanism to contain high pressure is complex and costly, and is accessible only by depressurizing the entire primary system. By contrast, in the pressure tube design, the control rod mechanisms are not part of the pressurized system, and therefore are simpler and more accessible. Because each pressure tube contains only one or two fuel elements, it is possible to orifice the flow to each pressure tube and thereby balance unequal flux distribution. For the same reason the detection of failed fuel elements is also made easier because each pressure tube can be monitored.

The use of many pressure tubes instead of a single pressure vessel does have certain disadvantages. Because the moderator surrounds the pressure tubes and is contained in a tank at atmospheric pressure, at low temperature, heat is lost to the moderator fluid. This heat loss is a result of conduction through the pressure tube walls, neutron thermalization and gamma heating in the moderator. The total heat loss is approximately 12 percent, compared with a pressure vessel heat loss of less than 1 percent.

Because the pressure tubes must be located close together to achieve an optimum nuclear arrangement, the piping tends to be somewhat complicated. Each tube must have an inlet and an outlet pipe connection, which must then be led to a larger pipe. The arrangement and location of these pipes constitutes the problem. A corollary effect of the many small pipes is a relatively high pressure drop compared with the smaller loss in a single pressure vessel. This will result in a requirement for a pump (or pumps) capable of delivering flow at a higher head.

Because the pressure tubes must be located in the active portion of the core, their material must have a low neutron absorption cross section. The material must also be corrosion resistant and have high strength at the operating conditions. For such applications, zirconium base alloys are frequently chosen. However, data is still limited on the properties of such materials when exposed to direct neutron bombardment for periods in excess of five years. Here again the single pressure vessel has the advantage; because the core is completely contained and therefore the pressure vessel material is located outside the intense irradiation field, the single vessel material is not subjected to as intense a neutron exposure as are the pressure tubes.

To conclude the comparison of the pressure tube and pressure vessel, it appears that for present design capacities the initial cost of many small pressure tubes will exceed the cost of a single pressure vessel which would contain a core of the same power rating. Whether this higher initial cost and high pumping costs can be offset by some of the advantages discussed previously will be watched carefully in the prototype CVTR plant.

novel features of CVTR

The use of the pressure tube in the CVTR is not its first or only application to nuclear reactors. As examples, the Canadian reactors NPD-2 and CANDU, and PRTR make use of this concept. The gas cooled reactor of the Florida West Coast Nuclear Group (FWCNG) is also exploring the use of the Zircaloy pressure tube.

The CVTR, however, does introduce an important development in pressure tube application; namely, the principle of "cold tube" design. In this concept, the pressure tube is insulated from the high temperature circulating water; this allows the designer to use higher stresses in the pressure tubes because of the increased material properties available at the lower temperature.

The CVTR differs from most power reactors in that the moderator is heavy water. About 0.02 percent of ordinary water is D_2O, with separation accomplished by chemical exchange, distillation and electrolysis processes. For reactor purposes, heavy water normally has an isotopic purity of 99.75 percent D_2O.

In certain respects, heavy water provides the best moderator available today. Two basic factors determine whether a substance is a good moderator. One is the slowing down power; i.e., the ability to quickly slow down (or thermalize) the neutrons by scattering collisions. From this point of view, light water is a good moderator. The second factor is a low probability of capturing neutrons. By these standards, heavy water is an excellent moderator.

When heavy water is used, certain additional considerations enter into reactor design. These include the conservation of the D_2O and the maintenance of the heavy water isotopic purity. For example, primary to secondary system leakage in light water plants is allowable only so long as it does not contaminate the secondary system excessively. Although plants can continue to operate with certain activity levels in the secondary system, such leakage in a heavy water plant means an unrecoverable D_2O loss (at a current price of $28/lb). This necessitates design for leak tightness and the best possible leak detection system. At the same time, such factors as secondary blowdown, or using steam for heating where it is vented to the atmosphere, must be limited. Such losses from the secondary system slow down the buildup of contamination or the D_2O content, one of which must be retained in a certain minimum quantity for leak detection purposes.

In a nuclear plant, the isotopic purity of heavy water must be kept at high levels to avoid affecting the nuclear characteristics adversely. This is sometimes accomplished by attaching a small distillation facility to the plant to continuously remove traces of light water; alternately the heavy water may be returned to the government reprocessing facility at Savannah River. In either event, an additional expense is incurred.

Heavy water reactors are also designed to be as compact as possible. Because of the high cost of heavy water, plants are often designed with "undersized" pipes and tolerate increased pressure drops in order to reduce the heavy water inventory. Steam generators, heat exchangers and other components thus have another criterion to meet—that of minimum fluid inventory.

Disposal of wastes is another point of difference in heavy water plants. Heavy water bearing wastes cannot be handled as simply as those of light water since as much D_2O as possible should be recovered. Wastes must be stored and sampled before mixing so that water of varying purity is not intermingled, with consequent degradation.

Another point to be considered is the buildup of tritium, which is generated in much greater amounts in a D_2O plant than in an H_2O plant. This requires special protection for the workmen and extra precautions during refueling.

future prospects

Although the CVTR may utilize both natural and enriched fuel, the heavy water moderator feature, with its excellent moderating qualities, advances the ultimate possibility of using only natural uranium as fuel in a large power reactor.

The ultimate use of only natural uranium in reactors depends on many factors in reactor design, including the amount of fuel and its geometric arrangements. However, of basic importance is neutron economy, i.e., the maximum use of available neutrons. Heavy water, as a more efficient moderator than light water, makes available for use more thermal neutrons (less are captured) and therefore increases the probability of fission. The potential use of natural uranium in a reactor designed primarily as a power producer has many advantages, and the CVTR reactor should provide valuable information toward this end.

A great deal will be learned about the nuclear, mechanical, and thermal behavior of this reactor, which can be applied to a full scale power reactor.

For example, the reactivity coefficients under transient conditions as a function of lifetime will be better understood by the work on this prototype reactor. Similarly, heavy water losses during operation of the reactor are an important factor in the design of an economic nuclear power plant. These losses can be determined accurately only through actual operation of a prototype plant.

The future of a heavy water moderated and cooled pressure tube reactor is very dependent on advances in pressure tube material technology—notably in zirconium metallurgy. Increasing the strength of the zirconium alloys at the operating temperatures will allow designers to reduce the thickness of the pressure tube and fuel cladding, thereby reducing the parasitic capture of neutrons and making possible the use of lower fuel enrichments. These developments will undoubtedly lead to a more efficient heavy water reactor design.

REVOLUTIONARY ERA FOR POWER TRANSFORMERS Among the future possibilities is a transformer with no copper losses.

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The remarkable technological progress in the past few decades is often described in terms of striking new concepts—for example, semiconductor devices and nuclear power. But, while such developments have attracted much interest, a similar revolution has been occurring in many well-established devices. The power transformer is a case in point.

The basic principles of power transformation have not changed in a half century, yet transformers themselves have changed radically. Both the individual and collective effects of such developments as the Form-fit tank, reduced insulation levels, oriented electrical core steels, and thermally stabilized insulation are sizable. For example, by improved coordination of lightning arresters in a grounded system, the insulation level of the power transformer can be reduced with significant results. A two-step reduction in insulation level for a typical 100-mva, 230-kv generator transformer produces the following results:

Weight—reduced by 70 000 pounds, or 20 percent.

Losses—reduced by 7 percent, or in dollar equivalent, $10 000.

Original cost—lowered by 20 percent.

Impedance—reduced by 15 percent, allowing improved system stability and voltage regulation.

The net effect of all design improvements is a reduction in weight per kva from five pounds in 1940 to one and one-half pounds per kva in 1960. Another indication of the extent of the development progress is the recent manufacture of a 750-kv transformer; the completed design of a 600-mva unit; and the willingness of designers to undertake an 800-mva transformer (in 1950, the largest unit was about 100 mva).

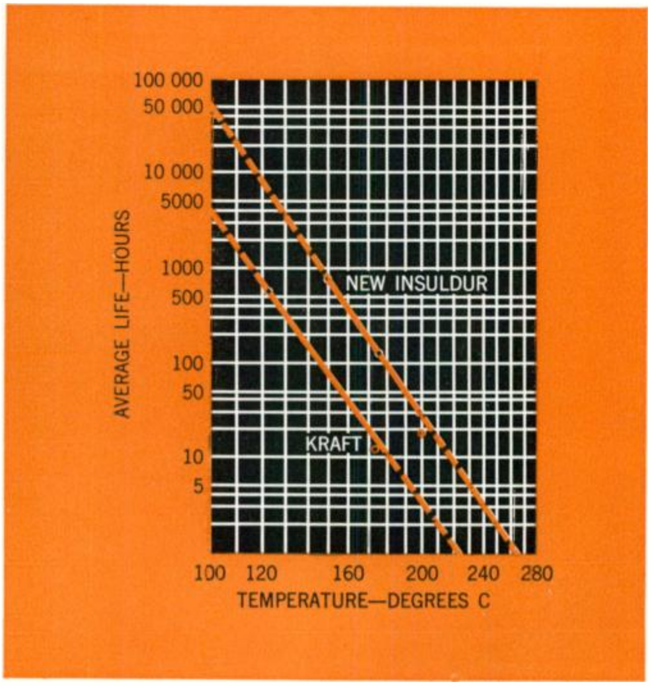
Despite these design improvements, however, the future needs of utilities will be for even larger and more efficient transformers. The trend toward larger generating stations means larger transformer units in a single package.

Many unique new materials may serve as catalysts for major design innovations in transformers. A review of these materials indicates the theoretical possibilities of providing improved reliability and life in terms of "lifetime guarantees"; elimination of any fire hazard; reduction in size of units in the order of 75 percent; reduced losses, even to the point of no copper loss at all with superconductors; and lower initial costs. Consider the possibilities.

Insulation is, of course, of great importance in a transformer. Cellulosic materials have been used for many years, even though cellulose is subject to dehydration and deterioration at high operating temperatures and is not particularly strong mechanically. Recently, its thermal capabilities have been improved through chemical stabilization. The Westinghouse method of stabilization, called the Insuldur system, increases insulation life and, hence, transformer life. As a result, the capacity of transformers has been increased by twelve percent. The actual improvement to the material is shown in Fig. 1.

As a next step, epoxy and other casting resins should prove ideal for application as insulation. The logical approach would be to cast the coils solid with the resin. This creates an ideal electrical insulation structure. Only a heat removal system is necessary to produce an overall suitable condition for transformer operation. This is most easily performed by one of the perfluorocarbon liquids, or other similar materials now under development. The liquid chosen here is one that would vaporize at approximately 100 degrees C, so that it can rise to a condenser where the heat transfer takes place, and can return to the coil structure in the form of a liquid. In carrying out this natural cycle of vaporization and condensation, the hot spot on the coils will not exceed 110 degrees C, at which temperature the solid encapsulant is not subject to deterioration; thus an unlimited life can be assured for this structure. In addition, since the cast solid insulation is much more efficient dielectrically and structurally than the cellulose, size and weight of the unit are reduced approximately 25 percent. On the problem side of this development is the fact that unless the mass surrounding the conductors is perfectly solid, the unit would be susceptible to corona.

Fig. 1 The relative improvement of the Insuldur system over kraft paper is apparent in this diagram. Fifty percent of the original bursting strength was used as the end point.



For example, any gaps between the conductors and the insulation could be a location where corona could start. While this has not proven to be a problem at 15 000 volts and below, it may be serious at higher voltages. However, present work on encapsulants with the same coefficient of expansion as the coil look promising, and if they prove suitable, the corona problem should be lessened.

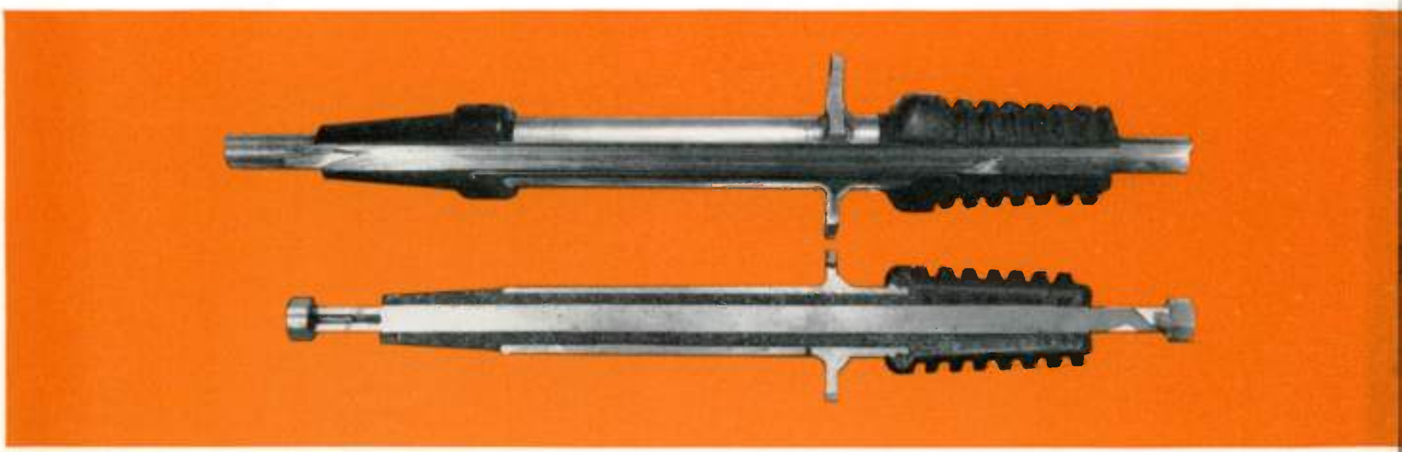
When complete encapsulation of the coils can be accomplished on a production basis, a tank structure will be unnecessary, as will separate bushings, since the encapsulant will be perfectly satisfactory for indoor use in its present state and, through addition of a simplified housing, for outdoor use. Similarly, the leads will be insulated from each other in coming out of the coil structure through the encapsulant. Bushings per se will not be needed.

However, until such a transformer does become commercially feasible, this same resin material may prove successful for bushings on conventional transformers. This development is quite advanced, and bushings of this type have been used for smaller transformers, and at present, the development of the epoxy-filled bushing for use at 25, 34.5, and 69 kv is proceeding rapidly (Fig. 2). In larger bushings, the epoxy is used as a filler, since a protective weather shed may be needed for outdoor use. Tests have proved very satisfactory, as the electrical characteristics in the table below indicate.

The excellent performance of cast epoxy as an insulating material is clearly illustrated by the fact that these test results were on a cast resin bushing of much smaller dimensions and half the weight of the conventional oil-filled condenser bushing. This material also provides a very strong mechanical structure, which should be particularly well adapted to breaker use and, unlike porcelain, it will not be susceptible to breakage. The exposed weather shed is made of a molded butyl rubber, aluminum oxide trihydrate combination. The aluminum oxide trihydrate is a nontracking compound that forms the basis for the outstanding performance of this bushing insofar as susceptibility to flashover is concerned. It is particularly effective under conditions of atmospheric contamination when, with a porcelain insulator, there is an increased potential for flashover. The principle of operation of the aluminum oxide trihydrate is that it provides an OH radical that, during periods of flashover and high temperature, combines with the carbon to produce carbon monoxide, hydrogen, and carbon dioxide, thus eliminating any carbon track and consequent cause of susceptibility to flashover.

Although the encapsulated coil transformer thoroughly covers the requirement of a fireproof unit, considerable development work remains before large power transformers will use this principle. However, large power fireproof units can be designed with other new materials made available since World War II. A new class of fluorine containing liquids is chemically inert, thermally stable, nontoxic, and its vapors have a high dielectric strength. Furthermore, vaporization cooling is a much preferred medium for cooling since it has a much higher heat transfer rate. As an example of the improvement, to transfer heat at the rate of one watt per square inch by natural convection and radiation from an open tank surface, the temperature rise of that surface over the ambient air must be approximately 90 degrees C. For the same rate of heat transfer in oil by natural convection, the required temperature difference is about 15 degrees C. Compared to these, in heat transfer by condensation of pure fluorocarbon vapor, the required temperature difference vapor-to-surface is only about 3 degrees C, and by boiling of the fluorocarbon liquid on the surface, the required difference is only $\frac{1}{3}$ degree C. Thus, this new material is very satisfactory as an insulating material and much superior as a coolant.

In the application of this material, however, a problem arose. While it is a good dielectric in a vapor state, the



	RI Test	One Minute Dry Withstand	10 Second Wet Withstand	Impulse Full Wave	Impulse Chopped Wave
Standard 34.5 kv ASA Requirements	250 mv at 21.9 kv	95 kv	95 kv	200	230
Cast Resin Bushing	10 mv at 30 kv	95 kv	99+ kv	207	240

material is in a liquid form before the transformer is energized. This meant that either the liquid would have to be preheated to convert it to a vapor state, or it would have to be used in conjunction with another noncondensible gas that is a satisfactory dielectric. Actually, such a noncondensing gas was available. This material is sulfur-hexafluoride (SF_6). Thus, initial dielectric strength is obtained through the SF_6 gas, and when the transformer comes up to temperature, the perfluorocarbon vapor provides increased dielectric strength and cooling. The SF_6, if used alone, does not present as ideal conditions of insulation and cooling. This is principally due to the heavy density of the gas and the difficulty in moving it from the coils to the tank wall for cooling. Thus, the first units use a combination of sulfurhexafluoride and the perfluorocarbon liquid.

The operation of the unit is somewhat similar to a shower bath (see Fig. 3). The liquid in the sump is pumped up to a spray nozzle above the coils and poured down on the coils. The heat of the coil vaporizes the liquid, and the vapor is then carried to the condenser and returned to the sump. Such units are now in commercial operation, and additional larger units are being developed. (See Fig. 4).

Still further transformer improvements now appear possible. For example, it now appears feasible to build a transformer that can be throat-connected to the generator. This would allow elimination of the low-voltage duct and minimize the land area needed for yard structures. Such a transformer could also include a third winding, thus making the need for an auxiliary transformer unnecessary.

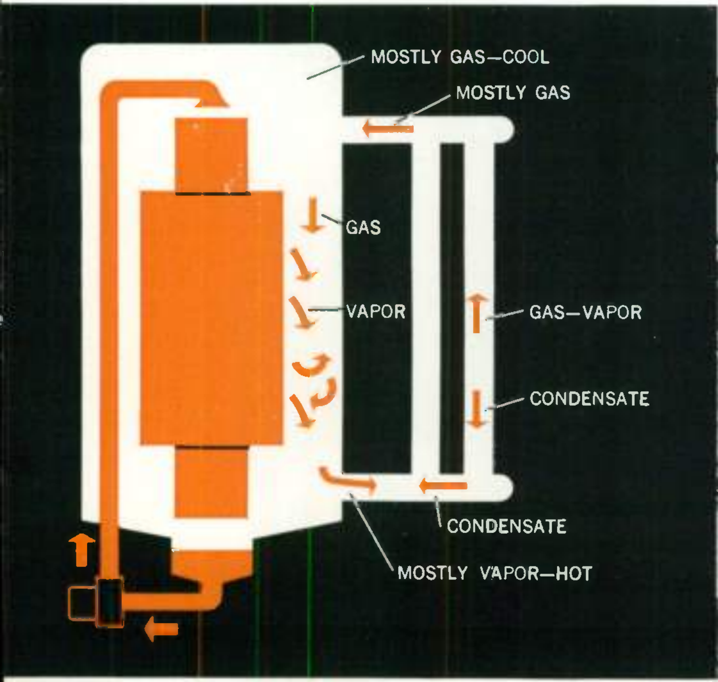
Fig. 2 (Left) Cutaway views of a development model of an epoxy filled bushing for use at 25, 34.5 and 69 kv, and a table of electrical characteristics.

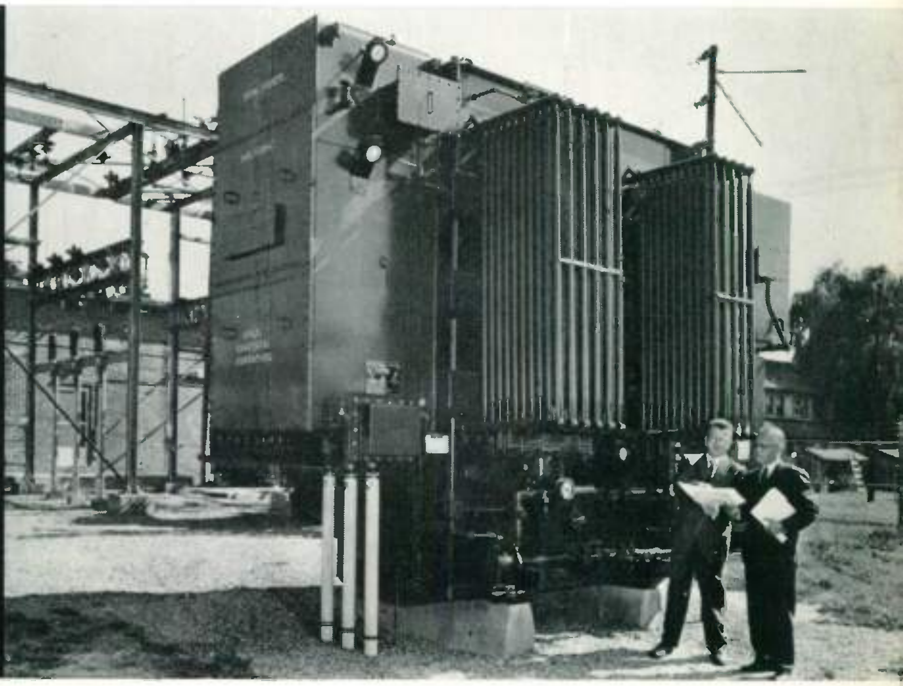
Fig. 3 (Center) In this vapor/gas cooled transformer, liquid flows over the coils, vaporizes, and condenses in the radiator.

Fig. 4 (Right) This is a 7500-kva substation transformer that uses the vapor/gas principle for cooling and insulation.

As mentioned previously, the sizes of large generator and tie-line transformers have been reduced more than 3 to 1 since 1940, from five pounds per kva to approximately one and a half pounds per kva. Developments under study, along with new coil configurations, such as inner-cooled construction, will continue this trend, to about one pound of transformer materials per kva within the next decade. If single transformers for use with the large generators now being considered are to be built and shipped, such a reduction is essential. With present generators being built at 800 mw and consideration of units at 1000 mw, the transformer industry must keep pace by providing larger units to match the generating capacity. Improvement in operating efficiency should also stay in step, which appears possible with the new materials available.

But even these presently indicated increases in rating requirements should not be considered a limit. Thus, in the future, even greater reductions in size and improvements in performance will be required. One theoretical possibility of reducing the size of transformers by 75 percent and virtually eliminating any copper loss lies in low-temperature operation. This has recently become possible through improvement in the means of producing the low temperatures, in the order of 4 to 7 degrees K, necessary for superconductivity. The availability of equipment to achieve these lower temperatures now makes the dream of a superconductor device possible. In addition, studies are being conducted of the performance of insulation at these low temperatures, and a study is also being made to use new conductor materials, such as niobium, which will act as superconductors at these low temperatures. With a superconductor, there will be no loss in the windings. Much remains to be done in the area of cryogenics, but if a major break-through is to be achieved in the science of transformer design, this may well prove to be its foundation.





OIL CIRCUIT BREAKERS OR POWER-CLASS RECLOSERS?

Distribution systems can accommodate both. A careful appraisal of the characteristics of each will permit the substation designer to select the device best adapted to a particular application.

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Automatic circuit reclosers were introduced to the electric utility industry three decades ago to provide a low-cost single-phase sectionalizing device for urban and rural feeder circuits. The excellent service provided by these inexpensive units led to the development of a three-phase automatic circuit recloser, which could be applied to distribution substations. The device was an assemblage of three single-phase reclosers mechanically ganged together on a single headcasting. The continuous-current rating, interrupting capability, and insulation level remained the same as the single-phase counterparts.

With subsequent continuing growth of distribution systems, the economic advantages of a power-class three-phase recloser with higher continuous-current ratings and greater interrupting ability became evident. Such a device was introduced five years ago. It is rated as a NEMA Class II automatic circuit recloser with self-contained closing and tripping mechanism, overcurrent-sensing and timing elements, and an integral reclosing sequencing device. Later a higher capacity unit with 12 000 amperes maximum interrupting ability was developed and rated as a NEMA Class III device.

The obvious question soon arose—where does the application of automatic circuit reclosers stop and the use of small, distribution-class oil circuit breakers begin? Other problems also need clarification, such as: what criteria can be used for comparison when the short-circuit requirements of the system are met by both devices, and what are the merits of the two types of reclosing schemes? To further complicate the picture, the power-class automatic recloser can be equipped with overcurrent phase and ground relays for fault sensing in place of the series-trip device. This shunt-tripped recloser retains the integral mechanical reclosing device, thereby differentiating it from the circuit breaker, which always employs a separate reclosing relay. The shunt-tripped recloser falls between the series-tripped recloser and the commonly used relay-tripped oil circuit breaker in both characteristics and cost.

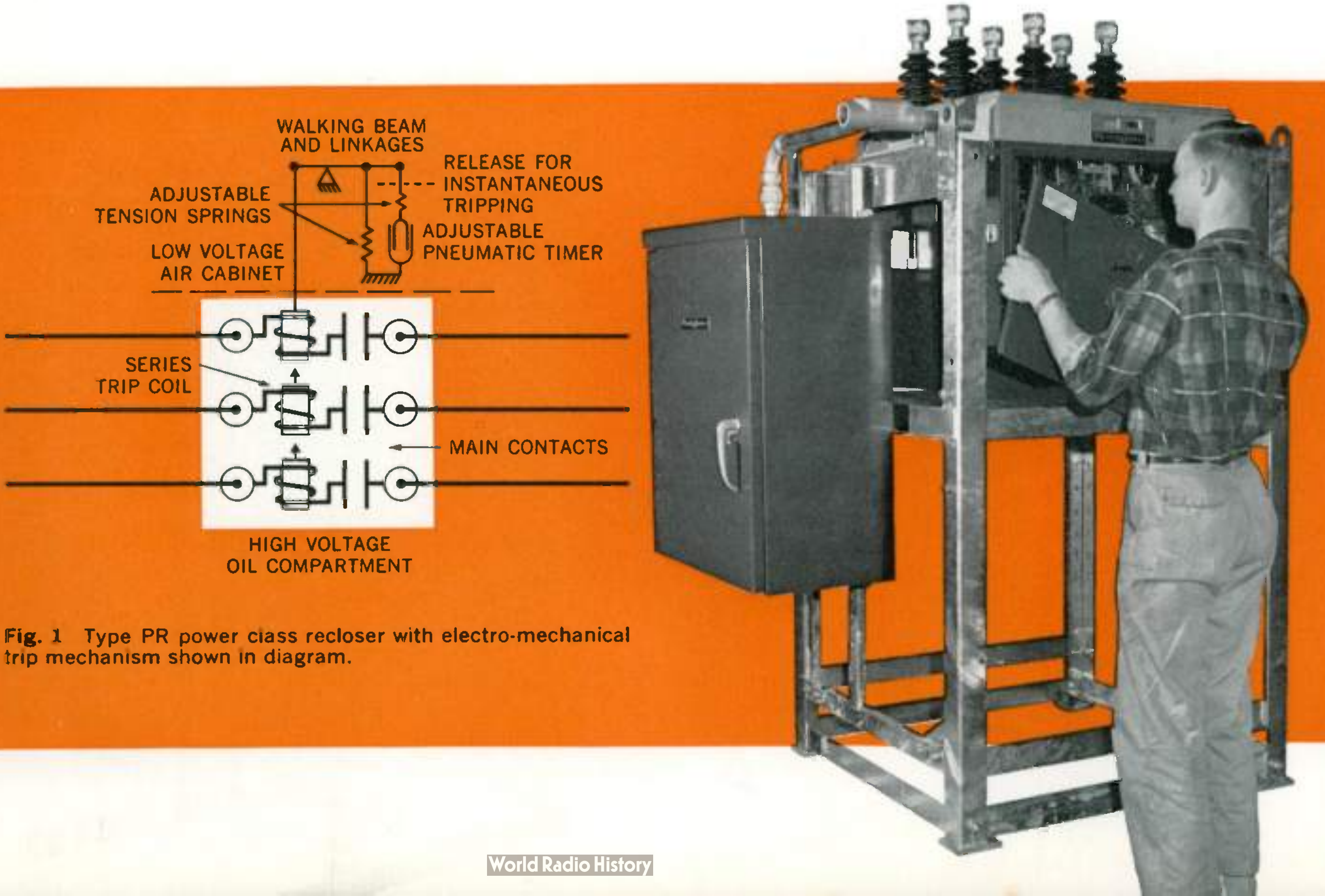

Fig. 1 Type PR power class recloser with electro-mechanical trip mechanism shown in diagram.

general description of each device

The automatic circuit recloser is illustrated in Fig. 1. It can be mounted on an adjustable free-standing frame for substation use, or equipped with a bracket for crossarm mounting in smaller distribution substations and on feeder circuits. Many units are equipped with thermal demand ammeters and an auxiliary control box that permits operating control elements to be accessibly located.

The major items of the integral control compartment of the recloser are: (1) series-trip timing elements; (2) reclosing timing element, which is the same type as used on the series trip; (3) reclosing motor, which requires a single-phase, 240-volt ac power source; (4) shunt-trip coil; (5) four-pole auxiliary switch; (6) integrator and integrator-reset mechanism; and (7) ground-trip relay.

A three-phase, single-tank distribution-class oil circuit breaker is illustrated in Fig. 2. This frame-mounted 14.4 kv unit is available in ratings of 100, 250 and 500 mva. The operating mechanism and control-relay panel are enclosed in the weatherproof cabinet. When the breaker is equipped for automatic reclosing, an additional panel containing the necessary relays and operating switches is mounted in this cabinet. Phase tripping can be accomplished either directly from current transformers, three of which are standard equipment, or indirectly by overcurrent relays. A ground overcurrent relay can also be provided. Reclosing is controlled by a standard reclosing relay, which is actuated by a synchronous motor.

design standards

The automatic circuit recloser and the distribution-class oil circuit breaker, although applied for the same purpose and at the same location on electric power systems, are designed, manufactured, and tested under separate standards.[1] These standards are written by two different groups of engineers, whose fundamental philosophy is influenced by their primary interest. Since distribution-class oil circuit breakers are included in power circuit breaker standards, their requirements follow the economic reasoning and design margins deemed necessary for the most rigorous of circuit breaker applications—such as transmission circuits that impose severe recovery-voltage conditions. This accounts for the many differences in ratings, definitions, and test standards, when compared to the recloser standards, which are based strictly on distribution system economics and operating practices. A complete comparison of characteristics and ratings is contained in Table I.

continuous current rating

The series-tripped or shunt-tripped recloser is available in frame sizes with maximum continuous-current capability of 400 and 560 amperes. These are compared to distribution-class oil circuit breakers with continuous current ratings of 600 and 1200 amperes. On 4160-volt circuits the continuous-current rating tends to limit the maximum substation size on which these units can be applied—except for the 1200-ampere circuit breaker rating. On 12 470-volt circuits and above, the maximum substation size, in all cases, is limited by the interrupting rating.

Since the recloser has a series coil that corresponds in rating to the load current, increases in load current require

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[1] Recloser requirements are contained in a publication of the American Standards Association entitled, "American Standard Requirements for Automatic Circuit Reclosers and Automatic Line Sectionalizers for Alternating-Current Systems" (C37.22–1959). Distribution-class oil circuit breakers are included in a series of standards relating to power circuit breakers (37.4, 37.6, 37.7, 37.8, 37.9, and 37.11).

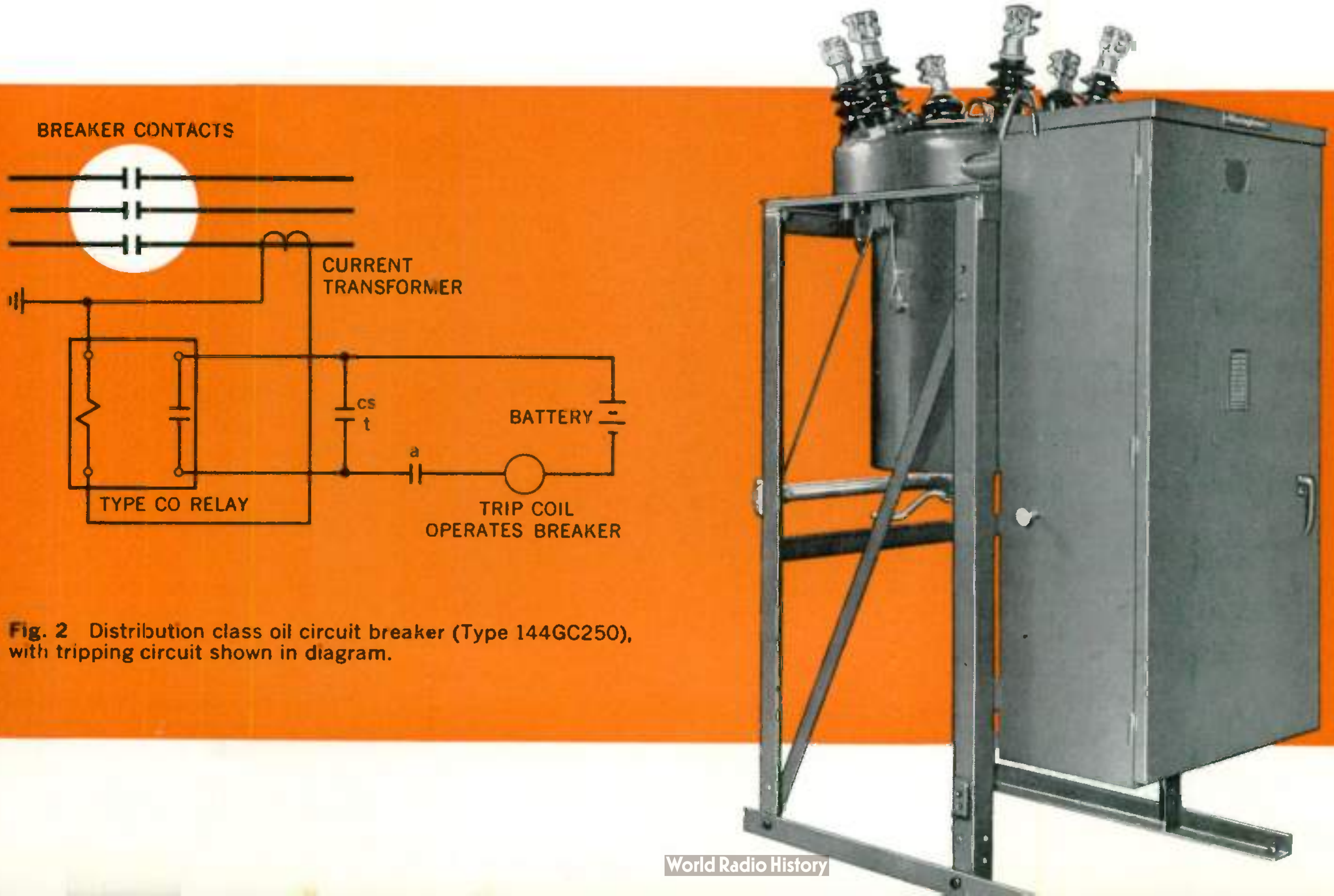

Fig. 2 Distribution class oil circuit breaker (Type 144GC250), with tripping circuit shown in diagram.

Table I COMPARISON OF RATINGS—OIL CIRCUIT BREAKERS AND RECLOSERS

	Series Trip Recloser		Shunt Trip Recloser		Reclosing Breaker		
Type Designation	400PR	560PR	400PRR	560PRR	144GC100	144GC250	144GC500
Continuous Current [Maximum]—Amperes	400	560	400	560	600	600 And 1200	
Rated Voltage—Kv	2.3—14.4		2.3—14.4		14.4		
Interrupting Rating—MVA	100	200	100	200	100	250	500
Maximum Interrupting Amperes at Minimum Voltage	6000	12 000	6000	12 000	15 000	25 000	25 000
Maximum Interrupting Amperes at Maximum Voltage	4000	8000	4000	8000	4000	10 000	20 000
Insulation Level [BIL]—Kv	110		110		110		
Low Frequency Withstand—Kv	50		50		50		
Short Time Rating—Momentary	None		12 000	18 000	24 000	40 000	40 000
Short Time Rating—4 Second	None		8000	12 000	15 000	25 000	25 000
Interrupting Time—Cycles	3		3½		5		
Reclosing Time [Minimum]—Cycles	30		30		30		
Maximum Allowable Temperature Rise—Degrees C	45		45		30		
Duty Cycle [Unit Operations]	72-0	52-0	72-0	52-0	2-CO	2-CO	2-CO
Weight With Oil—Pounds	1120	1150	1100	1130	2440	2440/2500	

Table II DIFFERENCES IN INTERRUPTING RATINGS FOR CIRCUIT BREAKERS AND RECLOSERS

Device	Rating	Calculated Fault Current*	Application Requirement
Circuit Breaker	R_{CB}—RMS Amperes (Symmetrical or Asymmetrical)	I_F	$R_{CB}>I_F\times 1.1$
Recloser	R_R—RMS Amperes (Symmetrical)	I_F	$R_R>I_F$

*I_F = RMS Symmetrical Fault Current $=\dfrac{KVA\ \text{(base)}}{\sqrt{3}\ E_{L-L}\times Z\ \text{(percent)}}$

Table III COORDINATION AND ADJUSTMENT CHARACTERISTICS

Function	Series Trip Recloser	Shunt Trip Recloser	Reclosing Breaker
Time-Current Characteristics	Springs-Pneumatic Timer	Over-Current Relays	Over-Current Relays
Minimum Tripping Time	2½ Cycles	3 Cycles	3½ Cycles
Tripping Sequence—Instantaneous	0, 1, 2, 3, or 4	0, 1, 2, 3, or 4	0, 1, or 4
Time Delay	4, 3, 2, 1, or 0	4, 3, 2, 1, or 0	4, 3, or 0
Reclosing	Mechanical Integrator	Mechanical Integrator	Electrical—Synchronous Motor
Reclosing Time	30 Cycles—120 Seconds	30 Cycles—120 Seconds	30 Cycles—100 Seconds
Reclosing Sequence—Typical	O-I-CO-2-CO-2-CO	O-I-CO-20-CO-20-CO	O-I-CO-15-CO-45-CO
Reclosing Time-Adjustment	Same for All TD Reclosures Field Adjustable	Same for All TD Reclosures Field Adjustable	Variable for Each Reclosure Field Adjustable
Number Operations to Lockout	1 to 4	1 to 4	1 to 6
Reset Time—After Lockout	10 Seconds to 2 Minutes, fixed	10 Seconds to 2 Minutes, fixed	1½ to 9 Seconds
Reset Time—O-I-C	10 Seconds to 2 Minutes, fixed	10 Seconds to 2 Minutes, fixed	1 to 6 Minutes
Reset After Lockout	No	No	No
Minimum Volts to Trip	Zero	15 Volts	Needs Capacitor Trip

series coil replacement to take advantage of the full thermal capability of the recloser. When a circuit breaker load is increased, corresponding changes must be made in relay settings and current-transformer taps or ratio to avoid operating problems.

temperature rise

Recloser design standards allow a temperature rise of 45 degrees C above ambient as compared to the present conservative circuit breaker limit of 30 degrees C. This difference is obviously unrealistic because essentially the same materials are used in both devices. It has been recognized that circuit breaker standards are over-conservative in this area and corrective action is being taken.

Temperature rises as a function of load are shown for the PR560 recloser in the curves of Fig. 3. The shape is characteristic of many such devices, the temperature rise increasing approximately as the 1.6 power of load. The design shown will permit a 12 percent overload before exceeding the permissible 45 degree C rise.

interrupting rating

Although distribution apparatus protective devices are historically rated in amperes, interrupting ratings in mva have been developed (Table I) for the recloser for comparison with oil circuit breaker ratings. However, the meaning of the term differs when applied to each of these devices. Interrupting ratings in terms of maximum interrupting amperes at minimum voltage and maximum interrupting amperes at maximum voltage are also shown. In this instance the actual amperes are not the same, so that the ratings cannot be compared directly.

A circuit breaker is rated in rms amperes at a prescribed voltage, the product of which multiplied by $\sqrt{3}$ is the power rating, usually expressed in kva or mva. The power rating is constant down to a specified minimum voltage, at which point current has increased to the *maximum ampere rating*, and becomes the limiting factor. At a given voltage, the circuit breaker can interrupt any current whose rms value does not exceed the rating at the instant when contacts part, regardless of the degree of asymmetry. A table of multiplying factors based on breaker operating speed and system characteristics is provided in the circuit breaker standards for determining current amplitude when contacts separate from the calculated rms symmetrical fault current. For 5-cycle breakers, as considered here, the factor is 1.1.

The automatic circuit recloser is rated in rms symmetrical amperes based on a standard X/R ratio, which varies with applied voltage and test current. This rating can be compared directly to the calculated value of short-circuit current unless the system X/R ratio is greatly different from the test ratio. Because of reduced design margins and the integral reclosing mechanism, interrupting capabilities at voltages other than normal cannot be obtained by interpolation. The automatic circuit recloser is not considered applicable under the constant-kva rule. Therefore, as voltage decreases, mva rating also decreases.

The differences in interrupting ratings of these otherwise compatible devices are shown in Table II. The table lists the steps necessary to modify calculated system fault current for comparison with the interrupting capability of each device.

Another problem that confronts electric utility engineers is the special situation where the economy of using a lower rated device is evident, and maximum usage from a given piece of equipment is desired. On larger power circuit breaker applications, at the transmission voltage level, the necessity for including considerable margin for added future generation precludes an initial close matching of the interrupting capacity of the system to the interrupting capability of the device. This condition does not normally exist in distribution system planning because large increases in system generation can occur without increasing interrupting requirements at the distribution level.

The curves in Fig. 4 indicate graphically the relationship between rated voltage and interrupting capability in amperes for reclosers and oil circuit breakers. The important points to note from these curves are that the interrupting capability of the recloser varies in large discrete steps with voltage, while the interrupting capability of the comparable breaker varies along a constant-kva curve down to the minimum rated voltage. Curves A, A' and A'' are the interrupting ratings of an oil circuit breaker applied on a CO- (close-open) 15 sec-CO duty cycle. If the same curves are replotted with the moderate derating factors taken from the recently revised standards for oil circuit breakers operating on a four opening-reclosing cycle, they fall back on the curves marked B, B' and B''. The circuit breaker range of interrupting capabilities is then somewhat reduced. The comparable recloser is not derated for any number of reclosing operations.

short time rating

The recloser, with a series trip coil, has no need of a short time rating since it cannot remain in the circuit for any externally specified period. Fault current determines actual tripping time, and provides energy for tripping. Therefore, the short-time and momentary ratings need not be considered in applying reclosers, since mechanical and thermal limits are inherently protected in providing proper rating for interrupting capability.

The series trip coil is sized to load current. However, it does have a mechanical limit which determines the interrupting rating of the recloser. This variation in interrupting rating due to the mechanical limit of the coil is shown in Fig. 5. The oil circuit breaker interrupting rating is not affected by load current.

interrupting time

The automatic circuit recloser standards do not specify an actual interrupting time since it is a function of the internal series-trip coil. For the oil circuit breaker, interrupting time is a separable characteristic, since fault sensing and timing are accomplished with an external relay. However, total clearing time of distribution-class oil circuit breakers and automatic circuit reclosers can be compared if the time-current characteristic of the protective relay is added to the time-current characteristic of the breaker (Fig. 6). A relay time of ¼ cycle at high currents and ½ cycle at lower currents is used for instantaneous-tripping distribution type oil circuit breakers. Although the series-trip recloser has a faster total clearing time at high current ratings, it falls behind the general and high-speed distribution class circuit breakers at currents below 25 percent of the maximum current rating. However, since speed of operation on instantaneous trip settings is usually only important at very high currents, where conductor burn down or T-link fuse miscoordination can occur, the range between 80 and 100 percent of rating is the primary area of interest. Here, the modern distribution oil circuit breaker is about one-half to one cycle slower than the series-tripped recloser.

duty cycle and maintenance

An interesting comparison of standard requirements is shown in Table I under the heading of duty cycle or unit operations required by their respective standards to meet interrupting ratings. While the automatic circuit recloser must go through a total of 72 or 52 operations to meet the ratings, the comparable oil circuit breakers are only re-

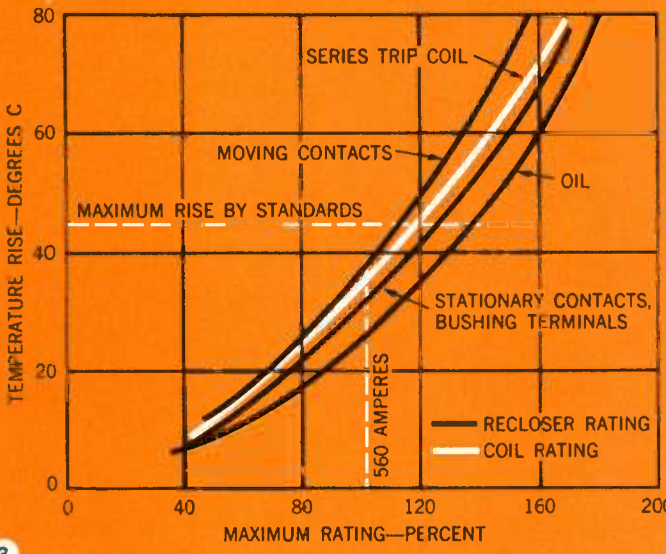

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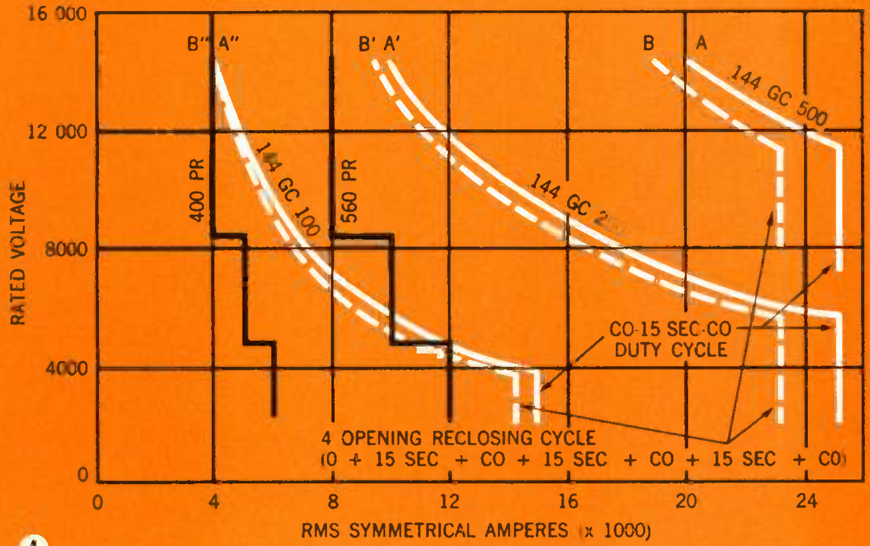
Fig. 3 Temperature rise curves for PR 560 recloser.
Fig. 4 Interrupting ratings of oil circuit breakers and power class reclosers.
Fig. 5 Variation of interrupting ratings with continuous-current rating.
Fig. 6 Total clearing time of distribution class oil circuit breakers and automatic circuit reclosers.



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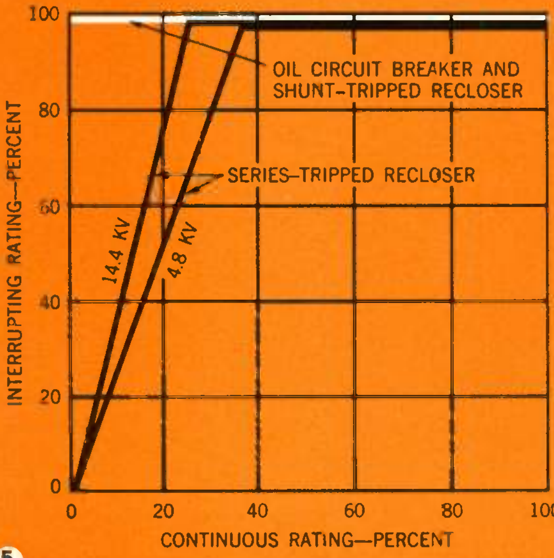

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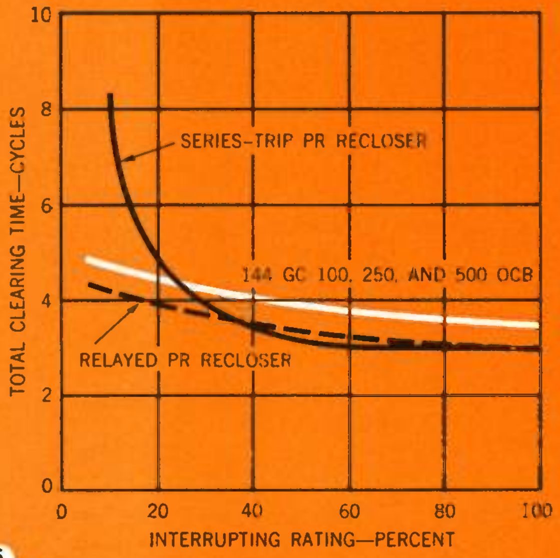

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quired to perform two CO-15 sec-CO operations to meet the standard. This paradox in the standards again indicates that the distribution-class oil circuit breaker is still classified in the family of power circuit breakers.

Although the statement is sometimes made that substation reclosers require more maintenance than any other single piece of distribution apparatus, this is obviously not because of lack of design test requirements, as indicated above. Actual maintenance requirements can be evaluated by a comparison of structural features. The breaker is more ruggedly constructed, but this can lead to slower operating speeds and, occasionally, longer arcing times. Since these are compensating factors, they probably do not result in a significant difference in the rate of deterioration of contact parts.

coordination characteristics and adjustments

The automatic circuit recloser with its integral series-trip coil and reclosing mechanism cannot hope to attain the flexibility, ease of adjustment and accuracy of the panel-mounted relays used with the oil circuit breaker. This is to be expected, not only because of a wide difference in cost, but also because the fault-sensing coils, timing devices, and reclosing mechanism of the recloser must be designed to withstand the shock and contamination problems inherently associated with integrally mounting these components on the same head-casting that supports the interrupters. Nevertheless, the present power class reclosers have time-current characteristics that are compatible with relays, power fuses, and fuse cutouts in the great majority of applications. These characteristics are available either from pre-established standard curves or adjustable curves, which can be matched to any other device characteristic. They are field adjustable, accurate, and very stable after setting. Therefore, in the typical substation serving residential and light industrial customers, the time-current characteristics of either recloser or relays can be positively coordinated to give the required system protection. The fact that the instantaneous trip pickup can be different from the time-delay pickup on the relayed breaker is a distinct advantage; however, this feature is often offset by the inherently faster tripping time of the recloser.

Sensitive ground protection can be obtained on both recloser and circuit breaker. Pickup of ground trip is independent of the phase-fault tripping device in both units.

Reclosing and sequencing in the automatic circuit recloser is accomplished by a mechanical integrator and separate reclosing timer as distinguished from the circuit breaker, which uses a synchronous-motor-driven reclosing relay. While both schemes accomplish the same final result, some fundamental differences do exist, and are summarized in Table III.

The tripping sequence for the reclosers is a screwdriver adjustment and is completely reversible; that is, any combination of instantaneous or time-delay operations from zero to four can be obtained. The reclosing relay is restricted to a combination of zero-four or one-three, the most common arrangement being one instantaneous and three time-delay operations. If four instantaneous reclosings were used on an oil circuit breaker the derating factor would, by standards, be very severe.

The reclosing time on the series-tripped recloser is fixed for each opening, but can be changed over the range shown in Table III. The range of reclosing times available is comparable for both the recloser and oil circuit breaker; however, the oil circuit breaker reclosing relay can have different times for each opening if desired. The reclosing sequence reset time is consistent on reclosers; however, it is variable on the reclosing breaker depending upon the number of operations selected before lockout or on number of operations before successful fault clearing. This is because the synchronous motor continues to turn during the complete reclosing cycle and must rotate around to the start position regardless of the number of operations during any one fault. Neither of the reclosing schemes resets after lockout until the unit is reclosed and stays closed, a desirable feature.

An important point often overlooked is the necessity for external energy sources for tripping the reclosing breaker, as against the series-trip recloser which uses the fault energy itself to obtain tripping energy. Elimination of a battery and its necessary charging equipment or a capacitor trip device is an important by-product of automatic circuit reclosers.

Because the fault-sensing element on the recloser has an instantaneous reset time, reclosings following time delay tripping can be either instantaneous or as short as desired. This is not true with the reclosing breaker, since the reclosing contact must be held open long enough to allow the overcurrent relay to reset so that proper coordination will be maintained on subsequent tripping. Therefore, the minimum reclosing time which can be used and still obtain full time delay operation, is a function of the reset time of the overcurrent relay.

summary

Cost has been deliberately avoided in this discussion. Obviously a difference exists in both initial cost and installed cost, usually substantially in favor of the recloser. How each utility evaluates this cost difference is a function of individual accounting practices. However, the difference in total cost should be considered in actual dollars or deferred investment costs rather than dollars per kva of substation capacity, since the cost of transformers, structures, switches, and primary equipment will probably swamp the protective-device cost.

The fundamental problem can therefore be reduced to the overlapping area of application, the same problem that has long plagued utility engineers in considering station versus line-type lightning arresters, or step versus induction-feeder voltage regulators.

If voltage rating, continuous current rating, and interrupting ability of both devices meet both present and future requirements, the substation designer must investigate the known characteristics of each device—physical, operating, and electrical—for the important differences. Each device has distinct advantages: the recloser is smaller, lighter, and faster; the oil circuit breaker has greater design margin, relaying flexibility, and simpler field adjustment. Analysis of the usefulness of these features to the particular application plus scrutiny of the less obvious differences should result in a logical selection.

EXPERIMENTAL PSYCHOLOGY... A New Variable in Design

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Designers of control and display equipment for modern military systems usually have limited contact with the ultimate operator of the equipment. However, if the equipment is to be used most effectively, the human operator's needs and capabilities must be considered. The application of psychological research techniques to improve this "human accommodation" is a relatively recent art.

The problem of adapting equipment to people first arose in manning military aircraft and selecting pilots at the beginning of World War II. Two possible solutions were obvious: (1) lower the selection standards; or (2) simplify the design of the aircraft and the instruments and control in the cockpit. Obviously, the latter alternative was the more logical possibility.

In the early work, the need for an analytical and experimental investigation program became obvious. The program should consider the human from two viewpoints: as a mechanism receiving inputs from the machine, and as a device putting inputs into the machine.

Much of the experimental work done in this field can be classified into four major categories:

1. The relationship between the characteristics of the eye and radar display design.
2. The relationship between the human's perceptive capability and the reconnaissance system design.
3. The human as a processor of information.
4. The human's characteristics as an integral part of a tracking system.

the human sensor—the eye

Since the human obtains most of his information through his eyes, knowledge of their functioning is necessary in the design of equipment used to present information to an operator. This knowledge was first used to "dark adapt" night fighter pilots, who wore red goggles during the period before taking off. This application was based on the differential sensitivity of parts of the eye to light wavelengths (Fig. 1). The *scotopic* curve is the response of the part of the eye that has relatively poor resolution, yet has great sensitivity and can detect very small amounts of energy. The *photopic* curve shows the response of the part that has high resolution but whose sensitivity is not good at low levels. The shaded section shows the portion of the visible spectrum that can be used to stimulate that area of the retina that has higher resolution, while at the same time minimizing the response of the area that has high sensitivity. This differential spectral sensitivity was the reason for using the red goggles.

These principles were also applied to the first radar facilities. However, a detailed analysis of the operator's task indicated that his problem was not detection of the lowest level of display output, but rather, detection of a *difference in brightness* between target and background.

Since this early work, many basic investigations have been completed. In a series of studies, one investigator[1] varied: (1) length of time a target was exposed to the subjects; (2) the visual size of the target in terms of visual angle, where

$$\begin{array}{l}\text{Visual Angle}\\ \text{(In minutes of arc)}\end{array} = \frac{3438 \times \text{Linear Dimension of Target}}{\text{Distance from Target to Eye}};$$

(3) brightness of background against which the target was observed; and (4) brightness of target. The subject's task was to determine target presence. The graphs in Fig. 2 are taken from the basic data of this study. These curves indicate that as the size of the target at the eye increases, the required difference in brightness between the spot and the background decreases.

A further relationship is that decreases in exposure time require increases in brightness difference. These relationships hold regardless of the background brightness. A restriction on these values is that they have been determined for the 50 percent threshold (i.e., the target would be seen 50 percent of the time). For a probability of detection of 90 or 95 percent the values required would be higher.

This information can be used in specifying requirements for cathode ray tube (CRT) displays. After the analytical requirements of the beam width and other characteristics of the radar are considered, the analytical results must be combined with psychological findings. The exposure time to the operator is roughly equivalent to the dwell time of a sweeping radar beam on the target. For a given background brightness, a CRT brightness can be determined to insure the desired probability of target detection.

Since CRT characteristics must be matched with human requirements, the physical arrangement by which the operator receives the light energy from the tube must be examined. For the case of CRT phosphors, target-spot brightness consists of two parts—sweep brightness and brightness due to energy from the target. These two add linearly to produce the target spot brightness to be compared to background brightness.

For example, assume that dwell time is 0.1 second, the target has an extent of 3 mm and is viewed at 645 mm (visual angle = 16 minutes), and total background brightness is 100 foot lamberts; the required difference is shown (Fig. 2) to be 1.78 foot lamberts (antilog of 0.25). If the sweep trace provides 1.00 foot lambert, the energy from the target must supply enough voltage to generate 0.78 foot lamberts at the CRT face.

Target spot brightness, intensity, and size are related by the simple equation:

$$B = I/A$$

where B is brightness, I is intensity, and A is spot area. Although the human operator responds to brightness, variations in brightness must be accomplished electronically by adjusting either spot size or intensity. CRT beam

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[1] Blackwell, H. R., "Brightness Discrimination Data for the Specification of Quantity of Illumination," *Illuminating Engineering*, 1952, Vol. 47, pp. 602–9.

intensity is simplest to vary since spot area is kept relatively constant by beam size and phosphor particle size.

A second application of psychological data to radar scope design is the adjustment of the CRT to enable the operator to detect a target on the scope with a minimum return of energy from the target. These adjustments are required to meet the demands of different environments of the target and different ambient light levels for the operator. Several experiments indicate the existence of an optimum equipment parameter setting for target detection. One such study was performed at the Naval Research Laboratory[2] (Fig. 3).

In this study, the subject was required to locate a target on an oscilloscope. Trace brightness is determined by a combination of noise level at the CRT grid, and pedestal level, a voltage added to signal at control grid permitting luminous output that is due to signal drive. An examination of Fig. 3b shows that for low noise at the grid and high pedestal voltage, trace brightness is low so that little additional brightness from the energy of the target is required for detection. Under these conditions, a weak signal will provide the necessary energy. This prediction is substantiated by the basic test results shown in Fig. 3a. If there is low noise but insufficient trace brightness, larger signals are required to achieve threshold values.

human imaging tube—perception capability

The original purpose of radar was the detection of single objects or groups of objects; the use of radar as a reconnaissance device required the development of hardware to provide the necessary resolution and range. With the development of surveillance radar came the problems of pattern recognition and of differentiating objects within the pattern. Within the past ten years, psychologists have developed information in a form for engineering application. The concept is the "probability of occurrence" model; its use in psychological experiments is illustrated by the following example:

Assume three lines of black and/or white dots side by side, with no space between them (Fig. 4). The occurrence of a white dot or a black dot has a *stated probability* in each of the three lines. For a display of a given size the number of dots depends upon their size. The question is: What probabilities of the black and white dots will give the highest probability of detection and recognition of a pattern? With appropriate equipment, experimental displays can be generated to determine the factors that influence visual pattern recognition. With this information and the appropriate mathematical models, the probabilities can be translated into equipment parameters.

Although the data is still incomplete, enough is available to suggest future lines of research. For example, it suggests that the tasks the operator is asked to perform can influence the results; this was demonstrated by tests[3] in which the subjects were given a sample object, and then required to find that object in a display containing several others. For a given target size, the matrix cell size can be varied

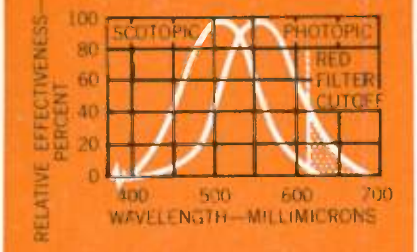

Fig. 1 Relative efficiency of the human eye as a function of wavelength.

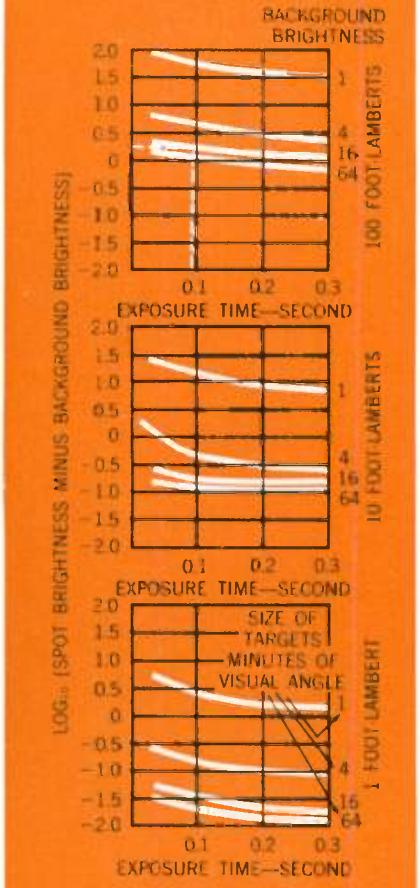

Fig. 2 This series of curves shows the relationship between background brightness, exposure time, and target size and brightness for a 50 percent probability of target detection.

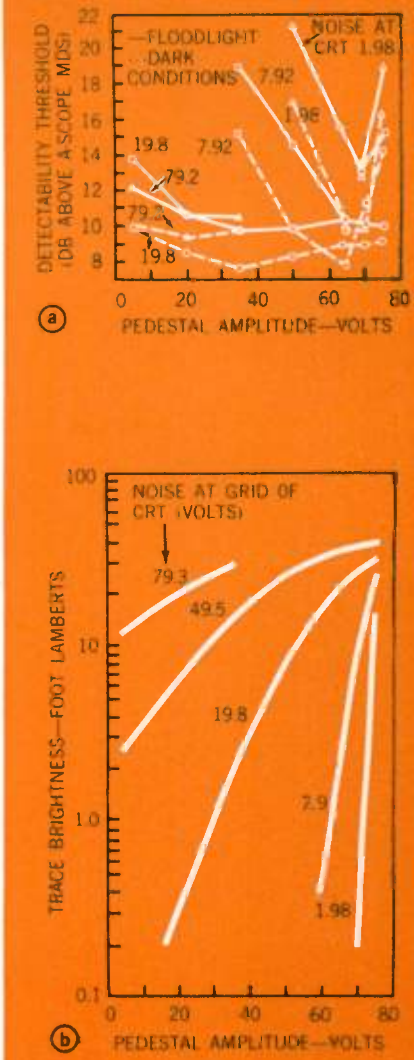

Fig. 3 (a) These test results indicate that an optimum equipment parameter setting can be determined for target detection. (b) CRT trace brightness is a function of grid noise and pedestal voltage.

Fig. 4 The basic concept of the "probability of occurrence" model is shown above. In this example, the probability of a black dot on an odd numbered line is 0.30; the probability of a black dot on an even numbered line is 0.70. A typical object of the model is to determine what difference in probability between odd and even lines is required for the subject to recognize a horizontal line pattern.

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[2] Gardner, R. E. and Carl, J. M., "The Effects of Ambient Illumination, CRT Bias, and Noise Upon Target Detectability with a B-Display." *Naval Research Laboratory Report 5264*, January 28, 1959.

[3] Steedman, W. C. and Baker, C. A., "Target Size and Visual Recognition," WADC TR 60–93, February 1960.

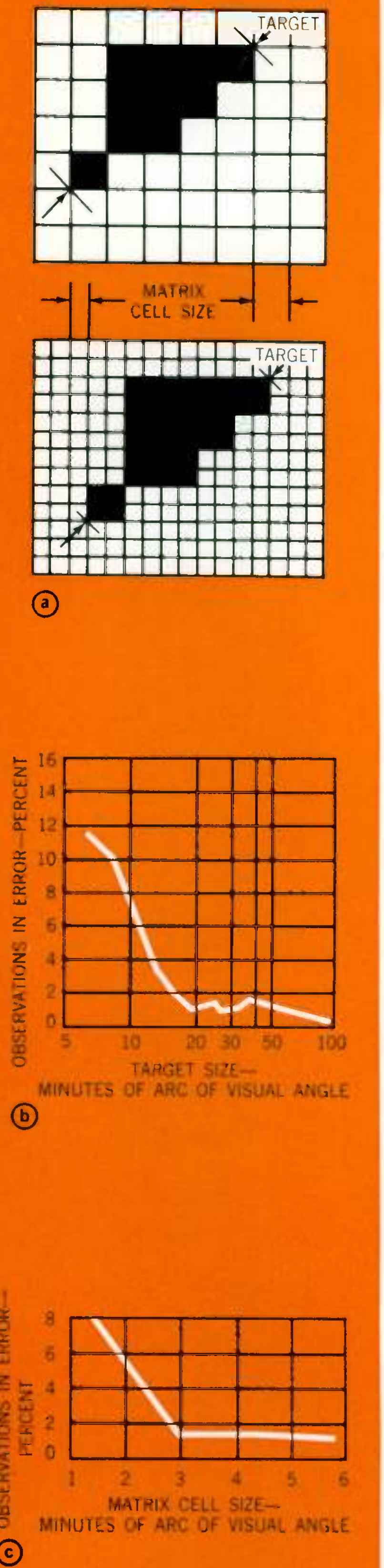

Fig. 5 (a) Both target size and matrix cell size affect detectability. (b) Influence of target size on detectability. (c) Influence of cell size on detectability.

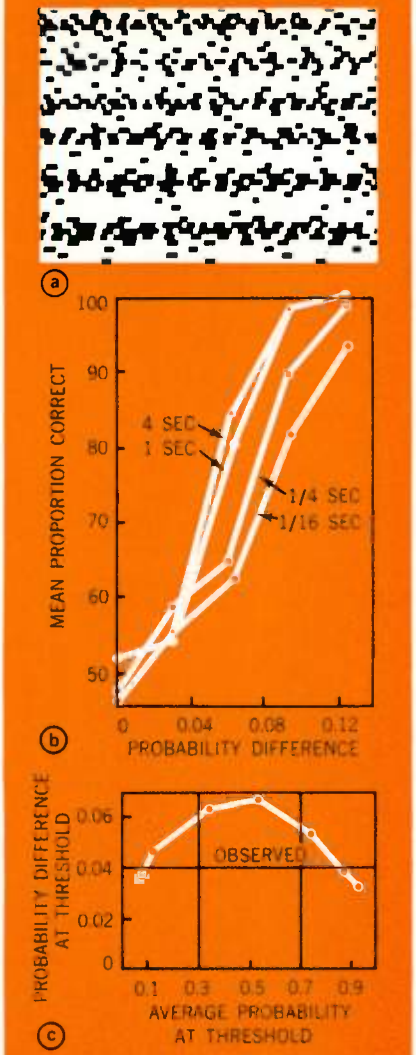

Fig. 6 (a) Test pattern in which subject reports the orientation of black and white bars after viewing pattern for given time period; pattern variable is the probability of occurrence between black spots in adjacent lines. (b) Performance as a function of exposure time and difference in occurrence probability. (c) Probability difference at threshold as a function of average probability at threshold.

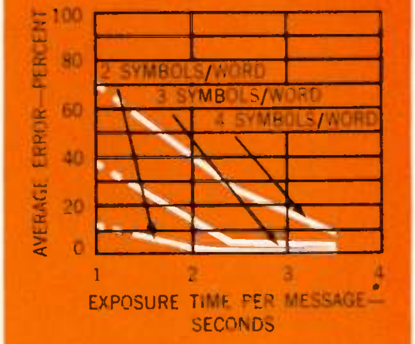

Fig. 7 Test results in which performance is shown to improve with longer exposure rates and fewer symbols per word.

(Fig. 5a). Once the target's extent was between 15 and 20 minutes of arc the subject's performance was practically perfect (Fig. 5b). The effect of matrix cell size is shown in Fig. 5c. Such data makes it possible to determine the requirements for surveillance systems in which the operator's task is comparable.

In a second type of test the operator is required to find a single pattern in the total display, with no visual reference. In one study[4] (Fig. 6a), the subjects were required to report when they saw the orientation of black and white bars on the display after viewing the display a fixed period of time. The basic results of this study are shown in Fig. 6b. The abscissa in this figure is the difference in probability between the occurrence of a black spot in two adjacent bars of equal width. These results suggest that after an exposure of one second little improvement in performance is achieved. The result of a second experiment in the series is shown in Fig. 6c. In this figure, the abscissa is a measure of the average number of dots at the threshold of detection. While the ordinate is the probability difference at threshold, the results suggest that there is an optimum number of dots, which must be distributed to accentuate the black and white bars.

human information processing

In the preceding sections, man has been examined either as a sensing device or an imaging tube with a detector function. Man is also a data processor. This human function has only recently become a problem for the psychologist. System engineers developing semiautomatic and automatic systems need quantitative information on the man's data-handling capability to solve such problems as air traffic control and air defense control. In one study,[5] the object was to determine the performance of the subject as a function of the number of messages he received per minute and the number of symbols that occurred per word. The "words" were a series of geometric figures, numbers, and letters presented visually to the subjects. The subjects were required to indicate the number of pairs of identical symbols in the message. The results are summarized in Fig. 7. The figure indicates that for a high message rate, word size must be kept small to minimize errors. This study did not require any interpretation or decision on the part of the subject; however, the results suggest that messages longer than two symbols per word at high rates can easily tax the short time storage capability of the operator, if he is required to make decisions on the basis of the messages received.

humans as system components

Early in the study of man-machine systems it became evident that the human operator's characteristics were an important variable in the determination of tracking systems performance. Much early work was related to radar-computer systems for gun-aiming equipment aboard ships; engineers attempted to analyze the human operator as if he were a mechanical or electrical component of a servo

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[4] Green, B. F., Jr., Wolf, A. K. and White, B. U., "The Detection of Statistically Defined Pattern in a Matrix of Dots," *American Journal of Psychology*, 1959, Vol. 72, pp. 503–20.

[5] Jeantheau, G., "The Differential Effects of Speed and Load Stress on Task Performance," *WADC Tech. Report* 59–7, July 1959.

system. Various investigators have been working on the problem of getting a "transfer function" for the human operator.

A second and more empirical approach has been taken by some psychologists. Much of this work concerns systems that combine a radar system, a computer, and an airplane into an optimally functioning system. These kinds of experiments have been conducted by Westinghouse engineers and psychologists as a part of an effort to develop optimum manually operated systems.

Examination of the tracking system in Fig. 8 indicates that, given restraints in the dynamics of the vehicle and the environment, the only places that changes can be made easily are in the displays. Taking this approach,[6] an examination was made of the influences of system noise magnitude, frequency of the forcing function, and scale factor (sensitivity) used to scale the error into the operator's display. Some results of this study are summarized in Fig. 8a. As indicated, selection of the right scale factor will definitely improve operator performance. The curves suggest that the operator contributes "noise" that maintains the error at a nominal value.

Having found the existence of an optimum scale factor, the next problem was to determine whether this factor is influenced by system dynamics. This possibility was suggested by other studies, which indicated that as exponential delays with increasingly large time constants were inserted between the control and the display of error, the scale factor had to be increased so that, in fact, there was no optimum. Rather than conduct the study in a framework of exponential delays, which have no practical meaning in the design of an aircraft control system, experimenters chose to work directly with aircraft control system characteristics. The *roll time constant* of the control system, which determines the speed of response of the vehicle in the roll dimension, was chosen as the variable. Other variables in the study were the system forcing function frequency and the scale factor (sensitivity). The results (Fig. 8b) indicate that with the optimum scale factor, the effect of variation in roll time constant is minimized and for practical purposes is negligible.

At the moment, neither these studies nor those attempting to develop an equation to describe human performance have provided a satisfactory model that permits prediction of operator performance over a broad range of parameters. But the studies to date do indicate that man's behavior is susceptible to analysis. What may be needed is a more detailed examination of human behavior. An example[7] of

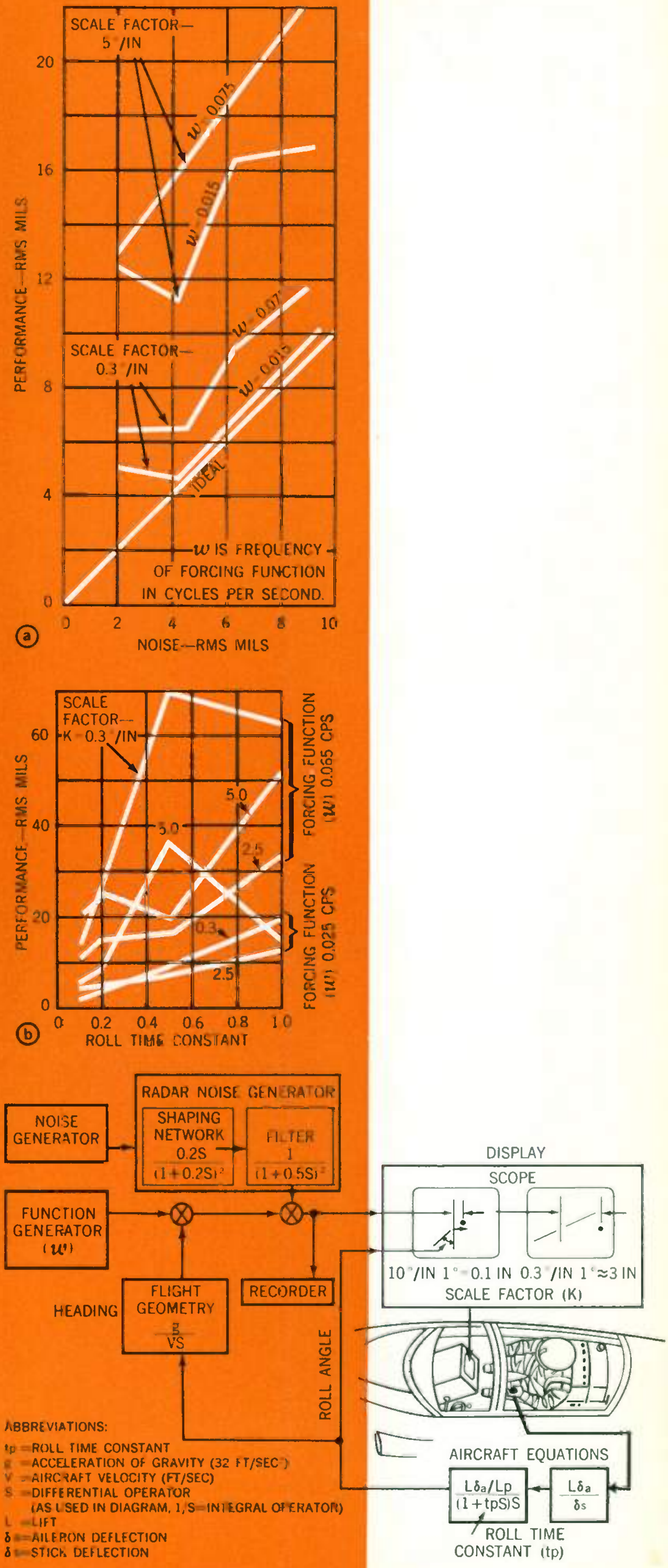

Fig. 8 Diagram of tracking system test setup for determining the effect of varying system roll time constant; other variables are system noise, forcing function frequency, and operator display sensitivity (scale factor). (a) Test results show that the display scale factor can be optimized. (b) Test results indicate that choice of an optimum scale factor can minimize the effects on operator performance, roll time constant, noise, and forcing function frequency.

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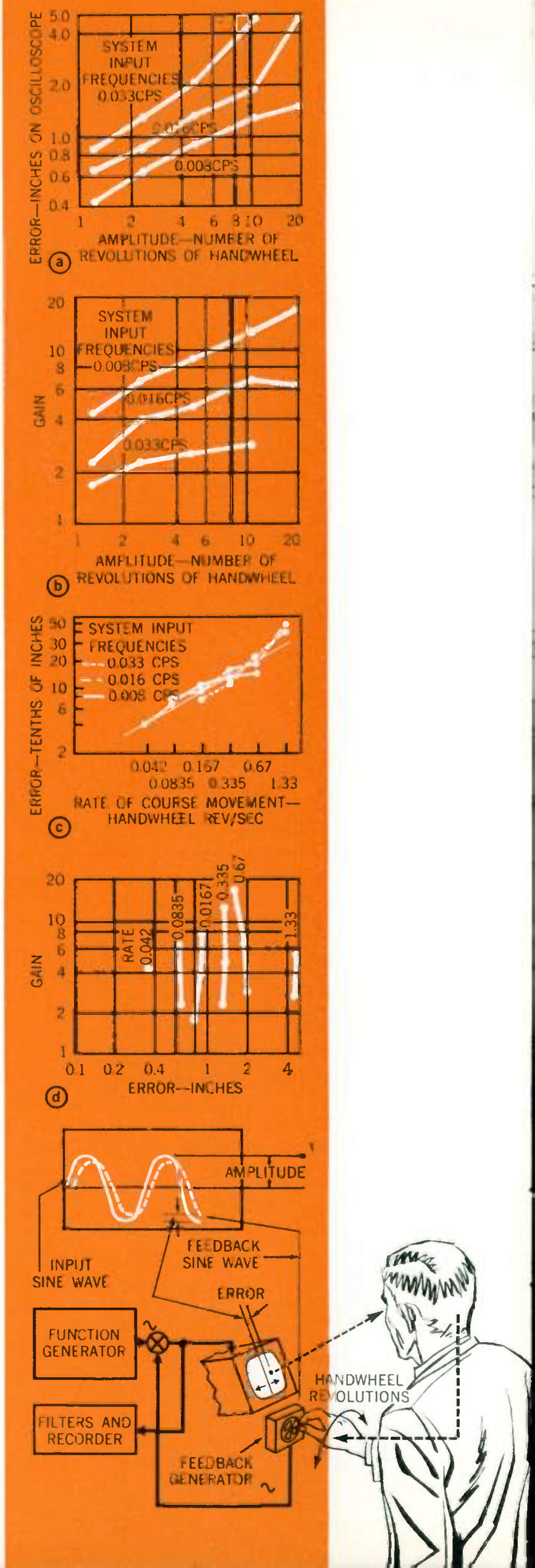
[6] Kahn, A. and Mazina, M. "Performance as a Function of Scope Sensitivity, Forcing Function, and Roll Time Constant." Paper presented at Manual Servo Conference, Stamford, Connecticut, 1959.

[7] Kahn, A. "The Human Operator as a Linear Element in a Servo System." Paper delivered Midwestern Psychological Association, April 1954.

Fig. 9 Test setup for analyzing human operator performance. Function generator feeds low-frequency signal into system, which operator attempts to match in amplitude, guided by error indication. (a) Operator average error is shown to be a function of both system input voltage frequency and amplitude. (Amplitude is calibrated in number of revolutions of the operator handwheel. In the actual test setup, one revolution was equal to 1.5 volts.) (b) Operator "gain" is a function of input frequency and amplitude. (c) Operator performance is shown to be a direct function of handwheel turning rate. (d) Operator performance is shown to be a direct function of handwheel turning rate, rather than system input frequency or amplitude.



this kind of effort is demonstrated by an investigation of the human as a linear element in a servo system.

The test setup is shown in Fig. 9. A function generator feeds a very low-frequency sine wave signal into the system. This signal is fixed in both frequency and amplitude for each trial run. The subject attempts to match the *magnitude* of this input signal with a feedback signal, the value of which he controls by turning a handwheel (in either direction). The operator-controlled feedback signal is compared with the system input signal, and the error displayed on the oscilloscope as a dot, moving back and forth across a centerline. The operator attempts to keep this error as small as possible. The results of the study are analyzed in Fig. 9.

A meaningful conclusion was found by converting frequency and amplitude to *rate* at which the operator must turn the handwheel. A value for rate was found as follows: Since sine wave *amplitude* is calibrated in terms of handwheel turns, a complete cycle would require four times this number of turns (total in forward and backward direction). Hence, for an amplitude of 1.3 turns, a total of 5.2 turns per cycle would be required; this can be converted to turns per second (rate) by multiplying by frequency in cycles per second:

$$5.2\,\frac{\text{turns}}{\text{cycle}}\times 0.008\,\frac{\text{cycles}}{\text{second}}=0.042\,\frac{\text{turns}}{\text{second}}$$

A plot of performance versus rate (Fig. 9c), shows that the subject actually does respond directly to rate.

When gain is replotted as a function of error (Fig. 9d), the measure of error associated with each rate is indicated. Since each point on the separate rate lines represents a different frequency-amplitude combination, the curves suggest that the subjects have set themselves an error that they will try to maintain and this error changes with rate. The subjects seem to shift their "gain" up and down to maintain this error. How this is accomplished or what "gain" means in this context is not known.

challenge of the future

The foregoing paragraphs illustrate the contributions of the experimental psychologist to the problems that develop in the design of human-operated equipment. In the future, these problems will become more pressing. As space flight nears reality, the need for solutions will become more and more urgent. Automation changes the nature of the problem, but does not eliminate it if the human must interact with the equipment.

Man is not the weak link in the system—only his requirements are ignored. But his requirements can be determined precisely if the necessary effort is made.

DIGITAL INSTRUMENTS FOR ACCURATE STRIP-PROCESS MEASUREMENTS

The measuring precision required by modern strip-process industries can best be obtained and maintained with digital instruments. These instruments eliminate the drift problems and parameter changes inherent in analog devices.

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A new digital speed and speed-difference indicator gives the strip-process industries measuring accuracy and reliability never before available under mill conditions. The indicator measures strip surface speed, speed difference between sections, and speed ratio between sections of process lines handling rapidly moving strips of steel, paper, plastics, and textiles. Its accuracy helps operators improve product quality and uniformity, increase production, and check section speed regulators.

A strip length indicator developed for the same industries also employs digital techniques for accurate and reliable measurements.

Both instruments are completely transistorized and consist largely of modular building blocks. They are inherently accurate throughout their service lives and do not require constant calibration checks. Both display their measurements in easy-to-read numerical form.

SPEED AND SPEED-DIFFERENCE INDICATOR

why measure speed and speed difference?

Most continuous strip process lines consist of several sections in line, through which a strip of material is fed continuously. The amount of stretch (or slack) in the strip between sections must be controlled to make a consistently high-quality product. This requires, among other things, accurately set speed differences between sections. Before speed differences can be set accurately, section speeds must be measured accurately.

The need for more accurate industrial speed and speed-difference indicators has become acute in recent years. Production speeds have risen steadily, and this makes measurement requirements more and more exacting.

Also, many process lines now have electric sectional drives powering each section independently, with the overall line speed and section-to-section speed differences set and held by regulating systems. Operators must know if section load swinging indicates section speed variations or merely correct regulator action keeping the speed constant under a cyclic mechanical load. Maintenance personnel need a speed and speed-difference measuring instrument to isolate any section regulators that need attention.

Finally, when changing products or grades, operating information from previous runs can be invaluable. With it, operators can set section speeds for the new product and start the strip through the line without further adjustment, significantly reducing the time required to get the line into production.

the accuracy problem

Speed difference between two process sections operating at approximately the same speed has heretofore been difficult to measure. This difference is important, though, because it determines the tension in a strip of material passing through the sections, and the tension affects the product's characteristics. For a relatively inelastic material that will not stand much tension without breaking, the speed difference between adjacent sections must be kept very small—a few tenths of a percent. Therefore, if two adjacent section speeds are to be subtracted to obtain a meaningful speed difference, each speed must be measured with great accuracy.

As an example, consider a 2000 foot-per-minute (fpm) process line having speed indicators on adjacent sections with nominal overall accuracies of $\pm\frac{1}{2}$ per cent. These show each section speed within ±10 fpm, so the speed difference is known within ±20 fpm. Assume, however, that the actual difference is only 3 percent of line speed, or 60 fpm; the difference then is indicated with an accuracy of $\pm 33\frac{1}{3}$ percent. Since measuring accuracies are usually stated as a percent of full scale, the reading is twice as inaccurate (±67 percent) at 1000 fpm.

This illustrates the need for high accuracies in speed-measuring systems. Such accuracies can be obtained and maintained most consistently with a digital system.

A useful instrument should retain its accuracy without periodic calibration. Operators have sometimes been reluctant to depend on analog speed-difference indicators because of their tendency to drift; in contrast, the all-digital instrument described in this article is well accepted.

The instrument measures speeds in increments of 1 or 0.1 fpm. This precision is great enough so that errors introduced by such normally neglected quantities as strip slippage over its carrying rolls, roll diameter changes caused by wear and temperature variations, and roll crown (convexity) effectively limit any meaningful further accuracy improvement under normal industrial conditions.

operation

The basic speed and speed-difference indicator consists of several digital tachometers and a readout instrument. It is a self-contained device requiring only standard mill ac power for operation.

The gasketed watertight digital tachometers (Fig. 1) are mounted on the various process-line sections. They contain a toothed soft-iron wheel and a magnetic reluctance pickup. The rotating wheel causes the pickup to produce a signal, which the readout instrument (Fig. 2) uses to determine speed and speed difference.

Each tachometer's output frequency is directly proportional to the surface speed of the roll connected to that tachometer. That is,

$$f = K(fpm),$$

where K is a proportionality constant dependent on the roll diameter, gear ratio between roll and tachometer, and number of teeth on the tachometer's toothed wheel. Since frequency is pulses per unit time (p/t_u),

$$p = Kt_u(fpm).$$

The readout instrument is calibrated to make t_u equal to $1/K$ and thereby make the pulse count numerically equal to the roll surface speed in feet per minute.

Thus, the instrument obtains a digital speed indication in feet per minute by counting the pulses of the output signal for a definite time t_u, which depends on the roll diameter, gear ratio between drive and roll, and number of teeth on the tachometer wheel.

The indicator's operating cycle is represented in Fig. 3. At the end of time t_u, the total count is equal to the surface speed of the roll. This speed is displayed on the readout instrument with a plus sign in front of it.

The count-up and count-down times t_u and t_d are obtained from a very accurate crystal controlled oscillator circuit and a binary counting chain. Count time is the time required for the oscillator to drive the binary chain from zero to a number set on the diode matrix.

To obtain speed difference between two sections, a reversible counter is employed. The cycles from one section are counted up (adding pulses) for the time t_u, and then the cycles from the second section are counted down (subtracting pulses) for the time t_d required by its roll diameter, gear ratio, and number of tachometer-wheel teeth. At the end of time t_d the total down count (which is equal to the surface speed of the second roll) has been subtracted from the up count (the surface speed of the first roll). The counter now contains a count equal to the speed difference between the two rolls.

If the speed of the first roll is greater than that of the second, say by 1.9 fpm, the difference is indicated on the readout as +1.9. If the speed of the second roll is greater than that of the first roll by 1.9 fpm, the counter goes through zero and contains the number 9998.1 fpm. Instead of displaying this number, the instrument senses that the counter has gone through zero and changes back to counting up. At the same time, it changes the plus sign to a minus sign and displays, in this example, −1.9.

In many strip processes, rolls are resurfaced occasionally. This changes the roll diameter and the ratio of roll rpm to surface speed and, therefore, the required counting time. For this reason, the speed and speed-difference indicator's counting time for each section is adjustable.

For a more complete description of the readout instrument, see *Readout Instrument*, p. 120.

construction and application

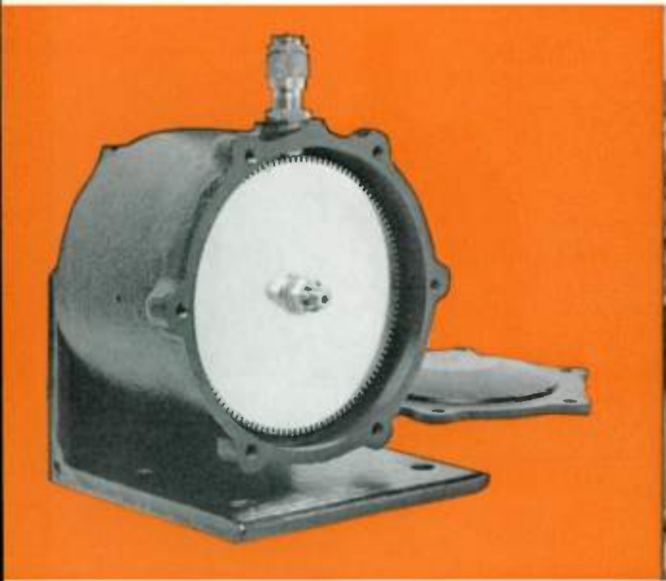
General—Because the indicator's external wiring is relatively simple, no specially trained personnel are needed during installation. Calibration is accomplished simply and quickly.

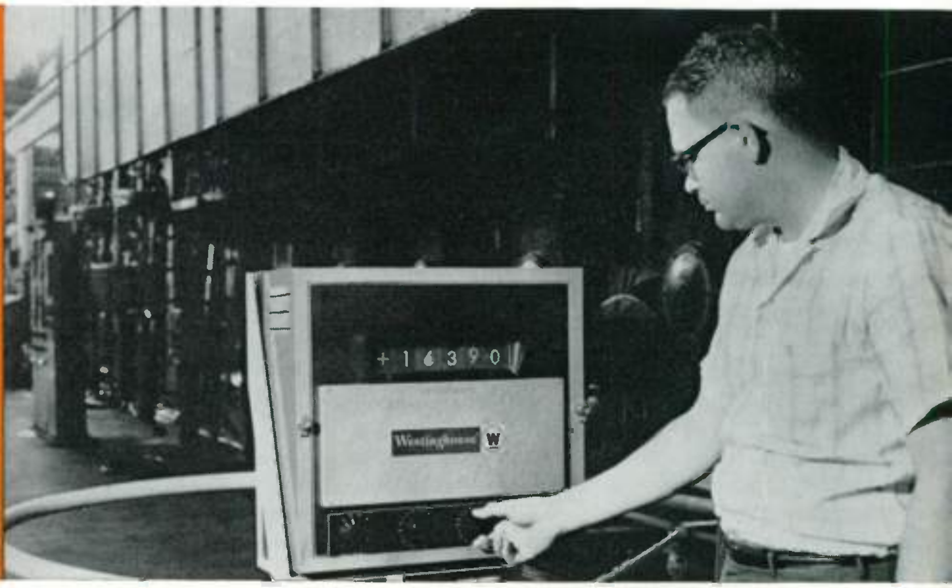
Carrying an inventory of spare modules has not been found necessary. However, module replacement, should it

Fig. 1 (Left) The tachometer's toothed wheel and magnetic reluctance pickup generate the signals required for digital measurements.

Fig. 2 (Center) Speed and speed-difference indicator readout instrument at the Pensacola Mill of the St. Regis Paper Company. The instrument is displaying a section speed.

Fig. 3 (Right) Speed and speed-difference indicator operating cycle. T_u is count-up time, T_d is count-down time, T_o is operating time (counting time plus switching time), and T_r is display time (determined by operator with display time selector switch).





be required, is facilitated by keyed plugs and color codes that prevent incorrect placement.

The speed and speed-difference indicator, in its present design, can measure speed at 18 sections of a process line. When measuring in increments of one foot per minute, the instrument requires only one second to determine speed difference; it requires approximately ten seconds to determine speed difference when measuring to the nearest tenth of a foot per minute.

Selector Switches—Decked section selector switches make it possible to determine speeds and speed differences for the various machine sections. These may be manually operated switches (Fig. 2) or stepping switches operated by pushbuttons at remote locations. Normally, one deck of each selector switch is used to connect the tachometer signal to the counting circuitry. The second deck usually picks out the timing signal required by the tachometer connected by the first deck. This arrangement permits the pulses from each tachometer to be counted for the period of time required by that section's roll diameter, gear ratio, and number of teeth on the toothed wheel.

To measure the speed of a section, one section selector switch is turned to the position corresponding to that section and the other is turned to the "S" (for speed) position. The switch turned to "S" does not admit pulses from any section, so nothing is subtracted from the count coming from the section selected with the other switch. The instrument then displays the section's speed.

To measure speed difference between two sections, one section selector switch is turned to the position corresponding to one section and the other is turned to the position corresponding to the second section. The instrument then displays the speed difference for a time determined by the setting of the display time selector switch.

By setting both section selector switches to the same position, the counter is made to count both up and down on the frequency from one section. The instrument then displays zero speed difference if the section speed remains constant while the instrument is counting. If the section is decelerating, the up count is greater than the down count and the instrument displays a positive speed difference. Similarly, the instrument displays a negative speed difference if the section is accelerating. The instrument can thus be used as a swing detector to indicate how well a section speed control is functioning.

DIGITAL CIRCUITRY TERMS

Flip-Flop A circuit with two stable states. It changes from one stable state to the other whenever it receives an input signal.

Gate A circuit that either permits or inhibits the flow of signals from its input to its output terminals, depending on the voltage applied to its control terminal or terminals. A gate is said to be "open" when it permits signal flow.

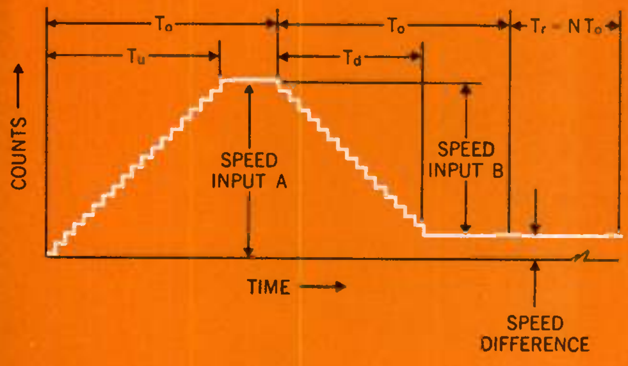
AND Gate A gate circuit with more than one control terminal. It permits signals to pass from its input to its output terminals when a voltage is present on all of its control terminals.

NOT Gate A gate circuit that does not permit signals to pass when a voltage is applied to its control terminal. Removing the control voltage permits signals to pass.

OR Circuit An electrical "funnel" that accepts signals from two or more sources and delivers them at a single output terminal.

One-Shot Multivibrator A circuit with only one stable state. It yields a rectangular output voltage of a prescribed height and width for a narrow input pulse.

Ring Counter A circuit that has several stable states and changes from state to state in a prescribed order when input signals are applied. The state changes can be used to count the input signals.



Satellite Readouts—In applications encountered thus far where stepping switches operated by remote pushbuttons have been used, satellite readouts at the remote locations have also been desired. The instrument's circuitry is flexible enough to allow wiring several readouts to the basic indicator and lighting only the readout associated with the depressed pushbutton. A deck on the stepping switch lights the proper readout.

Component Arrangement—The readout instrument's main physical components are shown in Fig. 4. The module chassis can be swung out to make the plug-in modules accessible, and these modules are functional packages that permit trouble-shooting with the aid of only a block diagram and a wiring diagram. The instrument's calibrating panel is shown in Fig. 5.

Percent Speed Difference—The readout instrument can be modified to display percent speed difference instead of speed difference in feet per minute. Percent speed difference, usually defined as the difference in speed between two sections divided by the speed of the first section, is shown in increments of 0.1 or 0.01 percent.

To determine percent speed difference, the instrument counts pulses from one section until a fixed number of pulses has been obtained from the second section. Suppose, for example, that the first section is going 1 percent faster than the second section and the number of counts from the second section is set at 1000. During the time it takes the second section to transmit 1000 pulses, the first-section

Text continues on page 122. The readout instrument is described in detail on pages 120 and 121.

READOUT INSTRUMENT

The speed and speed-difference indicator's readout instrument consists of three main components: a reversible counter and readout, an adjustable timing unit, and a programmer to coordinate the count-up, count-down, and display functions. These components are illustrated schematically in the system diagram, below.

reversible counter and readout

Counter—The counter consists of a chain of five identical units called decades, one for each digit of the output indication (see counter decade diagram, facing page). Each decade is a biquinary counter; that is, the input signal drives a flip-flop that in turn drives a ring counter of five elements. Each has seven output terminals, two from the flip-flop and five from the ring. The count is determined by which flip-flop terminal and which ring terminal has voltage. One output pulse is obtained from a decade for each ten input pulses, and the output pulse drives the next decade in the chain.

The decades are arranged to count down as well as up. In switching from counting up to counting down, it is necessary to reverse the direction in which the ring counter operates. This is achieved by providing the ring with two operating lines, one for counting up and one for counting down. Transistor switching connects the appropriate stage of the flip-flop to the correct operating line of the ring, depending on the direction in which the ring is to count. There is also transistor switching between decades to make the interconnection changes necessary when converting from counting up to counting down.

Power Amplifiers and Decoders—For each counter decade there is a power amplifier and decoder (*A1*, *A2*, etc.). These convert, or decode, the seven signals resulting from the two possible states of the flip-flop and the five possible states of the ring in each decade into signals representing the digits from one to ten. They also raise the signal level enough to light bulbs in the projection readout. These functions are carried out by seven switching amplifier stages, each consisting of a low-level input transistor and a power transistor in cascade.

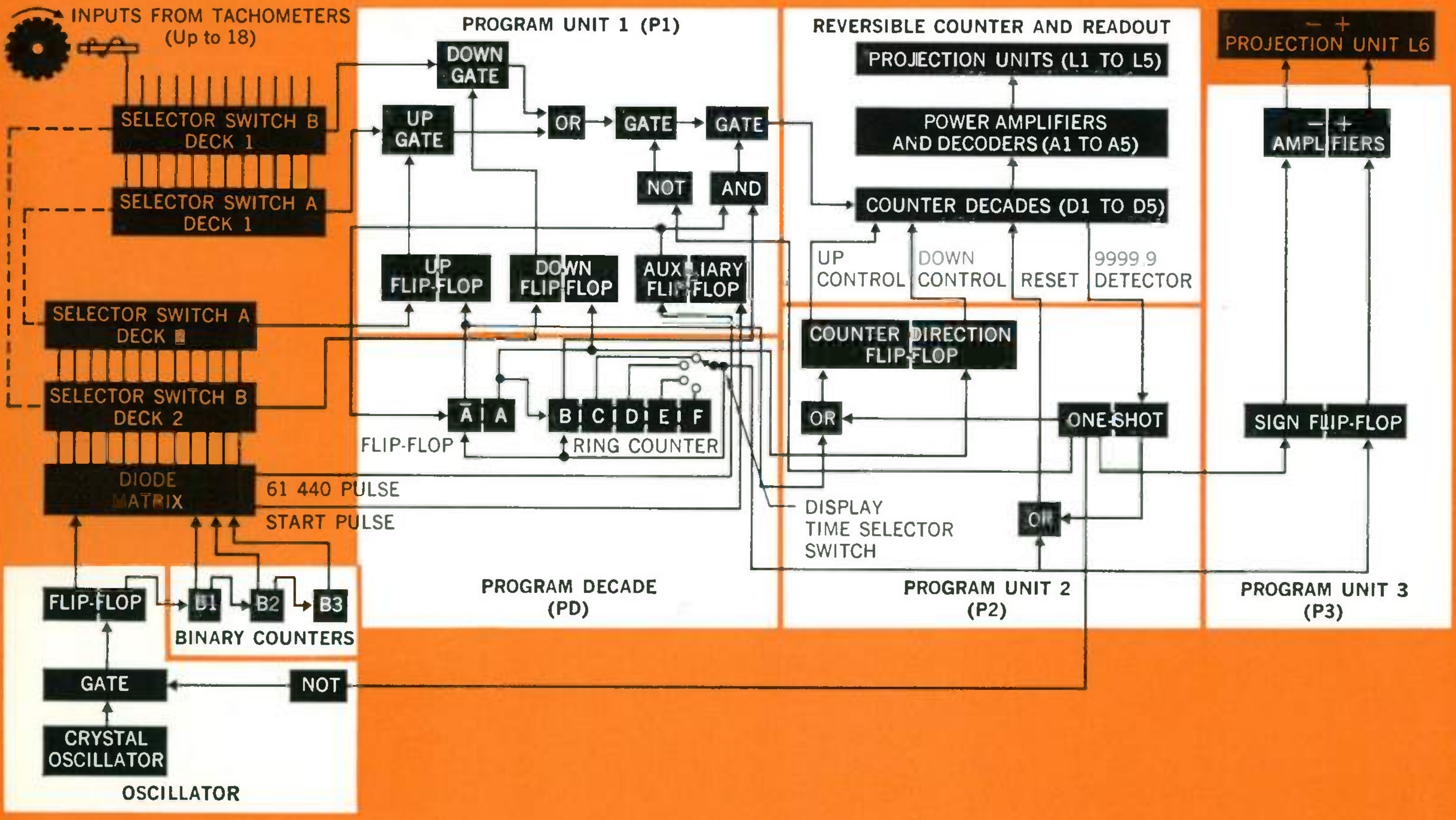
Projection Readout—The power amplifiers energize projection units (*L1*, *L2*, *L3*, *L4*, and *L5*), each consisting of lamps, diodes, lenses, photographic transparencies, and a translucent screen. Ten lamps and transparencies in each unit are used for the numerals from zero to nine; the other two can be used for decimal points. (Another projection unit, *L6*, is operated by the programmer to display plus and minus signs.)

adjustable timing unit

Oscillator—The oscillator is a crystal-controlled unit with high accuracy. An amplifier, a NOT gate, and a flip-flop are included in the oscillator module.

Binary Counters—*B1*, *B2*, and *B3* each contain five flip-flops. These modules, with a flip-flop in the oscillator module, form a 16-element binary counting chain. The entire chain returns to its zero state every 65 536 (2^{16}) cycles of the oscillator, which is 5.461 seconds for a 12-kc oscillator.

Diode Matrix—The diode matrix reads the binary counting chain. Timing in the entire unit is referenced to the zero state



of the counting chain, and the diode matrix yields a pulse when the chain reaches the given number (N) determined by the preselected positions of the diodes. Therefore, the diode matrix proportions the entire time cycle for the chain to one part in 65 536. The actual time for N, in seconds, is 5.461 times N divided by 65 536.

The diode matrix contains a group of diodes for each input section. Each two-deck section selector switch (A and B) selects a tachometer signal with one deck and, with the other deck, selects the diode group that yields the proper count time for that signal.

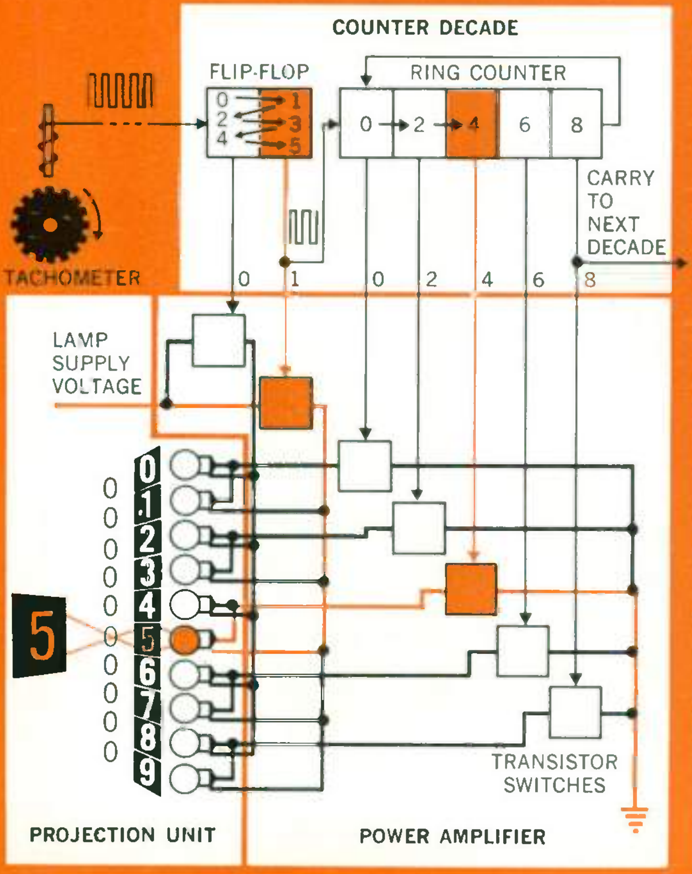
Screw connections form the diode groups, allowing the timing to be adjusted over a range of 18 percent to compensate for changing roll diameter. (The diode groups theoretically yield a 25-percent adjustment, but part of the total 5.461 seconds is reserved for switching and programming needs.)

Auxiliary Functions—A circuit associated with the diode matrix yields a pulse when the binary counting chain reaches the number 61 440, which is 5.12 seconds from the time the counter started from zero and 0.341 seconds before the next time the counter is in its zero state. This pulse initiates switching in the sequencing circuits; the 0.341 seconds is the time allotted to complete the switching from an up count to a down count and vice versa.

A pulse corresponding to the zero state of the binary counting chain is obtained by detecting the rise in voltage in the last flip-flop in the chain.

programmer

Program Decade (PD)—The program decade is similar to the counting decades ($D1$, $D2$, etc.) except that it counts in only one direction. It is primarily a sequence control unit.



Program Unit 1 (P1)—This unit contains four gates, two of which are controlled by flip-flops. The last gate is controlled by an AND circuit.

Program Units 2 and 3 (P2 and P3)—$P2$ contains a flip-flop and a one-shot multivibrator, and $P3$ contains a flip-flop and two power amplifiers. When the counter goes through zero counting down and reaches 9999.9, these two units change the reading to 0000.1, change the counting direction to up, and change the plus sign in the readout to minus.

Program Routine—An input signal from selector switch A passes through the flip-flop controlled up gate in $P1$ into an OR circuit. The input from selector switch B passes through a flip-flop controlled down gate into the same OR circuit. From the OR circuit the signals pass through two gates on their way to the counter. The up and down flip-flops open the gates one at a time, permitting signals to pass through them, when they receive a pulse from PD. The gates remain open until a signal from the diode matrix trips the flip-flops to the opposite state, allowing the gates to close and thereby block signals.

At the start of the program routine, the flip-flop in PD has instructed the up gate to be open, and the B section of the PD ring counter is supplying one of the necessary signals to open the AND gate. The flip-flop also has instructed $P2$ to give a count-up command. In this condition, the signal selected with selector switch A reaches the counter. The up gate remains open until the up flip-flop receives a pulse from the diode matrix signaling the end of the counting time. Nothing happens until a pulse on the 61 440 circuit trips the auxiliary flip-flop in $P1$. This removes a signal from the AND input gate, causing it to open and prevent signals from reaching the counter. It also signals PD to advance one count, which in turn signals $P2$ to command the counters to count down. Advancing PD also causes the down flip-flop to switch, opening the down gate.

Although the gates and counters are now ready to receive pulses from the section selected on selector switch B, counting does not proceed until the *start* pulse from the binary counting chain signals its zero state and restores the auxiliary flip-flop. This flip-flop then supplies a signal to the AND controlled gate, and counting now proceeds in the down direction—subtracting one for each pulse from the count accumulated in the counting-up mode.

If the counter goes through zero counting down and reaches 9999.9, it operates the one-shot multivibrator in $P2$. This causes $P2$ to change the command to the counters from count-down to count-up. It also resets the counter to 0000.1 and changes the plus sign to minus.

The counter continues counting until a signal from the diode matrix corresponding to the section chosen with selector switch B causes the flip-flop controlled down gate to close. The next 61 440 pulse again trips the auxiliary flip-flop and advances PD one count. From here until PD is reset, the signal it delivers to the AND controlled gate is removed and the readout displays the speed difference.

The resetting of PD is, in a sense, an operation of pulling itself up by its bootstraps. Each succeeding 61 440 pulse advances PD one count. When the count has proceeded to the point selected by the display time switch, the minus sign changes to a plus sign, PD resets to its original position, and the counter resets to zero. PD resetting causes the up gate to open.

The 61 440 pulse that causes PD to reset also trips the auxiliary flip-flop. The next pulse resulting from the binary chain going through zero restores the auxiliary flip-flop and starts the counting-up period. The entire program routine then repeats.

Left Readout instrument system diagram.
Right Functional diagram of a counter decade, power amplifier and decoder, and projection unit. The assembly is shown sensing and displaying a count of five.

pulse counter receives 1010 pulses. The instrument is arranged to subtract the fixed 1000 counts and place a decimal point before the last digit, so it displays +001.0—the percent speed difference.

If the first section is going 1 percent slower than the second, the counter receives only 990 pulses during the time 1000 pulses are generated by the second section. Subtracting the 1000 counts and placing the decimal point makes the display —001.0. The sign of the reading indicates which section is going faster.

STRIP LENGTH INDICATOR

The need for an accurate length measuring device is obvious in products, such as cloth, that are sold by length. Even when the product is sold by weight, a record of the length often is useful for calculating the number of items that can be fabricated from a roll.

Length is considerably simpler to measure than speed because the time element is absent. The strip length indicator uses a digital tachometer (identical to that used for speed measurement) geared to a roll in such a way that each pulse represents one unit length of material, say one foot. The pulses are merely counted and displayed. Auxiliary programming controls the counting start and stop, usually in such a way that the length counted is the length of product in the unit shipped to the customer.

The standard length counter employs the same digital principles and transistorized modules as the speed and speed-difference indicator. It counts up to 99 999 feet and displays the length to the nearest foot. An automatic recorder can be provided to make a typed record at the end of each counting cycle.

The counter can be modified for a capacity of more than 99 999 feet and to count in increments other than the foot. Means can be provided to enable the operator to set the instrument so that when a certain length is reached a contact closes to light an indicating lamp or pick up a relay. The unit might be set to light a warning signal a few hundred feet before the desired length is reached, notifying the operator to slow the process. A second setting might light a stop signal when the desired length is reached.

CONCLUSIONS

Great reliability is inherent in the speed and speed-difference indicator and the length indicator. All of the circuitry operates in the switching mode, eliminating the drift problems and parameter changes that plague analog circuitry. Further, accuracy depends on only two factors—the degree of accuracy with which tachometer frequency can be related to strip speed, and (in the speed and speed-difference indicator) the stability of the crystal oscillator.

The modular transistorized components make a completely static instrument that is easy to maintain. The visual readout indicates the desired values directly and is easily read.

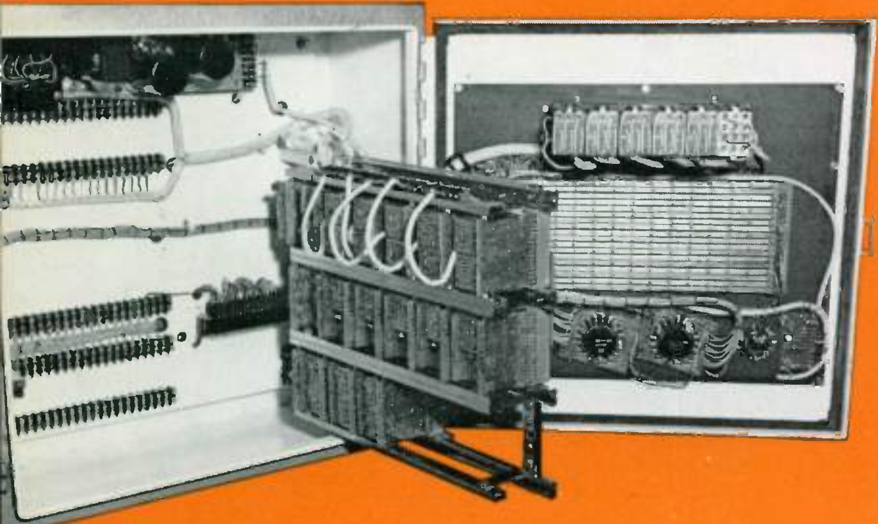
A number of the instruments have been installed since their introduction less than two years ago. Operators have quickly developed confidence in them, a major factor in the success of any process instrument.

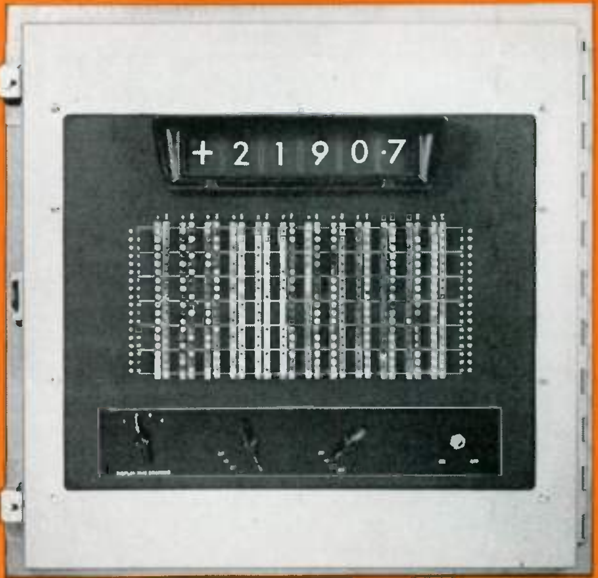
Maintenance personnel use the speed and speed-difference indicator to check reports of section speed variation and to isolate regulator or mechanical problems. Most important, the indicator facilitates production of high-quality products consistently and with a minimum of lost time.

Westinghouse
ENGINEER
July 1961

Fig. 4 (Left) Readout instrument with door open. The power supply (top) and module chassis (swung out) are in the cabinet; the projection units, diode matrix, and switches are on the door.

Fig. 5 (Right) Readout instrument with cover plate removed to show calibrating panel. The screws make contacts that form the diode groups required for setting the proper count time for each section input.





ADJUSTABLE-FREQUENCY AC DRIVE SYSTEM WITH STATIC INVERTER

Solid-state components supply ac power and control its frequency in a new electric drive system.

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The ideal electric drive system would combine wide speed range, high efficiency, static components, and great flexibility with reliability, negligible maintenance requirements, and nearly foolproof protection. A short time ago this combination of characteristics sounded like something in the remote future, but now most of them have been developed in TAFI—the Trinistor adjustable-frequency inverter. Developed initially for special applications in the chemical fiber industry, the TAFI system also has great promise in many other areas. Group control of motors is the initial application, but the system's useful properties can be applied to special single-motor drives also.

The TAFI drive system, as the name implies, is an adjustable-frequency system that uses frequency regulation to control drive-motor speed. With proper control, an ac motor can operate nicely over a wide range—20:1 or more, depending on the load characteristics of the system and the choice of frequencies.

Conventional adjustable-frequency systems derive their power from rotating machines, either synchronous generators or induction frequency changers. These converters are driven by some kind of adjustable-speed drive to obtain an adjustable-frequency output. A typical unit is the synchronous generator powered by a dc adjustable-speed drive, illustrated schematically in Fig. 1a. Because of the power conversion loss in each machine, the rotating converter's overall efficiency is 65 percent at best, and usually is less. In addition, the rotating converter requires considerable space and substantial maintenance attention.

In contrast, the TAFI system produces its adjustable-frequency output with efficiency as high as 90 percent and no moving parts (Fig. 1b). It does so by means of a special solid-state inverter using Trinistor controlled rectifiers. (See *Inverter Operation*, p. 125.)

Trinistor characteristics

The Trinistor controlled rectifier is well suited to switching operation because it blocks an applied forward voltage until a "gating" signal is fed to its third element (Fig. 2). It then conducts until the load current goes to zero. The

Fig. 1 Two methods of obtaining adjustable-frequency ac power for group drives are illustrated in these simplified diagrams: (a) a rotating converter; (b) a typical TAFI system.

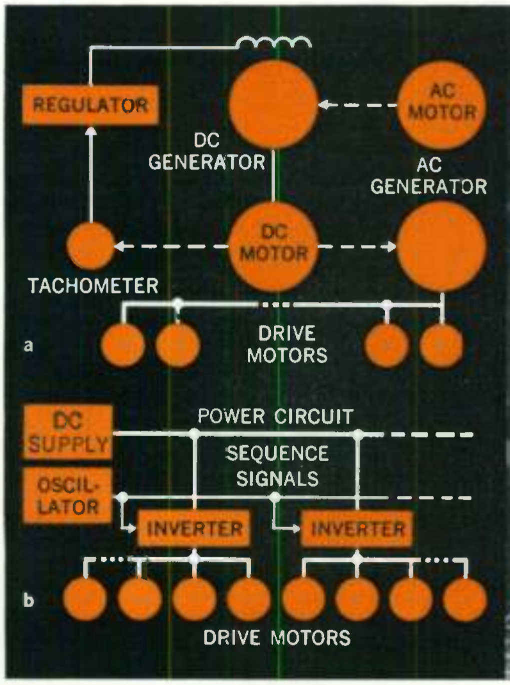
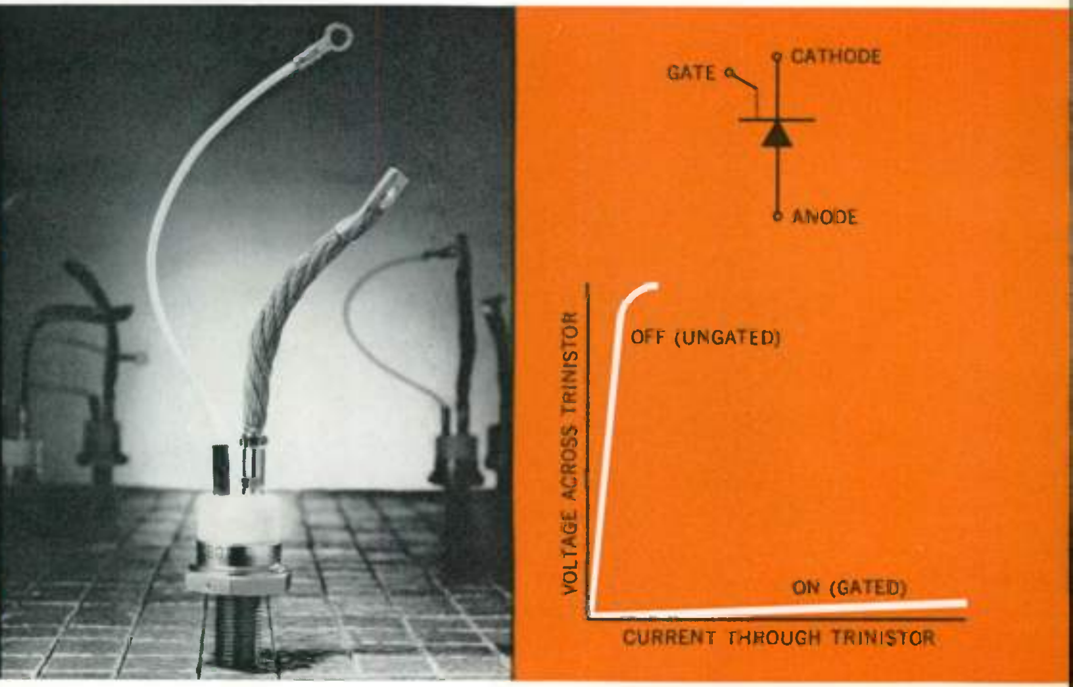


Fig. 2 A typical Trinistor controlled rectifier (left). At right, the device is diagrammed and its switching characteristics are illustrated graphically.



gating signal can be a very short pulse or spike, because the device's switch-on time is only a few microseconds.

Switching the Trinistor device off for inverter operation is somewhat more difficult. In the inverter, a unidirectional dc voltage is applied across the Trinistor device, so there is no natural tendency for the current to go to zero and permit switch-off. The gating signal is ineffective for switching off, so special circuits are required.

The turn-off problem can be solved in different ways, all of which require the current to fall (or be driven) to zero long enough for the Trinistor device to regain blocking control. In some applications, capacitors are discharged in such a way as to drive the current to zero. In others, the load current is momentarily diverted from the switching device by an auxiliary device, permitting the switching device to recover control. If the ac load operates with a leading power factor, the current goes to zero before time for zero voltage, and this permits the Trinistor device to recover automatically.

frequency control

To obtain the desired frequency control, the gating pulses are controlled in the proper sequence and at the proper time interval. The firing *sequence* is fixed, determined by the circuit configuration. *Timing*, however, must be variable to permit varying the inverter output frequency.

This control is effected by a simple oscillator that produces a train of timing pulses at a rate determined by the oscillator frequency. For example, a three-phase inverter operating from 40 to 400 cycles per second (cps) requires an oscillator frequency adjustable from 240 to 2400 cps. (The factor of six comes from the three-phase inverter circuit configuration.)

system characteristics

The master oscillator alone determines the inverter output frequency and, therefore, the motor synchronous speed. A changing load on the inverter, even during transients, does not affect the system frequency. This is a unique feature of inverters, and it cannot be duplicated by conventional rotating converters.

Furthermore, the problem of drift, or slow change in setpoint, is confined to the oscillator. Where drift control is especially important, as in precisely-regulated chemical fiber spinning-machine drives, the oscillator is designed with special care to minimize drift and sometimes is mounted in a temperature-controlled box. These measures virtually eliminate drift.

These characteristics produce very stable speed control, free from drift and transient variations, without a feedback regulator. The TAFI drive system is basically an open-loop system, with attendant simplicity and reliability.

motor load requirements

The characteristics of the load to be driven have a definite influence on a TAFI system design. First, a motor load ordinarily operates at a lagging power factor, and the resulting inductive effect aggravates the switch-off problem for the controlled rectifiers.

Second, and more basic, is the requirement of a motor to operate at constant volts per cycle. (For example: 440 volts at 60 cycles, 220 volts at 30 cycles, 110 volts at 15 cycles.) For a given torque load, the motor operates most effectively with constant flux (which implies constant volts per cycle), and substantial deviation from the design value causes overheating or loss of torque capacity. A problem arises from the fact that a simple inverter produces a *constant output voltage*, regardless of operating frequency. For a small speed range, 1.5:1 or less, it may be desirable to oversize the motor for operation at *constant voltage* instead of modifying the power supply to achieve *constant volts per cycle*. For wider variations, however, some method of voltage control is necessary for satisfactory motor performance.

A simple voltage-control method is the use of a variable-ratio output transformer. This may be either a transformer

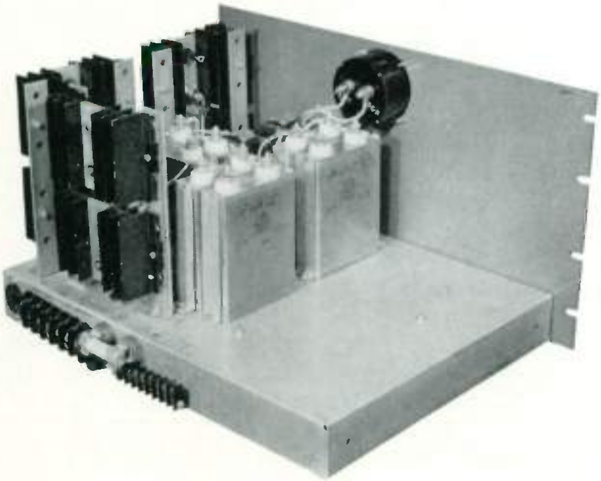


Fig. 3a The TAFI inverter section removed from its cabinet. This section, which contains the Trinistor controlled rectifiers, produces ac power from dc power.

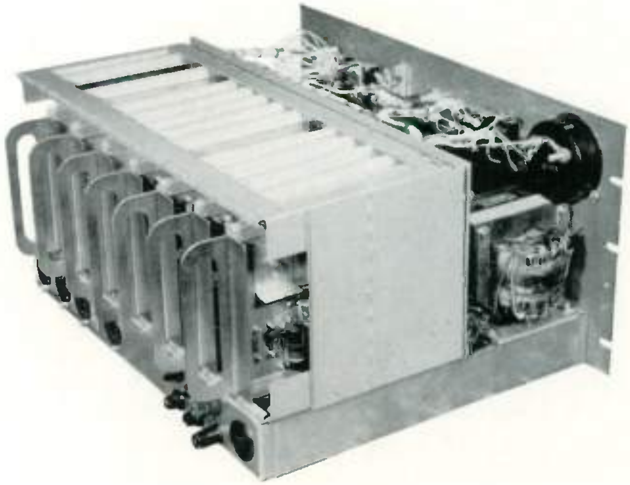


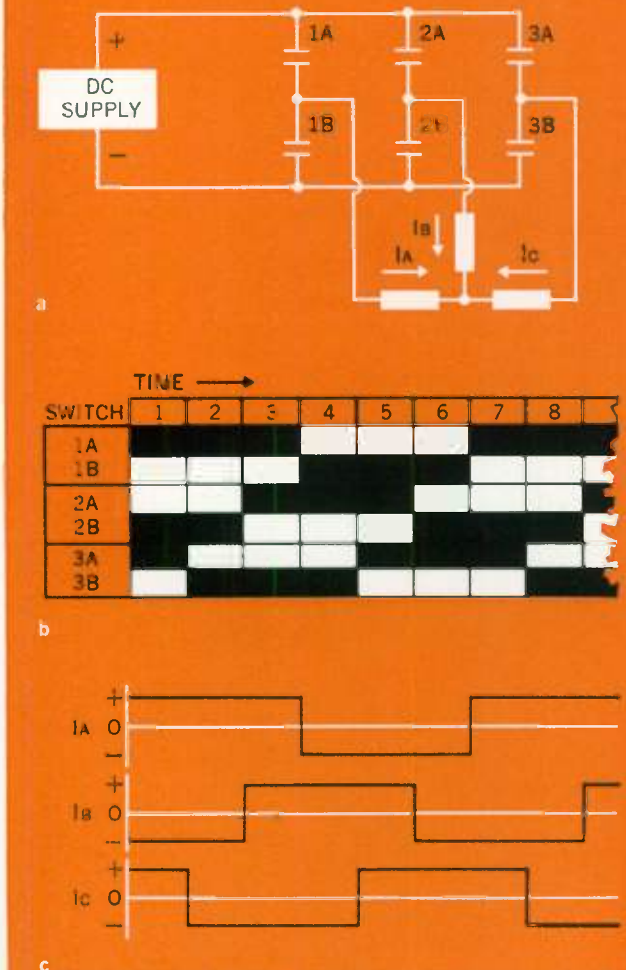
Fig. 3b The oscillator section determines switching frequency. The operator selects the desired frequency with a dial on the front of the section.

INVERTER OPERATION

An inverter is a device for changing dc power to ac power. Its operating principle can be explained by analogy to a switching circuit such as that shown in the illustration. The switches operate in pairs and no pair ever has both contacts closed at the same time, for this would cause a short circuit across the dc bus.

By actuating the switches in the sequence shown, current through any load resistor is made to flow first in one direction and later in the opposite direction. The result is a three-phase square-wave alternating current through the load resistors. The sequence timing is the sole factor determining output frequency, so frequency can be controlled by controlling the timing.

While a system using mechanical switches *could* be made to function, the upper frequency would be quite limited and maintenance undoubtedly would be a severe problem. A better system is achieved by using a high-speed electrical switch with no moving parts. Such a device is the new solid-state Trinistor controlled rectifier, which has already proved itself in power inversion.



SWITCH	1	2	3	4	5	6	7	8
1A	■	■	■	□	□	□	■	■
1B	□	□	□	■	■	■	□	□
2A	□	□	■	■	■	□	□	□
2B	■	■	□	□	□	■	■	■
3A	■	□	□	□	■	■	■	□
3B	□	■	■	■	□	□	□	■

Illustration of inverter operation: (a) switching circuit, with arrows indicating positive direction of current flow; (b) switching sequence; (c) load current.

with taps for each increment of speed range or a variable-ratio auto-transformer for continuous voltage adjustment proportional to frequency. This method, of course, sacrifices the ideal of completely static control in exchange for simplicity and low cost.

Another method, which does not involve moving parts, is controlling the dc voltage applied to the inverter so that output ac voltage is correct for the desired frequency. This is most easily done by obtaining the direct current from a polyphase rectifier employing Trinistor devices, whose voltage is controllable by phasing-back. Other methods are possible, and selection of the best one depends on how the drive or drives are to be used.

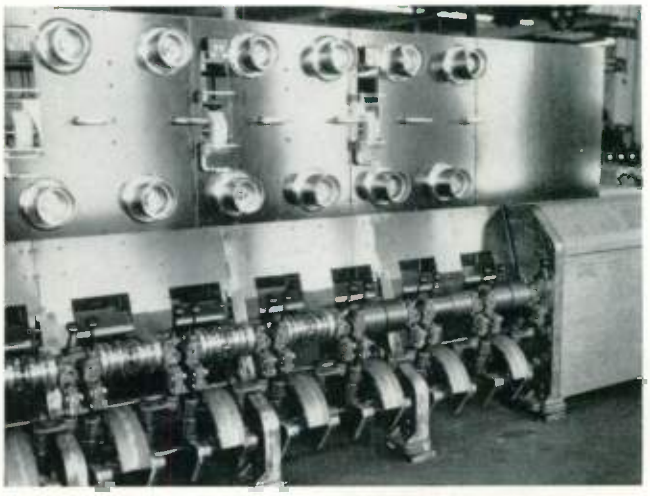
type of drive motor

A final consideration is the type of motor to be used. Any ac motor can be supplied from an inverter, but some are better suited than others. The general-purpose squirrel-cage motor, with its ruggedness and freedom from maintenance, is the simplest and least expensive. One drawback, however, is its high starting current—normally about six times as great as full-load current. Since the solid-state switches must be selected on the basis of peak current requirements, a TAFI power supply for a *single* motor would have to be oversized for starting. For *groups* of motors, however, the incremental starting load of one squirrel-cage motor may be of no concern.

A motor that is much better suited for use with solid-state inverters is the hysteresis motor. (See *The Modern Hysteresis Motor*, p. 127.) It is a simple nonexcited synchronous motor with very low inrush current, and it is presently available in fractional-horsepower ratings. The hysteresis motor typically draws 150 percent current on starting. This makes it nearly ideal for use in TAFI drive systems, even when synchronous motor operation is not required. In addition, synchronous operation makes exact speed measurement a matter of frequency determination, which can be accomplished remotely without mounting tachometers on the motor.

Fig. 4 This takeup machine for synthetic fibers uses a TAFI drive system for close speed regulation of several drive motors.

Credit: Foster Machine Company



ratings

TAFI drive system ratings are, of course, closely associated with Trinistor controlled rectifier ratings. The unit shown in Fig. 3 is rated at 7.5 kva, and it uses 16-ampere Trinistor devices. Larger power requirements are met with 50- and 100-ampere Trinistor devices, and even larger devices are available in pilot quantities.

Basically, the important rating of a TAFI drive system is output kva. A transformer ordinarily is used on the inverter output, so any practical motor voltage can be matched. This permits using the controlled rectifiers at their most favorable operating points. The rating thus obtained is independent of frequency, because switching time becomes a limitation only at frequencies much higher than motors can use.

system coordination

Many factors must be coordinated when selecting the components of a TAFI system. Motor frequency, type of motor, voltage control method, peak current requirements, load characteristics, and method of control are vital considerations. Selection of the optimum rating and arrangement of component blocks may have great importance. Failure to consider these factors properly can lead to poor realization of the system's best features, so the TAFI drive is marketed as a coordinated system.

economics

The economics of the system depend closely on Trinistor controlled rectifier ratings and cost. Ratings have increased greatly in the past two years, and volume production has decreased prices. Thus, the system's economic picture improves with the passage of time.

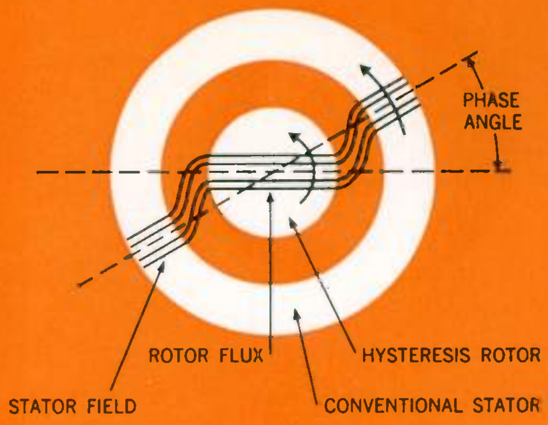
At present, the most economical applications for the TAFI drive are those that benefit most from its unique features. It is well suited to group control of small motors, especially where close speed regulation is required.

A good example is the synthetic-fiber takeup machine shown in Fig. 4. Each small Godet roll is driven by a synchronous motor, so all rolls operate at exactly the same speed. To produce high quality yarn, the speed of all rolls must be held within extremely narrow limits, even during load transients and power supply disturbances.

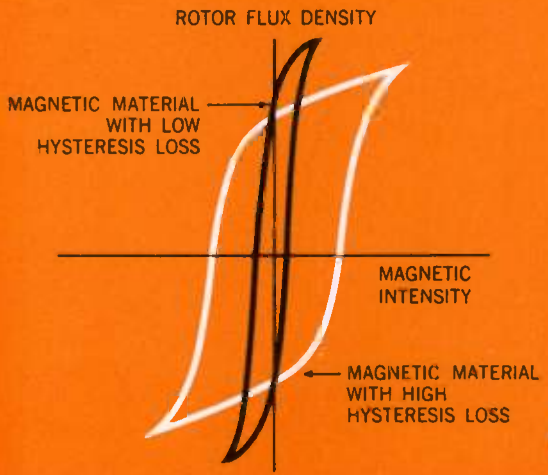
The system also can be very effective with high-speed motors in such applications as internal grinders, certain wood-working machines, and glass-yarn winders. Because of the high motor speeds required, high-frequency ac motors often are used in preference to dc motors. Especially in small power ratings, the static inverter is economically attractive in these applications when compared with alternative methods using rotating converters.

conclusion

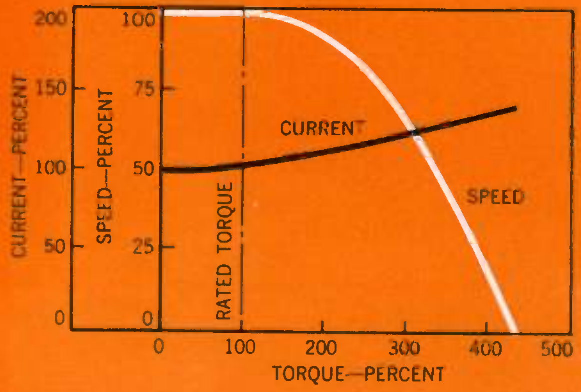
The Trinistor adjustable-frequency inverter has been in development for more than three years. Basic work on fixed-frequency inverters has been going on much longer than that. New circuitry has been devised at each step, new techniques developed, and new devices evaluated. The result is the present TAFI drive system—highly flexible, easily controlled, rugged, and completely static.



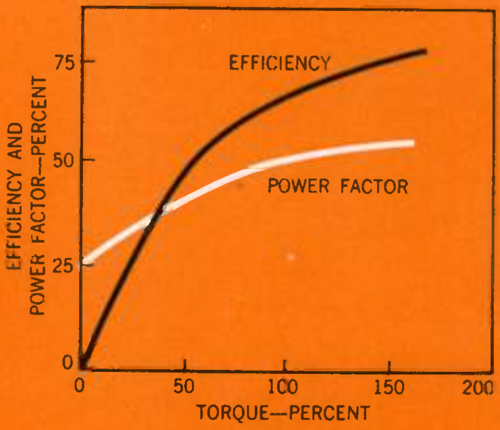
1a



1b



2a



2b

THE MODERN HYSTERESIS MOTOR New designs and materials that increase the power and efficiency of this motor make its unique advantages widely applicable.

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Motor and systems designers have recently taken a long second look at the hysteresis motor's unique characteristics. Its uniform torque, low starting current, and lack of synchronizing problems suit this motor to a number of modern industrial applications, and they also fit the requirements of new adjustable-frequency drive equipment. (See *Adjustable-Frequency AC Drive System with Static Inverter*, p. 123.)

The hysteresis motor is a type of synchronous motor that once was thought to be of limited usefulness. Two of its characteristics—extremely uniform torque and practically noiseless operation—have long been used in a few subfractional drive motor applications such as clocks, phonographs, and timing devices. Unfortunately, however, little torque could be derived from hysteresis loss in the early motor designs, and this seemed to limit the hysteresis motor to very small sizes.

The present intensive study and development of the hysteresis motor was stimulated by two additional advantages. First, the motor can pull into synchronism *any* load inertia that it can accelerate, a feat that no other type can perform; second, its starting and accelerating current is extremely low—about 150 percent of full-load current requirement.

These characteristics are attractive, especially in chemical fiber production and other industrial processes where group drives can be supplied advantageously by adjustable-frequency power supplies. As a result, the hysteresis motor has been redesigned with new materials to increase its ratings and make it more efficient. It is now available in large fractional ratings.

construction

The hysteresis motor's stator is exactly like that of a conventional squirrel-cage motor. Its special characteristics result from the hard magnetic material of which the rotor is made and the simple rotor construction. Unlike other synchronous motors, the hysteresis motor has a perfectly round and symmetrical rotor. The rotor has no salient poles, so it has no preferred direction for synchronizing.

Fig. 1a Hysteresis loss causes the rotor flux to lag behind the rotating stator field. The resulting displacement (phase angle) between rotor flux and stator field produces hysteresis torque. **Fig. 1b** Typical hysteresis loops of rotor materials used in hysteresis motors (high hysteresis loss) and conventional motors (low loss). The phase angle in a hysteresis motor is proportional to the area of the rotor material's hysteresis loop. **Fig. 2** Performance characteristics of a small hysteresis motor for high-inertia applications (0.125 horsepower, 60 cycles per second, four pole, designed for 150-percent pullout).

Motors that do have salient poles have a definite discontinuity between operation *below* synchronous speed and final operation *at* synchronous speed. This discontinuity causes synchronizing problems in conventional synchronous motors, and these problems must be dealt with.

operating principles

While the hysteresis motor's construction is simple, the same cannot be said for its theory of operation.[1] Briefly, several effects interact to produce torque.

Below synchronous speed, torque is produced primarily by the hysteresis effect (Fig. 1). As the stator field sweeps around the rotor, the rotor flux cannot sweep along in phase because the rotor is made from magnetic material that has high hysteresis loss. (The rotor flux, in fact, lags the stator field by a phase angle proportional to the *area* of the rotor material's hysteresis loop.) This angular displacement of rotor flux with respect to stator field is precisely what is needed to produce torque, so the rotor receives an accelerating force.

In addition, the rotor flux induces eddy currents as it sweeps through the rotor at speeds below synchronism. These eddy currents produce additional torque for acceleration, which is why the motor's torque is greatest at lower speeds (Fig. 2a).

Once the rotor reaches synchronous speed, the rotor flux ceases to sweep around it. Both eddy-current and hysteresis torque disappear, leaving the rotor magnetized and the motor running essentially as a permanent-magnet motor.

Motor designers have optimized both subsynchronous and synchronous operation by experimenting with different rotor materials and configurations.

synchronizing considerations

In a motor with physical poles, the poles are favorably aligned to pull into synchronism only for a definite fixed time. Since the time is fixed, it follows that a high-inertia load requires more synchronizing torque than does a low-inertia load. This is why all synchronous machines with physical poles are greatly affected by load inertia.

With a uniformly round rotor, this limitation does not exist. In both theory and practice, there is no discontinuity whatever in hysteresis-motor operation below synchronism and at synchronism. Since no discontinuity exists, the motor has no concern for the load inertia connected to it. This is a great advantage in such applications as textile machines, where many loads (Godet rolls, windup rolls,

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[1] Teare, B. R. "Theory of Hysteresis Motor Torque," Trans. Am. Inst. Elec. Engrs. Vol. 59, p. 907.

pull rolls, spindles, etc.) have very high inertia compared with the motor inertia. Such loads have commonly required a motor rating determined by the synchronizing limitation rather than by the actual running load requirements. With the hysteresis motor, however, the rating is chosen according to the normal running load.

current inrush considerations

The very low inrush current characteristic of the hysteresis motor is also associated with its rotor design. Accelerating torque is produced by hysteresis and eddy-current action instead of by induction-motor action, so the high starting currents associated with squirrel-cage windings are not necessary. In fact, the rotor currents in the hysteresis motor are limited to a low value by the high reactance and resistance inherent in the rotor configuration and the special magnetic materials used.

Squirrel-cage motors usually employ designs of low reactance and low resistance, resulting in about 600 percent starting current. With conventional synchronous motors, other design factors increase the locked-rotor current as much as 10 or 15 times normal full-load current.

Thus, a hysteresis motor with 150 percent inrush current may take only one-tenth as much starting current as other synchronous motors. This is especially significant in adjustable-frequency systems, where hysteresis motors are supplied from relatively small alternators.

power supply considerations

With the increasing use of adjustable-frequency systems, in chemical fiber production for example, it is necessary to consider the effect of starting disturbances on the system. Usually, the alternators used are very small compared with the normal stiff 60-cycle power bus. These alternators often must be protected from sudden load changes, such as those caused by linestarting a conventional synchronous motor, to keep the system frequency and/or voltage within acceptable tolerances. Hysteresis motors give this protection because of their low starting current requirement.

Also, if a hysteresis motor becomes overloaded and stalled, the increment of load current drawn is so small that the alternator is not affected. If a conventional synchronous motor were to stall in such a system, a very high pulsating current would be imposed on the alternator system and probably would cause undesirable variations.

performance

Several performance features combine to make the hysteresis motor an important factor in the small synchronous motor field. The motor's advantage on high-inertia loads permits use of a smaller frame for a given application, resulting in a more efficient application of the motor to its load. Also, it can be made to operate with efficiency and power factor equal to or better than those of other motors, especially in fractional-horsepower ratings where the premium cost of the rotor material is not so great.

Typical performance curves for a modern fractional-horsepower hysteresis motor are shown in Fig. 2. They represent a vast improvement over early hysteresis motors, and already the motor that they are based on is being superseded by newer designs resulting from continued development of rotor configuration and materials.

applications

The hysteresis motor introduces a new application factor. In most uses of conventional synchronous motors, pull-out torque is seldom a governing factor because the pull-in phenomenon is more critical. Thus, if a motor can synchronize its load, it usually has ample pull-out torque. However, the hysteresis motor has no synchronizing problem, so it is important to apply it with knowledge of the maximum torque requirements of the load.

Many loads, especially in chemical fiber production, are quite steady. Consequently, a good application usually results if the motor is applied on the basis of known running load requirements, with a margin of say 50 per cent for abnormal conditions. Moreover, the consequence of pulling a hysteresis motor out of synchronism on overload is negligible. Motor current increases slightly, but the motor continues to run smoothly below synchronism without disturbing the rest of the system.

summary

The most promising applications of the modern hysteresis motor appear to be in conjunction with power supplies that use solid-state devices to generate adjustable-frequency ac power. Because these power supplies must be applied carefully on the basis of peak current demand, the low inrush-current requirement of the hysteresis motor is ideal for them.

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PERSONALITY PROFILES

PHILLIP G. DEHUFF has been primarily concerned with technical management for many years, but his original metallurgy training has served him well.

DeHuff graduated from the Department of Metallurgy of Lehigh University in 1940. His first job was with the Carnegie Illinois Steel Company where, among other things, he worked on armor plate problems. A year later he returned to Lehigh to take part in an industry-sponsored study aimed at producing better castings for ship propulsion units and in 1942 joined Westinghouse to work on similar problems. In 1945, he moved to the newly formed Aviation Gas Turbine Division as head of the metallurgical engineering section.

In 1955, DeHuff transferred to the Bettis Laboratories, where the Shippingport Project was just getting well underway. Here he became manager of the section responsible for developing nuclear fuel elements for the plant. In 1956, he became assistant manager of the project, with responsibility for core engineering.

In 1959, DeHuff moved to the Atomic Power Department; in January 1960, he became manager of the CVTR Project.

The career of M. E. FAGAN has carried him into three quite different and seemingly unrelated fields.

Fagan graduated from Brown University in 1938, with an AB Degree in Chemistry. He then went to work for a textile finishing firm as a chemist. He joined the Westinghouse International Company in 1946, as an engineer in the electric utility section. In 1948, he went to the Westinghouse Transformer Division, in the ordnance department where electric torpedoes were developed and manufactured. He became engineering manager of this department in 1953, and manager in 1954. A few years later he became engineering manager for the power transformer department.

It is not always easy to get two engineers together to author an article comparing their competing products. We therefore consider it a small triumph for the spirit of "engineering objectivity" to have the article by R. W. FLUGUM and G. B. CUSHING.

George Cushing came with Westinghouse in 1939, after obtaining his BSEE and MSEE from Lehigh University. He joined the switchgear division and shortly thereafter completed the company's Electrical Design School. He turned to power circuit breaker engineering, where he has worked with high-power, high-voltage oil circuit breakers, intermediate-voltage oil circuit breakers, and resistor-equipped oil circuit breakers for capacitor-switching service. Cushing is presently manager of the oil circuit breaker development section.

Robert Flugum came on the Graduate Student Course from the University of Wisconsin (BSEE) in 1948. After completing the company's consulting and application engineering training course in 1949, Flugum worked as an Electric Utility C&A Engineer in Chicago and Milwaukee. His principal responsibility was protective devices.

Flugum joined the Distribution Apparatus Department in 1958, and now is a senior engineer in the technical section.

DR. ARTHUR KAHN is the first psychologist to write for the Westinghouse ENGINEER; perhaps this will contribute to the engineering profession's realization that psychology is a vital ingredient in today's engineering designs.

Dr. Kahn received his BA in chemistry and his MA in psychology from the University of Pennsylvania in 1938 and 1941. During the war years, he served in the U. S. Air Force as an aircraft maintenance inspector. He returned to school to obtain his Ph.D in psychology from Indiana University in 1952. Kahn joined the Westinghouse Air Arm Division in 1954. Here he has worked on various human factor design studies for such projects as Aero 13 and the B-70 defensive subsystem, and on human factor research. Kahn is presently an advisory engineer in charge of the human factors group.

S. SALOWE and W. C. CARTER combine the viewpoints of an instrument designer and an application engineer.

Salowe graduated from Polytechnic Institute of Brooklyn with a bachelor's degree in electrical engineering in 1951 and immediately joined the Meter Division. He worked first on design and application of indicating instruments and then on new products. He earned his MEE from Brooklyn Polytech in 1955 and his MS in mathematics from Stevens Institute of Technology in 1959.

Carter won a Westinghouse scholarship to Carnegie Institute of Technology and received his BSEE there in 1956. He joined Westinghouse on the Graduate Student Course in 1957. He is now working on his thesis for an MS from the University of Pittsburgh. Carter is an application engineer for paper-industry drives in the general mill section, Industrial Engineering Department.

The team of C. G. HELMICK and I. M. MACDONALD is a natural one for describing the Trinistor adjustable-frequency drive system, for both work with industrial drive and control systems.

Helmick received his BSE in electrical engineering from the University of Michigan in 1950 and his MSE the following year. He joined Westinghouse in 1951 and, after completing the Graduate Student Course, was assigned to the general mill section of the Industrial Engineering Department. Most of Helmick's time is devoted to applications for the chemical fiber industry.

Macdonald earned his BSc degree in electrical engineering at the University of Glasgow in 1951. He served in the Royal Navy and then in the analysis department of the British Thomson-Houston Company Limited. He joined the Westinghouse Systems Control Department in 1957 to develop semiconductor circuits for ac drive systems.

J. H. CHAPMAN earned his BS degree in electrical engineering at the University of New Hampshire in 1939 and has taken graduate courses at the University of Pittsburgh and the American International College. He joined Westinghouse in 1942 and was assigned to the Magnetics Laboratory, where he prepared magnet data and developed magnetic materials. He went to the Appliance Division in 1951 and contributed to motor development there. He is now a senior design engineer at the Manufacturing and Repair Division plant in Springfield, Mass.

SPACE COMMUNICATIONS WITH ULTRAVIOLET

A new space communications system under development by Westinghouse will use a beam of ultraviolet light for the transmission of information. Demonstrating how the new system would work, this photograph depicts the ultraviolet beam as it carries a message from an orbiting satellite to a space ship. Engineers working on the project have achieved in the laboratory transmission of a communication signal by means of an ultraviolet beam.