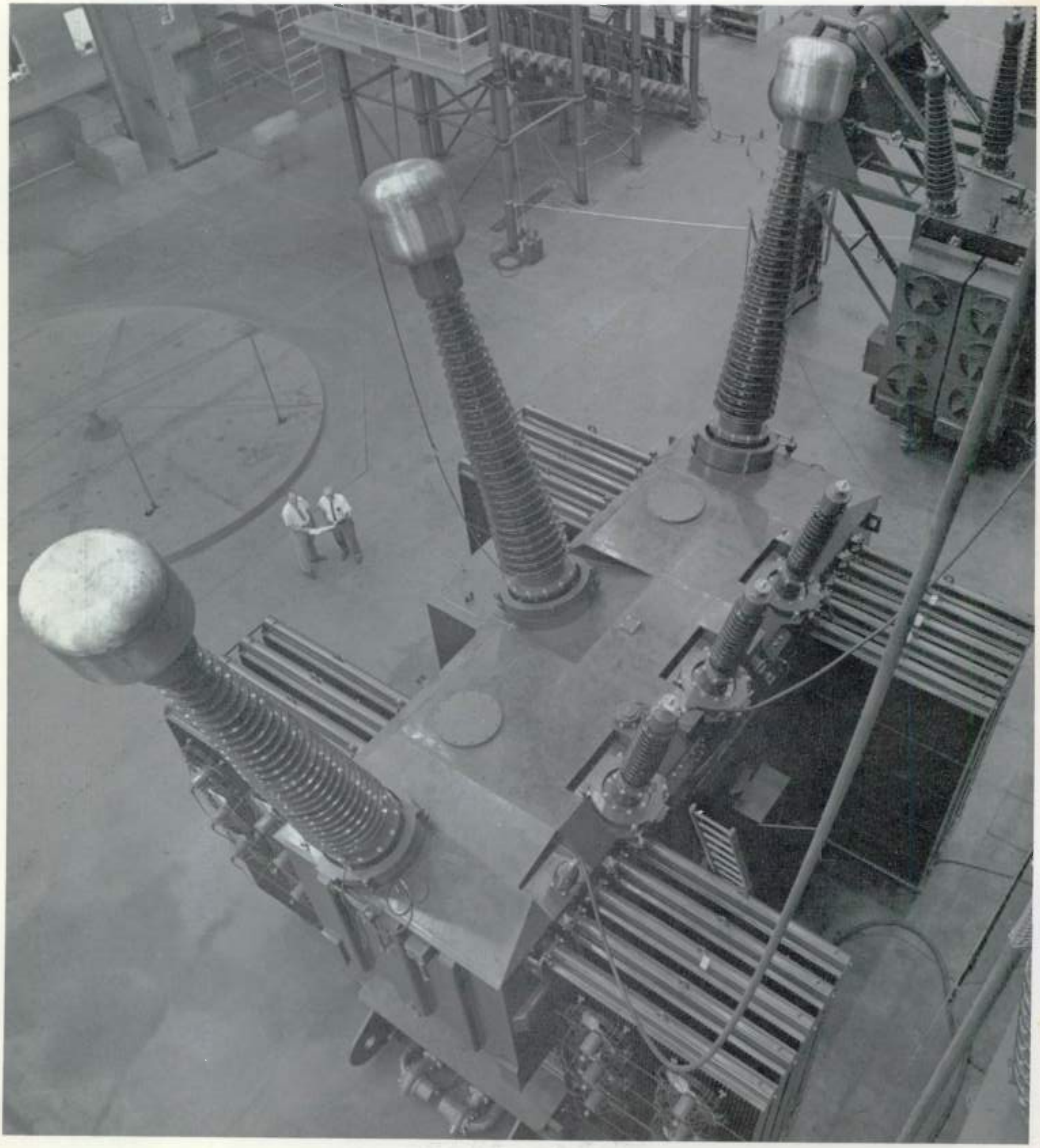
Westinghouse ENGINEER

January 1965



About the Authors

J. H. Clotworthy graduated from the University of Virginia in 1946 with a BEE degree. For the next two years, he worked as a broadcast technician for Radio Station WCAO while taking graduate courses in engineering at Johns Hopkins University.

Clotworthy joined the Westinghouse Baltimore Electronics Division in 1948, where he worked on the design and development of high-frequency communications transmitters, UHF transmitters, and marine radar. In 1952, he was made a project engineer with responsibility for the video distribution and processing equipment for the Bomarc missile ground control equipment.

In 1956, Clotworthy was selected for the Middle Management Program at the Harvard Business School, and upon completion of the program, was assigned to the Transformer Division as assistant to the vice-president. His next assignment was administrative assistant to the vice-president and chairman of the Executive Committee of the Corporation, where he worked on a number of general management problems associated with Westinghouse foreign operations, broadcast stations, and defense activities.

In January 1960, Clotworthy was appointed assistant manager of the Underseas Division, and in October of this same year, assumed his present position, vice-president and general manager of the Underseas Division, Westinghouse Defense and Space Center.

Donald W. Drews was the Westinghouse project engineer for the machinery plants developed for oceanographic research ships built recently by the U.S. Navy and the U.S. Coast and Geodetic Survey. He also has contributed to the development of the propulsion control for many of the electric-drive submarines built by the Navy since World War II.

Drews received training in electronics in the U.S. Army Signal Corps. After his discharge, he earned his BS in electrical engineering at Princeton University, and he has since taken graduate work in control engineering. He joined Westinghouse on the graduate student course in 1947 and was assigned to industrial control engineering at Buffalo, where he served as a design engineer in the marine and general mill section. Drews transferred in 1960 to the marine and transportation engineering group (later the marine systems department) at East Pittsburgh. There he continued to design and coordinate propulsion, control, and auxiliary systems for surface vessels, submarines, and deep-diving research vehicles. He joins the systems engineering group of the Westinghouse Marine Division, Sunnyvale, California, this month.

Paul E. Lego earned his BS in electrical engineering at the University of Pittsburgh in 1956 and his MS there in 1958. Lego joined Westinghouse on the graduate student course and was assigned to the Advanced Systems Engineering and Analytical Department at East Pittsburgh, where he worked on regulation and simulation problems and on digital computer programming. In 1958, he joined the Computer Advisory Service in Engineering, a group that had been organized to acquire computer technology and see to its profitable employment in engineering operations.

Lego returned to the advanced systems department in 1960 to work on basic control computer programming techniques. As engineer in charge of the computer application group, he was responsible for the programming of the Public Service of New Jersey automatic steam plant control. He joined the Computer Systems Division in 1963 and is now manager of the application programming section.

Joseph C. Rengel has had over ten years experience in pressurized water reactor technology, ranging from ship propulsion to commercial atomic power plants. He is presently general manager of the Atomic Power Division.

Rengel joined Westinghouse in 1937, following his graduation from the U.S. Naval Academy. Subsequently, he held positions in the marine and transportation departments, and in 1952 became assistant to the sales manager of the Defense Products group of Westinghouse.

In 1954, he became project manager for the large ship reactor at the Bettis Atomic Power Laboratory. In August of 1955, he became project manager for the PWR Project, where he directed for Westinghouse the design, development, and construction of the reactor portion of the Shippingport Power Station.

In 1959 Rengel moved to the Atomic Power Division, where he first became project manager responsible for the development of a large commercial nuclear power plant. In 1961, he was made manager of advanced development and planning of closed cycle nuclear plants. In 1962 he became deputy general manager of the Division, and in 1964 was made general manager, his present position.

J. H. Cronin and **H. E. Lokay,** both Sponsor Engineers in the Westinghouse Electric Utility Engineering Department, discuss the economics of peaking generation in this issue.

Cronin attended a two-college joint program, graduating (1949) with a BA in mathematics from Washington and Jefferson College, and a BSEE from Carnegie Tech. He joined the Duquesne Light Company on its student training program. Upon completion of the program, he was assigned to the company's Transmission and Distribution Department, where he held positions of junior engineer, materials engineer, and division line engineer.

Cronin came with Westinghouse in 1957 as a project engineer in the Electric Utility Engineering Department. He held positions of generation engineer and advanced development engineer prior to assuming his present position of sponsor engineer for the Central Zone.

Lokay graduated from the Illinois Institute of Technology with a BSEE in 1951. He obtained his MSEE from the University of Pittsburgh in 1956, while working in the Electric Utility Engineering Department at Westinghouse. Lokay initially concentrated on electric utility distribution systems. He is presently involved in a variety of systems planning studies in generation and transmission. Lokay was made a sponsor engineer for the Midwest Zone in 1959.

Multiple time exposures (note the star tracks) were used to obtain this dramatic photograph of a sixty-cycle flashover test of the 500-kv Type V-2 disconnect switch. The photograph was taken at the new Westinghouse EHV test center, where equipment ranging through the 1000-kv class can be tested fully.

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Left: A transformer for the nation's first commercial 500-kilovolt transmission line was given its final tests recently before shipment. In addition to routine tests, the transformer successfully withstood a man-made lightning stroke of 1,500,000 volts. The 500-kilovolt transformer will be installed in a substation near Waynesboro, Virginia, to serve the extra-high-voltage line being built by the Virginia Electric and Power Company (VEPCO).

VEPCO's new mine-mouth generating plant at Mt. Storm, in the coal fields of the eastern West Virginia panhandle, will produce 1,080,000 kilowatts of electricity. Its two turbine generators are rated 540,000 kilowatts each, and it will consume 2,800,000 tons of coal a year. Its power will be transmitted over EHV lines throughout Virginia when it goes into operation later this year.

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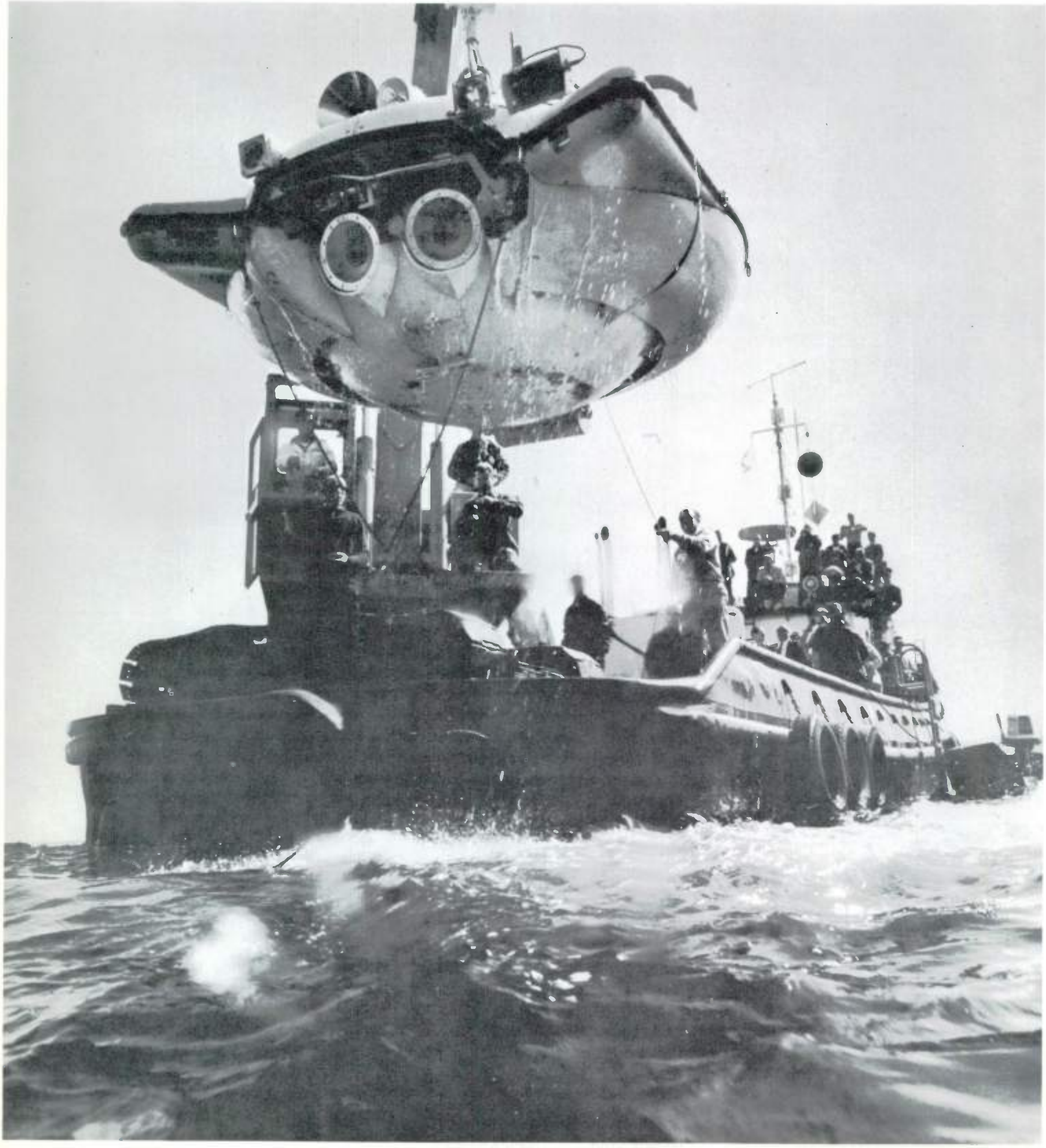
Prodac

Cover Design: Almost three-fourths of the earth's surface is covered by water, and is largely unexplored. This mysterious frontier is depicted on this month's cover by artist Thomas Ruddy.



Oceanography—A Field of Expanding Horizons for the Engineer

by J. H. Clotworthy

Earth's vast "inner space," the sea, is still virtually unexplored. New oceanographic survey and research tools are needed to gather the information necessary for studying the sea's physical and biological systems.

The sea is a mantle that covers 71 percent of the surface of the earth to an average depth of 12,000 feet. If all of the irregularities of the earth's surface were smoothed out, this mantle would cover the complete planet to a depth of 7500 feet. Four-fifths of the animal life on earth, except for insects, live within the sea. On the sea bottom are many forms of animal life, some swimming, some crawling or burrowing, and others, like the coral, stationary. Little is known about the process of birth, life, death, procreation of these organisms, and little is known of the physical environment in which they live—its temperature, salinity, density, sediment, turbidity, currents, oxygen content, light, and many other variables that may be undiscovered and unnamed.

There is abundant wealth within the sea. At a penny a pound, the salt in a cubic mile of seawater is worth 2.3 billion dollars; in this same cubic mile, there is magnesium worth 3 billion dollars, 250 tons of bromine, and 3.8 million tons of potassium sulfate. The sea is of immense economic potential to mankind and immense military significance to America.

Within the last several years there has been a general awakening in the United States to the importance of the sea. The budget for oceanographic research has grown threefold since fiscal 1961, and the U.S. now has a national oceanographic program "to acquire the understanding of the ocean and to translate this understanding into operational concepts and hardware that will enable the United States and its allies to exploit our peculiarly oceanic position militarily, economically, and politically." An Inter-Agency Committee for Oceanography has been formed to coordinate the activity of some eight different government agencies who have an interest in the future of the sea. The Chairman of the ICO, a Navy Assistant Secretary for Research and Development, reports directly to the President.

Challenges for the National Oceanographic Program

To exploit the sea in any manner, the behavior of the sea must first be understood; the natural laws it follows must be known. From these natural laws and observations of covariants, the sea's subsequent behavior should be predictable in much the same way that weather can be forecast. With the sea's behavior accurately predicted, systems of men and equipment can be designed for the sea's exploitation. For example, a ship is a simple man-machine system for transportation over the sea. Its sea-keeping ability is based upon an application of existing knowledge of winds, waves, tides, and surface currents. The first sailors went through painful trial-and-error procedures before learning to forecast the behavior of a given hull form in the sea. Today's modern ocean liner usually weathers the heaviest assault by the elements in the North Atlantic, but a 25-foot cabin cruiser cannot last long under such conditions. This is about the extent of progress in mating man, equipment, and the environment of the sea.

Man's knowledge of the sea is truly minute, perhaps because the sea cannot really be defined generically—its systems are largely unknown. Today's scientific investigation, which must be the basis for future progress, is generally devoted to extending assumptions based on an uncertain knowledge of the medium. Indeed, basic knowledge of the sea is so severely limited as to frustrate efforts of researchers to advance knowledge at a rapid rate.

The history of the investigation of currents provides an example: In the late eighteenth century, Benjamin Franklin became the first American to chart and attempt to explain the Gulf Stream. While a great deal of work has been done to learn more about this current, very little has been accomplished in locating and charting new current systems. It was 1951 before a major subsurface current was discovered and named for Townsend Cromwell, one of its discoverers. This current flows eastward along the equator at an intermediate depth, 300 feet. Its speed is 4 knots. It lies below a surface current which flows in the opposite direction. The Cromwell Current has been traced for some 3000 miles across the Pacific. Its volume of flow is equivalent to more than 1000 Mississippi Rivers.

In addition to these chartable currents, transient currents form as a result of discontinuities and gradients resulting from variations in water density and temperature. These currents generate what are known as internal waves. These waves are quite variable, and the ability to predict their behavior will depend upon the advances in knowledge of the variation in the parameters that cause them.

New currents are also being discovered. Until the *Trieste* made its 36,000-foot dive to the bottom of the Challenger Deep, water in the deep trenches was believed to be motionless. However, the crew of the *Trieste* observed marine life in the Challenger Deep. This demonstrated the existence of bottom currents, for without them oxygen transport, a necessity for the support of life, could not take place.

Currents in the upper atmosphere exist just as do currents in the depths of the sea. These atmospheric currents in time will come to be linked integrally with phenomena observed at sea, because the atmosphere and sea in combination form a gigantic

Undersea vehicle Diving Saucer is shown being lifted from the water during operations off the California coast. This operation is part of a world wide charter facilities for ocean exploration, operated by Westinghouse. The undersea service will provide a support ship and crew, a submersible, personnel and equipment for investigation and exploration by scientific, government and private agencies.

J. H. Clotworthy is Vice-President and General Manager, Underseas Division, Westinghouse Defense and Space Center, Baltimore, Maryland.

thermodynamic machine. One such current has been discovered in recent years in the upper atmosphere, parallel to the equator at an altitude of approximately nine to eighteen miles. These winds, above the jet stream, move for twelve months in an east-to-west direction. For the succeeding twelve months, the flow is reversed. The velocity of flow has a half-cycle period of six months.

From discoveries like these, scientists have reason to ask what other systems—physical and biological—have yet to be discovered that will be of tremendous significance in exploiting the sea for military and economic gain.

Designing Tools for Oceanographic Research

Before beginning a design project, the problem to be solved must be defined. But this problem is inherently difficult where the sea is concerned, because in many cases no one knows precisely what to look for. The scientist, who must define the problem, is often groping for some basic knowledge from which he may propose a meaningful thesis. Take, for example, the problem of mapping four-dimensional space. Assume that distribution of temperature, density, and sound velocity is to be determined for a volume of water 100 miles by 100 miles by one mile deep. Instruments are available that can measure each of these parameters. But to what accuracy must variations be known to characterize accurately the conditions found in the given volume? Must temperature be measured to one degree, a tenth degree, or one-hundredth degree accuracy to explain the operation of the thermodynamic system within this volume of water? If a sweep is made with an instrument chain, must the sensors be one foot apart, ten feet apart, one hundred feet apart, or one thousand feet apart to properly characterize the conditions? And if a path is made for one hundred miles now and, twelve hours later, a parallel path in the opposite direction, will there be any correlation between the two sets of data; or has the passage of time played such an important role in the processes at work that the second path is meaningless for purposes of correlation? And furthermore, how far apart should the paths be? Is a ten-mile spacing close enough, or should it be one mile? If one mile is the answer, an entirely new problem has been introduced. Can position on the ocean with less than one mile precision be determined?

There's another real danger in mapping this volume of water. If too little data is taken, it may be impossible to learn what is going on within the volume. On the other hand, too much data might be impossible to process and understand. Thus, if scientists knew precisely what they were looking for, the problem of definition would be made somewhat easier. There is the real danger of overlooking a significant effect by using data of too coarse a grain.

This example simply demonstrates the difficulty in defining certain basic problems related to research at sea, and it has within it an important lesson for scientists and engineers. Any system designed today, regardless of the basis on which it is established, must be inherently flexible so that redefinition of the basic problem, growing out of newly acquired knowledge, does not result in the system's immediate obsolescence. Each system today must have growth potential so that higher degrees of accuracy can be recorded and processed and more variables recorded. Finally, the data must be in a raw form that allows correlation processes to be explored.

Seagoing Surveys

The development of instrumentation for survey purposes has suffered for lack of an incentive for the growth of research techniques. In the past, most marine scientists were engaged in individual research and sought tools with a capability peculiar to their own endeavor. With few exceptions, there has been little effort to standardize survey tools, and those that have been standardized are archaic by any present-day standards. The reasons for lack of attention to survey type instruments are obvious. The most obvious is the lack of funding for oceanographic pursuits in general. This has resulted in a dearth of good instruments designed particularly for survey purposes. Thus, significant advances in the marine sciences will require design, development, and manufacture of survey instruments that are characterized by high reliability and repeatability and that can be produced at a price that will encourage the construction of survey instrumentation suits consistent with the magnitude of the job to be done.

There is a further need for the development of integrated oceanographic systems. These are systems in which a number of fundamental sensors are combined for the simultaneous observation and recording of a number of variables.

Basically, there are two types of integrated instrumentation systems. First are the research or special purpose systems. These systems are specifically tailored to perform unusual and not necessarily repetitive tasks. They require a high degree of thought and planning if the on-station time of the scientist is to be economically used. The second type system, the survey system, must perform a repetitive function in examining large masses of data from which forecasting techniques can be developed. Simply stated, the need here is for an efficient, reliable data-gathering system designed for the routine acquisition of large quantities of data of all types over world-wide ocean areas. Furthermore, the system must have reserve capability for making the detailed observations required from time to time by specific scientific or military objectives.

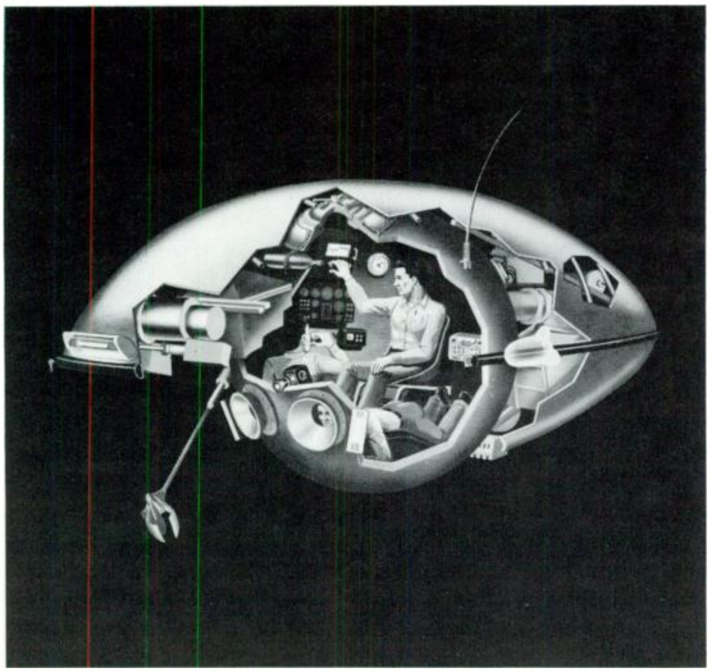
To meet these requirements, the international implications of survey data collection must be kept in mind. Inputs from the researches of many nations must be combined to form a central pool of knowledge from which the basic laws of the sea can be derived. Therefore, many national and international agencies must cooperate in the conduct of survey operations. This necessity demands flexibility in performing measurements of varying types, quantities, and accuracies.

Survey System Design

To meet the requirements of a survey system, the equipment designer must be aware of the constantly changing art of sensor design. Anticipated improvements in the future dictate that the system have sufficient growth potential to accommodate sensors of new types and greater accuracy. Although all the possible applications of the survey system cannot be foreseen at this time, changes will inevitably occur both in the physical implementation and application of the system. Therefore, it is important that the basic data-handling techniques designed into the system at the outset be adaptable to the cycle of change.

A good example of this need is bathymetry. In the past, depth information has been recorded and measured by an acoustic fathometer with a 60-degree beam width. In shallow depths, beam width was of no particular consequence. When measurements were made in deeper water, the area covered (e.g., more than 1,000,000 square feet at 1000 foot depth) became critical. The return from the bottom, read on the fathometer record, showed many inseparable responses from a single transmitted pulse and, in fact, measured only the shortest acoustical path. This caused loss of bottom detail and usually indicated a depth less than actual depth. Any system designed to handle data received from this type device would be hopelessly inapplicable in light of recent developments in the field of bathymetry. Oceanographers can now measure depths of points located so close together that the points cannot be clearly differentiated geographically. This precision for the resolution of bottom variations is valuable to many investigators even though a geographic plot is never made of each point. Using a vertically stabilized precision fathometer with a beam width of 7 degrees, the area illuminated is 100 times less than if a 60-degree instrument were used, thereby providing a far more detailed description of a given area. Besides permitting accurate exploration of sharp discontinuities, this precision will enable a potential user to decide whether a bottom submarine could safely hide in the mass of bottom clutter that would appear on a bottom-mapping sonar.

Deepstar cutaway view shows the vessel's interior, designed to permit two men to recline in front of the viewing ports while a third maneuvers the vehicle. A lighting system will illuminate the ocean floor at murky depths and a communications system will provide contact between the crew and the surface support ship.



In measuring ambient light, the same considerations apply. It is important for the oceanographer to know the average transmission factor as a function of depth, but those interested in light beam communications or in visual detection of underwater objects will want to know how the transmission factor fluctuates.

It appears that prediction of the performance of all communications and detection systems depends on knowing the noise background as well as the average transmission factor. Therefore, to collect data of military interest, bandwidth must be preserved. Scientists are interested in knowledge of energy transmission that can be inferred from the study of mixing phenomena and the accurate measurements of gradients, both of which require that the higher frequency components of the data be preserved. Temperature, salinity and sound velocity microstructure and sharp gradients are important to the sonar and also require large sensor and recording bandwidths. Scientific discoveries in this field have always followed sensor improvements. The danger of failing to observe new phenomena because of restricted frequency response is real.

The actual noise records for the quantities measured are of no basic significance, since the measurements are not repeatable. Nevertheless, the autocorrelation and cross-correlation functions for these quantities may be of great importance. The amount of recorded data might be reduced if the spectra or correlation functions could be derived aboard ship, and only the results recorded. Unfortunately, because of the variables in the process of deriving spectra correlation functions and collecting suitable data, the effect to be searched for must be known in advance. Such surveys can be made possible by designing an adequate survey system.

After a survey system is put into operation, many unanticipated data requirements may arise. The new requirements may be so important as to force the removal of certain basic survey sensors if the system is not capable of handling the increased load. For this reason, the capabilities not only of the recording system but also of the cable transmission bandwidth and the computer must be generous in the basic design. In addition, the system should be open-ended.

Given this theory of system design, consider a tangible equipment design problem: data transmission over a cable.

Several problem areas arise in telemetering data over a cable. First, background noise may reduce reliability and accuracy and increase the error rate of any coding scheme. These noises may originate from thermal noise, cable and terminating losses, cable pickup from the ship and external impulsive noise sources, cable flexing, code and transmitter sensor, bias errors, or counting errors. The problem of test and calibration of the instruments in the sensor package imposes a limitation on the design of the package. Problems associated with the cable, its characteristics and their vulnerability with time from cable to cable, may make certain types of coding schemes completely impractical.

Finally, although the emphasis must be placed on reducing and recording data in digital form, there may also be a requirement for presenting continuous analog data. If some of the possible coding schemes were used, data at the receiving end of the cable would be available only in sampled form. Therefore, interpolation or at least smoothing would have to be used to reconstitute the analog form. This interpolation means that the data either must be bandwidth limited by the reciprocal of the sample rate or that induced inaccuracies outside this bandwidth be tolerated but minimized by careful choice of the set of interpolation functions. The disadvantage of smoothing is that it would average the data and remove the more rapid fluctuations due to microstructure from the reconstituted analog data. Neither of these situations presents an attractive choice, but these constraints must be considered in the choice of a coding scheme.

There are challenging mechanical problems also. Operations at sea are notoriously precarious because of the lack of a stable base from which to work. The vagaries of sea state and weather seem to be in constant conspiracy with corrosion and marine fouling to make man's intrusion of the sea's domain a failure. A platform that is satisfactory in a five-knot wind might break apart or be totally unsuitable in a 30-knot wind when the waves kick up to between 14 and 28 feet. When operating a long way from home base, the seagoing platform must be capable of withstanding adverse weather. If it can't adjust to a wide range of conditions, its usefulness suffers. The result is a continuing series of compromises involving economy in design and manning, speed, endurance, range, and the type of work the platform must carry out.

The modern oceanographic research survey ship makes many calls on a mechanical engineer's skill. The mission may call for the ship to hover over a particular spot on the ocean floor and lower a package of instruments to obtain a profile of oceanographic variables as a function of depth, or perhaps to extract cores from the sea floor. When the ship is under way, it may also tow packages of instrumentation. These may be either deep-running or close to the surface. There is a tempting array of design problems involved in the task of towing a 1000-pound instrument package at five to ten thousand feet below the surface at a speed of five to ten knots. The interaction of drag with cable profile and strength per unit of cross section presents an interesting combination of variables, and present towing systems are so poor as to make the solution of this one problem an economically fertile field for the developer of something better.

Modern oceanographic ships someday will be equipped with submersible vehicles that can carry two or three men to the bottom of the sea. Handling vehicles weighing ten tons or more in a heavy sea is difficult, but the problem must be solved. The vehicles will be much less useful if their operation is limited to those days when the sea is calm.

Important problems of ship control exist. Economic pressure for more effective use of the limited national oceanographic budget suggests that all elements of ship control be examined to eliminate human effort wherever possible. Unfortunately, ships are designed along traditional manning lines. As a result, the ship is first a seagoing hotel, and second a useful piece of marine equipment.

But economies can be effected in all phases of a ship's operation: on the bridge, in the engine room, on deck, and in the crew-support functions. This is being accomplished as evidenced by two recent Class I oceanographic survey ships equipped with a centralized engine-room control system. (See *Oceanographic Ships With Computer-Assisted Central Engine-Room Control, p. 7.*) This system permits safe, efficient marine power plant operation with a one-man engine-room watch. It includes centralized remote operation and automatic centralized techniques. Its use should reduce operating and construction costs, increase reliability, and decrease downtime in ships' operation. But this is only a beginning.

In summary, the outfitting of a seagoing oceanographic survey or research platform presents a challenging opportunity for all branches of the engineering profession to join together in devising the most appropriate and economical system. This system must be designed from the keel up. The interdependence of displacement, sea-keeping ability, speed and directional control, prime and auxiliary power requirements, navigational system, communications equipment, the scientific equipment complement, and the manpower required to operate the station must be recognized. A truly successful system in all senses will be achieved only when these variables are competently balanced, optimizing them with regard to the immediate mission, and, at the same time, leaving the system open-ended, so that as requirements change the capability of the ship can also be changed. The *Atlantis II*, recently completed for the Woods Hole Oceanographic Institution, and the recently authorized catamaran type of vehicle for the Chesapeake Bay Institute of The Johns Hopkins University, are evidence of this trend. The design of the total ship system is a field that is just beginning to be developed. Thus, a great opportunity exists for a significant contribution by the engineering profession to an expanding science.

This discussion has been concerned primarily with the tools for obtaining information, but other areas of oceanographic concern, which can only be successfully explored with the help of engineering innovation, should not be overlooked. These include farming the sea for fish and other living organisms; recovering of minerals, particularly the undersea completion of oil and gas wells; the recovery of fresh water from the sea; waste disposal; and many new military problems that will arise from man's increasing store of knowledge of the sea.

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Oceanographic Ships With Computer-Assisted Central Engine-Room Control

by Donald W. Drews

Two oceanographic survey ships now being built have central engine-room control systems for operational speed and efficiency. A digital computer serves both the scientific instrumentation and the engineering plant.

Important steps in man's journey of exploration into the sea around him will be made with the help of two new oceanographic survey ships scheduled to go into service this year. The ships are the largest ever built in the United States for this service and also the most highly automated oceanographic survey vessels in the world. Advanced propulsion, control, and scientific systems will enable the ships to operate efficiently in deep or shallow waters, under way or fixed on station, and in arctic or tropical seas.

The ships, essentially identical, will be operated by the Coast and Geodetic Survey, U.S. Department of Commerce. They are designated Class I oceanographic survey ships and will be named *Oceanographer* (OSS-01) and *Discoverer* (OSS-02). Each is about 303 feet long, with a displacement of about 3800 long tons. They will have a sustained speed of around 16 knots at 18-foot draft and will carry about 116 scientists, officers, and crew. The ships are being built by Aerojet-General Shipyards, Inc., Jacksonville, Florida, in accordance with specifications prepared by the Maritime Administration, U.S. Department of Commerce.

Integrated information-processing equipment will free the scientists from much of the former tedious data-reduction tasks by reducing scientific data to meaningful information as it is gathered. The heart of this equipment is a digital computer system. The computer system has enough capacity for additional work, so it is also used in the central engine-room control system. It is operated on a shared-time basis, with priority for the engineering functions.

The engine-room control system enables a single operator to operate the engineering plant from a central station. Electronic monitoring and data logging gives early warning of any abnormal conditions and thus permits fast corrective action through an extensive system of remote controls. The engine-room control system also enables a bridge officer to control speed and direction of the ship's propellers directly.

Such control is a long step toward the ultimate goal of a completely automated ship's engineering plant, a goal that promises significant reduction of ship operating costs. In commercial shipping, operating cost reduction will improve the shipowner's competitive position in the world market.[1]

The computer system used in this pioneering application is a Prodac 510 system that has a core-type memory with a capacity of 16,384 eighteen-bit words. Access time to all core memory locations is 1.8 microseconds, with a complete read-write cycle time of 4 microseconds. Add time is 8 microseconds, average multiply time is 38 microseconds, and floating-point operations through a subroutine take approximately 600 microseconds. The core memory is fully protected against loss of memory due to voltage transients or loss of power.

Main Machinery

Propulsion Plant—The vessels' missions demand great maneuverability, station keeping, and course stability at low ship speeds. These requirements are met by a twin-screw, diesel-electric, dc adjustable-voltage propulsion system augmented by a bow thruster. Power is provided by four 1000-kw, 450-volt, dc generators, each driven by an eight-cylinder, two-stroke, opposed-piston diesel engine. Normal operating speed range is from 475 to 850 rpm when used for propulsion. The generators are directly coupled to the engines, totally enclosed, and cooled by shaft-mounted fans and sea-water heat exchangers. They are stabilized shunt wound with class F insulation. Temperature rise is 60 degrees C at the normal rating of 1000 kw, 75 degrees C at maximum continuous rating of 1150 kw. Each has a single sleeve bearing lubricated by oil from the engine lubrication system.

The two 2500-hp, 900-volt dc propulsion motors, one for each propeller, are single-armature machines directly coupled to the propeller shaft. Full-power speed is 150 rpm. The motors are shunt wound with class F insulation. Temperature rise is 60 degrees C at the normal rating of 2500 horsepower, 75 degrees C at maximum continuous rating of 2750 horsepower. Each motor has two sleeve-type journal bearings, and a Kingsbury thrust bearing at the after end. Static excitation is employed to minimize maintenance and space requirements. The motor fields are connected to a common dc excitation bus energized from the ship's service ac power system through silicon rectifier units. Tapped resistors in series with the shunt fields of each motor provide field current adjustment to suit the various generator combinations. Motor field currents are adjusted automatically by the generator set-up switches.

The propulsion generators require a wider range of field adjustment, and it is provided by thyristor static exciters. Since the static exciters have only one polarity of output, magnetic contactors are used to reverse the polarity of the generator fields when required. The firing control circuits for the static exciters accept load current signals from the propulsion armature circuits for current limiting. The shunt fields of the two port generators are supplied from one static exciter, while a second static exciter supplies the fields of the two starboard generators. A third unit serves as a standby.

The propulsion drive has the Ward-Leonard adjustable-voltage system of speed control, with generator field control employed in the lower speed range and engine speed control in the higher speed range. Reversing is accomplished by reversing the generator shunt fields. Inherent overload protection is provided for the diesel engines by a load-limiting circuit in the

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Donald W. Drews is a senior engineer in the Marine Division, Westinghouse Electric Corporation, Sunnyvale, California.

[1] "Central Engine-Room Control for Cargo Ships," R. E. Stillwagon, *Westinghouse ENGINEER*, May 1964, p. 86.

generator static exciters. A small voltage signal proportional to the propulsion motor armature current is fed into a control circuit in the generator exciter. When this signal exceeds a value representing full-load current, the generator excitation is reduced to reduce the motor speed and load until the overload condition passes. An overload of short-circuit magnitude will trip an instantaneous overload relay and remove all excitation from the generators.

Auxiliary Uses of Propulsion Generators—The flexibility of diesel-electric drive makes it possible to use one or two of the propulsion generators for the bow thruster and dc auxiliaries when they are not required for propulsion (Fig. 1). Each generator has its own set-up switches, which are interlocked to prevent improper operation.

The bow thruster consists of a fixed-blade propeller mounted in a transverse tunnel near the bow of the ship below the waterline. One propulsion diesel generator is operated at 475 rpm for this duty; it supplies adjustable voltage up to 250 volts dc for speed control and reversing of the 400-hp bow-thruster motor. A separate static exciter with reversing contactors is available for whichever propulsion generator is selected for bow-thruster power.

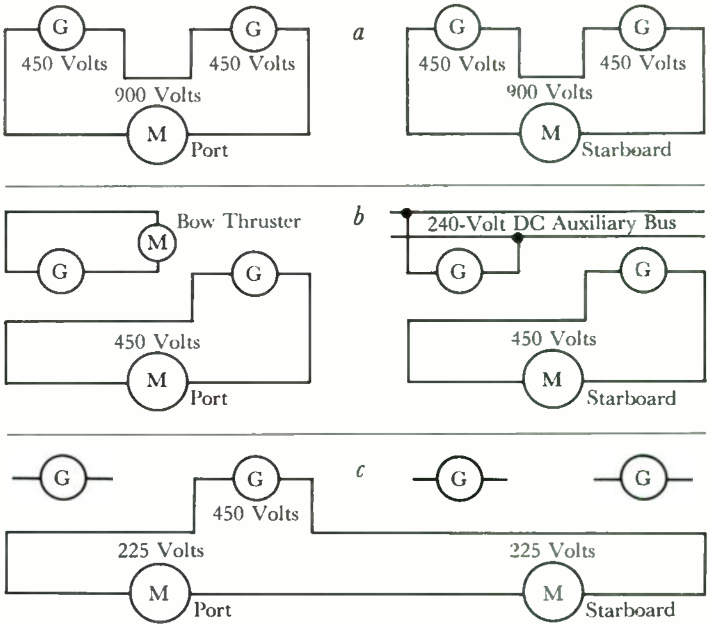
Either one of the two propulsion generators arranged for connection to the dc auxiliary bus can be used to supply constant voltage at 240 volts dc for such auxiliary loads as the 150-hp motor driving the hydraulic deep-sea anchor and coring winch. Again, a separate static exciter provides excitation and regulates voltage.

Auxiliary Generators—Ship's service electric power is supplied by three 400-kw diesel generators, and a 100-kw emergency diesel generator provides power for emergency service. Power is generated at 450 volts, three phase, 60 cycles. The generators are brushless machines with attached exciters and static voltage regulators.

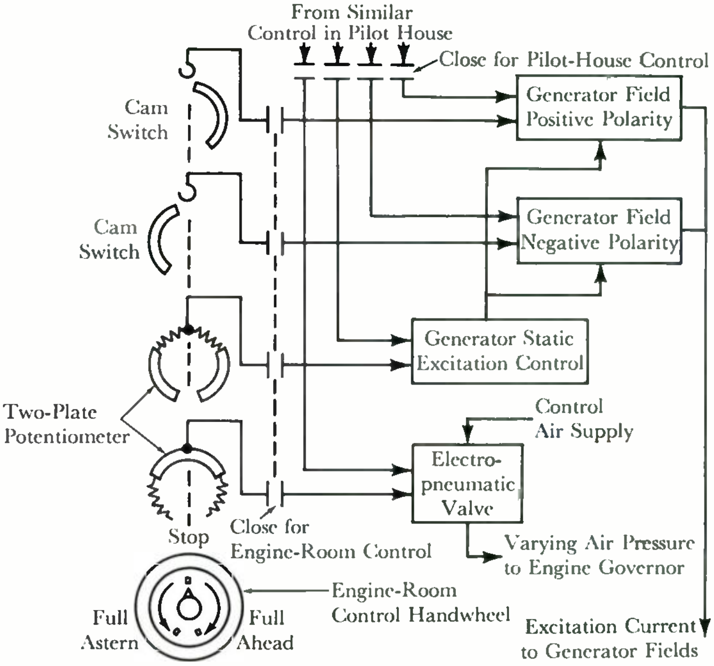
Central Control

The basic intent of central engine-room control (CERC) is to permit reliable operation of the ship's machinery plant with fewer people by reducing the number and complexity of the operator's duties. This intent is accomplished by placing more operations under automatic control, by more extensive use of remote controls and automatic sequencing, and by providing the operator with enough information so that in an emergency he can take the proper action promptly and correctly.

A CERC system, whether for a steam or a diesel plant, should include the following minimum features if it is to fulfill its purpose: Pilot-house control of propeller speed and direction, with means for automatically limiting transient loads to a safe value; pushbutton start-up and shutdown of the main and auxiliary diesel-generator sets, including automatic synchronizing of the ship's service generator sets; pushbutton start-up and shutdown of self-regulated auxiliary systems; central pushbutton remote control of vital electric motors and piping valves; central instrumentation to display the operating conditions of critical systems; central alarm panel to give im-



1—Diesel-electric propulsion generators can be connected in several ways. (*a*) For full-power propulsion, all four are connected to the dc propulsion motors. (*b*) When only half propulsion power is needed, two can be disconnected from the propulsion motors and one connected to the bow-thruster motor while the other supplies the dc auxiliary bus. (*c*) For one-fourth power with single-engine drive, any one generator can be connected to both propulsion motors.



2—Propulsion speed control system, diagrammed in simplified schematic form, is operated by two-plate potentiometers in the engine room and on the bridge. One plate controls polarity and magnitude of propulsion generator fields; the other controls engine speed. This combination produces smooth control of motor speed and direction.

mediate warning of abnormal conditions; and automatic engine-room data logging, including limit checks of certain readings to actuate alarms if any are outside preselected limits.

Because every ship has its own mission and every shipping operator his own operating requirements, the specifications for each CERC system will be different. The two oceanographic survey ships, for example, have all of the features just mentioned plus a few additional ones. Among these are automatic control of fuel tank selection and an automatic deballasting sequence, both controlled by the computer system. The application of CERC in these ships will reduce the number of men assigned to regular engine-room watches and thereby make more men available for day work assignments more closely connected with the mission of the ship.

Pilot-House Control—As soon as the desired number of propulsion diesel-generator sets have been started and set up for operation, the engine-room operator can transfer control to the pilot house. The pilot-house operator has his choice of four control stations. Three are mechanically tied together—one in the pilot house itself and one in each bridge wing. The fourth control station is aloft in the "crow's nest." The engine room can take over control from the pilot house at any time by switching back to local control.

All-electric control of each propulsion motor is accomplished by a two-plate potentiometer at each engine-room and bridge control stand (Fig. 2). These potentiometers are connected to the propulsion control circuit when their respective locations are selected for propulsion control. One plate of each potentiometer is connected to the propulsion generator static exciters; it controls the polarity and magnitude of the propulsion generator fields to control speed and direction of the motors. The other plate controls a small electropneumatic valve that applies a control air pressure to the engine governor in proportion to the amount of current flowing through the valve coil. The two plates are arranged in such a fashion that as the control lever is moved from the "Stop" position in either the ahead or astern directions, the engines are all held at their minimum operating speeds while the generator fields are brought from zero gradually to their full field positions. After the generators have reached full field, further movement of the control lever gradually increases the speed of all engines together until rated speed is reached. This combination of generator field and engine speed control results in smooth accurate control of voltage to the propulsion motors.

Pushbutton Control of Diesel-Generator Sets—The inherent flexibility of the diesel-electric propulsion system is enhanced by provisions for starting any engine by the touch of a button on the engine-room control console. The operator first presses a "Standby" button for the engine he wishes to start. This initiates a checking sequence. If the engine is ready to start—emergency stop lever and manual turning gear are disengaged, jacket water is warm, and starting air pressure is available—a "Ready" light on the console lights. The operator then presses the "Start" button, which opens a solenoid valve in the starting air line to crank the engine. When the tachometer indicates that the engine has started, the operator releases the button, shutting off the starting air. A pressure switch in the engine fuel pump discharge then closes and energizes the engine alarm system. These alarms check oil pressure and temperature, cylinder temperatures, cooling system pressures and temperatures, and fuel pressure as long as the engine is running. The engine runs at idling speed until the generator is switched into the propulsion loop, at which time it is set at the speed called for by the setting of the propulsion controller then in use.

Once the engine is started, loss of electric power to the control system will not stop it. To stop an engine, the operator must press the "Stop" button, which opens a solenoid valve to apply air pressure to the governor shutdown system. The operator can switch to local manual control of the engine at any time with a selector switch.

Ship's service diesel-generators are started and brought to idling speed in a similar manner. When the operator is ready to put a generator into service, he energizes the automatic synchronizing system, which slowly brings the generator up to rated speed. As the generator voltage and frequency approach that of the bus, a transistorized voltage, frequency, and phase detector senses the proper moment for synchronizing, initiates automatic closing of the circuit breaker, and stops the governor speed changer from any further increase in governor setting. The operator then switches to manual generator control to equalize kilowatt and reactive load among the generators connected to the bus. If necessary, the operator can synchronize manually by using a conventional synchroscope and breaker control switch. A ship's service generator set is shut down by first unloading the generator and tripping the breaker in the usual way, and then pressing a "Stop" button that interrupts current to the governor solenoid and stops the engine.

Auxiliary Systems—Most ships have a number of auxiliary systems, or "sub-loops," that are essentially self-regulating: once started, they perform their functions with little attention from the operator. Some of these sub-loops are engine speed governors, generator voltage regulators, automatic boiler controls, salt water evaporators, and oil purifiers. They usually can be incorporated into a CERC system as they are or, at the most, with some slight modifications.

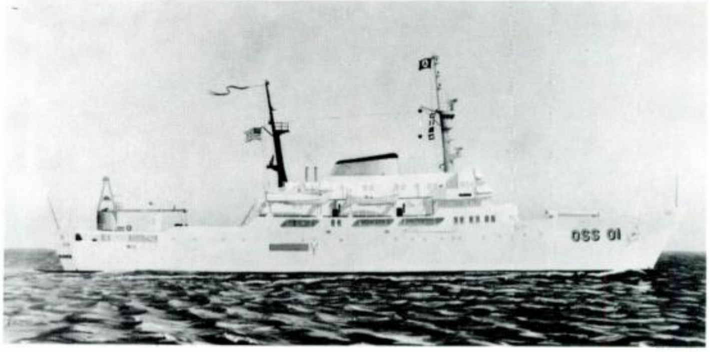
The oceanographic ships' propulsion diesel engines are controlled by governors arranged for pneumatic remote control, and the ship's service diesel-generator sets by electric speed-changer motors. The voltage regulators controlling the brushless ship's service generators are all-static type WZM with type WTM static pilot exciters. Automatic field flashing eliminates the necessity for manual flashing, although pushbuttons are provided for this purpose should it be necessary. The governors and voltage regulators on the ship's service sets have speed droop and reactive power droop to assure proper sharing of load during parallel operation.

Two small auxiliary boilers for heating are started and controlled from a local control panel, but provision is made for emergency shut-down of either boiler from the central engine-room control. Pressing a "Trip" button shuts down the boiler and prevents it from restarting until a "Reset" button is pressed.

The two salt-water evaporators are arranged for complete remote control, with sequenced start-up from a master push-button in the central control console. When the button is pressed, the salt-water feed pump, vacuum pumps, and brine pump are started in the proper sequence. As soon as the required vacuum has built up, a light on the control console indicates that it is time for the operator to supply heat to the evaporator. Normally, this is done by feeding warm jacket water from the ship's service diesel engines to the evaporator, but provisions are also made for use of steam if jacket water heat is inadequate. As distillate builds up in the hot well, a float switch starts the distillate pump. The first distillate is dumped to the bilge, but when temperature and salinity are normal, the dump valve is closed and the distillate is piped to the ship's fresh-water tanks. During start-up, the alarm circuits that monitor the operation of the evaporator are automatically energized. If a pump fails, all other pumps are shut down automatically, an alarm sounds, and the operator is warned to shut off the heat supply. A normal shutdown is accomplished by first shutting off the heat admission and pressing the master stop button, which shuts down all the pumps and alarm circuits after a five-minute time delay. In addition to the master controls, individual remote controls are provided for each pump and local manual control for the evaporators.

Fuel purification is necessary because oil taken directly from the ship's fuel tanks usually contains such impurities as scale, sludge, and seawater. After purification, the oil is stowed in day tanks that keep a limited amount of fuel ready for immediate use. The two centrifuges that are the heart of the purifier system can be started remotely from the control console. The operator starts them by holding down the "Start" button until the motor ammeter indicates that the centrifuge is up to speed and then pressing the "Run" button, which seals in the motor contactor and brings the overload relays into the circuit. Next, the operator starts a pump that feeds recycle water to the centrifuge to provide a bowl seal and assure that the proper level of fluid will be maintained in the bowl during periods of low fuel demand. Finally, he starts the raw-fuel feed pump to supply oil from the storage tanks. The system is then in operation on a self-regulating basis. A level control in the main-engine day tank operates a three-way valve in the discharge of the feed pump so that, when the day tank is full, the raw oil feed is returned to the feed line. On a demand for more fuel, the valve admits the full output of the feed pump to the purifier until the day tank is filled again. The operation of the system is continuously monitored by alarms in the control area that warn of low pump discharge pressures, low day-tank fuel level, excessive centrifuge vibration, and overflow of the diesel oil standpipe.

Remote Control of Auxiliary Motors—About 30 pumps, blowers, and compressors considered vital to the operation of the engineering plant are arranged for remote starting and stopping from the control area. Others do not have remote control but have running indication in the control area. All of these pushbuttons and indicating lights are grouped together in a vital-auxiliary motor panel.



Class I oceanographic survey ships will carry about 116 scientists, officers, and crew. They will gather oceanographic and geophysical data, which will be reduced and correlated by an on-board digital computer system.

As a further aid to the operator, some of the pumps controlled from this panel have solenoid-operated suction valves and lift-check valves on the discharge side. The suction valves are interlocked with, or directly controlled by, the motor starters to insure safe and proper pump operation.

Instrumentation—The preceding paragraphs have shown how CERC extends the operator's hands into all parts of the machinery plant, in effect, by giving him fingertip control from a central location. Instrumentation extends his eyes by enabling him to observe the operating condition of machinery. Use of an automatic data logger, however, makes it possible to reduce instrumentation to a minimum.

Each diesel engine has a remote-reading tachometer and an indicating pyrometer with a selector switch for reading individual cylinder temperatures and common exhaust temperature. The ship's service generator switchboard and the propulsion motor control board are so placed that the operator can readily see the electrical instruments mounted on them.

A large window enables the operator to view the main engine room, and he can observe the auxiliary machinery room, the propulsion motor room, and the steering engine room on television screens connected to cameras in those compartments. Ten microphones in the same areas pick up machinery sounds to go with the pictures.

Central Alarms—Ordinarily, a plant of the size installed in the oceanographic ships would have an engineer's alarm panel with about 30 separate circuits to monitor such critical quantities as cooling air temperatures and oil pressures. CERC, however, makes it practical to include nearly 200 individual quantities. These include the standard alarms, plus such additional quantities as oil temperatures, oil sump levels, cylinder temperatures, and fuel pressures. (Some of them have been mentioned in the description of the auxiliary systems.) Many of these alarms are initiated in the data logger; readings are compared with stored preset limits there, and if one exceeds the stored limit the appropriate alarm circuit is energized. For the basic critical alarms, the data logger is backed up by conventional pressure switches or temperature detectors.

An alarm condition sounds an alarm horn and flashes a red light to identify the item in trouble. The operator acknowledges the alarm by pressing a button on the console. This silences the horn, but the alarm light continues to glow until the condition returns to normal.

Automatic Data Logging—The engineer is completely relieved of the tedious task of touring the engine room every hour to record the readings of the gauges, thermometers, and instruments in his engine-room log. A computer system performs the task for him much more quickly and accurately than he could do it himself. Once an hour, or at any other time on demand of the operator, it reads and prints out about 165 readings of temperatures, pressures, electrical quantities, and other variables. Various types of transducers mounted in the machinery and piping produce the analog signals that represent these variables, and the signals are converted into digital signals in the computer. These are translated into engineering units and printed out on the log with the time of reading. Such readings as kilowatts and power factor are calculated by the computer system from measurements of voltage and current.

The log printer is installed in the central control area where it can be referred to at any time by the operator. Although the complete log is normally printed out only once an hour, the computer system is continuously at work. It scans all of the log points every 15 seconds and compares about a third of them with limiting values stored in its memory. If it detects an off limit reading, it energizes the appropriate alarm circuit, and a second printer mounted beside the logging printer comes into action. This "trend printer" identifies the circuit being alarmed and prints out the latest reading. It continues to print the reading at one-minute intervals until it returns to normal or is discontinued by the operator. The trend printer can handle as many as four off-limit points at the same time.

The trend printer also records the start-up and shutdown of major machinery and auxiliary systems, and it documents changes in limit settings fed into the computer by the operator. The log printer serves as a standby for the trend printer should the latter require service.

A panel adjacent to the two teleprinters enables the operator to select any reading from the data logger for display in digital form. He first sets up the coded identification of the desired point in a decade register and presses a "Read" button. The quantity appears on the panel in digital form and is corrected every 15 seconds as the data logger scans the system. A similar register is provided for entering new information into the computer.

Computer-System Control of Fuel and Ballast Tanks—Fuel oil for the engines is carried in 34 tanks distributed throughout the ship. Some are "deep" tanks that rise above the level of some of the machinery, and others are "double-bottom" tanks in the space between the lowest deck and the keel. The ship becomes lighter as the fuel is used, so the tanks must be emptied in the proper sequence to keep the ship on an even keel as much as possible. As tanks are emptied, they must be filled with seawater ballast to preserve the stability of the ship. When the time comes for refueling, these tanks must first be deballasted, or pumped dry.

The sequence of fuel tank pumping is automatically controlled by the computer system. Each tank contains a float switch that tells the computer when the tank is empty; the computer then actuates the power-operated valves on the suction manifold to shut off suction to the empty tank and open the suction valve for the next tank in the sequence. The computer system also controls a central display that tells, with indicating lights, whether each tank is empty, contains fuel, or contains seawater. It determines the tank status from its core memory, which keeps a record of the valve and piping set-up used the last time the tank was filled.

Ballasting and fueling are performed manually by the operator, without assistance from the computer beyond the storage of information in the memory as to the contents of the tank. All manifold discharge valves controlling fuel or ballast fed to the tanks are manually operated, but their positions are shown on the tank status display in the control area.

Deballasting is controlled automatically by the computer in the same sequence used for pumping fuel, except that the pumping is stopped automatically after a certain number of tanks have been emptied and before the stability of the ship is threatened.

The sequence of tank pumping can be changed, or a tank bypassed, by feeding new information into the computer memory. Tank sequence can also be selected manually, if desired, from the central control station.

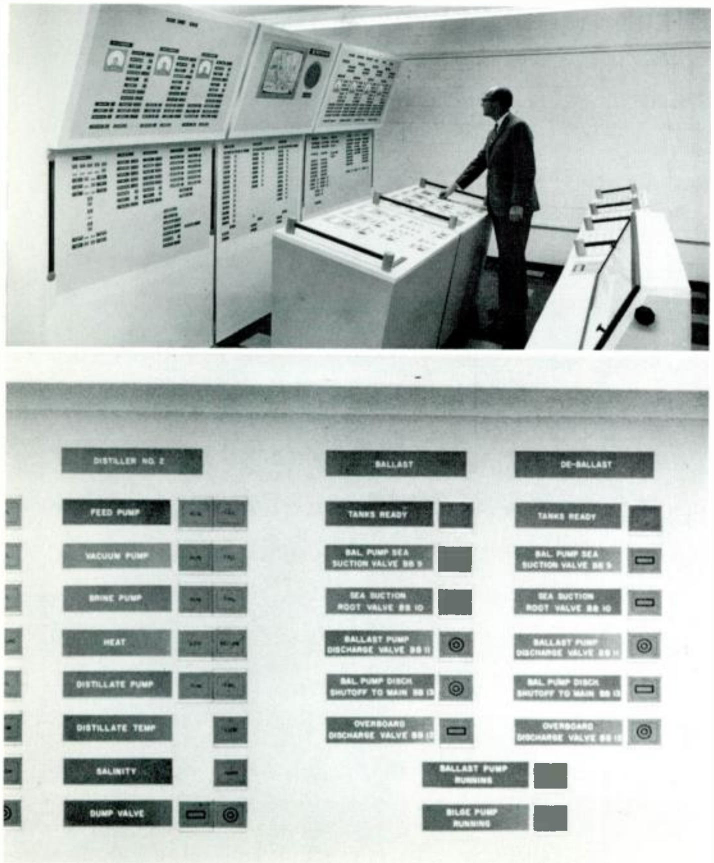
Arrangement of CERC Equipment

The engine-room control station is located on an upper level of the engine room in a space about 10 feet wide and 50 feet long. The space is totally enclosed, thermally and acoustically insulated, and provided with large windows overlooking the engine room proper. Components are located in such a way that all essential displays and controls are continually under the surveillance of a single operator. The ship's service generator switchboard and the distribution switchboard are located near one end of the room, and the propulsion generator and motor control boards near the other end. The remaining control equipment is grouped in the central part of the room on an engine-room control console, an engine-room mimic board, and a vital-auxiliary motor panel and alarm desk (Fig. 3).

The engine-room control console is a free-standing, deck-mounted desk. It contains the instruments and controls for operating the main diesel-generator sets, ship's service diesel-generator sets, distilling plant, and parts of the diesel-oil transfer and purifier equipment. It also has camera and sound controls for the television and listening system.

The engine-room mimic board shows the status of the various engine-room systems. Its upper left section contains the display of the ship's service diesel-generator sets. Below it are displays of the electic power system, distilling plant, and the ballast and deballast systems. The upper center section has the television monitor, a speaker, and a simplified diagram of the fuel and ballast piping system. The lower center section contains the status display of the fuel tanks and the remote valve controls for manual deballasting or fuel-tank selection. The propulsion diesel-generator sets are displayed in the upper right section, and below it are the displays of the propulsion motors, fuel and lubricating oil purifiers, day-tank and settling-tank levels, and heating boilers.

3—**Central part of the engine-room control area** is illustrated by this mock-up (top). At left is the mimic board that displays the status of main and auxiliary systems. It includes a television screen and speaker to enable the operator to see and hear remote machinery areas. An engine-room control console in the center contains the control equipment used most frequently. The vital-auxiliary motor panel and alarm desk is at right; above it, in the actual ship, will be a large window through which the operator can see into the engine room. Bottom: Representation of ballast piping is one of the sections of the mimic board. The entire row of green lights must be on before the ballast pump can be started to take on or discharge seawater. Circle and bar symbols indicate open and closed valves, respectively, and lights at the bottom show that pumps are running.



Because of the complexity of the many systems involved, it was not feasible to use conventional piping mimics in which valve positions and the like are displayed within a diagram of the system. Instead, a unique display arrangement was developed to show the status of the systems by a checkoff method (Fig. 3). Each major piece of machinery or sub-loop is represented by a group of legend plates listing functions associated with it. Opposite each plate is a red or green light, or both, that shows whether or not that function is behaving as desired.

During ballasting, for example, a solid row of green lights tells the operator that he has set up all of the piping valves in the correct position and that he may start the ballast pump. This technique minimizes the risk of operator error, which might occur if the operator had to follow a conventional mimic diagram to determine which valves to open or close. The pump starter is interlocked with the valve positions so that the pump motor cannot start unless all valves are in the correct position. A manual override is provided for use in emergencies.

The vital-auxiliary motor panel and alarm desk is installed below the windows facing the engine room. It contains all of the engine-room alarms, the pushbuttons for remote control of vital electric motors, and the computer-controlled logging and trend printers with their operating panel.

The computer system programmer's console, central processor, and input-output cabinet are located in an air-conditioned room near the scientific laboratories two decks above the engine spaces. A small operator's panel is mounted in the engine control area for use by the engineer in gaining access to the computer system.

The Future

At present, CERC is supplementary to the conventional means of machinery control. The engineer could totally ignore it and operate the engine room as he would on any other ship, because all of the gauges needed to make out a handwritten engineering log are still there and all of the automatic start-up sequences are backed up by manual controls. These back-up features are important now in gaining acceptance of the pioneering CERC installations. In future installations, however, as automatic controls earn more confidence from operators and regulatory agencies, it may be possible to simplify the plant by eliminating those instruments and controls that are no longer used.

Also, the CERC concept can be expanded in some areas. More manual operations can be mechanized, more sub-loop systems can be arranged for complete central control, and complete tank-level sensing and logging can be considered. As a ship's home-office engineers review engineering logs from a fleet of ships, they will see possibilities for improving the data-logging arrangement to make a better evaluation of the ship's performance and efficiency. All of this could lead inevitably to the day, probably not far off, when the entire engineering plant of a ship can be turned over to mechanized controls supervised by a computer and monitored from the bridge.

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Programming for Process Control

by Paul E. Lego

The constant pressure on business and industry to reduce process costs has stimulated development of reliable process-control computer systems. Economic programming of these computer systems is a vital part of the control application.

The power of the digital computer stems partly from its ability to perform long sequences of computations at enormous speed without human intervention and partly from its ability to make logical decisions that alter its future actions. However, the computer cannot do these things of its own volition; its program tells it what to do, step by step. As the use of control computers grows, awareness grows that programming ("software") is an important part of the control package—a part that represents just as real a cost, in time and dollars, as the tangible equipment ("hardware"). The better the programming, the better the process control; the more efficient the programming, the more economical the control installation.

Many of the first computer control applications were in the electric utility industry and in steel rolling mills, applications that employed rather large, fast, and therefore expensive, computers. As these systems have proved themselves, interest has developed in computer control for simpler processes. These processes, too, need the advantages of more effective control, but the large investment in control equipment could not be economically justified for them. The smaller Prodac 50 computing control system developed to meet this need is one of the most significant advances in recent industrial progress.[1]

Precisely because the new control system *is* small and relatively inexpensive, the task of programming it varies in some respects from that of programming the large machines. Shorter word length, somewhat slower input-output equipment, and smaller memory contribute to these differences. The problems posed have been overcome (with consequent economy of time and effort and saving of cost to the user) in a number of ways. These ways are extensive borrowing of experience from the programming of large control computers, development of such programmers' aids as assemblers and compilers, simulation of the small computer's operations on large computers, and refinement and standardization of programming and documentation techniques. The products of these techniques are, in effect, packaged programs readily adapted to a specific process.

Control Computers

Computer Language Development—Digital computers are electrically suited for communication in binary language (the arithmetic system that uses only two values, 1 and 0). These binary digits, called "bits" for short, are represented in the electronic computer by such conditions as a switch on or off, a device electrically charged or not charged, or a bistable relay flipped or flopped. Bits are grouped into "words," with the number of bits in a word being a function of the computer instruction complement, computer design, data accuracy required, and memory size. The Westinghouse Prodac 500-series computers, for example, employ 18-bit words; the Prodac 50, 14-bit words.

A word usually conveys information in one of two ways: it is a binary number or it is an instruction. If the word is a binary number, it has a sign and magnitude:

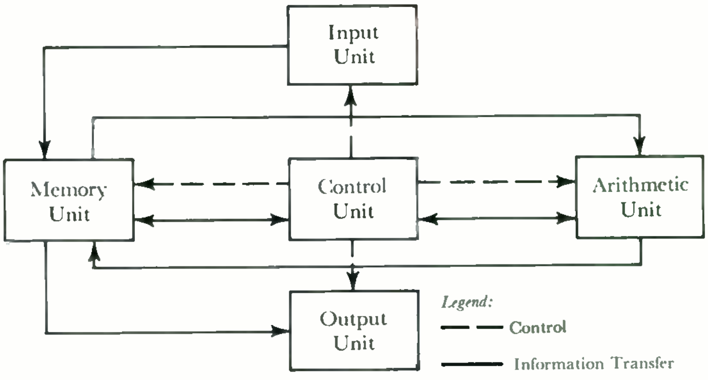
Sign	Magnitude

If it is an instruction, it is usually composed of three parts:

Operation	Index-Register Identification	Address

The operation part of an instruction is a binary code that "tells" the computer's control unit what operation to perform—for example, add, subtract, divide, multiply, bring, store, branch. The index-register identification specifies the applicable index register, which is a register whose contents are used primarily to perform address modification. The address part is a binary number that usually is employed to select a word in the memory so as to retrieve the information contained in that memory location. (See Fig. 1.)

At first, the programmer had to communicate with the machine in its own language. Since this entailed working with long strings of binary digits, it was time-consuming and tedious. Later, programmers learned communications shortcuts; for example, speaking to the machine in octal (base 8) arithmetic



1—Digital computer consists essentially of these elements. A memory unit stores information brought in through the input unit and gives it up, on demand, to the control unit. The latter decides what to do on the basis of the coded information it finds in the memory, and it also directs information transfer between computer units. The arithmetic unit performs basic arithmetic and logic operations as required on the binary numbers stored in the memory. The output unit communicates information to the outside world when instructed to do so by the control unit. Input and output units consist basically of communicating devices, such as typewriters, and buffer registers that temporarily hold information. The combination of control unit, memory unit, and arithmetic unit is called a central processor.

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after first programming it to translate each value to binary. Programmers also learned to use punched tape and cards for inputting and outputting binary instructions and data.

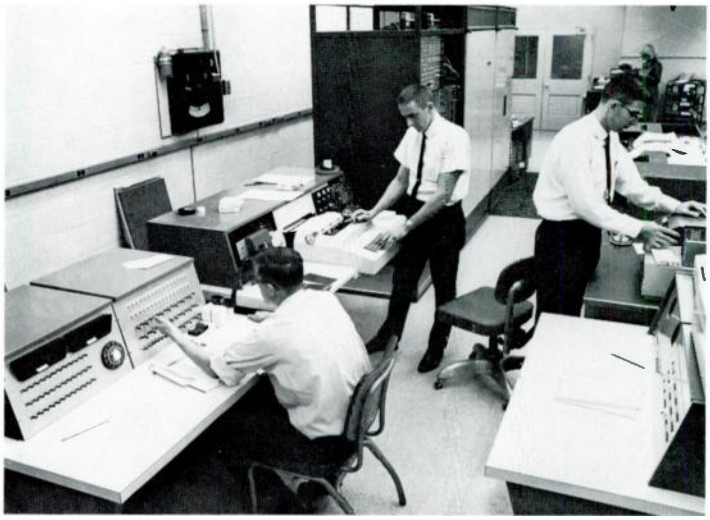
Another step was to write programs in octal that can input the binary representation of alphabetic characters by typewriter-punch combinations. Then, by defining unique groups of alphabetic characters—i.e., mnemonics—the machine can be programmed to "look up" their unique equivalents in a table of function codes. The computer combines this information with the binary representation of the instruction address, in its memory storage, and thus arrives at the value to be stored in its memory for immediate action or later use. This programmer's aid is called a *mnemonic loader program*. Such communications short-cuts have enabled programmers to put part of the burden of translation on the computer.

Even more sophisticated translator programs are the symbolic assembler and the compiler. The *symbolic assembler* seeks to solve the programmer's problem of balancing the required program against available memory storage space. He writes his program in names or symbols that represent various pieces of data, memory locations, or instructions. The symbols are interpreted and processed by the assembly program, then assigned definite numerical values. In effect, the symbolic program is translated into an "absolute" program. (Every working program must be absolute: that is, all data and instructions must be assigned definite locations in memory before they can be executed.) Usually, there is direct one-for-one correspondence—one line of symbols for each line of computer instruction.

The *compiler* language is prepared by adapting a natural language, or a combination such as English and mathematics, into a subset that is logical and comprises a definite number of possible statements. From this subset is created a compiler, which is an elaborate program to decode and translate permissible statements into machine language. Compiler program languages can be learned by the relatively inexperienced in a short time. However, because compilers are large and complex internally, they cost substantial amounts to write. The investment may range from a few man-months to as much as ten man-years, with a typical figure of two to three man-years.

Such investment is difficult to justify unless there is reasonable hope of adequate return, which in turn depends on fairly heavy use of the compiler. The type of work to be programmed also is a factor; for example, a compiler may be justified by enabling relatively inexperienced people to communicate with the computer, especially people whose time is exceptionally valuable because of their skills in other kinds of work.

Control Computers and General-Purpose Machines—Differences between process-control computers and other kinds of computer cause differences in the type of programming required. The control computer is an equipment complex capable of precisely reading and defining process parameters. It can take readings at hundreds of checkpoints in a split second and repeat this scanning of the total process as often as required, within programming and machine limitations. It can store this data with total recall, recognize and even anticipate trends, and provide reference points for future operating conditions. In short, it is the first practical means developed for really finding out *what the critical parameters of a process are and how they are interrelated*.



System laboratory provides facilities for the simulation and real-time computing used to assemble and debug process-control programs.

Most business and scientific computers input and output data, and make computations, at speeds dictated by economic considerations; the process-control computer, however, works on a real-time basis. Its required speed is dictated by the nature of the process, by the speed, nature, and number of input-output devices, and by the need for communicating with the plant and the human operator.

Process-control computers employ multiprogramming—time-sharing of the central processor by sequential operation of multiple programs. The order in which the programs are executed is controlled by a supervisory, or executive, program. Some machines also have duplicate hardware units or input-output channels for multiprocessing (simultaneous execution of more than one program). Programs are assigned relative priorities, and a system of interrupts is set up so that the usual sequence can be changed when a condition in the plant (process interrupt) requires or when other types of interrupts demand attention. Provision also must be made for saving the data in the interrupted program to permit resumption later.

Control Computer Functions—A digital control computer is organized to perform three general classes of function—reporting, supervising, and control.[2] In the first, the output may be in the form of typed or printed records to be examined later; in the second, in the form of signals to the operator, usually so that he can take some desired action; in the third, signals transmitted to control the process.

In *reporting*, the computer may produce raw data (such process variables as flows, temperatures, pressures) or production data, which the computer outputs under added programmed instruction after smoothing the raw data and performing calculations. Examples of production data are totals, averages, integrated values, trends, efficiencies, operating costs, accounting data (such as inventory records, ordering information, and raw-materials scheduling), and engineering information (such as correlation of input-output data, analysis of overall operation, data for improving existing control, and data for use in devising a mathematical model of the process).

In the *supervisory* mode, the computer scans input voltages representing physical variables of the process and compares each with a correct value stored in its memory. It may actuate alarms if variables exceed specified limits, and it can also initiate special printouts that give numerical values of a deviation from desired levels. If process equipment fails, the computer can, if so programmed, provide a record of prior events for the previous ten minutes, say, or ten hours. It can also be programmed to enter an "analysis mode" if it detects a process abnormality—sounding an alarm, for instance, in the event of an unacceptably high temperature and immediately scanning surrounding areas for high temperatures.

Control functions are more advanced, with the exception of such relatively simple operations as sequencing (starting and stopping of turbine-generators, for instance, and sequenced operation of a rolling mill). An example of more complex control functions is programmed exploration—the changing of controlled process inputs by discrete steps and the recording of resultant changes for optimization experimenting or for developing a mathematical model of the process. Multivariable control is a level of control beyond that provided by single-loop analog controllers; for example, a control quantity may be a function of several other variables and not in itself directly measurable. In noninteracting control, the interactions among several input and several output variables can be reduced or eliminated. Optimizing control is the use of a mathematical model of the process, the solution of equations to find a maximum or a minimum value for each, and consequent modification of the model for optimizing the process. Feed-forward control anticipates the effects of disturbances occurring upstream and adjusts the process to compensate for them.

The mathematical model merits added mention. Since any production process is basically a complex of cause and effect, the total process pattern can be expressed in mathematical terms. The computer uses this total pattern, or mathematical model, as a simulation of the process to obtain, by repeated trial and error, the optimum value for each variable in certain parameters. The complex mathematical model could require thousands of man-hours of calculation if prepared manually, but a computer can help prepare the original model in a much shorter time. With similar speed, it can perform the necessary calculations for later revision of the model until it approaches the optimum for the process. Also of practical importance, the mathematical model can be represented by a set of Boolean equations, the mathematics of logic, which give the computer a trial-and-error description of the process.

Actual control of the process is rather basic. Output data goes from the computer as needed to signal the setting of valves, adjustment of speeds, opening and closing of relays, actuation of solenoids, and virtually every other kind of regulating function.

Each process, and therefore each computer application, has different characteristics. Some processes are well defined; others require great preliminary study for definition of the interrelationships between variables. The success of any computer application depends on thorough knowledge of the process system, familiarity with what a digital computer can do, and ability to recognize similarities to and differences from other computer applications.

Programming for Process Control

Programming involves much more than simply coding instructions for the computer. The tasks can be classified as follows, with typical percentage figures for the amount of time spent on each: Organization, 30 percent; program writing, 20 percent; individual program debugging, 20 percent; system program debugging, 25 percent; documentation, 5 percent. Installation of the system also requires programming services.

Organization—This includes (1) defining the precise functions to be performed by the computer, and the system organization of these functions, and (2) organizing the computer internally—memory layout, space assignment, priority arrangement, and real-time execution considerations.

Communication between man and computer is an important aspect of organization. Some of the input functions that must be programmed for the operator to perform with his operator's console are: Initiate process start-up and shutdown; set decimal values on selector switches and store these in specified computer memory locations; initiate and interrupt various input scanning sequences; add to or eliminate from any scanning sequence; demand, at any time, logging or trending of any number of input variables; request display of any quantity stored in computer memory.

For output functions through the operator's console, the computer should be programmed to show requested information on backlighted displays, printers, or by other means, activate alarms, and provide any other information the operator needs for making intelligent decisions under either normal or unusual conditions.

Also needed are programs to convert computer data into the data needed for display or for actuating alarms on the operator's console. Frequently, the user demands that the data being input to the computer via the operator's console be in decimal or engineering units; this affects the choice of units to be used for internal computations involving system variables.

A programmer's console is the vital communications link between programmer and computer. Its primary use is during testing and debugging of programs. The programmer must be able to insert his programs easily, observe the contents of various machine registers and print out their contents and the contents of memory registers, control the instruction counter contents so he can conveniently jump to various program sections, and change the contents of memory locations for both data and instructions. The programmer should be able to communicate with the computer in whatever units—binary, decimal, octal—are most convenient at a given time, and also in terms of the mnemonics that describe his complement of instructions (or "repertoire").

Many other programming functions can be provided by the programmer's console. Examples are various forms of input-output formats for typewriters or punches and such convenient machine modes as "single step." The latter is a means of executing a program one step at a time with a halt after each step.

Programmer's-console features can be implemented either by programming or by hardware. There are strong arguments for each method, with one deciding factor being the function of the particular application. Small computers with limited memory and computational capabilities are restricted in the use of programmed programmer's-console functions, but Westinghouse has developed an effective answer to the problem. Programmers here simulate the operation of the smaller machine on a larger computer and also use the larger computer's programming functions as writing and debugging aids for the small unit's programs.

Communication between computer and plant is equally important in controlling an industrial process on a real-time basis. The two classes of variables, from the control-signal viewpoint, are digital variables and continuous system variables. Digital variables have only two states, are always in one or the other (or in the process of going from one state to the other), and can be represented directly by either of the binary numbers "0" and "1." Continuous system variables, or analog inputs, can be measured by a sensing device that produces a functional relationship represented as a voltage. Examples of digital variables are the status of switches, valves, oil levels, dampers, and contacts; of continuous system variables, temperatures, pressures, and flows.

The digital (two-state) variable can be represented by a contact-type input which the computer can accept as being either open or closed. Such inputs are grouped into registers, in quantities dictated by the computer word structure. The state of contacts can be tested conveniently by programming, and the contacts can also be tested in groups that represent a given system function. Frequently, too, an automatic hardware comparison is made against a stored pattern, with an interrupt provided in case of a discrepancy. Input pulse signals may also represent continuous variables. Examples are the output of some telemetering devices, flowmeters, and digital clocks. This information is usually bulky, so facilities must be provided for quickly scanning and interpreting the data.

Provision must be made for control of plant equipment by output contacts that are easily opened, closed, or changed under program control. These contacts have to be operable in random patterns, defined within the limitations of the computer word size, for convenient setting of more than one contact at a time.

Continuous system variables, or analog inputs, are brought into the computer system by analog-to-digital converters (ADC). These devices receive a voltage as input and produce a functionally related binary output. Temperatures may be converted directly by thermocouples or resistance temperature detectors; pressures and flows may be indirectly converted by strain gauges or differential transformers actuated by the motion of diaphragms or bourdon tubes. Low-level signals must be amplified ahead of the ADC.

The ability to multiplex inputs—connect each input to the ADC for a brief time to have its value read, converted, and taken into the computer for processing—is a primary advantage of the computer for process control. It permits use of common instead of individual equipment for reading a variety of inputs.

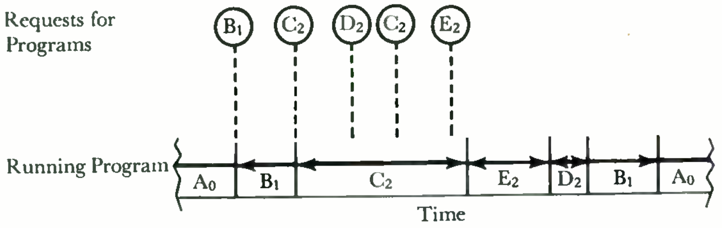
Analog inputs may require conversion to engineering units or vice versa, and this again poses the problem of memory storage; the computer must have values, in one form or another, against which it can compare incoming analog signals to make sure they are within acceptable ranges, since they represent important process conditions. Often, too, various system variables must be compared, and that requires their expression in a common or base set of units.

Analog input accuracy is an important concern in process control. Factors involved include the accuracy of sensing devices on the process, the ability of multiplexing equipment to filter out line noise and hold the value read, and the accuracy of ADC equipment. The speed of scanning analog inputs is affected by such factors as the characteristics of the multiplexing scheme, filtering, ADC rate, amplifying, and the speed with which the basic computer can take in or put out data. Time-sharing of hardware helps here, and also the fact that all check-points need not be scanned at the same rate or frequency. In the future, if economic justification allows it, digital sensing devices may replace analog inputs.

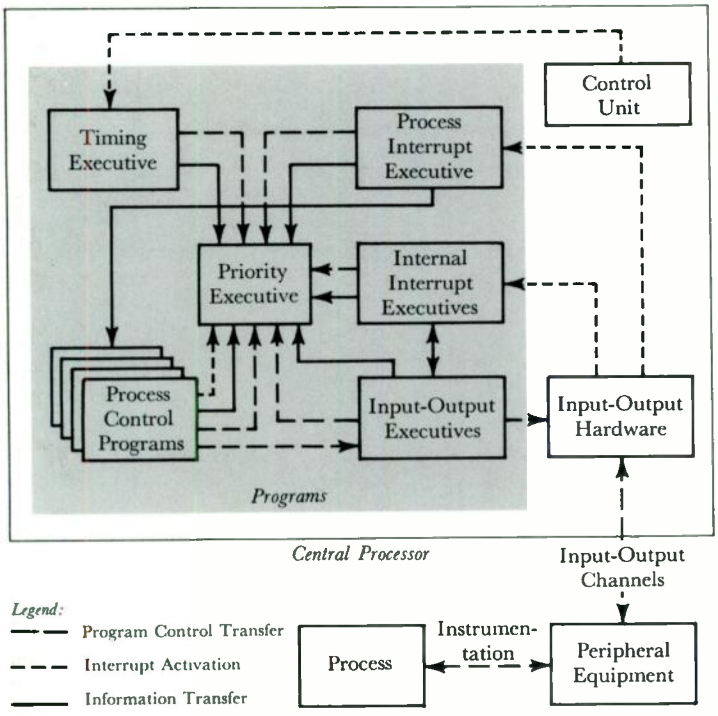
Digital-to-analog (DAC) units enable the control programmer to adjust process setpoints with analog outputs. The program provides for converting from whatever units are being used in the computer into those compatible with the DAC unit. Usually, one DAC is supplied per set-point controller. A commonly used device is the stepping motor; others are relays and binary-weighted resistor networks. Programmed functions probably will replace analog controllers in the future to reduce cost.

What if a sensor on a process becomes defective? Its signals would be false, so the programmer must devise schemes that enable the computer to recognize the signals as false instead of taking unwarranted alarm action. The human operator can insert a "flag" that instructs the computer to ignore the false signals until repairs have been made. This, of course, assumes that under at least some conditions the control system can distinguish between false and true out-of-limits signals.

The same approach can be taken for contact inputs. The programmer stores a matrix of binary numbers in computer memory, with each digit representing a particular contact,



2—Priority principle permits the more important programs to interrupt the less important ones, and it also permits the operator to interrupt a running program to make changes. Relative priorities are assigned to programs; in this illustration, the programs are identified by letter and the priority levels by numerical subscripts. The dashed vertical lines along the time scale indicate requests for programs; the solid vertical lines, actual program changes. Arrowheads indicate start and completion of programs; lack of arrowheads indicates interruption of a program or resumption of an interrupted program. The same priority level may be assigned to more than one program. Programs at the same level do not interrupt each other, but a definite priority is assigned to each program at the same level.



3—Control computer programming structure reveals interrelationship between hardware and software. Control unit provides basic time pulses to the timing executive, which supplies the real-time base for starting periodic programs. Priority executive handles program requests and interrupt requests from process and hardware, allowing those with highest priority to occupy central-processor time. Input-output executives handle the implementation, bookkeeping, and execution required to get data into and out of the computer.

and the operator sets a "1" in each of these bit positions to correspond to a defective contact. The computer thus would "know" if a contact is defective. This problem also can be handled by hardware.

Usually, a specific response time is associated with process action—the opening or closing of a valve, for instance. The control system waits until the required time has elapsed, then checks results. This requires "real-time delay." Hardware clocks to do this by priority interrupt are fairly expensive, so delay by interrupt programming is ordinarily preferred.

Priority plans are needed, because an emergency condition in a process-control system must be able to interrupt normal operation and ask for action.[3] Also, the operator must be able to interrupt the running program to make changes. The priority principle is essentially a programmed order in which each kind of interrupt is assigned to a certain level (or perhaps several to the same level), depending on relative importance and on characteristics of the process it represents (Fig. 2).

Provision is made for various kinds of interrupts, and for means of handling them, while preserving data from the interrupted work to permit its resumption. Also, the programmer must plan for continuing other work by the computer if the nature of the interrupt permits. Central control programs called interrupt executives are made responsible for activating requested interrupt programs (Fig. 3). Among considerations the programmer must take into account are space-sharing (in computer memory) for such programs and means of continuing programs during input-output operations. The latter is frequently handled by "buffering" input and output—using controlled interrupts to get data into and out of memory. The programmer also can set up a sort of super priority for executive programs by interrupt lock-out, which is a way of making the executive programs run without a break regardless of interrupt bids.

Program Writing and Debugging—As the foregoing discussion indicates, a number of individual programs have to be provided for each control computer application. In addition, since few if any individual programs can be independent of others, they must be interrelated. The techniques and the requirements of computer time-sharing, memory space-sharing, interrupt, centralized data collection, logging, and alarming inherently tend to create interdependent programs.

When individual programs have been written, the programmer "debugs" them—runs them on laboratory or production equipment to make sure of their correctness and to eliminate any errors that may have crept in. He uses known values to compare the results of, for example, conversion of digital numbers to engineering units. Next comes system debugging, in which the programmer checks out the total program package by placing the programs together in a logical order and running them. The executive programs are placed in the computer and tied to a real-time source to provide timing for scans, time delays, and other periodic programs.

Documentation and Field Installation—The programmer prepares precise and complete documentation, which includes program listings, flowcharts, decision-table listings, instruction books, and program descriptions. He also helps make the final system verification when the computer—hardware and software—is delivered. Program and documentation changes are more difficult to make in the user's plant than back home, and plant contingencies may dictate computer time scheduling. Both factors can cause high field installation costs if the system was not carefully programmed and debugged before shipment.

Controlling Programming Costs

A commonly used measure in programming is the average time required for preparing instructions (usually referred to as the instruction per man-hour rate). When the first large control computer installations were made, the industry average was one-fourth to two instructions per man-hour. Continuing improvement since then has improved the figure to about four instructions per man-hour. One of the primary concerns of application programmers is to improve the figure still further. Standardization of programs, so they can be reused, is one means. Others are development of advanced assemblers and compilers and improved procedures and facilities for testing and debugging.

Standardization—This implies more than the writing of programs that can be used more than once. The same memory configuration and layout, and, as nearly as possible, the same standard input-output devices and wiring, are used.

Precisely the same program can be used over again for some functions, such as trigonometric, square-root, natural logarithm, conversion, Fortran compiler, and steam tables. Programmer's-console programs also are standard, and they make the writing and debugging of programs an easier task. A few of them are trace, binary loader, binary punch, mnemonic loader, mnemonic dump, and decimal dump.

With most programs, however, it is not possible to reuse the exact data, storage requirements, storage locations, and output information. Nevertheless, practically all control computer applications have common functional areas, which makes it possible to develop functional skeletons for programs and then add flesh to them by using processors or generators to produce the individual running programs. This approach is especially practical for the executive area, where the heart of the programs are standard and one need only add tables of data to complete the programming. Scanning, alarming, limit checking, and conversion programs all fall into this category. Inputs to these programs are such data as scan frequency, alarm limits, dead-band limits, sensor type, conversion accuracy, calibration data, and memory storage information; from these data, the entire scan, alarm, limit check, and conversion package is generated and punched out on tape.

Maintenance programs, for diagnosing computer hardware difficulties, also can be highly standardized; they are so written that input data on machine configuration and peripheral equipment can be fed to them to adapt them to the given installation. Typical programs are core, command, and drum test. On-line diagnostic programs are highly standardized except for a table that defines the specific machine configuration and peripheral devices. The table is placed in the computer at execution time. These programs check analog input system, drum, contact input-output system, power supply, and so on.

The processors used to translate data into scanning programs also can be employed to provide signal lists for hardware development and for wiring-list production, development of parts location in cabinets, and signal-level information for testing. Operator's console functions can be standard program skeletons, fleshed out by the processing of input data. Standardization of these functions leads to standardizing the operator's console panel itself, and the associated wiring.

In the logging and alarming areas, the problems of handling data with many different scale factors and a variety of output formats can be difficult. A message writer compiler has been developed to enable the programmer to use compiler-type control formats for binary and alphabetic material, with the various conversion burdens put into a standard program.

The standardization of program functions and techniques is, of course, limited somewhat by marketing requirements, cost, and customer acceptance. Memory sizes and configurations must be fixed around the basic standardizing approach, and the programs must be as general as possible, flexible where possible, and yet reusable.

Information Transfer—One of the most time-consuming (and therefore costly) phases of applying a process-control computer system occurs near the beginning: the transfer of information from the process engineers to the programmers. A traditional vehicle, the flowchart, is deficient in two ways. First, the engineer must devise a flowchart that envisions and correctly resolves every possible contingency in the process before programming can begin. All factors have to be so arranged that the possibility of contradiction is precluded. Second, custom flowcharts must be translated into programming, or at best custom linkages, before they can be tested; they must be tested before they can be debugged; and they must be debugged before they can be tried in the plant.

Decision-table programming is a step toward overcoming this problem. It permits the process engineer to write the logic and rules of his functional task, supply information bearing on the logic and rules, and have this data processed into computer programs. A decision table is made up, essentially, of *actions*, which are functions, operations, or calculations needed for process control, of *conditions*, which are controlled variables or critical conditions dictating when or why actions are needed; and of *rules*, which link actions and conditions by showing the status of conditions when the actions are to take place.

Decision tables can be used to describe any computer logic, and their terms (unlike flowchart terms) usually are all in the same format. The benefits of the decision-table technique depend on the proportion of logic programs to relative size of action programs.

For on-line decision table use, there are three basic programs: the *condition processor*, which makes all the table conditions binary in form for use by a *decision processor*, and the *action routines.* The decision processor gathers the binary conditions that apply to a given decision table, compares the present status of variables with the rules stored in the computer, and initiates the actions required.

Off-line programs for reducing program writing and revision include translators for the decision routine and for the condition processor, edit programs, and others. Since process engineers are generally familiar with the principles of Boolean algebra and logic design, they are in a good position, with program organization guidance, to prepare the rules and logic for the decision-table input for a particular application. This data then can be processed into computer programs.

Assembler techniques, which a programmer uses to make one-for-one translation of mnemonic codes into machine-language instructions, can be refined and made more useful. With the addition of more pseudo- and macro-operation instructions (instructions to the assembly program that can create several machine instructions or even subroutines), the assembler begins to form the basis for compilers.

The compiler permits problem definition in a language easily written and understood by human beings, with as much as possible of the translation burden placed on the machine. Another function of the compiler is to organize a program for a job in a way that optimizes time and storage capabilities. This is especially important in real-time control applications, since the computer must run at a pace dictated by the controlled system or process. Unfortunately, the algebraic-language compilers widely used for general engineering and scientific studies did not adequately meet this need, and special control compilers had to be developed.[4] An algebraic-language facility is, however, a part of control compilers that permits real-time engineering computations and effective utilization of spare capacity for solving off-line problems.

Efficient arithmetic packages have to be used with compiler-produced programs and run on-line as part of these programs. Both the compiler-produced programs and their subroutines must be translated into convenient core-drum segmented packages for use in memory-shared systems.

Testing and Debugging—Difficulties arise if the programmer attempts to test and debug process-control programs on the control hardware if the latter has not itself been completely debugged. The solution developed by Westinghouse is laboratory simulation for program system debugging. Two large (Prodac 580) computers are tied together by a high-speed data channel. One machine simulates any desired input-output configuration, serving, in effect, as a stand-in for the user's process. It simulates static, rate-of-change, and dynamic inputs to the other machine. The other machine is the applications computer, containing the programs for process control.

Prodac 50 Computer Programming

If the techniques just discussed were not employed, the programming of such computer systems as the Prodac 50 computing control system would be extremely time consuming. The total number of man-weeks required for programming a large computer is greater than for a small one because the scope of the application is greater. However, reduction in programming cost is not always proportional to the reduction in the size of the job. Reducing hardware to achieve the lowest price can and frequently does tend to increase the cost per instruction in small computer programming. Unless progress in programming is kept abreast of progress in the hardware design, the inherent limitations of fewer commands and shorter addresses could partially defeat the original purpose, which was to produce a system with the lowest overall cost.

Writing a complex assembler or a compiler for the Prodac 50 computer also is less feasible than for the larger machines because of limitations of input-output and memory. The input-output equipment (tape readers, punches, typewriters) used with the smaller computer are generally less elaborate and do not have the speed of equipment employed with the larger machines.

Nevertheless, the smaller machines can be, and are, programmed efficiently. Standardization is one aid. The computer systems, although destined for various kinds of applications, are functionally alike so that programs can be used repeatedly. Binary and mnemonic loaders were among the first prepared, as they are essential for field installation and for the user's programming purposes. An in-machine assembly program also is available. Standard executive programs, maintenance routines, sub-routines, diagnostics, and message-writer programs have been written and are modified as required to meet individual computer requirements.

Simulation of the small machine on a large computer that already has programming tools also helps. For example, the assembly program of the Prodac 500 computer has been modified to produce Prodac 50 computer output. Macro-instructions permit programming in Prodac 50 computer language, assembling on the Prodac 500 machine, and producing tapes for the Prodac 50 computer. Compiler output can be in macro form to fit the assembler and therefore permit use of the compiler for producing Prodac 50 computer programs. Similarly, the Prodac 50 computer's central processor and the input-output equipment are simulated in a Prodac 500 computer program. This permits debugging and program testing in the simulation laboratory, with all its extensive capabilities.

These procedures enable programmers to produce debugged programs for the Prodac 50 machines efficiently and quickly. This is an especially important advantage when programming for a machine that is produced in considerable volume.

Westinghouse ENGINEER
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References:
1. "Small Control Computers . . . A New Concept," F. G. Willard, *Westinghouse ENGINEER*, Nov. 1964, p. 174.
2. "Application of Digital Control Computers," R. O. Decker, *Westinghouse ENGINEER*, Sept. 1961, p. 141.
3. "Priority Considerations in Control Computers," R. S. Banks and R. E. Hohmeyer, *Automation*, Nov. 1963, p. 83.
4. "PROGEN: A Special Purpose Compiler for Producing Machine Language Programs from FORTRAN Type Statements," C. L. Carney, R. F. Karlceik, and J. E. Tysinger, *Westinghouse Analytical Department Report No. 64–1013*, April 1964.

Developments in Pressurized-Water Reactors

by J. C. Rengel

Large strides are now being made in the improvement of pressurized-water reactors, as experience in design and operation of nuclear plants accumulates. Some of the advances involve new concepts, others a single component, but all contribute to improved performance and economics.

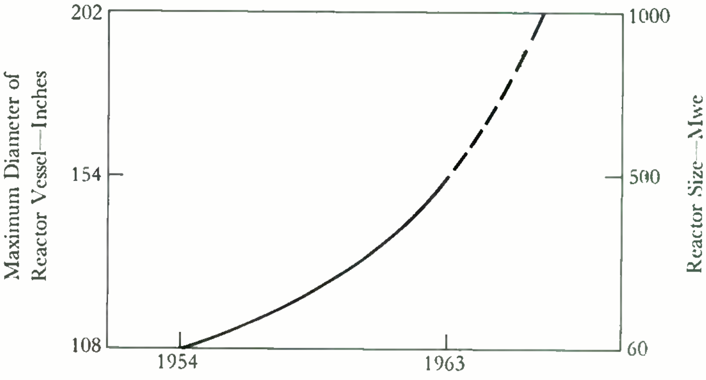
The development of pressurized-water reactors is now in a very fruitful stage, in which refinements of the earlier designs are yielding substantial improvements in both performance and economics of nuclear plants. Perhaps the most striking advances are occurring in the basic building blocks of PWR systems—cores, reactor vessels, steam generators, and coolant pumps—but parallel refinements in core design are also contributing heavily. These developments have already had a significant effect on the economics of nuclear power, and new developments will continue the trend. Consider, then, some of the developments now in progress, and their likely effect on pressurized-water reactor plants of the present and future.

Layout and Components

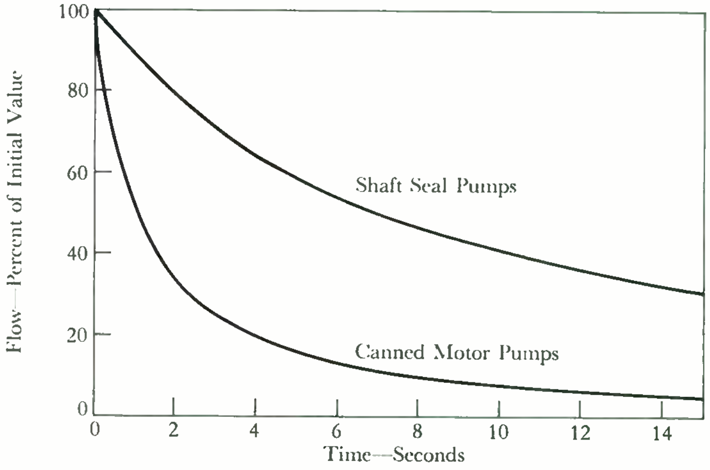
With the ever-increasing trend toward increased plant ratings, correspondingly *larger reactor vessels* will be necessary, foreseeably attaining a foot or more in thickness. The unique features of the pressurized-water reactor allow this increase without excessive vessel size and cost. The progressive growth of reactor vessel size for PWR plants over the last decade is shown in Fig. 1, along with a probable extrapolation of near future nuclear plant ratings. Vessels up to the maximum size indicated in the figure (1000 mw and more) are feasible. Vessel fabrication technology and metallurgical quality control should keep pace with advances in PWR technology, thus meeting the demand for the larger ratings.

Due to inability to preserve the initial integrity of their seals, conventional *pumps* have not been employed to date in PWR main coolant applications. Canned motor pumps were therefore developed to fill this requirement, and those incorporated in operating PWR plants have proven reliable in service. A comparison of canned motor pump characteristics for several PWR plants is shown in Table 1. Certain distinct advantages, however, can accrue from the use of more conventional pumps. For example, lower operating costs can be achieved through higher drive motor efficiency. Enhanced reactor safety is attained through the high inherent inertia ("coastdown") of a shaft seal pump. The effect of such inherent inertia on the reactor coolant flow for a typical four-loop PWR plant is shown in Fig. 2. The "flywheel" effect improves the pump's coastdown characteristic in event of loss of power to the pump motors. On-site maintenance is also simplified since repairs or adjustments to shaft seal pumps can be made at the plant or in nearby shops, rather than at the factory. Controlled leakage shaft seal pumps have been under intensive development over a number of years, and are now offered as alternates for use in PWR plants.

Heat transfer loops have also received substantial development attention. A typical PWR main coolant loop comprises a pump, a steam generator and the necessary piping. System pressure is maintained through use of a pressurizer unit connected to one of the loops in a multiloop plant, with the number of loops influenced by plant rating and plant layout considerations. The successful development of very large reactor plant components has made possible the transport and transfer of large amounts of thermal energy per loop (Table 2). Thus, in PWR plants committed today, steam generators have heat transfer areas of about 28,000 square feet and main coolant pumps have capacities of about 64,000 gpm. Such demon-



1—Reactor vessel size has kept pace over the last decade with growth in size of reactor plants.



2—Effect of inherent inertia on reactor coolant flow after total loss of pump power.

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strated ability to build large components has been a major factor in reducing the cost of nuclear power.

Modular Concept

Improved economics, reliability, and simpler plant maintenance can be obtained from the standardization of systems and components. Thus, Westinghouse has adopted the "*modular*" or "*unitized building block*" concept in the design and construction of its pressurized-water reactor plants.

This modular approach means that re-engineering of plants and components is at an absolute minimum consistent with individual customer requirements. Thus, there is a continuing and highly concentrated effort to design plants that use standard components such as steam generators and pumps.

Reactor Plant Design

Considerable progress also has been made toward simplification of the reactor plant by the planned *elimination* of components. Examples of such simplification are the absence of primary coolant stop valves and check valves in multiloop PWR plants currently being designed and built. Primary coolant systems isolation stop valves require high standards in their design and fabrication, and in their associated operating system. Thus, considerable expense is involved in this area if the valves are to function effectively. Similarly, coolant pump check valves have proven significant items of capital expense. Studies of PWR operating criteria and considerations of safety show no need for either of these valves.

Simplification of the reactor's internal structure has also produced significant economies, plus easier refueling and maintenance. For example, refueling of the Yankee reactor involved almost five days of effort due to the necessity of removing the control-rod drive shafts, in-core instrumentation package, guide tubes (each lifted and removed separately), vessel head, and upper core support plate before access to the fuel assemblies could be achieved. In the SELNI reactor, this "jigsaw puzzle" arrangement has been simplified so that only *two* lifts will be required to achieve access to the core. SELNI in-core instrumentation is fitted to an instrumentation support plate that is removed as a unit at the time of refueling. The guide-tube support assembly is also extracted as a unit, and is the only part of the internal structure that is removed for core loading.

Intensive development is also taking place in instrumentation suitable for in-core installation. Knowledge of actual neutron flux distributions enables a plant operator to safely extract the maximum output from the core and to confidently predict the progress of fuel burnup. In current designs, neutron flux can be determined over the entire length of the reactor fuel assembly. The information can be presented to the operator in analog or digital form, or may be furnished as input to a computer for determination of appropriate control action.

Containment

In effect, a "line" of containment design has been developed that considers individual plant site conditions. For relatively low population densities, a steel or concrete-lined container provides sufficient protection. Where population density is somewhat higher, filtration and a spray system augment the protection. For very high population zones, such as the Malibu plant of the City of Los Angeles Department of Water and Power, "double" containment is supplied. Thus, the Malibu reactor containment utilizes a "sandwich" type of construction wherein a layer of porous "popcorn" concrete is enclosed between inner and outer layers of steel with reinforced concrete as the outer layer. The porous area is maintained at a negative pressure with respect to the surrounding concrete. A pumpback system ensures that any gases that entered the porous concrete would be "pumped back" safely to the interior of the containment. Thus, any leakage would be inward, rather than outward to the environment (Fig. 3).

Such a broad spectrum of containment design permits tailoring of PWR plant designs to the requirements of specific sites.

Chemical Shim Control

Chemical shim control* differs from chemical shutdown in that the latter is utilized only to achieve cold shutdown; whereas with chemical shim control, the neutron absorber (boric acid) remains in the coolant system during reactor operation, but is gradually reduced in concentration to compensate for fuel burnup. The use of chemical shim as a supplement to mechanical control-rod operation in PWR's was first demonstrated in the Yankee plant on a short term experimental basis. Prior to Yankee employment of chemical shim control, extensive re-

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*See "Chemical-Shim Control for Nuclear Reactors" by P. Cohen and H. W. Graves, Jr., *Westinghouse ENGINEER*, May 1964, p. 90–93.

Table 1—Comparison of Reactor Coolant Pump Characteristics

Reactor Coolant Pumps	*Yankee*	*SELNI*	*SENA*	*San Onofre*
Type of Pump	Canned	Canned	Canned	Shaft Seal
Flow Capacity, gpm	23,700	24,500	25,700	63,800
Effective Head, psi	79	59	57	78.4
Synchronous Speed, rpm	1,800	1,500	1,500	1,200
Input Power (Hot-Each), kw	1,380	1,040	1,070	3,400
Total Pumping Power, kw	4,520	4,160	4,280	10,200
Overall Height, inches	140	155	155	300
Overall Efficiency, percent	63	65.7	64.7	80.8

Table 2—Comparison of Loop Data

Component	*Yankee*	*SELNI*	*SENA*	*Conn. Yankee*
Reactor Loops	4	4	4	4
Vessel Diameter, inches	109	126	126	154
Coolant Pump Flow, gpm	23,700	24,500	25,700	63,800
Steam Generator (ft^2)	13,430	14,990	14,990	27,700
Turbine (lp cyl.)	2-40″	2-40″	2-33½″ (3000 rpm)	4-44″

search and development work was sponsored by the Atomic Energy Commission and undertaken by Westinghouse. The effectiveness of chemical shim control led to its use in Yankee, Indian Point and in presently committed plants.

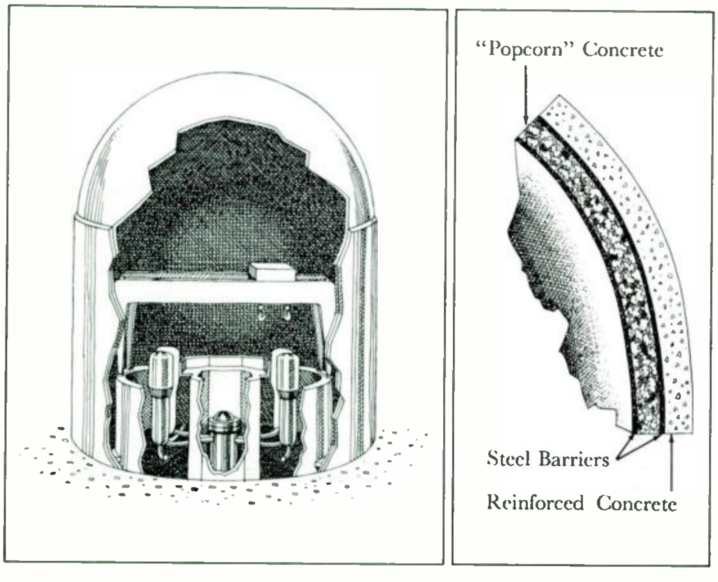
The operation of chemical shim control is quite simple. At the beginning of fuel cycle, a predetermined concentration of a neutron absorber (boric acid) is mixed with the reactor coolant to hold down excess reactivity. As the core's initial reactivity decreases with time, the boric acid in solution is withdrawn from the coolant in precise amounts. By this means it is possible to control the reactivity effects of temperature changes in the coolant; the buildup and decay of xenon and samarium; and the depletion of fissionable material and consequent buildup of all fission products. Chemical shim is *not* used to control rapid changes, such as load transients, or for scram, since these functions are accomplished by mechanical control rods.

The use of chemical shim control in the pressurized-water reactor contributes markedly better power distribution and fuel utilization, and lower cost of achieving control.

Rod Cluster Control

To date, cruciform control rods have been employed for PWR reactor control and shutdown. In new PWR designs, these rods are supplemented by chemical shim control. A new mechanical control concept is currently under intensive development by Westinghouse for the United States Atomic Energy Commission. In this concept, termed "rod cluster control," the control element consists of a cluster of cylindrical absorber rods contained within a fuel assembly (Fig. 4). Each cluster control rod is approximately the length and diameter of a fuel rod, and moves vertically in a thimble or hollow tube that replaces a fuel rod in a fuel assembly. The cluster rods are connected at the top to a multifingered "spider," which, in turn, is coupled to a control assembly drive shaft. The drive shaft is raised and lowered by means of a mechanism mounted on the reactor vessel head, with the lower portion of each thimble serving as a dashpot for shock absorption during scram. Guide tubes installed above the core stabilize and guide the individual absorber rods as they are withdrawn or inserted.

3—Double barrier containment concept; at right is a cross section of the layers.



The rod cluster control concept, by replacing the former cruciform rod absorber-follower control assembly concept, offers the following distinct advantages: (1) more uniform power distribution; (2) increased reactivity worth per unit weight and per unit volume of absorber material; (3) elimination of control-rod followers; (4) less expensive control rods; (5) elimination of separate shock absorbers; (6) less expensive reactor vessel internal structure; (7) a shorter reactor vessel; and (8) a less expensive plant containment vessel.

To expand briefly upon one facet of the above, the total absence of control-rod followers results in significant economies. For example, a shorter and less expensive reactor vessel can be used—a saving of up to seven feet in height being possible for a 500 mwe plant. Use of a smaller reactor vessel naturally decreases reactor coolant system volume requirements. Simplified reactor vessel internal design is also achieved. Greater power is also obtained per unit of the core, thus providing operating economies and improved burnup.

Fuel Technology

Improvements in the area of fuel technology have contributed to the continuing reductions which have been achieved in fuel costs. Technology advances have been realized in the area of fuel assembly design, materials, and fuel management systems.

Fuel Assembly Designs

The cores of PWR plants ordered today contain essentially the same material as the first Yankee core—slightly enriched uranium dioxide pellets enclosed in metallic tubing to form fuel rods. There is a major difference, however, in the way current fuel rods are combined to form fuel assemblies.

In the Yankee fuel assembly, the fuel rods were brazed to spacers placed between the rods to form an essentially rigid fuel assembly. In current fuel designs, a support is assembled much in the way an egg crate is put together, and the assembled pieces are brazed to form a rigid grid. The grids have fingers or "spring clips" which hold each rod firmly in place. Several such grids are then welded at approximately one-foot intervals, to perforated metal sheets, to form a rigid fuel can. Fuel rods are then inserted individually into the grids.

Many advantages result from this new fuel assembly design. First, since the fuel rods are not physically bound to the grids, they are free to expand radially and axially as they heat, and they will not bow because of differential expansion in adjacent rods. Second, since the strength and support function of the assembly is now vested in the can and grids, the materials of the fuel rods themselves can be chosen for nuclear reasons; i.e., Zircaloy cladding can be used with stainless steel cans or grids. Third, the cladding used, be it stainless steel or Zircaloy, can be thinner than the corresponding cladding in a brazed fuel assembly. This is because the clip assembly manufacturing procedures do not expose the fuel cladding to any welding or brazing operations. Thus, the cold-worked properties of the clad materials are retained.

Fuel assemblies of this advanced type have been tested extensively and successfully in test loops and in the Saxton reactor. Based on the excellent results of such tests, the spring clip fuel assembly is being used in current pressurized-water reactor designs.

Materials

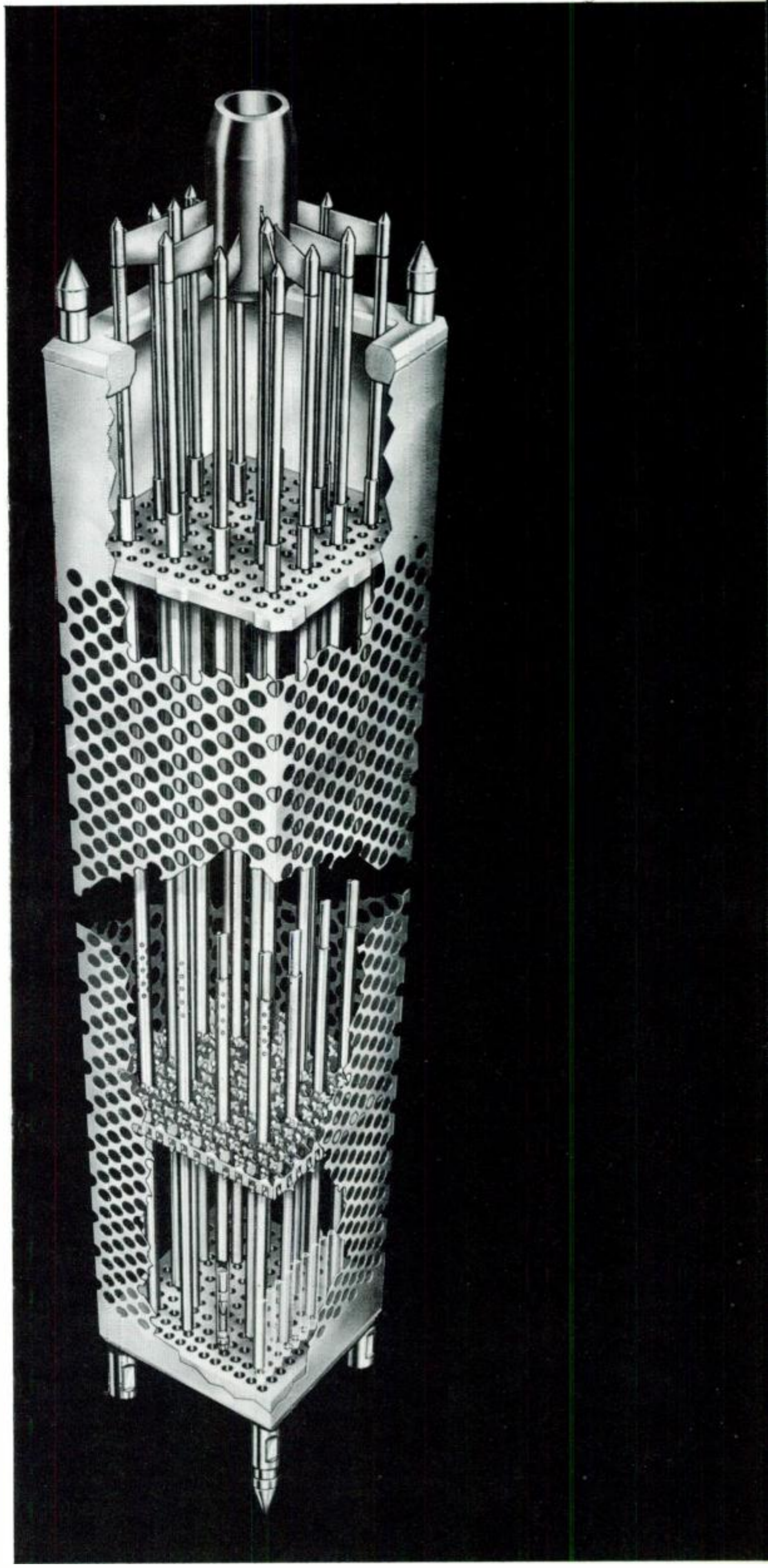
Stainless steel has performed very well as a fuel cladding material in PWRs. The close control of coolant chemistry possible in this type of reactor, with its separate primary and secondary circuits, can hold oxygen and chloride contents down to such low values (0.1 ppm maximum) that chloride stress corrosion and "intergranular stress-influenced corrosion cracking" are of no concern. Yankee fuel rods clad with annealed Type 348 stainless and Saxton rods of cold-worked Type 304 stainless steel cladding have already been exposed to high fuel burnup rates and high radiation exposures with no signs of failure. By contrast, failures of this material have been reported with only half such exposures in reactors not designed for such close control of coolant chemistry.

Zirconium-based alloys are also used for fuel cladding. Under pressurized-water environments, the corrosion product is a firm, black, adherent temper film. If there is a high oxygen content in the coolant, the corrosion rate increases. Experiments at Hanford National Laboratory have shown that with only 0.8 ppm of oxygen in the water, the corrosion rate of Zircaloy-2 is increased tenfold from the normal corrosion rate at 540 degrees F, thus equaling the normal corrosion rate at 750 degrees F.

The rate of hydrogen sorption was unaffected by flux intensity or integrated flux. Because hydrogen sorption, rather than corrosion, usually limits the effective life of a zirconium alloy in a nuclear reactor by reducing ductility, Westinghouse has changed to Zircaloy-4. This appears to be a better material, since it has a hydrogen sorption rate of one-half to three-fifths that of Zircaloy-2, thus permitting extended lifetime in pressurized-water environments.

Saxton Plutonium Program

As part of the Westinghouse program for advancing water reactor technology, complete fuel assemblies enriched with plutonium oxide are to be tested in the Saxton Reactor under a Euratom-USAEC Joint Program. The purpose of the pro-



4—Model of prototype rod cluster control assembly. Arrangement of the cluster is shown at top.

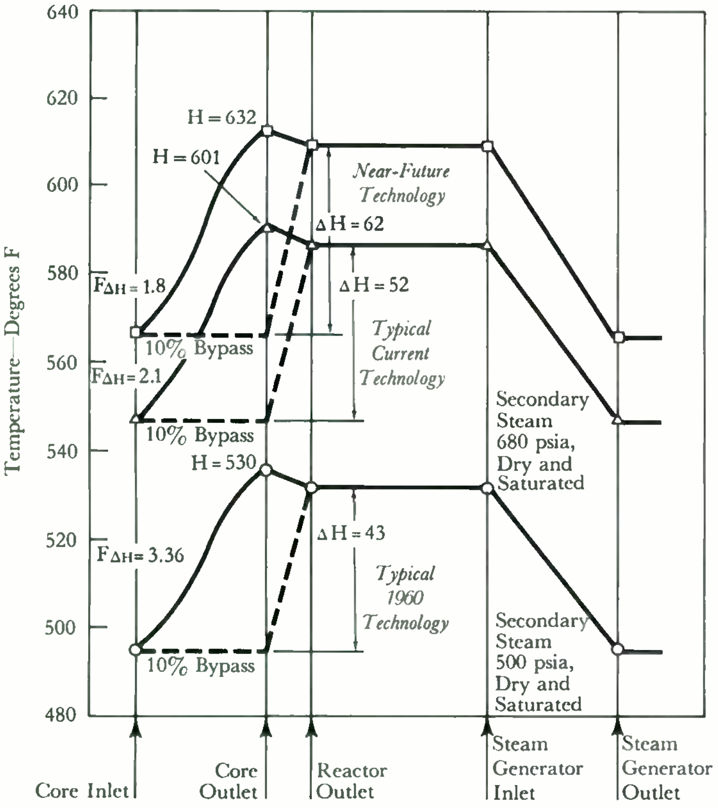
gram is to obtain performance information on complete plutonium-enriched fuel assemblies under pressurized-water reactor operating conditions. Eight assemblies, containing a total of 660 plutonium-bearing fuel rods, are to be irradiated. The tests will provide valuable information on the utilization of plutonium in power reactors.

Fueling Systems

Several fueling techniques are available to the reactor designer and operator. Each method has its advantages and disadvantages, and the one selected depends upon the circumstances.

With *batch loading*, all fuel elements are placed in the core at the same time and all are removed for reprocessing at the same time. With *uniform batch loading*, all fresh fuel elements are identical. The Yankee Core I was an example of uniform batch loading. The principal advantages of this method are simplicity and possibly long periods of operation between refueling. The main disadvantages are poor power distribution (control rods are ordinarily used to improve the power distribution), and low discharge burnup in terms of megawatt days per metric ton.

The disadvantage of a poor power distribution can be alleviated somewhat by using a *nonuniform batch loading*. For example, the core might be divided into several regions, each region fueled with a different enrichment to improve the power distribution. However, if all fuel is discharged at the same time, the average discharge burnup for a given average feed enrichment is still quite low and fuel costs are affected adversely.



5—PWR core performance advancements since the Yankee design are shown here.

To achieve the high burnups associated with low fuel costs, fuel is *cycled*. Instead of removing all of the fuel at a given refueling, only the most depleted fuel is removed and replaced by fresh fuel. The less depleted fuel remains in the reactor and is forced to higher burnups by the presence of the fresh fuel.

With *region cycling*, the core is ordinarily divided into two or more concentric zones. Fresh fuel is added to one zone while other zones are shuffled and the most depleted zone is discharged. Although many variations of this method are possible, the most common is "out-in" cycling. Here, the central zone of fuel assemblies is discharged, the remaining assemblies are moved progressively inward, and the fresh fuel is installed in the outer zone. In many reactors, this method has the advantages of improving the power distribution and increasing the discharge burnup. This method has been utilized in the two-region Yankee Core III, and in the three-region SELNI core.

As reactor core designs are extended to larger sizes and higher burnup, region cycling may prove inadequate. To overcome the problems in very large pressurized water reactors, the "*roundelay*" *cycling* method is being developed. Instead of locating all fresh fuel in a single region, it is distributed uniformly throughout the core, and ordinarily is not moved again until it is discharged for reprocessing. With this method, depleted and fresh fuel elements are intimately mixed, resulting in strong neutronic coupling. The gross power distribution tends to be improved and high burnups are possible. Another advantage is that only a fraction of the fuel assemblies are handled at each refueling. A disadvantage is that local power peaking, showing as a ripple from assembly to assembly, results from mixing the fresh and depleted fuel assemblies. Studies for a 1000 mwe PWR indicated considerable potential for roundelay cycling in that size core.

The important point is that improvements in the fuel technology of pressurized-water reactors have arrived quickly. Planned experiments under "pushed" operation at the Saxton plant are expected to suggest even further improvements.

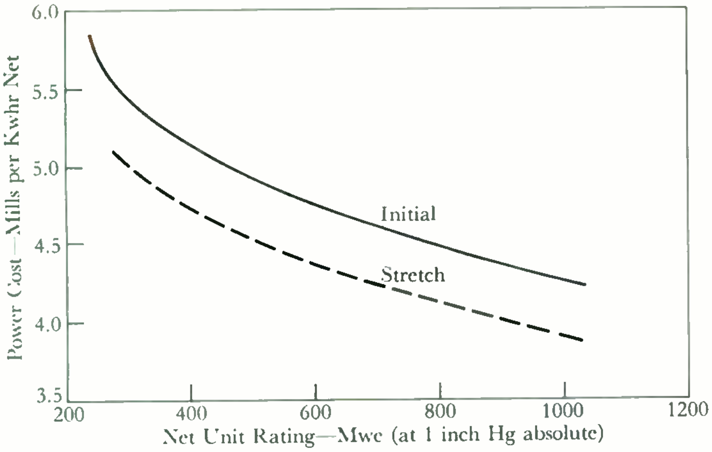
Application of Improved Technology

Through the operation of Yankee, much has been learned about the ability of PWR plants to follow load requirements. This has resulted in better utilization of reactor control systems. The demonstrated durability and reliability of Yankee plant components, together with increased knowledge of the physics behavior of large power reactors, has contributed significantly to Yankee's power increase to 185 mwe. This power increase results in extremely favorable economics in terms of dollars per kilowatt. In 1958, for example, when design of Yankee's first core was in progress, an equilibrium fuel burnup of about 9000 MWD per metric ton was considered the practicable limit. Technological improvements since that time, however, have increased this figure to an equilibrium burnup in excess of 20,000 MWD per metric ton of uranium. Even higher burnups appear attainable from current programs.

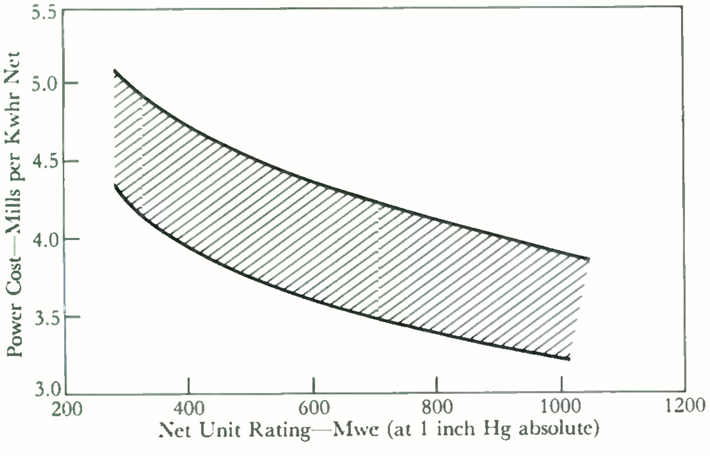
The significant advancements in reactor core thermal performance since the initial Yankee design are indicated in Fig. 5.

Economics

The estimated cost of power produced from nuclear units committed today is shown in Fig. 6, utilizing ground rules currently in use in the United States. Many utilities have found it advantageous to install a turbine generator and secondary plant considerably larger than the initial reactor rating to take advantage of further projected improvements in reactor technology. This additional capability, referred to as "stretch," is obtained at low incremental cost and further improves the economics of power generation as the technology advances. The demonstrated ability of PWR plants to incorporate and take advantage of such future technological advances is a feature unobtainable from conventional plants.



6—Power cost from a PWR unit committed today. The data presented is based on costs in the United States for a good site location. Fuel cycle costs are based upon lease of enriched uranium at an annual charge of 4¾ percent with the value established by the U.S. AEC on July 1, 1962. Plutonium is evaluated at $10 per gram fissile as nitrate. Annual charges on capital are taken as 12.8 percent and the load factor is 90 percent.



7—Power cost from a closed-cycle water reactor unit committed in future; because of uncertainties, costs are shown in a band.

The power costs shown in Fig. 6 are functions of variables other than unit ratings. Among these variables are specific customer and system requirements, financing conditions, and siting. A meaningful evaluation of nuclear power advantages can only be obtained by careful analysis of all factors under specific customer conditions at a definite plant location, and by considering the operation of the utility system as a whole. Unless this is done, data such as that presented in Fig. 6 or in various associated tabulations must be used with caution.

Nuclear units committed in the future are expected to have even lower power costs. A reduction of 10 percent in present capital cost is anticipated as a result of continuing development programs and cost-reduction efforts. Operating reliability should result in a reduction of insurance premiums. The estimated cost of power produced by nuclear units committed in the future is shown in Fig. 7.

Predictions

Up to this point, the discussion has centered on PWR plants either operating, under construction, or in the design stage. What of the future? What size will be required to meet the power needs five or ten years from now?

Size of Plants

The overall power plant experience of the last decade in the USA might be used to predict the size trend over the next ten years. Ten years ago, the average fossil unit size ordered in the U.S. was 150 mw electric; i.e., one-half of the new capacity ordered was in units larger than 150 mwe, and one-half was in smaller units. The largest unit on order then was a fossil unit rated at about 350 mwe. Today, the estimated average unit size of all types on order is about 500 mwe, and the largest unit is rated at 1000 mwe.

Today nuclear plants are available in sizes over this entire range, and several PWR plants in the 500 mwe range have already been ordered. In fact, PWR units up to 1000 mwe are now being offered on a firm commercial basis.

In the next decade the "average" unit size will be about 800 mwe. The largest unit ordered by 1975 is expected to be about 1800 mwe, and will probably be all nuclear. The outlook today is that PWR technology will keep abreast of power needs both in the United States and throughout the world and will play an increasingly important role in meeting these needs.

Economics of Peaking Generation

by J. H. Cronin
H. E. Lokay

The low capital cost of peaking plants makes this type of generation increasingly desirable for electric utility systems. The optimum ratio of peaking to base-load generation depends upon system characteristics and upon the difference in capital costs between the two plant types.

Can peaking units serve today's growing and changing power system loads more economically? And if peaking plants can be applied economically to a system how can they be integrated into a unit expansion plan containing base-load type units? With these questions facing many utilities today, peaking plant economics has become one of the most discussed subjects in the electric utility industry.

Why Peaking Plants?

Electric utility load characteristics are changing: system annual load duration curves show higher peaks without always showing a corresponding increase in average load. Such peaks are principally due to the increase in weather-sensitive loads, such as cooling and heating, and the higher the saturation of these loads, the more extreme the annual peaks are likely to be. Generating capacity must be available for the peak hour of the year, both to carry the load and to provide moderate reserve. Thus, the growing weather-sensitive load may increase disproportionately the amount of generating capacity needed for the peak hour and the few hours near it. Many utilities use the top 20 percent of their available generation less than 5 percent of the time, which amounts to only a few hundred hours a year.

Historically, system capacity has been expanded by adding large, efficient steam turbine plants to carry base load. Older less efficient plants have been operated at progressively lower load factors until they were retired. Because their operation amounted to only a few hundred hours per year, their poorer efficiency could be tolerated. Thus, the availability of new highly efficient machines resulted in the displacement of peak load to older machines. But today, the situation is changing.

Up to now, turbine-generator efficiencies have improved faster than systems have grown so that the addition of a new machine has always resulted in substantial improvement in overall system generating efficiency. The purchase of special peaking units could not be justified because this would have deferred installation of the more efficient base-load units that provided real system economies. However, heat rates no longer are improving so rapidly. As systems come to have machines with uniformly low heat rates, displacement of load to older units will no longer be an economical way of providing peaking capacity. Instead, the incentive will be to apply low-capital-cost, less efficient peaking sources.

Types of Peaking Power

One source of peaking capacity is the *gas turbine*. Gas turbines are suited for peaking service because of their low first cost, low installation cost, low operating cost, low maintenance cost, possible automation, simplicity of control, quick starting ability, and overload ability. To illustrate the last two advantages, a gas turbine, under emergency conditions, can be started cold and be carrying full load in 15 minutes; its load capability increases five percent for every 10 degrees F decrease in ambient air temperature. Operating experience, mostly industrial, with gas turbines has been good, with over 365 units representing 2.5 million kilowatts in service. A recent development, which makes gas turbines even more attractive for peaking service, is the use of fluid injection. In this cycle, fluid is injected into the combustor to increase the mass flow through the unit. The result is a gas turbine unit with five times the output of a conventional gas turbine unit, and therefore a lower dollar-per-kilowatt capital cost.

Another source of peaking capacity is the *diesel plant*. The diesel has low first cost, low installation cost, and a relatively good heat rate. It is capable of fast start, 1.5 minutes, and automatic operation. It has the disadvantages of burning only high-cost distillate oil and of increasing maintenance costs as operation exceeds 1000 hours per year. For these reasons, diesels have an economic handicap except when used for carrying the peaks a relatively few hours per year. Another deterrent to widespread use of diesels is their physical size; their dimensions and weights are higher per kilowatt than any other type of peaking machine. They also come in smaller unit mw ratings. Their fast startup frequently permits them to be considered part of the spinning reserve requirements.

A third source of peaking power is the *pumped-storage* hydro installation. Energy is stored during light-load periods, such as nights and weekends, by pumping water from a lower source to a storage pond behind a dam. During subsequent periods of peak load, water is run through the pump-turbines in the opposite direction to generate peaking energy. While pumped-storage plants have relatively good overall efficiency, as high as 70 percent, their application is limited by available sites. Consequently, they may be an attractive peaking source, but many systems cannot install enough capacity to meet full peaking requirements.

A fourth source of peaking power is the *special steam unit*. In one form, large units can be used for efficient base-load operation, but the boiler-turbine combination is designed for extra mw capability at reduced efficiency during peak periods. The additional capacity is obtained by modifying plant operation, such as bypassing feedwater heaters, increasing pressure, etc. Another form of special steam peaking unit is a low-pressure, low-temperature unit designed specifically for peaking operation. By using these steam conditions along with full-size auxiliary drives with no spares, a low-capital-cost plant can be obtained. None of these plants are in operation to date, but some electric utility systems might well justify such a peaking plant in the future.

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Study Approach

Many approaches can be taken when planning the expansion of a particular system. Each alternative involves the development of a future base-load unit expansion plan containing fixed unit sizes and types. Expansion plans should integrate peaking plants with base-load units. Following a specific load-growth plan, annual revenue requirements can be calculated for all future plant additions. By following specific load duration curves (daily, weekly, monthly, or annual), unit availabilities, unit dispatching, plant operating costs, and system production costs can be calculated. This calculation should be done for each alternative expansion plan, and an economic comparison made. High-speed digital computers can be used to perform these detailed calculations.

The development of expansion plans that include peaking plants presents a complication; where future generation is to be expanded with two entirely different types of generation, the proper combination of each type must be used. This problem suggests that a preliminary study is needed to determine the optimum combination of peaking and base-load plants.

An analytical method has proved very helpful in developing expansion plans that can include peaking units. Once feasible expansion patterns have been developed, accurate and comprehensive evaluations can be made with the standard Powercasting programs using high-speed digital computers. The remainder of this article will discuss an analytical method for evaluating the feasibility of peaking plants, and for developing the optimum combination of peaking and base-load plant expansion plans or patterns for the system.

Study Example

The analytical method for evaluating the need for new peaking capacity takes into consideration all existing units, anticipated load growth, retirements, and annual load duration curves. Although the mathematics involved in the method are cumbersome and detailed, the method basically consists of developing each future year's revenue requirement equation, which includes production or operating costs and carrying charges for all new required plant additions. The equations for each year are differentiated, set equal to zero, and the minimum cost determined by solving for the optimum mix of the different types of units.

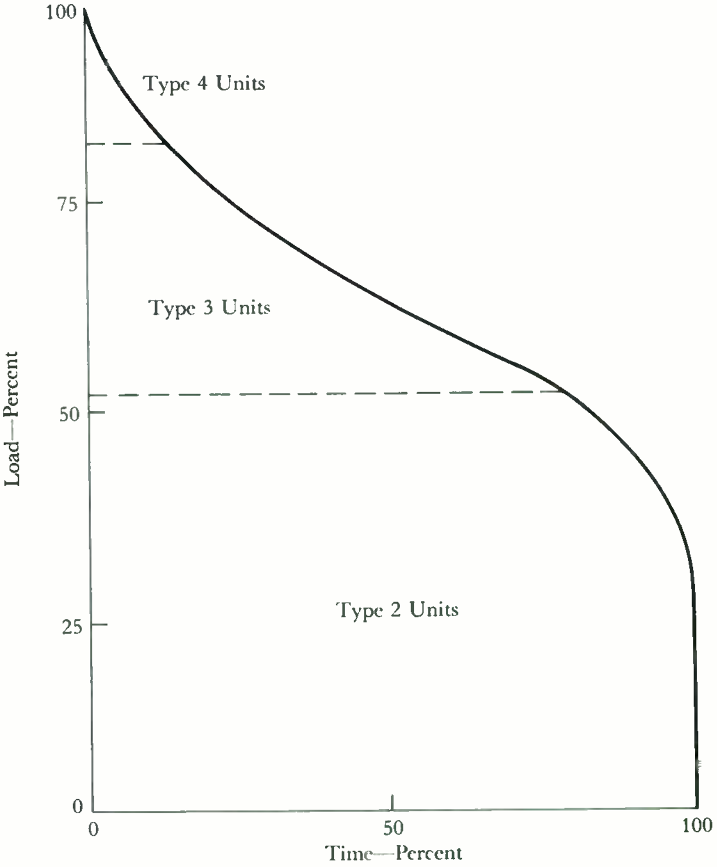
To illustrate the method and the results that can be expected from a peaking study, a model system will be considered. The characteristics of the model system are listed in Table 1.

The system defined in Table 1 contains three types of conventional generation—reheat, non-reheat, and low pressure. The annual load duration curve for the system is shown in Fig. 1, along with the energy portions under the load duration curve produced by the three types. With a load growth rate of 7.2 percent annually, system load will double every ten years; however, the shape of the load duration curve is assumed not to change during the study period. Required future capacity will be either base-load units, defined as Type 1, or gas-turbine peaking units defined as Type 5 in Table 1. In this analytical

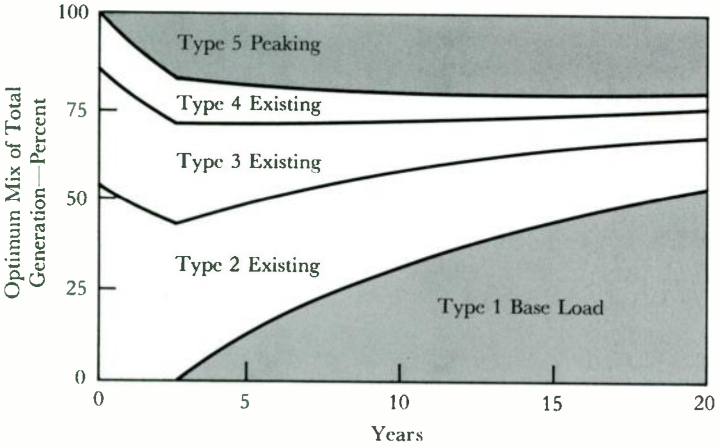
Table 1—Characteristics of System Model

Description of Model System		
Peak Load	1500 mw	
Rate of Load Growth	7.2 percent annually	
System Load Factor	65 percent	
Carrying Charge Rate	14 percent	
Cost of Money	6 percent	
Present Generation		
Type	Capability	Production Cost
Type 2 (Reheat)	890 mw	2.7 mills/kwhr
Type 3 (Non-reheat)	500	3.2
Type 4 (Low Pressure)	278	3.8
New Generation		
Type	Capital Cost*	Production Cost
Type 1 (Base-load, reheat)	145 $/kw	2.6 mills/kwhr
Type 5 (Peaking-gas turbine)	75 $/kw	7.6

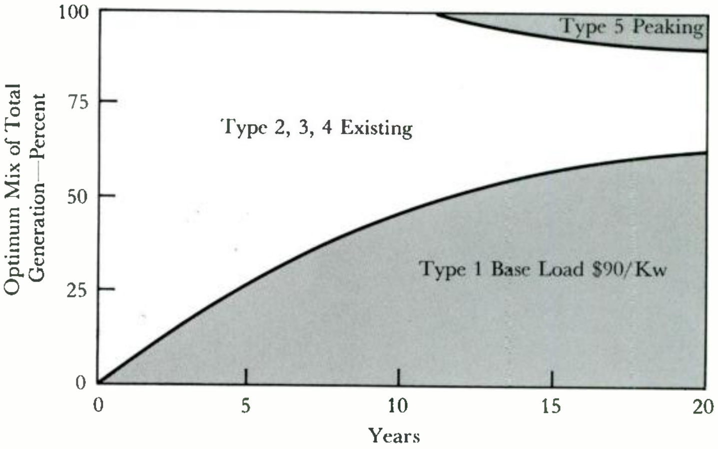
*Costs estimated for the study example. Certain peaking gas turbines can be applied at 65 $/kw.



1—Annual load duration curve for the model system of Table 1 shows energy produced by each unit type (load factor—65 percent).



2—Optimum saturation of each unit type is shown for the 20-year study period. New generation costs are listed in Table 1.



3—Optimum saturation of each unit type will depend upon the cost of unit addition. Here, the new generation costs of Table 1 are used except for Type 1 units, which are $90/kw.

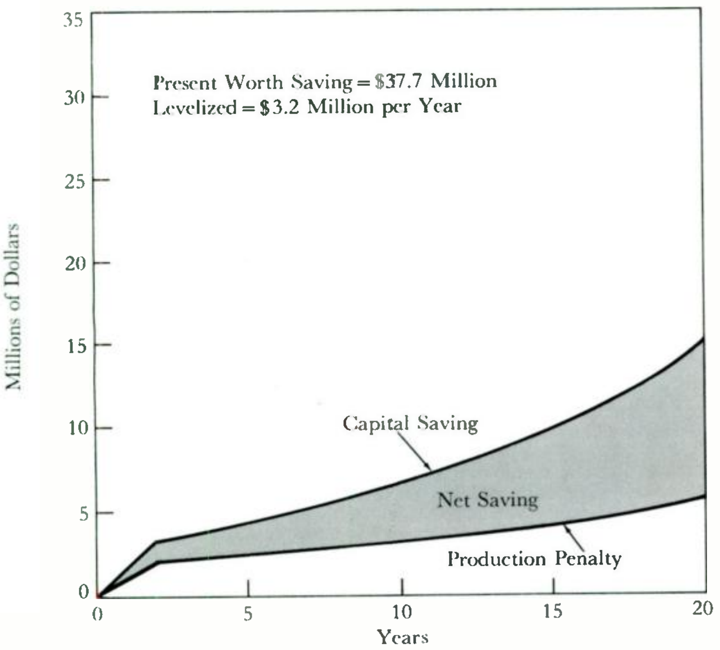
method, no specific unit sizes are added; just enough capacity is added per year to satisfy load plus reserve requirements.

Using the cost data from Table 1 and determining the percent mix of each type of capacity to give minimum revenue requirements each year, the curves showing the optimum percent mix of the total generation each year are shown in Fig. 2. The initial (year zero) percent mix is determined from the total capacity of existing units—Types 2, 3, and 4. As new capacity is added, the percent of total generation for the existing generation decreases as shown in Fig. 2. The curves show that by year 20, the total amount of Type 5 peaking capacity should be 22 percent of the total generation. Furthermore, it shows that for the first few years, only peaking capacity should be added. When peaking capacity reaches about 16 percent of total generation, the average system heat rate has climbed, due to the peaking plants, to the point where the improvements possible by adding the efficient Type 1 generation will overcome its higher initial capital cost. Beyond this point, generation expansion is a combination of base-load and peaking units, with a saturation point for the peaking units at about 22 percent.

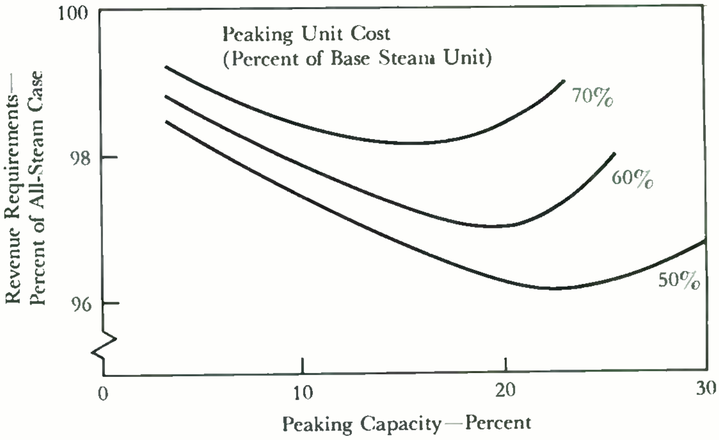
Once the optimum make-up of total generation is known, expansion plans can be developed containing specific unit sizes and types such that their installation dates will follow closely the optimum percent mix. Since units will be added in distinct sizes, actual curves will be step curves surrounding the smooth curves shown in Fig. 2. Following the curves will greatly reduce the number of expansion plans to be studied for developing the most economic expansion plan.

The optimum mix of the various unit types is very sensitive to the dollars per kw of unit addition. For example, if the Type 1 base-load units had a capital cost of $90/kw instead of $145/kw, the optimum percent curves for the same study period are shown in Fig. 3. In this case, all future addition should be Type 1 up to year 11. From this point on, incremental improvements in system heat rate due to adding Type 1 units is not great enough to offset the capital cost differential between Type 1 and the peaking Type 5 units. Beyond year 11, a combination of the two types should be added and, as expected, the saturation percentage of peaking capacity is reduced to approximately 10 percent.

For comparison, the capital charges and total production cost for the 20-year study were calculated for the optimum pattern shown in Fig. 2, and for the same system in which only Type 1 base-load units are added. The annual capital cost savings and the production cost penalty obtained when following the optimum combination pattern are shown in Fig. 4. The difference between the two curves is the net savings attributable to the optimum combination or peaking pattern. The difference increases rapidly during the early years as the original deficiency in peaking units is corrected. The rate of increase in savings then levels off somewhat, but increases again during the latter years. This latter increase is due to the higher load



4—Difference in annual capital and production costs from expansion by optimum percent mix (shown in Fig. 2) and expansion by conventional base-load units only (Type 1).



5—Effect of peaking unit cost and saturation on revenue requirements are shown for the model system of Table 1.

level, the higher saturation of peaking units, and the relatively small improvement in system heat rate effected by further additions in Type 1 units. Total present worth of future revenue requirements is $37.7 million. This represents an annual savings of $3.2 million per year levelized over the 20 years.

In general studies, it is often of interest to determine the penalty for not following the optimum peaking pattern. To determine this for the system described in Table 1, the peaking plant percent curve was varied above and below the 22 percent saturation value and the capital costs and production costs were determined. The results are plotted for different percentage peaking costs in Fig. 5. The curve that shows peaking unit costs approximately 50 percent of base-load unit costs has a fairly flat range around the optimum 22 percent saturation. For peaking capacity saturations between 16 and 24 percent, the savings are within 5 percent of theoretical maximum. Since this is within the accuracy limits of the input data, it can be concluded that a peaking capacity saturation between 16 and 24 percent will offer the greatest system savings. It is evident from Fig. 5 that as the cost difference between peaking and base-load units gets smaller, the optimum percent of peaking capacity decreases.

Conclusion

Obviously, in the method and results described above, all of the factors that affect peaking plant economics have not been included. Transmission requirements, fast start-up, available plant sites, maintenance, and operating flexibility are some other factors that also must be given full consideration in any detailed economic study.

While the general study method described uses a single production cost, capital cost, and carrying charge for each plant type, these assumptions are not limitations of the method. Different values can be used for each year. Also load factor and load duration can be changed each year. The greatest single influence on the economic percentage of capacity that should be peaking for any year is the difference between the capital costs of the two plant types. When a plant is required to operate at low capacity factors, such as is true of peaking units, the savings resulting from smaller capital investment in plant more than balance the higher fuel cost, thereby providing a net saving to the utility.

In determining the optimum amount of peaking for any given electric utility system, it will be noted that one of the items requiring careful consideration is the production cost penalty due to *not* installing base-load units. Since the improvement in electric utility plant efficiency between successive modern units is getting smaller, this factor is likewise becoming less important. The more efficient the present system, the smaller the production penalty incident to *not* installing new base-load type units and the greater the saving from the installation of peaking units.

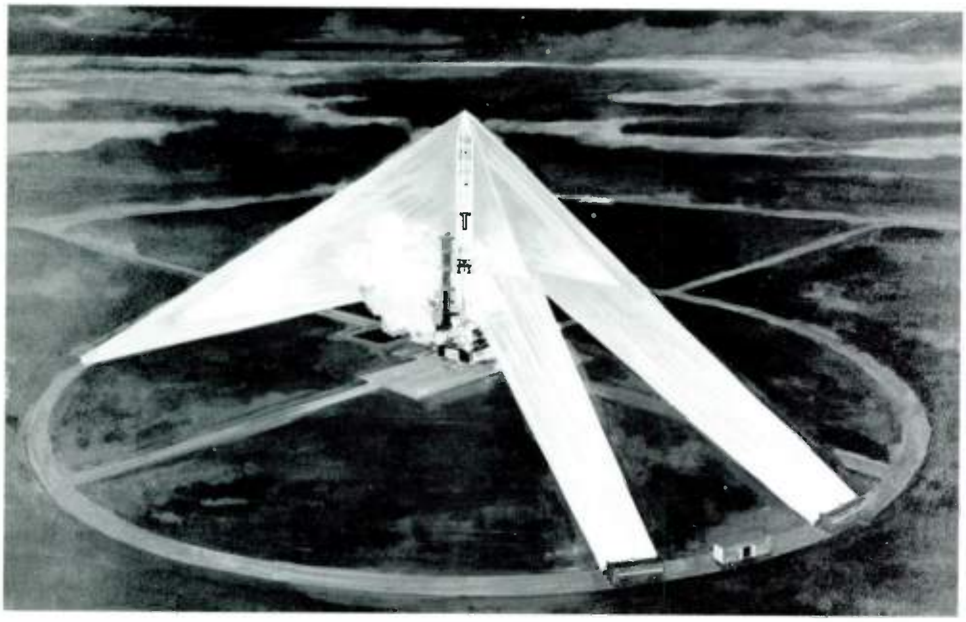
Launch Illumination System Will Track Rockets

When large rockets are launched, they are closely monitored by television and motion-picture cameras during the critical first thousand feet or so of rise. The accurate photometric records thus made are necessary to evaluate any malfunctions in such things as hold-down-clamp release, umbilical-cord separation, and nozzle action. Daylight has been necessary for close observation by these means, and this has effectively limited many rocket launches to daytime hours.

Now, however, a three-element launch-area illumination system is being designed to illuminate a rising rocket brightly and uniformly enough for high-quality color motion-picture photography at night. This test system will consist of two mobile trailers carrying 36 powerful searchlights each, a power van, and a tracking system to automatically keep the lights trained on the rocket as it climbs skyward. It will be tested by Westinghouse and evaluated by the U.S. Air Force at Cape Kennedy, Florida. (A complete system, illustrated here, would have 216 searchlights carried by six trailers to permit photography from any angle.)

The lighting and tracking systems will be controlled from a remote station.

Each searchlight will have a 6000-watt short-arc xenon lamp in a reflector about 36 inches in diameter. Thus, a six-trailer system would have 1,296,000 watts of lighting, enough to keep the rocket in shadowless artificial daylight. The xenon lamp produces 275,000 lumens; in the searchlight fixture, it provides 80,000,000 beam candlepower.



Tracking illumination system will keep a rocket brilliantly and uniformly lighted for observation and photographing during the critical first moments of its flight. The system is illustrated here by an artist's conception of how the powerful searchlights mounted in six trailers would be used.

Cable Connector Is Light and Strong

A new coaxial cable termination, shown here both unencapsulated and complete, has been developed for aerospace applications. It can be soldered or welded to printed circuit boards to make a strong rigid connection. This connection is lighter, more compact, and more reliable than the conventional type because there are no separate coaxial connectors. Moreover, the termination method reduces electrical noise, an advantage that is especially important when connections must be made to sensitive areas such as r-f circuits on a printed wiring board. Initial applications have been in radar systems for space rendezvous and airborne fire control at the Westinghouse Aerospace Division.

Power-Water Plant for Virgin Islands

A combination power and fresh-water plant to be built in St. Thomas, Virgin Islands, will produce 7500 kilowatts of electricity and purify 1,000,000 gallons of seawater a day. It will provide badly needed water and power for the 20,000 residents of the island and for a large and growing tourist influx.

The island now has little natural fresh water except for captured rain; it gets most of its water in barge shipments at $1.45 per thousand gallons. Pure water from the desalting plant will cost $.90 or less per thousand gallons.

Motor Cases in Production for Titan III-C Rocket

Rocket motor cases ten feet in diameter are being built on a production basis for the booster rockets of the U.S. Air Force Titan III-C space launch vehicle. They are the biggest rocket motor cases in large-scale production in the free world. Each case consists of five cylindrical segments, ten feet long, and two hemispherical end closures. When readied for firing, the segments and end closures are connected by pin and clevis joints.

The case segments and end closures are made from plates and forgings of an intermediate-carbon, low-alloy, high-strength steel designated D-6ac. The components are heat treated after fabrication to produce an ultimate strength of 195,000 to 215,000 psi.

Manufacturing equipment and techniques were developed to impart exceptionally high reliability, because the Titan III-C is rated for man-carrying missions. Manufacturing precision helps attain this reliability and also makes parts interchangeable.

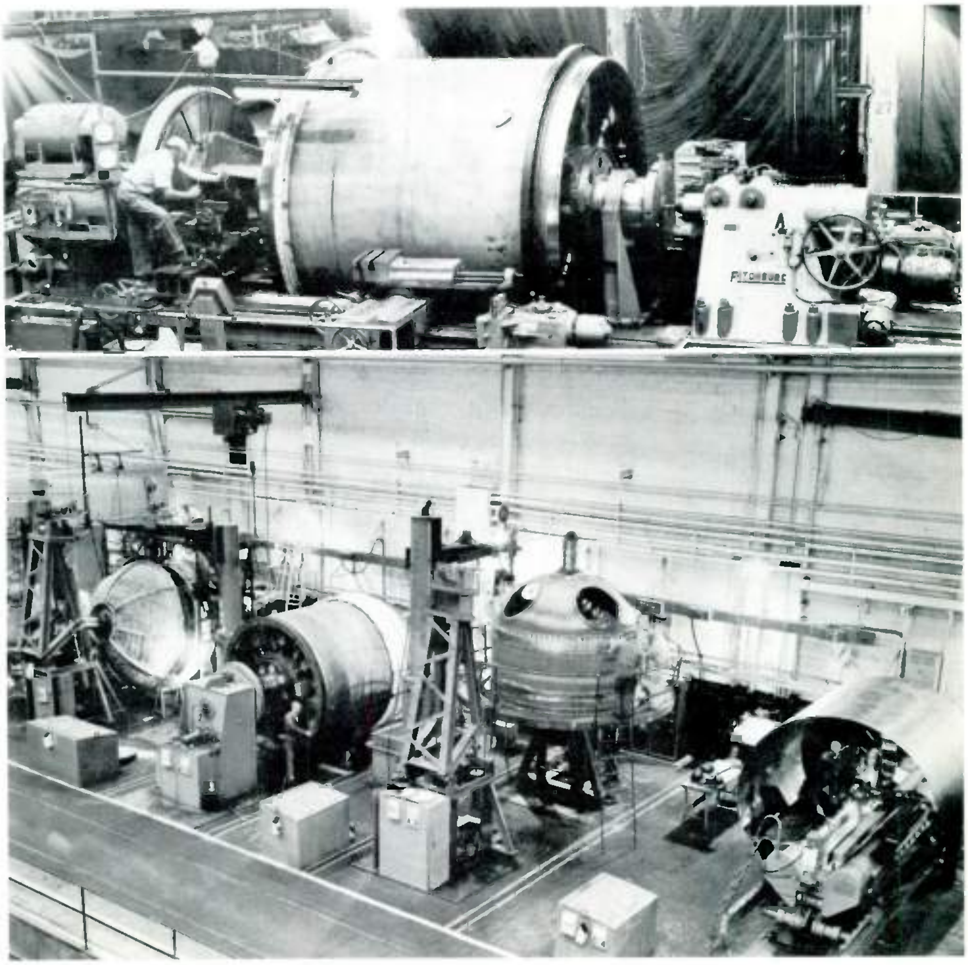
In all welding, components are preheated to 650 degrees F and kept at this temperature during welding, and the welds are held at 750 degrees F for an hour after welding. This temperature control assures that the weld metal and parent metal in the heat-affected zone will transform to bainite rather than martinsite. Careful fixture design prevents distortion from thermal expansion during heating and welding operations.

For the cylindrical segments, a plate is first rolled into a cylinder. Then the ends of the plate are matched accurately in a special welding fixture, since mismatching would increase bending stresses with consequent reduction of reliability. The fixture clamps the ends under extremely high pressure to prevent their shifting, and the long seam of the plate is then welded in several passes by the tungsten inert-gas process.

The welded cylinder is sized to insure precise roundness and to remove any flats or peaks in the weld area, because these flats or peaks would cause undesirable bending stresses when subjected to internal pressure. Sizing is accomplished by inserting an austenitic stainless-steel mandrel into the segment and heating both the mandrel and the segment to 1150 degrees F. Because the mandrel expands more than the cylinder, it stretches and forms the case by slow deformation, or "creep."

A ring forging for the clevis-pin joints is welded to each end of the cylinder. After heat treating and final machining, the segment is tested hydrostatically at 905 psi for two to three minutes. The segments are also inspected at various stages by magnetic-particle, x-ray, and ultrasonic tests.

The hemispherical end closures are formed by spinning a ½-inch steel plate over a mandrel. The plate is heated to about 1750 degrees F and formed to the



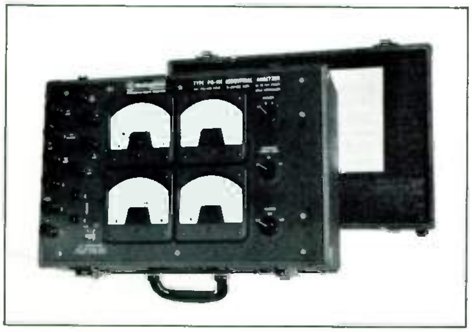
Rocket motor case components are fabricated accurately to assure reliability and interchangeability. At top, the forged rings for the clevis-pin joints are machined. At bottom, case segments and end closures are in various stages of fabrication in the main welding aisle. The longitudinal welds of the cylindrical segments are made at Station One (extreme right). The welded segment is then assembled with a pair of end forgings in a fixture at Station Three (third from right), and the forgings are welded to the segment. At Station Two (second from right), components of the aft closure are assembled and welded. Components of the forward closure are assembled and welded at Station Four (fourth from right), and some machining also is done there.

contour of the mandrel by pressing a roller against it as it rotates. The resulting dome is machined on the outside to the desired wall thickness with a specially developed tool that has a tracer mechanism to follow the contour of the inside of the part. The dome is rotated about its major axis, and the cutting tool follows the desired path over its outer surface under the guidance of the tracer mechanism. (The inside does not have to be machined.) After machining, the end closure is thermally creep-sized over a stainless-steel mandrel in a process similar to that used for the cylindrical case segments.

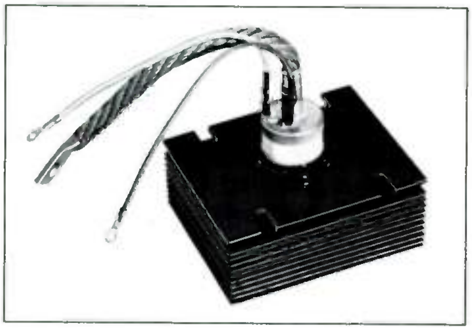
The Titan III-C motor cases are built by the Westinghouse Rocket Motor Case Department, Lester, Pennsylvania, under a contract from United Technology Center, a division of the United Aircraft Corporation.

Products for Industry

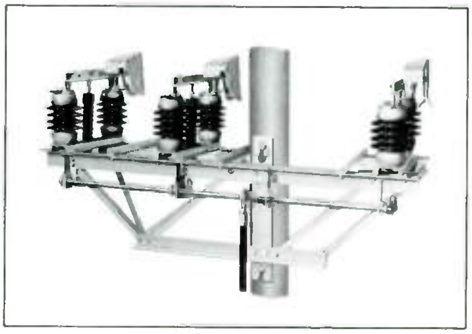
New ac industrial analyzer, type PG-191, tests single or polyphase power circuits up to 600 volts and 125 amperes. It can also be used to test any ac motor. The unit contains a triple-range ammeter, triple-range voltmeter, triple-scale polyphase wattmeter, and polyphase power-factor meter. Ammeter and voltmeter have taut-band suspension; all four instruments have guaranteed accuracy of plus or minus one percent of full-scale deflection. The analyzer is accurate on 25 to 150 cycles and can be specially calibrated for use on 400 cycles. It weighs 26 pounds. *Westinghouse Relay-Instrument Division, Plane and Orange Streets, Newark, N. J. 07101.*



High-power silicon controlled rectifiers, JEDEC 2N3430 series, have compression-bonded encapsulation (CBE) and integral heat sinks. CBE construction eliminates solder joints by use of high-pressure contacts between the silicon wafer and the base. This construction is completely free from thermal fatigue. The integral heat sink eliminates case-to-sink thermal impedance found in conventional semiconductors. Maximum current rating is 400 amperes rms (half-wave average rating of 250 amperes). Forward blocking voltages range from 50 to 1000 volts. *Westinghouse Semiconductor Division, Youngwood, Pa. 15697.*



Gang-operated loadbreak switch, LB-3, is a three-phase pole-mounted type for line sectionalizing, capacitor switching, and transformer switching. Maximum continuous and loadbreak rating of the 15-kv switch is 400 amperes, basic impulse level is 110 kv, and momentary rating is 20,000 amperes. The arc is extinguished by a quick-break blade and Delrin arc chute. Operating handle provides safe manual operation. *Westinghouse Distribution Apparatus Division, P. O. Box 341, Bloomington, Ind. 47402.*



Ultrasonic generator, rated 3 kw and 20 kc, employs solid-state circuitry to provide high-power ultrasonic energy for heavy-duty cleaning applications. It features instant start-up, automatic full output for variations in tank volume or load, light weight, air cooling, and 60 to 70 percent operating efficiency. The only manual control is an on-off circuit breaker located on the front panel. Power requirements are 220/440 volts, three phase, 60 cycles, 5 kva. The unit is 30 inches wide, 12 inches deep, and 46¼ inches high. *Westinghouse Industrial Electronics Division, 2519 Wilkens Avenue, Baltimore, Md. 21203.*

New Literature

The Impact of EHV on Protective Relaying is an illustrated 18-page comprehensive report. It reviews the systems and equipment presently available, the problems likely to be encountered, and the practices of protective relaying for EHV. Special attention is given to backup relaying, primary and backup protection schemes, and the effect of series capacitance. The protective relaying report is designated RPL 64-13, and copies of it are available from the Westinghouse Relay-Instrument Division, Plane and Orange Streets, Newark, N.J. 07101.