Nuclear Power Development in the United States

Government and industry are engaged in a joint effort to achieve economically competitive power by 1968.

Frank K. Pittman

There have been times when responsible individuals have seriously questioned the need for further development of atomic energy for the production of power. These attitudes have been motivated by economics, when it has been difficult to reconcile what appears to be an overabundance of relatively low-cost fossil fuels with costs of nuclear power development.

It is true that these costs have been high. Government and industry are spending about $200 million a year on civilian reactor development alone. However, the development program is directed toward building a new industry, achieving nuclear power production economically competitive with power from fossil fuels in areas where fossil fuels are costly (35 cents per 1000 Btu), and, subsequently, making nuclear power production economically competitive in more and more locations and with an ever-increasing range of plant sizes.

Significant advances have been made, but substantial problems remain to be solved before our objectives are achieved.

At the present time nuclear power is produced in custom-built, complex plants that are costly to build and operate because of their requirements for special fuels, materials, safety, and technology. The tremendous capital costs make it necessary for utilities to amortize nuclear stations as base-load power sources over the lifetime of the plants to achieve acceptable power costs. This is not a problem usually faced by utilities when they build and operate fossil-fueled power stations.

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According to all predictions, the recent tremendous rate of growth in the demand for electricity in the United States will continue. It has been estimated that by 1980 our present generating capacity of about 175 million kilowatts will have increased to approximately 465 million kilowatts, and that in the United States about 2235 billion net kilowatt-hours of electricity will be produced in 1980 as compared with current production of about 830 billion. Those who have made a careful study of our fossil-fuel resources say that our fuel supply is undoubtedly adequate to meet this predicted growth. They further say that any increase in the delivered cost of fossil fuel in the future probably will be largely offset by the tendency toward construction of larger generating units and by an expected continued decrease in the number of Btu's consumed for each kilowatt produced. For example, two units of 500 megawatt-electrical (MWE) capacity are currently in operation, and units of 800-MWE capacity are being built by the industry. The capital cost factor in plants such as these can be appreciably less than that in plants which are standard today.

Potential of Nuclear Power

Such competition is indeed formidable. It means that to make nuclear power competitive in the United States we must take full advantage of all the engineering and mechanical know-how of our science and industry to simplify design, to decrease construction costs, to increase thermal efficiencies, to make maximum use of fuel, and to minimize operation and maintenance costs. This job will not be accomplished overnight with the construction of a few experimental and prototype plants. It will only have been started when more power stations have been built and have reached equilibrium. Nevertheless, we are convinced that nuclear power can be a major factor in meeting the new generating requirements of the United States, and our nuclear development program stems from this conviction.

The key to progress in nuclear power production is improved and demonstrated technology. We did not even know that some of our problems existed until atomic fission and turbogenerating equipment were first united for power production in 1951. There was no need for materials capable of operating in an environment of extremely high temperature, pressure, and radiation prior to the era of nuclear power, and without this need, vast areas of materials technology remained unexplored. Therefore, the emphasis of our program has been on the development of this technology, which can enable us to achieve increased capability in the generation of nuclear power.

Concurrently with our development of materials we have had to determine the technical feasibility of various reactors and, after verifying this, determine the economics of each.

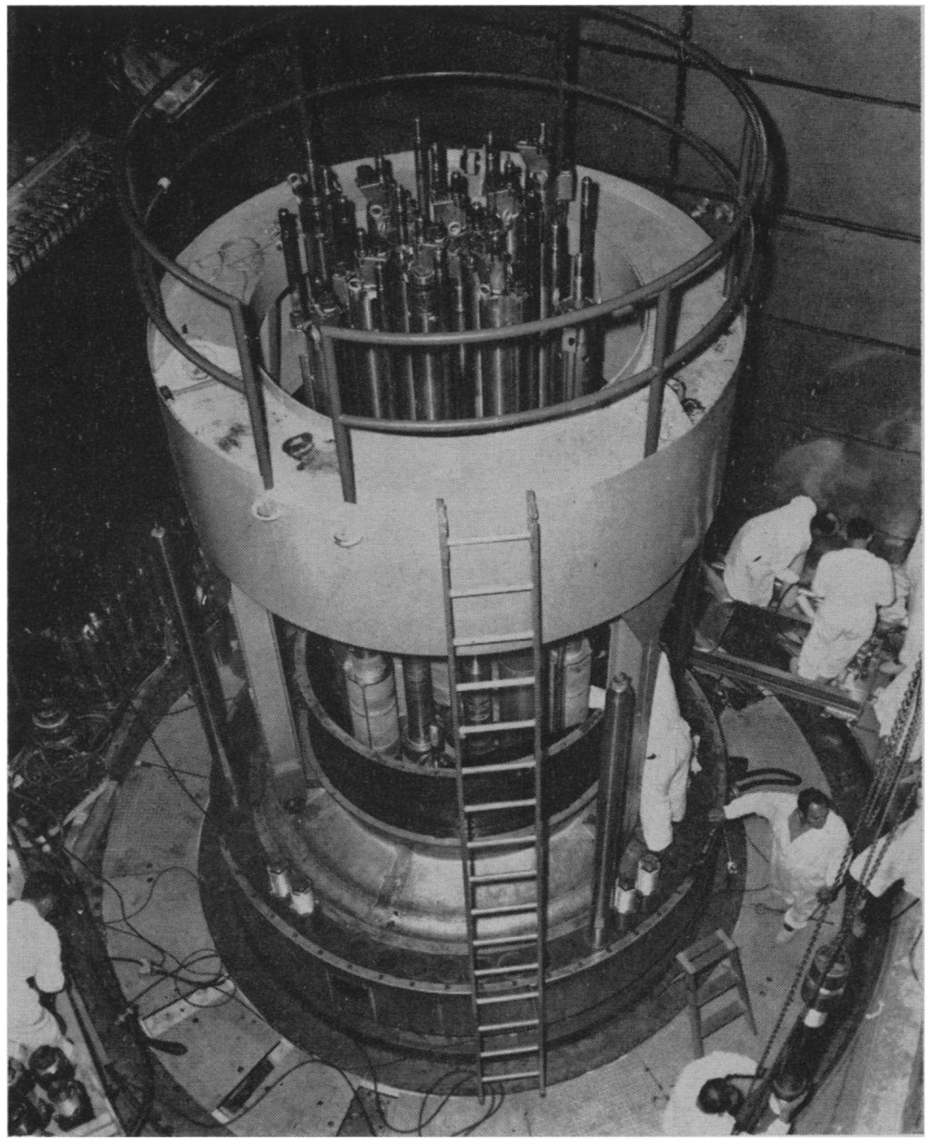
In order to appreciate the extent of the Atomic Energy Commission's development program, let us review some of the more significant aspects.

The development program is carried out in Commission, educational, and private laboratories and through construction and operation of experimental and prototype reactors.

Several reactor systems that appear to offer promise of producing economically competitive nuclear power are being examined. When classified according to coolants, the major reactor systems can be identified as light-water-cooled reactors (these include pressurized and boiling-water systems) and organic-cooled, sodium-cooled, gas-cooled, and heavy-water-cooled reactors.

Light-Water Reactors

Reactors cooled and moderated with light water, fueled with slightly enriched uranium in the form of UO_2 clad in stainless steel or zirconium, and producing saturated steam for the turbines are the type farthest developed technologically in the United States. Therefore, these systems seem the most promising for meeting our objective of producing economically competitive nuclear power in high-cost fuel areas by 1968. In the development program for these systems we are critically examining possible alternative reactor components and fuels in an effort to achieve further reductions in costs.



Yankee Atomic Electric Company reactor vessel head in place, 9 August 1960.

Pressurized-Water and Boiling-Water Systems

For the pressurized-water system, we are obtaining significant data on fuels, such as data on the lifetime-reactivity burnup of the enriched uranium seed and natural uranium blanket core, from operation of the Shippingport (Pennsylvania) Atomic Power Station. The 110-MWE Yankee Atomic Electric Company plant at Rowe, Massachusetts, with a pressurized-water reactor that achieved criticality 19 August 1960, will provide information on the use of slightly enriched fuel clad in stainless steel. The 255-MWE plant of the Consolidated Edison Company at Indian Point, New York, which is scheduled to become operational this year, with a thorium-U^{235} fuel mixture, will provide additional knowledge about reactor fuels. The Indian Point Station has a 151-MWE reactor and a 104-MWE oil-fired superheater. During 1961 the Saxton nuclear experimental reactor at Saxton, Pennsylvania, will begin operating and will provide information on higher specific power and heat flux, boiling of the coolant in the core, and use of dissolved poison for shim control. Later, if our discussions with utilities are successful, we will obtain information through the construction and operation of larger pressurized-water plants. Operation of plants of 300-MWE capacity or more could establish the validity of our assumption that, with current pressurized-water reactor technology, lower nuclear power costs can be achieved most readily with large plants.

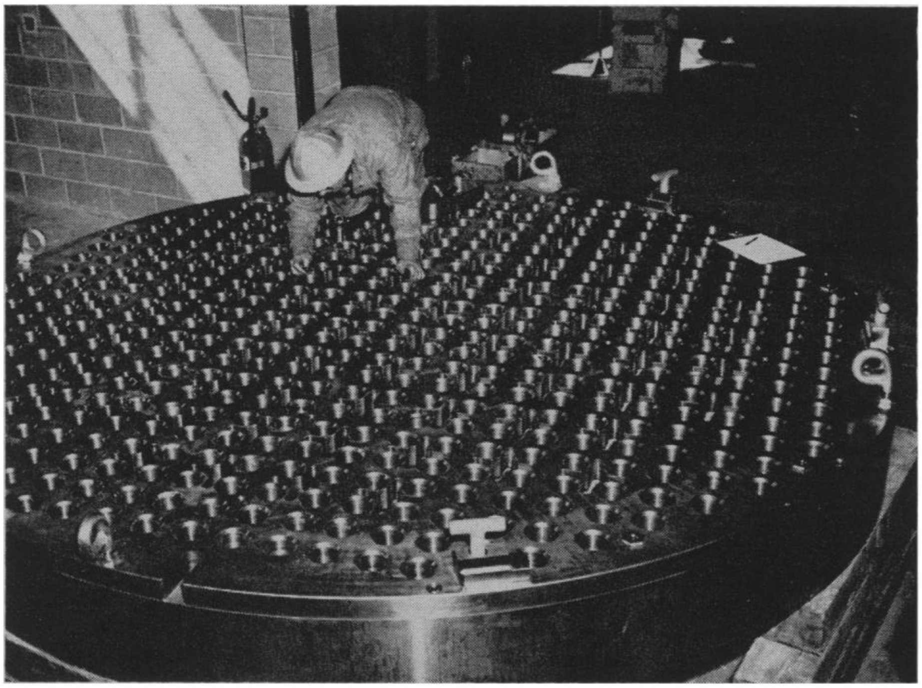
We are also examining a spectral-shift reactor which has the basic characteristics of the pressurized-water system. This reactor uses a variable mixture of heavy and light water as moderator and coolant and has the potential advantage of providing more even power distribution, resulting in operation at higher power levels with higher average fuel burnups, and in high conversion ratios.

Where there are unusual operating or logistic conditions, use of small reactors can be justified, and our civilian reactor development program is reinforced by programs to develop reactors for special purposes. Data are obtained from our program (with the Army) to develop small-size reactors. We also obtain information applicable to the development of central nuclear power stations from our program (with the Navy) to develop nuclear power plants for submarines and surface ships, from our program (with the National Aeronautics and Space Administration) for developing nuclear rocket engines, from our efforts (with the Maritime Commission) to produce reactors for the propulsion of merchant ships, and very importantly from our program (with the Air Force, NASA, the Navy, and others) to develop systems to produce nuclear auxiliary power for space and other needs.

Much of our work on the boiling-water system involves simplifying design, reducing fuel costs, increasing the power density of the core, and improving the vapor-containment techniques.

Much of the development program for the resolution of these problems has been conducted with the Commission's experimental boiling-water reactor at Argonne National Laboratory, the boiling-reactor experiments at the National Reactor Testing Station in Idaho, and the privately owned Vallecitos boiling-water reactor at Pleasanton, California.

In addition, nuclear power stations that use boiling-water reactors have been, and are being, built by utilities



Bottom core support plate of the reactor pressure vessel is inspected for tolerances at the Dresden Nuclear Power Station, 23 March 1959.

and by the Atomic Energy Commission to produce electricity for commercial power systems. These operations will produce economic data which can be as important as the technical data obtained from reactor experiments. The 180-MWE Dresden station of the Commonwealth Edison Company, near Chicago, and the 22-MWE Elk River (Minnesota) plant are examples of such stations.

The Dresden reactor began operating last year but was shut down when stress cracks were discovered in some of the control-rod drive index tubes. Replacement parts are being fabricated, and resumption of operation is expected by the time this article appears in print.

The Elk River plant will soon be completed. It has an indirect-cycle boiling-water reactor plus a coal-fired superheater, and it will provide experience in the use of thorium oxide and uranium oxide fuels and of an intermediate heat exchanger in the boiling system.

Construction was started on the 50-MWE high-power-density reactor by the Consumers Power Company of Michigan in May 1960. The plant is scheduled to achieve criticality in the fall of 1962 and will provide technical and economic information on operation at power densities up to 60 kilowatts per liter, with fuel lifetimes and fuel fabrication costs similar to those achieved at lower densities.

Construction was also started last year on a 48.5-MWE plant at Humboldt Bay, near Eureka, California. This Pacific Gas and Electric Company plant is to be completed in late 1962 and will be the first to use a new pressure suppression and containment system in which vapor from a reactor accident would be expelled through a pool of water and pressure would be reduced by condensation. This may remove the need, in some cases, for a pressure containment building, further reducing capital and power costs.

Nuclear Superheating

Another method of reducing power costs is through the use of superheating. Superheating makes possible the production of steam by nuclear reactors at temperature and pressure conditions found to be most efficient in modern generating equipment. Oil- or coal-fired superheaters, such as that used at the Elk River plant, can be used, but we are especially interested in *nuclear* superheating.

The desirability of using nuclear superheating varies with the size of the unit. In small reactors, superheating appears to be of more value in the direct-cycle than in the indirect-cycle reactors. Although superheating is applicable to both boiling- and pressurized-water reactors, it appears to be of most economic benefit when used with direct-cycle boiling-water reactors.

As part of our effort to develop nuclear superheating, we are initiating critical experiments and conducting tests of heat transfer, steam separation, corrosion-erosion, and steam purity. In addition, three plants are now under construction which will examine integral nuclear superheating arrangements. One is the government's boiling-reactor experiment No. 5, BORAX V, scheduled to begin in mid-1961, to provide data on superheating and on forced circulation and various core configurations for the further development of boiling-water reactors. The other plants are the Pathfinder atomic power plant at Sioux Falls, South Dakota, and the boiling nuclear superheat reactor, called BONUS, at Punta Higuera in Puerto Rico. Pathfinder will have a superheater that is centrally located with respect to the boiling-core region. It is scheduled to achieve criticality in mid-1962. BONUS, which will have a peripheral superheating region, is scheduled to be in operation in early 1963.

The Commission is also investigating the use of separate superheating reactors.

A group of utilities recently announced the financing of a development program which could result in the design and construction of a large nuclear plant. Use of a nuclear superheating reactor is under consideration. If the development effort is successful and a nuclear superheating reactor is chosen, this will encourage other utilities to consider using nuclear superheaters when they decide to construct nuclear power stations.

Organic Systems

The organic-cooled and moderated reactor is similar in many respects to the water system but offers the additional advantages of operating at low pressure and of presenting fewer corrosion problems. Its advantages are somewhat offset by the fact that the organic materials now available are polymerized by radiation and must be continuously replaced. However, with construction of a 50- to 75-MWE organic prototype reactor, to be initiated late this year or early in 1962, and the recent development of a new, improved fuel system, there is every reason to believe that the organic-cooled and moderated system will be capable of meeting our program objective of production of economically competitive nuclear power by 1968.

The new fuel system, which uses UO_2 as the fuel material capable of long exposure, is clad in an aluminum–aluminum oxide cermet. This fuel has satisfactory strength and heat-transfer characteristics at high temperatures.

While this new fuel was being successfully developed, there was a buildup of film on some of the fuel elements in the Commission's organic-moderated reactor experiment (OMRE), which resulted in partial blocking of fuel-element cooling channels. The film is believed to have been caused by coolant decomposition and by inorganic particulate matter in the coolant. The reactor is being modified to correct the problem. Much of our development of the system to date has been through operation of this reactor. We are building an experimental organic-cooled reactor (EOCR) to complement the work of this facility.

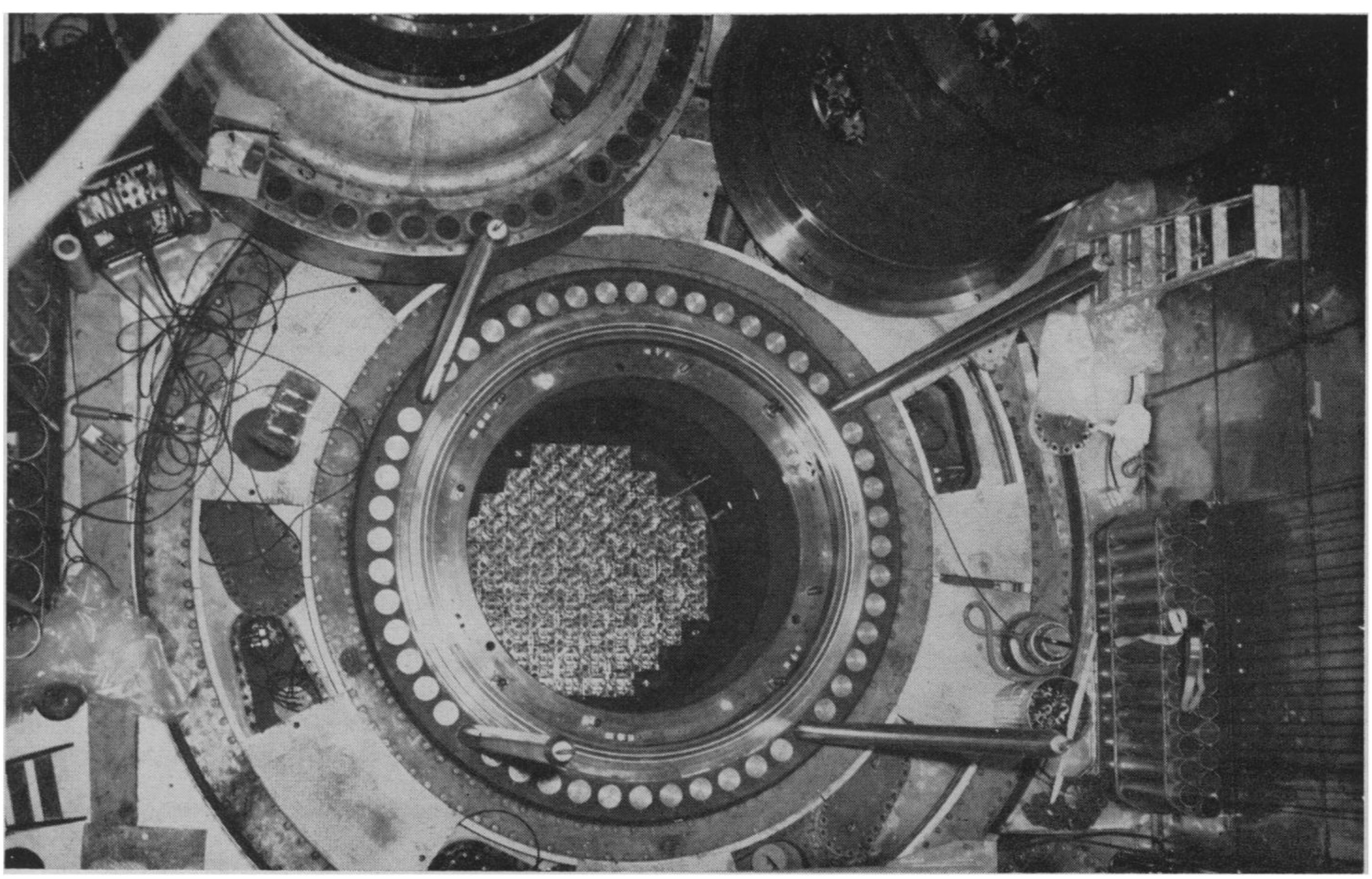
The first operating organic-cooled reactor to be incorporated in a utility power system is that in the Piqua plant at Piqua, Ohio. This 11.4-MWE reactor is scheduled to go into operation late this year. Its operation will demonstrate the technical and economic feasibility of using small organic reactors in nuclear power stations.

Use of the new fuel in a larger prototype will demonstrate the ability of organic reactors to meet the short-range objective—production of economically competitive power by 1968. It is expected that operation of this new prototype and of the OMRE, the EOCR, and the Piqua plant will show that this system is also capable of subsequently achieving our long-range objective—economical production of nuclear power.

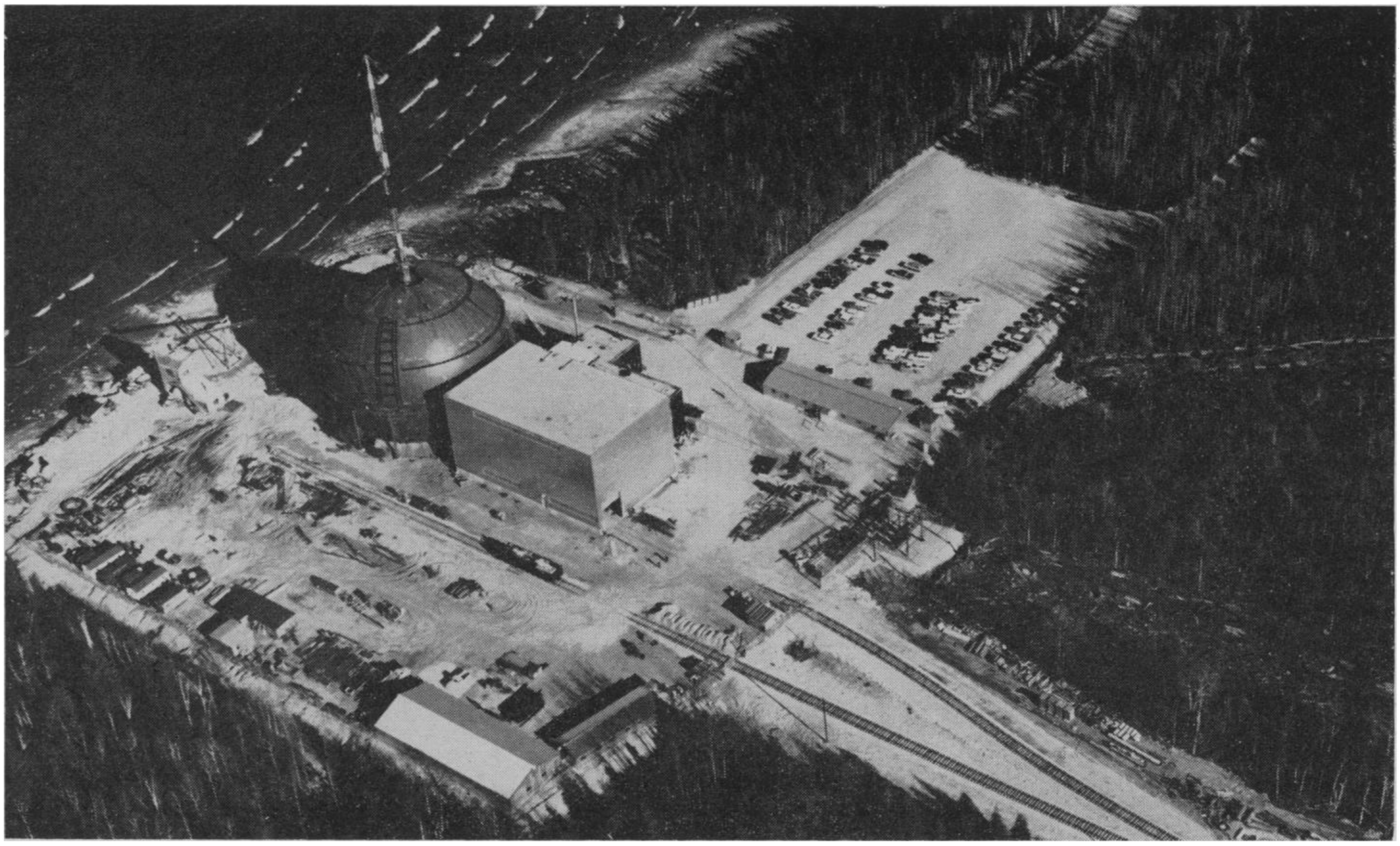
Sodium-Cooled Systems

Liquid sodium is the metal that seems most promising as a power reactor coolant at the present time. Sodium-cooled reactors can operate over a wide spectrum of neutron energies, from fast to thermal, depending upon the design characteristics of the core. Another attractive feature of such reactors is their use, at relatively low pressures, of a liquid which has a high boiling point, reasonably low neutron absorption, and excellent heat-transfer and heat-transport capabilities. These features result in very high plant efficiency, and although reactors cooled by liquid metal may not be competitive by 1968, they are expected to meet our long-range objective.

We have used the Atomic Energy Commission's experimental breeder reactor No. 1 (EBR-1) to investigate fast-reactor stability, and we will use EBR-2 when it is completed, late this year, to demonstrate the engineering feasibility of using a fast reactor for power generation. In addition, two nuclear power stations, the 94-MWE Enrico Fermi plant at Monroe, Michigan, and the 75-MWE Hallam plant at Hallam, Nebraska, are under construction. They will provide significant operating data, which can be integrated with that obtained from other sodium-cooled facilities to help us determine what research and development effort should be made for this system. However, just as variations of the other concepts are being studied,



Yankee Atomic Electric Company core loaded in the reactor, 29 July 1960.



Consumers Power Company's Big Rock Point plant under construction, 23 November 1960.

variations of the basic liquid-metal system are being examined. For example, studies are being made of an advanced epithermal reactor which, at this stage of development, appears capable of retaining the high thermal efficiency and low pressures of a sodium-cooled system while achieving a high conversion ratio with uranium-233 as fuel. The studies on this particular reactor are being conducted by the Commission and by private industry.

We are also obtaining information about sodium-cooled fast reactors from foreign countries. We are engaged in a cooperative research and development program with the United Kingdom, and our programs are coordinated to avoid duplication of effort. The French have made progress with their program, and we hope to expand our collaboration with them.

Gas-Cooled Systems

In the gas-cooled reactor development program, the major Commission effort is directed toward the design and construction of a 25-MWE experimental gas-cooled reactor scheduled for completion at Oak Ridge, Tennessee, next year and of a privately-owned 40-MWE high-temperature gas-cooled reactor to be constructed at Peach Bottom, Pennsylvania. These plants will provide information and experience with high-temperature helium systems, fuels, and components which are needed in the long-range effort to achieve gas-cooled power plants that operate economically.

Additional projects contributing to the development of gas-cooled reactor technology include examination of a pebble-bed reactor concept and a beryllium oxide experiment.

The pebble-bed reactor uses a stationary bed of spherical fuel bodies containing fissionable and fertile material in the form of coated particles (discussed in more detail below) which are dispersed in a graphite matrix. Cooling is accomplished by helium gas flowing through the bed. Potential advantages of this reactor are simplified fuel fabrication and handling, and high thermal efficiency.

Construction of a 10-MW (thermal) beryllium oxide experiment is being initiated to obtain basic engineering and physics data on beryllium-moderated, gas-cooled reactors.

As with the sodium-cooled system, the gas-cooled system is being developed through a cooperative arrangement with the United Kingdom. This is the power reactor system most used in Great Britain. In the United States the gas-cooled system is expected to meet the Commission's long-range objective by becoming economically competitive sometime after 1968.

In addition to all of these activities, the Army gas-cooled reactor experiment, which has been operating since February 1960, will continue to provide operating experience which will contribute to the development of gas-cooled reactors for the civilian economy.

Heavy-Water-Moderated Systems

One other major reactor system under development can help us achieve competitive nuclear power. This is the heavy-water-moderated system. The biggest advantage of this system is that natural uranium fuel can be used, dependence upon enriched uranium in the fuel cycle thus being removed. This makes natural-uranium heavy-water reactors especially important to countries not having diffusion plants or other means of providing enrichment. The biggest disadvantage is that natural-uranium heavy-water reactors are physically large and that high capital costs are associated with the plant and with the heavy-water inventory. In addition, the reactivity lifetime of natural uranium is more limited than that of enriched uranium.

In the United States two heavy-water-moderated reactors are under construction, and another is in operation. Two of these reactors are test reactors located at Commission sites, one at Hanford (Washington) and the other at Aiken (South Carolina). The third, a plant being built by Carolinas-Virginia Nuclear Power Associates at Parr, South Carolina, is a 17-MWE nuclear power plant. All use enriched fuel, but the technology developed will be applicable to heavy-water-moderated reactors fueled with natural uranium, such as those in Canada.

Our program for developing heavy-water reactors is closely coupled with the Canadian program. As our contribution to the joint effort, we are conducting research and development work in this country, concentrating on developing improved methods for predicting reactivity lifetime; on means, including fuel-management techniques of extending the lifetime of fuels; on methods for minimizing heavy-water inventory and loss; and on improved techniques for component fabrication.

The arrangement with Canada has been designed to give us as much information as we could have obtained if we had built in the United States the plants that are being built in Canada.

Fluid-Fuel Systems

In addition to developing systems that give promise of attaining program objectives, we are investigating advanced technical and engineering concepts—for example, fluid-fuel reactors, which use fuels of molten plutonium and molten salt. These systems offer the potential advantages of high thermal efficiency, high power density and specific power, and simplified fuel processing.

We do not know whether a promising power-producing reactor can be developed from these or from other, more advanced, concepts, but engineering studies, research and development, and evaluation of the concepts will be continued to the point where a decision can be made either to proceed or to terminate our efforts.

Nuclear Technology Development Program

While working on specific reactor systems, the Atomic Energy Commission has set up programs to develop technology *generally* applicable to reactor systems and related operations. The objectives of this broad-based nuclear engineering and development program are to provide data on such matters as reactor fuels and materials, reactor physics, reactor components, reactor safety, and environmental and sanitary engineering, and to provide tools, such as test and research reactors and remote-handling devices, for use in our research and development effort. All of this work is important and significant results are being obtained in many areas.

A good example of the type of work carried out under this program is the research and development program on nuclear fuels and materials to determine the potential of fuels and materials for reactor applications, to define their basic properties, and to develop engineering and design information for reactor systems. The over-all objective is to reduce fuel-cycle costs through increasing the life of the reactor core and fuel burnup, increasing the irradiation stability of nuclear fuels, reducing fuel fabrication costs, and attaining operation of fuel assemblies at higher temperatures.

Vibratory-compaction techniques for fabricating the UO_2 fuel elements have been developed and demonstrated; 90 percent of the theoretical oxide density is readily attainable. Powdered fuel is inserted into a tube, and the powder is compacted by the application of cyclic forces. The tube then can become a fuel rod when placed in a reactor. Successful development of the vibratory-compaction technique will eliminate some present difficulties—those of obtaining uniform pellet density and of inspecting hundreds of pellets individually, and difficulties due to the extremely close tolerances between the fuels and their containing tubes. The new compaction technique appears to be particularly applicable to remote fabrication of "recycled" fuels. Increased amounts of fission products will be released from the fuel when it is processed by this technique. However, it is expected that this problem will be overcome and that the technique can be extended to the fabrication of thorium oxide and uranium carbide fuels.

Recent developments in the retention of fission products by spherical UO_2 particles coated with Al_2O_3 dispersed in graphite matrix fuel have been very encouraging. This development may eliminate the need for fuel cladding as we now know it in gas-cooled reactors.

In the "coated-particle" process, small particles of the fissionable nuclear fuel compound, such as uranium oxide or carbide, are coated individually with a dense, refractory material such as alumina or pyrolitic graphite. After coating, the fuel particles are evenly dispersed in a material, such as graphite, which can be shaped into reactor fuel elements by mass-production methods. This coating protects the fuel from damage by chemical reaction at high temperatures and prevents escape of the troublesome radioactive by-products formed in the fuel by the fission process.

Coated-particle fuels appear attractive for high-temperature operation because only ceramic materials are utilized. Since good neutron economy can be expected, coated-particle fuels should also be useful in low- and intermediate-temperature reactors.

Future Development in Fuels and Materials Research

Further research work in fuels and materials is being directed toward establishing more basic information concerning the alloys and ceramics of uranium, thorium, and plutonium. Intensified research work is required on the properties of materials at elevated temperatures and the determination of the effects of radiation on the properties and performance of reactor materials in reactor environments. The effects of long-term irradiation are of particular importance. Improved fuel-element fabrication methods will continue to be sought. Additional effort will be directed toward an understanding of the mechanisms of fission gas retention and of the behavior of oxide fuel elements under irradiation at temperatures which result in central melting or vapor-phase transfer of the fuel. Research on nondestructive testing techniques will continue, with special emphasis on development of improved testing equipment.

In our reactor development program we will continue to work to simplify design, to minimize maintenance, and to increase dependability of reactor plant operation. We will be seeking ways to get more power from present fuels, to improve and simplify fuel-processing techniques, and to develop methods whereby radioactive wastes will be less of an economic burden.

Reactor safety will continue to be one of our most important areas of study, testing, and evaluation.

All of this will continue to require a relatively expensive program, but while it is true that development costs are high and that fossil fuels will meet our nation's power needs for many years to come, other factors, such as the needs of our national defense, the need to conserve our natural resources, and—also of major importance—the need for man to continue to explore the new frontiers of science and technology, will require the continued development of nuclear power. In addition, we will be developing a new and healthy industry which gradually will assume a more important role in our economy. As industry assumes more responsibility for nuclear power development, we will be able to turn to other areas of this new science—areas which require resources that only the government can supply.

Protection of Rainbow Bridge National Monument

An exchange of views on the effects of Glen Canyon dam shows that complex problems remain to be solved.

Comment by Halliday

The problem of protecting Rainbow Bridge National Monument from the waters of Glen Canyon reservoir is complex. Although there has been a 5-year period during which detailed studies could have been made—studies on which rational decisions might be based—available data on the subject are scanty, incomplete, and contradictory.

Many factors must be considered before acceptance of the drastic and irreversible step of abolishing, or abandoning by default, national-monument-type protection for Rainbow Bridge, as recently proposed by A. M. Woodbury in *Science* (*1*), and as proposed on other occasions by other supporters and by officials of the Bureau of Reclamation. Since the effects of this proposal would be irreversible, available data must be analyzed in detail, and certain alternative proposals which were ignored or summarily dismissed by Woodbury must be given due consideration. At the present time, such a "default decision," based on governmental inaction rather than on rational considerations, is imminent. As discussed below, the impending filling of Glen Canyon reservoir now threatens Rainbow Bridge National Monument (*2*, *3*) despite its supposed legal protection (*4*). The filling of the reservoir would also provide a precedent for the construction of Echo Park dam in Dinosaur National Monument, a recently revived project, and for construction of other dams which have been proposed in locations which would adversely affect Yellowstone National Park, Grand Canyon National Monument, Glacier National Park, and other units of the National Park System. In evaluating Woodbury's article on Rainbow Bridge it should be remembered that in 1954, when the Bureau of Reclamation was struggling for approval of the Upper Colorado Storage Project Act, Woodbury similarly advocated construction of Echo Park dam in Dinosaur National Monument, in two articles in *Science* (*5*, *6*), and dismissed as of little importance "whether we are setting a precedent of invading a national monument, *and various other minor matters*" (italics mine) (*5*).

Many discrepancies on both vital and trivial matters in reports and public statements of the Bureau of Reclamation make it difficult to conduct a precise analysis of this matter. In one official report, for example, the distance from Rainbow Bridge to the Colorado River is variously given as 6 miles and 4½ miles (*7*). In 1957 it was stated that the surface of the reservoir would be at 3700 feet 7 percent of the time (*8*). In 1959 and 1960 (*1*, *7*), the figure was given as 13 percent. An official 1954 "Fact Sheet" of the Department of the Interior not only used an incorrect name for the national monument but erroneously stated that it was threatened by the San Juan River arm of the reservoir, and that the monument could be protected by a mere "dike" (*9*). These and similar errors and inconsistencies which have come to light during study of this problem contrast remarkably with the professional reputation of the Bureau of Reclamation. However, it does appear, upon careful study of available data, that enough information is available to permit considered action—and to indicate that it is needed in the immediate future.

Basic Geographic Factors

Rainbow Bridge National Monument (Fig. 1) is located in the slick-rock country of south-central Utah, about five miles north of the Arizona-Utah state line, in the magnificent Glen Canyon area. The monument encompasses 160 acres on the north fork (Bridge Canyon) of a tributary canyon (Aztec Canyon) of the Colorado River's Glen Canyon section. Bridge Canyon is spanned by Rainbow Bridge.

Because of the length and difficulty of the trails from the nearest road ends, most of the 2000-odd annual visitors to Rainbow Bridge National Monument (*10*) now use the river route. In linear distance, the monument is about 2¼ miles from the Colorado River, but the gentle trail up Aztec Canyon and Bridge Canyon is about 4¾ miles long, as determined by Bureau of Reclamation surveys. Rainbow Bridge itself spans an inner gorge of Bridge Canyon, which will be completely filled at high water of the reservoir if no barrier dam is erected.

Woodbury was in error in statements about the maximum height of the reservoir and hence about the proximity of the reservoir to the base of