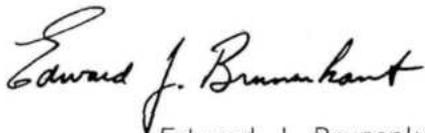# NUCLEAR REACTORS

U.S. ATOMIC ENERGY COMMISSION / Division of Technical Information

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

NUCLEAR REACTORS/CONTENTS

ABOUT THE COVER

A large mosaic portraying the tremendous energy and limitless scope of the peaceful atom is mounted on the concrete shield of the new TRIGA teaching and research reactor at Kansas State University. The mosaic was designed by students of the University's Department of Architecture after consultation with the Department of Nuclear Engineering. Six and one-half feet high and four and one-half feet wide, the mosaic contains nearly 10,000 pieces of colored glass. At the lower left are "hands of supplication" to convey mankind's hope that the gift of nuclear energy will be used wisely. Photos courtesy Kansas State University and General Dynamics Corporation.

ABOUT THE AUTHOR

John Hogerton is a chemical and nuclear engineer (B.E., Yale, 1941) who has worked in the atomic industry from its beginning. He is now an independent consultant.

Mr. Hogerton was coauthor of the final report on the wartime gaseous diffusion project at Oak Ridge. He also served on the Manhattan Project Editorial Advisory Board which coordinated the writing of the multivolume National Nuclear Energy Series.

The first edition of the Atomic Energy Commission's four-volume *Reactor Handbook* was edited by Mr. Hogerton. For the American Society of Mechanical Engineers, he contributed to *A Glossary of Terms in Nuclear Science and Technology* and

NUCLEAR REACTORS

By John F. Hogerton

INTRODUCTION

The discovery of nuclear fission, announced by the German scientists, Otto Hahn and Fritz Strassmann, in January of 1939, set the stage for the era of atomic energy development. But the real beginning came three years later. That was when a group of scientists led by Enrico Fermi demonstrated that a self-sustaining fission chain reaction could be achieved and, even more important, could be controlled.

Fermi's operation of the first nuclear reactor began at 3:25 p.m. on December 2, 1942, in an improvised laboratory beneath the stadium at the University of Chicago. By today's standards it was a fairly crude apparatus — essentially an assembly of uranium and graphite bricks about $24\frac{1}{2}$ feet on a side and 19 feet high. The method of assembly, which was simply to place one brick on top of another, gave rise to the name "atomic pile"; "nuclear reactor" is now the preferred term.

Several hundred nuclear reactors have been placed in operation in the United States since then. Later we will discuss the various ways in which reactors are being used and examine the major development programs. Before we do this we should first discuss general reactor principles.

HOW REACTORS WORK

The best place to start is with the fission reaction itself. In this reaction the center, or nucleus, of certain atoms, upon being struck by a subatomic particle called a neutron, splits into two radioactive fragments called fission products. These fly apart at great speed and generate heat as they collide with surrounding matter. The splitting of an atomic nucleus is accompanied by the emission of gamma radiation, similar to X rays, and by the release of two or three further neutrons. The released neutrons may in turn strike other nuclei, causing further fissions, and so on. When this process continues we have what is known as a chain reaction.*

A nuclear reactor is simply a device for starting and controlling a self-sustaining fission chain reaction. For reasons that will become evident, it could as well be called a "neutron machine."

Nuclear reactors are used in several ways:

1. To supply intense fields or beams of neutrons for scientific experiments;
2. To produce new elements or materials by neutron irradiation;
3. To furnish heat for electric power generation, propulsion, industrial processes, or other applications.

The basic parts of a nuclear reactor are illustrated in Figure 1. They are:

A "core" of fuel (number 5 in diagram);
A neutron "moderator," which is a material that aids the fission process by slowing down the neutrons (6);
A means of regulating the number of free neutrons and thereby controlling the rate of fission (1);
A means of removing the heat generated in the core (in the reactor diagrammed, this is done by the coolant water (6)); and
Radiation shielding (3 and 4).

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*For basic atomic science, see *Our Atomic World*, a companion booklet in this series.
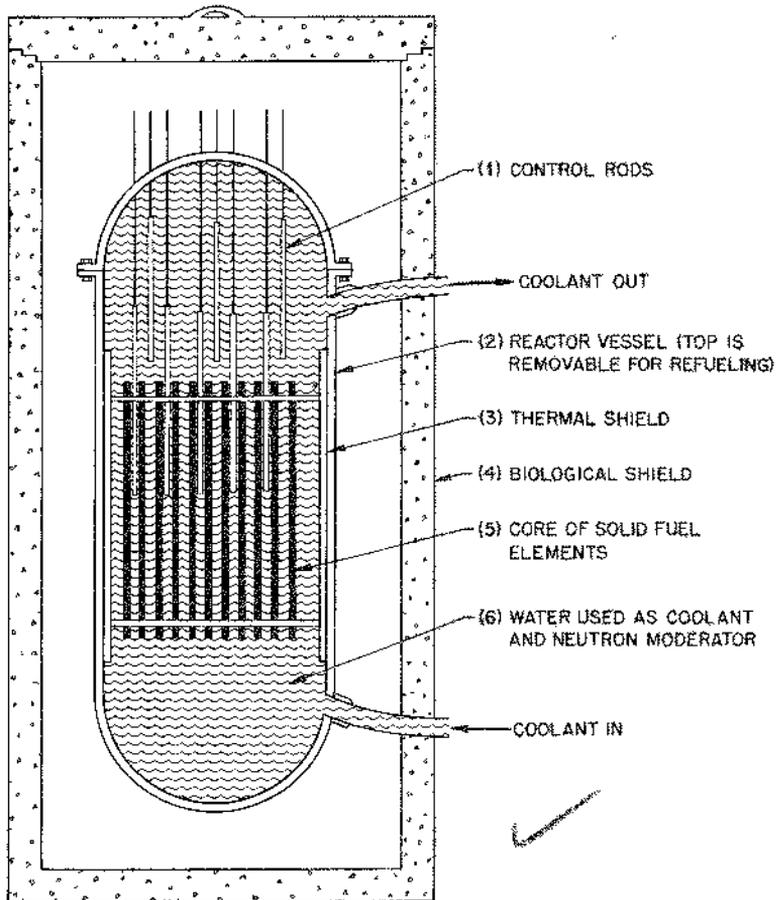
Figure 1   Nuclear Reactor (Pressurized Water Type).

The Fuel   The essential ingredient of reactor fuel is a fissionable material—that is, a substance that readily undergoes fission when struck by neutrons. The only naturally occurring substance fissionable by slow neutrons is uranium-235, an isotope of uranium constituting less than one percent (actually 0.71%) of uranium as it is found in nature. Almost all the rest of the natural element is
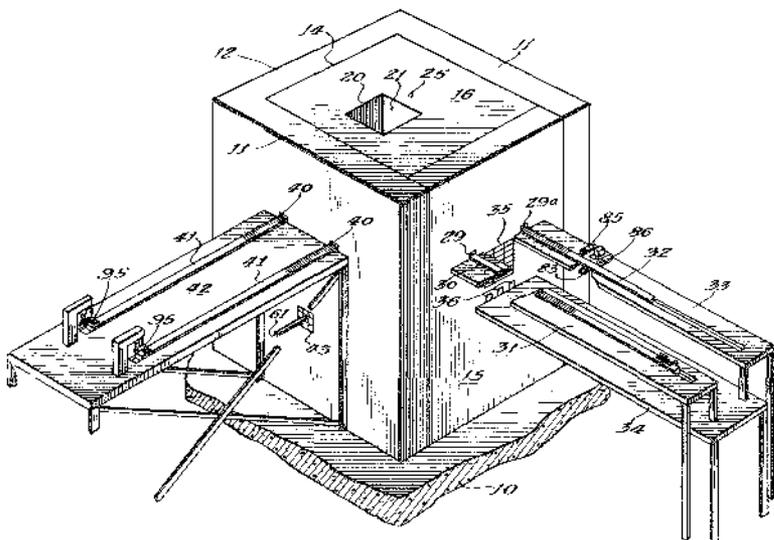
Figure 2   *Patent No. 2,708,656 was issued on May 18, 1955; the invention it covers includes the first nuclear reactor, Chicago Pile No. 1. The joint inventors were Enrico Fermi and Leo Szilard. Although the patent was applied for in December 1944, it could not be issued until years later when all the secret information it contained was made public. This drawing was in the patent application.*

uranium-238, which is called a fertile material because it can be converted into a fissionable substance—namely, plutonium. This occurs when uranium-238 is irradiated by neutrons.*

Reactor fuel usually contains a mixture of fissionable and fertile materials. As the fuel is irradiated in the course of reactor operation, atoms of the fissionable material are consumed; at the same time, *new* fissionable atoms are formed from the fertile material. The ratio of new fissionable atoms consumed to new fissionable atoms formed depends on the design of the reactor. It is possible to achieve a small net gain of fissionable materials in a so-called breeder reactor, but almost all present-day reac-

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*Similarly, another fissionable substance, uranium-233, can be produced by neutron irradiation of the element thorium. There are thus three basic fissionable materials (uranium-235, plutonium, and uranium-233) and two fertile materials (uranium-238 and thorium).
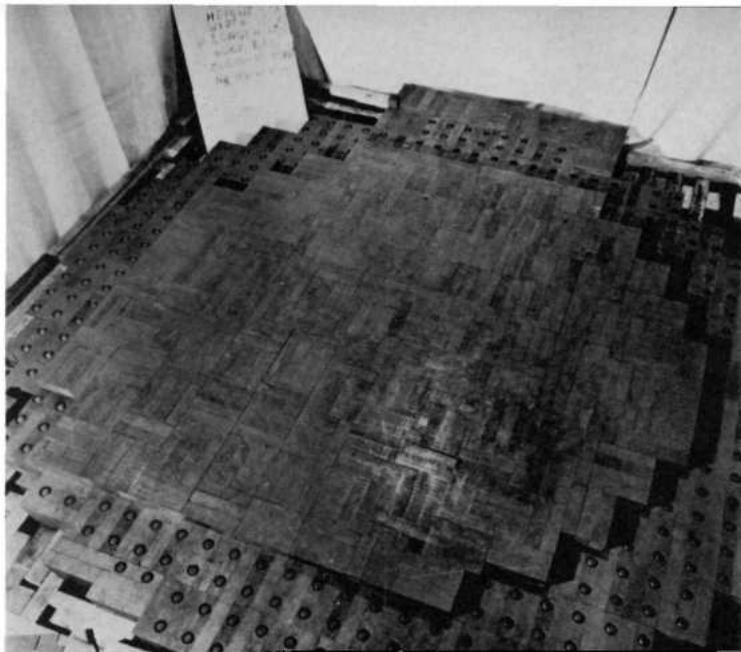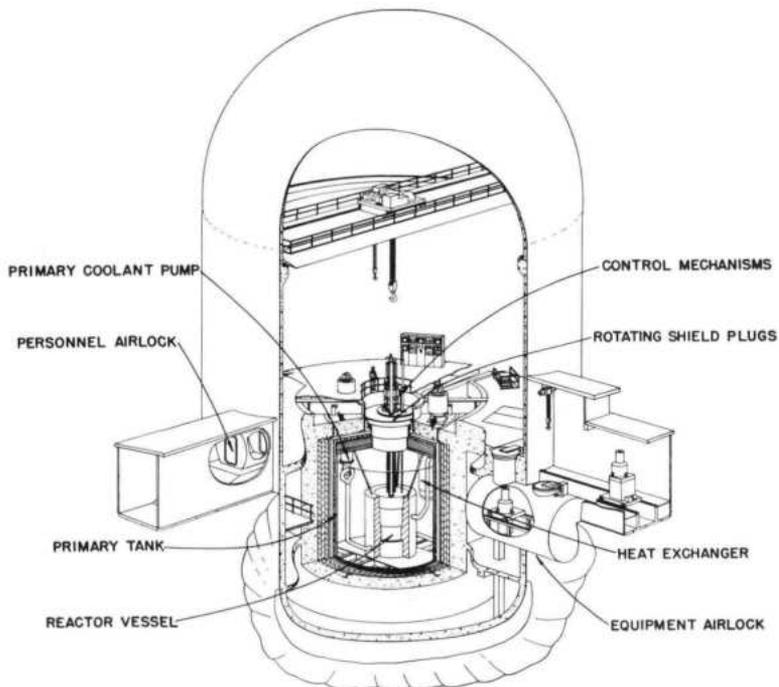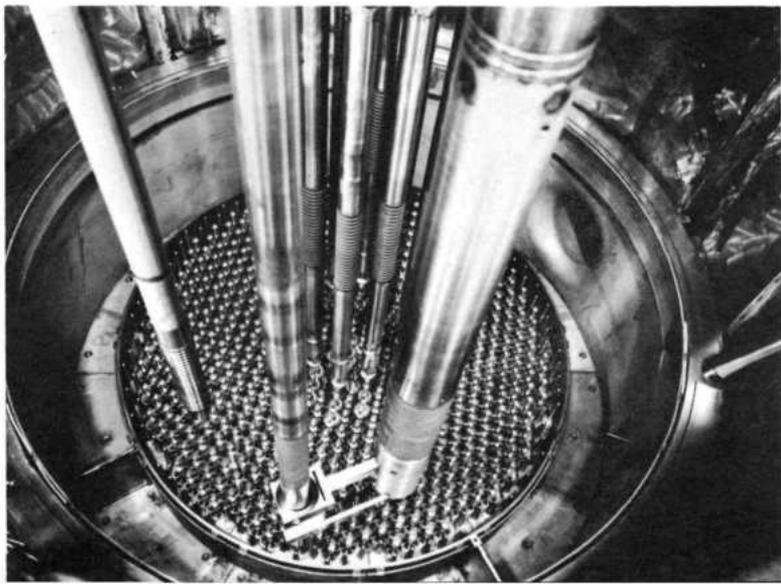
Figure 4 *Schematic of the Experimental Breeder Reactor No. 2 (above). This reactor was the first to be equipped with its own fuel reprocessing and refabrication facilities. Below, a view of the reactor core of EBR-2. In the foreground are the hold-down and gripper drive shafts; in the background are the control-rod drive shafts.*

Courtesy Argonne National Laboratory

uranium; some, especially those designed for propulsion applications, where compactness is especially important, use highly enriched uranium.*

Another important aspect of reactor fuel is the physical form in which it is used. Some reactors use a fluid fuel, such as an aqueous solution of enriched uranium. But in the main the fuel is a solid — either metallic uranium or a ceramic such as uranium oxide or uranium carbide. The solid fuel material is fabricated into various small shapes — plates, pellets, pins, etc. — which are usually clustered together in assemblies called fuel elements. A reactor core may contain from tens to hundreds of these fuel assemblies held in a fixed geometrical pattern by means of grid plates.

Almost all solid fuel elements incorporate what is known as fuel cladding. This takes the form of a protective coating or sheath which prevents direct contact between the fuel material and the reactor coolant and also serves as part of the structure of the fuel element. Stainless steel and zirconium alloys are commonly used as cladding materials in power reactors; aluminum is generally used in research reactors.

The Moderator Neutrons liberated in a chain reaction travel at first at very high speeds. They lose speed as they collide elastically with surrounding matter in the reactor core. This loss of speed is desirable because it happens that slow-moving neutrons are more effective in triggering fission than are fast neutrons. But if very many collisions are involved, an individual neutron runs considerable risk of bumping into an atom that will absorb it unproductively. (Fission products, for example, readily absorb neutrons.) What is needed, therefore, is a material that has the ability to slow down neutrons quickly and which, at the same time, has little tendency to absorb neutrons. Such a material is called a moderator.

Neutrons have a mass approximately the same as that of a hydrogen atom; therefore materials containing a concen-

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*Enriched uranium, ranging in fissionable content from one percent on up to ninety percent or more, is obtained by putting the natural element through an isotope-separation process.

tration of hydrogen or other lightweight atoms are the most effective moderators.* Materials used for this purpose include ordinary water, heavy water, graphite, beryllium, and certain organic compounds.

It is obvious that the moderator should be well distributed within the fuel zone. In some reactors this is accomplished by the spacing of the fuel elements; in others the fuel and moderator materials are intimately mixed together.

It should be added that reactors using highly enriched fuel in a concentrated array are capable of operating with fast neutrons and therefore do not require a moderator. Such systems are known as fast reactors.

The Control System Most nuclear reactors are controlled by regulating the "population" of neutrons in the core. This is done with control "poisons"—substances, such as boron and cadmium, that have very high coefficients for neutron absorption. (In effect, a control poison acts as a neutron blotter.) Usually these substances are inserted into the reactor by means of adjustable rods, called control rods. Typically a reactor is equipped with one set of control rods (referred to as regulating rods) for routine control purposes, and a supplementary set (referred to as safety rods) to permit rapid shutdown in an emergency.

It will be recalled that each atom of fuel which undergoes fission releases two or three neutrons. The free neutrons exist a very short time—perhaps about one ten-thousandth of a second—between the time they are released and the time they trigger another fission event or are otherwise absorbed. On this basis, if only a slight increase in the neutron population were to take place from one neutron generation to the next, the rate of fission could easily multiply many hundreds of times every second. Fortunately, some neutrons are not released instantaneously. By keeping down the neutron population of the system to the point where these delayed neutrons are needed to sustain the fission chain reaction, the normal rate in-

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*To understand the reason for this it is only necessary to imagine trying to use a bowling ball to slow down a ping-pong ball.

creases are only one or two percent per second. These are gradual enough to be kept readily under control.

From these few facts the rudiments of reactor control can be grasped. When fuel is loaded into the device, a number of regulating and safety rods are in the "in" position. When the reactor is fully loaded it is placed in operation by withdrawing the safety rods and partially withdrawing the regulating rods. The latter step is carried out gradually and in response to signals from neutron-counting instruments used to monitor the rate of fission. Once the reactor is critical, meaning that the chain reaction has become self-sustaining, movement of the regulating rods becomes a matter of adjustment to maintain steady-state operating conditions. If the operator wants to increase the power level—that is, the steady-state reaction rate—the regulating rods are further withdrawn and then again adjusted as needed. If he wants to shut down the reactor, the regulating and safety rods are fully inserted.

A related aspect of reactor operation which should be mentioned at this juncture is loss of reactivity. We have seen that, as fuel is consumed, fission products are formed. These substances absorb neutrons wastefully and, as they accumulate, reduce the reactivity of the fuel. (It is as though a fire were gradually smothered by its own ashes.) To compensate for this effect (and also for the consumption of fuel) it is necessary to load the reactor with more fuel than the bare minimum needed to get a chain reaction started. This extra fuel provides excess reactivity which can be drawn upon to keep the reaction going. It is held in check by a balancing amount of control poisons, which are gradually removed as the operation proceeds. The amount of excess reactivity required has an important bearing on the design of the control system.

The Heat Removal System The pattern of energy release in the fission process is roughly as follows:

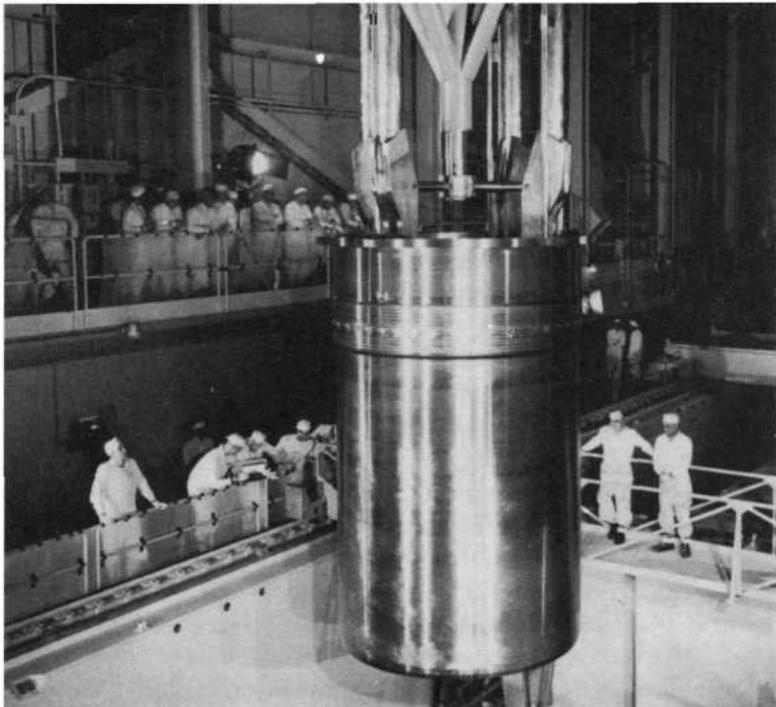|	
Kinetic energy of fission products	84.0%
Kinetic energy of neutrons	2.5
Instantaneous release of gamma rays	2.5
Gradual radioactive decay of fission products	11.0
	100.0%

Figure 5 *The core of the Shippingport Atomic Power Station reactor in Pennsylvania is lowered into position (photo). The diagram shows the interior of the core. Fuel assemblies are locked into the top grid and bottom plate. The close array forms a critical mass. The resulting chain reaction generates heat which is carried away by coolant water flowing upward through channels. The projecting rods are controls for regulation and safety.*

Courtesy Westinghouse Electric
Corporation
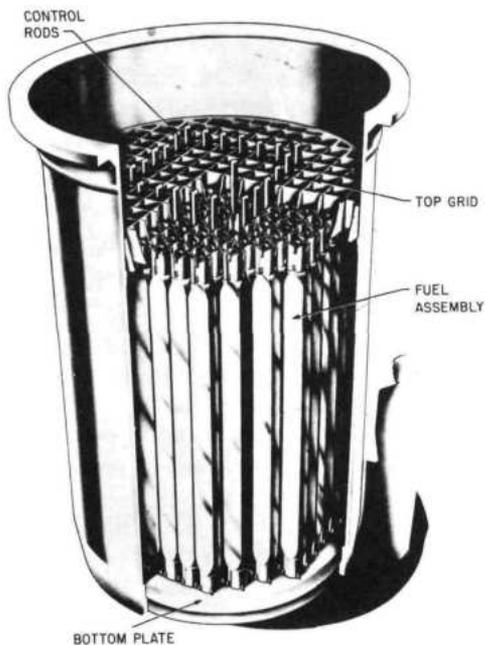
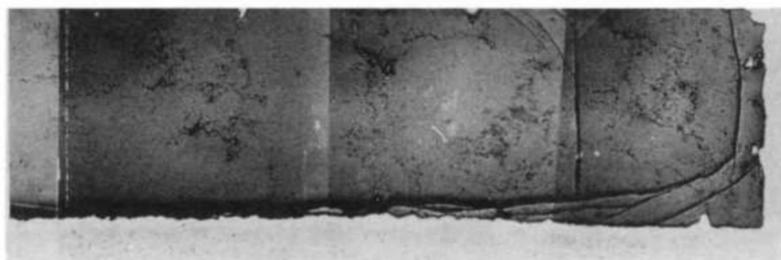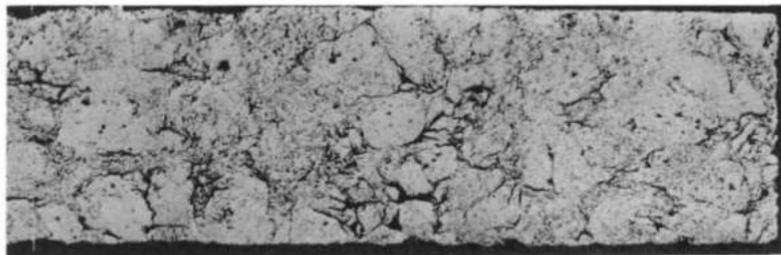**Figure 6** *The seed elements of the Shippingport core contain a mixture of enriched uranium oxide and zirconium oxide, the latter serving as a diluent. These photographs, magnified 75 times, show the densification that takes place after a short period of radiation exposure (bottom photograph), compared with the original material (top photograph).*

As the fission products (and neutrons) collide with surrounding matter, their kinetic energy is more or less instantly converted to heat. Most of the heat is generated within the reactor core.

If the reactor is operated at essentially zero (only a few watts) heat output, the small amount of heat that is generated can be allowed to dissipate itself, and no cooling system is needed. But most reactors operate at appreciable power levels (kilowatts or megawatts of heat output) and therefore must be cooled to prevent overheating and melting the core. In power or propulsion applications, the heat that is carried away from the core is, of course, the primary product of the reactor.

One of the most interesting things about nuclear reactors is that they are capable, in principle, of operation at virtually any power level; the limiting factor, from a practical standpoint, is the rate at which the cooling system can carry the heat away from the core. Some reactors rely

upon natural convection of the coolant; most, however, are equipped with a forced circulation system. Various coolants are used, including gases such as air, helium, and carbon dioxide; liquids such as ordinary water, heavy water, and certain organic compounds; and liquid metals such as sodium and lithium. In some reactors, the coolant serves also as the neutron moderator; in others, the coolant and moderator are separate materials.

Reactors used for research are generally operated at fairly low temperatures (below 200°F). Reactors used for power generation or propulsion operate at relatively high temperatures (above 500°F) to facilitate conversion of the heat to electrical or motive power.

The Radiation Shield That part of the fission energy release which does not instantly appear as heat appears as penetrating atomic radiation. Nuclear reactors must therefore be heavily shielded. Here a distinction should be made between an internal or "thermal" shield, which is used in high-power reactors to protect the walls of the reactor vessel from radiation damage, and the more familiar external or "biological" shield, which serves to protect personnel from radiation exposure. The internal shield usually consists of a steel lining; the external shield typically takes the form of several feet of high-density concrete surrounding the reactor installation.

REACTOR DESIGN

At this stage the reader may well be visualizing a nuclear reactor as a kind of three-dimensional and very high-speed pinball game played with neutrons in a box of fuel and moderator atoms, with an adjustable plunger for control and a fan for cooling. What does a reactor look like? The answer is that many basically different reactor designs have been worked out and many more are possible. (See diagrams in the Appendix.)

There are several reasons for the multiplicity of reactor designs. First, as has been brought out, the designer has a wide choice of reactor materials. Second, there is a broad

spectrum of reactor uses. Third, different reactor designers often have different ideas as to the best way of designing a reactor for a given purpose.

On the last point, reactor design is a subject on which unanimity of expert opinion is not to be expected and, for that matter, is not even desirable, since if it existed it would mean that reactor technology was no longer in a dynamic state of development. The performance of any reactor depends on the performance limits of its basic materials. Research on reactor materials, notably fuels, and on other reactor components (pumps, valves, etc.) is constantly creating new design possibilities. Therefore the relative merit of alternative designs requires frequent re-evaluation. This is healthy as it inevitably stimulates renewed development effort.

It is time now to talk about how reactors are used and to look in on the principal development programs.

RESEARCH, TEACHING, AND MATERIALS TESTING REACTORS

Research Reactors Research reactors are a uniquely versatile source of atomic radiation for experimental purposes. Some examples of the ways in which they can serve subject areas of science are:

Nuclear physics. Studying nuclear reactions by irradiating target materials.

Solid-state physics. Determining the crystal structure of materials by neutron diffraction techniques.

Radiation chemistry. Studying the effects of radiation on chemical reactions and on the properties of materials such as plastics.

Analytical chemistry. Identifying trace impurities in materials by activation analysis techniques.*

*Every species of radioactive atom has a distinctive pattern of radioactive decay. In activation analysis, a sample is made radioactive by neutron activation. By analyzing the resulting radioactivity with sensitive detection instruments, the identity of substances present in the sample is determined. For more about this subject, see *Neutron Activation Analysis*, a companion booklet in this series.

Biology. Inducing genetic mutations in plant species by seed irradiation.

Medicine. Experimental treatment of certain brain cancers by a technique known as neutron capture therapy.

*Other.* Production of radioisotopes for use in laboratory programs.

In some experiments, materials are inserted in the reactor for irradiation; in others, experimental apparatus is set up in the path of neutron beams emanating from openings (ports) in the reactor shield.

Research reactors are usually categorized by their neutron flux, meaning the intensity of the neutron fields or beams they generate. Neutron flux is related to the power level at which a reactor operates, but also depends on design factors.

There are several basically different research reactor designs. The two most commonly used are "pool" reactors and "tank" reactors. In the former, as shown in Fig. 7, the reactor core is suspended in a deep, open pool of water, which serves as coolant, moderator and radiation shield. This arrangement affords flexibility, since the position of the core can easily be shifted and experimental apparatus can readily be positioned; also it permits direct observation of the proceedings.

Figure 7   *Typical pool-type research reactor. The glow given off by the reactor core at the bottom of the pool is known as "Čerenkov radiation" and results when electrically charged particles pass through a transparent medium at a velocity in excess of the speed of light in that medium.*

Courtesy University of Michigan
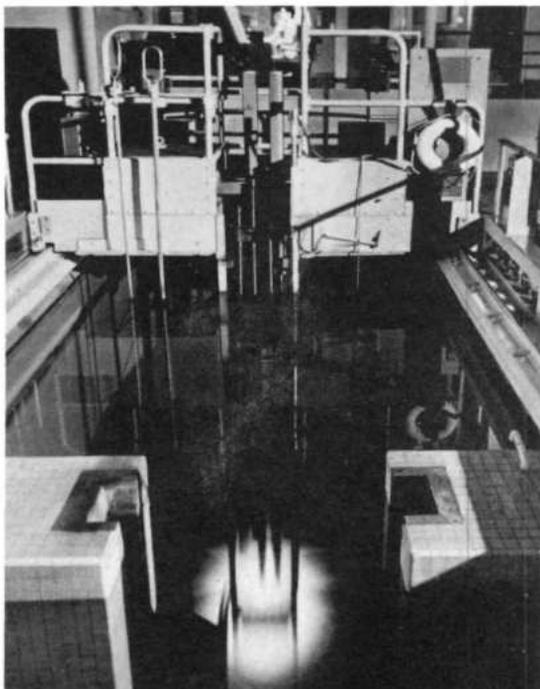
In tank reactors, the reactor core is held in a fixed position inside a closed tank. The coolant most often used is ordinary water, but some installations use heavy water. Tank reactors generally operate at higher power levels than pool reactors and therefore as a rule provide a higher neutron flux.

It is difficult to generalize on the cost of research reactors since much depends on the type and extent of auxiliary facilities provided. In very round numbers, the capital cost of a pool reactor installation, including a building and supporting facilities, is generally in the range, $1 to $3 million. A corresponding range for a tank reactor installation is $1 to $5 million.*

Teaching Reactors These are small, low-flux reactors designed to be used as teaching aids and to meet limited research and radioisotope production requirements. There are several types on the market. Some are self-contained units shipped as prepackaged assemblies ready for installation in available laboratory space. Their cost is in the $100,000 to $200,000 range, delivered and installed. Others, somewhat more elaborate but also more versatile, range in cost up to about $500,000.

Materials Testing Reactors These are high-flux reactors used to test the performance of reactor materials and equipment components under irradiation, thereby obtaining data essential for new reactor designs. They generally carry a diverse test load and are operated principally in support of power reactor development programs. The largest installation in service in the United States is the Engineering Test Reactor (ETR) (Fig. 8) at the Atomic Energy Commission's National Reactor Testing Station near Idaho Falls, Idaho. The ETR, similar in design to a tank-type research reactor but much larger, operates at power levels up to 175,000 kilowatts heat output and represents an investment of approximately $16 million. It is equipped with "in-pile" test loops which make it possible to conduct many irradiation experiments under tempera-

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*For more information, see *Research Reactors*, a companion booklet in this series.
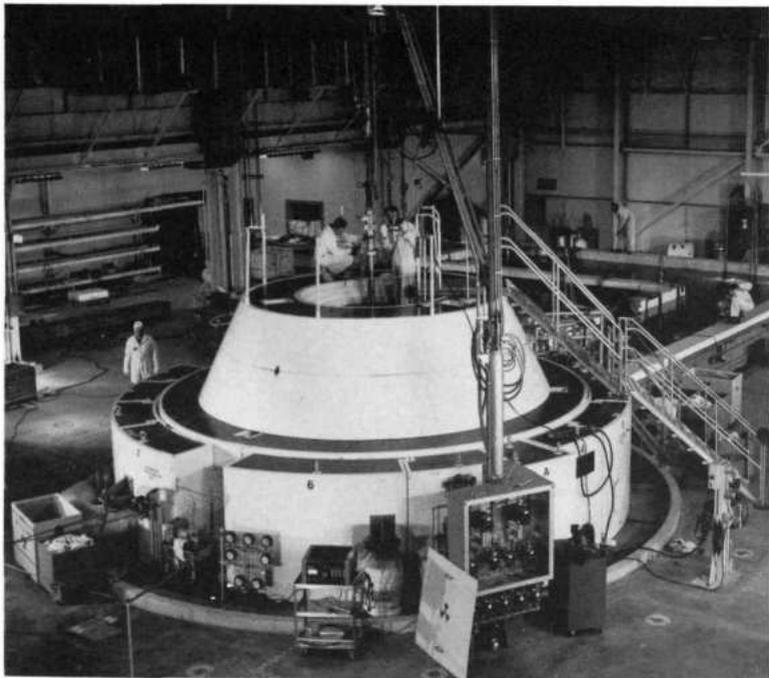
Figure 8   *The Engineering Test Reactor showing the upper section of the reactor shield.*   Courtesy Phillips Petroleum Company

ture, pressure, and flow conditions representative of actual power reactor operation. An even larger installation, known as the Advanced Test Reactor, is scheduled for completion at an adjacent site in 1965. It will have a heat output of 250,000 kilowatts.

PRODUCTION REACTORS

About a dozen production reactors have been built in the United States to supply plutonium for defense stockpiles. These facilities are located at two AEC production centers — the Hanford Works at Richland, Washington, and the Savannah River Plant near Aiken, South Carolina.

The reader will recall that plutonium is formed by capture from irradiation of uranium-238. The general name for the

process of making one chemical element from another is transmutation. The specific reaction can be written:

$$\text{uranium-238} + \text{one neutron} \rightarrow \text{uranium-239}$$

$$\text{uranium-239} \xrightarrow[\text{2.3 minutes}]{\beta} \text{neptunium-239}$$

$$\text{neptunium-239} \xrightarrow[\text{2.3 days}]{\beta} \text{plutonium-239}$$
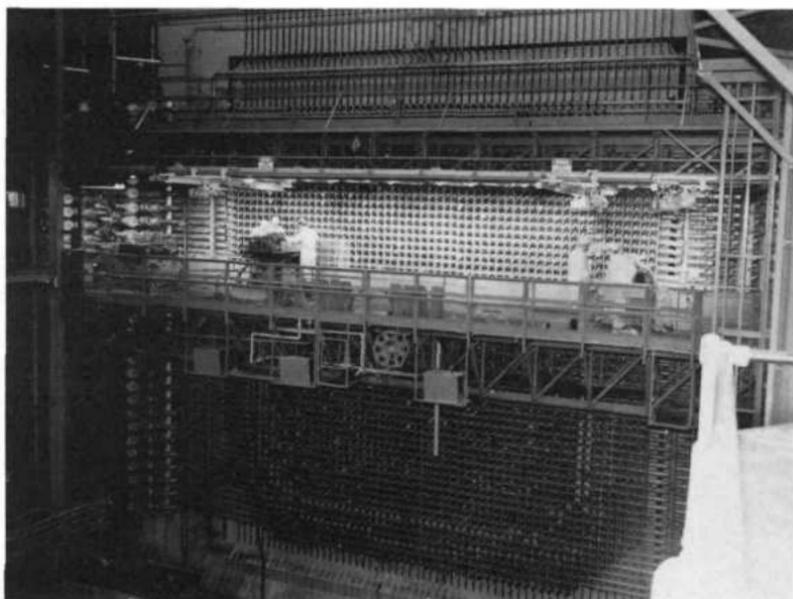

Figure 9   *View of the entire front face of a Hanford production reactor shows operators on the work platform getting ready to "charge" fuel elements into one of the more than 3,000 process tubes. As fresh fuel elements are inserted, the irradiated fuel elements they replace are ejected from the discharge end of the tube at the rear face.*   Courtesy General Electric Corporation

This in effect means that uranium-239 and neptunium-239, both highly unstable substances with relatively short half-lives (2.3 minutes and 2.3 days,* respectively), are formed

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*Meaning, in the case of neptunium, for example, that half of the atoms undergo radioactive decay every 2.3 days. Thus, if there are 100 neptunium atoms in a sample at time zero, there will be 50 atoms 2.3 days later, 25 atoms 2.3 days after that, etc.
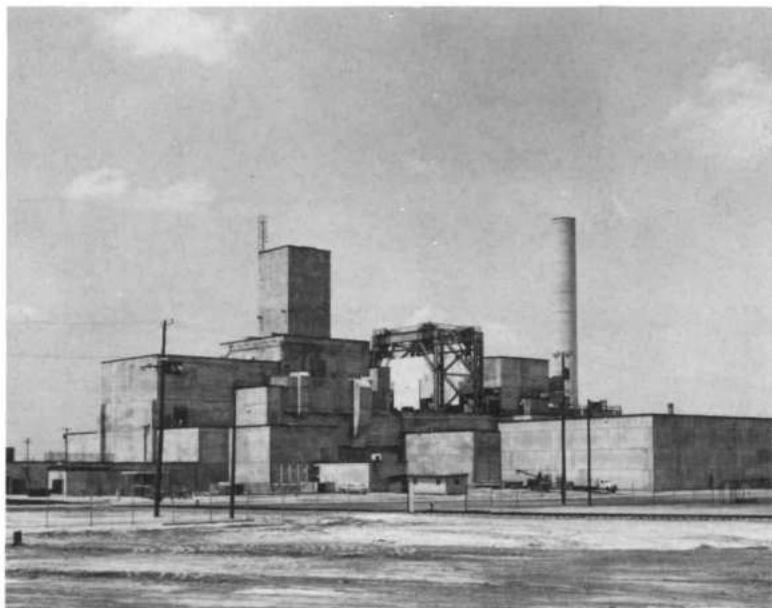
Figure 10 *One of the plutonium production reactors at the Savannah River Plant.* Courtesy E. I. du Pont de Nemours & Company

as intermediate products, the latter throwing off a beta particle* to form plutonium.

The production steps are: (1) fabrication of natural uranium metal into fuel elements, (2) operation of a reactor with these fuel elements, thereby irradiating the uranium-238, (3) temporary underwater storage of the irradiated fuel elements to allow a period of time for radioactive decay—a step known as decay cooling, and (4) chemical processing of the still intensely radioactive material to remove fission products (which are then stored in underground waste tanks) and to separate the plutonium from the residual uranium.

The Hanford reactors are moderated with graphite and cooled with ordinary water. They are large (building-size) graphite structures honey-combed with tubes into which cylindrical fuel slugs are loaded and through which the

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*An electron emitted from an atomic nucleus is called a beta particle, symbol, β.

cooling water flows. The Savannah River reactors, one of which is shown in Fig. 10, are tank-type units, moderated and cooled with heavy water.

The heat generated in all but one of the existing plutonium production reactors is at too low a temperature to be useful. However, one recently completed at Hanford operates at a higher temperature, and facilities are being installed to convert the heat to by-product electricity.

REACTORS FOR ELECTRIC POWER GENERATION

Civilian Atomic Power Programs In conventional steam-electric power plants, a fossil fuel (coal, oil or natural gas) is burned in a boiler and the resulting heat is used to generate steam. The steam is used, in turn, to drive a turbogenerator, thereby producing electricity. In an atomic power plant, a nuclear reactor furnishes the heat; the reactor thus substitutes for the conventional boiler.

Some 1.5 million kilowatts of atomic power generating capacity are now installed or at an advanced stage of construction in the United States. (A large power reactor is shown in Fig. 11.) That is not an inconsiderable amount,

Figure 11   *The Yankee Atomic Electric Station, a 175,000 kilowatt installation near Rowe, Massachusetts, was the first electric generating plant to be built under the Atomic Energy Commission's Power Demonstration Reactor Program.*
Courtesy Westinghouse Electric Corporation

being comparable to the presently installed capacity of the largest U. S. hydroelectric project (Grand Coulee), or of the state of Connecticut, or of Denmark. However, it is not a large amount by overall U. S. standards, representing only one percent of the country's total power generating capacity. The fact is that atomic power is just beginning to emerge from the cocoon of research and development. What is notable about the U. S. atomic power program is not its size in kilowatts, but its technical scope.

It usually costs several tens of millions of dollars and takes hundreds of man-years of scientific and engineering effort to develop a new power reactor concept from the idea stage to the point where a demonstration plant can be built. Even that is by no means all, since a great deal of additional work is needed before the full potential of the concept can be realized. Several power reactor concepts have been carried past the demonstration stage, several others are in that stage, and still others are at earlier stages.

Space does not permit discussion of all these concepts but the Appendix brings out some of their more important features. Nor is it possible to describe here the more than two dozen experimental or demonstration atomic power projects that have been undertaken to date. The larger projects are listed in the table on page 42. In the aggregate, these projects represent a capital investment of nearly three-quarters of a billion dollars.

The U. S. power reactor program is a partnership effort of government and industry, with the former bearing the greater part of the research and development costs and the latter making the greater part of the capital investment. The objective is to develop atomic power plants that are economically competitive with conventional steam-electric plants. The benefits expected are two-fold. First, as atomic power becomes competitive it will act to stabilize electricity costs in areas where high price fossil fuels are used. Second, the ability to draw on atomic fuels will greatly strengthen our long-range energy position.

In the latter connection, it is a remarkable fact that, with barely more than 5% of the world's population, the United States produces and consumes more than one-third

of the world's electricity. An equally remarkable statistic is that, taking all forms of energy into account, the United States will probably use as much fuel in the next twenty years as it did in all its previous history. And that rate of fuel consumption is expected to double in the twenty years following. If this trend continues, our reserves of fossil fuels, vast as they are, will rapidly be depleted. Opinion varies on this point, but even allowing for the discovery of new deposits, the chances are that if fossil fuels continue to carry as large a share of our energy burden as they do now, we will begin to experience some depletion effects as early as the turn of the century. Our reserves of atomic fuels are large in comparison, being estimated to be anywhere up to ten times the equivalent of our fossil fuel reserves. If we successfully develop technology for breeding (producing more fissionable fuel from fertile material than is consumed in the operation of a reactor), our nuclear fission fuel reserves will be almost limitless. Ultimately, though, we may have to look to still other energy sources, and that may be where *thermo*nuclear power comes in (see discussion on page 37).

To put atomic power on a competitive footing with conventional power is not an easy task, for conventional power has had the benefit of several decades of development and plants are still being improved. A good indicator of the progress in this field is the efficiency of fuel utilization. About the time of World War II the average fuel consumption in the U. S. electric utility industry was 1.3 pounds of coal (or the equivalent) per kilowatt-hour of electricity produced; today it is less than 0.9 pounds —a gain in efficiency of 30%. An even better indicator is the unit cost of power generation, which, on a national average, is about the same today as it was twenty years ago despite steep increases in fuel prices and labor costs.

The electric utility industry gains have been accomplished in three principal ways: (1) by raising the temperature and pressure of steam boiler operation, thereby delivering higher quality steam to the turbine-generator and achieving improved efficiency in converting heat to electricity; (2) by increasing the size of power generating installations, which tends to reduce the capital investment

per unit of plant capacity and thereby to lower fixed charges per unit of power output; and (3) by refinements in plant and equipment design. These same avenues are being traveled in the development of atomic power technology.

How is atomic power doing? On the whole quite well. Several years ago the Atomic Energy Commission set as a short-term goal the demonstration of competitive atomic power by 1968 in areas of the United States where fossil fuel prices are high. It now appears that this goal will be met in at least some areas as early as 1967. It should be added, however, that only about one-fifth of our electricity is produced in areas with high fossil fuel costs, and that it will take many years before atomic power becomes competitive in all areas.

Military Atomic Power Program Antarctica may not seem a likely place to find atomic power plants, but one is already in use there. It is a small installation (1500 kilowatts) located at McMurdo Sound, the main support base for U. S. scientific activity in the Antarctic. Shipped in prefabricated sub-assemblies, it arrived at the site on December 14, 1961, the 50th anniversary of Amundsen's South Polar expedition, and began operation 80 days later.

The designation of the McMurdo Sound installation is PM-3A, which stands for "Portable Medium Power Plant No. 3A." It is one of a family of small atomic power plants being developed jointly by the Department of Defense and the Atomic Energy Commission to supply electricity and heat to remote bases and, also, for emergency use in disaster areas. The plants range in power output from several hundred to ten thousand kilowatts, and are of three types: stationary, portable and mobile.*

The plants thus far placed in service have been of the pressurized water type. However, a prototype gas-cooled reactor is being tested for mobile power plant applications, and a high-temperature liquid-metal reactor system is be-

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*A mobile-reactor is one mounted on a barge, trailer, or flatcar.

Figure 12   *Portable atomic power plant, PM-3A. Above, section of plant being unloaded at McMurdo Sound in Antarctica. Below, general view of completed installation.*

Courtesy Martin Marietta Corporation

ing developed to supply an extremely compact power system for military field requirements.*

The military reactor program was prompted by the logistic advantages of atomic fuels, which are extremely compact, and hence, relatively easy and inexpensive to transport.

How compact are atomic fuels? Well, the fissioning of one gram of fissionable material releases 23,000 kilowatt hours of heat. This means that one ton of uranium has roughly the same potential fuel value as 3,000,000 tons of coal or 12,000,000 barrels of oil. In practice only a small

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*For more about these reactors, see *Power Reactors in Small Packages*, a companion booklet in this series.

fraction of the potential energy value of atomic fuel is extracted during a single cycle of reactor operation. Even so, a ton of reactor fuel still substitutes for many fully-loaded freight trains of conventional fuel.

REACTORS TO SUPPLY HEAT

Nuclear reactors are of interest as a means of producing heat for desalting water. In situations where there is a substantial demand for water there is also a complementary demand for electricity. In these situations dual-purpose water and electricity-producing reactor plants appear to offer possibilities for use in the near future.

Preliminary studies have shown that the heavy-water-moderated, organic-cooled reactor concept has great potential for the generation of electricity and heat for desalting by flash distillation. A prototype plant for such a system may be built within a few years.

Use of reactors for low-temperature (up to 400°F), low-pressure steam for use in common manufacturing operations (drying, evaporation, distillation, etc.) or for ordinary building heating also has been studied. High-temperature applications, in the range of 1500 to 3000°F, for certain chemical processes, including the gasification of coal, also have been investigated. The studies indicate that it will be some time before process heat reactors can be built and operated cheaply enough to substitute for ordinary low-pressure steam boilers.

REACTORS FOR PROPULSION

Ship Propulsion The first power reactor ever built began operation on March 30, 1953, in a section of a submarine hull at the National Reactor Testing Station in Idaho.* This

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*It should be mentioned that this was not the first time electricity was generated by a reactor installation. In a demonstration in December 1951, token amounts of electricity were produced by an experimental breeder reactor (EBR-1) at the National Reactor Testing Station.

land-based installation was the forerunner of the pressurized water system used in the submarine, *Nautilus*, which was launched the following year and began sea trials in 1955. Such were the first milestones of the Naval Reactors Program, a joint effort of the Navy and the Atomic Energy Commission, which has revolutionized naval strategy.

The United States now has a large fleet of nuclear-powered naval vessels in being or under construction, representing an outlay of several billions of dollars. The principal classes of ships, all of which are powered by pressurized water reactors, are:

Class	Lead Ship
Fast attack submarine	USS *Skipjack*
Polaris missile submarine	USS *George Washington*
Destroyer	USS *Bainbridge*
Cruiser	USS *Long Beach*
Aircraft carrier	USS *Enterprise*

The revolutionary nature of this fleet is due primarily to the compactness of atomic fuel and, in the case of submarines, to the fact that oxygen is not required for engine operation. These factors translate into increased range and cruising speed and, in submarines, capacity for sustained submersion.

To illustrate, conventional diesel-powered submarines have a maximum surface speed of about 18 knots, which they can sustain for only half an hour or so. Their performance underwater is even more limited; World War II submarines could make only 8 knots submerged, and after an hour at this speed had to resurface to recharge their batteries. They operate submerged less than 15% of the time they are on sea duty. In contrast, nuclear-powered submarines characteristically operate submerged more than half of the time. They can steam at full power for days or even weeks and travel faster underwater than on the surface. Their maximum speed has not been disclosed but is known to be in excess of 20 knots. Their range is remarkable; for example, *Nautilus* steamed more than 96,000 miles on her second fuel loading. In 1960, the submarine *Triton*

made a submerged circumnavigation of the world parallel-
ing the route taken by Magellan in the early 16th century.
The 36,000-mile voyage, which took Magellan's expedition
nearly three years, was made by *Triton* in 83 days.

Speaking of distances at sea, the next number that comes
to mind is 350,000 miles, which is the cruising range of
the nuclear-powered merchant ship *Savannah* (Fig. 15). A
combination passenger-cargo vessel, the NS (for Nuclear
Ship) *Savannah,* was built as a joint project of the Maritime
Administration and the Atomic Energy Commission to dem-
onstrate the safety and reliability of using nuclear propul-
sion for commercial purposes. *Savannah* displaces 22,000
tons and is powered by a pressurized water system that
delivers 22,000 shaft horsepower. She satisfactorily com-
pleted sea trials in 1962 and is being operated experi-
mentally.

The potential economic advantages of nuclear propulsion
for commercial vessels are: (1) elimination of fuel tanks
(oil) or bins (coal), making more space and tonnage avail-
able for cargo; and (2) improved ship utilization, due to
higher cruising speed and elimination of the need for fre-
quent refueling. At present these advantages are cancelled
out by the fact that the capital costs of nuclear propulsion
equipment are substantially higher than those of conven-
tional diesel equipment. Opinion varies on when the balance
will shift in favor of nuclear propulsion but it is expected

Figure 13   *The USS* Alexander Hamilton, *second of the Lafayette
class Fleet Polaris missile submarines, is shown here in the wa-
ters of Long Island Sound.*   Courtesy U. S. Navy
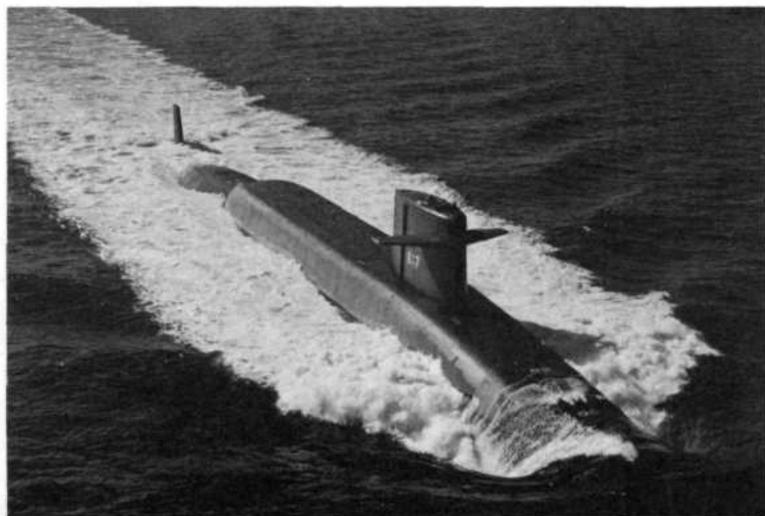
that this will occur in bulk cargo applications, such as ore carriers and oil tankers, before it does in passenger or passenger-cargo service.*
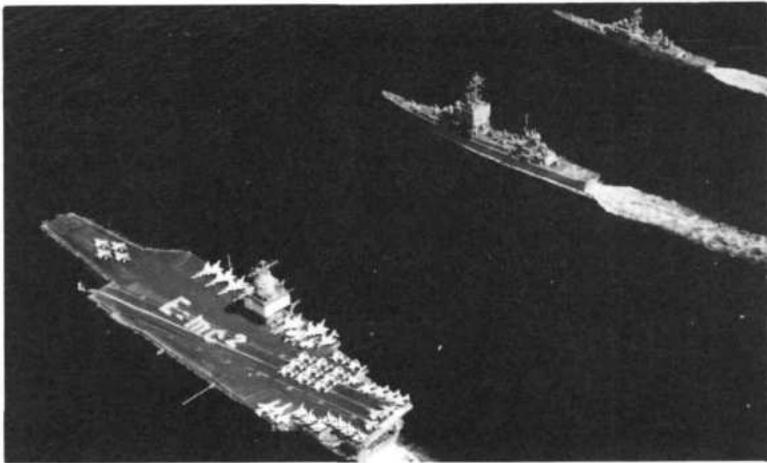

Figure 14 *The USS* Enterprise, *USS* Long Beach, *and USS* Bainbridge *in formation in the Mediterranean Sea. The crew of the* Enterprise, *in formation, spell out the equation for Einstein's equation for mass-energy equivalence.* Courtesy U. S. Navy

Figure 15 *The NS* Savannah *during one of her sea trials.*
Courtesy States Marine Lines

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*For more about this topic see *Nuclear Power and Merchant Shipping,* a companion booklet in this series.

Aircraft Propulsion For a number of years the Air Force and the Atomic Energy Commission jointly sponsored a program aimed at developing reactors for the propulsion of manned military aircraft. This was a very extensive effort which involved, along with air-frame studies and other work, research on two basically different high-temperature reactor systems: (1) an air-cooled system for use in a direct-cycle power plant, and (2) a lithium-cooled system for use in an indirect-cycle power plant. In each case a substantial part of the research took the form of basic investigations of high-temperature reactor materials.

Early in 1961, after an expenditure of roughly $1 billion, the program was stopped on the grounds that "the possi-

Figure 9

achieving a militarily useful aircraft in the fore-
ture is still very remote." The great progress in
velopment during the years when aircraft nuclear
had been under development was undoubtedly a
this decision. While the program did not meet its
objectives, it did produce a wealth of new reactor
much of which is proving of value in other re-
cations.

REACTORS FOR SPACE

Space technology is too young to be predictable,
reason to believe that only through exploitation of
els will it be possible to obtain enough independ-
m the earth to conduct manned interplanetary
n. The reason is in the almost certain imprac-
of using chemical fuels to propel the large pay-
ired for orbital maneuvering, protection of per-
bility on other planets, and other prerequisites of
n. And so in space, as on land and sea, atomic
mises to be an important factor.

Power The first application of atomic energy
nvolved a "nuclear battery," a device that gen-
all amounts (watts) of electricity by direct con-
the heat given off by a radioactive isotope as it
June 29, 1961, a nuclear battery weighing five

pounds and generating 2.7 watts of electricity was carried into orbit aboard a Navy navigational satellite. Its function is to power two of the satellite's four navigational transmitters. A similar nuclear battery was used in a second Navy satellite put into orbit November 15, 1961. The purpose of the satellites is to provide a worldwide means for ships and aircraft to determine their positions electronically. Other radioisotopic-power generators, providing up to 25 watts of power for satellites, have been launched since that time.*

The nuclear devices in the satellites were developed as part of the AEC SNAP (Systems for Nuclear Auxiliary Power) program. Under this program some 16 similar devices are being developed for special uses at remote weather stations, coastal light buoys and elsewhere.

Of more pertinence to this booklet, are SNAP projects to develop a series of extremely compact nuclear reactors, primarily for use in space. Their power outputs range from 500 watts to hundreds of kilowatts.

The first of the reactor series is SNAP-2,† a liquid-metal cooled, metal-hydride moderated reactor that drives a mercury vapor turbogenerator with a 3- to 150-kilowatt power range. The SNAP-10A uses the same type of reactor with a thermoelectric generator to supply between about 0.5 and 50 kilowatts of power. A 500-watt example of this type has been launched and tested in orbit. The SNAP-10A concept has the advantage of requiring practically no moving parts for power production. Both the SNAP-2 and SNAP-10A were developed for Air Force advanced space systems. These systems have been delayed, and their reactor power systems are being continued as part of a long-range AEC program.

SNAP-8 is a system being developed by the AEC in collaboration with the National Aeronautics and Space Administration (NASA). It is scheduled to be tested at 35 electrical kilowatts in a flight-configured ground test in 1968.

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*See *Power from Radioisotopes*, a companion booklet in this series, for more on SNAP devices.

†In the SNAP program, the reactors are given even numbers, the radioisotope projects odd numbers.

SNAP-50, a larger system of 300 and 1000 thermal kilo-watts output, is being developed for use in advanced electric propulsion (see discussion on page 33), as well as auxiliary power needs.
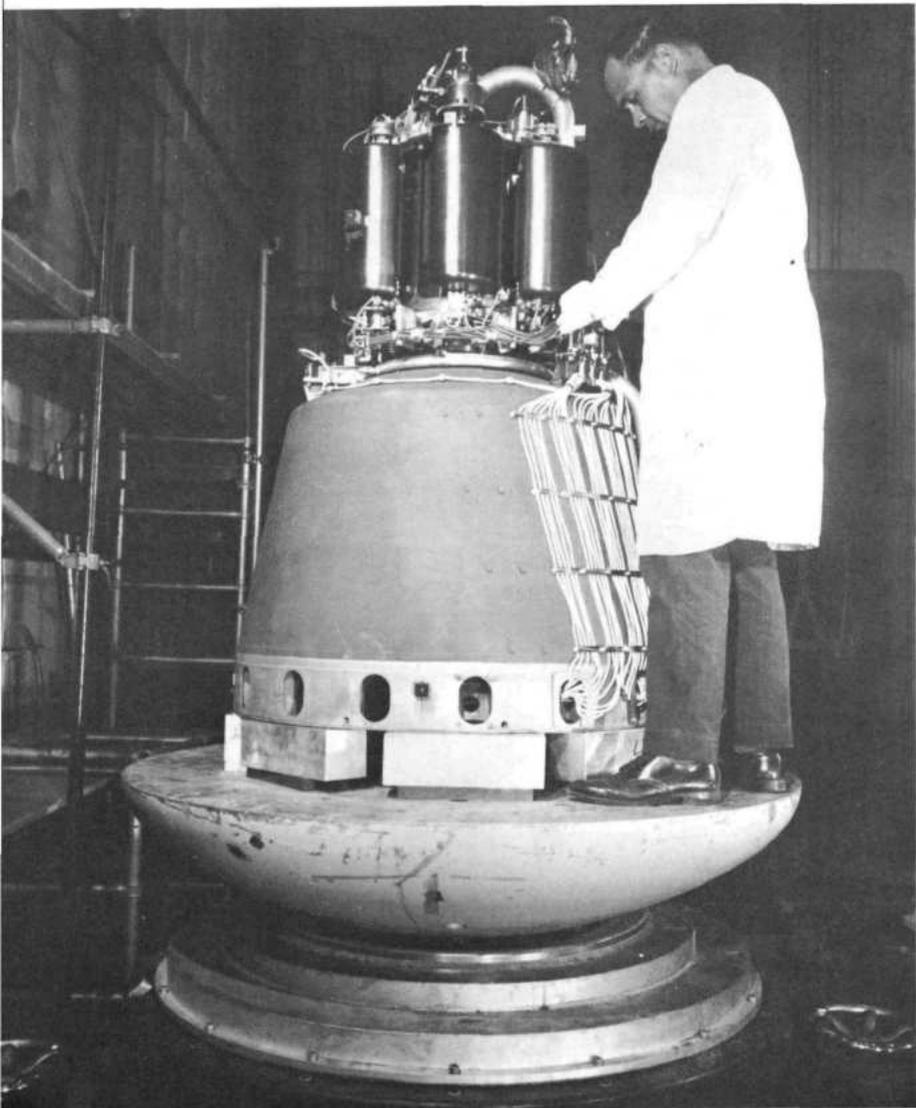

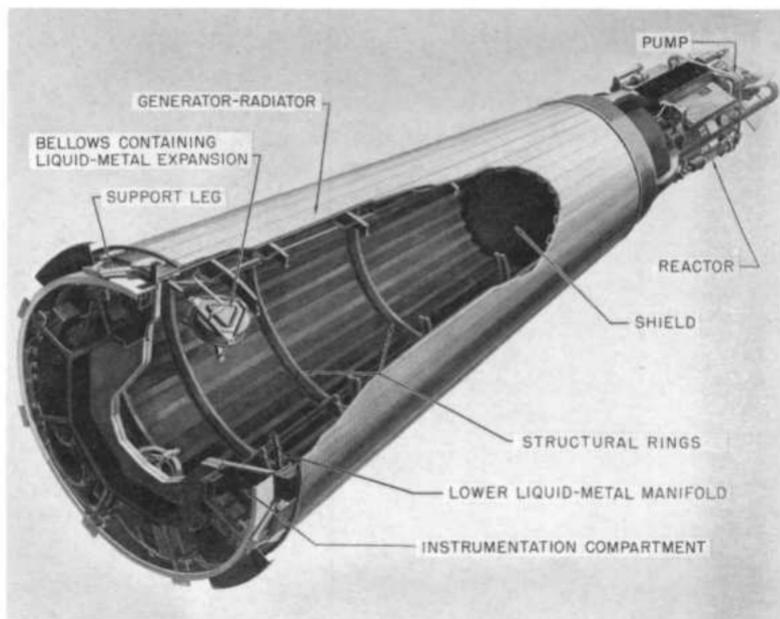**Figure 16** *SNAP-8 Reactor being prepared for vibration tests which simulate launch conditions.*

Figure 17   *Diagram of SNAP-10A system.*

Rocket Propulsion   NASA and the AEC jointly sponsor a program to develop nuclear rocket engines for space missions.

In a nuclear rocket, as presently conceived, liquid hydrogen would be vaporized; the resulting gas would then be heated to a high temperature in a reactor and ejected by expanding it through a rear nozzle, thereby developing thrust.

The specific impulse—that is, the pounds of thrust per pound of propellant ejected per second—that can be achieved in such a system is estimated to be two to three times that with chemical rockets.

Extremely high reactor outlet temperatures are required for efficient performance of a nuclear rocket. Very large power outputs—millions of kilowatts of heat—are required, and the reactor must be capable of starting and stopping quickly and precisely.

In the NASA-AEC program, the goal is development of an experimental ground-based nuclear rocket engine and
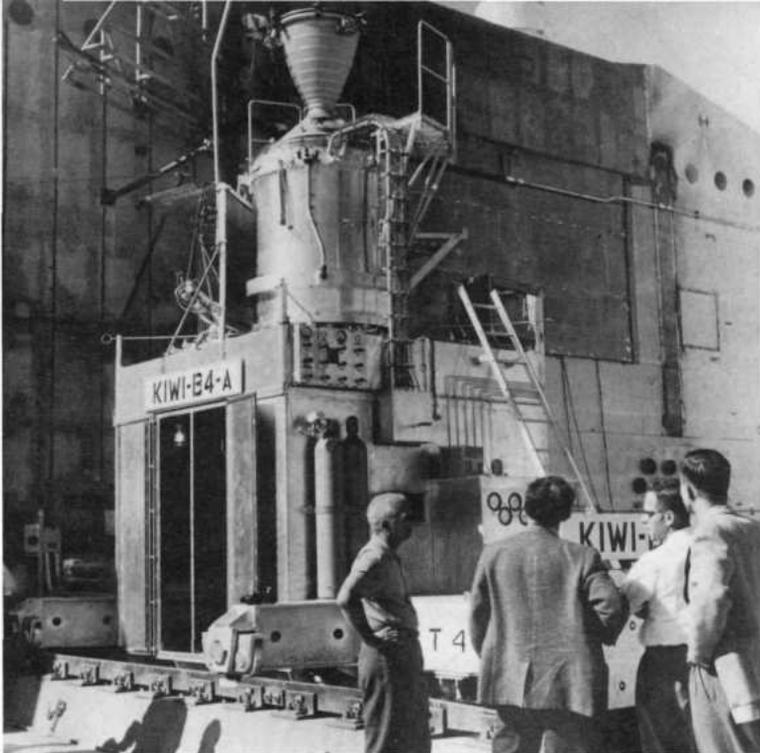
Figure 18 *Los Alamos Scientific Laboratory staff members conferring in front of the Kiwi-B4-A reactor at the National Rocket Development Station in Nevada.* Courtesy Los Alamos Scientific Laboratory

supporting research on advanced flight reactors, engines, and vehicles. Earlier experiments using solid-core graphite nuclear rocket reactors have been completed successfully under a project known as KIWI, named after an earthbound New Zealand bird.

The technology developed in these tests now is being used as a basis for flight reactor development under the NERVA (Nuclear Engine for Rocket Vehicle Application) project and for developing a higher powered graphite reactor. The NERVA engine will be 22-feet tall and will provide a thrust of approximately 50,000 pounds at a high specific impulse. Tests of a prototype reactor for the engine have been encouraging.

In addition, the AEC and NASA are investigating the possible use of tungsten as a fuel-bearing reactor material and are studying reactors using gaseous and liquid fuels.

Electric Propulsion The SNAP-50 reactor is being developed for electric propulsion as well as auxiliary power. Electric propulsion is a yet unproven concept for space vehicle propulsion; thrust would be produced by ejecting a high-energy beam of electrically charged particles (ions and electrons). In principle, very high specific impulses (of the order of ten thousand pounds of thrust per pound of matter ejected per second) could be achieved by this means; but, matter could be ejected only very slowly, at a rate of a few thousandths of a pound per second. Electric propulsion is thus intrinsically a low-thrust concept, and is therefore only particularly useful for maneuvering or propelling spacecraft that have been lifted out of the earth's gravitational field by other means. It appears suited for this, however, since the rate of propellant consumption would be very low, and extremely high jet velocities could be achieved.
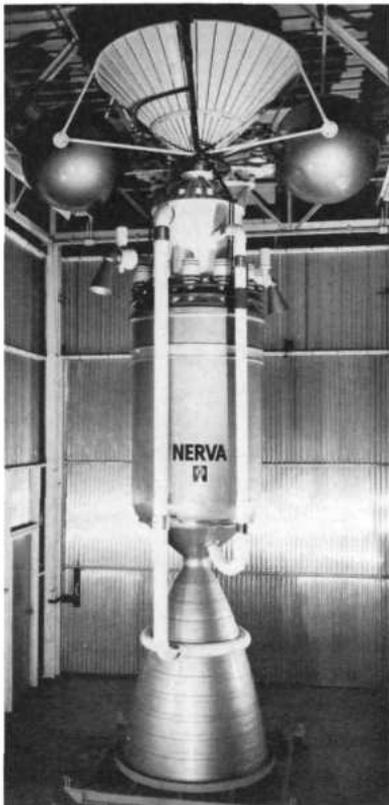
Because of the compactness of atomic fuel, nuclear reactors are believed to offer the most practical means of supplying the electric power needed to ionize and accelerate the charged particles. The acceleration might be done by applying electrical potentials to separated beams of ions and electrons; or it might be done by energizing a magnetically confined "plasma" of mixed ions and electrons.

Figure 19 *This full-scale wooden mock-up of the NERVA rocket engine is used by engineers to check location of various components and to study the limitations of the arrangement.*

Courtesy Aerojet-General Corporation

REACTOR SAFETY

A question that is sometimes asked is: Can a nuclear reactor blow up like an atomic bomb? The answer is: No. In the first place, the fuel used in most reactors could not be made to explode even in a bomb. In the second place, the design principles are entirely different. In a simple type of bomb, two or more pieces of essentially pure fissionable material are rapidly brought together to form a critical mass and held in compression long enough for a very large explosive force to be generated. In a reactor there is nothing to hold the fuel together. If a runaway reaction occurs, the intense heat generated causes the fuel to melt or otherwise come apart. Reactors are so designed that, if this happens, the fuel tends to disperse and the reaction automatically stops. Indeed, most types of reactors have an inherent self-regulating characteristic in that as the temperature begins to rise the reaction slows down. In such cases even a core meltdown is a virtual impossibility.

Apart from the physical damage to the reactor, the most serious hazard in the event of a core meltdown—or a structural failure, or any other conceivable reactor accident—is the possible escape of radioactivity. There are thus two main aspects of reactor safety: (1) prevention of reactor accidents, and (2) containment of radioactivity in the event of an accident.

Prevention of reactor accidents starts with conservative design of the reactor core and control system and conservative engineering of the reactor installation. Maximum advantage is taken of natural laws to build inherent safety features into the system. Starting with this base, the designer seeks to anticipate the possible sources of human error and electromechanical failure and to make provision for them in the design. For example, safety rods are designed on a "fail-safe" basis and automatically insert themselves into the reactor should preset conditions occur.

Accident prevention takes many other forms, notably in the care that is taken to select and train operating personnel and in specifying operating procedures. And before a nuclear power plant may be built in the United States, vigorous safety review procedures must be followed, including,

among other steps, a specific safety review of the proposed project by an impartial board of reactor experts (Advisory Committee on Reactor Safeguards). This review takes into account not only the features of the proposed reactor installation but also the environmental characteristics of the proposed location—distance from population centers, terrain, meteorological conditions, and the like. A similar but even more detailed review is made before a license is granted to operate the plant. Once the plant is in service, an amendment to the license must be obtained before any significant change may be made in the operating pattern.

In the containment aspect of reactor safety, fission products account for nearly all the radioactivity in most power reactors, so they are what must be contained. In normal operation, the fission products are locked in the fuel by the fuel cladding, which is thus the plant's first line of defense against release of radioactivity.* This material leaves the premises, so to speak, when "spent" (used) fuel elements are removed from the reactor and shipped to a fuel reprocessing plant.† If any trace of the fission products escapes into the reactor coolant through defects in the fuel cladding, it is scavenged from the coolant by purification equipment, packaged and shipped to an AEC site for safe burial.

In the event a major accident, such as a core melt-down, should occur large amounts of fission products would escape their normal confinement in the fuel. Therefore all civilian power reactors except those in very remote locations are provided with a second line of defense—usually a gastight enclosure. In most plants this takes the form of a large containment shell, which encloses the reactor installation.‡ These shells are designed to withstand the maximum vapor pressure that might be generated, and are rugged enough to resist possible shrapnel effects. They ex-

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*In this connection, it is the ability of fuel and fuel cladding materials to withstand physical deformation under irradiation which often determines the allowable "fuel burnup"—that is, the length of time fuel elements can be allowed to remain in a power reactor.

†A plant at which residual fuel is recovered.

‡In some cases an airtight building suffices for containment; in other plants, major parts of the reactor system are individually contained in steel tanks.

Figure 20 *Steam escaping from the open tank of a reactor during a purposely planned safety test conducted to study the self-regulating ability of a boiling water reactor system.*

plain the familiar spherical or hemispherical shape of atomic power plants.

Over the more than two decades that have passed since the Fermi experiment, during which literally hundreds of reactors of various types and designs have been built for a great many purposes, an impressive safety record has been achieved. With every new reactor and each new year of operating experience, new knowledge is constantly being gained—and this is perhaps the most important safeguard of all. An equally important source of new knowledge is the Atomic Energy Commission's reactor safety program. This is a major effort and has two principal aspects: (1) study of basic accident mechanisms and (2) testing of safety features. In the latter, laboratory and prototype models of various types of reactor systems are put through rigorous tests under extreme conditions to determine the safe limits of designs, materials, and equipment components.* (See Fig. 20.)

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*For more information on reactor safety, see *Atomic Power Safety,* a companion booklet in this series.

REACTORS OF TOMORROW

A final point that should be made in this introduction to nuclear reactors is that "tomorrow"—or the day after—we may also have at our command an entirely different species of machine, namely thermonuclear reactors. In such machines power would be generated by the controlled fusion of light atoms,* rather than by the controlled fission of heavy atoms. How this might be done is a subject unto itself; suffice it to say that scientists and engineers in at least half a dozen major laboratories in the United States, and their counterparts abroad, are busily at work on the problem.

And so it is clear that nuclear reactors, whether activated by fission or fusion, will play a significant part in the affairs of men for many years to come.

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*Specifically, deuterium and/or tritium. These are isotopes of hydrogen, sometimes referred to as "heavy hydrogen" and "heavy heavy hydrogen." For more about this subject see *Controlled Nuclear Fusion*, a companion booklet in this series.

Appendix   CHARACTERISTICS OF U. S. CIVILIAN POWER REACTOR CONCEPTS

Pressurized Water Reactor (PWR)

FUEL—Slightly enriched uranium oxide clad with stainless steel or zirconium alloy
MODERATOR—Water
COOLANT—Water
PRESSURE OF PRIMARY SYSTEM—2,000 pounds per square inch (psi)
COOLANT OUTLET TEMPERATURE—550°F

NOTES—Well developed technology. Coolant pressurized to prevent bulk boiling in core; hence high operating pressure.

Boiling Water Reactor (BWR)

FUEL—Same as PWR, above
MODERATOR—Boiling water
COOLANT—Boiling water
PRESSURE OF PRIMARY SYSTEM—1,000 psi
COOLANT OUTLET TEMPERATURE—550°F

NOTES—Well developed technology. Coolant allowed to boil in core; hence lower operating pressure than PWR. Physical size of core larger than in PWR.

High-temperature Gas-cooled Reactor (HTGR)

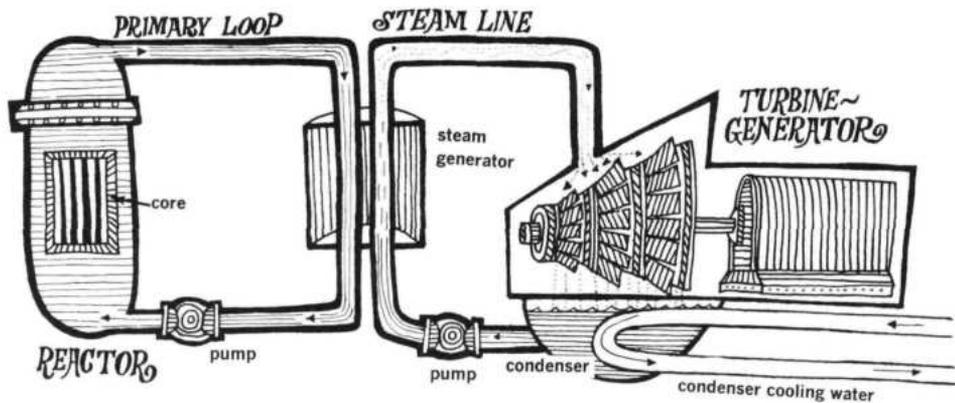FUEL— Highly enriched uranium carbide mixed with thorium carbide and clad with graphite
MODERATOR—Graphite
COOLANT—Helium
PRESSURE OF PRIMARY SYSTEM—300–400 psi
COOLANT OUTLET TEMPERATURE—1380°F

NOTES—Use of helium as coolant permits achieving high temperatures at modest pressures and minimizes corrosion problems, offsetting the fact that a gas is not a very efficient heat transfer medium. Core design of HTGR has many excellent features from a physics standpoint. Engineering features of concept difficult to evaluate pending operation of first HTGR plant (1964–1965).

PRIMARY LOOP STEAM LINE

TURBINE~
GENERATOR

steam
generator

core

REACTOR   pump

pump   condenser

condenser cooling water

REACTOR   STEAM LINE

TURBINE~
GENERATOR

core

condenser

condenser cooling water

pump

PRIMARY LOOP   STEAM LINE

REACTOR

TURBINE~
GENERATOR

steam generator

core

COMPRESSOR

pump   condenser   condenser cooling water
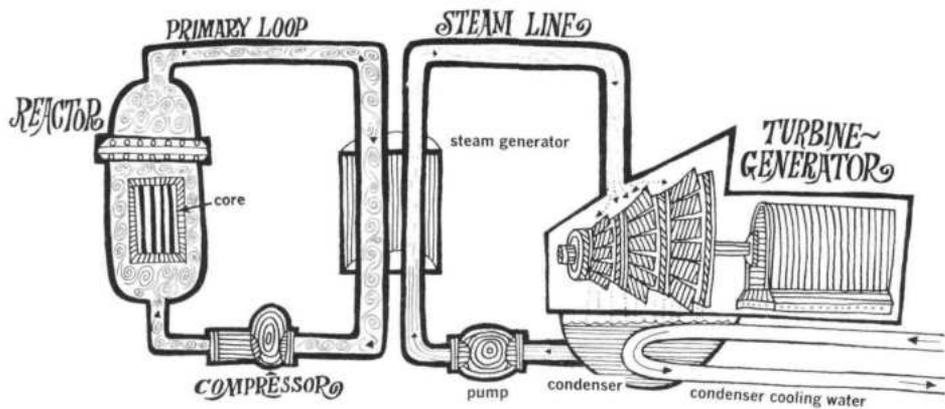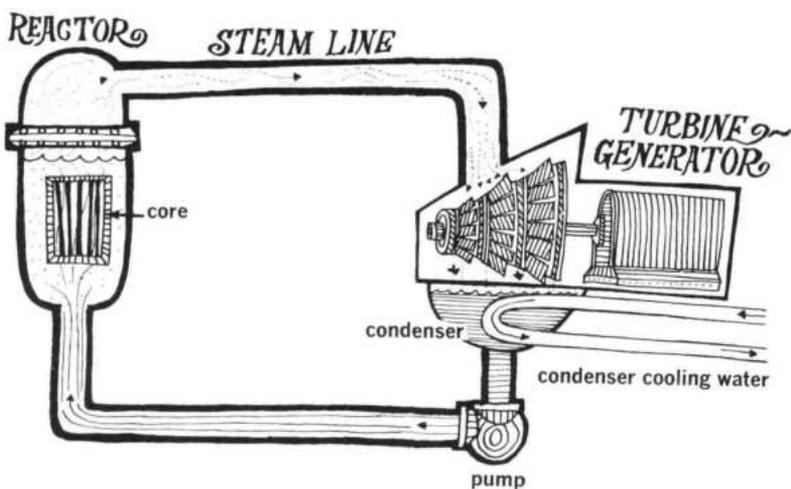
Heavy Water Moderated Reactor (pressure tube type)

FUEL — Uranium metal or oxide clad with zirconium alloy
MODERATOR — Heavy water
COOLANT — Heavy water
PRESSURE OF PRIMARY SYSTEM — 750 psi
COOLANT OUTLET TEMPERATURE — 500°F
   NOTES — Promise of low fuel costs through use of natural or only slightly enriched uranium.

Nuclear Superheating

FUEL — Slightly enriched uranium oxide clad with stainless
   steel or other alloy material
MODERATOR — Water and steam, or steam alone
COOLANT — Water and steam, or steam alone
PRESSURE OF PRIMARY SYSTEM — 600 – 3,500 psi
COOLANT OUTLET TEMPERATURE — 825 – 1050°F
   NOTES — Two schemes: "Integral superheating" in which steam is recycled through a superheat zone in the core, thereby raising the temperature ceiling. "Separate superheating," meaning the use of a saturated steam-cooled reactor to raise the temperature of steam produced by a separate reactor.

Molten Salt Reactor (MSR)

FUEL — Molten solution of highly enriched uranium and
   thorium in fluoride salt mixture
MODERATOR — Graphite
COOLANT — See notes below
PRESSURE OF PRIMARY SYSTEM — Nominal
COOLANT OUTLET TEMPERATURE — 1000°F
   NOTES — Circulating fuel system as above, but absence of pressure and less severe corrosion problem make engineering problems less difficult. Concept in experimental stage.

Liquid Metal Cooled Reactors

Sodium-Graphite Reactor (SGR)

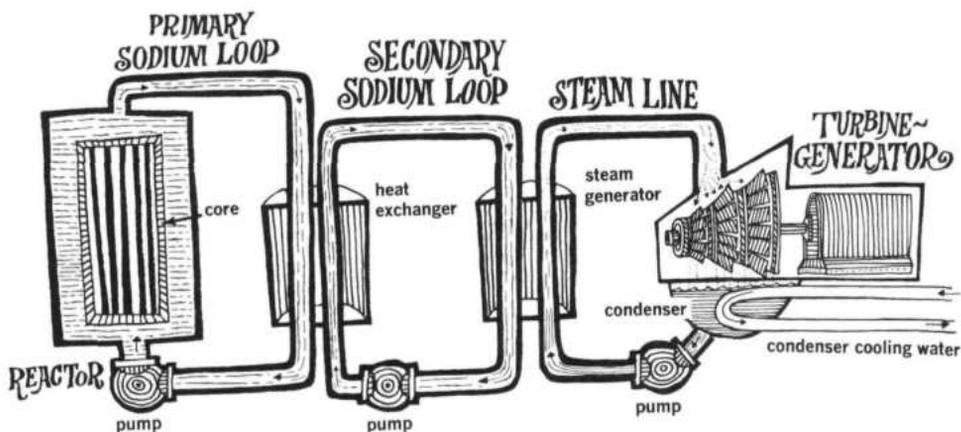FUEL — Slightly enriched uranium alloy or uranium carbide clad with stainless steel

MODERATOR — Graphite

COOLANT — Liquid sodium

PRESSURE OF PRIMARY SYSTEM — Nominal

COOLANT OUTLET TEMPERATURE — 950°F

NOTES — Use of sodium as coolant permits achieving high temperatures at nominal pressure; also, sodium is a very efficient heat transfer medium. The handling of sodium introduces some design and operating complications.

Fast Breeder Reactor (FBR)

FUEL — Highly enriched uranium alloy clad with stainless steel (use of uranium-plutonium oxides or carbides projected)

MODERATOR — None

COOLANT — Liquid sodium

PRESSURE OF PRIMARY SYSTEM — Nominal

COOLANT OUTLET TEMPERATURE — 800–1150°F

NOTES — Promise of low fuel costs and efficient utilization of fuel resources through breeding. See SGR above for notes on sodium.

U. S. CENTRAL STATION NUCLEAR POWER PROJECTS*

January 1965

Name	Location	Type	Capacity†	Owner	Startup
Shippingport Atomic Power Station	Shippingport, Pa.	Pressurized water	100,000‡	AEC (steam portion)-Duquesne Light Co. (electrical portion)	1957
Dresden Nuclear Power Station	Morris, Ill.	Boiling water	200,000	Commonwealth Edison Co.	1959
Yankee Atomic Electric Station§	Rowe, Mass.	Pressurized water	175,000	Yankee Atomic Electric Co.	1960
Indian Point Station	Indian Point, N. Y.	Pressurized water	255,000¶	Consolidated Edison Co. of New York	1962
Hallam Nuclear Power Facility§	Hallam, Neb.	Sodium-graphite	75,000	AEC (steam portion)-Consumers Public Power District of Nebraska (electrical portion)	1962
Humboldt Bay Power Plant	Eureka, Calif.	Boiling water	48,500	Pacific Gas and Electric Co.	1963
Big Rock Nuclear Power Plant§	Charlevoix, Mich.	Boiling water	72,800	Consumers Power Co.	1962
Enrico Fermi Atomic Power Plant§	Lagoona Beach, Mich.	Fast breeder	60,900	Power Reactor Development Co. (steam portion)-Detroit Edison Co. (electrical portion)	1963
Pathfinder Atomic Power Plant§	Sioux Falls, S. Dak.	Boiling water with integral nuclear superheating	58,500	Northern States Power Co.	1964
Peach Bottom Atomic Power Station§	Peach Bottom, Pa.	High temperature gas-cooled	40,000	Philadelphia Electric Co.	1965
La Crosse Boiling Water Reactor§	Genoa, Wisc.	Boiling water	50,000	AEC (steam portion)-Dairyland Power Cooperative (electrical portion)	1965
San Onofre Nuclear Generating Station§	San Clemente, Calif.	Pressurized water	375,000	Southern California Edison Co. and San Diego Electric Co.	1966
New Production Reactor and Power Plant**	Richland, Wash.	Graphite	800,000	AEC and Washington Public Power Service System	1966
Malibu Nuclear Plant§	Corral Canyon, Calif.	Pressurized water	462,000	Los Angeles Department of Water and Power	1968
Connecticut Yankee Nuclear Power Station§	Haddam-Neck, Conn.	Pressurized water	462,000	Connecticut Yankee Atomic Power Co.	1967
Oyster Creek Station	Oyster Creek, N. J.	Boiling water	515,000	Jersey Central Power and Light Co.	1967
Nine Mile Point Plant	Oswego, N. Y.	Boiling water	500,000	Niagara Mohawk Power Co.	1968
Elk River Reactor	Elk River, Minn.	Boiling water	23,000	AEC and Rural Cooperative Power Association	1962
Carolinas-Virginia Tube Reactor	Parr, S. C.	Pressure tube, heavy water	17,000	Carolinas-Virginia Nuclear Power Associates, Inc.	1963
Piqua Nuclear Power Facility	Piqua, Ohio	Organic cooled and moderated	11,400	AEC and the City of Piqua	1963
Boiling Reactor Nuclear Superheat Project	Punta Higuera, Puerto Rico	Boiling water, integral nuclear superheat	16,500	AEC and Puerto Rico Water Resources Authority	1964

*Projects proposed but not definitely committed on December 16, 1964, not listed.
†Kilowatts of electricity-net.
‡Reactor power level equivalent to 135,000 kwe net.
§Projects which have received government assistance under the USAEC's Power Demonstration Reactor Program.
¶Includes contribution of fossil-fired superheaters.
**Dual purpose plant for producing plutonium and electric power.

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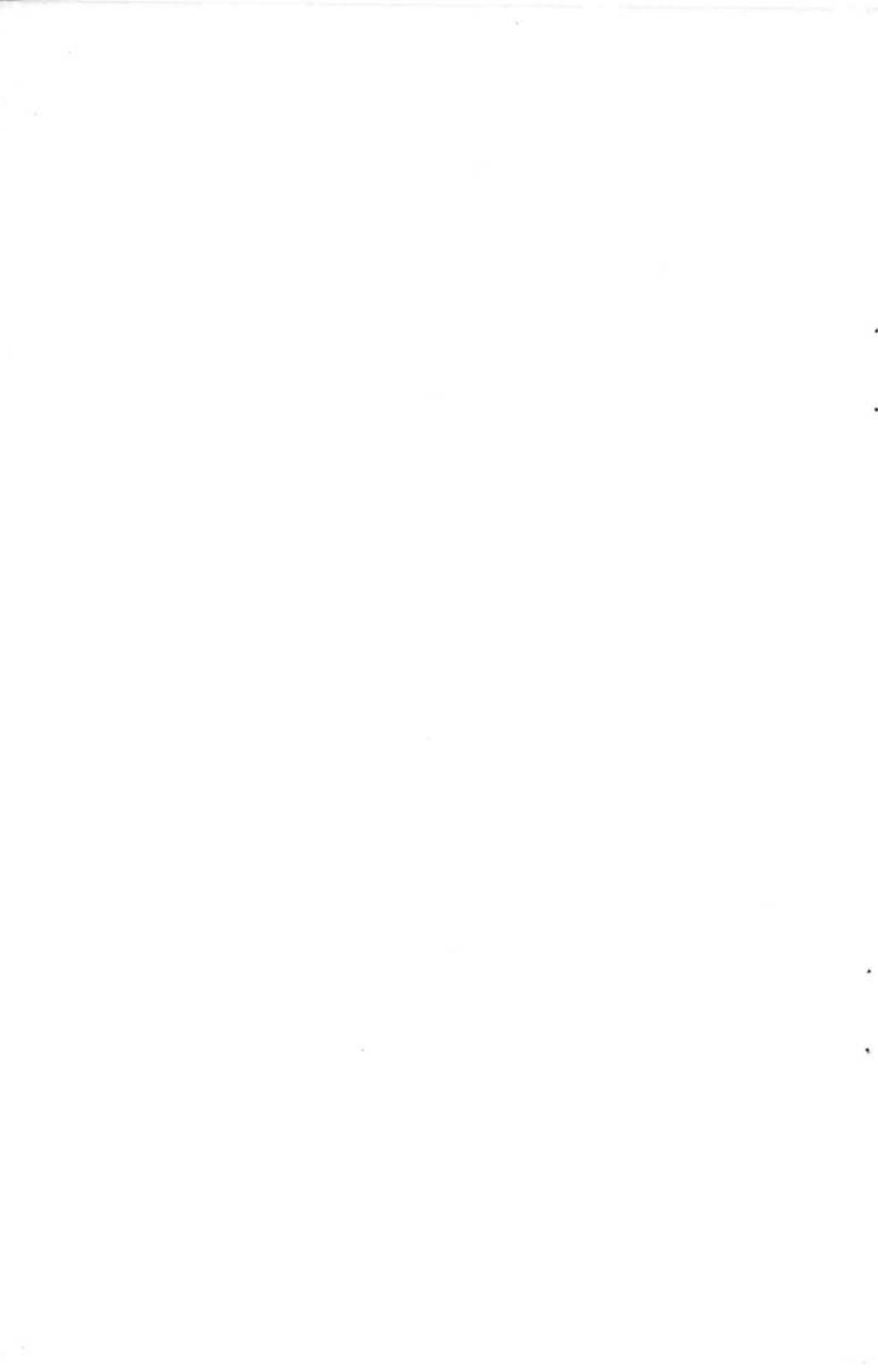
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