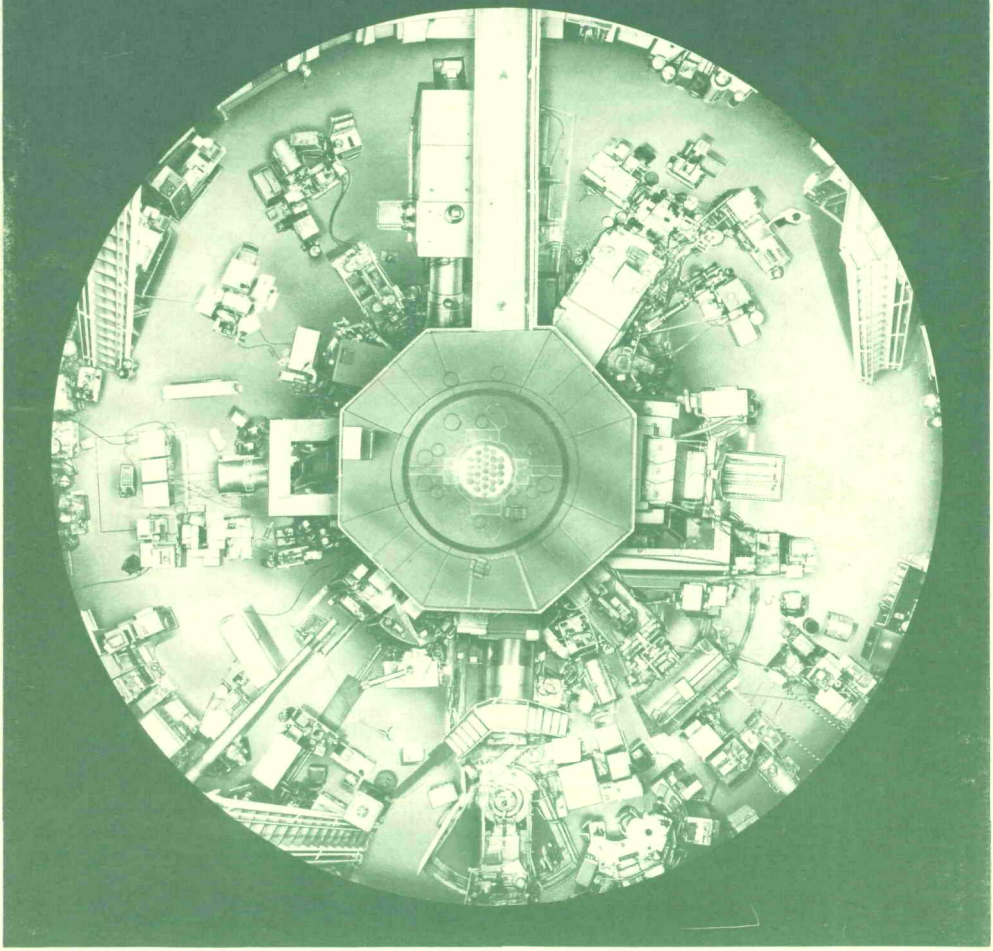
Research Reactors



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

ONE
OF A SERIES ON
UNDERSTANDING THE ATOM

UNITED STATES
ATOMIC ENERGY COMMISSION

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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
Director
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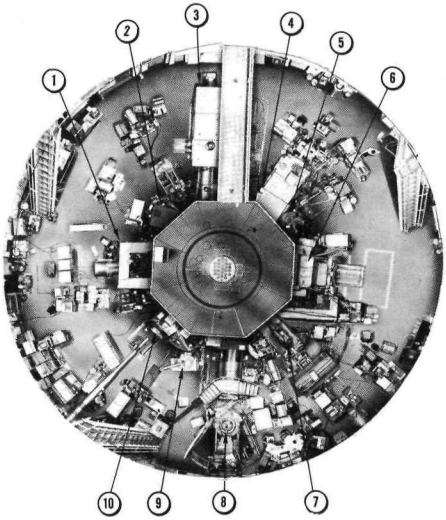

THE COVER

The cover photograph is a composite of 18–22 separate photographs taken from a circular bridge crane over the CP-5 research reactor at the Argonne National Laboratory in Illinois. These were stripped together in the fashion of an aerial mosaic. Lens distortions were removed with an air brush and then the work print was rephotographed. Experimental apparatus surrounding the reactor includes (1) cold neutron scattering facility; (2) neutron diffraction spectrometer; (3) compton spectrometer; (4) nuclear magnetic resonance; (5) neutron diffraction spectrometer; (6) neutron-gamma ray toxicity; (7) neutron crystal monochromator; (8) bent-crystal spectrometer; (9) neutron diffractometer; and (10) neutron chopper.

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Research Reactors

By
FREDERICK H. MARTENS
and
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INTRODUCTION

Outstanding among men are those who create, perfect, and use the machines and devices for exploring unknown worlds. Often, though not always, machines used for discovery share with their operators a popular image of special significance. Of course, not all vehicles for probing the unknown are as glamorous as a space capsule or a bathyscaph, nor as unique as a particle accelerator. Nor are many as prosaic as, for example, an optical microscope.

Somewhere between these extremes is the nuclear reactor.

Reactors have gained fame in great measure, to be sure. Known widely is the role of the first chain-reaction-sustaining pile* which launched the atomic age. In submarines and in electric power plants, reactors have won status.

*The term "pile" was in common use early in the atomic era because the first reactors were essentially piles of graphite blocks and uranium fuel.

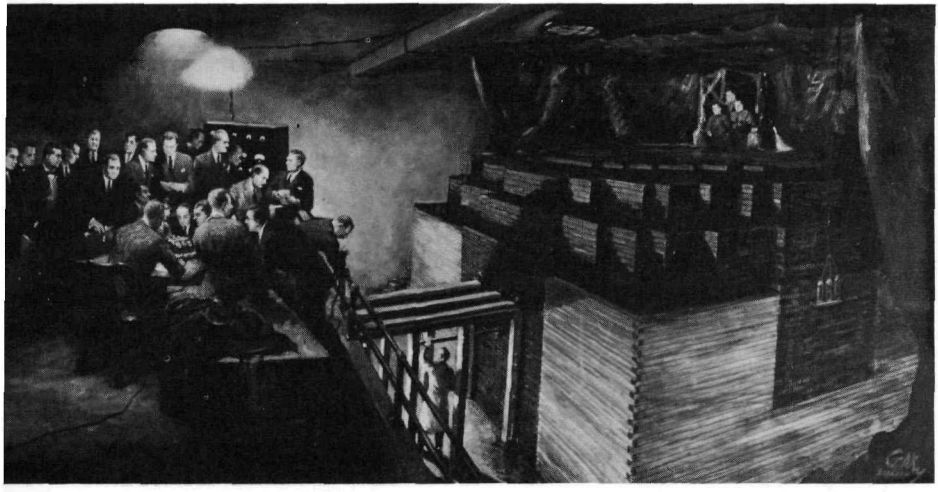

Figure 1 *This painting illustrates the achievement of the first self-sustaining chain reaction with the first nuclear reactor (pile) on Dec. 2, 1942, under the West Stands of Stagg Field at the University of Chicago. (Painting by Gary Sheahan.)*

But hundreds of other reactors have been built since 1942 and entrusted to the care and use of men of science. The contributions made possible by these research reactors are little known.

Today reactor-originated research spreads over a broad spectrum of advanced science and technology and serves nations on every continent. The significance of this endeavor scarcely can be overestimated. Some experimenters use research reactors to simulate radiation expected in nuclear rocket environments in space. Others gather information on radiation-produced defects in metals, radiation effects on humans, or treatment of malignant tumors.

Research reactors also are used as sources of radioactive isotopes for scientific experimentation and industrial processing, for irradiating food products, for mutation breeding for new plant and animal species, and for solving countless problems in fission chemistry, geology, mineralogy, and other sciences.

There are more than 300 research reactors operating around the world. Many thousands of scientists and technicians have been and are being trained on these reactors—

in government, in industry, and in universities. And at dozens of universities a research reactor is a focal point for advanced study in nuclear science and engineering and for radiation research.

RESEARCH REACTOR DEFINED

What is a research reactor? The American Standards Association has prepared this description, which most users accept: "A research reactor is one designed to provide a source of neutrons and/or gamma radiation for research into basic or applied physics, biology, or chemistry, or to aid in the investigation of the effects of radiation on any type of material. A distinguishing feature is the incorporation of many beam holes to allow neutrons and gamma rays to leave the core. Generally, the reactor has provision for certain types of isotope products."

This definition includes words which may be unfamiliar. A "neutron", for example, is an uncharged elementary particle found in the nucleus of all atoms heavier than hydrogen. Neutrons are ejected from nuclei as a result of some nuclear reactions, including nuclear fission and nuclear fusion; neutrons so ejected are unstable, but are highly penetrating and can enter into other nuclear reactions. They also sustain the fission chain reaction in a nuclear reactor. For meanings of other words, you may wish to refer to *Nuclear Terms, A Brief Glossary,* a companion booklet in this series.

All reactors—whether used for research, power production, or other purposes—have in common this basic function: They allow a neutron chain reaction to take place safely under controlled conditions.* Certain components are found in almost all reactors:

1. The *fuel,* uranium, which fissions to produce neutrons and to release energy.
2. The *moderator,* which slows the neutrons so that they will cause fission more readily. The moderator is

*For information about atomic energy in general, or about how a reactor works, see *Our Atomic World* and *Nuclear Reactors,* companion booklets in this series.

usually water (because of its hydrogen atoms), "heavy water", beryllium, or carbon; the lighter the element the better it moderates. The fuel and moderator together may be referred to as the "core".

3. The *coolant,* which flows through the core to remove the heat released by the fission process.
4. The *reflector,* which surrounds the core. (Some neutrons escape from the core, collide with atoms in the reflector, and are returned to the core.) The same substances used for moderators are useful as reflectors.
5. The *control system,* which regulates the rate of the reaction.
6. The *shield,* which absorbs most of the intense radiation produced in the core.

Frequently some of these items have more than one basic function; for example, in some reactors, the moderator also may be the coolant, reflector, and shield.

PARTS OF A REACTOR

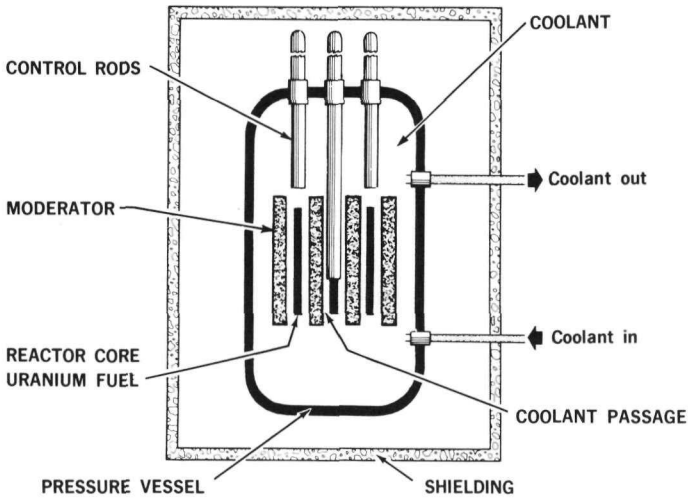

Figure 2 *A reactor is basically an atomic furnace, in which the fissioning or splitting of atoms of nuclear fuel can be controlled and put to useful work. This simplified diagram shows the basic components of a reactor.*

How Neutrons Are Produced

How, then, does a research reactor produce the particles and radiation needed by scientists?

The fuel in a research reactor is always uranium, usually enriched in the proportion of the fissionable isotope uranium-235 it contains. When a neutron strikes the nucleus, or center, of an atom of uranium-235, it may cause the nucleus to split apart, or fission. When the nucleus of a uranium-235 atom fissions, it breaks into two parts or fragments of approximately equal mass, gives off two or three neutrons, and releases a large amount of energy. The neutrons released are then capable of entering other atoms of uranium to repeat the process. This series of events—a neutron entering a uranium atom, the fission of that atom, and the resulting release of more neutrons, one or more of which enters another uranium atom—is called a "chain reaction". (The neutron that initiates the reaction usually comes from one of the neutron sources described later.) Reactors are designed so that this chain reaction takes place in a controlled manner.

On the average, 2.54 neutrons are released in the fission of each uranium atom. One of these must be used to sustain the chain reaction if the reactor is to continue to operate. This leaves 154 other neutrons unused for each 100 fissioning atoms. Some of these are absorbed in other components in the reactor. Some are absorbed in uranium without causing fission. But many remain, and a research reactor allows these excess neutrons to pass from the core of the reactor through outlet tubes so that they may be used in research.

Some of the energy released in the fission process is in the form of gamma rays, which are powerful X rays. Because these gamma rays are very penetrating, a thick layer of concrete must be built around the core of the reactor to protect the users. The fragments left by each fission also are radioactive and increase the need for shielding.

What Neutrons Are Good For

One of the prime functions of a research reactor is to produce neutrons, which have properties making them ex-

tremely useful in research. Neutrons are relatively heavy compared with other fundamental particles, having about the same mass as protons (which are really the nuclei of hydrogen atoms) and about 1850 times the mass of electrons. Because of this weight, neutrons have fairly high energy even while moving slowly. If a neutron is used as a projectile to penetrate matter, the fact that it is moving slowly greatly increases the probability of its interaction with target atoms.

Another characteristic of a neutron is that it has no electric charge. Therefore it can pass through an atom's electron shells and into or near the nucleus without being deflected by the positive charge of the nucleus.

Scientists are interested in several kinds of interactions of neutrons with other matter. One is "neutron absorption". In this interaction a neutron enters the nucleus of the target atom and becomes a part of it. Scientists, using neutrons moving at different velocities and against many different targets, study the probability that this will occur and the effects on the nucleus of the new isotope* that is so formed. The new isotope, which is usually radioactive, may be studied to gain insight into the fundamental structure of matter. The isotope also may be used as a "radioactive tracer", which can be added to other material to make observation of its movement and activity possible.

"Neutron scattering" is another interaction of scientific interest. Neutrons can be bounced off other materials, especially crystalline ones, and the way they scatter may give scientists new facts concerning the structure of the target material.

Nuclear reactors are the primary source of neutrons. It is possible, however, to obtain neutrons by other methods, but only in much smaller quantities. For example, if the nucleus of a beryllium atom is struck with either an alpha particle or a very energetic gamma ray, a resulting nuclear reaction releases a neutron. These reactions are called "alpha N" (α,n) or "gamma N" (γ,n) reactions. Neutrons also may be produced by a reaction between atoms of heavy

*An isotope is a variant form of a chemical element. Isotopes of the same element have the same number of protons in their nucleus but different numbers of neutrons.

hydrogen, or deuterium, if they are made to collide with enough energy.

HOW REACTORS ARE DESCRIBED

A reactor can be described by its particular features. Reactor *size* is indicated most frequently in terms of power and neutron flux. In research reactors, power levels range from 10 thermal kilowatts to more than 50 megawatts.* Any reactor producing less than 1 megawatt is said to be in the "low-power" class; reactors producing from 1 to 5 megawatts have "medium power"; and a level of 10 megawatts or more puts the machine in the "high-power" class.

Possibly the most important feature of a reactor is its *flux,* that is, the measure of the neutron intensity. The neutron flux is defined as the number of neutrons passing through an area of 1 square centimeter in 1 second. It depends not only on the number of neutrons emitted but also on their speed, and it is determined by multiplying the number of neutrons in a cubic centimeter of fissioning material by the average speed at which they are moving. Usually given in neutrons per square centimeter per second, neutron flux is abbreviated "nv". At a place in a reactor where a million million neutrons cross a 1-square-centimeter area each second, there is a flux of 10^{12} nv. Almost all research reactors have this much flux; any with a flux above 5×10^{14} nv are high-flux reactors. The highest flux in any research reactor now in existence or being built is 10^{16} nv, and only a few of these very-high-flux machines exist. (See page 32 for descriptions of advanced reactors under construction.)

Reactors also are classified by other features, such as the vessel that holds the core, the moderating material, and the type of fuel used.

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*Power, the time rate at which energy is converted from one form into another, commonly is measured in watts: a kilowatt is 1 thousand watts; a megawatt is 1 million watts. Reactor power is the rate at which work can be done by the reactor heat, and is measured in thermal watts; some reactors also produce steam to drive generators, which have an *electric* power output measured in electrical watts.

Experimental Devices

Apparatus are built into research reactors so that neutrons and other radiation may be used efficiently. Most research reactors have beam tubes, thermal columns, sample tubes, and "rabbit" devices, and some have additional features. Typical devices are identified in the cutaway drawing of a pool research reactor (Figure 3) and in the layout for a TRIGA* reactor (Figure 4).

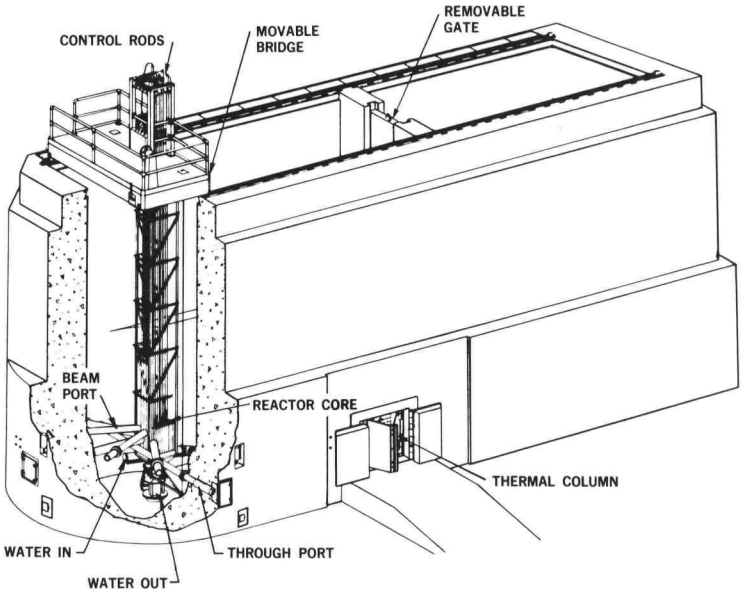
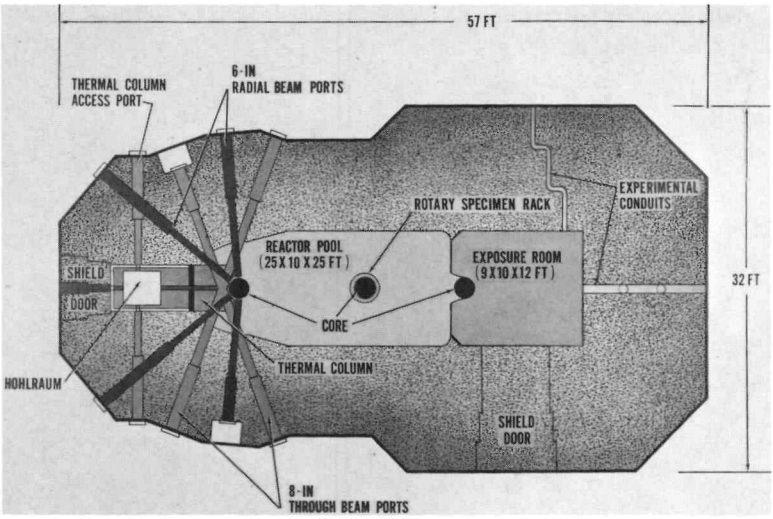


Figure 3 *Experimental facilities associated with most research reactors are identified in this drawing of a pool reactor.*

Common experimental facilities are:

1. A *beam tube* (or beam port) is a hollow tube that passes to the surface of the shielding from a position in or near the core. This gives a free path for neutrons to pass into experimental equipment outside the shield. Usually a gate or beam shutter is located in the shielding to shut off

*For Training, Research and Isotope Production Reactor—General Atomic, a trade name of General Atomic Division of General Dynamics Corporation.



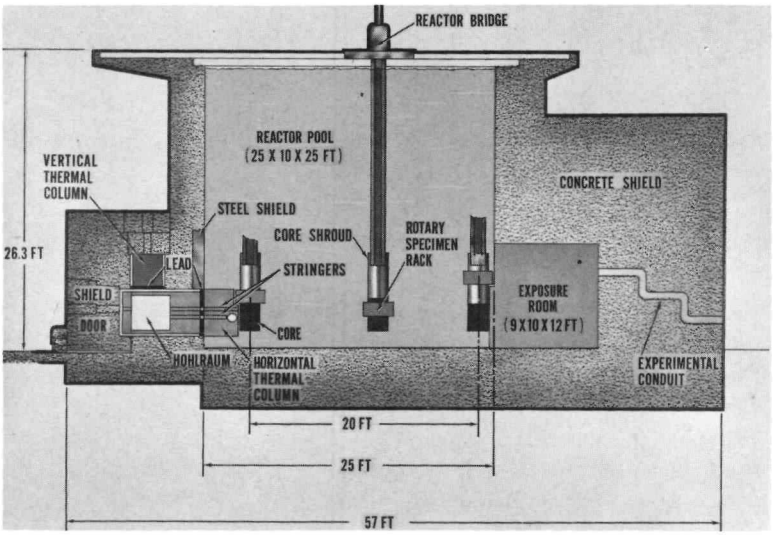


Figure 4 *Horizontal (above) and vertical (below) sections of experimental facilities of an advanced pool reactor. The large walk-in exposure room is useful for many experiments. Note the three locations for the core. The "hohlraum" is an empty space surrounded by a good moderator, in which an almost uniform flux is available. The shielding is indicated by the stippled areas.*

the beam of neutrons when it is not wanted. It acts in much the same way as a camera shutter, except that it is usually 2 feet thick and moves quite slowly.

Such a shutter is shown, partly open, in Figure 5. A scientist using a beam tube frequently lines it with material

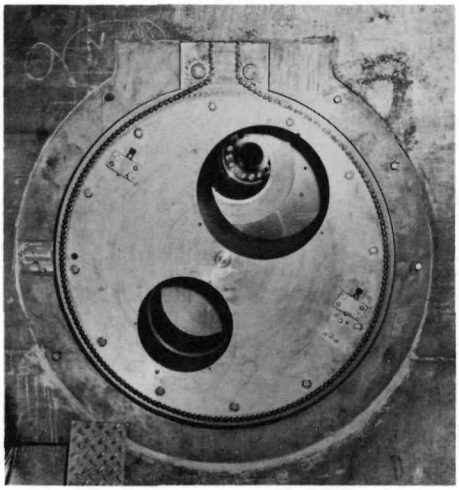


Figure 5 *A beam shutter shown in open position. The end of the beam tube is visible in the upper opening of the shutter.*

to change the size or shape of the beam as he wishes. Often a narrow pencil of neutrons is desired, and so a *collimator*, or focusing device, removes all except those traveling in a well-defined area and direction. If the effect of the gamma rays from the core interferes with a neutron experiment, a bismuth or lead filter, which absorbs gammas but allows neutrons to pass freely, can be placed in the beam tube.

2. A *rabbit* provides a means for rapidly and easily inserting test specimens of material into the area of high neutron flux. A sample in a carrier is moved through a tube and into the core by gas or water pressure. When the irradiation is completed, the sample is moved directly to a laboratory for study.

3. A *thermal column* is an opening through the shielding into the edge of the reflector. It is filled with a material that slows neutrons without absorbing them. Graphite is commonly used because it is plentiful and inexpensive and also because it can be machined easily and accurately.

Other possible materials are D_2O (heavy water) and beryllium or beryllium oxide. The neutrons emerging from the column, having lost all the extra energy they received from fission, are said to have only thermal energy. For this reason they are called "thermal neutrons". Consequently the source from which they emerge is called a thermal column.

4. A *through tube* is a tube through the entire reactor, passing near the core, in which test samples can be irradiated for study. If for any reason the apparatus on one side of the core cannot be moved and the material to be irradiated must be changed frequently, a through tube allows access from the other side. One common use is the study of materials that absorb neutrons and emit gamma rays as a consequence.

5. *Sample irradiation tubes* lead into regions of the highest neutron intensity, in which containers of material to be irradiated can be inserted, exposed to the desired amount of radiation, and then removed into a shielded container for further study. These tubes aid study of samples with short "half-lives".*

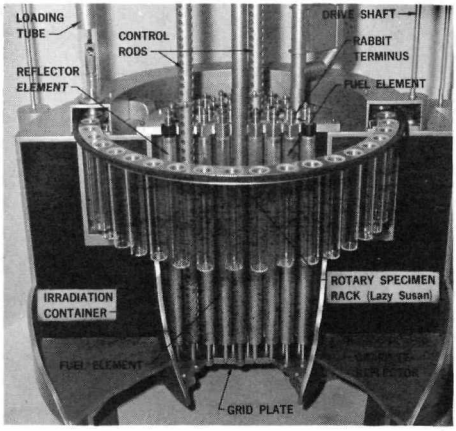


Figure 6 *Cutaway model of graphite-reflected core showing experimental facilities such as Lazy Susan and Pneumatic Rabbit. A water-reflected core has similar facilities.*

*The half-life of a radioactive substance is the time it takes for its radioactivity to decrease to half its original value. In samples with short half-lives, radiation dies out rapidly.

6. *Test loops* in the reactor core allow materials to be irradiated for extended periods of time (often months and occasionally years) under constant conditions. Cooling water or gas passes over the samples, and thermocouples often are installed to measure and control the temperature.

The components of a constant-temperature test-loop and cooling-coil assembly are shown on the left in Figure 7.

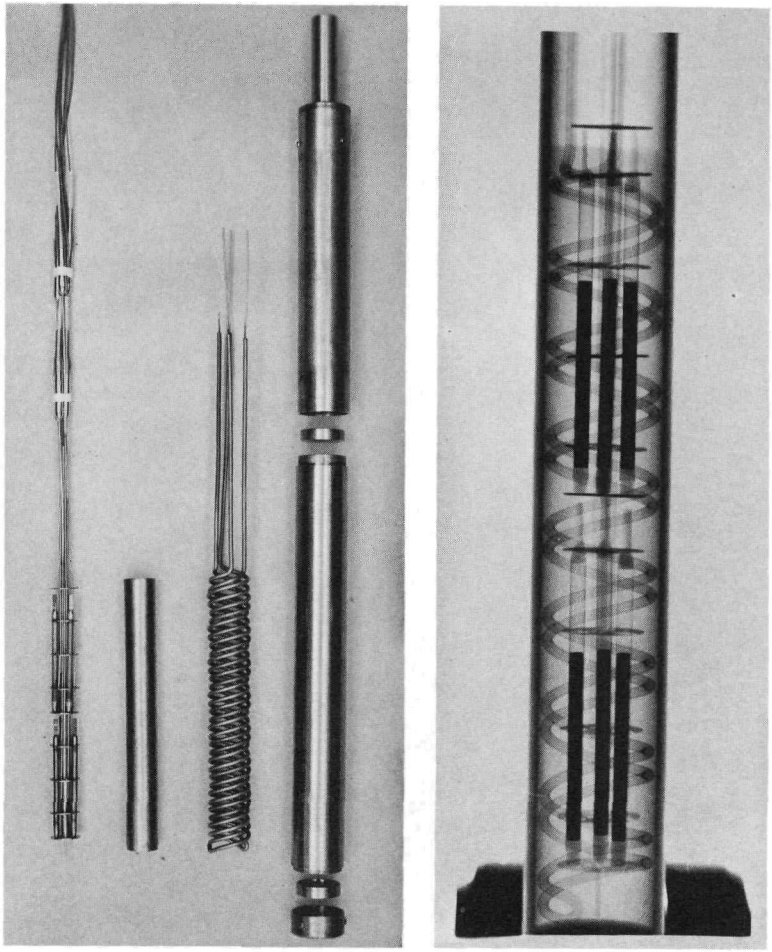


Figure 7 *Components of a constant-temperature device in a research reactor. On the left are the specimen holder and cooling coils before assembly. On the right is a radiograph of the assembled apparatus, showing coils surrounding the specimen holder.*

On the right is a neutron radiograph of the assembled facility. This picture is similar to an X-ray photograph; neutrons, rather than X rays, were used to produce the image, however.

An interesting additional irradiation device is a *rotary specimen rack* or *lazy susan,* surrounding the core. Evenly spaced aluminum cups hold specimen containers. Rotation of the rack allows simultaneous and equal irradiation of 40 samples in a uniform neutron flux.

Comparison of Reactor Types

Reactors differ in type, depending on the use for which they were designed. We can learn about research reactors by comparing them with other types.

All reactors produce heat, radiation, and fission products. Those designed to make use of heat operate at high temperatures and "discard" the radiation; those designed to seek uses for radiation make no use of the heat. Fission products are usually waste materials requiring disposal, although sometimes they may be recovered and used as sources of radiation.

In a *power reactor*—one that is built to produce electricity—high temperatures in the core are necessary. Steam or pressurized water is heated in the core to 500°F or higher; and the higher the temperature, the more efficient the machine becomes. In a research reactor, however, a coolant is seldom raised to the boiling point. The temperature is kept as constant as possible because most experiments must be done under controlled conditions.

Even so, the average research reactor—if there is such a thing—produces 2 million thermal watts of power in the form of heat. If all this energy could be converted into electricity it would serve the needs of a city of about 4000 people, but the fact is that this heat is bothersome rather than useful. It must be removed by a secondary cooling system, which is expensive and often troublesome to the experimenters. Although water is the most common cooling medium, air, carbon dioxide, or helium is used in some research reactors.

Since water in a research reactor never boils, the vessel holding the reactor core does not have to withstand the high pressure occurring in a steam system. Therefore the tank may be made just strong enough to hold the materials in it. Aluminum less than 1 inch thick frequently is used. The tank of a power reactor, on the other hand, is usually made of steel at least 4 inches thick.

A *production reactor* is designed to produce elements and isotopes not usually found in nature. The most frequently produced element is plutonium, which can later be used as fuel in other reactors or in nuclear weapons. Plutonium reactors are designed so that excess neutrons produced are captured within the core in uranium-238, which then decays radioactively to become plutonium. Reactors designed to make radioactive isotopes by bombarding stable elements with neutrons are also called production reactors.

Finally, there is a distinction between a research reactor and an *experimental reactor*. A research reactor is designed to produce neutrons for research. An experimental reactor is itself an experiment. Experimental reactors test the design of new types of reactors and seldom are used for any external research. Experimental reactors usually try out new designs for power reactors.

SAFETY OF RESEARCH REACTORS

Research reactors in the United States have an excellent record of safety. This safety is achieved by building in "fail-safe" equipment that provides fast-acting electronic-mechanical shutdown systems and by designing fuel elements which are inherently safe because they operate independently of electronic systems in shutting down accidental excursions.* It is desirable that research reactors be as safe as possible since the factors determining safety also affect the experimental flexibility, the total reactor costs, and the decisions on where new reactors will be located.

Experiments at the U. S. Atomic Energy Commission's National Reactor Testing Station, Idaho Falls, Idaho, and

*An excursion is a sudden, very rapid rise in the power level of a reactor.

by reactor manufacturers have demonstrated the safety characteristics and limitations of research reactor fuels.

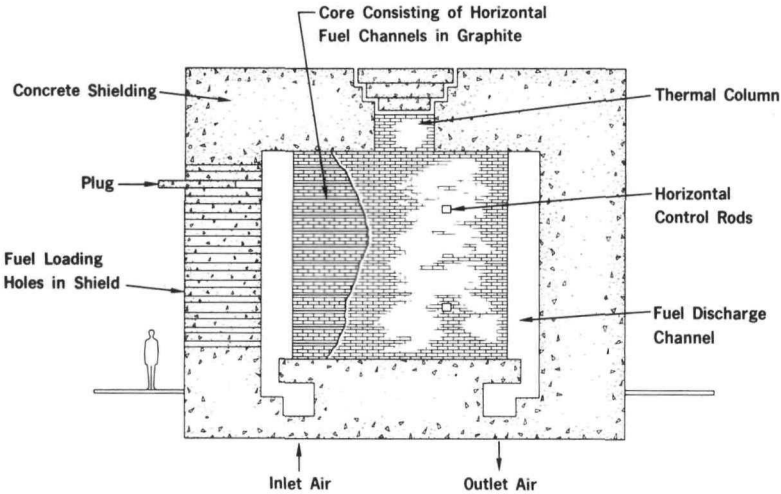
TYPES OF RESEARCH REACTORS

Reactors sometimes are classified as "heterogeneous" or "homogeneous". Most reactors are in the heterogeneous class; in these the fuel is separate from the moderator and is arranged in discrete bodies such as fuel elements. Homogeneous reactors are those in which the fuel is mixed with the moderator or coolant. Research reactors in this class include water boilers and TRIGA reactors, which are discussed later.

Several different research reactor designs have evolved from differing adaptations of fuel, moderator, coolant, and method of operation, and it is the design type which often is used to describe them.

Graphite Reactor

Named for its moderating material, the graphite reactor is the largest of all types. The very first chain reaction occurred in an assembly, or pile, of graphite blocks and uranium fuel. Several graphite reactors were built in the



Schematic diagram of graphite reactor.

United States some years ago, but at present no new graphite research reactors are being constructed or planned. The Oak Ridge National Laboratory Graphite Research Reactor now has been shut down after about twenty years of operation.

Graphite in a pure form absorbs very few neutrons but has properties that slow neutrons down. The combination of these characteristics makes graphite an excellent moderator. Moreover, with a graphite moderator, the core may

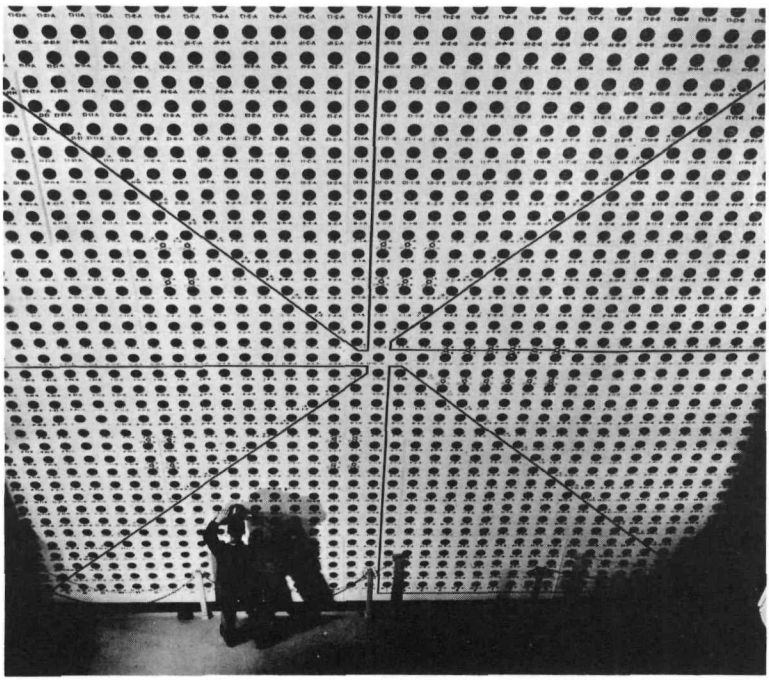


Figure 8 *The rows of holes in the south face of the Brookhaven Graphite Reactor are 8 inches apart and indicate the arrangement of the uranium metal in the graphite moderator. The holes can also be used to insert metals and other substances to be irradiated. The technician in the photograph is standing on an elevator that enables him to move to any level while charging holes. He is using a periscope to view the highly radioactive source materials while handling them by means of grappling tools and other remote equipment. A wall of heavy concrete 5 feet thick protects him from radiation.*

be very large. These factors make it possible to use "natural" uranium—a mixture of 99.3% uranium-238 and 0.7% uranium-235—as fuel, rather than the more expensive enriched uranium, in which the proportion of uranium-235 has been increased. In a graphite reactor the six basic parts described on page 3 have separate functions.

The Brookhaven National Laboratory Graphite Reactor at Upton, New York (Figure 8), has been operating almost continuously since 1950. It is the last research reactor of this kind operating in the United States. Fuel may be inserted into any of the 1368 holes in this reactor's 25-foot-square loading face. Or materials to be converted into radioactive isotopes may be inserted in some of the holes. Thirty beam tubes penetrate the shield and the graphite. Although the Brookhaven Graphite Reactor was designed to use natural uranium and although it operated with this fuel for several years, it has been modified and fueled with enriched uranium. With this fuel a higher flux (6×10^{12} nv) was obtained at the same power level (30 thermal megawatts). This heat is removed by blowing 1.8 million pounds of air per hour through the core and is discharged into the atmosphere.

In some graphite reactors, small animals may be irradiated for experimental purposes.

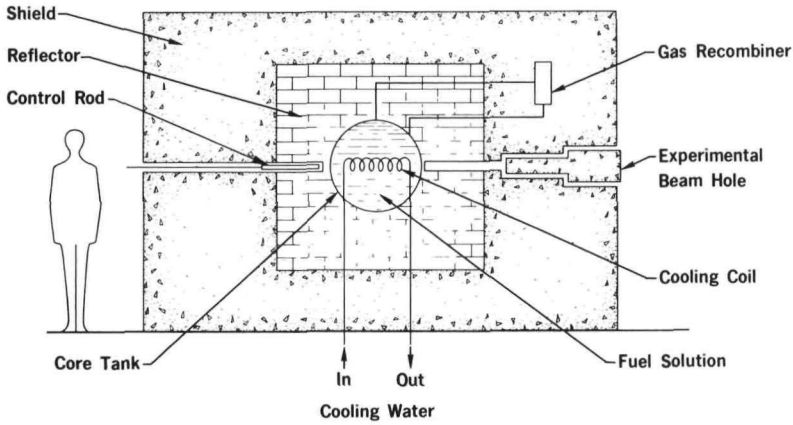
Water-Boiler Reactor

A "water-boiler" reactor does not really boil water. Rather, the fuel is a uranium salt dissolved in water, and gases given off when the reactor is operating cause bubbles so that the solution appears to be boiling.

The water boiler is perhaps the simplest of all reactor types. It consists essentially of a stainless-steel sphere with a coil of tubing inside. There are several openings into the sphere. One allows the solution to enter the shell, another permits a control rod to be inserted to regulate the rate of reaction, and a third carries away gases that are formed.

The sphere (Figure 9) is always set in the center of a "reflector", usually of graphite, although beryllium or beryllium oxide may be used. The arrangement of parts

allows neutrons to stream to experimental equipment outside the sphere.



Schematic diagram of water boiler reactor.

Figure 9 *Fuel is in a water solution in the core of this water-boiler reactor used for research and training at the Enrico Fermi Study Center in Milan, Italy. Upside down for easier assembly, the core is circled by precision-milled graphite blocks.*

When the reactor is not operating, the fuel solution (usually uranium sulfate) is stored in pipes that are separated in such a manner that a chain reaction cannot take place. To start the reactor, the solution is pumped into the shell, and a control rod is withdrawn to regulate the rate of reaction. A stream of cold water passes through the coil inside the shell to remove heat.

Although a water boiler is simple, the need for shielding is as great as in any reactor of equal power. Although the power is generally limited to about 50 thermal kilowatts, a water boiler has certain advantages: There are no fuel-fabricating costs because the fuel is simply dissolved and put into the reactor in solution form; if additional fuel is needed, it may be added easily. One disadvantage is the possibility of fuel leakage and contamination.

A water boiler at the Armour Research Institute in Chicago has five beam tubes, two through tubes, four vertical tubes, one thermal column, one gamma-irradiation facility, and one reentrant tube. The reentrant tube passes directly through the center of the core and is used to irradiate materials requiring the highest flux and to study the effect of various materials on the chain reaction.

The first university research reactor, at North Carolina State College, Raleigh, was a water boiler.

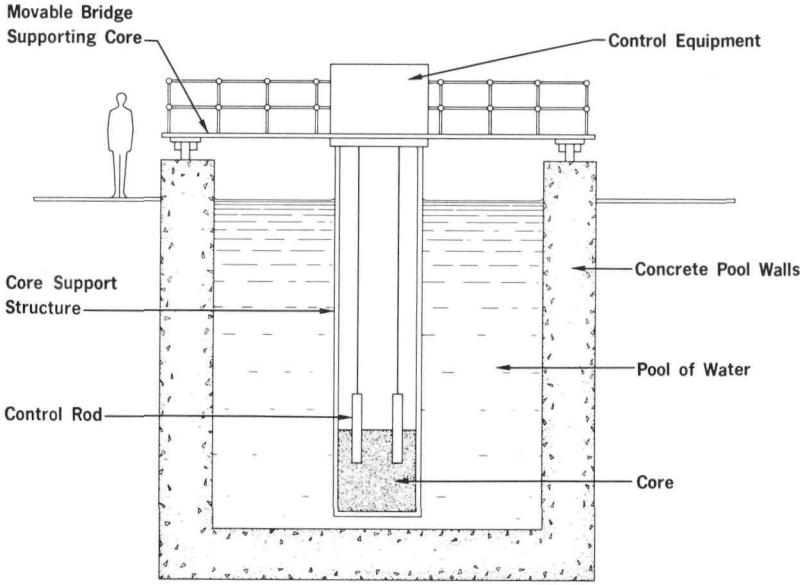
Pool Reactor

The pool reactor is one of the most widely used and versatile types. The first university pool reactor was installed at Pennsylvania State University, University Park, in 1955, and many other universities have built them since or are now constructing them.

This reactor is built in a large pool which resembles a regular swimming pool but which is at least 18 feet deep and has no shallow end. This depth is necessary to provide sufficient shielding for the core.

Water in the pool acts as coolant, reflector, and shield. Many pool reactors utilize the water as moderator also; in one series, however, uranium–zirconium–hydride (U–Zr–H) is used as a fuel, which provides a significant fraction of the moderation, along with the water.

The core of the reactor is suspended from a bridge across the pool. The bridge is on wheels so that it may move along the pool sides; the framework holding the core may move laterally on the bridge. This combination of movements permits the core to be placed in any part of the pool, one of the principal advantages of a pool reactor.



Schematic diagram of pool reactor.

An experiment may be receiving radiation from the core in one area of the pool while the work of setting up, taking down, or modifying another experiment proceeds at another point.

In many pools one end is shaped so that beam tubes and thermal columns can be installed to conduct neutrons from the core to experimental facilities. Some pool walls have beam holes or thermal columns at several locations. One of the latest designs provides them at both ends, as well as allowing experimental devices to be placed in the water itself. This arrangement is shown in Figure 10.

Two basic types of fuel are used in pool reactors. The first, a highly enriched uranium-plate fuel, often called

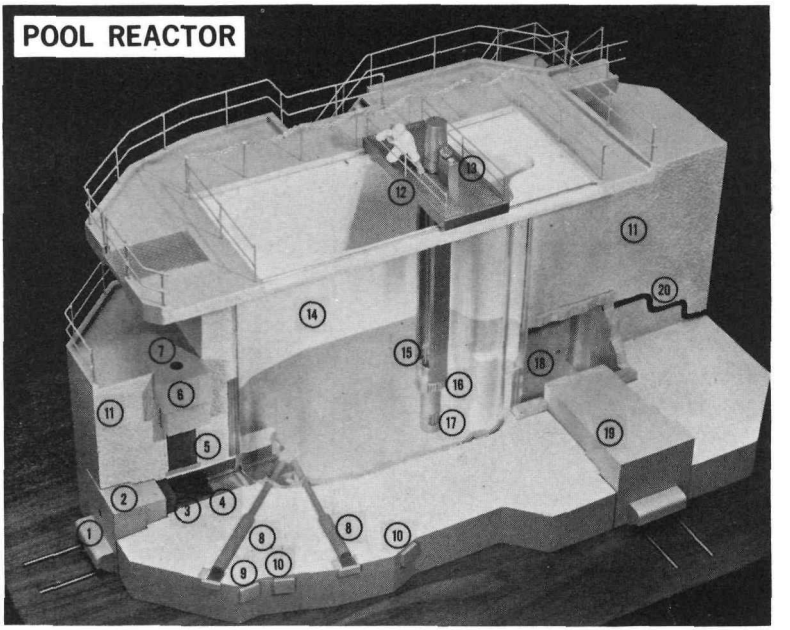


Figure 10

1. *Stringer Access Port*
2. *Thermal-Column Shield Door*
3. *Hohlraum*
4. *Horizontal Thermal Column*
5. *Vertical Thermal Column*
6. *Vertical-Thermal-Column Shield Plug*
7. *Vertical Access Port*
8. *Radial Beam Ports*
9. *Thermal-Column Access Port*
10. *Intersecting Through Ports*
11. *Concrete Shielding*
12. *Movable Bridge*
13. *Control-Rod Drives*
14. *Reactor Pool*
15. *Pneumatic Transfer System (Rabbit)*
16. *Isotope-Production Facility (Lazy Susan)*
17. *Reactor Core*
18. *Exposure Room*
19. *Exposure-Room Shield Door*
20. *Experimental Access Conduits*

MTR* fuel, consists of sheets of uranium alloyed with aluminum. A cladding of pure aluminum is bonded to the alloy. Several of these plates are arranged in a frame to form an element, usually 3 inches square and 24 inches long. Each element contains between 140 and 190 grams of uranium. From 20 to 25 elements are used in the core,

*For the Materials Testing Reactor at the AEC National Reactor Testing Station, for which this type was developed.

depending upon their arrangement and upon the experiment in progress.

Other pool reactors utilize rod-shaped elements, usually called TRIGA elements, of enriched uranium alloyed with zirconium hydride. A cladding of stainless steel surrounds the fuel material. Each element is about 1.5 inches in diameter and 28 inches long and contains approximately 39 grams of uranium-235. Approximately 65 to 85 elements are used in the core.

The mechanisms for controlling the reaction are located on the bridge, with extension rods reaching down into the core.

The power level of the early plate-fueled reactors was only 1 or 2 thermal megawatts. It was limited by (1) the

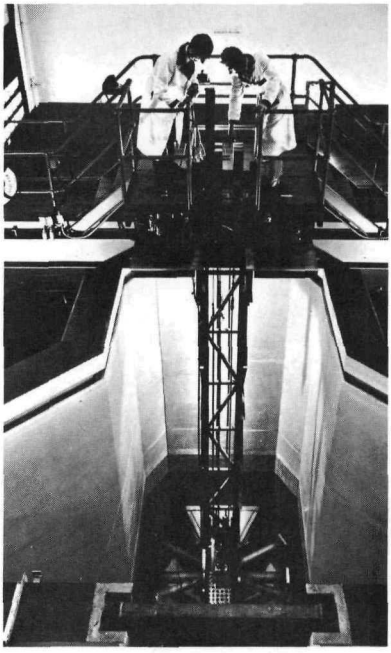


Figure 11 *A pool reactor has been operating at the Battelle Memorial Institute, West Jefferson, Ohio, since 1957. In 1959 the power level was raised from 1 to 2 megawatts.*

radioactivity created in the pool water by neutrons from the fissioning fuel interacting with oxygen in the water to produce nitrogen-16 (half-life 7.35 seconds), and (2) the rate at which heat from the fissioning fuel could be removed from the water by natural convection currents. It was

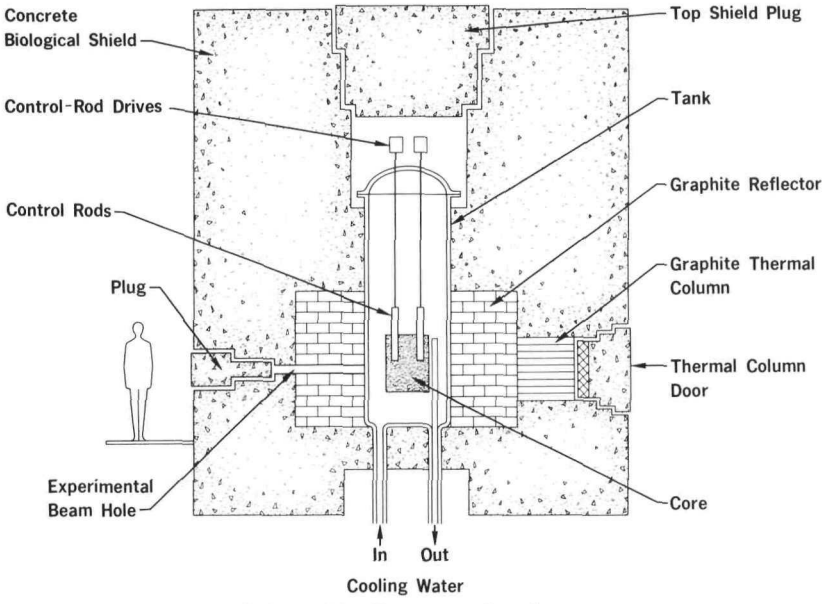
originally felt that the power of pool reactors could not be increased materially because water containing the radioactive nitrogen would make approach to the surface of the pool potentially hazardous to reactor personnel, if the nitrogen accumulated faster than it decayed. And, of course, the higher the power, the more heat and the more nitrogen-16 resulted.

This problem of limited power was solved ingeniously by the use of pumps or water fans to keep the water containing nitrogen-16 deep in the pool until its radioactivity had died out. This process leaves a blanket of nonradioactive water on top, which effectively shields workers. Moreover, a high-capacity pumping system that forces water through the core is used in plate-fueled reactors that produce 1 thermal megawatt of power or more. A large "holdup" tank is used to retain the water (containing nitrogen-16) pumped from the core until the radioactivity has decayed. In some pool reactors the core is enclosed in an inner container, or plenum, and cooling water is circulated in this and then out to heat exchangers.

Some pool reactors may be modified so that they can be used in what is known as a "pulsing" operation (see section on pulsed reactors, page 28). In a pulsed reactor the power quickly rises to a high level and then quickly drops. The latest pool reactors are capable of operating at steady power levels of 10 megawatts and steady fluxes of 5×10^{13} nv, with higher power and flux levels in a pulsing operation.

Tank Reactor

A tank reactor is similar in many ways to the pool type. There are two basic versions. The first might be termed the "open-tank reactor", and it has a power level up to about 5 megawatts. The second might be called the "top-shielded tank reactor", and it has power capabilities up to very high levels. The tank in a tank reactor is as deep as the pool in a pool reactor but is smaller, and the core remains in one location. Indeed, a tank reactor might be considered a vertical, cylindrical pool reactor with a diameter just large enough to enclose the core. This arrangement of a fixed core provides more beam tubes, which can lead in all directions from the core. Access to



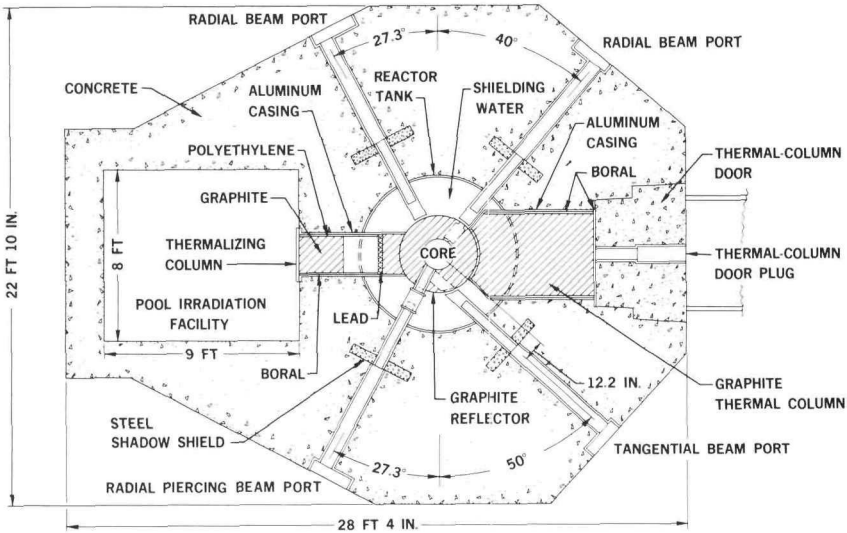
Schematic diagram of tank reactor.

the core from above is still possible. One of the advantages of the tank is that experimental apparatus may be installed and left inside the core or very near it, since the core does not move.

Open-tank research reactors are located at many universities. Some are capable of both steady-state and pulsing operation (Figure 12).

One of the most powerful U. S. research reactors is a top-shielded tank reactor, the AEC's Materials Testing Reactor (MTR). This reactor (Figure 13) is located in a tank 30 feet deep and 6 feet in diameter. When it is operating, a steel lid is placed over its top. The MTR has 17 beam tubes and 1 horizontal thermal column. In addition, there are many vertical holes accessible from the top of the reactor and available for experimental use. The MTR operates at a power of 40 megawatts and has a flux of 3×10^{14} nv.

Sealed-tank reactors like the MTR make possible very rapid circulation of cooling water under high pressure; hence a high power level can be achieved in a small core. This is not possible in any other type.



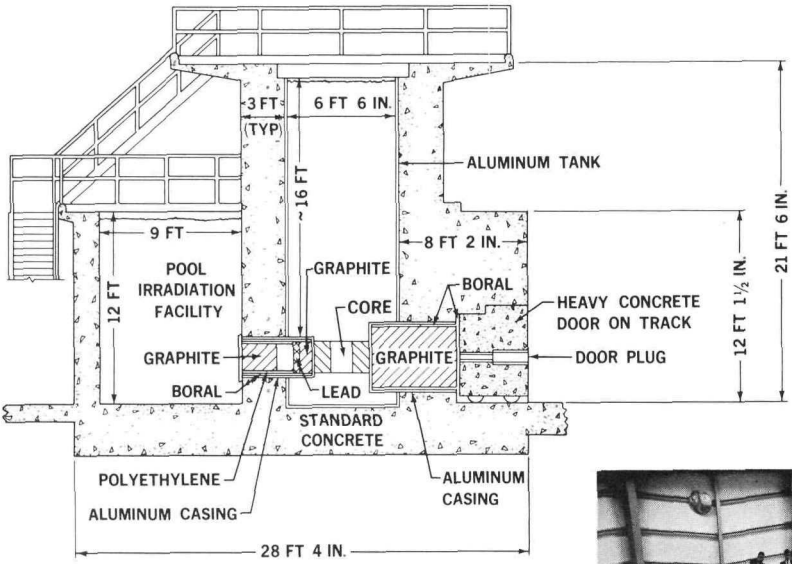


Figure 12 *Open-tank reactor at Kansas State University, which has dual capability for steady and pulsing operation. Experimental equipment is labeled in the horizontal (above) and vertical (below) section views. A large mosaic portraying the tremendous scope of atomic energy for peaceful purposes is mounted on the concrete shield.*

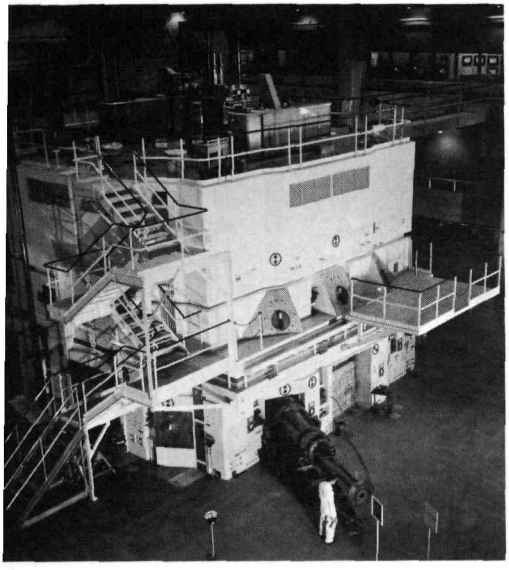


Figure 13 *The Materials Testing Reactor at the AEC's National Reactor Testing Station in Idaho, has played an important role in the development of materials for reactor construction. The "coffin" for loading and unloading materials under test is pushed against the beam hole in the foreground.*

Top-shielded reactors may be built in much shallower tanks provided with lids and sufficient concrete for shielding above the core. This eliminates easy access to the core but makes the installation more compact.

Heavy-Water Reactor

Deuterium is an isotope of hydrogen which weighs almost twice as much as ordinary hydrogen. When combined with oxygen, deuterium forms heavy water (D_2O). Although deuterium has the same chemical properties as ordinary hydrogen, its nuclear properties are considerably different. Heavy water absorbs neutrons much less readily than ordinary water does. To put it another way, neutrons can travel much farther in heavy water; therefore a reactor core using heavy water as a moderator can be spread over a larger volume. This provides room for more beam tubes and additional irradiation space. In addition, since fewer neutrons are absorbed in the core, greater numbers are available for experiments.

Heavy-water reactors are invariably the top-shielded (closed-tank) type. Heavy water is expensive (about $28 a pound) and this more compact reactor system requires a

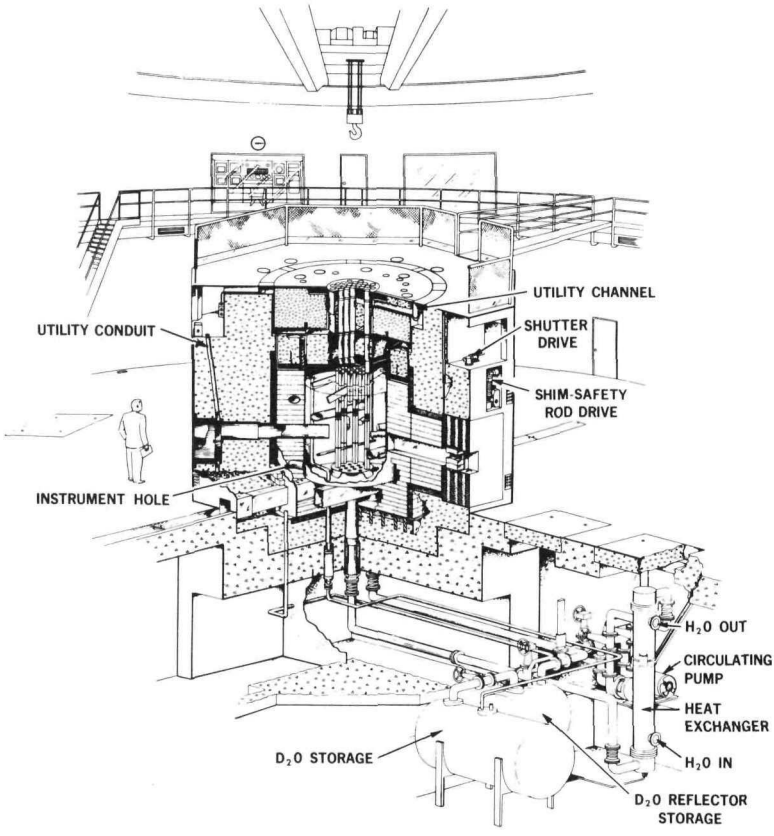


Figure 14 *The tank containing the core can be seen in the center of the shielding in this cutaway drawing of the CP-5 reactor at Argonne National Laboratory. Beam tubes and a thermal column extend into the tank. (Also see cover.)*

smaller amount. Also, some of the deuterium captures reactor neutrons and is converted to tritium, an even heavier, radioactive isotope of hydrogen. If the D_2O were not in a closed system, some would evaporate into the air, contaminating it with radioactivity from the tritium. Moreover, water vapor in the atmosphere would condense into the heavy water, decreasing its isotopic purity.

In most heavy-water research reactors, enriched uranium is used as a fuel. This, in combination with the

heavy-water moderator, gives the highest neutron flux in relation to the power level.

Possibly the best-known heavy-water reactor is the CP-5,* built at the Argonne National Laboratory. This reactor operates at a power level of 5 megawatts and has a flux of 10^{14} nv. It has a total of 18 horizontal beam tubes, through tubes, and thermal columns and contains over 50 vertical access holes in which to install equipment and samples. A feature of the CP-5 is fuel shaped in the form of hollow tubes. This allows experimental material to be placed inside a fuel element for irradiation from all sides.

Pulsed Reactor

One of the most important recent developments in reactor design makes use of "pulsing". A pulsed reactor is one in which the power quickly rises to a very high level and then quickly drops. The burst of power takes only a fraction of a second and at its maximum may reach a level above 1000 to 5000 thermal megawatts. This may be compared with the average operating power of 250 kilowatts to 5 megawatts in nonpulsing research reactors (see Figure 15).

The power that a reactor is producing at any instant is directly proportional to the number of neutrons present in the core. This number may increase by a factor of over 10,000 in a second. The pulsed, or transient, reactors are built so that this may occur.

Pulsing is useful because it provides a "neutronic-shutter" action for precise control and reproducibility of radiation-dose conditions. It is of interest to note that a single pulse will instantly create up to 35 times more short-lived radioisotopes (half-lives less than 30 seconds) than continuous irradiation to saturation at normal power.

The first pulsed reactors were used experimentally to determine the effect of rapid power changes on reactor design. The experiments were valuable in assuring reactor safety, and the information gained was then used to produce

*CP-5 stands for Chicago Pile No. 5, the fifth reactor built at the Argonne National Laboratory in Argonne, Illinois. It is also known as the Argonne Research Reactor.

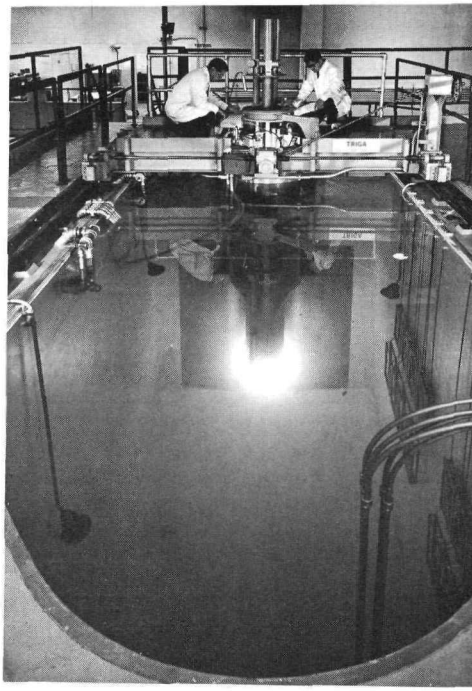
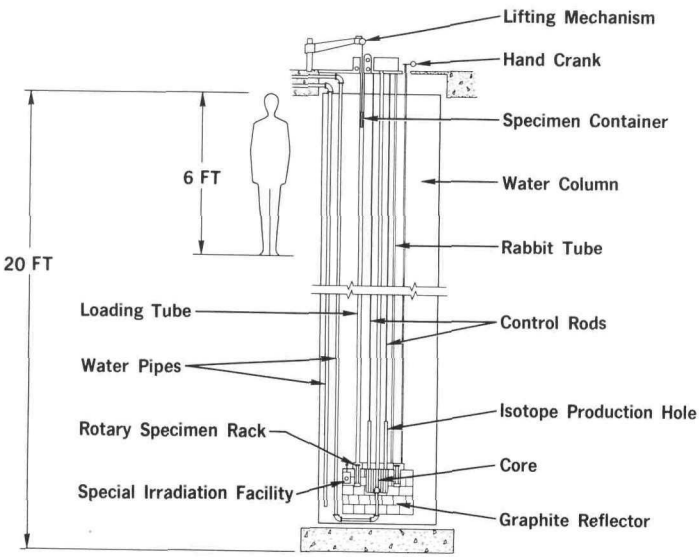


Figure 15 *An intense, short pulse of radiation shows as a bright blue flash at the core of this reactor, designed to deliver reproducible pulses of neutron and gamma rays for nuclear effects research and testing.*



Schematic diagram of pulsing reactor.

a new type of research reactor. In recent years research with reactor pulses has greatly expanded.

Some research reactors can have both routine pulse operation and steady operation. One family, the TRIGA series, uses enriched uranium evenly distributed with zirconium hydride (U–Zr–H), in the form of a metallic alloy, as fuel. In this solid material the hydrogen atoms in the zirconium hydride serve to a considerable extent as a neutron moderator, augmenting the moderating effect of the water in the pool. Because there is such intimate association of fuel and moderator in the alloy, when a power pulse occurs the heat that results remains within the fuel–moderator and raises its temperature; the moderator, in other words, is heated as rapidly as the fuel. This provides a self-regulating action that shuts off the pulse almost as soon as it starts. It works this way:

The function of a moderator in a reactor, you recall, is to slow the fast neutrons released from the fissioning fuel to a pace at which they will be more likely to produce new fission and keep the chain reaction going. This velocity is not a specific rate, however, but increases with the temperature of the fuel; a slow neutron that will cause new fission is also known as a thermal neutron because its speed is in equilibrium with the thermal, or kinetic, energy of the molecules of the moderator.

But in the U–Zr–H reactor the hydride moderator temperature rises exactly as fast as that of the fuel; so an increase of the fuel temperature during a power burst immediately brings an increase in the average energy of the molecules of the moderator, which is then greater than that of the ejected neutrons. Therefore, although the increased power results in emission of many more neutrons from the fuel, they are not slowed by the moderator to thermal energies, and thus there actually are fewer neutrons that will produce new fission. The pulse of power, instead of building up to higher and higher levels, accordingly shuts down instantly. (This type of reactor, as well as many others, is said to have a prompt negative-temperature coefficient, which means it is inherently safe, and accidental "runaway" power excursions will not occur.)

In addition, when the temperature rises in the U–Zr–H, the temperature of the water surrounding the core also rises, and the water expands. Some of it is forced farther away from the fuel, and fewer water atoms are left to help slow the neutrons. Also, since each atom of the water moderator has more energy at its high temperature, it can remove less energy from a neutron that strikes it. These two effects combine to cause the water moderator also to be less effective in slowing the neutrons.

Finally, in a U–Zr–H fuel element, about 80% of the uranium is uranium-238, which is nonfissionable and which has, as one of its intrinsic properties, the ability to absorb neutrons of many different speeds without a nuclear fission occurring; there are eight peak levels of neutron energy where this absorption probability is high in uranium-238. As the temperature of uranium-238 rises, these peaks broaden out, and the neutron absorption is increased.

All these responses stop the rise in power almost immediately when a pulse occurs, and the power levels out, without subsequent pulses, at a steady rate of several hundred thermal kilowatts. The fuel elements have a high heat capacity and transfer the pulse energy (heat) to the cooling water slowly enough that there is no sudden release of steam. A few minutes later the reactor can be pulsed again—about ten times an hour if desired.

Another pulsing design has been developed recently. The first reactor incorporating this design is at the Western New York Nuclear Research Center on the campus of the State University of New York at Buffalo. In this system, called PULSTAR,* low-enrichment uranium oxide (UO_2) fuel pins are used in a typical pool reactor. The proportion of uranium-238 is 94% of the total uranium; and, as the oxide fuel heats during a power pulse, more neutrons are lost by nonfission absorption so that the power level drops rapidly due to the same broadening of the absorption peaks that occurs in the U–Zr–H fuel we have just discussed.

This effect is enhanced, in the uranium-oxide reactor, by maintaining an exact relation between the amount of

*A trade name of AMF Atomics Division of American Machine and Foundry Corporation.

water moderator in the pool and the amount of UO_2 in the core. The high heat capacity of UO_2 makes the operation safe by permitting energy releases for a brief period without an excessive rise in the core temperature. Heat is transferred slowly to the pool, preventing explosive formation of steam. A series of AEC tests in 1963 on UO_2 cores at the National Reactor Testing Station, in which deliberate attempts were made to cause damage by sudden increases of power, preceded the installation of the Buffalo reactor.

Some steady-power pool reactors may be modified in the next few years to permit pulsed operation. This can be done by converting the fuel system from uranium–aluminum plates to U–Zr–H or UO_2 systems.

Another recently developed research-reactor design, the Pressure-Tube Reactor (PTR), also can be utilized in pools for more versatile operation and higher steady power. Conversion of a pool reactor with the PTR principle can raise the power substantially. In this design a pressure tube is placed around each fuel element, so that the element can be operated at a high temperature (because of increased pressure) without boiling the surrounding coolant water. The PTR also allows power levels to 25 and 40 thermal megawatts. The principle can be used in new reactors as well as in conversions.

High-Flux Reactor

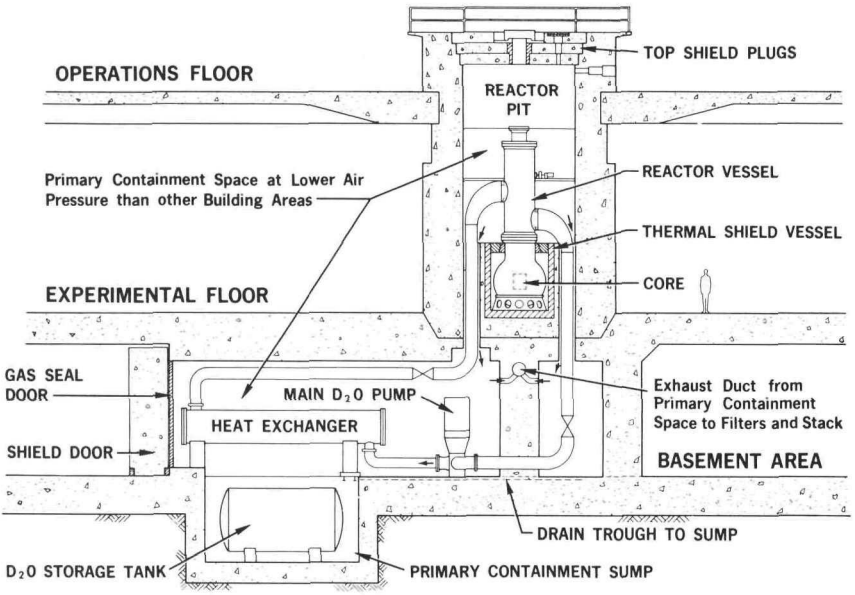
Reactor design has progressed to the point at which engineers can now design and build high-flux reactors with a maximum flux above 10^{15} nv. Three such reactors are now being planned or built, at Brookhaven, Oak Ridge, and Argonne National Laboratories.

The Oak Ridge High Flux Isotope Reactor (HFIR) is designed to produce radioisotopes. It is valuable in creating isotopes with higher atomic numbers than plutonium—the transplutonium elements such as curium, berkelium, californium, einsteinium, and fermium.*

The Brookhaven High Flux Beam Reactor (HFBR) at Upton, New York (see Figure 16), is designed to have a

*For more information about these elements, see *Synthetic Transuranium Elements*, a companion booklet in this series.

neutron flux about eight times that of the Materials Testing Reactor, which operates at the same power. Many beam tubes are located and oriented to give fluxes for experiments requiring particularly intense neutron beams.



HIGH FLUX BEAM REACTOR

Figure 16 *Vertical section drawing through the core of the High Flux Beam Reactor shows the arrangement of the three floor levels and the shielding and containment arrangements.*

The Argonne Advanced Research Reactor is designed for a power level of 240 megawatts with a maximum flux of 10^{16} nv. For the reactor to produce this power, the coolant, ordinary water, must be pressurized to prevent its boiling. There will not be enough water in the core to slow the neutrons completely; so they will have energies intermediate between the slowest (or thermal) neutrons and fast neutrons. The reactor has a beryllium reflector, in which the neutrons will be slow, or have thermal energy. This reactor also has an internal "flux trap" (described in the next section).

Special Reactors

Many research reactors are designed with features for particular purposes.

One feature is the "flux trap", an arrangement in which the neutron intensity in one portion of the reactor may be increased several times above the average of the whole reactor. The usual method of achieving this rather neat trick is to put an island of a good moderator in the center of the core. The island contains no fuel. Since there is almost no absorption of neutrons in this region, the thermal flux is very high, even higher than that in the surrounding core region. Flux traps now are used in several research reactors, one of which is the Juggernaut Reactor at Argonne National Laboratory.

It is possible to build reactors without moderators, although they require highly enriched uranium (containing a great deal more uranium-235 than does a moderated reactor). These reactors are called "fast reactors" since most of the fissioning is caused by fast neutrons—neutrons not slowed down appreciably after ejection at their very high speeds from a fissioning atom. Fast reactors are used in research requiring fast neutrons, including simulation of weapons effects and instrument testing.

Still another special purpose reactor is the Advanced Test Reactor (ATR) being built at the National Reactor Testing Station. The ATR will be used for irradiation testing of materials, fuels, and coolants for military and civilian reactors. The design of the ATR is unique: The equivalent of a group of nine flux-trap reactors will be placed side by side. A high-leakage core, the flux traps, and a favorable geometrical placement of fuel are expected to provide a highly effective arrangement for the nine engineering test loops which are to be included.

HOW EXPERIMENTERS USE RESEARCH REACTORS

For investigations of the phenomena of nuclear physics, a research or test reactor has no substitute. Physicists observe interactions of nuclear radiation with matter by measuring radiation effects and thermal-neutron scattering.

They study the structure of the nuclei of atoms with neutrons produced in research reactors, and they investigate the neutron itself. A free neutron is radioactive and decays as any other radioactive particle does. Moreover, it possesses a magnetic moment; that is, it behaves in many ways like a tiny magnet. These properties all can be observed, and, since neutrons are integral parts of the nuclei of all atoms except hydrogen, knowledge of these particles contributes to the understanding of the structure of atoms.

One special kind of study possible with research reactors involves "time-of-flight" measurements.

Time-of-Flight Measurements

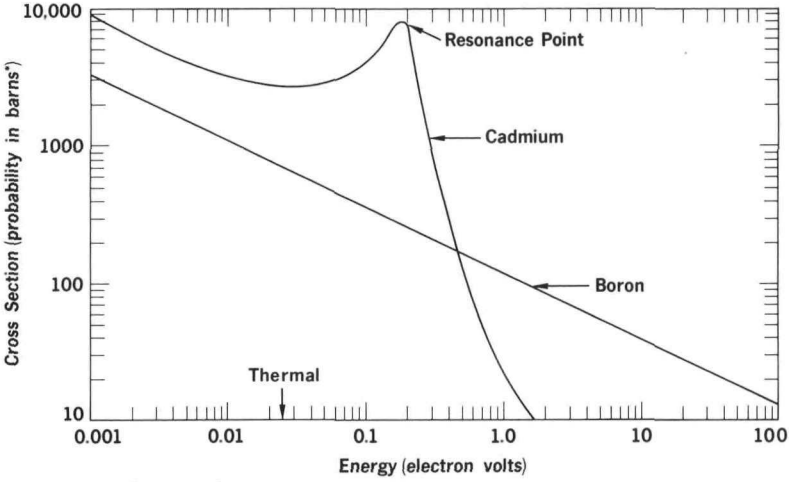
Physicists measure the ability of certain materials to absorb or to scatter neutrons with the time-of-flight technique. A device called a "fast chopper" is used; it breaks a stream of neutrons into short pulses, which are timed as they travel through a long tube. A fast-spinning shutter allows a burst of neutrons to emerge during the open portion of each rotation—about 400 times each second. Each burst, lasting about one-millionth of a second, contains neutrons of all speeds. They travel along a tube 100 yards long and strike an electronic detector, which signals as each neutron arrives. By measuring the velocity of neutrons over this distance, physicists can calculate their energy and plot it on a graph showing the number of neutrons in relation to their energy. This is called an "energy spectrum", or an "energy distribution".

A thin sheet of some appropriate material is then placed across the neutron beam, and the energy distribution is again plotted. By comparing this graph with the original distribution, scientists may learn how effective the sample material is in removing neutrons from the beam. This effectiveness is referred to as the "cross section", a term which denotes the probability that a neutron of a certain energy will be absorbed or scattered by an atom of the sample.

The cross section of some materials varies drastically with neutron energy. The graph of the cross section in these cases shows very high peaks at energies where the sample absorbs very strongly. These peaks are called "resonances".

The cross section of other materials, on the other hand, may vary little as energy changes.

The cross sections of two elements, cadmium and boron, are shown in Figure 17. The boron cross section decreases steadily as the neutron energy becomes higher. Cadmium,



*A barn is the unit of cross section.

CROSS SECTIONS OF CADMIUM AND BORON

Figure 17 *Cross sections of the elements cadmium and boron represented by curves obtained with "neutron choppers".*

however, has a high resonance, but its cross section decreases sharply at energies above that point. At a number of research laboratories, a program of measuring the cross sections of all available isotopes of all the different elements is being carried out.

Research reactors also are useful in probing other horizons—in chemistry, in biology and medicine, in food technology, and in agriculture—horizons that might not be explored otherwise. A few of these are noted here.

Chemistry

The techniques of using radiation and radioisotopes have been applied by research specialists with considerable suc-

cess in radiochemistry, radiation chemistry, and direct syntheses.

Perhaps the most spectacular method in radiochemistry is a new technique called "activation analysis". The substance to be analyzed is exposed to a neutron flux, often in a research reactor. Some of its atoms are changed into radioactive isotopes, each decaying with its characteristic half-life and giving off its own pattern of gamma- and beta-ray energies. By studying these patterns, scientists can detect and identify extremely minute quantities—as little as 1 part per billion—of some substances in compounds or mixtures.*

Biology and Medicine

Quantities of many radioisotopes produced in reactors are being employed as tracers and as radiation sources in diagnostic, therapeutic, and basic-science applications.

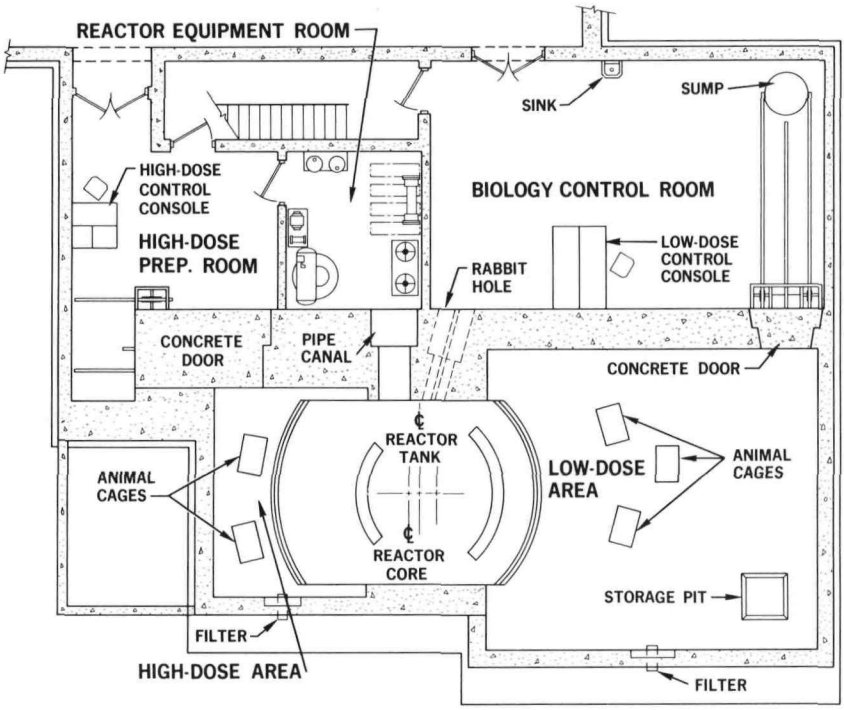
Many types of plants and animals are exposed to neutrons to permit the study of the effects of radiation on living organisms and the relations between radiation exposure, aging, and life-span. The effect of neutron exposure on particular tissues is studied selectively; that is, by the shielding of all other parts of the body, one organ is isolated for investigation.

Activation analysis also is being used in biological and medical investigations.

At Argonne National Laboratory a new reactor called "Janus" will be used to evaluate the effects of both acute and chronic exposure to radiation from neutrons. Janus (Figure 18), named for the two-faced Roman god, is designed with two irradiation portals, which permit studies of effects at different levels of radiation. Radiation that might be encountered by personnel who work with nuclear reactors is the particular concern of this research.

Specialized reactor facilities serve medical scientists. Those located at the Massachusetts Institute of Technology (Figure 19) and at Brookhaven National Laboratory (Figure 20) are pioneer installations of this kind. Reactor facilities have been added more recently to the Walter Reed

*For more information about this method, see *Neutron Activation Analysis*, a companion booklet in this series.



JANUS REACTOR

Figure 18 *Janus is a new biological irradiation reactor at Argonne National Laboratory. Many specimens can be handled quickly in the large cells for high and low radiation doses. Note the reactor "faces" in two directions.*

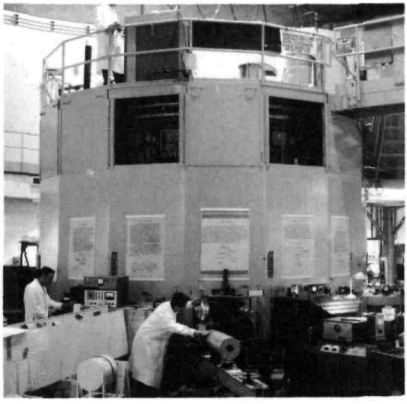
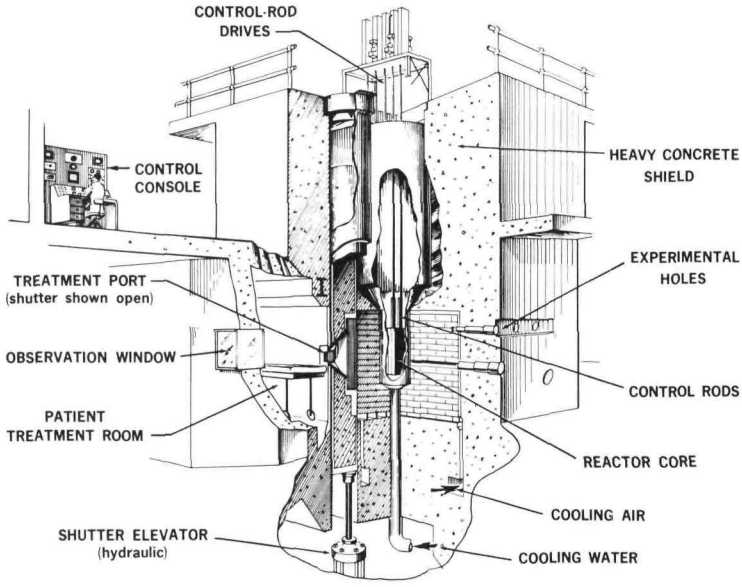


Figure 19 *The Massachusetts Institute of Technology Reactor is shown with several biological experiments set up outside beam holes in the shield.*



MEDICAL RESEARCH REACTOR

Figure 20 *This Medical Research Reactor at Brookhaven National Laboratory, shown by cutaway drawing, provides external neutron beams and is used in clinical research. Tumor areas in patients can be irradiated selectively.*

Army Institute for Research and the Armed Forces Radiobiology Research Institute, both in Bethesda, Maryland, and to other research centers.

Food and Agricultural Research

Research reactors, used as sources of thermal neutrons or adapted for use as sources of fast neutrons or gamma rays, are employed to produce experimental mutations and to determine biological effects per unit dose of radiation.*

Scientists use radioisotopes of relatively short half-life to study the role of elements required for plant growth and to perform other botanical and agricultural experiments. These usually are obtained from nearby reactors so they will not decay before they can be used.

*For more information on this research topic, see *Atoms in Agriculture*, a companion booklet in this series.

Irradiation as a means of preserving food products—especially fish, fruit, and grain—is a prospect of great importance.* In many studies the radiation source is an isotope (such as cobalt-60) produced in a research reactor, but gamma radiation from spent reactor-fuel elements also has been used in the past to irradiate many tons of food for food-preservation research.

Radiation is used successfully to destroy some insects. In the southeastern states a very troublesome cattle pest called the screwworm fly has been eliminated. In Puerto Rico work is under way to eradicate the corn borer; in Greece the olive fly has been a prime target. By this method male insects are made sterile by gamma rays from radioactive sources prepared in reactors. The males are released to mate with wild female pests, which then lay eggs that do not hatch. The pest population is greatly reduced in succeeding generations and finally disappears.

TRAINING FOR REACTOR RESEARCH

The impact of reactor research on scientific and industrial experimentation is becoming so broad that it is apparent many more persons will need to know about reactor operation. Reactor operators are needed. Specialized nuclear engineers and reactor engineers are required for supervisory positions. Engineers or scientists with specialized education in a traditional discipline (electrical, mechanical, or chemical engineering or physics, for example) plus additional basic training in nuclear science and reactor theory are also especially valuable to the nuclear industry.

A research reactor can be a focal point of university training in reactor utilization as well as reactor operation. Perhaps more appropriate and certainly more practical, from the viewpoint of student operation, is the effective use on many campuses of "teaching" reactors. These are considerably easier and less expensive to operate than the higher-powered, specialized reactor facilities we have

*For more information on this subject, see *Food Preservation by Irradiation*, a companion booklet in this series.

discussed previously. A "subcritical assembly" is another device that serves useful training purposes; this is a reactor without enough fuel to sustain a chain reaction. Reactor simulators also can be used effectively.

Universities often design laboratory courses to include both classical experiments in nuclear physics and modern radiation-detection techniques. A typical nuclear-engineering program at a university may include these experiments: use of single-channel and multichannel analyzers, neutron generators, counters, recorders, and computers; study of beta- and gamma-ray spectra; determination of half-lives of short-lived isotopes; and measurement of reactor characteristics. The Atomic Energy Commission and the National Science Foundation often provide assistance to universities for this kind of training.

Many students who complete such an undergraduate program decide to pursue graduate work in nuclear subjects, some with the aid of fellowships. Hundreds of students from countries all over the world have received reactor training at the Oak Ridge School of Reactor Technology (ORSORT) and at the Institute of Nuclear Science and Engineering at Argonne National Laboratory (Figure 21).

At ORSORT, where nearly 900 scientists and engineers have been trained since 1950, students are offered 12-month

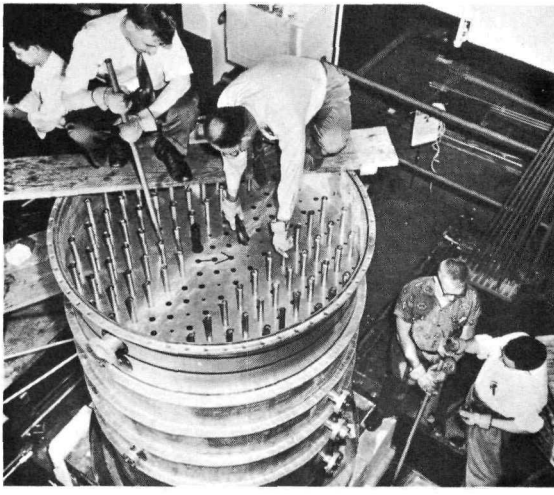


Figure 21 *Students from many foreign nations have gained experience operating research reactors at the Institute of Nuclear Science and Engineering located at Argonne National Laboratory. These students, placing uranium rods in aluminum tubes and then inserting the aluminum tubes in the reactor, are from Switzerland, the Philippines, Australia, Belgium, the United States, and Japan.*

courses in reactor-operations supervision and reactor-hazards evaluation. Three research reactors are available.

Not all who operate or otherwise contribute to the use of research reactors are graduate engineers or scientists with advanced degrees; many other kinds of skilled specialists also are required. In many cases the most attentive operators are men and women with high school educations and on-the-job training for specific work on reactors. Persons with particular skill and experience in electronics and mechanics are needed to maintain supporting equipment for a reactor installation.

THE FUTURE OF RESEARCH REACTORS

As productive as research reactors already are, there is wide interest in utilizing these unique and expensive tools even more effectively. Much effort has gone into improving the design of new reactors and modifying older ones for greater usefulness.

A trend at large research establishments is toward use of higher power and higher flux levels (and generally more expensive installations as a result). The versatility of any reactor increases as its flux intensity increases. So does the range of experiments that can be performed—and the crossing of each threshold opens up fresh possibilities. However, many experts believe that a great deal of important research can and should be done on existing reactors.

For universities and industrial firms where initial cost and yearly operating costs are important, the tendency is to begin with a modest, lower-power reactor. As needs require and funds allow, the power can be increased and additional facilities can be added. By clever design, experimenters using such equipment have achieved neutron-flux levels approximating those in higher-power reactors and have developed sophisticated experiments usually possible only in large, expensive reactors.

Those who have worked with reactor facilities for some time say there are still numerous unmet scientific needs. Use of research reactors, after all, has been going on for only a few years. For example, researchers say there is

particular urgency to achieve standardization and unification of methods of measuring neutron spectra, fluxes, and doses, as well as gamma-radiation fluxes and doses, in order to interpret irradiation experiments properly.

Research reactors all too often still are strange and unfamiliar to many experimenters, leaving considerable potential to be exploited in the future. The promise for these tools seems great. Already, achievements with reactor-initiated research far exceed anything imagined by the men who put the earliest ones to work only 20 years ago.

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