1.8 Nuclear Reactors

The qualitative discussion of nuclear physics presented in this chapter by no means covers the field in the depth needed to prepare libraries of cross sections for reactor-design purposes. On the other hand it should provide a sufficient familiarity with the basic definitions and concepts to serve as a starting point for the development of the field of reactor physics.

Before beginning this study, however, it may be helpful to discuss its final goal—reactors—in a qualitative fashion. We shall do this by first introducing some general terms and then describing various types of reactors from several different viewpoints.

General Considerations and Definitions

A reactor is an assembly of fissile material and other material (described below), put together in such a geometrical configuration and in such concentrations that a sustained neutron chain reaction can take place. A "sustained neutron chain reaction" is one in which the total number of free neutrons created per second by the fission process throughout the reactor exactly equals the total number of neutrons lost per second by absorption and by leakage out of the reactor. A reactor in this condition is said to be *critical*. A reactor in which the number of neutrons created per second exceeds those lost is said to be *supercritical*. One in which the number of neutrons lost per second exceeds those created is said to be *subcritical*.

Almost all reactors consist of a fuel-bearing region called the *core* and a surrounding non-fuel-bearing region called the *reflector*. In certain types of reactors there is also a region containing fertile material, called the *blanket* and usually located between the core and the reflector. (As such a reactor operates, neutrons will be absorbed in the blanket and fissile material will be produced. However, even when the fissile material builds up, this region is still called the blanket.)

Reactors can be classified in several ways:

1. By the energy range of the neutrons that cause most of the fissioning
2. By the material constituents of the reactor, including their physical state (solid, liquid, gas) and their purpose (fuel, structure, coolant, etc.)
3. By the purpose (or purposes) for which the reactor is to be used.

We shall discuss these classifications separately, although any particular reactor is usually characterized by a mixture of terms from the different classifications.

Classification of Reactors by the Energy Range in Which Fissions Occur

With respect to the neutron energy in which most of the fissions take place, the reactors being built in the world today are said to be *thermal* or *fast*. In a thermal reactor most of the fissions are caused by neutrons having an energy less than 1 eV. In a fast reactor the energy range in which most of the fissions take place is much wider, extending from ~100 keV to the top of the range of the fission spectrum (~15 MeV).

At present there seems to be no motivation for designing a reactor in which most of the fissions take place in the intermediate or resonance energy range (from 1 eV to 1 keV). The capture to fission ratio $\alpha^j(E)$ tends to be high in this range so that $\eta^j(E)$ is small: thus an insufficient number of extra neutrons (over the number needed to continue the chain reaction) become available for profitable use to justify the extra cost of building a reactor that operates in this energy range.

We shall see in Chapter 2 that when a neutron scatters from a light nucleus (H, D, Be, C) it can transfer a sizeable amount of its energy to that nucleus—the lighter the nucleus, the more energy transferred. Hence the neutron will emerge from the scattering event with a greatly reduced energy. It follows that, if we wish to build a thermal reactor, we must include along with the fissionable material (called the *fuel*) a significant amount of one or more of the lightweight elements (called *moderators*). Thermal reactors, for example, will always be found to contain H_2O or D_2O or graphite or ZrH_2 or Be, etc.

Conversely, if we wish to build a fast reactor, we must *avoid* the presence of light elements. Thus fast reactors have no moderator (except accidentally). Moreover they must not be cooled by a material, such as liquid water, that contains hydrogen. Instead it is necessary to cool with a gas or a liquid metal such as sodium.

Classification of Reactors by Material Constituents

The materials in a reactor usually are present for a specific purpose, and a classification of reactors according to their material constituents frequently includes mention of what each of the materials is used for. Thus a reactor can contain fuel, fuel cladding, moderator, coolant, fertile material, structural material, and control material (neutron absorbers which can be inserted or withdrawn in order to adjust the critical condition of the reactor).

Fuels. The term "fuel" is a bit ambiguous since the actual fissile material is almost always mixed with fertile material or diluent, and it is this mixture that is referred to as "fuel." Thus we have fuels of 15 percent $Pu^{49}O_2$ in natural UO_2, or "slightly enriched" UO_2 (i.e., uranium oxide having a content of 2 or 3 percent U^{25} rather that the 0.7 percent in the natural ore), or a "highly enriched" uranium-zirconium alloy, the uranium being 93 percent U^{25}.

Cladding. The fuel is generally covered with a protective material or *cladding* in order to prevent corrosion and in order to prevent the radioactive fission fragments (created by fissions taking place on the fuel surface) from getting into the coolant or moderator. The fuel plus its cladding is called a *fuel element.* A typical fuel element for a light-water-moderated thermal reactor is a 0.4-inch-diameter cylinder, 10 feet long, containing 3 percent enriched UO_2, and clad with 0.025-inch-thick zirconium. For a fast reactor a typical fuel element (frequently called a *fuel pin*) is a cylinder 0.25 inches in diameter and 4 feet long, containing 15 percent $Pu^{49}O_2$ in natural UO_2 and clad with 0.015-inch-thick stainless steel.

The ideal fuel-cladding material is strong, highly resistant to corrosion by the coolant, a low absorber of neutrons, and cheap. The best compromise between these conflicting specifications appears today to be an alloy containing principally zirconium (used for water-cooled thermal reactors) and stainless steel (used for sodium-cooled fast reactors).

Moderators. The ideal moderator is also a material that can only be approximated in nature. It should be a cheap, dense, chemically stable material of very low atomic weight having a very low absorption cross section and a very high boiling point. For the first atomic-powered electricity plant built (Calder Hall in England), graphite was used. It is relatively cheap and has a very low absorption cross section (0.0034 barns at 0.025 eV), but it is not too good a moderator (carbon has atomic weight 12) and thus leads to reactors of large size. Most of the power-generating reactors in the United States are now moderated by light water, which also serves as a coolant. The hydrogen in light water is the best of all moderators, but $\sigma_a^H(0.025)$ is 0.332 barns and the material has a low boiling point so that the reactor must be contained in a "pressure vessel." The use of heavy water is favored in Canada. With heavy water the chief problem is cost ($\sim$ \$55 per pound).

Other materials light enough to be effective moderators for neutrons are He, Li, Be, and B. Helium and boron have never been used: the first is a gas, and the second has $\sigma_a^B(0.025) = 759$ barns. Lithium and beryllium have been used for special-purpose reactors and are the principal moderating materials in molten-salt reactors, but they are expensive and difficult to handle. Organic compounds having a high boiling point have also been investigated for use as reactor moderators (and coolants). However the problem of chemical stability at high temperatures in a radiation field is still considered severe for those compounds investigated to date.

Coolants. If a reactor operates in a steady-state fashion at a power level in excess of a few kilowatts, it is generally necessary to cool it to prevent overheating of the fuel elements. In the case of power reactors the heat removed by the coolant is, of course, used profitably. However in some cases (for example reactors designed as high-intensity neutron sources) this heat is just thrown away.

The fluid used to remove heat from a reactor is called the *coolant*. It is usually pumped through the reactor in the form of a liquid or a gas. The ideal coolant should thus have a high specific heat and boiling point (if a liquid) and should be easy to pump. It should be cheap, noncorrosive, and chemically stable with regard to both high temperatures and radiation. It should have a low neutron-absorption cross section, and, if it is made radioactive in passing through the core, this radioactivity should decay very quickly so that the coolant need not be shielded after it leaves the reactor. Finally, for fast reactors, the coolant should be a poor moderator. In light-water-moderated reactors the light water is also used as a coolant, and the whole reactor—fuel, moderator, and coolant—is contained in a single "pressure vessel" and maintained at pressures in the range 1000–2000 pounds per square inch. For heavy-water moderation a separately pressurized coolant system using either light or heavy water is employed. Graphite-moderated reactors also have a separate cooling system employing light water, carbon dioxide, or helium. The most common coolant for fast reactors is sodium, although both helium and steam-cooled systems have been investigated. (The moderating effect of sodium is small because of its relatively high atomic weight, and that of the ~~the~~ gases is small because of their exceedingly low densities at high temperature.)

Fertile Materials. The fertile materials used in reactors are Th^{02}, which yields U^{23}, and U^{28} (or natural U), which yields Pu^{49}. They are generally present in the form of their oxides. (The solid metal has been used, but it has a tendency to grow in size when subject to fission-fragment and high-energy-neutron bombardment. Also it interacts chemically in an almost explosive fashion if the cladding fails and the metal is placed in contact with hot water.) The fertile material is either mixed with the fissile material to form the overall fuel element or is separately clad and placed in a separate region of the reactor called the *blanket*.

Structural and Control Materials. It is frequently necessary to support the fuel elements inside a reactor so that they do not vibrate or so that the coolant flow is directed in some desired way. The ideal properties of the extra "structural material" used to provide such support are the same as those of the cladding, and, in fact, the same material is generally used for both structure and clad.

The ideal properties of control material are also the same as those of the clad, with one essential exception: For control material we want the neutron-absorption cross section to be as *large* as possible. The most common control materials are an alloy of B^{10} in stainless steel ($\sigma_a^{B^{10}}(0.025) = 3837$ b) and hafnium, a metal having about the same metallurgical properties as zirconium along with a thermal-absorption cross section of ~ 100 b and a great number of absorption resonances in the energy range just above thermal.

The control material is usually present in the form of long, small-diameter rods or thin blades that can move in and out of the reactor.

Classification of Reactors According to the Purposes for Which They Are Used

We shall classify reactors by their applications under the categories:

1. To make neutrons
2. To test reactor theory
3. To convert one material into another
4. To generate power for propulsion
5. To generate electrical power.

Rather than providing a thorough discussion of each category, we shall cite some typical examples.

Reactors to Make Neutrons. The research reactor at MIT provides a good example of a facility used to make neutrons. Figure 1.7 shows a cutaway view of this reactor and some of its associated equipment.

The reactor itself is composed of fuel elements which are boxes (2 ft × 3 in. × 3 in.)

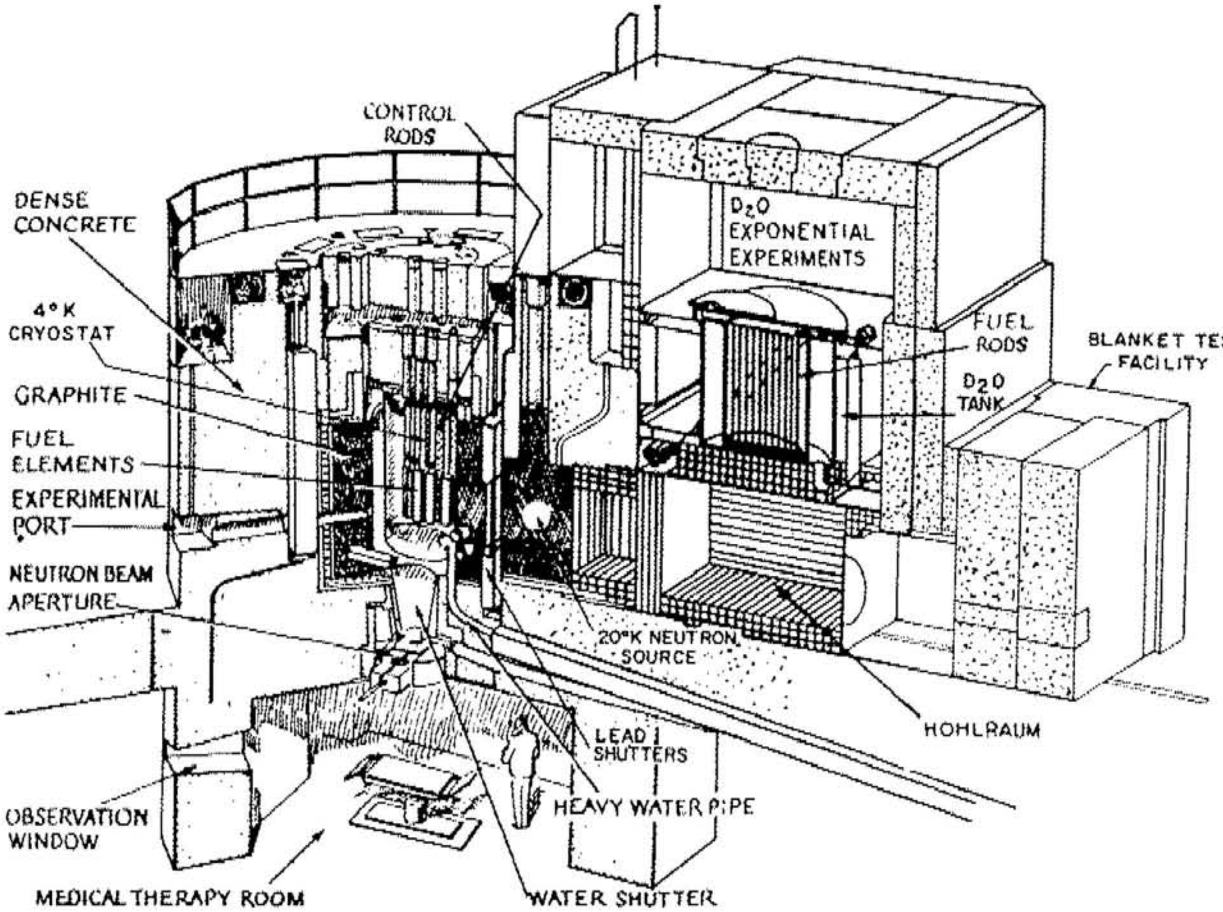

Figure 1.7 A view of the MIT research reactor showing major components and experimental facilities.

of aluminum-clad fuel plates separated by coolant channels, the fuel being 93 percent enriched uranium alloyed with aluminum. These fuel-element boxes along the reactor control rods are contained in a four-foot-diameter tank. Moderation and cooling is provided by D_2O pumped through and around the fuel boxes. A two-foot-thick graphite reflector surrounds the reactor tank. The operating power level is five megawatts.

Figure 1.7 also shows some of the facilities that use the neutrons leaking from the reactor. The largest of these is a hohlraum (cavity) into which low-energy neutrons leak (through a graphite column). Such neutrons then scatter from the walls of the hohlraum and thus supply an intense and extended isotropic source of low-energy neutrons. Shown above the hohlraum is a facility for studying the behavior of neutrons in a subcritical lattice of fuel rods, and shown to the right is a facility for studying the properties of fast-reactor blankets.

The medical-therapy room beneath the reactor can be seen clearly. However only one of some thirty neutron-beam ports piercing the concrete shield and graphite reflector is shown. Neutrons from these beam ports are used in conjunction with crystal spectrometers to investigate the interaction of neutrons with individual and chemically bound atoms.

Reactors to Test Reactor Theory. One of the facilities at the United States National Reactor Testing Site in Idaho (as well as a companion facility at the Argonne National Laboratory outside Chicago) has several zero-power fast reactors constructed of a core of U^{25} or Pu^{49}, and sodium, in stainless-steel cans surrounded by a simulated blanket of natural uranium and sodium (again in cans). Since they operate at only a few watts of fission power, the cooling requirements of these reactors are minimal. The relative proportions of the materials in the reactors can be adjusted, and different reactor configurations are constructed in order to validate theoretical predictions of neutron densities and of the reaction rates due to these densities.

If flexible reactors of this type are constructed so that they closely match the geometrical and material characteristics of some proposed design, they are called *mock-ups.* If, on the other hand, the geometry is kept very simple so that few approximations need be made in their theoretical analysis, they are said to be *clean critical reactors.* An additional term, *benchmark experiment*, is used to designate a cross between the clean critical and mock-up types of experiment. A benchmark experiment is supposed to be clean enough so that the theory can be tested unambiguously, yet close enough to some proposed design so that a model which successfully accounts for the benchmark behavior can be applied with some confidence to the actual design. There is some question of whether one can really have the best of both worlds.

Figure 1.8 shows a sketch of a reactor belonging to this class, the ZPR-6 facility. The two halves of the reactor are mounted on separate tables which can be pushed into contact to create a critical assembly. (There are also control rods available for fine adjustment and safety purposes.) The square grid visible on the face of the far section is where the drawers containing the fuel, fertile material and sodium wafers—all canned in stainless steel—are inserted. By altering the mixture of wafers in a given drawer and filling some drawers entirely with reflector material, experimenters can simulate many different kinds of reactor compositions and geometries.

Reactors to Convert One Material into Another. At the USAEC's Savannah River Facility in South Carolina there are a number of reactors used to convert one material into another—for example U^{28} into Pu^{49}, or Th^{02} into U^{23}, or Pu^{42} into the transplutonium elements Americium, Curium, Berkelium, and Californium. Every effort is made in designing these reactors to insure that all neutrons not needed to sustain the chain reaction are absorbed in fertile material. Thus the design consists of cylindrical fuel elements moderated and cooled by D_2O. The fuel elements themselves may be composed

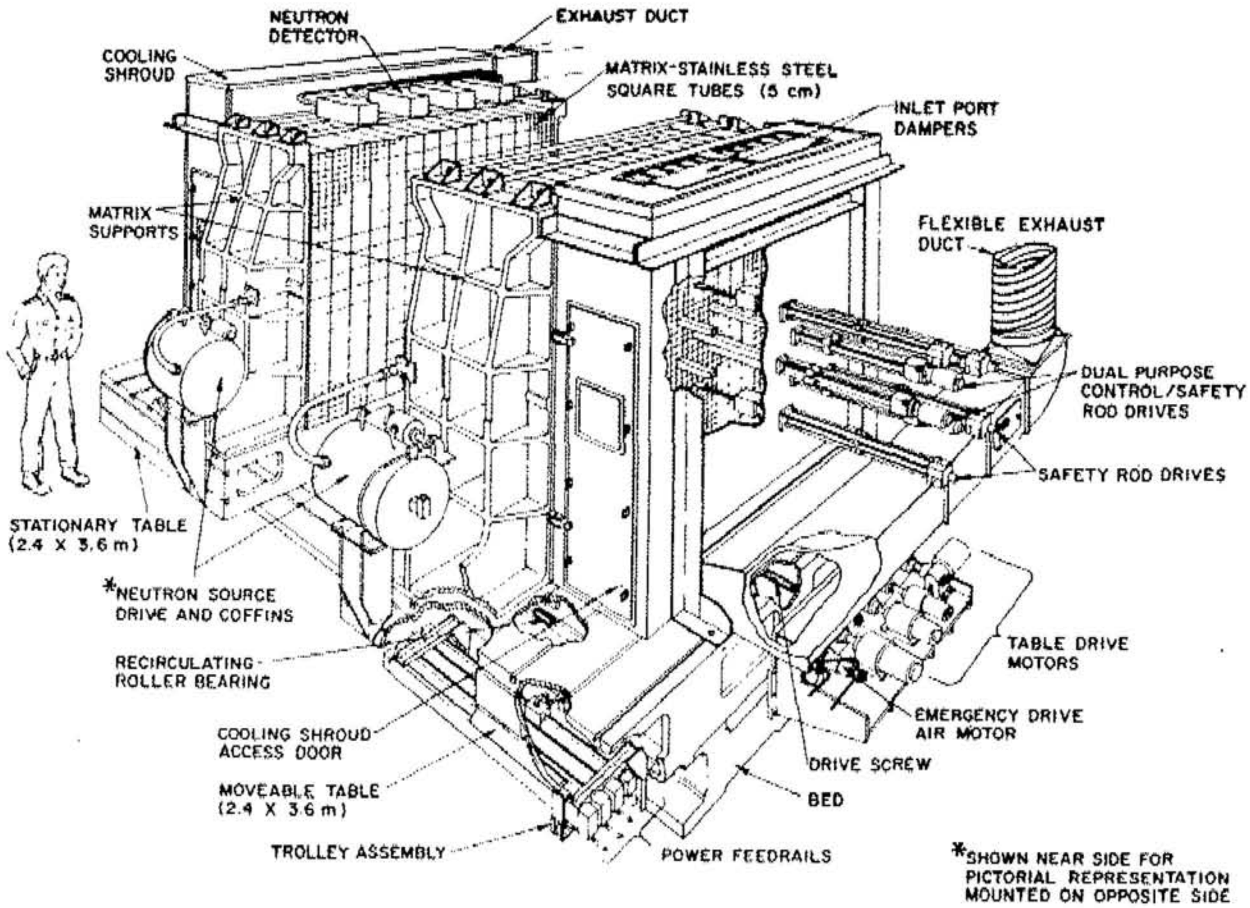

Figure 1.8 The Argonne fast critical facility (ZPR-6). Courtesy of Argonne National Laboratory.

of concentric shells or of a cluster of small cylindrical rods. The reactors are large, the D_2O tanks being in excess of 15 feet high and in excess of 16 feet in diameter, and the reactors operate at very high power. Figure 1.9 shows a lattice used to produce an extremely high neutron flux for the purpose of converting Pu^{42} into transplutonium isotopes. (The dark lattice positions were occupied by control rods and the lighter positions by fuel and target assemblies.) The cross section of a fuel element (two concentric shells of fuel with an inner and outer housing) is shown on the side. The element is about 3.5 inches in diameter, and the active part of the reactor lattice is approximately 6 feet high and 7 feet in diameter.

Reactors to Generate Power for Propulsion. In this category nuclear reactors for marine application provide the most common example. Highly enriched, light-water-moderated, cooled, and reflected cores with fuel elements consisting of a zirconium alloy have been used for this purpose. The hot coolant (H_2O at very high pressure) emerging from such a reactor flows through tubes of a boiler and is then pumped back through the core in

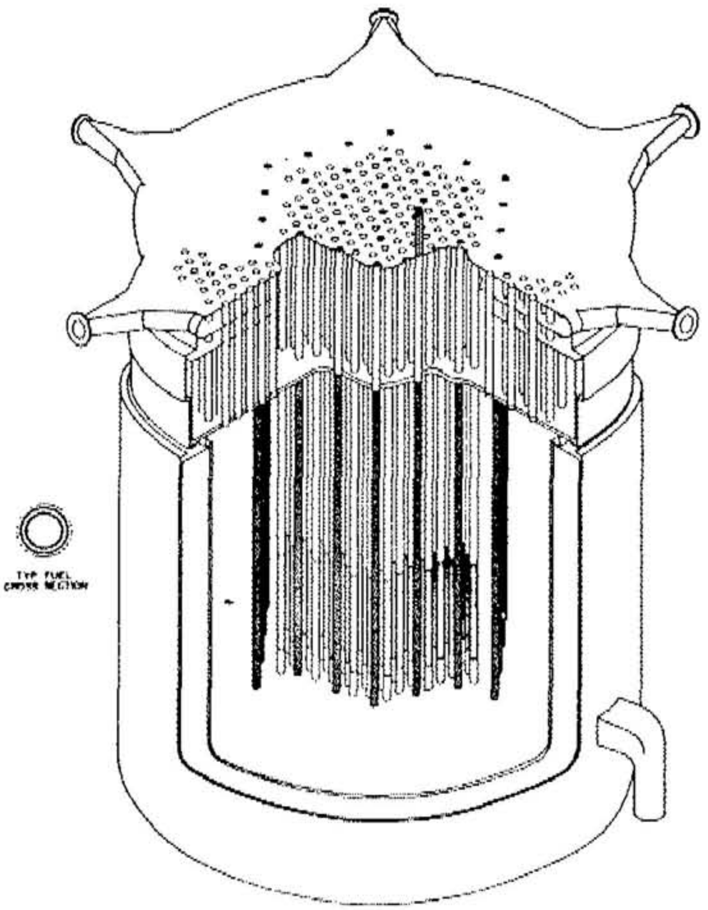

Figure 1.9 A high-flux demonstration lattice in a Savannah River reactor. Courtesy of E. I. Du Pont, De Nemours & Company.

a continuous closed-loop arrangement. Lower-pressure water on the other side of the boiler tubes is converted to steam which runs a turbine that, in turn, drives the ship's propeller.

The Nerva nuclear-powered rocket engine also illustrates the application of nuclear power to propulsion. Figure 1.10 shows a sketch of a proposed design. In this case hydrogen, originally in liquid form, is pumped into a highly enriched graphite-moderated core operating at extremely high power. The heat transferred to the hydrogen causes it to vaporize, expand, and blast out of the open nozzle at the bottom of the core, thus providing thrust.

Reactors to Generate Electrical Power. In the United States there are two classes of reactors that have been used most commonly to generate electric power. They are PWR's (Pressurized-Water Reactors) and BWR's (Boiling-Water Reactors). Both are slightly enriched, light-water-moderated, cooled, and reflected reactors making use of Zr-clad UO_2 fuel elements. A PWR is similar to the marine propulsion reactor just discussed,

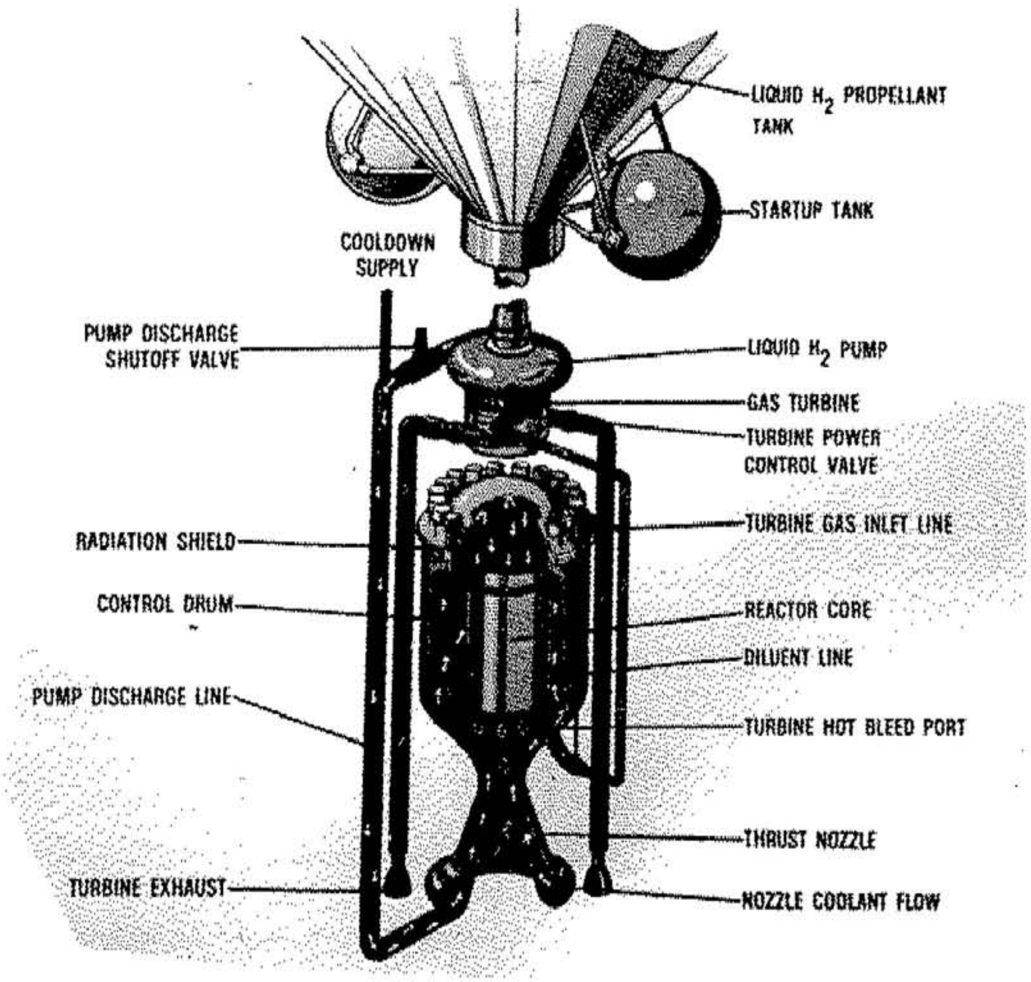

Figure 1.10 A schematic flow diagram of the XE nuclear-powered engine. Courtesy of Westinghouse Electric Corporation.

except that the steam turbine runs an electric generator rather than a propeller. In a BWR the moderator-coolant is allowed to boil in the core, and the generated steam drives the turbine directly. There is thus no intermediate heat exchanger.

A cutaway view of a PWR (the pressure vessel and its internals) is shown as Figure 1.11. The overall height of the reactor vessel and head is 44 ft. The height of the core is 12 ft and its diameter is ~11 ft. The individual subassemblies making up the core have a cross-sectional area of 9 in. × 9 in. They are composed of 0.42-inch-diameter, zirconium-clad, slightly enriched UO_2 rods. The reactor is controlled by multipronged control rods that fit into guide tubes replacing certain fuel rods.

Both PWR's and BWR's are called *burner reactors* because they make no attempt to produce large amounts of plutonium but, instead, try to burn in place much of the plutonium they make.

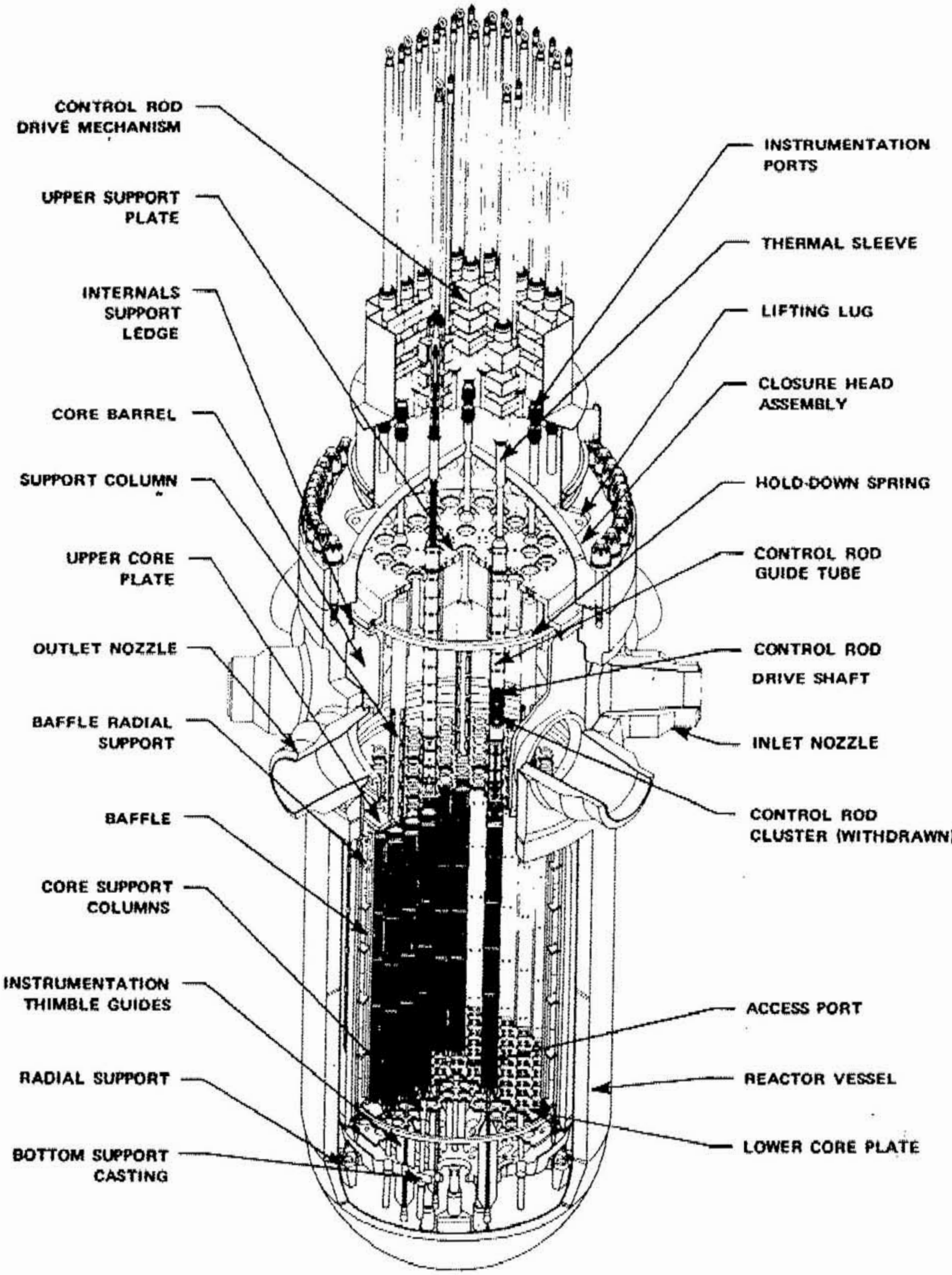

Figure 1.11 Cutaway of a typical pressurized-water reactor. Courtesy of Westinghouse Electric Corporation.

Another type of power reactor that shows long-range promise is the *breeder reactor*. The basic idea here, besides producing usable electrical power, is to make more fissionable material (Pu^{49} or Pu^{41}) than is destroyed. The favored design for this purpose is the fast reactor, fueled with stainless-steel-clad pins composed of $Pu^{49}O_2$ and natural uranium and cooled by liquid sodium. Although some Pu^{49} is created from the natural uranium that comprises 85 percent of the mixture in the fuel pins, most of the breeding (i.e., the creation of Pu^{49} from U^{28}) takes place in a sodium-cooled blanket of natural—or depleted—uranium that surrounds the core. A graphite reflector is usually placed outside this blanket to reflect as many neutrons as possible into the blanket area.

References

Evans, R. D., 1955. *The Atomic Nucleus* (New York: McGraw-Hill).

Kaplan, I., 1963. *Nuclear Physics*, 2nd ed. (Reading, Mass.: Addison-Wesley).

Keeping, G. R., 1965. *Physics of Nuclear Kinetics* (Reading, Mass.: Addison-Wesley).

Lamarsh, J. R., 1966. *Introduction to Nuclear Reactor Theory* (Reading, Mass.: Addison-Wesley), Chapters 1–4.

Nuclear Data

CINDA 69, An Index to the Literature on Microscopic Neutron Data, 1969. Edited by USAEC/DTIE, USSR/NDIC, ENFA/CCDN, and IAEA/NDU.

Drake, M. K., 1970. *Data Formats and Procedures for the ENDF Neutron Cross Section Library*, BNL–50274 (T–601).

Honeck, H. C., 1966. *ENDF 102*, BNL–50066 (T–467) (revised by S. Pearlstein, 1967).

Hughes, D. J., and Schwartz, R. B., 1958. *Neutron Cross Sections*, BNL–325, 2nd ed. (see also Supplement 2, Volumes 1 (1964), 2A, B, and C (1966), and 3 (1965); Volume 1 of the third edition was published in 1973).

Schmidt, J. J., 1962–1966. *Neutron Cross Sections for Fast Reactor Materials*, Part 1, *Evaluation*; Part 2, *Tables*; Part 3, *Graphs*, KFK–120 (EANDC–E–35 "U").

Schmidt, J. J., and Wall, O., 1968. *Tables of Evaluated Neutron Cross Sections for Fast Reactors*, KFK–750 (EANDC–E–88 "U"; EUR–37152).