Chapter 13

NUCLEAR FISSION

Nuclear power can cleanly and safely meet a substantial portion of the additional base-load electricity generation capacity the United States will require by 2030 if (1) the operating lifetimes of existing nuclear plants are extended (where this can be done safely with appropriate Federal oversight and technical support), and (2) utility executives once again consider the “nuclear option” technically, politically, and economically feasible when new capacity is planned.

(*National Energy Strategy, Executive Summary*, 1991/1992)

The Administration's policy is to maintain the safe operation of existing nuclear plants in the United States and abroad and to preserve the option to construct the next generation of nuclear energy plants. The policy is implemented by working with industry to enhance safety and by continuing to press for safe storage of spent nuclear fuel.

(*Sustainable Energy Strategy*, July 1995)

Society will face some difficult energy-related decisions in the coming decades. Among the most difficult ones is the future of nuclear energy. More specifically, the future of conventional nuclear reactors is uncertain. Conventional nuclear reactors are the ones that rely on nuclear fission to provide the heat necessary for generating electricity. Figure 13-1 illustrates the history and the current status of these reactors in the United States. A dramatic decline in the number of reactor purchases by the electric utilities reflects the well known loss of public confidence in the safety of these reactors in the aftermath of the accident at Three Mile Island. No new nuclear power plants have been ordered since 1979, when this nuclear accident occurred. The situation has been made worse by the 1986 accident at Chernobyl in Ukraine. It hasn't changed to this day.

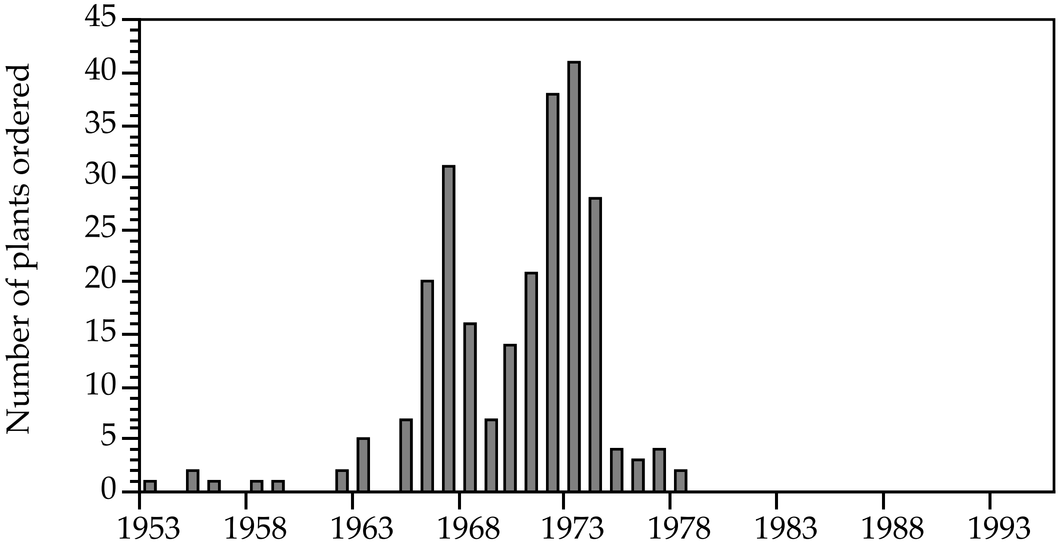


FIGURE 13-1. Number of new nuclear power plants ordered by electric utilities. [Source: Energy Information Administration.]

In the previous chapter we introduced all the physics needed to understand the main issues surrounding nuclear energy utilization. Here we show how nuclear energy is used today. We pursue further the simplistic analogy between the chemical reactions of combustion of fossil fuels and the nuclear reactions of fission of radioactive isotopes. We show that the origin of society's interest in nuclear energy lies in the fact that much more energy is released per unit mass of a nuclear fuel than per unit mass of a fossil fuel. This is a mixed blessing. It has led to the development of nuclear weapons (see Chapter 15). It has also provided the incentive to convert nuclear energy into abundant electricity. The peaceful development of nuclear energy in the aftermath of World War II was supposed to lead to the production of electricity that would be too cheap to meter. We know today that this did not happen. But can it still happen? The answer to this question depends to some extent on further technological developments. But it also depends on society's ability to evaluate objectively (and not just emotionally) this controversial energy option.

Principles of Nuclear Fission

In Table 12-1 we listed examples of radioactive nuclei that are important in nuclear fission. By far the most important one is uranium-235 (U-235). It is the principal constituent of the *fuel rods* in a nuclear reactor. In 235 grams of U-235 there are as many as 6×10^{23} atoms, an important number known as Avogadro's number (see p. 103). All these atoms can undergo fission, according to the following nuclear equation:

$$_{92}U^{235} + {}_{0}n^{1} = {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3\,({}_{0}n^{1})$$

In this fission event, one among billion quadrillion identical ones, the fissionable uranium atom (nucleus) reacts with a neutron, becomes temporarily unstable and is fragmented very soon thereafter into a nucleus of barium (Ba) and a nucleus of krypton (Kr).

Note that the number of protons on the left-hand side of a nuclear equation (in this case, 92+0=92) is equal to the number of protons on the right-hand side (56+36=92); the number of neutrons is also equal on both sides of the equation (235+1=144+89+3). Atoms are not conserved, but nucleons are. This is the difference between a chemical reaction and a nuclear reaction. We saw in Chapter 6 that atoms are conserved in chemical reactions; they are just rearranged to form different molecules. In nuclear reactions, nucleons are rearranged to form different nuclei but they are conserved.

What is of greatest interest to us in the above nuclear reaction is to calculate how much energy is released in each fission event and to observe that three free neutrons are produced for every neutron that is consumed.

Energy Content of Nuclear Fuels. To understand the fission reaction, and its difference from fusion, consider the simplistic but instructive analogy with the movement of marbles on a roller coaster (Figure 13-2). The path of the fission reaction is from left to right. From bottom to top, the energy of the reacting atoms (or marbles) increases; also, when these particles are in the valleys, they are relatively stable, and when they are at the crests, they are unstable. The energy of a nucleus of U-235 increases when it collides with and temporarily absorbs a neutron. This energy buildup makes the nucleus of U-236 very unstable. Because a neutron is electrically neutral, it does not take much energy to bring the radioactive U-235 to the “top of the hill.” Once it overcomes this “activation energy barrier,” the very unstable U-236 spontaneously “rolls downhill:” it splits into two fissionable fragments and eventually transforms into more stable fission products.

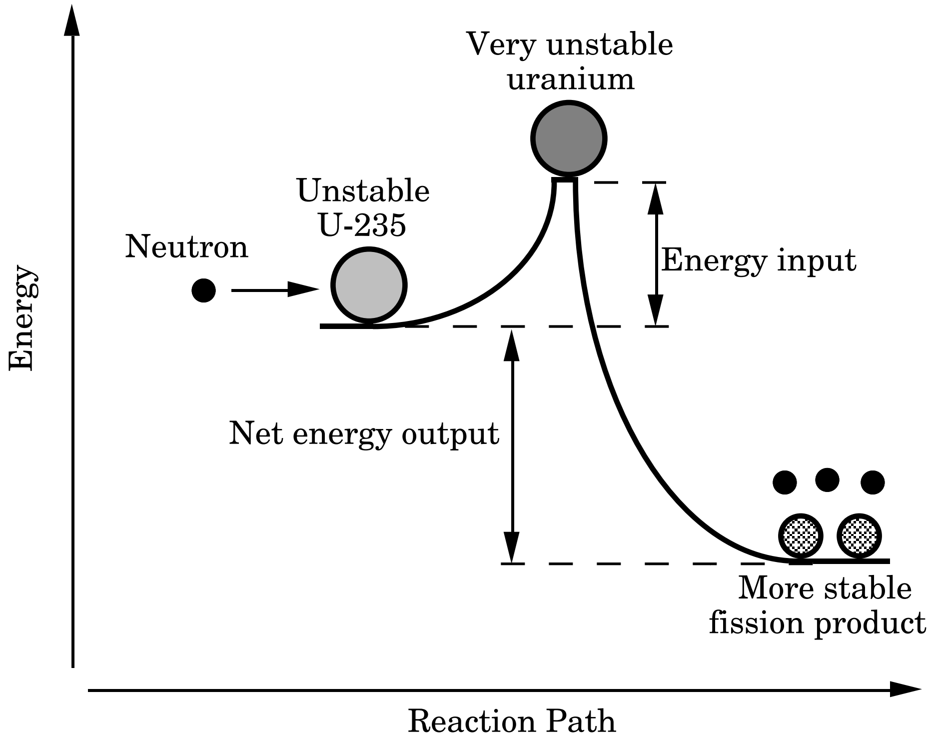


FIGURE 13-2. Schematic representation of a fission reaction.

The quantity of energy released is easily calculated if one knows the decrease in mass that accompanies the fission process. This calculation is shown in Illustration 13-1. It is important because it allows us to make the comparison between the energy released in fossil fuel combustion and the energy released in nuclear fuel fission.

Chain Reaction. As much as 85% of the energy released in the fission process appears as kinetic energy of the fragments. The rest is referred to as the ‘radioactivity’ (see Chapter 15). As the high-speed fragments collide with surrounding matter, they induce random motion of the surrounding atoms and molecules; their kinetic energy is thus converted to heat. This heat is used in turn to produce electricity in a nuclear reactor or is allowed to cause an explosion in an atomic bomb. The fate of the neutrons produced in the fission process is the key to understanding the difference between a controlled nuclear reaction, which takes place inside a nuclear reactor, and an uncontrolled nuclear reaction, which leads to the explosion of an atomic bomb.

Illustration 13-1. (a) If 0.190 a.m.u. are converted to energy for every nucleus of U-235 that undergoes the fission process, show that the energy released is indeed approximately 0.9 MeV, as discussed in Chapter 12. (b) Show that the fission of 1 kg of uranium-235 releases approximately a million times more energy than the combustion of 1 kg of coal.

Solution.

(a) $\Delta E = \Delta m\, c^2$

$$= (0.190 \text{ a.m.u.}) \left(\frac{1.66056\text{x}10^{-27} \text{ kg}}{1 \text{ a.m.u.}}\right) \left(3\text{x}10^8 \frac{\text{m}}{\text{s}}\right)^2 =$$

$$= (2.84\text{x}10^{-11} \text{ J}) \left(\frac{6.242\text{x}10^{12} \text{ MeV}}{1 \text{ J}}\right) = 177 \text{ MeV/nucleus}$$

$$= \left(177 \frac{\text{MeV}}{\text{nucleus}}\right) \left(\frac{1 \text{ nucleus}}{235 \text{ nucleons}}\right) = 0.75 \text{ MeV/nucleon}$$

(b) We have seen in Chapter 6 that the heating value of coal is of the order of 10,000 BTU per pound. For every kg of coal, choosing the upper limit, this is

$$\left(\frac{10000 \text{ BTU}}{1 \text{ lb coal}}\right) \left(\frac{2.2 \text{ lb}}{1 \text{ kg}}\right) = 2.2\text{x}10^4 \text{ BTU/kg coal}$$

For fission of U-235, taking into account that there are $6\text{x}10^{23}$ atoms in one mole (Avogadro's number) and that the molar mass is 235 grams, we have:

$$\left(\frac{177 \text{ MeV}}{1 \text{ nucleus U-235}}\right) \text{x}$$

$$\text{x} \left(\frac{1 \text{ nucleus U-235}}{1 \text{ atom U-235}}\right) \left(\frac{6\text{x}10^{23} \text{ atoms}}{1 \text{ mol}}\right) \left(\frac{1 \text{ mol}}{0.235 \text{ kg U-235}}\right) \left(\frac{1.52\text{x}10^{-16} \text{ BTU}}{1 \text{ MeV}}\right) =$$

$$= 6.90\text{x}10^{10} \text{ BTU/kg U-235}$$

So, the nuclear energy stored in 1 kilogram of radioactive uranium is equivalent to the chemical energy stored in approximately three million kilograms of coal. This represents a vast source of energy. How well it is harnessed depends on the efficiency of its conversion to useful energy. (See also Review Question 12-1.)

Nuclear fission is an example of a *chain reaction.* This is illustrated in Figure 13-3. Each one of the three neutrons produced in the first fission event goes on to collide with other U-235 nuclei. This new collision event will in turn produce three additional neutrons; so after two collisions, a total of nine neutrons will be obtained. This increase in neutron inventory (3-9-27-81-243-729-etc.) is similar to the population rise and is yet another example of exponential growth introduced in Chapter 5. Because this exponential growth is accompanied by heat release, an exponential build-up of heat occurs at the same time. There is no way to dissipate or carry away all this heat, so the temperature of the solid material (within which fission occurs) increases, the material melts and then vaporizes. This in turn causes a pressure build-up which ultimately results in an explosion, just like in an over-inflated balloon.

This simplified description of an uncontrolled chain reaction represents well the sequence of events in a nuclear bomb or in a major nuclear accident. (The “China syndrome” – an expression often used for a hypothetical nuclear accident – refers to the meltdown of the Earth caused by such heat release, the sinking of the reactor and the people around it through the molten Earth's crust and their appearance at the other end of the globe, in China! For an atomic bomb it has been estimated that approximately 15 billion BTU of heat are released in just 50 microseconds.) How can we control this process? The control of neutron inventory, or the maintenance of neutron balance, is the key. Both the quantity and the ‘quality’ of neutrons are important for the peaceful and effective utilization of this energy.

We first want to maintain a steady number of neutrons. Ideally, only one of the three neutrons produced in each collision will be allowed to “carry the chain” and continue the fission process until all fissionable material is consumed. Such a process generates a constant quantity of heat. This heat can be dissipated easily (see below) and the temperature of the material can be maintained below its melting point. This *self-sustained chain reaction* is illustrated in Figure 13-4.

A self-sustained chain reaction is achieved by the use of a material that is capable of absorbing neutrons. A typical example of such a material is the element boron. Its reaction with a neutron is very simple, as shown below:

$$\underset{\text{(boron)}}{{}_5B^{10}} \quad + \quad \underset{\text{(neutron)}}{{}_0n^1} \quad = \quad \underset{\text{(lithium)}}{{}_3Li^7} \quad + \quad \underset{\text{(helium)}}{{}_2He^4}$$

In contrast to uranium fission, in which we have a net production of neutrons (three neutrons produced for every neutron consumed), here we have a net consumption of neutrons; indeed, no neutrons are produced, as shown on the right-hand-side of this nuclear equation. If this material is present together with the fissionable uranium, it can control the neutron inventory. This is the principle of operation of the *control rods* in a nuclear reactor.

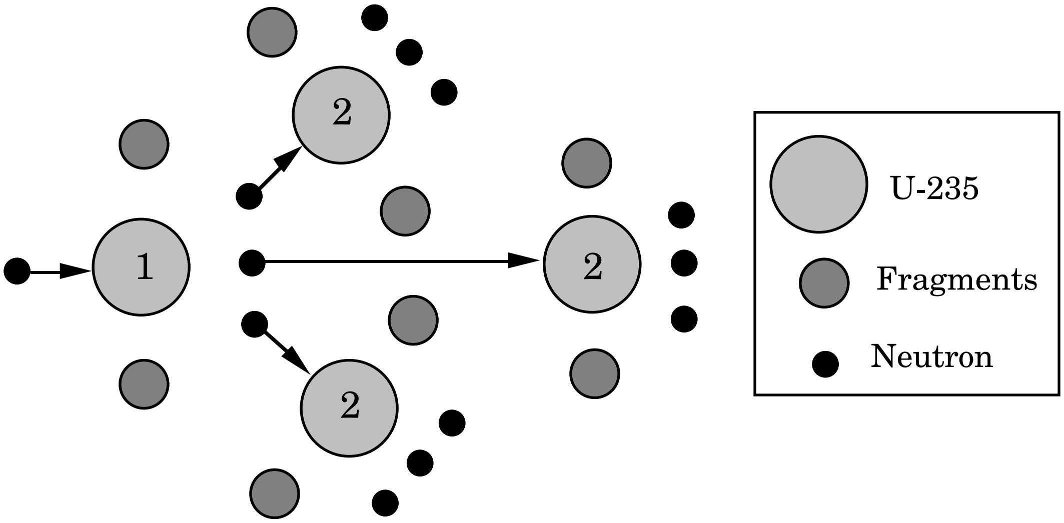


FIGURE 13-3. Schematic representation of a chain reaction.

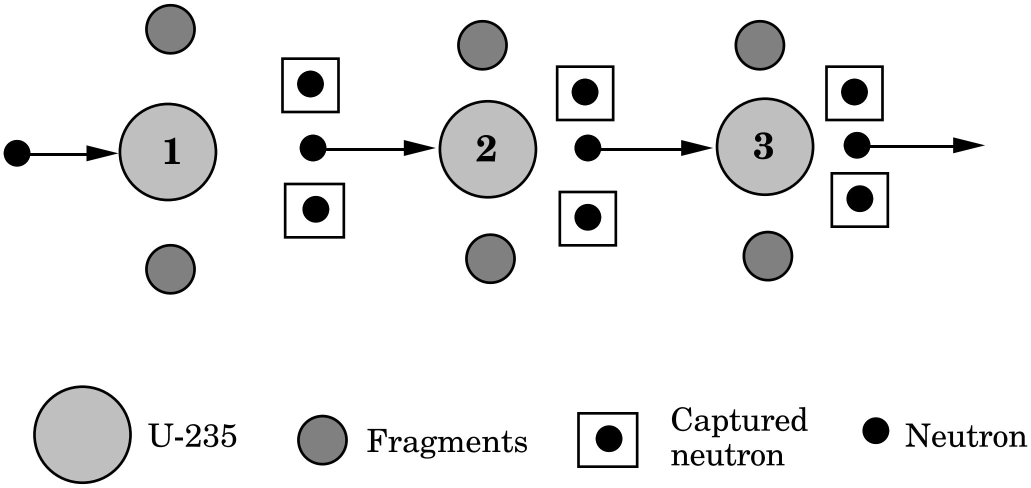


FIGURE 13-4
Schematic representation of a self-sustained (controlled) chain reaction.

The kinetic energy of the neutrons and fragments produced in a fission reaction is so large that they travel through the fissionable material at very high speeds. Yet it turns out that the neutrons having an intermediate speed are the ones that are most effective in forming the highly unstable U-236 and thus causing fission of U-235. If the speed of the neutrons is too low, they may not have sufficient energy to split apart the nuclei of U-235. It is clear then that the neutrons produced in the fission event need to acquire a well-defined ‘quality’. The *moderator* in a nuclear reactor is a material (for example, graphite or water) that has the ability to provide this optimum or moderate speed to the neutrons: as fast-traveling neutrons collide with the atoms of carbon or hydrogen, they are slowed down by just the right amount and are not absorbed (or lost).

Nuclear Reactors

In Chapter 12 we briefly summarized the most important scientific developments that laid the foundations for the eventual creation of a nuclear industry in the U. S. and in the world. Here we summarize the key events that led to the technology of nuclear reactors.

After the discovery of artificial radioactivity in the early 1930s, Enrico Fermi was quick to realize that bombarding a heavy isotope with neutrons is a very effective path to nuclear fission. At about the same time, the Hungarian scientist Leo Szilard (1898-1964) realized that “if we could find an element which is split by neutrons and which would emit two neutrons when it absorbs one neutron, such an element, if assembled in sufficiently large mass, could sustain a nuclear chain reaction” (Richard Rhodes, *The Making of the Atomic Bomb*, Simon & Schuster, 1986, p. 28). The good old uranium, with which Becquerel and the Curies initiated all this tinkering with the atomic structure, turned out to be precisely such an element. With World War II about to begin, the Austrian Lise Meitner (1878-1968), from her exile in Sweden, realized that the 1938 experiment of her former German colleagues Otto Hahn (1879-1968) and Fritz Strassmann (1902-1980) was a successful demonstration of the uranium fission reaction shown on p. 231. In the feverish months before the outbreak of the war, when Niels Bohr and others calculated just how much energy is released in the process, the military implications of this experiment became obvious on both sides of the Atlantic Ocean. The nuclear race began in earnest. It was to have a profound effect on society ever since.

A fascinating account of the dramatic development of the atomic (or fission) and hydrogen (or fusion) bombs is provided in two Pulitzer prize-winning books by Richard Rhodes, *The Making of the Atomic Bomb*, mentioned above, and *Dark Sun: The Making of the Hydrogen Bomb* (Simon & Schuster, 1995). For our purposes it is sufficient to point out that the generation of electricity in nuclear reactors came almost as an afterthought, when some of the military nuclear programs were turned over to civilian control after World War II. On August 1, 1946 President Truman signed into law the Atomic Energy Act, which created the Atomic Energy Commission (a forerunner of the currently existing Nuclear Regulatory Commission) as a replacement for the Manhattan Project. In January 1956 a congressional panel submitted a report to the Joint Committee on Atomic Energy entitled “Peaceful Uses of Atomic Energy.” It concluded that “atomic power gives promise of becoming an important new resource for the generation of electricity.” This fundamental link between nuclear reactors and nuclear weapons is clarified below and is taken up again in Chapter 15.

We saw in Figure 13-1 that, after the nuclear ‘boom’ of the 1960s and 1970s, no new nuclear power plants have been ordered in the U.S. since the accident at Three Mile Island in Middletown, PA. Nevertheless, there is a large number of nuclear reactors both in the U.S. and in the world today. Figure 13-5 summarizes the situation in the world. Some thirty countries have 431 nuclear reactors that are used to produce electricity. Their reliance on nuclear reactors is as high as 70% in the case of France, which continues to be committed to nuclear energy. The Swedes generate 50% of their electricity with nuclear reactors but they have voted to discontinue their use. Figure 13-6 shows that only a dozen states or so in the U.S. do not have at least one nuclear power plant. The Midwest and the Northeast account for a large percentage of the 109 nuclear reactors.

INTERNET INFO

For an update on the status of nuclear power plants in the U.S., see the following Internet sites: http://www.nrc.gov (Nuclear Regulatory Commission) and http://www.nuke.handheld.com.

For an update on the status of nuclear power plants in the world, see http://www.iaea.or.at (International Atomic Energy Agency in Vienna).

A *nuclear power plant* is in all respects similar to a fossil-fuel power plant (see Figure 4-6). The only difference is that the steam is produced by the heat released during a nuclear reaction, in a nuclear reactor, instead of being produced by the heat released during fossil-fuel combustion in a boiler. In other words, the nuclear reactor is a device in which nuclear energy is converted to thermal energy; it is, indeed, a large, complex and expensive water boiler. Subsequent conversion of thermal energy to mechanical energy takes place in a conventional turbine and the conversion of mechanical energy to electricity takes place in a conventional generator.

The fact that so many countries have “nuclear capability” means that they all could – and some do – possess nuclear weapons. This issue of “nuclear proliferation,” along with the problem of “nuclear waste,” is a major stumbling block for further development of the nuclear industry. (This important issue is taken up in Chapter 15.) But, even though some countries, mostly in Western Europe, have renounced to the future use of nuclear power, at least for the time being, the numbers shown in Figure 13-5 indicate that nuclear power will be with us for decades to come. It is important, therefore, that we take some time to analyze the types of reactors that exist and how they work. The objective here is to show that one does not really need to be a nuclear engineer to grasp the *essential* features of nuclear reactor operation. We deliberately retain some of the jargon because it is used in most media accounts of the events in this intensely scrutinized industry.

There are four principal components in every nuclear reactor:

- Fuel rods (also called reactor core)
- Control rods
- Moderator
- Heat-transfer medium (or coolant)

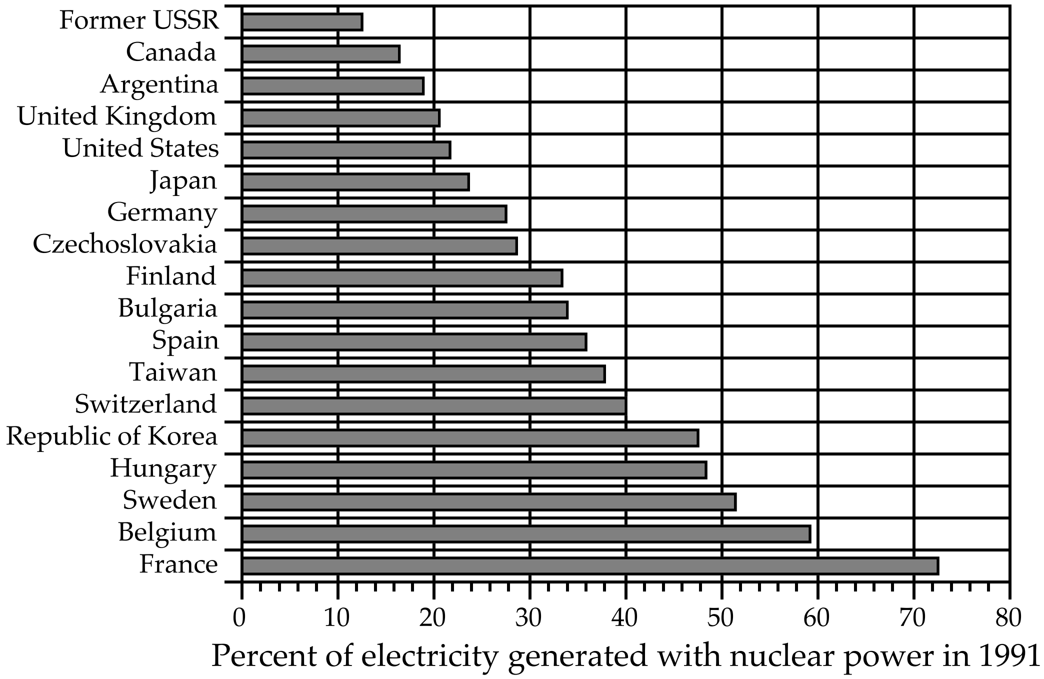


FIGURE 13-5
Illustration of the range of dependence on nuclear reactors for electricity generation. [Source: “The Future of Nuclear Power,” *American Scientist*, January-February 1993.]

The first three reactor components (fuel rods, control rods and moderator) were introduced in the previous section and they are discussed in more detail below. The heat transfer medium is necessary to carry away the heat generated in the reactor core. The thermal energy generated is used, either within the core itself or elsewhere in the reactor, to boil water and produce steam. At the same time, as the water circulates through the core, it cools the core and prevents it from melting.

The core consists of a large number (‘assembly’) of fuel rods. These are long thin metal cylinders (for example 3 meters long and 1 cm in diameter) that contain the individual pellets of the fissionable material, usually uranium-235. The material within the pellets is not all U-235. In a typical reactor, only 3% of the material is U-235; the rest is nonfissionable U-238. (The preparation of these pellets is described in the next section.) The rods can be loaded individually into the core and removed from it; this operation of fuel replenishment is important because the lifetime of the nuclear reactor (typically, 30 years) is longer than the useful lifetime (or activity) of the fuel in it. This useful lifetime is typically a few years, as shown in Review Question 13-3.

FIGURE 13-6
Map of the U. S. with the (approximate) location of commercial nuclear reactors.
[Source: Energy Information Administration.]

The control rods are similar to the fuel rods, except that they contain a neutron-absorbing material instead of the fissionable material. The elements boron (B) and cadmium (Cd) are commonly used for this purpose. These rods can be moved into the core and out of it. This allows the operators to control the production of neutrons within the core. Think of the control rods as being analogous to the accelerator pedal in an automobile, which controls the injection of fuel into the engine. All nuclear reactors have a Self-Controlled Remote

Automatic Mechanism (SCRAM): in the case of an accident, it inserts the control rods completely into the core in a very short time. This maximizes the absorption of neutrons and shuts down the reactor in much the same way as taking the foot off the accelerator pedal will cause the car to come to a stop.

The moderator material is also placed between the fuel rods. Indeed, it fills most of the space within the reactor core. As discussed earlier, its function is to slow down the neutrons emitted during fission and thus maximize the probability of sustaining the chain reaction. How it accomplishes this can be understood by considering the collisions between neutrons and nuclei to be analogous to collisions between billiard balls. A good moderating medium contains atoms with light nuclei, so that each collision of a neutron with an atom causes only a partial loss of its speed. Ordinary (‘light’) water contains hydrogen ($_1H^1$) atoms, which have the right size to achieve this. After a trajectory of only about 6 cm through water, the speed of the neutrons (ejected during fission) becomes adequate for further fission. One problem with the collision of a neutron and a hydrogen nucleus (proton) is that the neutron may be lost (absorbed) in the following reaction:

$$\underset{\text{(neutron)}}{_0n^1} \quad + \quad \underset{\text{(proton)}}{_1H^1} \quad = \quad \underset{\text{(deuterium)}}{_1H^2}$$

For this reason, other moderators are sometimes used, such as carbon (graphite) or ‘heavy’ (deuterated) water (water in which normal, light hydrogen is replaced by deuterium). A dramatic episode in World War II was the destruction of a German source of heavy water in Rjukan, Norway. If the Germans were indeed close to developing a usable atomic bomb in early 1944, this denial of access to heavy water by the Allies was the key to the breakdown of their atomic bomb project.

Figure 13-7 shows a simplified view of the reactor core. It helps us to visualize the sequence of events taking place in the reactor. As the fission reactions occur inside the fuel rods, high-speed neutrons and fission fragments are ejected from the radioactive atoms. As the fragments collide with the surrounding atoms within the fuel rods, they give up their kinetic energy as heat. The neutrons, on the other hand, escape from the fuel rods and, as they travel outward, they collide with the atoms of the moderator. They lose kinetic energy in this process. Their speed decreases and the probability of their splitting another fissionable atom, within another fuel rod, increases. This makes possible a self-sustained chain reaction. In their path, the neutrons may also encounter the control rods; when this occurs, they are absorbed and can cause no further fission. Finally, the heat-transfer medium (water or gas) flows through the spaces between the rods, cools them, becomes itself hotter and thus carries away the heat that is generated.

The sequence of events described above is common to all nuclear reactors. Neutron inventory is the key to their normal operation. This normal operation is often described in terms of a *reproduction constant*, K. This is the average number of neutrons from each fission event that will cause another fission event.

$K<1$: Reactor is ‘subcritical’ (chain reaction stops)
$K=1$: Reactor is ‘critical’ (self-sustained chain reaction)

K>1 : Reactor is 'supercritical' (power increases; the chain reaction may run away and even lead to explosion)

The reproduction constant of a reactor is regulated by the positioning of the control rods inside the core. It also depends on the quantity of fissionable material inside the core; this issue is discussed in the next section.

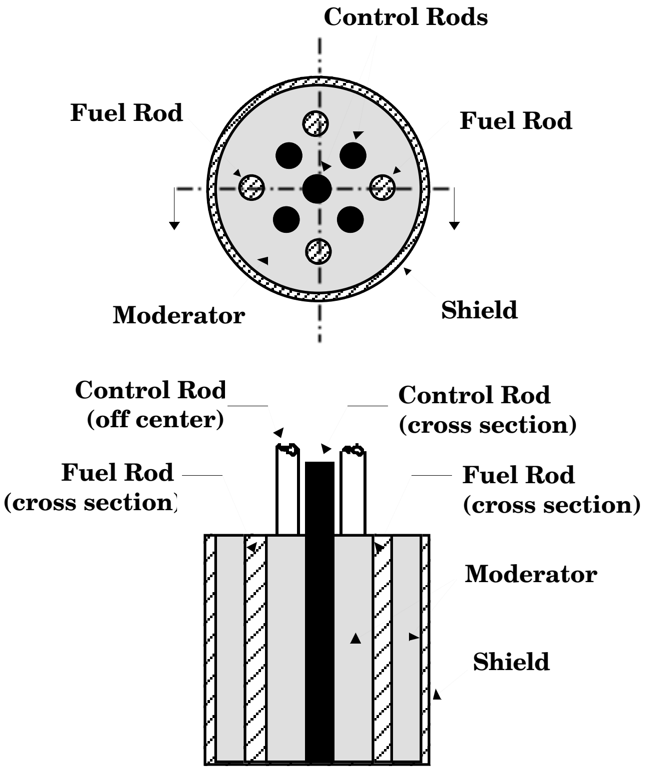


FIGURE 13-7

Cross sections (top and side) of a core in a nuclear fission reactor.

[Reproduced with permission from "Introduction to Energy," by E.S. Cassedy and P.Z. Grossman, Cambridge University Press, 1990.]

Commercial nuclear reactors differ only in the choice of the moderator material and the heat-transfer medium used. All the nuclear reactors in operation today in the United States use water both as the moderator and the coolant. These are the so-called light-water reactors (LWR). There are two types of light-water reactors, the pressurized-water reactor (PWR) and the boiling-water reactor (BWR). The majority of the reactors are of the former type, including the famous (or infamous) one at Three Mile Island.

FIGURE 13-8. Schematic representation of a pressurized-water nuclear reactor. [Source: Cassedy and Grossman, op. cit.]

Figure 13-8 shows the principal features of the pressurized-water reactor. The vessel that encloses the reactor core is under high pressure (2250 pounds per square inch, or 150 times higher than atmospheric pressure). This prevents the water from boiling inside the vessel. The effect of high pressure is the same as that of putting a lid on a kettle to minimize the evaporation of water. It is high-pressure water at a temperature of about 300 °C, and not steam, which leaves the reactor vessel. The distinguishing feature of this kind of reactor is that it has two separate water loops. In the primary loop, the circulating water cools the core, becomes very hot and transfers the heat to the water in the secondary loop. It is then pumped back into the core to repeat this heat transfer process. Water in the secondary loop is converted to steam in a heat exchanger. The spent steam, after delivering its energy to the turbine, is condensed, cooled further and pumped back into the steam generator. This cooling of water condensed in the turbine (say, from 100 °C to about 30 °C) is carried out in the most conspicuous building of any nuclear power plant, the cooling tower. The size of the building that houses the reactor itself, appropriately called the containment building, is modest in comparison.

It should be noted in Figure 13-8 that the design of a PWR is such that it minimizes the possibilities of radioactivity leaks. The water that flows through the core is radioactive, of course, because the products of fission reactions can dissolve in it. The primary loop, however, is entirely within the containment building (usually constructed of thick-wall concrete), and the escape of radioactive water, first through leaking valves or pipes, and then through the building, is highly unlikely. This is an important virtue of the PWR design.

FIGURE 13-9. Schematic representation of a boiling-water nuclear reactor.
[Source: Cassedy and Grossman, op. cit.]

Figure 13-9 shows the essential features of the boiling-water reactor. Here the reactor vessel is under lower pressure (about 1000 pounds per square inch or sixty times the normal atmospheric pressure). The water boils within the vessel and there is no need for a secondary heat exchange loop for steam generation. A potential problem with this design is that radioactive water from the core leaves the containment building. Therefore, the likelihood that a leak will cause radioactive emissions into the environment is greater for BWR than for PWR.

The relative merits of boiling water reactors vs. pressurized water reactors is a complex issue which goes beyond the scope of our discussion. One advantage of BWR over PWR is easily understood, however: it has a self-control mechanism against the China syndrome, the most dreaded of all the possible nuclear accidents (see Chapter 15). It turns out that steam is not an effective moderator for neutrons. So, when for whatever reason the reactor starts to overheat, more steam is produced, but the number of moderated neutrons decreases; this in turn slows down the chain reaction and the reactor cools down by itself.

Nuclear Fuel Cycle

When we discussed fossil fuels, we concluded that before they can be used, some must undergo more extensive processing than others. A petroleum refinery is a complex fuel preparation plant, but it pales beside the preparation processes necessary for nuclear fuel utilization. Uranium, the most common nuclear fuel in today's commercial reactors, requires very extensive processing both before and after its use in the reactor. The various processing steps – as they are practiced today in nuclear power plants – are summarized in Figure 13-10. They constitute the *nuclear fuel cycle.*

Mining and Milling. Like fossil fuels and minerals, uranium ore can be found in the earth's crust. It is mined in much the same way as other minerals. Both surface and underground techniques are used. Abundant resources exist in the U.S., Australia, Canada, Gabon, South Africa and the former U.S.S.R. Figure 13-11 summarizes the production patterns for uranium oxide, U_3O_8 (obtained from uranium ore) in the U.S. in the last forty years. Greatly increased trade is seen in the 1990s as a consequence of the break-up of the Soviet Union and the end of the Cold War. With these ups and downs and the uncertainty about the future of nuclear energy, it is not easy to find reliable numbers for uranium reserves and resources. Often quoted numbers for proven reserves of U_3O_8, at $50/lb in 1979, are 2.9 million tons in the world and 0.9 million tons in the U.S. Current prices are much lower, however (about $10/lb). With the ongoing conversion of weapons-grade nuclear fuel to reactor-grade fuel – as a consequence of the end of the Cold War – these reserves are likely to increase quite substantially (see Investigation 13-4). Typically, one ton of ore contains 2-4 pounds of uranium oxide (U_3O_8). In this uranium compound, 99.3% of the uranium is nonfissionable U-238 and only the remaining 0.7% is fissionable U-235.

FIGURE 13-10. Nuclear fuel cycle.

FIGURE 13-11. Production, exports and imports of uranium oxide (U_3O_8) in the U.S. [Source: Energy Information Administration.]

Illustration 13-2. Calculate how many kilograms of U-235 there are in 100 kg of uranium oxide, U_3O_8.

Solution.
The molecule of uranium oxide consists of three atoms of uranium and eight atoms of oxygen. Since the molar masses of U and O atoms are 238 and 16 grams, respectively, we have:

$$\%U = \frac{3U}{U_3O_8} = \frac{(3)(238)}{(3)(238) + (8)(16)} = 0.85\ (85\%)$$

Hence, there are 85 kg of uranium in 100 kg of uranium oxide. Of these 85 kg, only 0.7% is U-235. Therefore,

$\%U\text{-}235 = (0.007)\ (0.85) = 0.006$

In other words, there are 0.6 kg of U-235 in 100 kg of U_3O_8.

The calculation shown in Illustration 13-2 is important because it allows us to place into perspective the supply of nuclear fuels in the U.S. and in the world. This is done in Illustration 13-3.

After mining, the uranium ore is subjected to milling, a chemical process in which the ore is enriched in U_3O_8 to form a ‘yellowcake’ containing approximately 85% U_3O_8. The solid residue from this operation, the so-called uranium mill tailings, may be an environmental hazard and needs to be disposed of properly.

Enrichment. This is the most difficult process in the fuel preparation part of the nuclear fuel cycle. The concentration of fissionable uranium-235 in the yellowcake is not sufficient to produce useful amounts of heat in a power plant. Therefore, uranium – which is a mixture of U-235 and U-238 – must be enriched to about 3-4% U-235. For explosion in bombs, an enrichment of close to 90% is needed. This is why a nuclear reactor can never explode: there is simply not enough fissionable fuel in it. Explosions can and did occur in nuclear power plants, but they were not explosions of nuclear fuel.

The most common process by which enrichment occurs is gaseous diffusion, which takes advantage of the fact that U-235 is lighter than U-238 and can thus travel faster. So the solid uranium oxide (U_3O_8) is converted to a gas, uranium hexafluoride (UF_6), and this gas is allowed to travel for miles until the desired separation and enrichment is achieved.

Fuel Fabrication. The UF_6 enriched in U-235 is then converted back into a solid, uranium dioxide (UO_2), and this oxide is fabricated into cylindrical pellets (typically 10 mm x15 mm). The pellets are placed into fuel rods which typically have a diameter of half an inch and are 10-14 feet long. The rods are placed inside the reactor to form the core. In a typical modern reactor with a capacity of about 1000 MW, the core may contain 50000 fuel rods and have dimensions of 10 ft x 15 ft. The reactor vessel itself may be 70 feet high and 20 feet wide. This is typically a smaller device than the boiler in a coal-fired power plant of similar capacity.

Fuel Burnup. The consumption of nuclear fuel in the reactor is a complex process. Uranium-235 in uranium dioxide is the fuel most commonly used. Its fission and the subsequent fission of its products (known in the jargon of the nuclear industry as ‘daughters’, ‘granddaughters’, etc.) are complex nuclear reactions that produce a number of radioactive substances within the reactor core, where most of the fission energy is released. For our purposes, however, only one additional nuclear reaction is of interest. It is summarized in Figure 13-12. It illustrates another mixed blessing in the use of nuclear energy. Uranium-238, which makes up 96-97% of the uranium present in the reactor, cannot be used as a fuel; it is a non-fissionable material. However, its reaction with neutrons produced in the reactor leads to the formation of plutonium-239 which is, like U-235, a fissionable material. Depending on the conditions of operation of the reactor, this process occurs to a greater or lesser extent. The extent to which it occurs is quantified as a *conversion ratio*, defined as the amount of fuel produced (primarily plutonium-239) divided by the amount of fuel consumed (primarily uranium-235). Conventional nuclear reactors, also called *converter* reactors, have conversion ratios less than one (CR < 1), typically about 0.6. In other words, for every 10 atoms of U-235 consumed, six atoms of Pu-239 are produced from U-238. If CR > 1, the reactor is called a *breeder*. This is illustrated schematically in Figure 13-13.

Illustration 13-3. Calculate how much U-235 is needed for the lifetime of a nuclear power plant that produces 1000 MW of electricity. Consider that the lifetime of the plant is 30 years and that its efficiency is 34%. Assume that the efficiency of conversion of nuclear energy to heat is 100% and that the power plant operates at 100% capacity.

Solution.
In Illustration 13-1, we calculated that 1 kg of U-235 can be converted into approximately 10^{11} BTUs of kinetic energy. The representative power plant used as an example produces 1000 MW of electricity, or

$$(10^9 \frac{\text{J}}{\text{s}})\,(\frac{3.15\text{x}10^7\ \text{s}}{1\ \text{year}})\,(\frac{1\ \text{BTU}}{1055\ \text{J}}) = 3.0\text{x}10^{13}\ \text{BTU/year}$$

At 34% efficiency, the thermal energy required to produce this amount of electricity is:

$$(\frac{3.0\text{x}10^{13}\ \text{BTU(electric)}}{\text{year}})\,(\frac{1\ \text{BTU (thermal)}}{0.34\ \text{BTU(electric)}}) = 8.8\text{x}10^{13}\ \text{BTU/year}$$

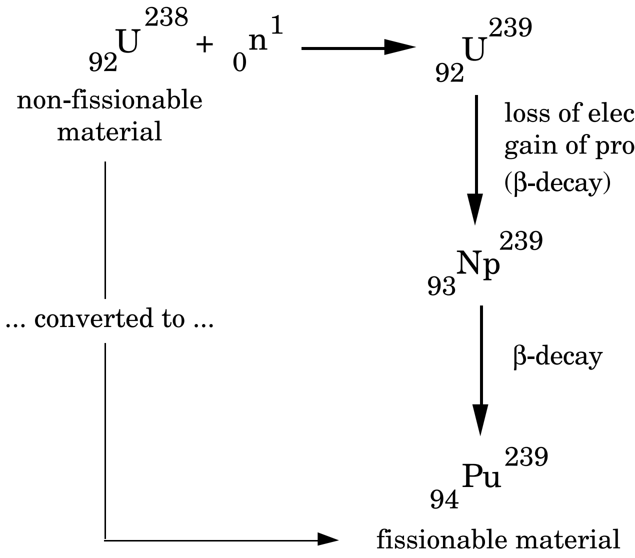
Over a lifetime of 30 years, the quantity of thermal energy required for one plant will be:

$$(\frac{8.8\text{x}10^{13}\ \text{BTU}}{1\ \text{year}})\,(30\ \text{years}) = 2.6\text{x}10^{15}\ \text{BTU}$$

Given the result of Illustration 13-1, we finally have:

$$(\frac{2.6\text{x}10^{15}\ \text{BTU}}{1\ \text{plant}})\,(\frac{1\ \text{kg U-235}}{10^{11}\ \text{BTU}}) = 26000\ \text{kg U-235/plant}$$

So about 26 tons of radioactive uranium are needed for a typical nuclear reactor. With this number and the information given in Figure 13-11, one can easily show that conventional nuclear fission is a depletable energy form.



$$\boxed{\mathrm{CR} = \frac{\text{Fuel produced}}{\text{Fuel consumed}}}$$

FIGURE 13-12
Illustration of the ‘breeding’ of ‘fertile’ material within a conventional fission reactor: nonfissionable uranium-238 is converted into fissionable plutonium-239.

FIGURE 13-13
Illustration of the difference between breeder reactors (CR > 1) and conventional reactors.

From a technical standpoint, the breeder reactor is close to being a commercial reality. While no such reactor is in operation in the U.S., France has had one (‘SuperPhoenix’) for many years and Japan is constructing one at a cost of $6.2 billion (see Investigation 13-2).

Breeder reactor technology is a mixed blessing. On one hand, if developed for nonmilitary applications, it would make nuclear fission a much less depletable energy form. Remember that 99.3% of the naturally occurring uranium is U-238. So, with this technology, compared to light-water-reactor technology, 100 times more energy can be obtained from the same amount of uranium. On the other hand, the production of plutonium in such a reactor makes the fuel enrichment process much easier. Now we have a fissionable substance that is chemically different from uranium. As such, it can be separated easily from the rest of the material in a fuel rod. The difficulty in separating U-235 from U-238 is that they are chemically identical substances. Once separated, the concentrated plutonium can be made easily into a nuclear bomb. This issue is explored further in Chapter 15.

Spent Fuel Reprocessing. Figure 13-13 shows that the inventory of fissionable uranium-235 decreases slowly to low values. It has been found impractical in commercial nuclear reactors to keep the fuel rods in the core until the fissionable material decays completely. At some point, before the fuel is consumed, the reproduction constant drops below one and the neutron inventory becomes too low to be able to sustain the chain reaction. At this point, refueling must take place (see Investigation 13-3). Typically, one fuel rod stays within the reactor for about three years and then it must be removed. Once removed, it is typically stored on site until it “cools off,” or until its radioactivity decays to less dangerous levels (see Chapter 15). This cooling process can take centuries and it would be a good idea to recycle the remaining fissionable material. Recycling would require spent fuel reprocessing, as shown in Figure 13-14. However, spent fuel reprocessing means separation of plutonium-239, and this provides bomb-making capability. Hence, this activity – which is commercially practiced today only in a handful of plants (located primarily in France, England and Japan) – is yet another highly controversial aspect of nuclear energy utilization.

Waste Disposal. No less controversial (and complex) is the issue of waste disposal. In a power plant that burns a fossil fuel, all the fuel is consumed and the waste is either used or stored without major technical problems. In contrast, once a nuclear reactor starts operating, it is not easy to shut it down or to ‘decommission’ it. The first U.S. ‘burial’ of a relatively small nuclear reactor (60 MW power plant at Shippingport, Pennsylvania) was completed not long ago, at a cost of about hundred million dollars (see Investigation 13-5).

At the moment, most of the spent fuel in commercial nuclear reactors is simply stored in water pools at the power plant site (see “USA's 122 nuclear plants,” in *USA Today* of 3/21/89). A more permanent disposal – yet to be realized on commercial scale – would involve enclosing the spent fuel within a glass material, storing the glass within a leak-tight capsule and finally burying the capsules in a deep salt mine. Such salt deposits are often preferred because their existence indicates that there has been no active groundwater in the area for centuries. Otherwise, the salt would have dissolved in it. The absence of water minimizes the risk of radioactive material being leached out and brought back to the surface. Nevertheless, the controversies over permanent storage facilities, such as that at Yucca Mountain in Nevada, have been going on for more than a decade now (see Chapter 15).

FIGURE 13-14. Nuclear fuel cycle including spent fuel reprocessing.

We conclude our discussion of the nuclear fuel cycle by noting, paradoxically, that the cycle remains open. At the dawn of the nuclear age, more than forty years ago, the prevailing attitude was that the lifetime of the first power plants would provide sufficient time to figure out how to close this cycle. Well, time is running out (see Chapter 15) and no clear technical solutions – let alone economic and socio-political ones – seem to be readily available. In Chapter 11 we saw that society is increasingly having difficulties in closing properly the *natural* carbon cycle, which has been 'operating' since life on earth began. Closing the nuclear fuel cycle – *artificially* initiated by society – will be even more difficult. If nuclear energy is set for a comeback, as a response to the greenhouse effect (see Investigation 13-1), this major technical, economic and political issue must be resolved soon.

What Happened at Three Mile Island?

Many books have been written and movies have been made about the malfunctioning of reactor No.2 at the Metropolitan Edison's Three Mile Island power plant, on March 28, 1979. It was the first major accident reported in a commercial nuclear power plant in the U.S. The most authoritative source of information on it is the “Report of the President's Commission on the Accident at Three Mile Island” (J.G. Kemeny, Chairman), Pergamon Press, New York, October 1979. For a novelized account, see, for example, “Three Mile Island,” by Mark Stephens, Random House, New York, 1980. Here we summarize very briefly what happened in this pressurized water reactor (see Figures 13-8 and 13-15). The technical information provided in Chapters 12 and 13 was chosen to allow the reader to grasp the basics of what went wrong at TMI and at Chernobyl.

The cause of the TMI accident was a combination of (a) mechanical failures, and (b) human error and lack of adequate training for emergency situations of the kind that developed in those critical hours. The sequence of events can be summarized as follows:

FIGURE 13-15. The pressurized-water reactor at Three Mile Island.

(1) During a routine repair of the water purification system in the secondary loop (the ‘polisher’), a valve in the secondary loop, which allows passage of water toward the steam

generator vessel, was accidentally closed. The turbine was thus shut down, but the reactor was still running.

(2) This interruption of flow of water to the steam generator is not an infrequent accident. When it happens, it requires that emergency feedwater supply from the water storage tanks be activated, to prevent the overheating of water in the primary loop. This was indeed done, but the operators did not realize that the addition of cooling water did not actually take place. This was because some valves between the water storage tanks and the primary water loop were accidentally left closed the previous day, during regular maintenance work.

(3) With no heat exchange (cooling) in the steam generator – the operators knew this – and no cooling by water from the emergency supply (unknown to the operators), the water in the primary loop overheated and boiled. This caused a pressure increase in the reactor. This in turn was a sign to shut down (or scram) the reactor, because the loss of coolant can lead to an overheating of the fuel rods and to the meltdown of the core. Continuous circulation of water through the primary and secondary loops is essential, however, because it takes some time for the reactor to cool down.

(4) When the pressure increased in the reactor vessel, a safety relief valve opened, to release the excess steam and bring the pressure down. However, when the pressure did decrease to the required level, the valve remained stuck in the open position, instead of automatically closing. The pressure decreased further. This combination of high temperature and low pressure of the water in the primary loop allowed further boiling of the water to take place. (Remember, this is a pressurized water reactor; water is not supposed to boil in it.)

(5) Significant quantities of radioactive steam thus escaped through the safety relief valve. The storage capacity of the drain tank for this water (condensed steam) was quickly exceeded, so the tank burst and the water had to be withdrawn to the auxiliary building, which is not as leak-tight as the containment building.

(6) The loss of coolant (water in primary loop) triggered the activation of yet another emergency system, a high-pressure direct water injection into the core. This did work. Alas it was prematurely stopped when a faulty reading indicated that an adequate water level had been restored. At this point, the water level in the reactor decreased further, “exposed the core” and a *partial* meltdown occurred.

(7) The now hot metallic material in the core (zirconium) reacted with water to form zirconium oxide. This process is accompanied by the release of hydrogen gas. A hydrogen bubble was thus created within the core. This gave rise to speculation about a possible explosion, in contact with oxygen; hydrogen is an excellent fuel. The explosion never occurred.

The radiation released during the accident is discussed in Chapter 15. The TMI reactor No. 2 is still shut down. The clean-up was completed only several years ago, at a cost that exceeded a billion dollars.

What Happened at Chernobyl?

In comparison with the accident at Three Mile Island, the accident at the RBMK-1000 reactor in Chernobyl (100 km north of Kiev in the Ukraine) – on April 26, 1986 – was much more serious. Indeed, it is the worst accident in the history of commercial nuclear power. Its consequences are also discussed in Chapter 15. Here we summarize what happened, with reference to Figure 13-16.

The RBMK-1000 is a 1000-MW, water-cooled, graphite-moderated reactor. It does not require a costly pressure vessel, because the pressurized water flows through individual tubes rather than between the fuel rods, as in a pressurized-water reactor. It also requires only a modest enrichment of U-235 (1.5%), because graphite is a better moderator of neutrons than water. However, this accident showed that the combination of a graphite moderator and a water coolant is more susceptible to a runaway chain reaction than other reactor designs and than the confident operators had thought.

The cause of the accident was unauthorized experimentation with the reactor. It is ironic that the experiment in question was a test of plant performance in the case of a minor accident. The sequence of events was as follows:

FIGURE 13-16. Schematic representation of the Chernobyl nuclear reactor.
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(1) During a planned shutdown for regular maintenance, an experiment was performed to test the turbine at low power (and thus low production of steam in the reactor).
(2) A staged power reduction was planned, but it was overdone, and the power dropped to 1% of its normal operation.
(3) In an attempt to raise the power back to the planned 25%, the control rods were removed almost completely, and this led to uncontrolled (runaway) fission, estimated at about 300,000 MW of heat, or 100 times more than normal.
(4) The large temperature increase that followed caused the evaporation of all the water and the meltdown of the core. The buildup of steam was so large that it blew away the roof of the building and radioactive products were released directly to the atmosphere.
(5) The hydrogen produced inside the reactor (by reaction of metals and graphite with steam) came into contact with oxygen in the air, and another explosion occurred.
(6) Finally the graphite itself reacted with oxygen, causing a fire inside the reactor.

The degree of damage was such that the population from a 30-kilometer radius (some 135,000) had to be evacuated; the effects were felt all over Europe. The area around Chernobyl will be radioactive for a long time. The reactor itself is entombed in concrete. It will have to be under strict and permanent vigilance for a very long time (see Chapter 15).

REVIEW QUESTIONS

13-1. Explain what is meant by a self-sustained chain reaction.

13-2. Explain the conceptual difference between a nuclear reactor and an atomic bomb.

13-3. A nuclear electric power plant produces 1000 MW of electricity at 35% efficiency. It produces heat by fission of uranium-235.
(a) Obtain the rate of consumption of this uranium, in nuclei per second, from the information provided in Illustration 13-1.
(b) If there are initially 2000 kg of U-235 in the reactor, estimate the approximate time when the fuel will have to be replaced.

13-4. Fill in the blanks: Conversion of chemical energy of fossil fuels involves the rearrangement of ___________ to form new _____________; this process is accompanied by heat release. On the other hand, conversion of nuclear energy involves the rearrangement of ___________ to form new ____________; this process is accompanied by a much _____________ release of heat.

13-5. Name the four principal components of a fission nuclear reactor.

13-6. Name the principal components of a nuclear power plant.

13-7. Explain the difference between a conventional fission reactor and a breeder reactor.

INVESTIGATIONS

13-1. Ever since concerns were raised about global warming, the nuclear energy industry has been ‘plotting’ a comeback. Has such a comeback occurred yet? See *Time* of 1/2/89 (“Nuclear Power Plots a Comeback”) and 4/29/91 (“Nuclear Power: Do we have a choice?”); PI of 9/9/90 (“Whence our energy? More nuclear power is the best alternative”); NYT of 10/8/90 (“Barriers Are Seen to Reviving Nuclear Industry”), 11/18/90 (“Reviving Nuclear Power From Its Coma”), 3/31/91 (“Can Nuclear Power Be Rehabilitated?”), 5/12/91 (“Is Nuclear Winter Giving Way to Nuclear Spring”) and 6/30/95 (“Outgoing N.R.C. Head Sees Nuclear Industry Revival”); *National Geographic* of 8/91 (“Our Electric Future: A comeback for nuclear power?”); *Economist* of 11/21/92 (“Nuclear power: Losing its charm”); and *World Watch* of May/June 1996 (“Meltdown”).

13-2. Find out about the most recent history of breeder reactors. See the *Proceedings of the American Philosophical Society*, Vol. 130 (3), p. 343, 1986 (“Are Breeders Still Necessary?”); NYT of 1/14/96 (“Japanese Suicide Linked To Nuclear Plant Leak”) and 2/24/96 (“Reactor Accident in Japan Imperils Energy Program”). See also Investigation 15-2.

13-3. Nuclear reactor refueling is a very important operation in power plants. Find out about some of the problems involved. See *Time* of 3/4/96 (“Warriors”); NYT of 5/26/96 (“Agency Discovers Refueling Errors at 14 Nuclear Power Plants”) and 9/3/96 (“A-Plant Managers Try Attitude Adjustment”).

13-4. Find out more about the effect of the end of the Cold War on the uranium industry. See “Market Place: Uranium Industry Hurt by Imports” in NYT of 11/19/91; and “A Grand Uranium Bargain” in NYT of 10/24/91.

13-5. Find out more about the challenges (and costs!) of decommissioning a nuclear power plant. You would expect that one can't just turn off the lights and leave. But are you ready for this: “When a Nuclear Reactor Dies, $98 Million is a Cheap Funeral,” *Smithsonian Magazine*, October 1989, p. 56? See also BW of 9/23/96 (“Giving new life to aging nuclear plants”).

13-6. Uranium mining, like coal mining, may be a hazardous occupation, but the diseases that could develop from it are quite different. Find out more about the main problems in uranium mines. See “‘These people were used as guinea pigs’” in BW of 10/15/90; “U.S. Fund Is Established to Pay Civilians Injured by Atomic Arms Program” in NYT of 10/16/90; and “A Legacy of Ashes: The Uranium Mines of Eastern Germany” in NYT of 3/19/91.

13-7. Find out more about the methods of uranium enrichment. See “Patents: A new method of uranium enrichment that might be used for bombs is ridiculed as unworkable” in NYT of 10/2/95.

13-8. Find out more about “smaller, safer and more flexible reactors” that are often advertised in the media by the nuclear industry. What is new in them? See “The Nuclear Industry Tries Again” in NYT of 11/26/89; “Next Generation Nuclear Reactors: Dare we build them?” in *Popular Science* of 4/90; “How to Build a Safer Reactor,” in *Time* of 4/29/91; and “Getting Nuclear Plants Down to Size” in NYT of 7/12/92.

13-9. December 2, 1992 was the 50th anniversary of the “chain reaction in Chicago that shook the world” (PI of 12/2/92). Make a summary of some of the media reports prepared for that occasion. Start with PI of 12/2/92, *USA Today* of 12/2/92 (“Half a Century of Nuclear Technology”) and NYT of 12/1/92 (“Milestones Of the Nuclear Era: A 50-Year Overview”). Also browse through some of the other periodicals of that time (*Newsweek*, *Time*, USNWR, etc.).

13-10. A typical operating lifetime of a nuclear power plant is 30-40 years. Some electric power plants want their nuclear reactors to run longer and to produce more electricity than they were designed for. Find out why they want to do this. See BW of 5/20/96 (“Hotter Nukes for Cooler Rates”).

13-11. In the African nation of Gabon there was a ‘natural’ nuclear reactor a few billion years ago. Nature ‘decommissioned’ it after several hundred thousand years of operation. Find out more about it. See *Scientific American* of 7/76 (“A Natural Fission Reactor”) and the *Journal of Chemical Education* of 6/76 (“Natural Nuclear Reactors: The Oklo phenomenon”).