CHAPTER 17

Nuclear Energy and the Environment

Indian Point Energy Center is a two-unit (originally three-unit) nuclear power plant installation on the eastern shore of the Hudson River within 24 miles of New York City. It must be relicensed, and, as the lower photograph shows, this is creating a major controversy about whether such an installation should be near tens of millions of people.

LEARNING OBJECTIVES

As one of the alternatives to fossil fuels, nuclear energy generates a lot of controversy. After reading this chapter, you should understand . . .

- What nuclear fission is and the basic components of a nuclear power plant;
- Nuclear radiation and its three major types;
- How radioisotopes affect the environment, and the major pathways of radioactive materials in the environment.
- The relationships between radiation doses and health;
- The advantages and disadvantages of nuclear power;
- What the future of nuclear power is likely to be.

CASE STUDY

Indian Point: Should a Nuclear Power Installation Operate Near One of America's Major Cities?

In 1962, after a series of contentious public hearings, Consolidated Edison began operating the first of three nuclear reactors at Indian Point, on the eastern shore of the Hudson River in Buchanan, New York, 38 km (24 mi) north of New York City. Indian Point's second and third reactors began operating in 1974 and 1976, respectively. The first unit had major problems and was finally shut down in 1974. The second and third have been operating since then, but their licenses run out in 2013 and 2015, respectively, and under U.S. law nuclear power plants must be relicensed. All three units are owned by Entergy Nuclear Northeast, a subsidiary of Entergy Corporation.

Twenty million people live within 80 km (50 miles) of this power plant, and this causes considerable concern. Joan Leary Matthews, a lawyer for the New York State Department of Environmental Conservation, said that "whatever the chances of a failure at Indian Point, the consequences could be catastrophic in ways that are almost too horrific to contemplate."[1]

The federal Nuclear Regulatory Commission (NRC) announced the beginning of the relicensing process on May 2, 2007. By 2008 the relicensing of the plant had become a regional controversy, opposed by the New York State government, Westchester County (where the plant is located), and a number of nongovernmental environmental organizations. The plant has operated for almost 50 years, so what's the problem?

There have been some: In 1980, one of the plant's two units filled with water (an operator's mistake). In 1982, the same unit's steam generator piping leaked and released radioactive water. In 1999, it shut down unexpectedly, but operators didn't realize it until the next day, when the batteries that automatically took over ran down. In April 2007, a transformer burned in the second unit, radioactive water leaked into groundwater, and the source of the leak was difficult to find. Most recently, in 2009, a leak in the cooling system allowed 100,000 gallons of water to escape from the main system. Uneasiness about the plant's location increased after the terror attack on September 11, 2001. One of the hijacked jets flew close to the plant, and diagrams of unspecified nuclear plants in the United States have since been found in al Qaeda hideouts in Afghanistan.[2]

Proponents of nuclear power say these are minor problems, and there has been no major one. As far as they can tell, the plant is safe. The Energy Policy Act of 2005 promoted nuclear energy, and the Obama administration is moving ahead with federal funding of nuclear power plants. For 2010, the administration has allocated $18.5 billion for new "next-generation" nuclear power plants. Others, however, such as New York State's attorney general Andrew Cuomo, believe the location is just too dangerous, and he has asked the Nuclear Regulatory Commission to deny Indian Point's relicensing, saying that it has "a long and troubling history of problems."

The conflict at Indian Point illustrates the worldwide debate about nuclear energy. Growing concern about fossil fuels has led to calls for increased use of nuclear power despite unanswered questions and unsolved problems regarding its use. This chapter provides a basis for you to decide whether nuclear power could be, and should be, a bigger supplier of energy in the future. We begin with the basics about the nature of nuclear energy, then go on to explore nuclear reactors, radiation, accidents, waste management, and the future of nuclear power.

17.1 Current Role of Nuclear Power Plants in World Energy Production

Today, nuclear power provides about 17% of the world's electricity and 4.8% of the total energy. In the United States, 104 nuclear power plants produce about 20% of the country's electricity and about 8% of the total energy used (Figure 17.1).[3] Worldwide, there are 436 operating nuclear power plants.[4] Nations differ greatly in the amount of energy they obtain from these plants. France ranks first, with about 80% of its electricity produced by nuclear energy (Table 17.1). The United States ranks tenth in the percentage of electricity it obtains from nuclear power plants.

Most of the world's nuclear power plants are in North America, Western Europe, Russia, China, and In-

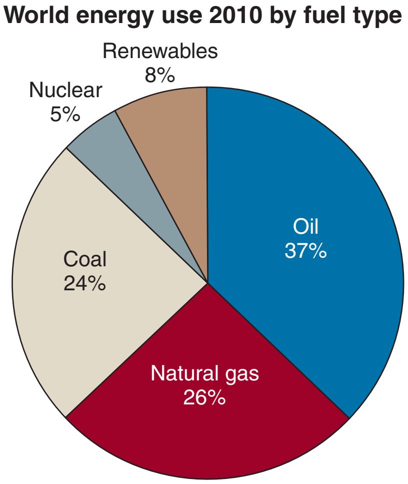

FIGURE 17.1 World energy use. (*Source*: D.B. Botkin, 2010.)

Table 17.1 LEADING NATIONS IN THE USE OF NUCLEAR ENERGY

COUNTRY	% TOTAL ELECTRICITY	GENERATION (MILLION KWH)
France	78%	368,188
Belgium	60%	41,927
Sweden	43%	61,395
Spain	36%	56,060
S. Korea	36%	58,138
Ukraine	33%	75,243
Germany	29%	153,476
Japan	28%	249,256
United Kingdom	28%	89,353
United States	19%	610,365
Canada	18%	94,823
Russia	12%	119,186
World Totals*	18%	2,167,515

(*Source*: D.B. Botkin, 2010.)

dia (Figure 17.2). Most of the U.S. nuclear power plants are in the eastern half of the nation (Figure 17.3). The very few west of the Mississippi River are in Washington, California, Arizona, Nebraska, Kansas, and Texas. The last nuclear plant to be completed in the United States went on line in 1996. However, since the early 1990s, U.S. nuclear plants have added over 23,000 MW, equivalent to the output of 23 large fossil fuel–burning power plants. The electricity produced from nuclear power plants increased 33% between 1980 and 2001, because only two thirds of their capacity was used in 1980, but this increased to more than 90% by 2002. Even if all these power plants operated at only 66% of their capacity, this would be the equivalent of building four new nuclear power plants.

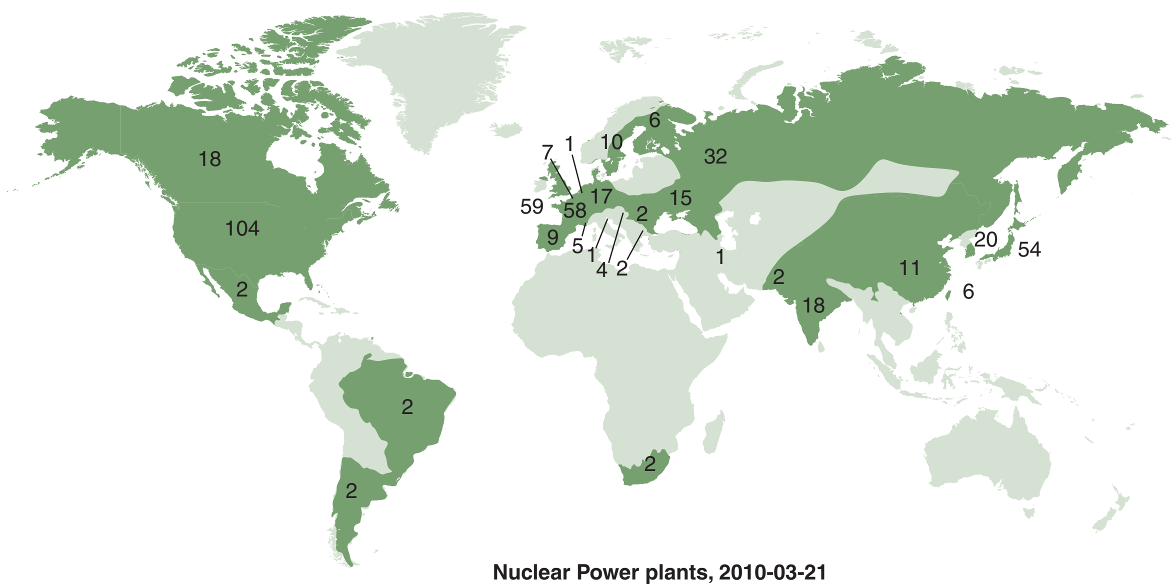

FIGURE 17.2 Where major nuclear power plants are worldwide. (*Source*: Informationskreis KernEnergie, Berlin.)

FIGURE 17.3 Where nuclear power plants are in the United States. (*Source*: http://www.insc.anl.gov/pwrmaps/)

17.2 What Is Nuclear Energy?

Hard as it may be to believe, **nuclear energy** is the energy contained in an atom's nucleus. Two nuclear processes can be used to release that energy to do work: fission and fusion. Nuclear **fission** is the splitting of atomic nuclei, and nuclear **fusion** is the fusing, or combining, of atomic nuclei. A by-product of both fission and fusion is the release of enormous amounts of energy. (Radiation and related terms are explained in A Closer Look 17.1. You may also wish to review the discussion of matter and energy in Chapter 14's A Closer Look 14.1.)

Nuclear energy for commercial use is produced by splitting atoms in **nuclear reactors**, which are devices that produce controlled nuclear fission. In the United States, almost all of these reactors use a form of uranium oxide as fuel.

Nuclear *fusion*, despite decades of research to try to develop it, remains only a theoretical possibility.

Conventional Nuclear Reactors

The first human-controlled nuclear fission, demonstrated in 1942 by Italian physicist Enrico Fermi at the University of Chicago, led to the development of power plants that could use nuclear energy to produce electricity. Today, in addition to power plants to supply electricity for homes and industry, nuclear reactors power submarines, aircraft carriers, and icebreaker ships.

Nuclear fission produces much more energy per kilogram of fuel than other fuel-requiring sources, such as biomass and fossil fuels. For example, 1 kilogram (2.2 lb) of uranium oxide produces about the same amount of heat as 16 metric tons of coal.

Three types—isotopes—of uranium occur in nature: uranium-238, which accounts for approximately 99.3% of all natural uranium; uranium-235, which makes up about 0.7%; and uranium-234, about 0.005%. However, uranium-235 is the only naturally occurring fissionable (or *fissile*) material and is therefore essential to the production of nuclear energy. A process called *enrichment* increases the concentration of uranium-235 from 0.7% to about 3%. This enriched uranium is used as fuel.

The spontaneous decay of uranium atoms emits neutrons. Fission reactors split uranium-235 by neutron bombardment. This releases more neutrons than it took to create the first splitting (Figure 17.4). These released neutrons strike other uranium-235 atoms, releasing still more neutrons, other kinds of radiation, fission products, and heat. This is the "chain reaction" that is so famous, both for nuclear power plants and nuclear bombs— as the process continues, more and more uranium is split, releasing more neutrons and more heat. The neutrons released are fast-moving and must be slowed down slightly (*moderated*) to increase the probability of fission.

All nuclear power plants use coolants to remove excess heat produced by the fission reaction. The rate of generation of heat in the fuel *must match* the rate at which heat is carried away by the coolant. Major nuclear accidents have occurred when something went wrong with the balance and heat built up in the reactor core.[5] The well-known term **meltdown** refers to a nuclear accident in which the coolant system fails, allowing the nuclear fuel to become so hot that it forms a molten mass that breaches the containment of the reactor and contaminates the outside environment with radioactivity.

The nuclear steam-supply system includes heat exchangers (which extract heat produced by fission) and primary coolant loops and pumps (which circulate the

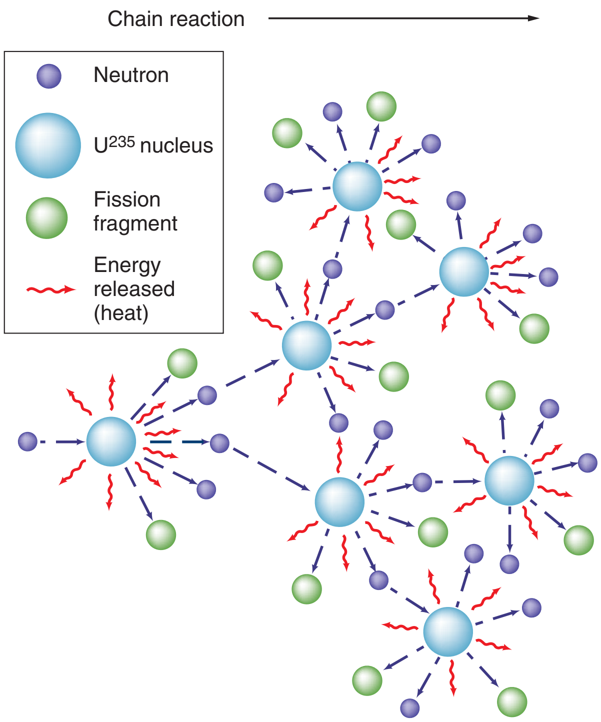

FIGURE 17.4 Fission of uranium-235. A neutron strikes the U-235 nucleus, producing fission fragments and free neutrons and releasing heat. The released neutrons may then strike other U-235 atoms, releasing more neutrons, fission fragments, and energy. As the process continues, a chain reaction develops.

coolant through the reactor). The heat is used to boil water, releasing steam that runs conventional steam-turbine electrical generators (Figure 17.5). In most common reactors, ordinary water is used as the coolant as well as the moderator. Reactors that use ordinary water are called "light water reactors" because there is also "heavy water," which combines deuterium with oxygen.[6]

Most reactors now in use consume more fissionable material than they produce and are known as **burner reactors**. Figure 17.6 shows the main components of a reactor: the core (consisting of fuel and moderator), control rods, coolant, and reactor vessel. The core is enclosed in the heavy, stainless-steel reactor vessel; then, for safety and security, the entire reactor is contained in a reinforced-concrete building.

In the reactor core, fuel pins—enriched uranium pellets in hollow tubes (3–4 m long and less than 1 cm, or 0.4 in., in diameter)—are packed together (40,000 or more in a reactor) in fuel subassemblies. A minimum fuel concentration is necessary to keep the reactor *critical*—that is, to achieve a self-sustaining chain reaction.

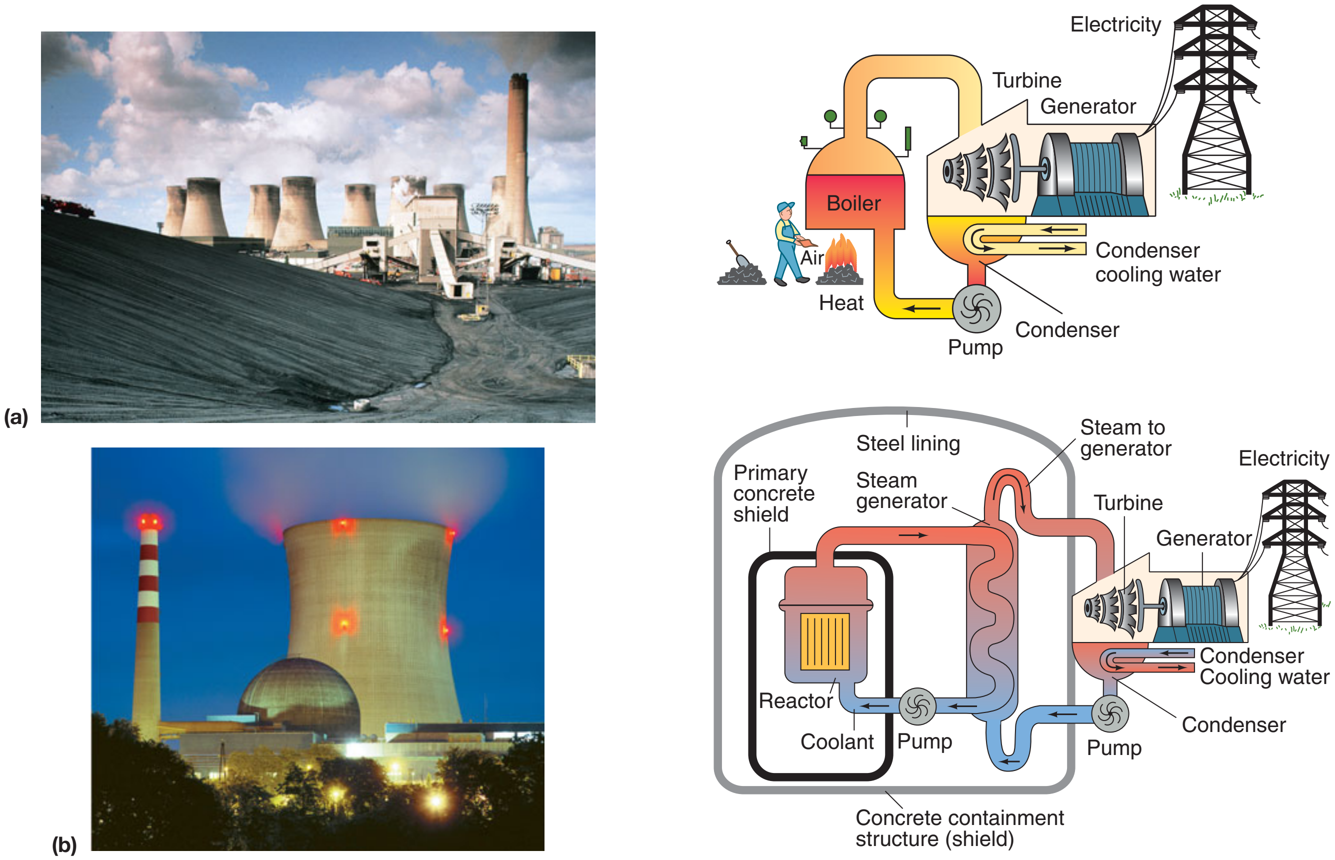

FIGURE 17.5 Comparison of **(a)** a fossil-fuel power plant and **(b)** a nuclear power plant with a boiling-water reactor. Notice that the nuclear reactor has exactly the same function as the boiler in the fossil-fuel power plant. The coal-burning plant **(a)** is Ratcliffe-on-Saw, in Nottinghamshire, England, and the nuclear power station **(b)** is in Leibstadt, Switzerland. (*Source*: American Nuclear Society, *Nuclear Power and the Environment*, 1973.)

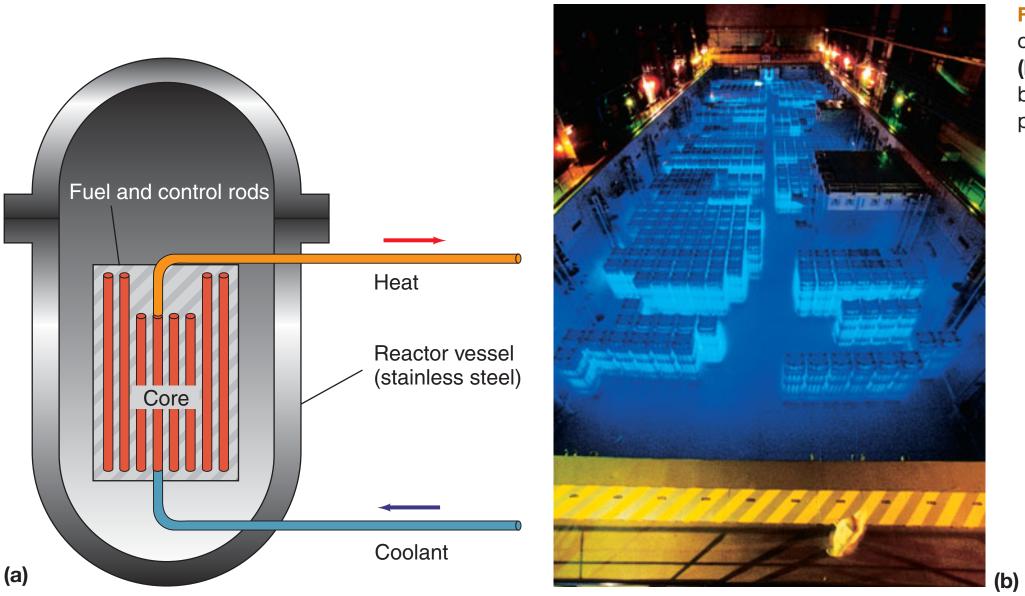

FIGURE 17.6 **(a)** Main components of a nuclear reactor. **(b)** Glowing spent fuel elements being stored in water at a nuclear power plant.

A CLOSER LOOK 17.1

Radioactive Decay

To many people, radiation is a subject shrouded in mystery. They feel uncomfortable with it, learning from an early age that nuclear energy may be dangerous because of radiation and that nuclear fallout from detonation of atomic bombs can cause widespread human suffering. One thing that makes radiation scary is that we cannot see it, taste it, smell it, or feel it. In this closer look, we try to demystify some aspects of radiation by discussing the process of radiation, or radioactivity.

First, we need to understand that radiation is a natural process, as old as the universe. Understanding the process of radiation involves understanding the **radioisotope**, a form of a chemical element that spontaneously undergoes **radioactive decay**. During the decay process, the radioisotope changes from one isotope to another and emits one or more kinds of radiation (Figure 17.7).

You may recall from Chapter 6 that isotopes are atoms of an element that have the same atomic number (the number of protons in the nucleus) but that vary in atomic mass number (the number of protons plus neutrons in the nucleus). For example, two isotopes of uranium are $^{235}U_{92}$ and $^{238}U_{92}$. The atomic number for both isotopes of uranium is 92 (revisit Figure 6.8); however, the atomic mass numbers are 235 and 238. The two different uranium isotopes may be written as uranium-235 and uranium-238 or ^{235}U and ^{238}U.

An important characteristic of a radioisotope is its *half-life*, the time required for one-half of a given amount of the isotope to decay to another form. Uranium-235 has a half-life of 700 million years, a very long time indeed! Radioactive carbon-14 has a half-life of 5,570 years, which is in the intermediate range, and radon-222 has a relatively short half-life of 3.8 days. Other radioactive isotopes have even shorter half-lives; for example, polonium-218 has a half-life of about 3 minutes, and still others have half-lives as short as a fraction of a second.

There are three major kinds of nuclear radiation: *alpha particles, beta particles*, and *gamma rays*. An alpha particle consists of two protons and two neutrons (a helium nucleus) and has the greatest mass of the three types of radiation (Figure 17.7a). Because alpha particles have a relatively high mass, they do not travel far. In air, alpha particles can travel approximately 5–8 cm (about 2–3 in.) before they stop. However, in living tissue, which is much denser than air, they can travel only about 0.005–0.008 cm (0.002–0.003 in.). Because this is a very short distance, they can't cause damage to living cells unless they originate very close to the cells. Also, alpha particles can be stopped by a sheet or so of paper.

Beta particles are electrons and have a mass of 1/1,840 of a proton. Beta decay occurs when one of the protons or

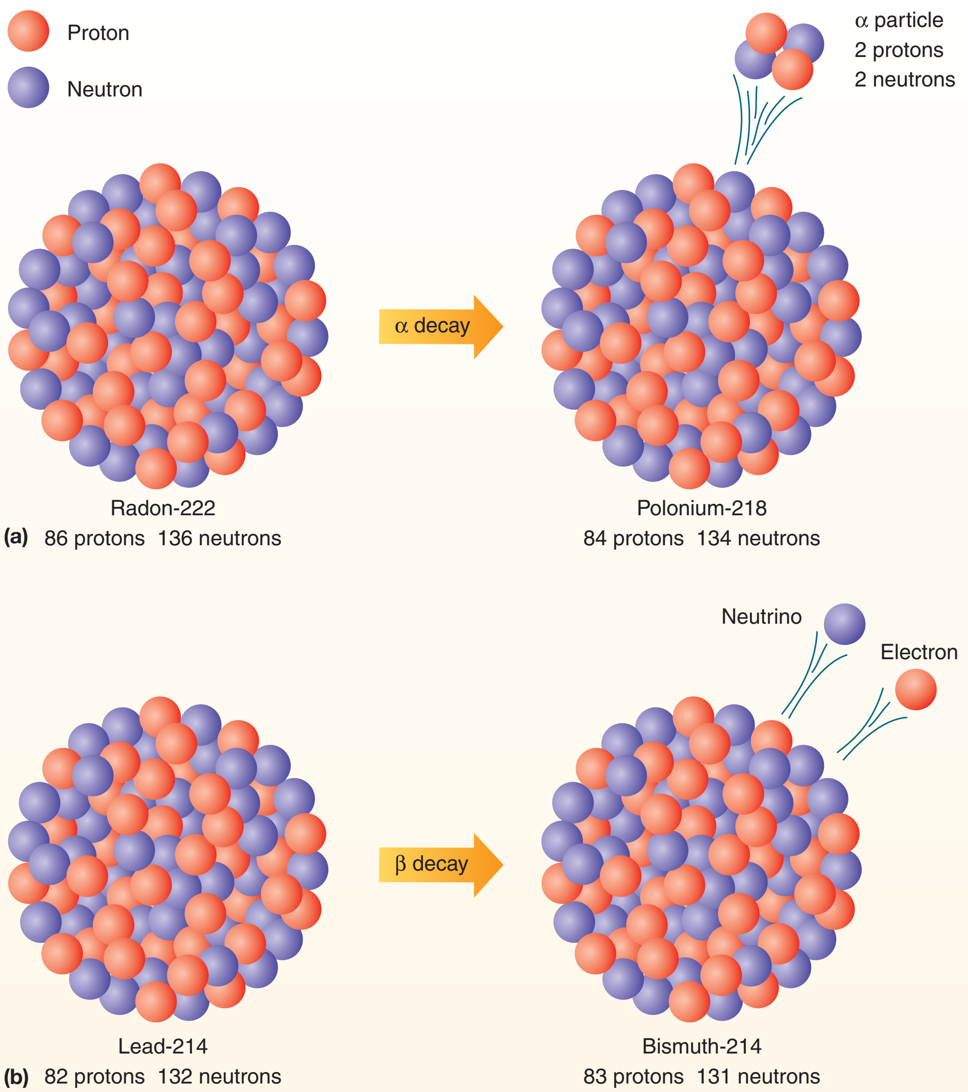

FIGURE 17.7 (Idealized diagrams showing **(a)** alpha and **(b)** beta decay processes. (*Source*: D. J. Brenner, *Radon: Risk and Remedy* [New York: Freeman, 1989]. Copyright 1989 by W.H. Freeman & Company. Reprinted with permission.)

neutrons in the nucleus of an isotope spontaneously changes. What happens is that a proton turns into a neutron, or a neutron is transformed into a proton (Figure 17.7b). As a result of this process, another particle, known as a *neutrino*, is also ejected. A neutrino is a particle with no *rest mass* (the mass when the particle is at rest with respect to an observer).[8] Beta particles travel farther through air than the more massive alpha particles but are blocked by even moderate shielding, such as a thin sheet of metal (aluminum foil) or a block of wood.

The third and most penetrating type of radiation comes from *gamma decay*. When gamma decay occurs, a gamma ray, a type of electromagnetic radiation, is emitted from the isotope. Gamma rays are similar to X-rays but are more energetic and penetrating; and of all types of radiation, they travel the longest average distance. Protection from gamma rays requires thick shielding, such as about a meter of concrete or several centimeters of lead.

Each radioisotope has its own characteristic emissions: Some emit only one type of radiation; others emit a mixture. In addition, the different types of radiation have different toxicities (potential to harm or poison). In terms of human health and the health of other organisms, alpha radiation is most toxic when inhaled or ingested. Because alpha radiation is stopped within a very short distance by living tissue, much of the damaging radiation is absorbed by the tissue. When alpha-emitting isotopes are stored in a container, however, they are relatively harmless. Beta radiation has intermediate toxicity, although most beta radiation is absorbed by the body when a beta emitter is ingested. Gamma emitters are dangerous inside or outside the body; but when they are ingested, some of the radiation passes out of the body.

Each radioactive isotope has its own half-life. Isotopes with very short half-lives are present only briefly, whereas those with long half-lives remain in the environment for long periods. Table 17.2 illustrates the general pattern for decay in terms of the elapsed half-lives and the fraction remaining. For example, suppose we start with 1g polonium-218 with a half-life of approximately 3 minutes. After an elapsed time of 3 minutes, 50% of the polonium-218 remains. After 5 elapsed half-lives, or 15 minutes, only 3% is still present; and after 10 elapsed half-lives (30 minutes),

Table 17.2 GENERALIZED PATTERN OF RADIOACTIVE DECAY

ELAPSED HALF-LIFE	FRACTION REMAINING	PERCENT REMAINING
0	—	100
1	1/2	50
2	1/4	25
3	1/8	13
4	1/16	6
5	1/32	3
6	1/64	1.5
7	1/128	0.8
8	1/256	0.4
9	1/512	0.2
10	1/1024	0.1

0.1% is still present. Where has the polonium gone? It has decayed to lead-214, another radioactive isotope, which has a half-life of about 27 minutes. The progression of changes associated with the decay process is often known as a *radioactive decay chain*. Now suppose we had started with 1 g uranium-235, with a half-life of 700 million years. Following 10 elapsed half-lives, 0.1% of the uranium would be left—but this process would take 7 billion years.

Some radioisotopes, particularly those of very heavy elements such as uranium, undergo a series of radioactive decay steps (a decay chain) before finally becoming stable, nonradioactive isotopes. For example, uranium decays through a series of steps to the stable nonradioactive isotope of lead. A decay chain for uranium-238 (with a half-life of 4.5 billion years) to stable lead-206 is shown in Figure 17.8. Also listed are the half-lives and types of radiation that occur during the transformations. Note that the simplified radioactive decay chain shown in Figure 17.8 involves 14 separate transformations and includes several environmentally important radioisotopes, such as radon-222, polonium-218, and lead-210. The decay from one radioisotope to another is often stated in terms of parent and daughter products. For example, uranium-238 is the parent of daughter product thorium-234.

Radioisotopes with short half-lives initially have a more rapid rate of change (nuclear transformation) than do radioisotopes with long half-lives. Conversely, radioisotopes with long half-lives have a less intense and slower initial rate of nuclear transformation but may be hazardous much longer.[9]

To sum up, when considering radioactive decay, two important facts to remember are (1) the half-life and (2) the type of radiation emitted.

Radioactive Elements	Radiation Emitted			Half-life		
	Alpha	Beta	Gamma	Minutes	Days	Years
Uranium-238	☢		☢			4.5 billion
Thorium-234		☢	☢		24.1	
Protactinium-234		☢	☢	1.2		
Uranium-234	☢		☢			247,000
Thorium-230	☢		☢			80,000
Radium-226	☢		☢			1,622
Radon-222	☢				3.8	
Polonium-218	☢	☢		3.0		
Lead-214		☢	☢	26.8		
Bismuth-214		☢	☢	19.7		
Polonium-214	☢			0.00016 (sec)		
Lead-210		☢	☢			22
Bismuth-210		☢			5.0	
Polonium-210	☢		☢		138.3	
Lead-206	None			Stable		

FIGURE 17.8 Uranium-238 decay chain. (*Source*: F. Schroyer, ed., *Radioactive Waste*, 2nd printing [American Institute of Professional Geologists, 1985].)

A stable fission chain reaction in the core is maintained by controlling the number of neutrons that cause fission. Control rods, which contain materials that capture neutrons, are used to regulate the chain reaction. As the control rods are moved out of the core, the chain reaction increases; as they are moved into the core, the reaction slows. Full insertion of the control rods into the core stops the fission reaction.[7]

17.3 Nuclear Energy and the Environment

The **nuclear fuel cycle** begins with the mining and processing of uranium, its transportation to a power plant, its use in controlled fission, and the disposal of radioactive waste. Ideally, the cycle should also include the reprocessing of spent nuclear fuel, and it must include the decommissioning of power plants. Since much of a nuclear power plant becomes radioactive over time from exposure to radioisotopes, disposal of radioactive wastes eventually involves much more than the original fuel.

Throughout this cycle, radiation can enter and affect the environment (Figure 17.9).

Problems with the Nuclear Fuel Cycle

- Uranium mines and mills produce radioactive waste that can expose mining workers and the local environment to radiation. Radioactive dust produced at mines and mills can be transported considerable distances by wind and water, so pollution can be widespread. Tailings—materials removed by mining but not processed—are generally left at the site, but in some instances radioactive mine tailings were used in foundations and other building materials, contaminating dwellings.
- Uranium-235 enrichment and the fabrication of fuel assemblies also produce radioactive waste that must be carefully handled and disposed of.
- Site selection and construction of nuclear power plants in the United States are highly controversial. The environmental review process is extensive and expensive, often centering on hazards related to such events as earthquakes.
- The power plant or reactor is the site most people are concerned about because it is the most visible part of the cycle. It is also the site of past accidents, including partial meltdowns that have released harmful radiation into the environment.
- The United States does not reprocess spent fuel from reactors to recover uranium and plutonium at this time. However, many problems are associated with the handling and disposal of nuclear waste, as discussed later in this chapter.
- Waste disposal is controversial because no one wants a nuclear waste disposal facility nearby. The problem is that no one has yet figured out how to isolate nuclear waste for the millions of years that it remains hazardous.

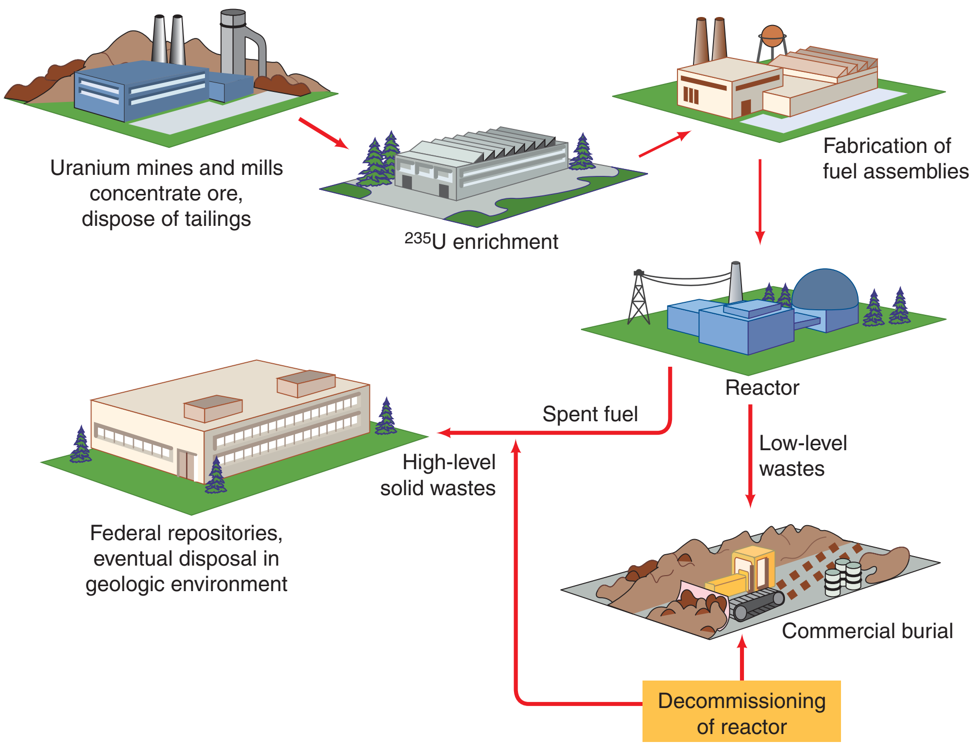

FIGURE 17.9 Idealized diagram showing the nuclear fuel cycle for the U.S. nuclear energy industry. Disposal of tailings, which because of their large volume may be more toxic than high-level waste, was treated casually in the past. (*Source*: Office of Industry Relations, The Nuclear Industry, 1974.)

- Nuclear power plants have a limited lifetime, usually estimated at only several decades, but decommissioning a plant (removing it from service) or modernizing it is a controversial part of the cycle and one with which we have little experience. For one thing, like nuclear waste, contaminated machinery must be safely disposed of or securely stored indefinitely.

Decommissioning or refitting a nuclear plant will be very expensive (perhaps several hundred million dollars) and is an important aspect of planning for the use of nuclear power. It will cost more to dismantle a nuclear reactor than to build it. At present, as we saw in this chapter's opening case study, power companies are filing to extend the licenses of several nuclear power plants that were originally slated to be decommissioned and taken down.

In addition to the above list of hazards in transporting and disposing of radioactive material, there are potential hazards in supplying other nations with reactors. Terrorist activity and the possibility of irresponsible people in governments add risks that are not present in any other form of energy production. For example, Kazakhstan inherited a large nuclear weapons testing facility, covering hundreds of square kilometers, from the former Soviet Union. The soil in several sites contains "hot spots" of plutonium that pose a serious problem of toxic contamination. The facility also poses a security problem. There is international concern that this plutonium could be collected and used by terrorists to produce "dirty" bombs (conventional explosives that disperse radioactive materials). There may even be enough plutonium to produce small nuclear bombs.

Nuclear energy may indeed be one answer to some of our energy needs, but with nuclear power comes a level of responsibility not required by any other energy source.

17.4 Nuclear Radiation in the Environment, and Its Effects on Human Health

Ecosystem Effects of Radioisotopes

As explained in A Closer Look 17.1, a radioisotope is an isotope of a chemical element that spontaneously undergoes radioactive decay. Radioisotopes affect the environment in two ways: by emitting radiation that affects other materials and by entering the normal pathways of mineral cycling and ecological food chains.

The explosion of a nuclear weapon does damage in many ways. At the time of the explosion, intense radiation of many kinds and energies is sent out, killing organisms directly. The explosion generates large amounts of radioactive isotopes, which are dispersed into the environment. Nuclear bombs exploding in the atmosphere produce a huge cloud that sends radioisotopes directly into the stratosphere, where the radioactive particles are widely dispersed by winds. Atomic fallout—the deposit of these radioactive materials around the world—was an environmental problem in the 1950s and 1960s, when the United States, the former Soviet Union, China, France, and Great Britain were testing and exploding nuclear weapons in the atmosphere.

The pathways of some of these isotopes illustrate the second way in which radioactive materials can be dangerous in the environment: They can enter ecological food chains (Figure 17.10). Let's consider an example. One of the radioisotopes emitted and sent into the stratosphere by atomic explosions was cesium-137. This radioisotope was deposited in relatively small concentrations but was widely dispersed in the Arctic region of North America. It fell on reindeer moss, a lichen that is a primary winter food of the caribou. A strong seasonal trend in the levels of cesium-137 in caribou was discovered; the level was highest in winter, when reindeer moss was the principal food, and lowest in summer. Eskimos who obtained a high percentage of their protein from caribou ingested the radioisotope by eating the meat, and their bodies concentrated the cesium. The more that members of a group depended on caribou as their primary source of food, the higher the level of the isotope in their bodies.

People are exposed to a variety of radiation sources from the sky, the air, and the food we eat (Figure 17.11). We receive natural background radiation from cosmic rays entering Earth's atmosphere from space, and from naturally occurring radioisotopes in soil and rock. The average American receives about 2 to 4 mSv/yr. Of this, about 1 to 3 mSv/yr, or 50–75%, is natural. The differences are primarily due to elevation and geology. More cosmic radiation from outer space (which delivers about 0.3–1.3 mSv/yr) is received at higher elevations.

Radiation from rocks and soils (such as granite and organic shales) containing radioactive minerals delivers about 0.3 to 1.2 mSv/yr. The amount of radiation delivered from rocks, soils, and water may be much larger in areas where radon gas (a naturally occurring radioactive gas) seeps into homes. As a result, mountain states that also have an abundance of granitic rocks, such as Colorado, have greater background radiation than do states that have a lot of limestone bedrock and are low in elevation, such as Florida. Despite this general pattern, locations in Florida where phosphate deposits occur have above-average background radiation because of a relatively high uranium concentration in the phosphate rocks.[10]

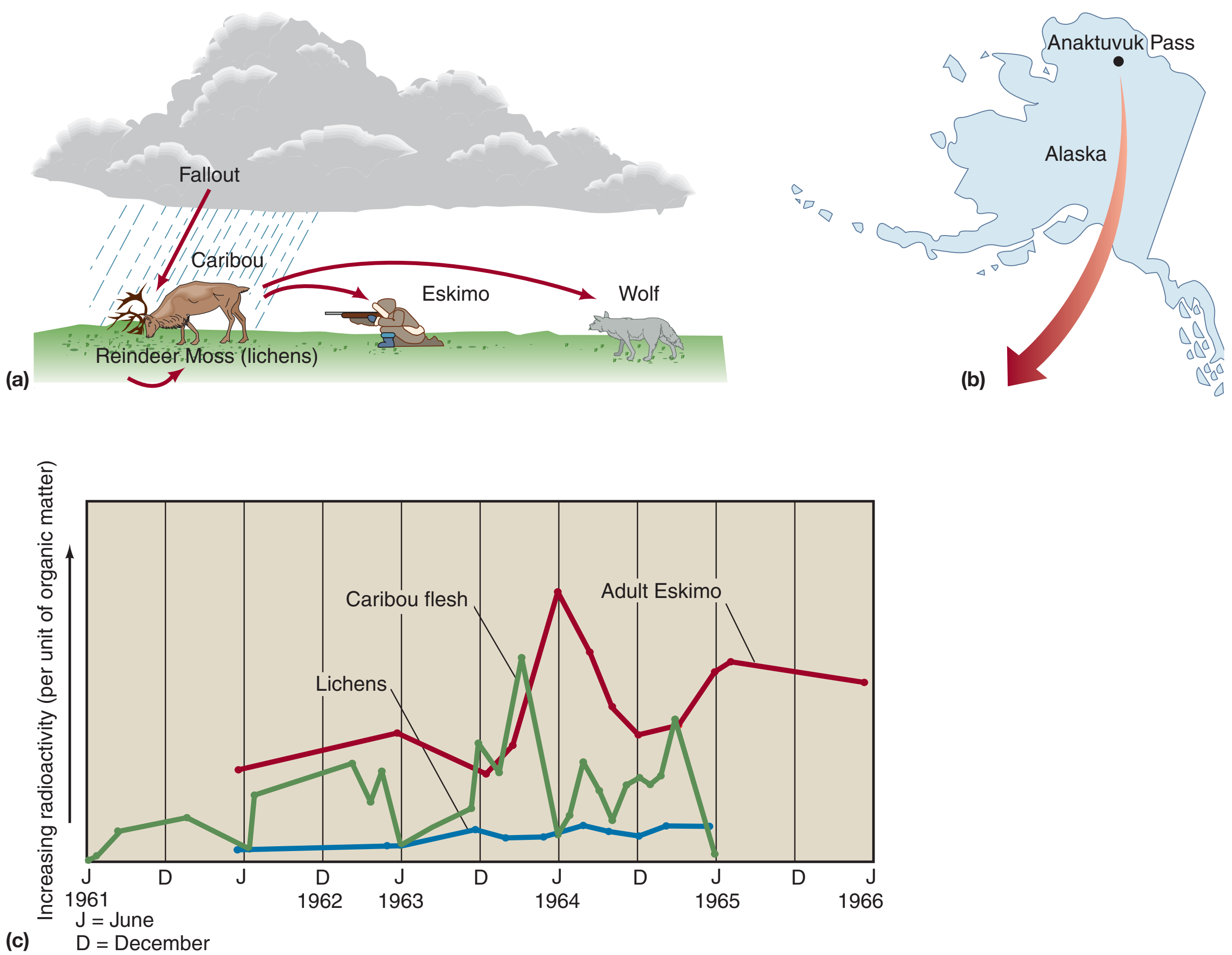

FIGURE 17.10 Cesium-137 released into the atmosphere by atomic bomb tests was part of the fallout deposited on soil and plants. **(a)** The cesium fell on lichens, which were eaten by caribou. The caribou were in turn eaten by Eskimos. **(b)** Measurements of cesium were taken in the lichens, caribou, and Eskimo in the Anaktuvuk Pass of Alaska. **(c)** The cesium was concentrated by the food chain. Peaks in concentrations occurred first in the lichens, then in the caribou, and last in the Eskimos. (*Source*: [c] W.G. Hanson, "Cesium-137 in Alaskan Lichens, Caribou, and Eskimos," *Health Physics* 13 [1967]: 383–389. Copyright 1967 by Pergamon Press. Reprinted with permission.)

The amount of radiation we receive from our own bodies and other people is about 1.35 mSv/yr. Two sources are naturally occurring radioactive potassium-40 and carbon-14, which are present in our bodies and produce about 0.35 mSv/yr. Potassium is an important electrolyte in our blood, and one isotope of potassium (potassium-40) has a very long half-life. Although potassium-40 makes up only a very small percentage of the total potassium in our bodies, it is present in all of us. In short, we are all slightly radioactive, and if you choose to share your life with another person, you are also exposing yourself to a little bit more radiation.

To understand the effects of radiation, you need to be acquainted with the units used to measure radiation and the amount or dose of radiation that may cause a health problem. These are explained in A Closer Look 17.2.

Sources of low-level radiation from our modern technology include X-rays for medical and dental purposes, which may deliver an average of 0.8–0.9 mSv/yr; nuclear weapons testing, approximately 0.04 mSv/yr; the burning of fossil fuels, such as coal, oil, and natural gas, 0.03 mSv/yr; and nuclear power plants (under normal operating conditions), 0.002 mSv/yr.[12]

Your occupation and lifestyle can affect the annual dose of radiation you receive. If you fly at high altitudes in jet aircraft, you receive an additional small dose of radiation—about 0.05 mSv for each flight across the

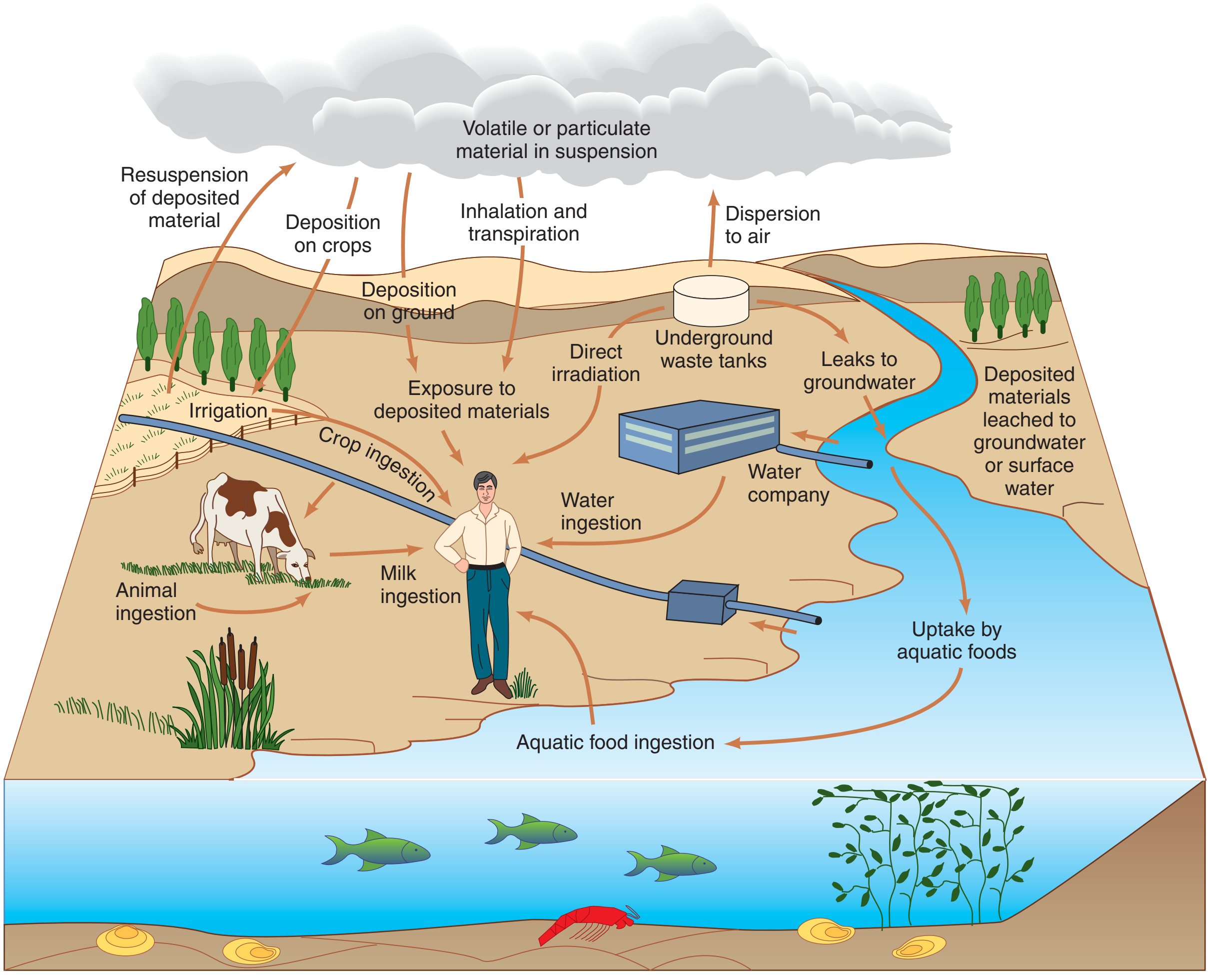

FIGURE 17.11 How radioactive substances reach people. (*Source*: F. Schroyer, ed., *Radioactive Waste*, 2nd printing [American Institute of Professional Geologists, 1985].)

A CLOSER LOOK 17.2

Radiation Units and Doses

The units used to measure radioactivity are complex and somewhat confusing. Nevertheless, a modest acquaintance with them is useful in understanding and talking about radiation's effects on the environment.

A commonly used unit for radioactive decay is the *curie* (Ci), a unit of radioactivity defined as 37 billion nuclear transformations per second. The curie is named for Marie Curie and her husband, Pierre, who discovered radium in the 1890s. They also discovered polonium, which they named after Marie's homeland, Poland. The harmful effects of radiation were not known at that time, and both Marie Curie and her daughter died of radiation-induced cancer.[11] Her laboratory (Figure 17.12) is still contaminated today.

In the International System (SI) of measurement, the unit commonly used for radioactive decay is the *becquerel* (Bq), which is one radioactive decay per second. Units of measurement often used in discussions of radioactive isotopes, such as radon-222, are becquerels per cubic meter and *picocuries* per liter (pC/l). A picocurie is one-trillionth (10^{-12}) of a curie. Becquerels per cubic meter or picocuries

FIGURE 17.12 Marie Curie in her laboratory.

per liter are therefore measures of the number of radioactive decays that occur each second in a cubic meter or liter of air.

When dealing with the environmental effects of radiation, we are most interested in the actual dose of radiation delivered by radioactivity. That dose is commonly measured in terms of *rads* (rd) and *rems*. In the International System, the corresponding units are *grays* (Gy) and *sieverts* (Sv). Rads and grays are the units of the absorbed dose of radiation; 1 gray is equivalent to 100 rads. Rems and sieverts are units of equivalent dose, or effective equivalent dose, where 1 sievert is 100 rems. The energy retained by living tissue that has been exposed to radiation is called the *radiation absorbed dose*, which is where the term *rad* comes from. Because different types of radiation have different penetrations and thus cause different degrees of damage to living tissue, the rad is multiplied by a factor known as the *relative biological effectiveness* to produce the rem or sievert units. When very small doses of radioactivity are being considered, the millirem (mrem) or millisievert (mSv)—that is, one-thousandth (0.001) of a rem or sievert—is used. For gamma rays, the unit commonly used is the roentgen ®, or, in SI units, coulombs per kilogram (C/kg).

United States. If you work at a nuclear power plant, you can receive up to about 3 mSv/yr. Living next door to a nuclear power plant adds 0.01 mSv/year, and sitting on a bench watching a truck carrying nuclear waste pass by would add 0.001 mSv to your annual exposure. Sources of radiation are summarized in Figure 17.13*a*, assuming an annual total of 3 mSv/yr.[13, 14] The amount of radiation received at certain job sites, such as nuclear power plants and laboratories where X-rays are produced, is closely monitored. At such locations, personnel wear badges that indicate the dose of radiation received.

Figure 17.13 shows some of the common sources of radiation to which we are exposed. Notice that exposure to radon gas can equal what people were exposed to as a result of the Chernobyl nuclear power accident, which occurred in the Soviet Union in 1986. In other words, in some homes, people are exposed to about the same radiation as that experienced by the people evacuated from the Chernobyl area.

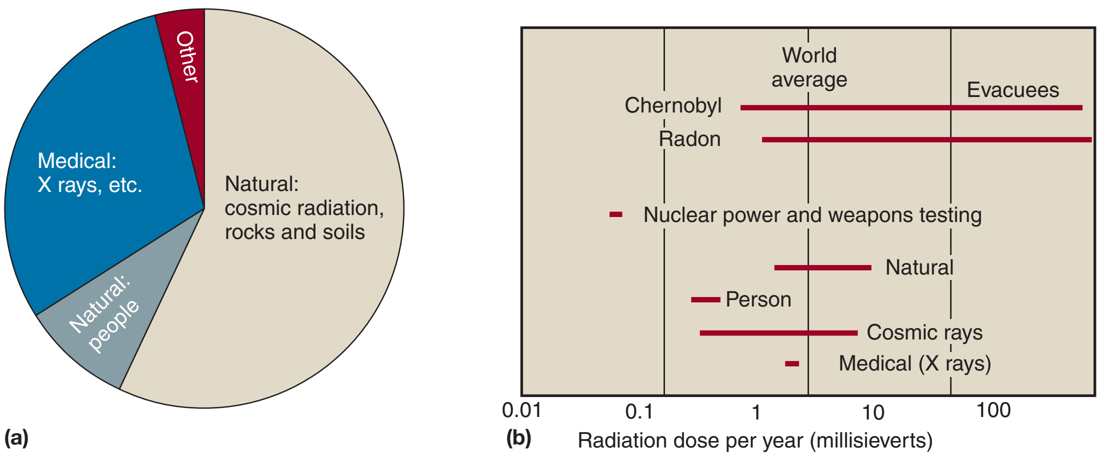

FIGURE 17.13 **(a)** Sources of radiation received by people; assumes annual dose of 3.0 mSv/yr, with 66% natural and 33% medical and other (occupational, nuclear weapons testing, television, air travel, smoke detectors, etc.). (*Sources*: U.S. Department of Energy, 1999; *New Encyclopedia Britannica*, 1997. Radiation V26, p. 487.) **(b)** Range in annual radiation dose to people from major sources. (*Source*: Data in part from A.V. Nero Jr., "Controlling Indoor Air Pollution," *Scientific American* 258[5] [1998]: 42–48.)

Radiation Doses and Health

The most important question in studying radiation exposure in people is: At what point does the exposure or dose becomes a hazard to health? (See again A Closer Look 17.2.) Unfortunately, there are no simple answers to this seemingly simple question. We do know that a dose of about 5,000 mSv (5 sieverts) is considered lethal to 50% of people exposed to it. Exposure to 1,000–2,000 mSv is sufficient to cause health problems, including vomiting, fatigue, potential abortion of pregnancies of less than two months' duration, and temporary sterility in males. At 500 mSv, physiological damage is recorded. The maximum allowed dose of radiation per year for workers in industry is 50 mSv, approximately 30 times the average natural background radiation we all receive.[15] For the general public, the maximum permissible annual dose (for infrequent exposure) is set in the United States at 5 mSv, about three times the annual natural background radiation.[16] For continuous or frequent exposure, the limit for the general public is 1 mSv.

Most information about the effects of high doses of radiation comes from studies of people who survived the atomic bomb detonations in Japan at the end of World War II. We also have information about people exposed to high levels of radiation in uranium mines, workers who painted watch dials with luminous paint containing radium, and people treated with radiation therapy for disease.[17] Starting around 1917 in New Jersey, approximately 2,000 young women were employed painting watch dials with luminous paint. To maintain a sharp point on their brushes, they licked them and as a result were swallowing radium, which was in the paint. By 1924, dentists in New Jersey were reporting cases of jaw rot; and within five years radium was known to be the cause. Many of the women died of anemia or bone cancer.[18]

Workers in uranium mines who were exposed to high levels of radiation have been shown to suffer a significantly higher rate of lung cancer than the general population. Studies show that there is a delay of 10 to 25 years between the time of exposure and the onset of disease.

Although there is vigorous, ongoing debate about the nature and extent of the relationship between radiation exposure and cancer mortality, most scientists agree that radiation can cause cancer. Some scientists believe that there is a linear relationship, such that any increase in radiation beyond the background level will produce an additional hazard. Others believe that the body can handle and recover from low levels of radiation exposure but that health effects (toxicity) become apparent beyond some threshold. The verdict is still out on this subject, but it seems prudent to take a conservative viewpoint and accept that there may be a linear relationship. Unfortunately, chronic health problems related to low-level exposure to radiation are neither well known nor well understood.

Radiation has a long history in the field of medicine. Drinking waters that contain radioactive materials goes back to Roman times. By 1899, the adverse effects of radiation had been studied and were well known; and in that year, the first lawsuit for malpractice in using X-rays was filed. Because science had shown that radiation could destroy human cells, however, it was a logical step to conclude that drinking water containing radioactive material such as radon might help fight diseases such as stomach cancer. In the early 1900s it became popular to drink water containing radon, and the practice was supported by doctors, who stated that there were no known toxic effects. Although we now know that was incorrect, radiotherapy, which uses radiation to kill cancer cells in humans, has been widely and successfully used for a number of years.[19]

17.5 Nuclear Power Plant Accidents

Although the chance of a disastrous nuclear accident is estimated to be very low, the probability that an accident will occur increases with every reactor put into operation. According to the U.S. Nuclear Regulatory Commission's performance goal for a single reactor, the probability of a large-scale core meltdown in any given year should be no greater than 0.01%—one chance in 10,000. However, if there were 1,500 nuclear reactors (about three and a half times the present world total), a meltdown could be expected (at the low annual probability of 0.01%) every seven years. This is clearly an unacceptable risk.[20] Increasing safety by about 10 times would result in lower, more manageable risk, but the risk would still be appreciable because the potential consequences remain large.

Next, we discuss the two most well-known nuclear accidents, which occurred at the Three Mile Island and Chernobyl reactors. It is important to understand that these serious accidents resulted in part from human error.

Three Mile Island

One of the most dramatic events in the history of U.S. radiation pollution occurred on March 28, 1979, at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. The malfunction of a valve, along with human errors (thought to be the major problem), resulted in a partial core meltdown. Intense radiation was released to the interior of the containment structure. Fortunately, the containment structure functioned as designed, and only a relatively small amount of radiation was released into the environment. Average exposure from the radiation emitted into the atmosphere has been estimated at 1 mSv, which is low in terms of the amount required to cause acute toxic effects. Average exposure to radiation in the surrounding area is estimated to have been approximately 0.012 mSv, which is only about 1% of the natural background radiation that people receive. However, radiation levels were much higher near the site. On the third day after the accident, 12 mSv/hour were measured at ground level near the site. By comparison, the average American receives about 2 mSv/year from natural radiation.

Because the long-term chronic effects of exposure to low levels of radiation are not well understood, the effects of Three Mile Island exposure, though apparently small, are difficult to estimate. However, the incident revealed many potential problems with the way U.S. society dealt with nuclear power. Historically, nuclear power had been considered relatively safe, so the state of Pennsylvania was unprepared to deal with the accident. For example, there was no state bureau for radiation help, and the state Department of Health did not have a single book on radiation medicine (the medical library had been dismantled two years earlier for budgetary reasons). One of the major impacts of the incident was fear, yet there was no state office of mental health, and no staff member from the Department of Health was allowed to sit in on important discussions following the accident.[21]

Chernobyl

Lack of preparedness to deal with a serious nuclear power plant accident was dramatically illustrated by events that began unfolding on Monday morning, April 28, 1986. Workers at a nuclear power plant in Sweden, frantically searching for the source of elevated levels of radiation near their plant, concluded that it was not their installation that was leaking radiation; rather, the radioactivity was coming from the Soviet Union by way of prevailing winds. When confronted, the Soviets announced that an accident had occurred at a nuclear power plant at Chernobyl two days earlier, on April 26. This was the first notice to the world of the worst accident in the history of nuclear power generation.

It is speculated that the system that supplied cooling waters for the Chernobyl reactor failed as a result of human error, causing the temperature of the reactor core to rise to over 3,000°C (about 5,400°F), melting the uranium fuel, setting fire to the graphite surrounding the fuel rods that were supposed to moderate the nuclear reactions, and causing explosions that blew off the top of the building over the reactor. The fires produced a cloud of radioactive particles that rose high into the atmosphere. There were 237 confirmed cases of acute radiation sickness, and 31 people died of radiation sickness.[22]

In the days following the accident, nearly 3 billion people in the Northern Hemisphere received varying amounts of radiation from Chernobyl. With the exception of the 30-km (19-mi) zone surrounding Chernobyl, the world human exposure was relatively small. Even in Europe, where exposure was highest, it was considerably less than the natural radiation received during one year.[23]

In that 30-km zone, approximately 115,000 people were evacuated, and as many as 24,000 people were estimated to have received an average radiation dose of 0.43 Sv (430 mSv).

It was expected, based on results from Japanese A-bomb survivors, that approximately 122 spontaneous leukemias would occur during the period from 1986 through 1998.[24] Surprisingly, as of late 1998, there was no significant increase in the incidence of leukemia, even among the most highly exposed people. However, an increased incidence of leukemia could still become manifest in the future.[25] Meanwhile, studies have found that since the accident the number of childhood thyroid cancer cases per year has risen steadily in Belarus, Ukraine, and the Russian Federation, the three countries most affected by Chernobyl. A total of 1,036 thyroid cancer cases have been diagnosed in children under 15 in the region. These cancer cases are believed to be linked to the released radiation from the accident, but other factors, such as environmental pollution, may also play a role. It is predicted that a few percent of the roughly 1 million children exposed to the radiation eventually will contract thyroid cancer. Outside the 30 km zone, the increased risk of contracting cancer is very small and not likely to be detected from an ecological evaluation.

To date, 4,000 deaths can be directly attributed to the Chernobyl accident, and according to one estimate, Chernobyl will ultimately be responsible for approximately 16,000 to 39,000 deaths. Proponents of nuclear power point out that this is fewer than the number of deaths caused each year by burning coal.[26, 27]

Vegetation within 7 km of the power plant was either killed or severely damaged by the accident. Pine trees examined in 1990 around Chernobyl showed extensive tissue damage and still contained radioactivity. The distance between annual rings (a measure of tree growth) had decreased since 1986.

Scientists returning to the evacuated zone in the mid-1990s found, to their surprise, thriving and expanding animal populations. Species such as wild boar, moose, otters, waterfowl, and rodents seemed to be enjoying a population boom in the absence of people. The wild boar population had increased tenfold since the evacuation. These animals may be paying a genetic price for living within the contaminated zone, but so far the benefit of excluding humans apparently outweighs the negatives associated with radioactive contamination. The area now resembles a wildlife reserve.

In areas surrounding Chernobyl, radioactive materials continue to contaminate soils, vegetation, surface water, and groundwater, presenting a hazard to plants

FIGURE 17.14 Guard halting entry of people into the forbidden zone evacuated in 1986 as a result of the Chernobyl nuclear accident.

and animals. The evacuation zone may be uninhabitable for a very long time unless some way is found to remove the radioactivity (Figure 17.14). For example, the city of Prypyat, 5 km from Chernobyl, which had a population of 48,000 prior to the accident, is a "ghost city." It is abandoned, with blocks of vacant apartment buildings and rusting vehicles. Roads are cracking and trees are growing as new vegetation transforms the urban land back to green fields.

The final story of the world's most serious nuclear accident is yet to completely unfold.[28] Estimates of the total cost of the Chernobyl accident vary widely, but it will probably exceed $200 billion.

Although the Soviets were accused of not paying attention to reactor safety and of using outdated equipment, people are still wondering if such an accident could happen again elsewhere. Because more than 400 nuclear power plants are producing power in the world today, the answer has to be yes. It is difficult to get an exact account of nuclear power plant accidents that have released radiation into the environment since the first nuclear power plants were built in the 1960s. This is partly because of differences in what is considered a significant radiation emission. As best as can be estimated, there appear to have been 20 to 30 such incidents worldwide—at least that is the range of numbers released to the public. Therefore, although Chernobyl is the most serious nuclear accident to date, it certainly was not the first and is unlikely to be the last. Although the probability of a serious accident is very small at a particular site, the consequences may be great, perhaps posing an unacceptable risk to society. This is really not so much a scientific issue as a political one involving values.

Advocates of nuclear power argue that nuclear power is safer than other energy sources, that many more deaths are caused by air pollution from burning fossil fuels than by nuclear accidents. For example, the 16,000 deaths that might eventually be attributed to Chernobyl are fewer than the number of deaths caused each year by air pollution from burning coal.[29] Those arguing against nuclear power say that as long as people build nuclear power plants and manage them, there will be the possibility of accidents. We can build nuclear reactors that are safer, but people will continue to make mistakes, and accidents will continue to happen.

17.6 Radioactive-Waste Management

Examination of the nuclear fuel cycle (refer back to Figure 17.9) illustrates some of the sources of waste that must be disposed of as a result of using nuclear energy to produce electricity. Radioactive wastes are by-products of using nuclear reactors to generate electricity. The U.S. Federal Energy Regulatory Commission (FERC) defines three categories of radioactive waste: mine tailings, low-level, and high-level. Other groups list a fourth category: transuranic wastes.[30] In the western United States, more than 20 million metric tons of abandoned tailings will continue to produce radiation for at least 100,000 years.

Low-Level Radioactive Waste

Low-level radioactive waste contains radioactivity in such low concentrations or quantities that it does not present a significant environmental hazard if properly handled. Low-level waste includes a wide variety of items, such as residuals or solutions from chemical processing; solid or liquid plant waste, sludges, and acids; and slightly contaminated equipment, tools, plastic, glass, wood, and other materials.[31]

Low-level waste has been buried in near-surface burial areas in which the hydrologic and geologic conditions were thought to severely limit the migration of radioactivity.[32] However, monitoring has shown that several U.S. disposal sites for low-level radioactive waste have not adequately protected the environment, and leaks of liquid waste have polluted groundwater. Of the original six burial sites, three closed prematurely by 1979 due to unexpected leaks, financial problems, or loss of license, and as of 1995 only two remaining government low-level nuclear-waste repositories were still operating in the United States, one in Washington and the other in South Carolina. In addition, a private facility in Utah, run by Envirocare, accepts low-level waste. Construction of new burial sites, such as the Ward Valley site in southeastern California, has been met with strong public opposition, and controversy continues as to whether low-level radioactive waste can be disposed of safely.[33]

Transuranic Waste

As noted earlier, it is useful to also list separately **transuranic waste**, which is waste contaminated by man-made radioactive elements, including plutonium, americum, and einsteineum, that are heavier than uranium and are produced in part by neutron bombardment of uranium in reactors. Most transuranic waste is industrial trash, such as clothing, rags, tools, and equipment, that has been contaminated. The waste is low-level in terms of its intensity of radioactivity, but plutonium has a long half-life and must be isolated from the environment for about 250,000 years. Most transuranic waste is generated from the production of nuclear weapons and, more recently, from cleanup of former nuclear weapons facilities.

Some nuclear weapons transuranic wastes (as of 2000) are being transported to a disposal site near Carlsbad, New Mexico, and to date more than 5,000 shipments have been delivered.[34] The waste is isolated at a depth of 655 m (2,150 ft) in salt beds (rock salt) that are several hundred meters thick (Figure 17.15). Rock salt at the New Mexico site has several advantages:[35, 36, 37]

- The salt is about 225 million years old, and the area is geologically stable, with very little earthquake activity.
- The salt has no flowing groundwater and is easy to mine. Excavated rooms in the salt, about 10 m wide and 4 m high, will be used for disposal.
- Rock salt flows slowly into mined openings. The waste-filled spaces in the storage facility will be naturally closed by the slow-flowing salt in 75 to 200 years, sealing the waste.

The New Mexico disposal site is important because it is the first geologic disposal site for radioactive waste in the United States. As a pilot project, it will be evaluated very carefully. Safety is the primary concern. Procedures have been established to transport the waste to the disposal site as safely as possible and place it underground in the disposal facility. Because the waste will be hazardous for many thousands of years, it was decided that warnings had to be created that would be understandable to future peoples no matter what their cultures and languages. But of course it is unclear today whether any such sign will actually communicate anything to people thousands of years from now.[38]

High-Level Radioactive Waste

High-level radioactive waste consists of commercial and military spent nuclear fuel; uranium and plutonium derived from military reprocessing; and other radioactive nuclear weapons materials. It is extremely toxic, and a sense of urgency surrounds its disposal as the total volume of spent fuel accumulates. At present, in the United States, tens of thousands of metric tons of high-level waste are being stored at more than a hundred sites in 40 states. Seventy-two of the sites are commercial nuclear reactors.[39, 40, 41]

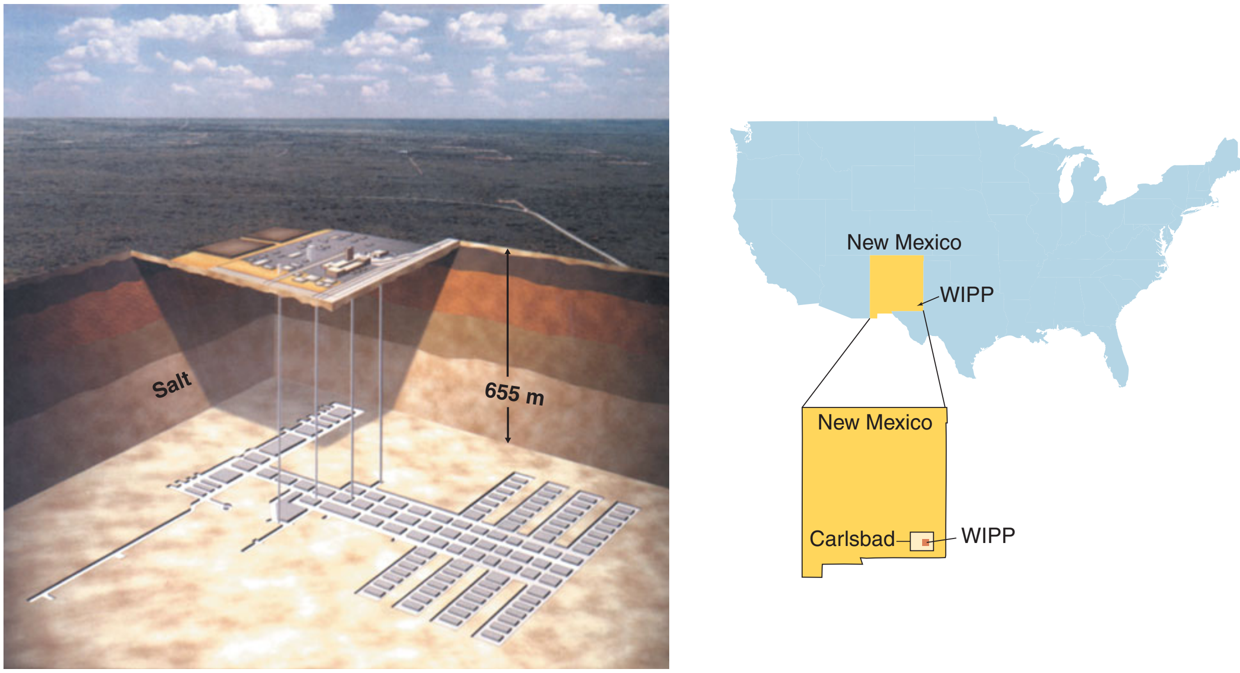

FIGURE 17.15 Waste isolation pilot plant (WIPP) in New Mexico for disposal of transuranic waste. (*Source*: U.S. Department of Energy, 1999.)

These storage arrangements are at best a temporary solution, and serious problems with radioactive waste have occurred where it is being stored. Although improvements in storage tanks and other facilities will help, eventually some sort of disposal program must be initiated. Some scientists believe the geologic environment can best provide safe containment of high-level radioactive waste. Others disagree and have criticized proposals for long-term underground disposal of high-level radioactive waste. A comprehensive geologic disposal development program should have the following objectives:[42]

- Identification of sites that meet broad geologic criteria, including ground stability and slow movement of groundwater with long flow paths to the surface.
- Intensive subsurface exploration of possible sites to positively determine geologic and hydrologic characteristics.
- Predictions of the behavior of potential sites based on present geologic and hydrologic situations and assumptions about future changes in climate, groundwater flow, erosion, ground movements, and other variables.
- Evaluation of risk associated with various predictions.
- Political decision making based on risks acceptable to society.

What Should the United States Do with Its Nuclear Wastes?

For decades in the United States, the focal point for debates over nuclear wastes has been the plan to bury them deep in the earth at Yucca Mountain, Nevada. But the Obama administration rejected that plan, and Secretary of Energy Steven Chu has set up a blue ribbon panel to consider the alternatives. At present, there are 70,000 tons of radioactive wastes from nuclear power plants, and federally authorized temporary storage facilities for these are said to be full. That is to say, there is no government-sanctioned and locally approved place to put any more nuclear wastes. Yet they continue to build up.

Why was the Yucca Mountain repository so controversial, and why has it finally been canceled, or at least put on hold? The Nuclear Waste-Policy Act of 1982 initiated a high-level nuclear-waste-disposal program. The Department of Energy was given the responsibility to investigate several potential sites and make a recommendation. The 1982 act was amended in 1987; the amendment, along with the Energy Power Act of 1992, specified that high-level waste was to be disposed of underground in a deep, geologic waste repository. It also specified that the Yucca Mountain site in Nevada was to be the only site evaluated. Costs to build the facility reached $77 billion, but no nuclear wastes have ever been sent there.[43]

Evaluation of the safety and utility of a new waste repository would have to consider factors such as the following:

- The probability and consequences of volcanic eruptions.
- Earthquake hazard.
- Estimation of changes in the storage environment over long periods.
- Estimation of how long the waste may be contained and the types and rates of radiation that may escape from deteriorated waste containers.
- How heat generated by the waste may affect moisture in and around the repository and the design of the repository.
- Characterization of groundwater flow near the repository.
- Identification and understanding of major geochemical processes that control the transport of radioactive materials.

One of the problems is just transporting the present amount of nuclear waste from power plants to any repository. According to previous U.S. government plans, beginning in 2010 some 70,000 tons of highly radioactive nuclear waste were going to be moved across the country to Yucca Mountain, Nevada, by truck and train, one to six trainloads or truck convoys every day for 24 years. These train and truck convoys would have to be heavily guarded against terrorism and protected as much as possible against accidents.

Extensive scientific evaluations of the Yucca Mountain site have been carried out.[44] Use of this site remains controversial and is generating considerable resistance from the state and people of Nevada as well as from scientists not confident of the plan. Some of the scientific questions at Yucca Mountain have concerned natural processes and hazards that might allow radioactive materials to escape, such as surface erosion, groundwater movement, earthquakes, and volcanic eruptions. In 2002, Congress voted to submit a license of application for Yucca Mountain to the Nuclear Regulatory Commission.

A major question about the disposal of high-level radioactive waste is this: How credible are extremely long-range geologic predictions—those covering several thousand to a few *million* years?[45] Unfortunately, there is no easy answer to this question because geologic processes vary over both time and space. Climates change over long periods, as do areas of erosion, deposition, and groundwater activity. For example, large earthquakes even thousands of kilometers from a site may permanently change groundwater levels. The earthquake record for most of the United States extends back only a few hundred years; therefore, estimates of future earthquake activity are tenuous at best.

The bottom line is that geologists can suggest sites that have been relatively stable in the geologic past, but they cannot absolutely guarantee future stability. This means that policymakers (not geologists) need to evaluate the uncertainty of predictions in light of pressing political, economic, and social concerns.[46] In the end, the geologic environment may be deemed suitable for safe containment of high-level radioactive waste, but care must be taken to ensure that the best possible decisions are made on this important and controversial issue.

17.7 The Future of Nuclear Energy

The United States would need 1,000 new nuclear power plants of the same design and efficiency as existing nuclear plants to completely replace fossil fuels. The International Atomic Energy Agency, which promotes nuclear energy, says a total of just 4.7 million tons of "identified" conventional uranium stock can be mined economically. If we switched from fossil fuels to nuclear today, that uranium would run out in four years. Even the most optimistic estimate of the quantity of uranium ore would last only 29 years.[47]

Nevertheless, nuclear energy as a power source for electricity is now being seriously evaluated. Its advocates argue that nuclear power is good for the environment because (1) it does not contribute to potential global warming through release of carbon dioxide (see Chapter 20) and (2) it does not cause the kinds of air pollution or emit precursors (sulfates and nitrates) that cause acid rain (see Chapter 21). They also argue that developing breeder reactors for commercial use would greatly increase the amount of fuel available for nuclear plants, that nuclear power plants are safer than other means of generating power, and that we should build many more nuclear power plants in the future. Their argument assumes that if we standardize nuclear reactors and make them safer and smaller, nuclear power could provide much of our electricity in the future,[48] although the possibility of accidents and the disposal of spent fuel remain concerns.

The argument against nuclear power is based on political and economic considerations as well as scientific uncertainty about safety issues. Opponents emphasize, as we pointed out earlier, that more than half the U.S. population lives within 75 miles of one of the nation's 104 nuclear power plants. They also argue, correctly, that converting from coal-burning plants to nuclear power plants for the purpose of reducing carbon dioxide emissions would require an enormous investment in nuclear power to make a real impact. Furthermore, they say, given that safer nuclear reactors are only just being developed, there will be a time lag, so nuclear power is unlikely to have a real impact on environmental problems—such as air pollution, acid rain, and potential global warming—before at least the year 2050.

Furthermore, uranium ore to fuel conventional nuclear reactors is limited. The International Nuclear Energy Association estimates that at the 2004 rate of use, there would be 85 years of uranium fuel from known reserves, but if nations attempt to build many new power plants in the next decade, known reserves of uranium ore would be used up much more quickly.[49] Nuclear power can thus be a long-term energy source only through the development of breeder reactors.

Another argument against nuclear power is that some nations may use it as a path to nuclear weapons. Reprocessing used nuclear fuel from a power plant produces plutonium that can be used to make nuclear bombs. There is concern that rogue nations with nuclear power could divert plutonium to make weapons, or may sell plutonium to others, even terrorists, who would make nuclear weapons.[50]

Until 2001, proponents of nuclear energy were losing ground. Nearly all energy scenarios were based on the expectation that nuclear power would grow slowly or perhaps even decline in coming years. Since the Chernobyl accident, many European countries have been reevaluating the use of nuclear power, and in most instances the number of nuclear power plants being built has significantly declined. Germany, which gets about one-third of its electricity from nuclear power, has decided to shut down all nuclear power plants in the next 25 years as they become obsolete.

There is also a problem with present nuclear technology: Today's light-water reactors use uranium very inefficiently; only about 1% of it generates electricity, and the other 99% ends up as waste heat and radiation. Therefore, our present reactors are part of the nuclear-waste problem and not a long-term solution to the energy problem.

One design philosophy that has emerged in recent decades in the nuclear industry is to build less complex, smaller reactors that are safer. Large nuclear power plants, which produce about 1,000 MW of electricity, require an extensive set of pumps and backup equipment to ensure that adequate cooling is available to the reactor. Smaller reactors can be designed with cooling systems that work by gravity and thus are less vulnerable to pump failure caused by power loss. Such cooling systems are said to have *passive stability*, and the reactors are said to be *passively safe*. Another approach is the use of helium gas to cool reactors that have specially designed fuel capsules capable of withstanding temperatures as high as 1,800°C (about 3,300°F). The idea is to design the fuel assembly so that it can't hold enough fuel to reach this temperature and thus can't experience a core meltdown.

One way for nuclear power to be sustainable for at least hundreds of years would be to use a process known as *breeding*. **Breeder reactors** are designed to produce new nuclear fuel by transforming waste or lower-grade uranium into fissionable material. Although proponents of nuclear energy suggest that breeder reactors are the future of nuclear power, only a few are known to be operating anywhere in the world. Bringing breeder reactors online to produce safe nuclear power will take planning, research, and advanced reactor development. Also, fuel for the breeder reactors will have to be recycled because reactor fuel must be replaced every few years. What is needed is a new type of breeder reactor comprising an entire system that includes reactor, fuel cycle (especially fuel recycling and reprocessing), and less production of waste. Such a reactor appears possible but will require redefining our national energy policy and turning energy production in new directions. It remains to be seen whether this will happen.

Possible New Kinds of Nuclear Power Plants

New Kinds of Fission Reactors

Several new designs for conventional nonbreeder fission nuclear power plants are in development and the object of widespread discussion. Among these are the Advanced Boiling Water Reactor, the High Temperature Gas Reactor, and the Pebble Reactor.[51, 52] None are yet installed or operating anywhere in the world. The general goals of these designs are to increase safety, energy efficiency, and ease of operation. Some are designed to shut down automatically if there is any failure in the cooling system, rather than require the action of an operator. Although proponents of nuclear power believe these will offer major advances, it will be years, perhaps decades, until even one of each kind achieves commercial operation, so planning for the future cannot depend on them.

Fusion Reactors

In contrast to fission, which involves splitting heavy nuclei (such as uranium), fusion involves combining the nuclei of light elements (such as hydrogen) to form heavier ones (such as helium). As fusion occurs, heat energy is released. Nuclear fusion is the source of energy in our sun and other stars.

In a hypothetical fusion reactor, two isotopes of hydrogen—deuterium and tritium—are injected into the reactor chamber, where the necessary conditions for fusion are maintained. Products of the deuterium–tritium (DT) fusion include helium, producing 20% of the energy released, and neutrons, producing 80%.

Several conditions are necessary for fusion to take place. First, the temperature must be extremely high (approximately 100 million degrees Celsius for DT fusion). Second, the density of the fuel elements must be sufficiently high. At the temperature necessary for fusion, nearly all atoms are stripped of their electrons, forming a *plasma*—an electrically neutral material consisting of positively charged nuclei, ions, and negatively charged electrons. Third, the plasma must be confined long enough to ensure that the energy released by the fusion reactions exceeds the energy supplied to maintain the plasma.

The potential energy available when and if fusion reactor power plants are developed is nearly inexhaustible. One gram of DT fuel (from a water and lithium fuel supply) has the energy equivalent of 45 barrels of oil. Deuterium can be extracted economically from ocean water, and tritium can be produced in a reaction with lithium in a fusion reactor. Lithium can be extracted economically from abundant mineral supplies.

Many problems remain to be solved before nuclear fusion can be used on a large scale. Research is still in the first stage, which involves basic physics, testing of possible fuels (mostly DT), and magnetic confinement of plasma.

CRITICAL THINKING ISSUE

Should the United States Increase or Decrease the Number of Nuclear Power Plants?

There are two contradictory political movements regarding nuclear power plants in the United States. The federal government has supported an increase in the number of plants. The G. W. Bush administration did, and the Obama administration has allocated $18.5 for new "next-generation" nuclear power plants. But in February 2010, the Vermont Senate voted to prevent relicensing of the Yankee Power Plant, the state's only nuclear plant, after its current license expires in 2012. In 2009 the power plant leaked radioactive tritium into groundwater, and the plant's owners have been accused of misleading state regulators about underground pipes that carry cooling water at the plant.[53] Also, as you saw in this chapter's opening case study, there are major political pressures at the state, county, and local level to prevent the relicensing of Indian Point Power Plant near New York City.

Critical Thinking Questions

1. Refer to the map of nuclear power plants in the United States (Figure 17.4) and to other material in this chapter. Taking into account safety and the problem of transporting large amounts of electricity long distances, choose three locations that you consider appropriate for new nuclear power plants. Or, if you believe there should be none, present your argument for that conclusion. (Be as specific as possible about the locations—include the state and, if possible, name the nearest city.) In answering this question, you can take into account information from other chapters you have read.
2. Should new nuclear power plants be licensed now and built as soon as possible using existing and proven designs? Or would you propose putting off any new nuclear power plants until one of the safer and more efficient designs has been proved—let's say, two decades from now?
3. Which do you believe is the greater environmental problem facing the United States: global warming or the dangers of nuclear power plants? Explain your answer.

SUMMARY

- Nuclear fission is the process of splitting an atomic nucleus into smaller fragments. As fission occurs, energy is released. The major components of a fission reactor are the core, control rods, coolant, and reactor vessel.
- Nuclear radiation occurs when a radioisotope spontaneously undergoes radioactive decay and changes into another isotope.
- The three major types of nuclear radiation are alpha, beta, and gamma.
- Each radioisotope has its own characteristic emissions. Different types of radiation have different toxicities; and in terms of the health of humans and other organisms, it is important to know the type of radiation emitted and the half-life.
- The nuclear fuel cycle consists of mining and processing uranium, generating nuclear power through controlled fission, reprocessing spent fuel, disposing of nuclear waste, and decommissioning power plants. Each part of the cycle is associated with characteristic processes, all with different potential environmental problems.
- The present burner reactors (mostly light-water reactors) use uranium-235 as a fuel. Uranium is a nonrenewable resource mined from the Earth. If many more burner reactors were constructed, we would face fuel shortages. Nuclear energy based on burning uranium-235 in light-water reactors is thus not sustainable. For nuclear energy to be sustainable, safe, and economical, we will need to develop breeder reactors.
- Radioisotopes affect the environment in two major ways: by emitting radiation that affects other materials, and by entering ecological food chains.
- Major environmental pathways by which radiation reaches people include uptake by fish ingested by people, uptake by crops ingested by people, inhalation from air, and exposure to nuclear waste and the natural environment.
- The dose response for radiation is fairly well established. We know the dose–response for higher exposures, when illness or death occurs. However, there are vigorous debates about the health effects of low-level exposure to radiation and what relationships exist between exposure and cancer. Most scientists believe that radiation can cause cancer. But, Ironically, radiation can be used to kill cancer cells, as in radiotherapy treatments.
- We have learned from accidents at nuclear power plants that it is difficult to plan for the human factor. People make mistakes. We have also learned that we are not as prepared for accidents as we would like to think. Some believe that people are not ready for the responsibility of nuclear power. Others believe that we can design much safer power plants where serious accidents are impossible.
- Transuranic nuclear waste is now being disposed of in salt beds—the first disposal of radioactive waste in the geologic environment in the United States.
- There is a consensus that high-level nuclear waste may be safely disposed of in the geologic environment. The problem has been to locate a site that is safe and not objectionable to the people who make the decisions and to those who live in the region.
- Nuclear power is again being seriously evaluated as an alternative to fossil fuels. On the one hand, it has advantages: It emits no carbon dioxide, will not contribute to global warming or cause acid rain, and can be used to produce alternative fuels such as hydrogen. On the other hand, people are uncomfortable with nuclear power because of waste-disposal problems and possible accidents.

REEXAMINING THEMES AND ISSUES

Human Population

As the human population has increased, so has demand for electrical power. In response, a number of countries have turned to nuclear energy. The California energy crisis has caused many people in the United States to rethink the value of nuclear energy. Though relatively rare, accidents at nuclear power plants such as Chernobyl have exposed people to increased radiation, and there is considerable debate over potential adverse effects of that radiation. The fact remains that as the world population increases, and if the number of nuclear power plants increases, the total number of people exposed to a potential release of toxic radiation will increase as well.

Sustainability

Some argue that sustainable energy will require a return to nuclear energy because it doesn't contribute to a variety of environmental problems related to burning fossil fuels. However, for nuclear energy to significantly contribute to sustainable energy development, we cannot depend on burner reactors that will quickly use Earth's uranium resources; rather, development of safer breeder reactors will be necessary.

Global Perspective

Use of nuclear energy fits into our global management of the entire spectrum of energy sources. In addition, testing of nuclear weapons has spread radioactive isotopes around the entire planet, as have nuclear accidents. Radioactive isotopes that enter rivers and other waterways may eventually enter the oceans of the world, where oceanic circulation may further disperse and spread them.

Urban World

Development of nuclear energy is a product of our technology and our urban world. In some respects, it is near the pinnacle of our accomplishments in terms of technology.

People and Nature

Nuclear reactions are the source of heat for our sun and are fundamental processes of the universe. Nuclear fusion has produced the heavier elements of the universe. Our use of nuclear reactions in reactors to produce useful energy is a connection to a basic form of energy in nature. However, abuse of nuclear reactions in weapons could damage or even destroy nature on Earth.

Science and Values

We have a good deal of knowledge about nuclear energy and nuclear processes. Still, people remain suspicious and in some cases frightened by nuclear power—in part because of the value we place on a quality environment and our perception that nuclear radiation is toxic to that environment. As a result, the future of nuclear energy will depend in part on how much risk is acceptable to society. It will also depend on research and development to produce much safer nuclear reactors.

KEY TERMS

breeder reactors **363**
burner reactors **349**
fission **348**
fusion **348**
high-level radioactive waste **361**
low-level radioactive waste **360**
meltdown **348**
nuclear energy **348**
nuclear fuel cycle **353**
nuclear reactors **348**
radioactive decay **350**
radioisotope **350**
transuranic waste **361**

STUDY QUESTIONS

1. If exposure to radiation is a natural phenomenon, why are we worried about it?
2. What is a radioisotope, and why is knowing its half-life important?
3. What is the normal background radiation that people receive? Why is it variable?
4. What are the possible relationships between exposure to radiation and adverse health effects?
5. What processes in our environment may result in radioactive substances reaching people?
6. Suppose it is recommended that high-level nuclear waste be disposed of in the geologic environment of the region in which you live. How would you go about evaluating potential sites?
7. Are there good environmental reasons to develop and build new nuclear power plants? Discuss both sides of the issue.

FURTHER READING

Botkin, D.B., ***Powering the Future: A Scientist's Guide to Energy Independence*** (Indianapolis: Pearson FT Press, 2010).

Hore Lacy, Ian, ***Nuclear Energy in the 21st Century*** (New York: Academic Press, 2006). A pro-nuclear power plant book.

World Nuclear Association, "Waste Management in the Nuclear Fuel Cycle." www.world nuclear.org/info/inf04.html. A major international organization's review of this problem.