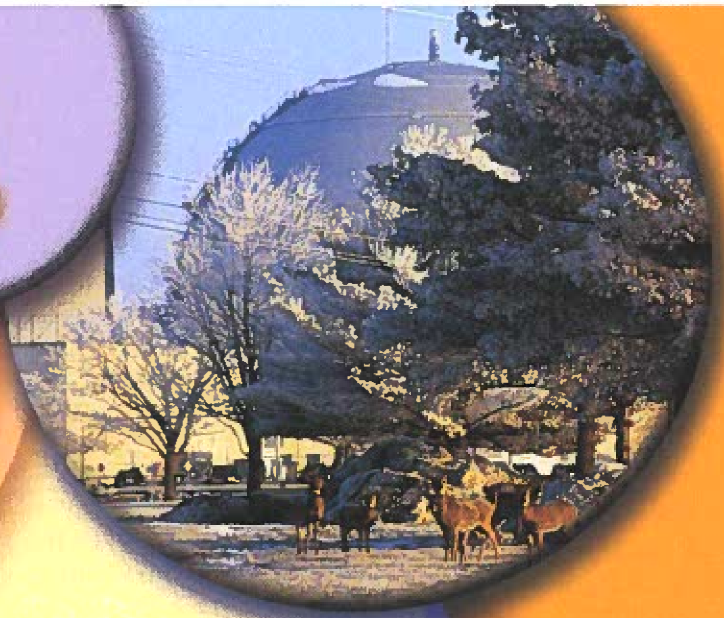
4

Nuclear Energy



Basic Concepts

- Describe the process of how electrical power is generated using nuclear fission as an energy source.
- Discuss the history of the nuclear power industry in the United States.
- List the environmental concerns associated with nuclear power.
- Identify how spent nuclear fuel is stored today and state plans for future storage.

Intermediate Concepts

- Describe how nuclear fuel is produced.
- Explain the major differences between the types of nuclear reactor designs in commercial operation in the United States today.
- Summarize why it is necessary to continue to explore nuclear fusion as an energy source.

Advanced Concepts

- Analyze the trade-offs associated with the use of nuclear power, in comparison to generating power via other means.
- Demonstrate how breeder reacting could multiply the energy potential of proven uranium reserves.

Nuclear energy, sometimes referred to as *atomic energy*, is the energy released from an atom in a nuclear reaction or through the radioactive decay of materials. There are two primary methods of creating nuclear reactions. One method involves fusing two smaller atoms together to produce one larger atom and a tremendous amount of energy. This method, known as ***nuclear fusion***, is only in experimental stages and is not presently in use to produce commercial power. The other method involves splitting a larger atom to produce two smaller atoms and a tremendous amount of energy. This process is known as ***nuclear fission***. It is used extensively throughout the United States and many other countries to produce heat for steam to make electricity. The entire process relies on an element in nature that is suitable to fission. This element is known as uranium.

Uranium: The Fuel for Nuclear Fission

Uranium is a nonrenewable energy source thought to be a substance in volcanic ash. This energy source probably spewed from a volcano onto the earth's surface millions of years ago. Rains dissolved the uranium out of the ash. The uranium was then carried back into the ground, where it has hardened into ore over the years. It is located near the surface of the earth. Therefore, it is mined in much the same way as coal. Like fossil fuels, uranium supplies will one day run out. Uranium is the most common type of nuclear fuel. It is used to fuel large nuclear power plants. Uranium can generate large amounts of energy in the form of heat. The heat produced is used to boil water, thus creating steam. The steam is then used to drive turbine-powered generators, which produce electricity. See **Figure 4-1.**

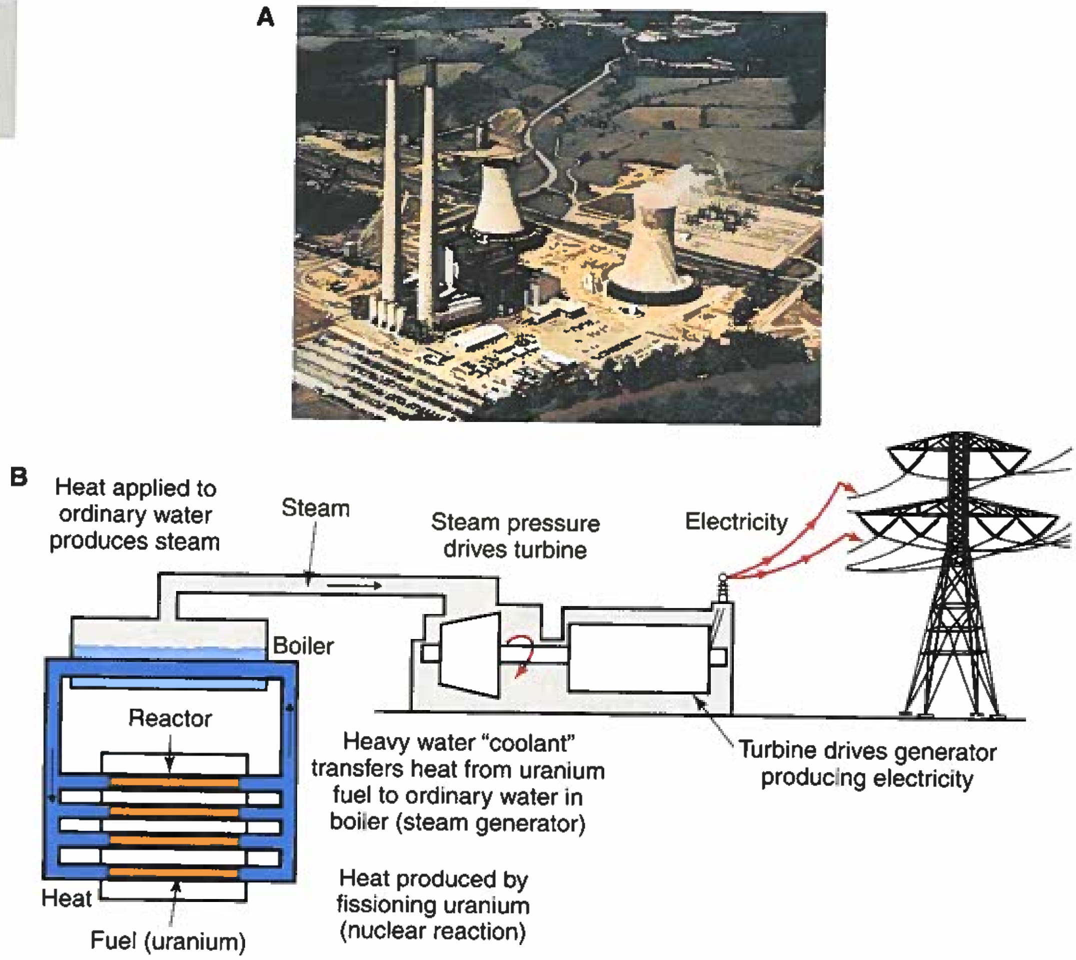
Nuclear fusion: The combining of two nuclei into a larger nucleus. The large nucleus weighs less than the two smaller nuclei that formed it. The result of this process yields a large energy release.

Nuclear fission. The process of splitting a larger atom to produce two smaller atoms and a tremendous amount of energy.

GREEN TECH

While uranium is a natural element, the way we use it can negatively impact the environment. Animals can contract health problems, while water and soil can also be affected.

Figure 4-1. Nuclear reactors generate heat to produce steam that, in turn, drives generators to produce electricity. A—This nuclear power station is one of more than 450 in operation or under construction worldwide. B—A simplified diagram of nuclear reactor operation. (Canadian Nuclear Association)



Uranium is an atom with a large and heavy nucleus. A ***nucleus*** is the center portion of an atom containing the protons and neutrons. ***Protons*** are positively charged particles. ***Neutrons*** are uncharged particles. Therefore, a lot of energy is bound inside the nucleus and can be used as nuclear fuel. Uranium atoms are bombarded by neutrons. This causes the nuclei to split apart. This splitting is known as *nuclear fission*. Lots of energy is released at the time of the splitting. When one nucleus splits, it releases energy and neutrons, which in turn, split other nuclei. A chain reaction thus occurs. This reaction produces huge amounts of energy in the form of heat. All of this reaction takes place inside a strong, closed container called a *reactor*. A nuclear reactor is to a nuclear power plant what a furnace is to a home. It produces the heat used to generate power at the plant. See **Figure 4-2.**

The fission of uranium is the only developed source of nuclear power in commercial use in the United States. The use of nuclear power produces about 20% of all the electricity produced in the United States per year. Nuclear power in the form of electricity is produced at a nuclear power plant. The amount of energy produced by uranium is incredible. In terms of pure British thermal units (Btu) per volume, no other fuel source comes close. One uranium pellet (which is about the size of your fingertip) can produce as much energy as 1780 pounds of coal, 149 gallons of oil, or 157 gallons of regular gasoline. See **Figure 4-3.**

There are some major concerns about using uranium to produce electricity. Uranium is a very hazardous substance. When the atoms of uranium decay, they give off atomic particles. This reaction produces ***radioactivity***, which is harmful to humans and other living things. Research is being done, especially at the Argonne National Laboratory, to make spent nuclear fuel less hazardous. See **Figure 4-4.**

Nucleus: The center portion of an atom containing the protons and neutrons.

Proton: A positively charged atomic particle.

Neutron: An uncharged atomic particle.

Figure 4-2. The pressure vessel where nuclear fission takes place, generating the heat to turn water to steam. The control rods are used to regulate the amount of nuclear activity taking place and, thus, the amount of heat generated. (Edison Electric Institute)

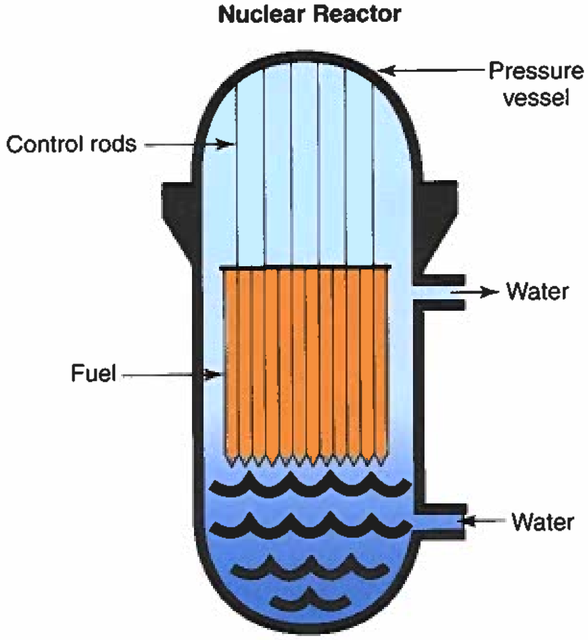
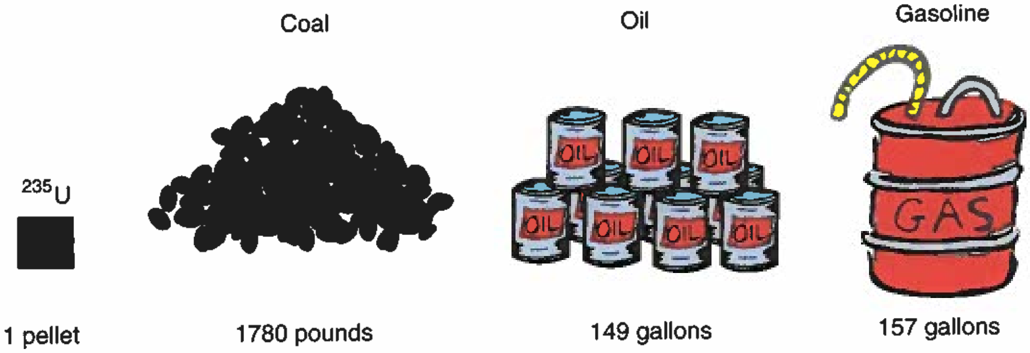


Figure 4-3. The amounts of various fuels needed to generate the same amount of energy.



Radioactivity: A property of some atoms, such as those of uranium decay, in which they give off atomic particles. The particles emitted are harmful to humans and other living things.

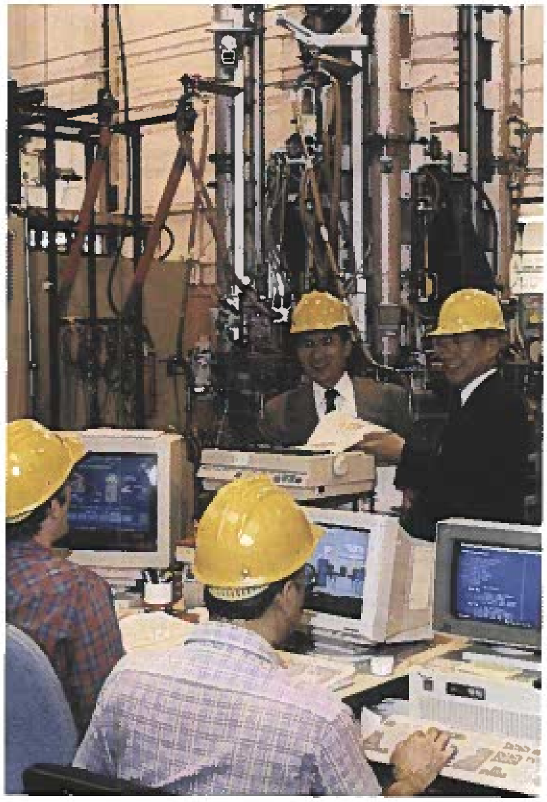
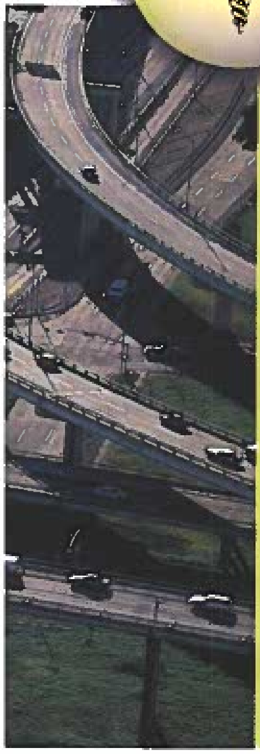


Figure 4-4. Researchers are working on reducing the risks of storing spent nuclear fuel. The electrorefiner equipment in the background separates spent fuel into long-lived and short-lived fission products. The long-lived products, such as plutonium, can be recycled to create new fuel. Short-lived (and lower radiation level) products can be stored with less costly methods than the original spent fuel. The research is a joint project of Argonne National Laboratory and the Central Research Institute of Japan's electric and atomic power industries. (U.S. Department of Energy)



Technology Link

Medicine: Health Risks of Radiation Exposure

Nuclear power plants contain many harmful elements. Power plant workers risk exposure to these elements every day. Radiation from these materials can cause cancer or possible genetic defects.

The materials found in a nuclear power plant include both uranium and plutonium. Exposure to these radioactive elements can result in, among other things, lung cancer and kidney damage. Workers in power plants come in contact with radioactive materials as seldom as possible, but the health risks still remain.

Medical technology is necessary to combat these health risks. Modern medicine offers options to prevent and treat disorders related to radiation exposure. The advances in medical technology allow for the diagnosis and treatment of radiation-related diseases.

While nuclear power plant workers are subject to radiation exposure, a properly functioning nuclear power plant emits almost no excess radiation. Plant workers wear dosimeters on their clothing, much like name badges. These devices closely monitor exposure levels. The workers are also checked for radioactivity as they enter and leave work. The instrumentation is so accurate that plant workers who have eaten bananas (a natural source high in potassium) can trip the alarm when entering the power plant. The bottom line is that people are exposed to more radiation on one long plane ride than most plant workers are exposed to in a year of on-site work.

Curricular Connection

Social Studies: The History of Nuclear Power

- During World War II, German and American scientists began working on nuclear weapons.
- In 1945, the American bomber, *Enola Gay*, dropped a nuclear bomb on Hiroshima, Japan. Three days later, another nuclear bomb was dropped on Nagasaki, Japan. These bombings ended the war, as Japan surrendered shortly afterward.
- The Atomic Energy Commission began investigating peaceful uses of atomic energy in 1947.
- President Eisenhower began a research and development program in 1953, entitled "Atoms for Peace."
- During the mid- to late 1950s, the government and industry cooperated and developed nuclear power plants from developmental reactors that had shown promise. See **Figure 4-A.**
- By the 1960s, utility companies were ordering nuclear power plants as an alternative to fossil fuel plants, since nuclear power plants could produce electricity at much less expense than conventional power plants.
- Many nuclear power plants were constructed in the United States during the 1970s. By the late 1970s, however, the tide was beginning to turn against nuclear power because of cost overruns on construction and environmental concerns about nuclear waste.
- In 1979, America's worst peacetime nuclear disaster occurred when a reactor at the Three Mile Island (TMI) nuclear plant near Harrisburg, Pennsylvania reached excessively high temperatures through a series of faulty readings and operator errors.
- A much more severe accident, the Chernobyl accident, occurred at a nuclear power plant in 1986, in Kiev, a city in the former Soviet Union. A poorly designed experiment led to a large quantity of radiation being released into the environment. Many people were killed, and the radiation spread throughout much of Europe. Radiation from the accident was even detected in the United States several days later.
- In recent years, several of the more than 110 nuclear power plants that once operated in the United States have closed down permanently.
- Most recently, utility companies are again expressing interest in nuclear power, as fossil fuel costs have risen dramatically.

Figure 4-A. Dresden I, a commercial nuclear reactor, opened in 1959 in Morris, Illinois, west of Chicago. The unit was retired from active service in 1978, although two later units remain in operation at the same site. The spherical object is the containment structure of the Dresden I reactor. (Exelon Energy)

The Fission Process

Uranium 235 (U235): An element whose atoms can be split more easily than most others, making it suitable for refining into nuclear fuel.

Fission is the term associated with the splitting of atoms. The nucleus of any atom can be split if it is smashed hard enough with a neutron. In the 1930s, however, it was discovered that one element, ***uranium 235 (U235)***, is split more easily than most others. The *235* in U235 is the atomic weight, which is the mass of the atom, relative to other atoms. The atomic weight of any element is approximately equal to the number of protons and neutrons in its nucleus. The result of the fission process of U235 yields several products, including a large amount of energy, small amounts of barium and krypton, and two additional neutrons. The mass of the various products does not quite equal the mass of the U235 atom. The cause of this imbalance is that some mass has been directly converted to energy. Additionally, the two free neutrons that are liberated from the nucleus can be used to split other atoms. This is how a chain reaction occurs. See **Figure 4-5.**

The Terminology and Measurement of Radiation

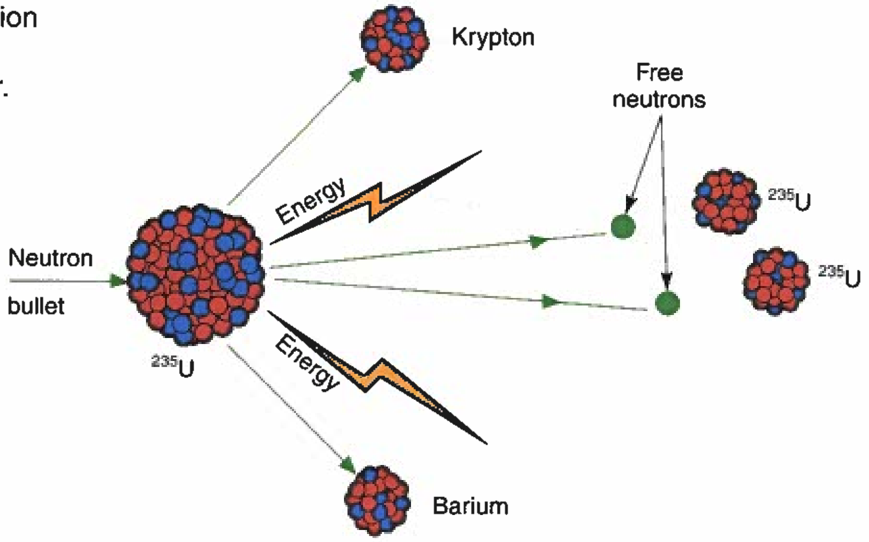
Half-life: The time it takes for half the atoms present in an unstable element to transform into a new element.

Half-life is a term most often associated with the radioactive by-products of nuclear fission, although it can be used when describing anything radioactive. As radioactive elements decay, they will eventually form other elements. A half-life is the time it takes for half the atoms present in an unstable element to transform into a new element.

After a period of one half-life, only half of the original atoms will remain. As a substance reaches each half-life, it becomes more stable and emits less radiation. Not all substances decay at the same rate as others, however. Half-lives of substances can range from a few seconds to thousands of years! **Figure 4-6** lists the half-lives of various elements, including U235, which is often used for fuel in nuclear power plants.

After a period of one half-life, the radioactivity of an element is decreased by 50%. The radioactivity is reduced to 25% of the original level after two half-lives. After three half-lives, the radioactivity would be reduced to 12.5% of the original state. When an element has reached its tenth half-life, it will emit less than .1% of the original radiation emitted.

Figure 4-5. The chain reaction that occurs from the fission process in a nuclear reactor.



Element	Half-Life	Primary Use
Technetium 99	6 hours	Medical imaging
Xenon 133	2.3 days	Lung ventilation, blood flow studies
Iodine 131	8 days	Diagnosis and treatment of thyroid problems
Strontium 89	54 days	Treatment of bone pain
Cobalt 60	5.2 years	Treatment of cancerous tumors
Plutonium 239	24,400 years	Nuclear power, nuclear weapons
Uranium 235	704 million years	Nuclear power, nuclear weapons
Uranium 238	4.5 billion years	Nuclear power, nuclear weapons

Figure 4-6. The half-lives of various radioactive elements.

The concept of the half-life is very important to the nuclear power industry, since some of the elements with the greatest half-lives are associated with nuclear power. Elements such as U235 exist in nature. Other elements, such as certain plutonium isotopes, are human-made. This leads to ethical questions about the need to produce such elements, only to require that they be isolated from humanity for thousands and thousands of years. Nuclear research has yielded some drastic technological improvements for the medical industry, however. Medicine makes use of some radioactive treatments that have been designed to destroy tumors and then lose their radioactive potency quickly, before damaging surrounding healthy tissue.

GREEN TECH

Unlike uranium, plutonium is a human-made element. Its creation and use can impact the environment similarly to the use of uranium.

How a Nuclear Reactor Works

There are two basic types of fission reactors in use in the United States today. Both are referred to as *light water reactors* because they use ordinary water instead of "heavy water" within the reactor core. *Heavy water* is a term used to describe water made up of oxygen and deuterium (a heavy isotope of hydrogen). It is used as a moderator within the reactor core to slow the rate of fission in many foreign reactors. The two types of reactors are boiling water reactors (BWRs) and pressurized water reactors (PWRs).

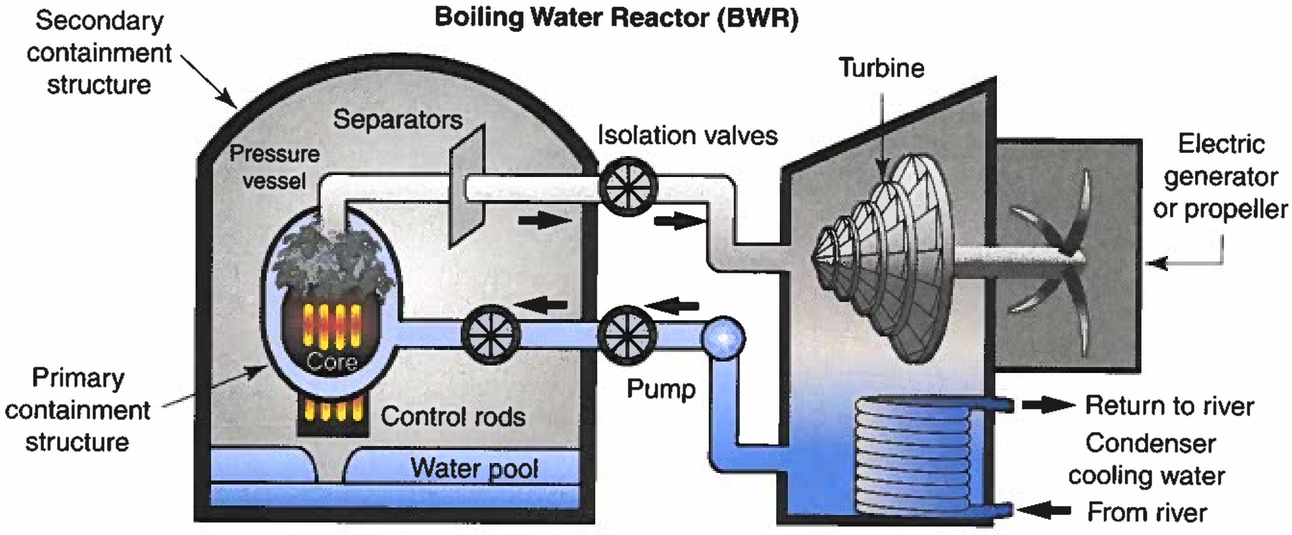
Boiling Water Reactors (BWRs)

The ***boiling water reactor (BWR)*** is the simplest of the reactors to describe. See **Figure 4-7.** Water surrounds the nuclear fuel core within the reactor. The ***control rods*** sit between the fuel rods. The fuel rods are assemblies that hold the fuel pellets of uranium in a specific configuration. Placement of the fuel rods is important, since they must be appropriately spaced for fission to occur at the right pace and so control rods can be inserted and retracted out of them to control the fission process. It is the job of the control rods to absorb stray neutrons. As long as they are properly inserted, fission cannot occur. When the control rods are retracted, the fission process begins to occur. A tremendous amount of heat is produced. This heat converts the surrounding water to steam. The force of the expanding steam spins a turbine to produce electricity, much the same way a turbine and generator are propelled with steam created in other

Boiling water reactor (BWR): A type of fission reactor in which water surrounds the nuclear fuel core within the reactor. Control rods sit between the fuel rods and absorb stray neutrons. When the control rods are retracted, the fission process begins to occur, and a tremendous amount of heat is produced. This heat converts the surrounding water to steam. The force of the expanding steam spins a turbine to produce electricity.

Control rod: Part of a fission reactor that sits between the fuel rods and absorbs stray neutrons. When the control rods are retracted, the fission process begins to occur.

Figure 4-7. The operation of a boiling water reactor (BWR).



ways, such as by burning coal. The spent steam is condensed back into a liquid when it is surrounded by cooler water in the condenser of the reactor. It is then pumped back to the reactor to be heated again.

The condenser is responsible for cooling the water in the steam loop. It often gets this water from a nearby river or lake and returns it to the river or lake. Cooling towers are used to reduce the temperature of the condensing water, since returning the water to the river or lake at too high a temperature could damage the ecosystem of the water source. These towers are massive structures. They actually have nothing to do, however, with the radioactive part of a nuclear power plant. In fact, cooling towers may be used at fossil fuel power plants for the very same purpose. The coolant is typically water. Some reactor designs, however, use liquid sodium or gases to dissipate heat.

The control rods are used to slow the rate of the chain reaction when fission is occurring. They are made of neutron-absorbing elements, such as graphite, cadmium, and carbon. When fully inserted, the control rods should be capable of stopping the chain reaction known as the fission process.

Pressurized Water Reactors (PWRs)

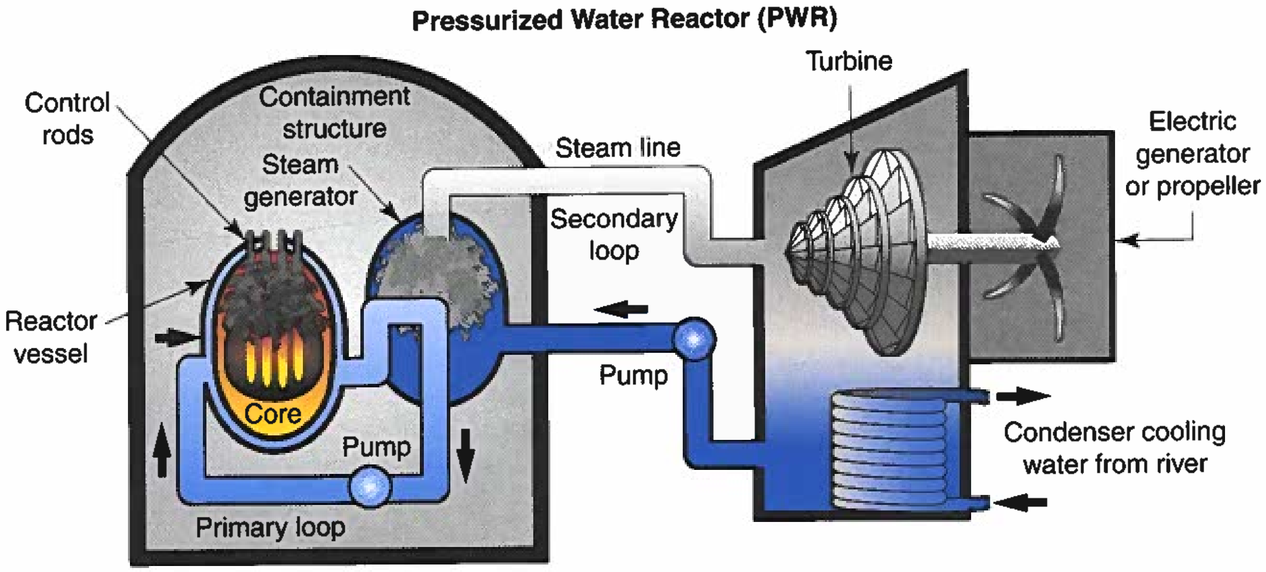
A ***pressurized water reactor (PWR)*** works similar to a BWR, except it makes use of a heat exchanger known as a steam generator. The PWR is slightly more complicated than the BWR. See **Figure 4-8.** The PWR can operate at higher pressures and temperatures than the BWR, since the water heated in the ***primary loop*** surrounding the reactor core does not come into direct contact with the turbine. The purpose of the primary loop is to collect heat from the reactor core and transfer the heat to a steam generator. Inside the steam generator, the heat from the primary loop is transferred to the water in the ***secondary loop***, thereby creating steam in the secondary loop. The steam in the secondary loop is used to drive the turbine that spins the generator. The generator is a big heat exchanger that allows for the transfer of heat from the primary loop to the secondary loop, while keeping the water in each loop isolated. This is

Pressurized water reactor (PWR): A reactor that works similarly to a boiling water reactor (BWR), except it makes use of a heat exchanger known as a steam generator. A PWR can operate at higher pressures and temperatures than a BWR. Unlike the BWR, the steam generator in a PWR allows the turbine to remain free of radioactive contamination.

Primary loop: The part of a pressurized water reactor (PWR) in which the water is heated. It surrounds the reactor core.

Secondary loop: The part of a pressurized water reactor (PWR) in which steam is created.

Figure 4-8. The operation of a pressurized water reactor (PWR).



important, since the water in the primary loop is radioactive, but the water in the secondary loop is not. Unlike the BWR, the steam generator in a PWR allows the turbine to remain free of radioactive contamination. This can be beneficial from a maintenance standpoint.

Supply and Demand for Nuclear Power

Today, approximately 100 operating power plants supply about 20% of all electricity produced in the United States. Regionally, the New England states rely on nuclear power the most. Nuclear power accounts for more than one-third of all electricity produced throughout New England. The western states have fewer nuclear power plants by far. See **Figure 4-9.**

Worldwide, nuclear power is expected to share a shrinking percentage of the world's electricity production over the next 20 years, even though generating capacity is increasing. Six new reactors began generating power in 1992. Four were located in China, one in South Korea, and another in the Czech Republic. As of 2004, there are 439 nuclear power reactors in operation around the world and several more under construction. See **Figure 4-10.** More than 19 countries worldwide rely on nuclear power for at least 20% of their electricity. Lithuania leads the way, with about 80% of all electrical generating capacity coming from nuclear power. France produces about 78% of its generating capacity from nuclear fission. Slovakia produces about 58% of its generating capacity from nuclear power. Even though there have not been orders for new nuclear power plants in the United States for some time, the economics of nuclear plant construction is more favorable in other countries. In certain countries that lack their own natural resources and have access to inexpensive labor markets, nuclear power is more appealing.

Nuclear power may also be a more desirable option to those countries that wish to increase capacity while reducing carbon dioxide (CO_2) emissions to reach targets set in the ***Kyoto Protocol***. This set of rules was devised in 1997, at a meeting of more than 160 nations in Kyoto, Japan.

Kyoto Protocol: Targets set in 1997 by countries wishing to increase capacity while reducing carbon dioxide (CO_2) emissions.

Figure 4-9. The distribution of the operating nuclear power plants in the United States.

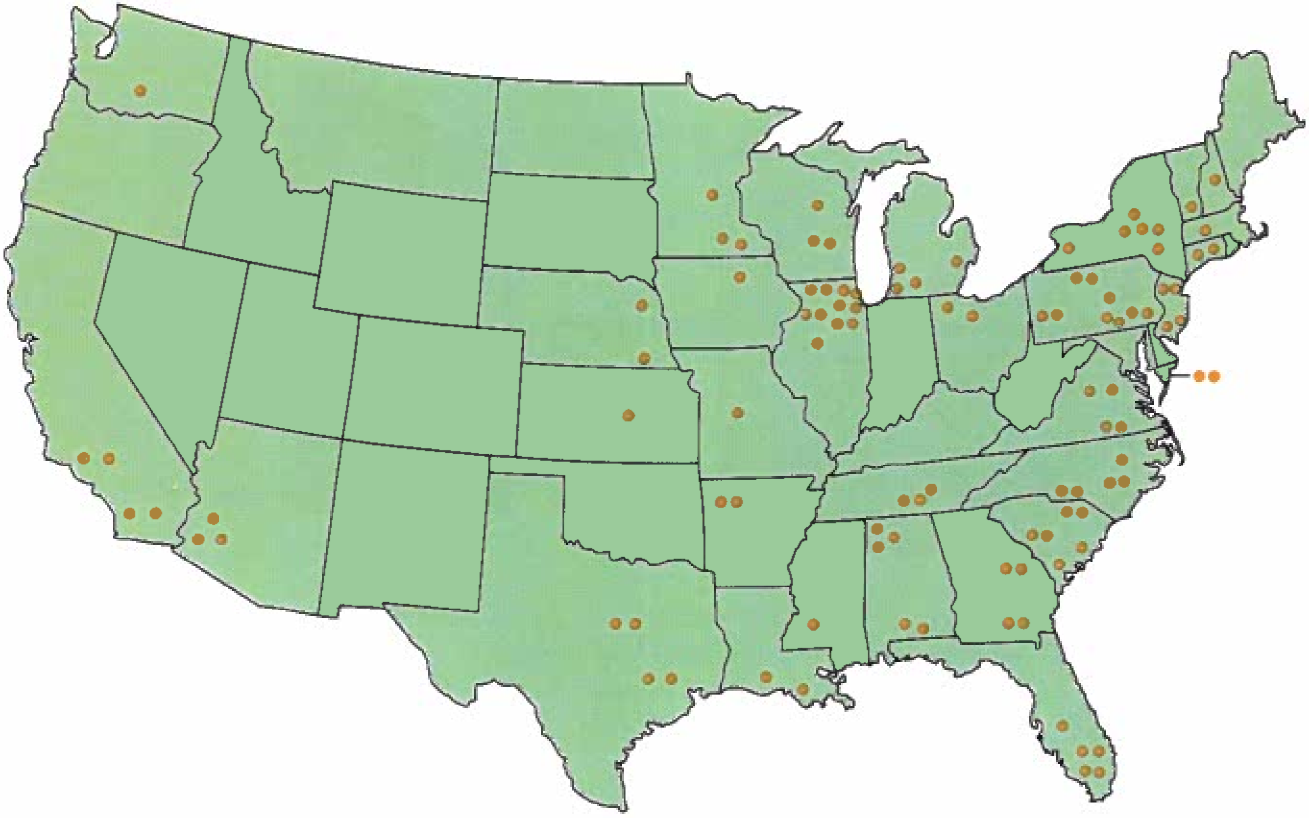
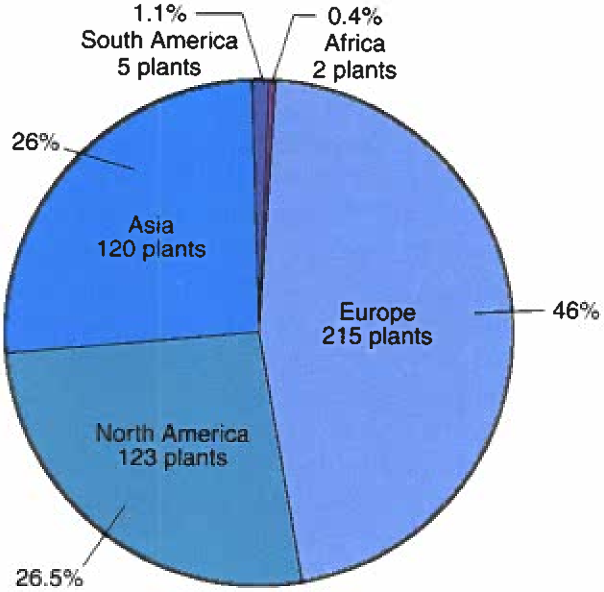
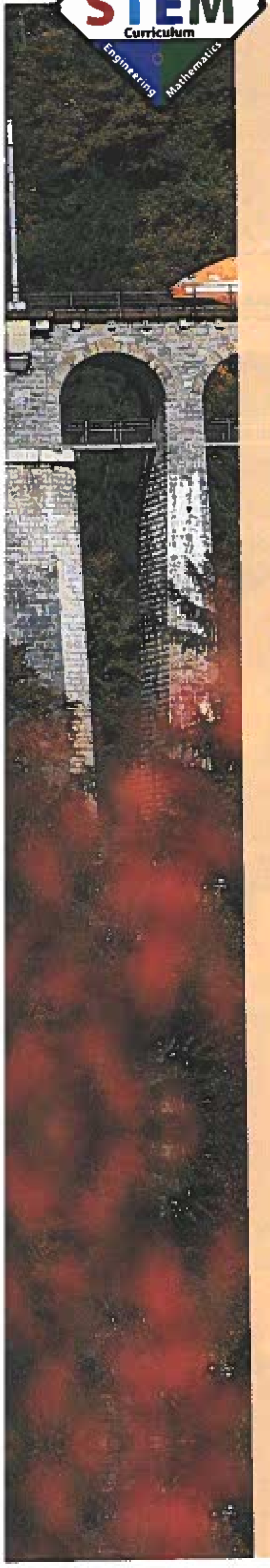


Figure 4-10. Worldwide nuclear power plant distribution. Europe and North America account for two-thirds of the existing or under-construction facilities. Asia accounts for most of the remaining one-third. (The graph was developed from the International Atomic Energy Agency data.)





STEM Connection

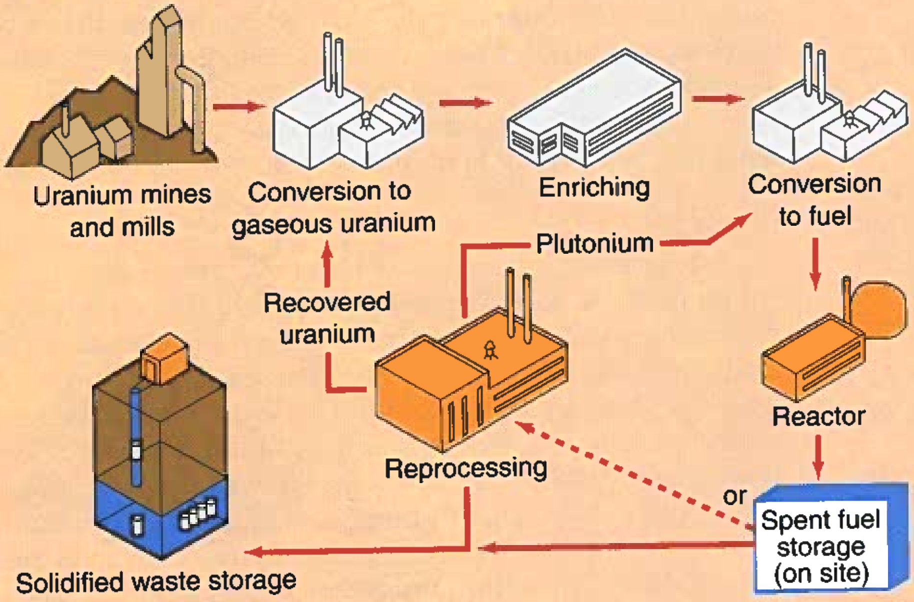
Technology: The Nuclear Fuel Cycle

The production of nuclear fuel begins with mining in a similar fashion to the way other resources, such as coal and metal ores, are recovered. See **Figure 4-B.** Most uranium mining operations in the United States exist in the western states of Colorado, Wyoming, Utah, and New Mexico. Some uranium mining is also performed in Texas. Worldwide, Russia and China appear to have an abundance of proven uranium reserves.

After the uranium-bearing ore has been extracted from the ground, uranium mills separate the uranium from other elements and refine it to an oxide known as yellowcake. The yellowcake is then shipped to a fuel enrichment plant, where it will be enriched to about 3–4% pure uranium 235 (U235), for use as a fuel in nuclear power plants. The fuel enrichment process is extremely technical in nature and not easily performed.

Once enriched, the fuel is manufactured into fuel pellets and loaded into fuel rod assemblies that space the fuel correctly for optimal fission and control. A fuel rod assembly can be expected to power a nuclear power plant for approximately 3–4.5 years before being removed for storage. Each year, approximately one-third of the fuel rods within a nuclear reactor are removed and replaced with fresh fuel rods. The oldest fuel rods are removed. The remaining fuel rods are reconfigured within the reactor core for maximum efficiency. The removed fuel rods are stored on-site in storage pools at the power plant to await permanent storage. Some low-level waste is sent to low-level storage facilities. Someday, it may be possible to reprocess nuclear waste into less harmful products.

Figure 4-B. The nuclear fuel cycle extends from mining uranium ore to storing spent nuclear fuel.



GREEN TECH

The EPA must take several aspects into consideration when choosing nuclear waste sites, including safety of local communities and effects of possible natural disasters.

These nations negotiated binding limitations on greenhouse gasses for developed nations. The outcome of the meeting was that developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The United States viewed the proposed limitations as too restrictive and did not sign the Kyoto Protocol. In spite of the controversies surrounding nuclear power, many scientists see the long-term use of more nuclear power as inevitable, both domestically and abroad.

Nuclear Power and the Environment

There are many aspects of nuclear power to consider when it comes to protecting the environment. The first that comes to mind is the storage of nuclear waste. As described earlier, almost all high-level waste is stored in on-site pools at the various power plants. These pools were never intended to serve as permanent storage facilities. Initially, operators of the power plants intended to chemically separate the unused uranium and plutonium taken from spent fuel rods and then recycle it as fuel for another fuel rod assembly. Reprocessing, however, concentrates plutonium into a form that is capable of being used to produce nuclear weapons, so President Jimmy Carter banned the process in 1977. Since the fuel could no longer be reprocessed, storage pools began to fill up. The storage pools at several nuclear power plants have now been filled to capacity, with no means of expanding them or reconfiguring the spent fuel to fit more in. If the spent fuel is placed too close together, chain reactions could occur. The solution has been the development of temporary aboveground nuclear waste storage casks.

What will become of all this nuclear waste? The federal government is supposed to take it from the utilities for permanent storage. Congress promised this in 1982, when it passed the ***Nuclear Waste Policy Act***. Since that time, utilities have charged their customers a one-cent surcharge for every kilowatt-hour (kWh) generated using nuclear power. The revenue generated is intended to help solve the long-term storage issue. The multibillion-dollar fund known as the ***Nuclear Waste Fund*** is used for the development of a permanent waste disposal site.

Nuclear Waste Policy Act: An act passed by Congress in 1982 promising that the federal government is to take nuclear waste from the utilities for permanent storage.

Nuclear Waste Fund: A multibillion-dollar fund used for the development of a permanent nuclear waste disposal site.

Storage of Nuclear Waste

For decades, scientists have been recommending that nuclear waste be stored in stable rock formations deep within the earth's surface. The most promising site appeared to be the government-owned Yucca Mountain facility in southern Nevada. The area sits adjacent to the Nevada Test Site, which served as a testing ground for early nuclear bombs. The land consists of porous rock that acts as a natural barrier to radiation. The location is seismically stable. Additionally, the water table in this unpopulated area is extremely deep. The idea for permanent storage would be to drill a shaft approximately 1000′ below the surface and then branch out in several directions with tunnels. An aboveground facility would accept the waste in transport casks and place it in permanent storage casks for underground disposal. The ***Yucca Mountain storage facility*** has been delayed several times. The opening date was originally scheduled for 1985. It was postponed until 1989, then 1998, and then 2003. Most recently, the Yucca Mountain site has been postponed indefinitely due to opposition.

Yucca Mountain storage facility: A government-owned facility in southern Nevada that was a planned site for permanent storage of nuclear waste. The waste would be stored in stable rock formations deep within the earth's surface.

World events like the 9/11 attacks on the World Trade Center Towers in New York City have called for renewed vigor in creating a permanent nuclear waste storage facility that would be difficult to sabotage.

Transporting Nuclear Waste

If nuclear waste is to be stored in a long-term storage facility, or if it is to be reprocessed, chances are it must be shipped from its current location to another location, often thousands of miles away. Spent fuel is protected for shipment against accidents and sabotage by the design of the ***shipping cask*** created to contain the fuel. See **Figure 4-11.** The tests these casks go through are extraordinary. A prototype cask is typically designed for testing. The casks are dropped onto the ground out of airplanes and helicopters, run into by diesel locomotives, and doused with jet fuel and ignited. All this is done to ensure the cask cannot be breached, even in a worst-case scenario during transport from one facility to another.

Shipping cask: A container designed to ship spent fuel from one facility to another.

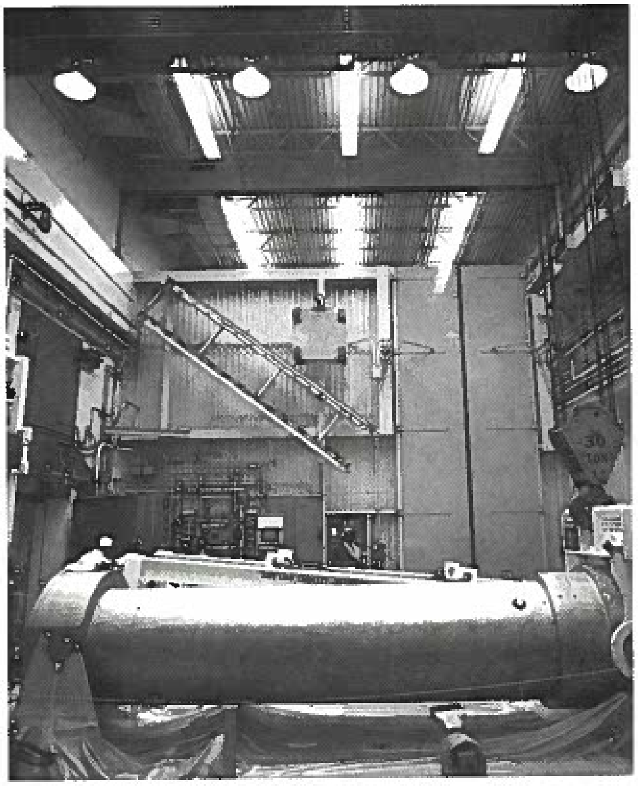
Recycling Nuclear Waste

With nuclear waste piling up in storage pools at power plants, spent fuels that have half-lives of thousands of years, and the dangers of nuclear proliferation, much attention has recently been focused on the possibility of recycling nuclear waste, rather than burying it. While funding for research remains critical, some progress has been made that would indicate that nuclear waste, even high-level waste, can be rendered harmless through processing techniques. Of course, one primary obstacle to recycling or reprocessing of nuclear waste may be more economic than technological. When all is said and done, it may simply be less expensive to bury the waste than it could be to recycle it. Burial of nuclear waste may prevail over other options that have less long-term risk, but are simply more expensive.

Nuclear Reactor Safety

Nuclear reactors have had a good track record in terms of environmental protection, particularly in the United States, where the reactor vessel is located within an environmental containment shield. Contamination from an explosion within the reactor vessel, regardless of how the explosion is caused, should not be capable of breaching the environmental containment shield. This is considerably different from the way some other countries constructed nuclear power plants. Many of the power plants in the former Soviet Union, including Chernobyl, were constructed within industrial buildings without any extraordinary effort to create an environmental shield. The reactor

Figure 4-11. The test of a cask design for use in shipping spent nuclear fuel to long-term storage facilities, such as Yucca Mountain. The cask is shown in a receiving facility at the Hanford Nuclear Facility in the state of Washington. (U.S. Department of Energy)



vessel was assumed to provide enough environmental protection. When a steam explosion demolished the reactor vessel and much of the surrounding building, there was simply nothing left to contain the release of radiation into the atmosphere. The results were that radiation fallout was found throughout much of Europe. See **Figure 4-12.**

All commercial reactors constructed within the United States must contain an environmental shield that has been engineered to withstand plane crashes, extreme weather conditions, and the possibility of explosion from within the reactor vessel. Since the reactor fuel is not configured like a nuclear bomb, it is doubtful a nuclear explosion could occur. A steam explosion, such as that which demolished the Chernobyl plant, is much more likely. Regardless of the means of explosion, what is most important is that the environment is protected. In the case of the ***Three Mile Island (TMI) accident,*** a small portion of the reactor core was melted when the reactor coolant was accidentally shut off. Emergency cooling water flooded the reactor core. Due to human error, however, the core was allowed to overheat for a period of time that caused irreparable damage. While only a small portion of the core was damaged, the image of a nuclear meltdown that destroyed the nuclear reactor and ultimately breached the containment vessel became etched in the minds of many Americans. Following the TMI accident, the entire nuclear power industry was overhauled to rely on more passive safety technology that is not capable of being manually overridden. This passive safety technology is regarded as being much more failsafe, as it does not rely on human intervention to protect the power plant. An example of a passive technology

Three Mile Island (TMI) accident: A nuclear disaster occurring in 1979 near Harrisburg, Pennsylvania. The Unit 2 reactor reached excessively high temperatures through a series of faulty readings and operator errors. Eventually, a small piece of the reactor core melted, rendering the reactor unusable before the situation was brought under control.

Figure 4-12. Radiation fallout from the Chernobyl nuclear power plant disaster.

would be a weld that is designed to fail if the reactor reaches a certain temperature. When the weld fails, it allows emergency cooling water to flood the reactor core without the aid of pumps, sensors, or human intervention. As a result of improved safety procedures and techniques, a detailed risk assessment of the probability of a major accident at a nuclear power plant involving death is estimated at 1 in 1 million. See **Figure 4-13.**

Breeder Reacting

Breeder reactor technology was born in America. It has been pursued for development, however, in other countries more than in the United States. ***Breeder reacting*** is a process that could extend the life of our proven uranium reserves by hundreds or perhaps even thousands of

Breeder reacting: Creating nuclear fuel from a substance that is not fissionable.

Figure 4-13. Estimates of health damage from a nuclear reactor accident.

Estimates of Frequency of and Damage to the Public from Three Types of Major Accidents to Nuclear Reactors					
Accident Type	**Frequency (Chance per Reactor–Year)**	**Health Effects Within One Year**		**Total First Year's Health Effects Plus Delayed Health Effects**	
		Deaths	**Illnesses**	**Cancer Deaths**	**Genetic Defects (for All Generations)**
Core meltdown	1 in 20,000	Negligible	Negligible	3	75
Plus above-ground breach of containment	1 in 1,000,000	1	300	5000	3800
Plus adverse weather conditions and population density	1 in 1,000,000,000	3000	45,000	45,000 (~1500/y)	30,000

Career Connection

Nuclear Engineers

Science, Technology, Engineering & Mathematics

Nuclear power generates about 20% of the electricity in the United States. Because of this, engineers are needed to design, operate, and maintain the equipment used in nuclear power plants and reactors. The work done by nuclear engineers may also be put to use in other areas, however, varying from the military to medical technology.

Much of a nuclear engineer's time may be spent either developing or modifying technology. This work may involve conducting research, developing formulas, and performing experiments. The task must also stay within the limits of safety regulations.

A nuclear engineer must have a broad range of skills. Proficiency is required not only in science and math, but also in reading comprehension and writing. A nuclear engineer must be able to read technical journals and prepare reports, proposals, and instructional materials. A bachelor's degree is required for work in this field. The yearly salary may range from $62,000 to $103,000.

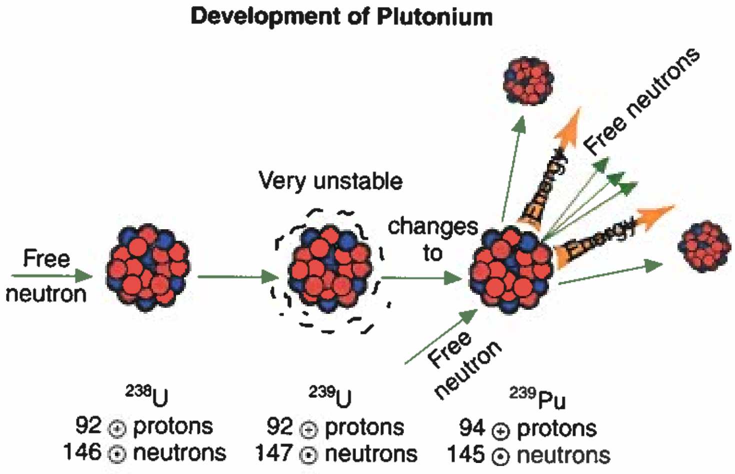
years. The technology of breeder reacting has been around since the early 1950s. In fact, the first electricity produced from a nuclear reactor was from a breeder reactor in 1951.

A breeder reactor is specifically designed to create nuclear fuel from a substance that is not fissionable. Imagine filling up your gas tank with 5 gallons of gas and 10 gallons of water and then driving around for a while. When you return home and check your tank, you have 14 gallons of gas! This is literally what breeder reacting can do. When uranium is mined out of the ground, about 99% of all uranium found is ***uranium 238 (U238)***, a nonfissionable element. Only the remaining 1% of uranium is U235, which is suitable for refining into nuclear fuel. A breeder reactor can create a fissionable fuel known as ***plutonium 239 (Pu-239)*** from U238. See **Figure 4-14.** This Pu-239 can then be used as fuel in other commercial nuclear power plants in the way that U235 is presently used. Thus, breeder reacting could have tremendous potential as an energy producer.

Uranium 238 (U238): A type of uranium that is a nonfissionable element. About 99% of all uranium mined is this type.

Plutonium 239 (Pu-239): A fissionable fuel created from uranium 238 (U238) by a breeder reactor.

Figure 4-14. Converting uranium 238 (U238) to plutonium in a breeder reactor.



If it sounds too good to be true, it may be. Like all energy sources, there are trade-offs. One of the biggest trade-offs with breeder reacting technology is the fact that, while Pu-239 can be used as a fuel source, it is also the material of which nuclear bombs are made. Additionally, the production and consumption of Pu-239 yields some of the worst by-products known to humanity. The half-life of high-level waste extracted from Pu-239 used as nuclear fuel would be expected to last over 24,000 years. This waste would either have to be reprocessed into something far less harmful or isolated from society for thousands of years. The possibility of proliferation is frequently mentioned when breeder reacting is discussed. ***Proliferation*** is the illegal acquisition of nuclear fuel for potentially harmful purposes. Since plutonium is extremely difficult to produce, those wishing to acquire plutonium for illegal purposes would have incentive to try to acquire it through any means possible. The more plutonium produced, the more likely it would be that someone with harmful intentions could acquire plutonium to fashion into a crude nuclear bomb.

Proliferation: The use of by-products of nuclear power for the production of nuclear weapons.

This has not hindered other countries, such as Japan, Russia, and particularly pronuclear France, from pursuing and developing breeder reactor technology. Japan has been converting several of its more than 50 operating nuclear reactors to run on a mixture of U235 and Pu-239. The mixture is presently coming from reprocessing plants in France and the United Kingdom, thus creating some environmental controversy regarding shipping of the fuel. Japan has plenty of reason to pursue this technology. It has virtually no domestic energy resources. Japan's electrical demand continues to increase, however, at about 4% per year.

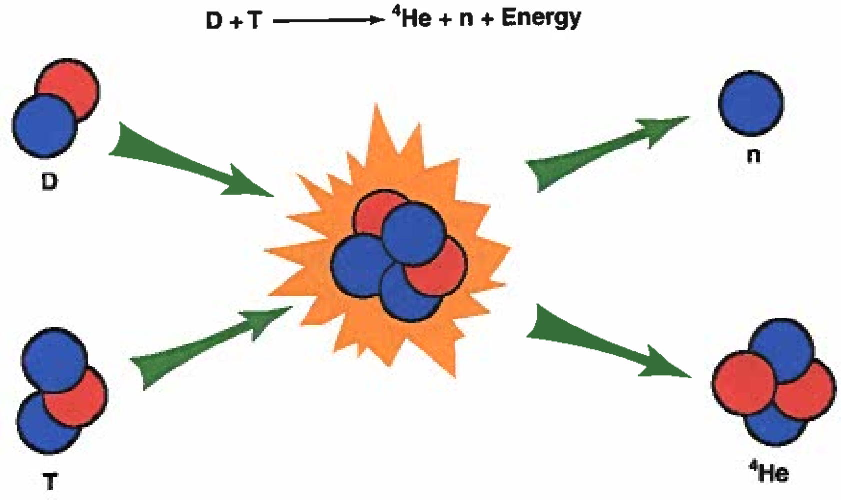
Nuclear Fusion

Nuclear fusion is considered by some knowledgeable scientists and technologists to be the ultimate energy source for electrical power generation. The initial concept of fusion, or the combining of light atoms, has been around as long as the nuclear fission process. As was described earlier, the fission process involves the splitting of an atom with a large nucleus, such as U235. The mass of the two smaller nuclei weigh less than the original nuclei. The loss of mass is converted into energy. Fusion is the combining of two nuclei into a larger nucleus. The large nucleus weighs less than the two smaller nuclei that formed it. The result of this process yields a large energy release. See **Figure 4-15.** One reason so many people are optimistic about the potential for nuclear fusion is that it represents a long-term solution to power production that cannot be matched by any other energy source, with the exception of solar energy. This is due in large part to the fact that the fuel source for nuclear fusion is found in water.

An ***isotope*** is a variation of an element. U235 and U238 are both isotopes of uranium. They have similar chemical properties and atomic structures, but their atomic weights vary slightly. Deuterium is an isotope of hydrogen. When found in water, its chemical configuration is H_3O instead of H_2O. Deuterium is found in about 1 out of every 6000–7000 hydrogen atoms. The fuel potential contained in deuterium found in just

Isotope: One of two or more atoms with the same number of protons but with different numbers of neutrons.

Figure 4-15. A fusion reaction involving deuterium (D) and tritium (T) results in the release of large amounts of energy. (Joint European Torus/European Fusion Development Agreement)



8 gallons of water is equivalent to the consumption of 2400 gallons of gasoline. Additionally, deuterium is easily and inexpensively extracted from water. Water is so plentiful, it is considered almost limitless.

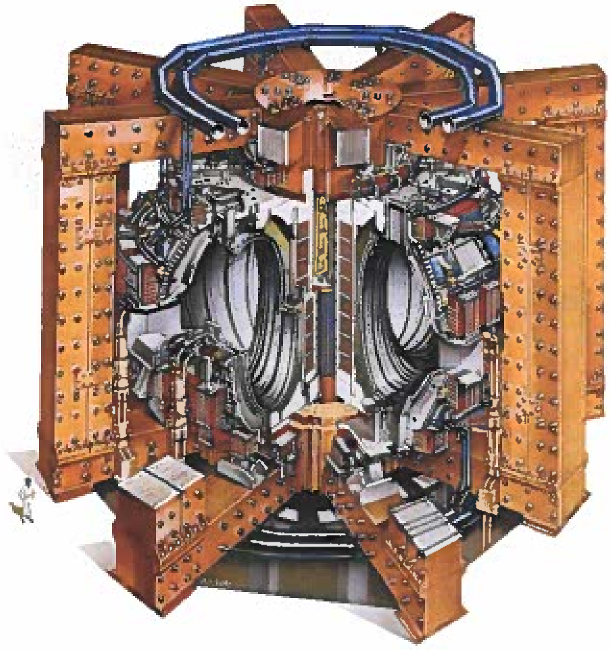
A fusion reactor would be inherently safer than a fission reactor. Unlike the chain reaction of a fission reactor, the fusion reactor could be continuously fed with fuel for fusion. If a problem were to occur, simply closing the fuel feed could stop the fusion, similar to the way a candle goes out when starved for oxygen. In theory, this would make a fusion reactor much safer than a fission reactor loaded with a dangerous fuel.

Electron: A negatively charged atomic particle.

Plasma: Ionized gas with an equal number of positive and negative charges.

Again, if it sounds to good to be true, it probably is. Fusion research has been ongoing since the 1940s. A fusion reaction that has yielded more energy than it has consumed, however, has yet to take place. Billions of dollars have been spent on research over six decades, without a reaction capable of the kind of sustained energy suitable for producing electricity. The technical requirements to sustain a fusion reaction include extremely high temperatures and confinement of materials. The temperature required for fusion is considered to be at least 50 million degrees Celsius. At these temperatures, the electrical bond between neutrons and ***electrons***, the negatively charged particles, is broken. The gas decomposes into free electrons and nuclei. This ionized gas with an equal number of positive and negative charges is known as ***plasma***. The plasma must be contained so the nuclei can fuse. Confinement at such high temperatures has proven difficult, however, since a heated gas expands to create great pressures. Confining the plasma using magnetism may yield the answer to a technological problem that has plagued fusion power development. The Tokamak Fusion Test Reactor, located at the Princeton Plasma Physics Laboratory, had some moderate success with fusion testing in the 1990s. A new type of magnetic confinement reactor began operation at Princeton in 1999. The world's largest tokamak is located in the United Kingdom. See **Figure 4-16.**

Figure 4-16. The tokamak vessel for fusion reactions, shown in this cutaway view, must safely contain the great pressure resulting from plasma with a temperature of more than 100 million degrees Celsius. This tokamak, located in the United Kingdom, is called the Joint European Torus (JET) and is a cooperative venture involving scientists from 15 nations that are part of the European Fusion Development Agreement (EFDA). (JET/EFDA)



Advantages of fusion power over fission power include that it is a virtually limitless supply of energy, with little radioactive waste and no possibility of a runaway reactor. The advantages over fossil fuels include the fact that fusion power would not contribute to global warming and that fusion power plants would operate at much higher efficiencies than conventional power plants. For all these reasons, fusion power research may be worth pursuing and may be considered essential to our continued existence on this planet. It may just be a matter of time before fusion power becomes a reality.

Summary

A nonrenewable element known as uranium 235 (U235) is the primary source of nuclear fuel for power plants. The only nuclear process used to produce nuclear power in use in the United States today is known as nuclear fission. Fission refers to the splitting of atoms in order to convert matter into energy. This process produces tremendous energy for the amount of fuel consumed. It also produces radioactive by-products, however, that must be isolated from society for thousands of years until they reach half-lives that are much safer for the environment. There are about 100 operating nuclear power plants located throughout the United States. Most are concentrated in the Northeast region of the country. These nuclear power plants produce about 20% of all the electricity produced in the United States. Even though nuclear power plants have had a relatively safe track record in the United States, no new plants have been ordered since a major accident at the Three Mile Island (TMI) nuclear power plant in Pennsylvania in 1979. In addition to reactor safety, economic issues and concerns about technical solutions for the long-term storage or reprocessing of nuclear waste have hindered the further development of nuclear power. Even so, the potential for breeder reacting, which can make usable fuel out of elements that cannot be used as nuclear fuel in their natural states, and the long-term potential of nuclear fusion, which uses elements found in ordinary water, make the need to continue nuclear research almost inevitable.

Key Words

All the following words have been used in this chapter. Do you know their meanings?

- boiling water reactor (BWR)
- breeder reacting
- control rod
- electron
- half-life
- isotope
- Kyoto Protocol
- neutron
- nuclear fission
- nuclear fusion
- Nuclear Waste Fund
- Nuclear Waste Policy Act
- nucleus
- plasma
- plutonium 239 (Pu-239)
- pressurized water reactor (PWR)
- primary loop
- proliferation
- proton
- radioactivity
- secondary loop
- shipping cask
- Three Mile Island (TMI) accident
- uranium 235 (U235)
- uranium 238 (U238)
- Yucca Mountain storage facility

Test Your Knowledge

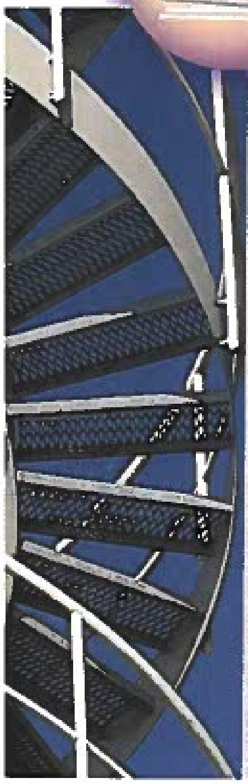
Write your answers on a separate sheet of paper. Do not write in this book.

1. Discuss in two or three sentences how nuclear fuel is produced.
2. Nuclear power is responsible for approximately _____% of all electricity produced in the United States.
3. *True or False?* The roots of the nuclear power industry can be traced to nuclear weapons.
4. *True or False?* Orders for new construction of nuclear power plants have been on the rise in recent years.
5. Recall in two or three sentences how nuclear fission is used to produce electrical power.
6. The term most often used to describe the rate at which a material loses half of its radioactivity is known as its _____.
7. *True or False?* Uranium 235 (U235) is the fuel most often used in nuclear power plants.
8. Rods used to regulate the rate of nuclear fission in a nuclear reactor are known as _____.
9. Summarize the major differences between BWRs and PWRs.
10. *True or False?* Most nuclear power plants in commercial operation in the United States are located in the western United States.
11. *True or False?* All high-level waste is presently stored in a federal repository.
12. Most spent nuclear fuel is stored in _____ at the _____.
13. *True or False?* Recycling nuclear waste is one way to reduce the possibility of proliferation of nuclear waste.
14. Write two or three sentences describing the present status of and future plans for storage of low-level and high-level nuclear waste in the United States.
15. *True or False?* The shipping casks used to transport nuclear waste are highly problematic and frequently leak.
16. Since the Three Mile Island (TMI) accident in 1979, reactors have been redesigned to rely primarily on _____ safety systems, which do not require human intervention.
17. Much has been learned about nuclear reactor safety since the accident at TMI. Describe advancements in nuclear power plant safety and design.
18. *True or False?* Breeder reactors can create more useful fuel than they consume.

19. *True or False?* Nuclear fusion is a process currently used to produce electrical power.
20. Identify the pros and cons of generating more electricity with nuclear power.
21. Compare the risks associated with generating electricity using nuclear power with risks of generating electricity from fossil-fueled power plants.

STEM Activities

1. With an adult, tour a nuclear power plant, if one is located near your geographic area.
2. Participate in a classroom debate to discuss the pros and cons of nuclear power.
3. Research the disposal of nuclear waste within your state.



Career Skills

Job Applications

A prospective employer may ask you to complete a job application form before having an interview. The job application form highlights the information the employer needs to know about you, your education, and your prior work experience. Employers often use these forms to screen applicants for the skills needed on the job. You might complete a form in a personnel or employment office. Sometimes you may get the form by mail.

The appearance of the application form can give an employer the first opinion about you. Fill out the form accurately, completely, and neatly. How well you accomplish that can determine whether you get the job. When asked about salary, write *open* or *negotiable*. This means you are willing to consider offers.

Many employers now request electronic applications, either through their company Web sites or independent job-search Web sites. When filling out an on-line application, it is extremely important to include key terms for which the employer may search. This will help you stand out from the many other applications the employer will receive.

When preparing your application, be sure to save it in the appropriate format. If a preferred format is not given, it is best to save the application in document file format or PDF file format. This will enable the employer to find specific search terms in your document. Be sure to complete all the fields of the application. Many job-search sites have sample forms on which you can practice before attempting a real application.