CHAPTER 16

Nuclear Energy

IN THIS CHAPTER

Summary: By the mid-1990's, roughly 20% of America's electricity was provided by licensed power reactors. Nuclear energy, using ^{235}U, has the capability to provide energy for several hundred years.

KEY IDEA

Keywords

✪ Fission, fusion, breeder reactor, uranium, Three Mile Island, radioactivity, Chernobyl, Nuclear Regulatory Commission, half-life, radiation

Nuclear Energy

Currently, nuclear energy provides the world with around 15% of its energy needs. In the United States, 20% of electricity comes from nuclear power generating plants. In fact, Vermont leads the nation with 85% of its electricity from nuclear power.

Public perception fluctuates with regard to nuclear power. When everything is running smoothly and providing clean energy, most people are happy. However, accidents happen, and when they do, nuclear energy claims more than its share of bad public opinion, where radioactive health risks and radioactive waste are show stoppers.

Uranium

Uranium is commonly found in minute amounts of the uranium oxide mineral *uraninite* (*pitchblende*) in granite and other volcanic rocks. Natural uranium is 99.3% ^{238}U and 0.7% ^{235}U. Nuclear energy comes primarily from uranium ^{238}U enriched with 3% ^{235}U.

Fission and Fusion

Nuclear power is created in one of two ways; *fission* (splitting) of uranium, plutonium, or thorium atoms; and *fusion* (merging) of two smaller atoms into one larger atom with a combined nucleus. As the nuclei merge, energy is released, but this method is scientifically complex and has never been shown to produce more energy than it consumes.

Nuclear Reactors

Most *nuclear reactors* contain a core with a large number of fuel rods loaded with uranium oxide pellets. The fuel pellets (usually around 1 cm diameter and 1.5 cm long) are commonly arranged in a long zirconium alloy tube to form a fuel rod—the zirconium is hard, corrosion resistant, and permeable to neutrons. Up to 264 control rods of neutron-absorbing material (e.g., silver, cadmium, boron, or hafnium) can be inserted or lifted from the core to control the reaction rate or to stop it. A moderator material, like water or graphite, slows down neutrons released from fission so more fission is created.

TIP

When a ^{235}U isotope undergoes fission, it absorbs a neutron and then splits into two fission pieces (and other atomic particles) that ricochet away at high velocity. When they stop, their energy is converted to heat—about 10 million times the heat of burning a carbon atom in coal.

Boiling water and *pressurized water reactors* are two types of similar nuclear reactors. They both have a hot reactor core, which heats water to steam and, in turn, spins turbines to generate electricity. Pressurized reactors use heat from the core to heat a second water supply for the turbines via a heat exchanger, and a third water system to cool steam from the turbines to be used again.

Breeder Reactors

Under the right operating conditions, neutrons given off by fission reactions can "breed" or create more fuel from otherwise nonfissionable isotopes. *Breeder reactors,* which produce more energy than they use, can provide energy for billions of years. The most common breeder reaction is that of plutonium (^{239}Pu), a by-product of nonfissionable ^{238}U. Uranium's most stable isotope, ^{238}U, has a half-life of nearly $4\frac{1}{2}$ million years. However, since breeder reactors use uranium by-products, which are extremely dangerous and can be used in nuclear weapons, policy makers are cautious about their construction.

Nuclear Capacity

Currently, there are 436 nuclear power plants worldwide, with 104 of those in the United States (as of June 2009). There are another 48 plants under construction in 15 countries. Figure 16.1 illustrates the parts of a nuclear power plant.

Water, heated to steam, drives a turbine which generates electricity. These plants produce nearly 20% of the world's total electricity. In addition, they create huge amounts of reliable energy from small amounts of fuel without the air pollution created by burning fossil fuels. However, reactors are only licensed for 40 years, and early reactors in the United States have been or are in the process of being decommissioned.

In 1973, only 83 billion kilowatt-hours (kWh) of nuclear power was produced. In 2005, nuclear power produced 2.6 *trillion* kWh of electricity and is expected to approach 4 trillion kWh by 2030. Despite the initial growth in U.S. nuclear power, the threat of radioactive release, waste disposal, and/or terrorism put a stop to it. In fact, no new nuclear power plants have been built since 1977.

TIP

Worldwide, France has the greatest number of nuclear power plants on a per capita basis and is second in installed nuclear capacity after the United States. Because of France's limited energy resources, energy security and imports are big concerns. The French government has strongly promoted nuclear power over the past 36 years. To date, roughly 75% of France's electricity comes from the country's 58 nuclear reactors. To reduce their dependency on fossil fuels (over 80% in 1973), the French invested heavily in nuclear power.

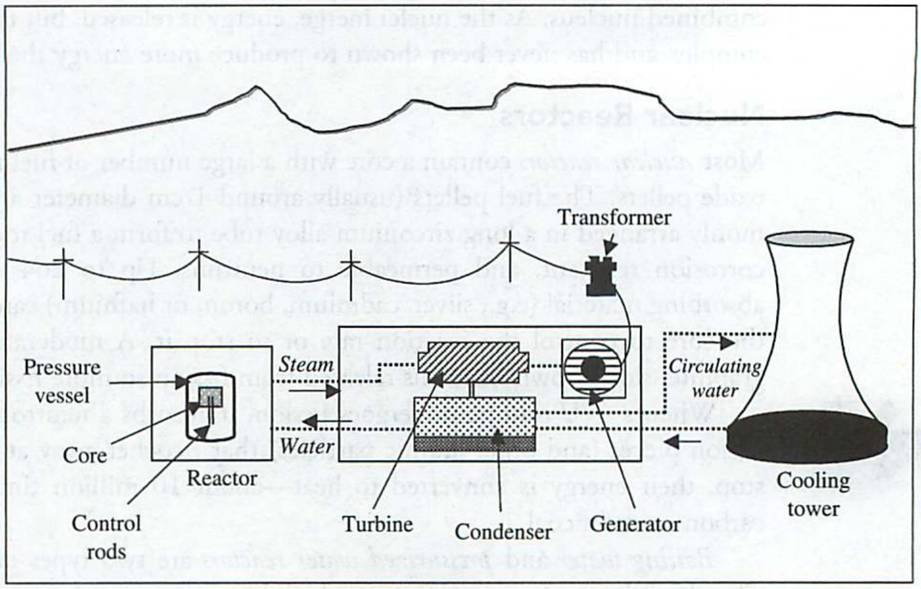

Figure 16.1 An impoundment hydroelectric power plant is commonly known as a dam.

Accidents

Nuclear power is reliable, but safety is critical since a nuclear accident can cause a huge environmental disaster.

Three Mile Island

On March 28, 1979, the nuclear accident at *Three Mile Island*, a two-unit nuclear plant on the Susquehanna River in Pennsylvania, caused great safety concerns and fears of radiation leakage.

At Three Mile Island, the reactor lost cooling water and overheated, and some of the fuel rods melted and ruptured. This resulted in a release of radioactive gases into the atmosphere and critical damage to the reactor. People within a 1-mile radius of the reactor were evacuated, but no one was injured.

The U.S. nuclear industry has been stopped in its tracks since the Three Mile Island accident, the worst nuclear accident in U.S. history. No company has continued with plans to build a new nuclear plant since the accident, even though former President George W. Bush backed new construction of nuclear plants as part of his energy policy.

In a possible public opinion change, some environmentalists are starting to rethink nuclear power, since unlike fossil fuels, it doesn't produce enhanced greenhouse gas emissions. Modern nuclear plant designs also contain smaller reactors, which create less radioactive waste and take into account 75 factors including human factors, seismic activity, water availability, and emergency preparedness issues.

Chernobyl

The world's worst nuclear plant accident occurred in the Ukraine, on April 26, 1986, at the Chernobyl nuclear power plant, where 31 plant workers died the day of the accident and nearly 200 of the 1,000 reactor staff and responding emergency personnel died from radiation poisoning within three weeks. The Chernobyl plant, a graphite-regulated reactor, did not have the concrete containment dome mandatory on all American nuclear plants.

The Chernobyl accident happened when two quick blasts blew off the reactor roof, spewing radioactive gases into the atmosphere. Fires, poor containment design, operator mistakes, and a power surge led to the catastrophic and deadly conditions. With the core continuing to heat up, Russian officials ordered aircraft to dump 5,000 tons of lead, sand, and clay onto the site to bring the temperature down.

The East-West politics of the time resulted in an early cover-up of the incident, until Swedish scientists detected the radioactive cloud moving across several countries and demanded an explanation.

Immediately after the Chernobyl accident, 116,000 people were relocated from the contaminated area. Later, another 350,000 were relocated from the most severely contaminated areas. Health studies linked increased birth defects and 4,000 thyroid cancer cases in children living in the Chernobyl area at the time to the accident.

Although radiation has nearly returned to baseline levels in much of the surrounding area, inhabitants were traumatized by relocation, economic losses, and the need for young people to seek jobs elsewhere. The number of deaths still tops births and gives the further perception that the area is tainted.

The China Syndrome

In addition to radioactivity, the spiraling temperature rise during a meltdown is a huge safety issue. This is known as the China Syndrome.

KEY IDEA

> The *China Syndrome* is a hypothetical concept that refers to what might happen if nuclear core temperatures escalated out of control, causing the core to melt through the Earth's crust all the way to the other side of the world (to China).

In 1979, a Hollywood movie entitled *The China Syndrome* described incidents that occurred at the Rancho Seco power plant in California. However, unlike the movie portrayal, the Rancho Seco emergency system shut the reactor down safely as it was designed to do.

Japan's Earthquake/Tsunami

The Japanese Kashiwazaki-Kariwa plant is the world's largest nuclear power plant in power-output with seven reactors generating 8.2 million kilowatts of electricity. It is located 135 miles northwest of Tokyo. On March 11, 2011, an 8.9 magnitude earthquake shook the coast of Japan and created a 10-meter (33-ft) tsunami. The earthquake-damaged and swamped nuclear plant released radioactive coolant water when pipes cracked and a containment building exploded. Contaminated radioactive water leaked into the Sea of Japan and ten days later, milk and spinach were found to have dangerous, elevated reactor byproducts (e.g., radioactive iodine-131 and cesium-137) within 105 km (65 mi) of the plant. High levels of iodine-131 are known to cause thyroid cancer, while cesium-137 damages cells and can cause cancer. As of August 2011, the official death toll reported by the Japan Fire Department from the earthquake and tsunami was 21,234 (16,477 deaths and 4,787 missing). They also reported 111,944 buildings destroyed with over 600,000 additional buildings partially destroyed and/or damaged.

Radioactivity

French scientist Marie Curie used the term *radioactivity* for the first time in 1898. Curie and her physicist husband Pierre found that radioactive particles were emitted as either electrically negative (–) *beta* (β) *particles* or positive (+) *alpha* (α) *particles.*

Radioactivity is considered a bad side effect of nuclear weapons and x-rays, but when properly shielded, radioactive elements are useful. In fact, radioactive elements provide power sources for pacemakers, satellites, and submarines.

Nuclear Reactions

Most chemical reactions are focused on the outer electrons of an element, sharing, swapping, and bumping electrons into and out of the combining reaction partners. However, nuclear reactions are different. They take place inside the nucleus.

There are two types of nuclear reactions. The first is the radioactive decay of bonds within the nucleus that emit radiation when broken. The second is the "billiard ball" type of reaction where the nucleus or nuclear particle (like a proton) is struck by another nucleus or nuclear particle.

Radioactive Decay

A radioactive element, like everything else in life, decays (ages). When uranium or plutonium decays over billions of years, it goes through a transformation process of degrading into lower-energy element forms until it settles into one that is stable.

When a radioactive element decays, different nuclear particles are given off. These radiation particles can be separated by an electric (magnetic) field and detected in a laboratory as

Beta (β) *particles* = negatively (−) charged particles

Alpha (α) *particles* = positively (+) charged particles

Gamma (γ) *particles* = electromagnetic radiation with no overall charge (similar to x-rays), but with a shorter wave length

Radioactive isotope decay is affected by an element's stability at a certain energy level. An instrument used to detect radioactive ions is called an *ionization counter.* Bismuth (Bi), atomic number 83, is the heaviest element in the periodic table with one stable isotope. Other heavier elements (e.g., thorium, einsteinium) are radioactive.

Half-life

All radioactive isotopes have a specific *half-life.* These are not dependent on pressure, temperature, or bonding properties, but on the specific energy levels of the isotope's molecular makeup.

> The *half-life* of a radioactive isotope is the time it takes for one-half of an elemental sample to decay.

For example, the half-life of plutonium ^{239}P is 2.13×10^6 years. The half-life of ^{238}U is 4.5×10^9 years, about the same age as the Earth. It is sobering to think that the uranium found today will be around for another 4 billion years.

Nuclear Disadvantages

A serious problem with nuclear power is the storage of radioactive waste. Each year, about 30 metric tons of used fuel are created by every 1,000-megawatt (MW) nuclear electric power plant. Most of this waste is stored at the power plants because of the lack of high-level radioactive waste disposal sites. Long-term storage is crucial as additional radioactive waste accumulates.

Although not much waste is created at any one plant, it is extremely dangerous. It must be sealed up and buried for decades, even centuries, to allow time for the radioactivity to gradually disappear.

Radioactive Waste Storage

STRATEGY

In January 2002, Energy Secretary Spencer Abraham recommended Yucca Mountain, Nevada, as the nation's permanent nuclear waste depository. His plan called for specially designed containers that would hold over 77,000 tons of nuclear waste from both power plants and nuclear weapons' manufacturing to be buried in a series of tunnels dug 302 meters below the mountain's peak and 274 meters above the water table.

Work has been halted on the Yucca Mountain site and it no longer receives federal funding. In 2012, President Obama's Blue Ribbon Commission on America's Nuclear Future submitted its final report to the Secretary of Energy on potential alternatives for nuclear waste storage.

Yucca Mountain's storage capacity was projected to be full within 25 years. The construction of another nuclear waste storage site or other storage option(s) is critical to addressing future U.S. radioactive storage requirements. Yucca Mountain's storage capacity is projected to be full within 25 years of its opening at current nuclear waste production rates. Therefore, its expansion or the construction of a second waste storage site must begin now to meet future U.S. radioactive storage requirements.

Geologists are studying the pros and cons of storing radioactive waste beneath the deep oceans and in stable (no tectonic activity) rock formations. The big concern is that sometimes groundwater can seep into land sites and become contaminated. States like Nevada, designated as radioactive repositories, are not happy about these significant safety hazards. Since the Earth is always surprising geologists, there is no way to guarantee that a chosen site will be stable and safe for radioactive storage for hundreds or thousands of years. The debate over nuclear energy will probably go on for a long time.

Transporting Waste

TIP

Another big controversy centers on the transportation of nuclear waste to any distant storage site by rail or truck. Since most nuclear power plants are in the eastern part of the United States, the waste must be transported about 2,000 miles westward if relatively unpopulated regions are to be considered for long term waste storage.

Besides the usual transportation mishaps possible on a long trip, the very real threat of terrorist sabotage hangs like a black cloud over the entire transportation plan. In any case, nuclear utilities are running out of radioactive waste storage capacity. If we continue to use nuclear power, we'll have to store the waste somewhere.

Regulations

Compared to the extreme Chernobyl accident, the Three Mile Island incident was not serious and no deaths occurred. In fact, the best thing to come out of Three Mile Island was much better plant and safety designs and the creation of the *Institute of Nuclear Power Operations* (INPO). The INPO established guidelines for excellence in nuclear plant operations and increased communication within the nuclear industry.

A strong regulatory impact in response to public outrage has been a big factor in the growth of nuclear power. In 2000, the *Nuclear Regulatory Commission* (NRC), in an encouraging nod to the U.S. nuclear power industry, granted the first-ever renewal of a nuclear power plant's operating license. The 20-year extension (2034 and 2036 for two reactors) was given to the 1700-MW Calvert Cliffs, Maryland, plant.

A 2011 U.S. opinion poll has shown a turn around with 62% of those polled favoring nuclear power production compared to 35% opposed. In fact, Southern Company (a utility company) has begun construction on two new nuclear units that are expected to provide commercial power by 2016 and 2017, respectively.

› Review Questions

Multiple-Choice Questions

1. A big concern facing geologists in long-term radioactive waste storage is that

(A) people living in the area will begin to glow in the dark
(B) the half-life will take even longer
(C) groundwater will seep into land sites and become contaminated
(D) people will mistake it for fluorescent minerals
(E) the public will not tolerate the necessary safety measures

2. The isotope of uranium that undergoes fission and releases huge amounts of energy is

(A) ^{190}U
(B) ^{225}Pt
(C) ^{60}I
(D) ^{235}U
(E) ^{90}Ba

3. A nuclear reactor contains a core with many fuel rods containing

(A) steel pellets
(B) uranium oxide pellets
(C) iron pellets
(D) palladium pellets
(E) silicon pellets

4. Which country's government has strongly promoted increases in nuclear power use over the past 30 years?

(A) Columbia
(B) Madagascar
(C) Holland
(D) France
(E) Spain

5. An instrument used to detect radioactive ions is called a(n)

(A) mass spectrometer
(B) metal detector
(C) ionization counter
(D) gas chromatograph
(E) high-performance liquid chromatograph

6. A strong regulatory backlash to nuclear power in the United States occurred in response to the

(A) Three Mile Island accident
(B) first U.S. nuclear power plant built
(C) September 11, 2001, terrorist attacks
(D) eruption of Mount St. Helens
(E) use of nuclear power in submarines

7. No new nuclear power plants have been built or planned in the United States since

(A) 1958
(B) 1962
(C) 1977
(D) 1983
(E) 1990

8. The time for a radioactive element or isotope to degrade is known as its

(A) half-life
(B) fission potential
(C) transmutability point
(D) radioactive potential
(E) radioactive point

9. Deep underground storage facilities are needed for

(A) mining of uranium
(B) Department of Energy's yearly retreat
(C) storage of new power plant construction material
(D) protection of local inhabitants in the event of a nuclear attack
(E) storage of radioactive waste from energy generation

10. The biggest advantage of nuclear energy generation is that

(A) it is free
(B) it doesn't generate greenhouse gases
(C) it takes very few people to operate a plant
(D) it produces low-wattage power
(E) many developing countries are rapidly increasing their nuclear portfolio

11. Decay of radioactive isotopes is affected by the

(A) isotopes' boiling point
(B) pressure
(C) properties of the isotopes' storage container
(D) stability of an element at a certain energy level
(E) size of the original sample

12. After Three Mile Island, much better plant and safety designs, along with the creation of which organization, occurred?

(A) Department of Energy
(B) Occupational Health and Safety Organization
(C) Department of the Interior
(D) Richard Smalley Nanotechnology Institute
(E) Institute of Nuclear Power Operations

13. Each year, roughly what amount of used fuel is created by every 1,000-megawatt nuclear electric power plant?

(A) 10 metric tons
(B) 25 metric tons
(C) 30 metric tons
(D) 50 metric tons
(E) 65 metric tons

14. French scientist Marie Curie coined what term in 1898?

(A) Radioactivity
(B) Isotope
(C) Half-life
(D) Geological time
(E) Fission

15. Besides alpha and beta particles separated in a magnetic field, what other short-wavelength particles can be detected?

(A) Joules
(B) Quarks
(C) Gamma particles
(D) Radioactive dust
(E) Omega particles

16. Radioactive elements provide power sources for all but which of the following?

(A) Pacemakers
(B) Generators
(C) Submarines
(D) Satellites
(E) Automobiles

17. What important action did the Nuclear Regulatory Commission take in 2000?

(A) They decided to stop work on the Yucca Mountain waste storage site.
(B) They issued the first-ever renewal of a nuclear power plant's operating license.
(C) They offered green credits for nuclear energy.
(D) They published a successful method of nuclear fusion.
(E) They collaborated with France on better ways to store electric power.

18. Nuclear power is commonly generated using the element

(A) copper
(B) actinium
(C) mercury
(D) uranium
(E) platinum

› Answers and Explanations

1. C—States designated as radioactive repositories are concerned about safety hazards.

2. D—Nuclear energy comes from enriched uranium (^{235}U).

3. B—The fission process uses uranium oxide pellets.

4. D

5. C—When uranium undergoes fission, high-energy ions are given off.

6. A

7. C

8. A—A radioactive isotope's half-life is the time it takes for one-half of an elemental sample to decay.

9. E—In specially designed containers, over 77,000 tons of nuclear waste from power plants and nuclear weapons will be buried in deep underground storage tunnels.

10. B—If you don't count radioactive waste, nuclear energy is nonpolluting to the air.

11. D—Bismuth is a stable, heavy, non-radioactive element.

12. E—The INPO established guidelines for excellence in nuclear plant operations and increased communication within the nuclear industry.

13. C

14. A—It was used to describe the energy generated by certain elements.

15. C—Gamma (γ) particles are electromagnetic radiation with no overall charge, but a shorter wavelength.

16. E—Currently, no automobiles have been designed to run on nuclear power.

17. B—The 20-year extension was issued for two reactors at a Maryland plant.

18. D

Free-Response Questions

1. France appears to be rethinking its nuclear push. Even though the French government planned to eventually have 100% nuclear power generation, strong environmental concern slowed nuclear growth. When Germany chose to phase out nuclear power, French public concern grew. Currently, French opinion polls favor an end to nuclear power.

Unfortunately, the French have no clean, affordable substitutes to handle the power demand. They must either replace aging nuclear plants with modern ones, or phase out nuclear power, since several reactors need replacement before 2020.

(a) Describe the difficulties France may encounter when attempting to switch from nuclear energy to lesser developed energy generators.
(b) What are the technological alternatives?
(c) Describe how these various alternatives might meet the demand.
(d) How might the switch be speeded up?

2. After discovery of corrosion in a major nuclear plant section in Ohio, the Nuclear Regulatory Commission ordered safety information on 68 other units. After checking the problem thoroughly, the problem was found to affect only the Ohio unit. The news media reported this problem thoroughly when it was discovered, but didn't follow-up on the other inspected units months later.

(a) Describe the impact of the initial story on the public's perception of nuclear safety.
(b) What should the government have done to allay public concern about U.S. nuclear energy and its safety record?
(c) Did this incident promote the argument for the construction of new nuclear plants?

Free-Response Answers and Explanations

1.
   a. There are several socioeconomic and environmental problems France may face. Added to shifting public opinion, the costs of completely changing energy-producing technologies would create a huge economic strain on France's government and population. Plus, energy prices would increase considerably, placing even more strain on the population. Disposing of hazardous nuclear waste is also a concern.
   b. Aside from various fossil fuel sources (e.g., coal, oil, and natural gas), there are clean energy sources available. Solar and wind power provide inexhaustible sources of energy whose costs are steadily declining thanks to market forces and government subsidies.
   c. Alternatives such as solar and wind power would have to be used together and/or in conjunction with other energy sources, like fossil fuels, to meet the demand.
   d. The switch could be sped up by beginning to phase out nuclear energy with other sources like wind and/or solar power in specific communities. It could also be accelerated if communities took more ownership of their own energy power needs.

2.
   a. Since the general public knows so little about nuclear plants, the story's initial impact would have caused alarm. Public fears about nuclear energy sources, especially after catastrophic events in the not too distant past due to plant failures, are easily aroused and can lead to panic.
   b. To allay public concern about the safety of nuclear energy, the government should have fully reported on the 68 safe units. The government must do a much better job of informing the public about nuclear energy. With more information, public opinion would be better informed and less likely to be aroused in a similar event.
   c. Yes and no. For those whom the story aroused fear about the prospect of nuclear energy, this incident would have prompted an argument for shutting down nuclear power plants and looking for alternative energy sources. However, those informed of nuclear energy's safety and benefits might have been persuaded by the incident to build new plants or update those in need of retooling.

❯ Rapid Review

- Uranium's most stable isotope, ^{238}U, has a half-life of nearly $4\frac{1}{2}$ billion years.
- Uranium oxide, found in granite and other volcanic rocks, is known as pitchblende.
- Nuclear power is created by fission (splitting) of uranium, plutonium, or thorium atoms; and fusion (merging) of two smaller atoms into a larger atom with a combined nucleus.
- Nuclear energy, using ^{235}U, has the capability to provide energy for several hundred years.
- Most nuclear reactors contain a core with a large number of fuel rods loaded with uranium oxide pellets.
- Breeder reactors produce more energy than they use.
- The most common breeder reaction is that of plutonium (^{239}Pu), a by-product of nonfissionable ^{238}U.
- Fires, poor containment design, operator mistakes, and a power surge led to the catastrophic accident in Chernobyl, Ukraine.
- The Chernobyl plant, a graphite-regulated reactor, did not have the concrete containment dome mandatory on all American nuclear plants.

- The China Syndrome is a hypothetical concept that refers to what might happen if nuclear core temperatures escalated out of control, causing the core to melt through Earth's crust all the way to the other side of the world (to China).
- Boiling water and pressurized water reactors are two types of similar nuclear reactors with hot reactor cores that heat water to steam, spin turbines, and generate electricity.
- The INPO established guidelines for excellence in nuclear plant operations and increased communication within the nuclear industry.
- The Curies found that radioactive particles were emitted as electrically negative beta (β) particles or positive alpha (α) particles.
- At Three Mile Island, the reactor lost cooling water, overheated, and the fuel rods melted and ruptured; in addition radioactive gases were released into the atmosphere.
- When a radioactive element decays, different nuclear particles (e.g., alpha, beta, and gamma) can be separated by a magnetic field.
- Gamma (γ) particles have no overall charge, but a shorter wavelength.
- Transportation of nuclear waste by rail or truck is an issue because of possible radiation release from rail or highway accidents and terrorism.