Chapter 17:

Nuclear Energy and the Environment

STR/epa/Corbis

2011 Fukushima nuclear power plant failure—aerial view of reactor burning.

Overview

- Current Role of Power Plants
- What is Nuclear Energy?
- Nuclear Energy and the Environment
- Nuclear Radiation in the Environment and Its Effects on Human Health
- Nuclear Power Plant Accidents
- Radioactive-Waste Management

Current Role of Power Plants

- Worldwide
  - 435 power plants
  - 14% of electricity
  - 4.8% of total energy

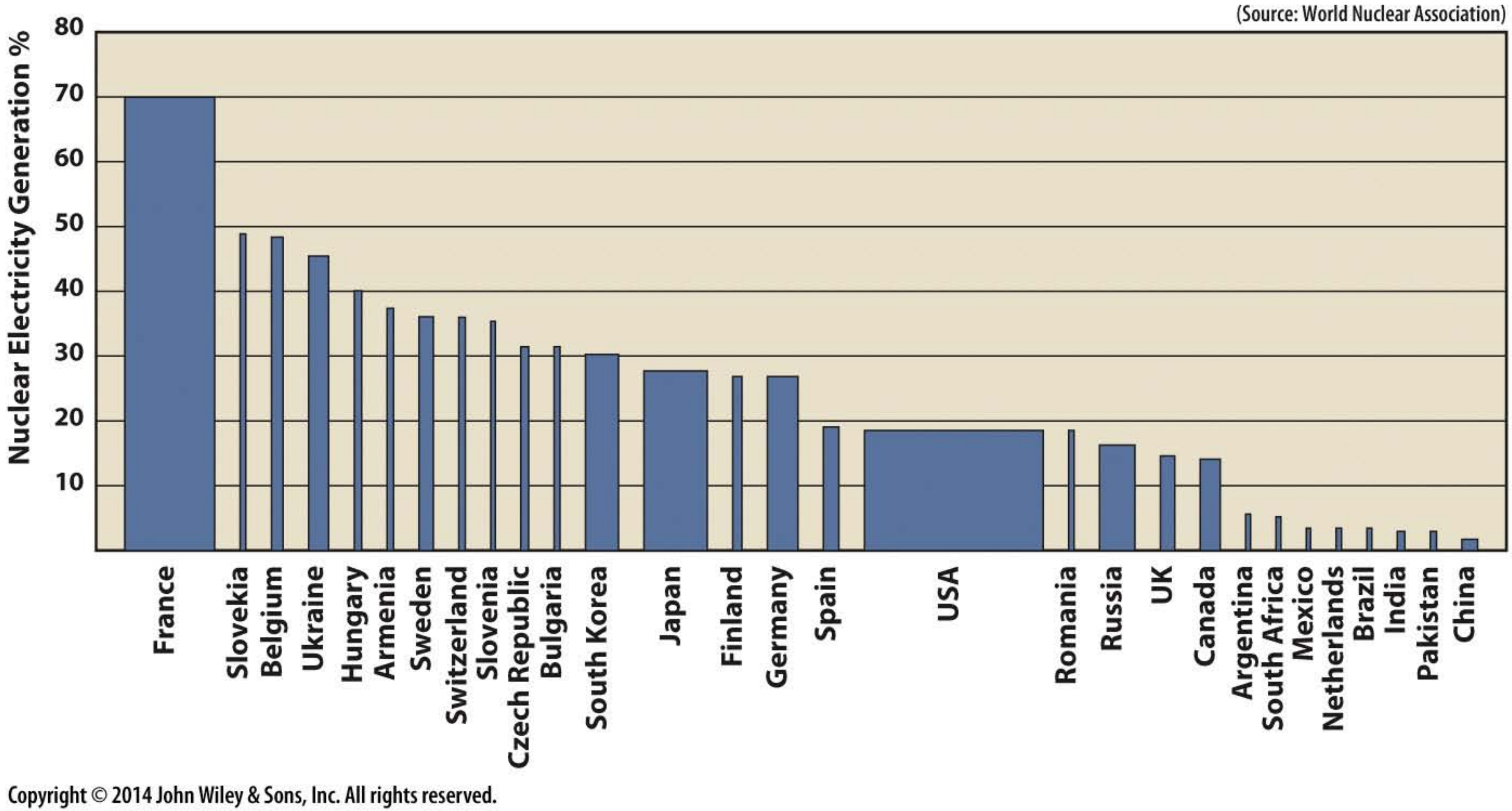


Figure 17.3 World generation of electricity by country in 2010. The width of bars shows the percentage of total nuclear power generated.

What is Nuclear Energy?

- Energy contained in the atom's nucleus
- Two processes can be used to release that energy
  - Fission—splitting of atomic nuclei
  - Fusion—fusing or combining of atomic nuclei
- Nuclear reactors
  - Devices that produce controlled nuclear fission
  - Used for commercial energy production

Conventional Nuclear Reactors

- First demonstrated in 1942
  - Led to development of nuclear energy to produce electricity
  - Currently powers submarines, aircraft carriers, and icebreaker ships
- Nuclear fission produces much more energy than fossil fuels.

Conventional Nuclear Reactors

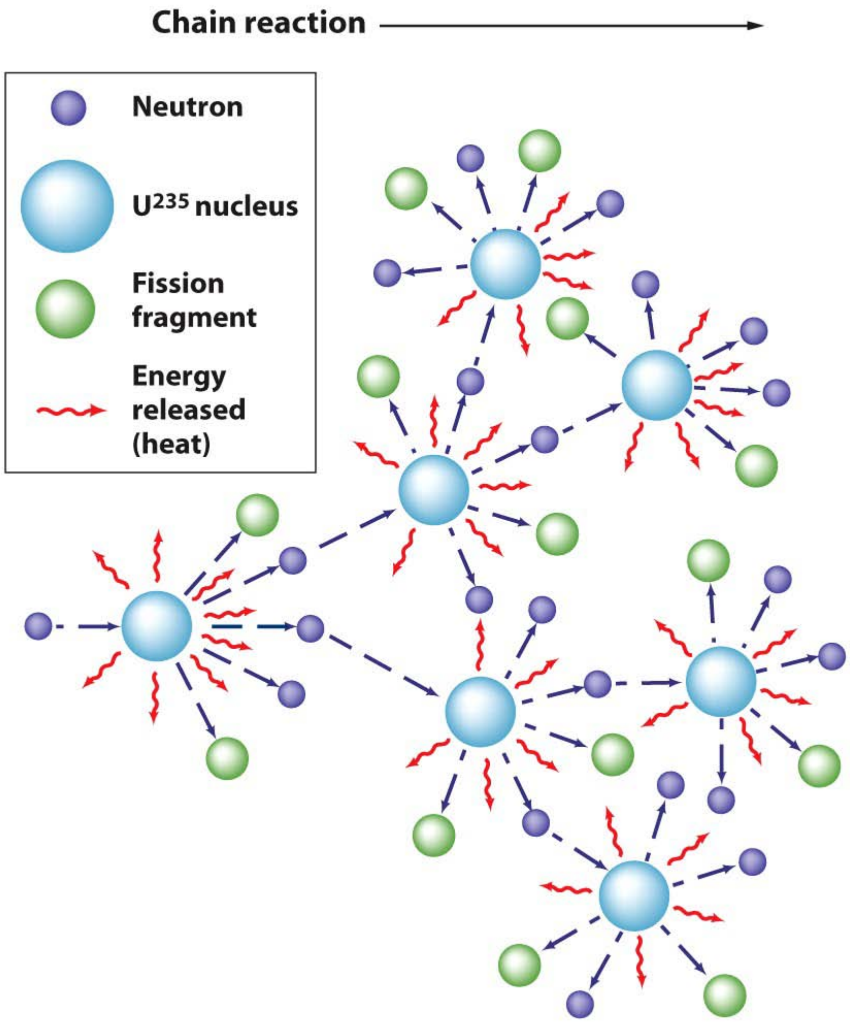
- Three isotopes of uranium occur in nature
  - Uranium-238
  - Uranium-235
    - The only naturally occurring fissionable material
    - Essential to production of nuclear energy
  - Uranium-234
- Enrichment of U-235 necessary
  - Processing to increase concentration of U-235
  - Enriched from 0.7% to about 3%

Conventional Nuclear Reactors

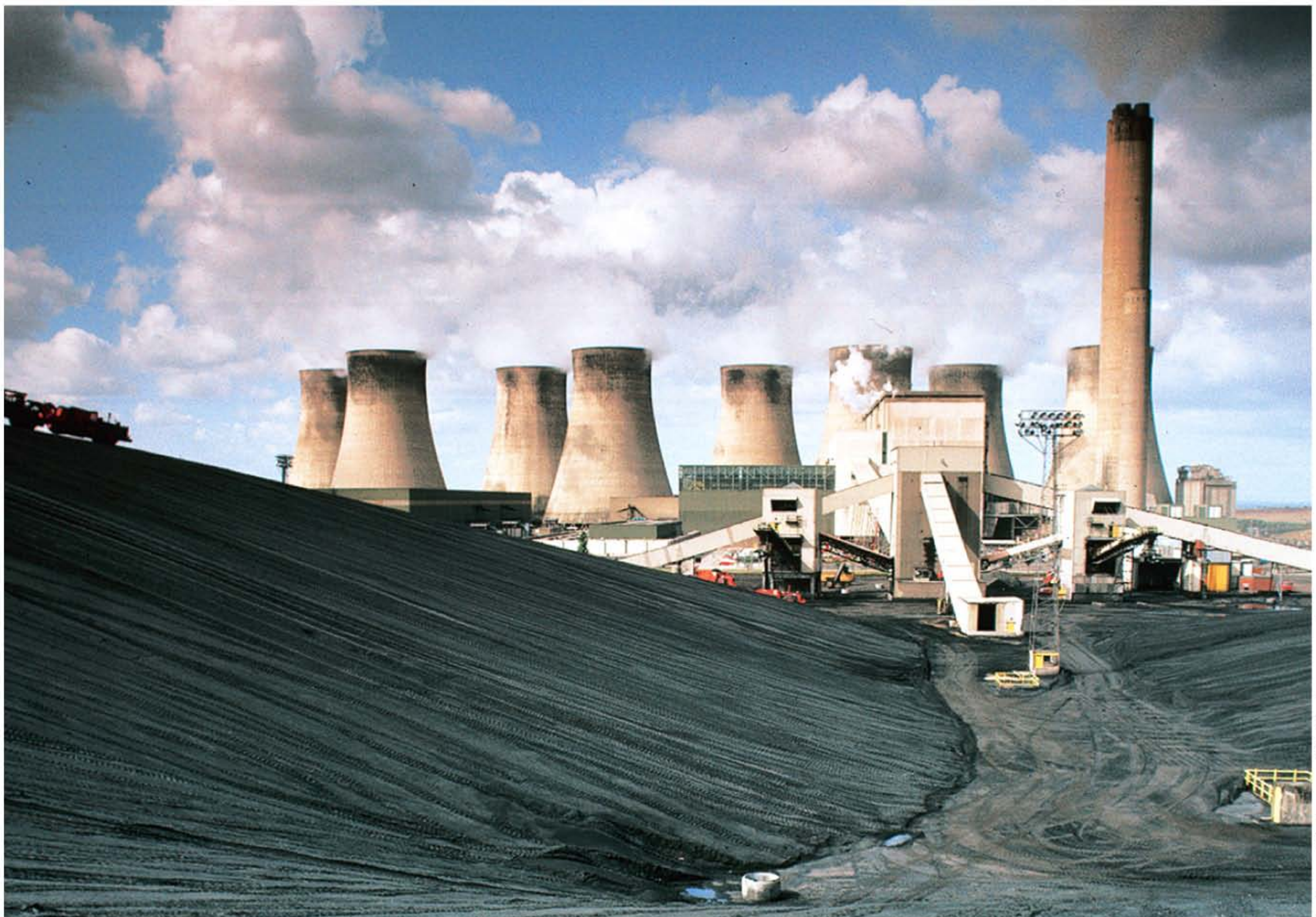
- Split U-235 by neutron bombardment
  - Reaction produces neutrons, fission fragments and heat
  - Starts a chain reaction
- Steam produced runs a turbine that generates electricity
  - Similar to coal or oil burning power plants

Fission of U-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



Coal or Oil Power Plant Ratcliffe-on-Saw, in Nottinghamshire, England,



Graham Finlayson/Getty Images, Inc.

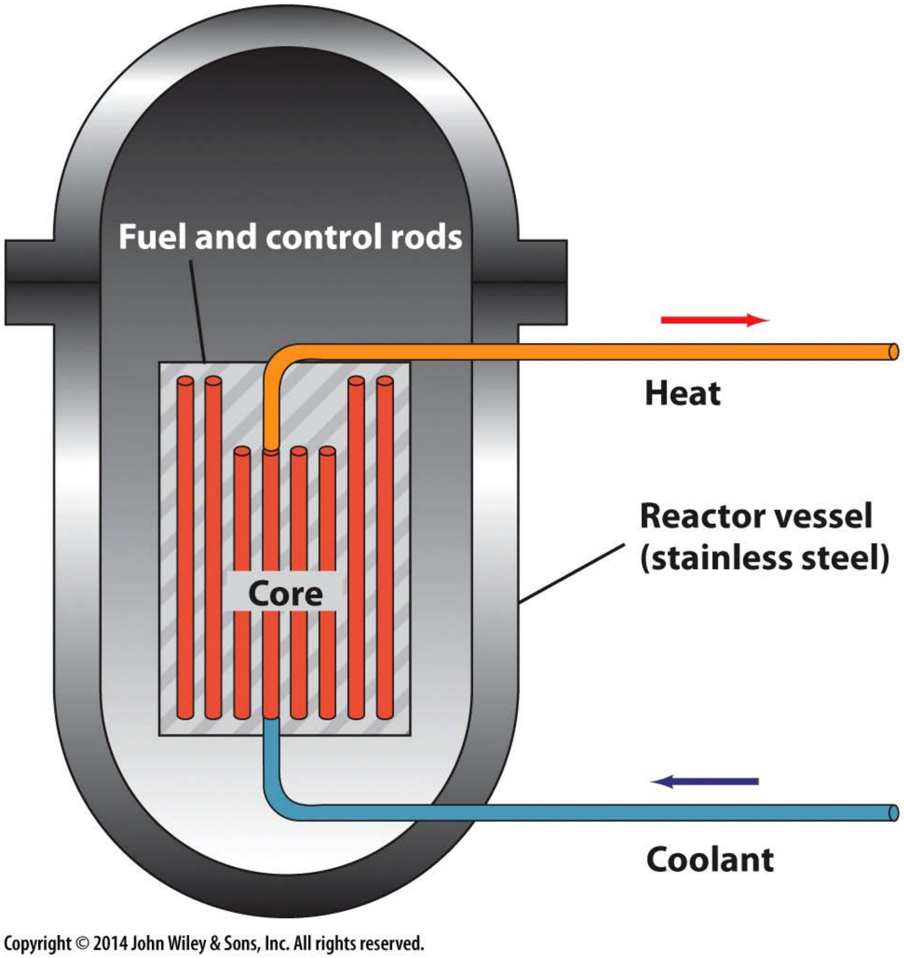
Nuclear Power Plant Leibstadt, Switzerland.

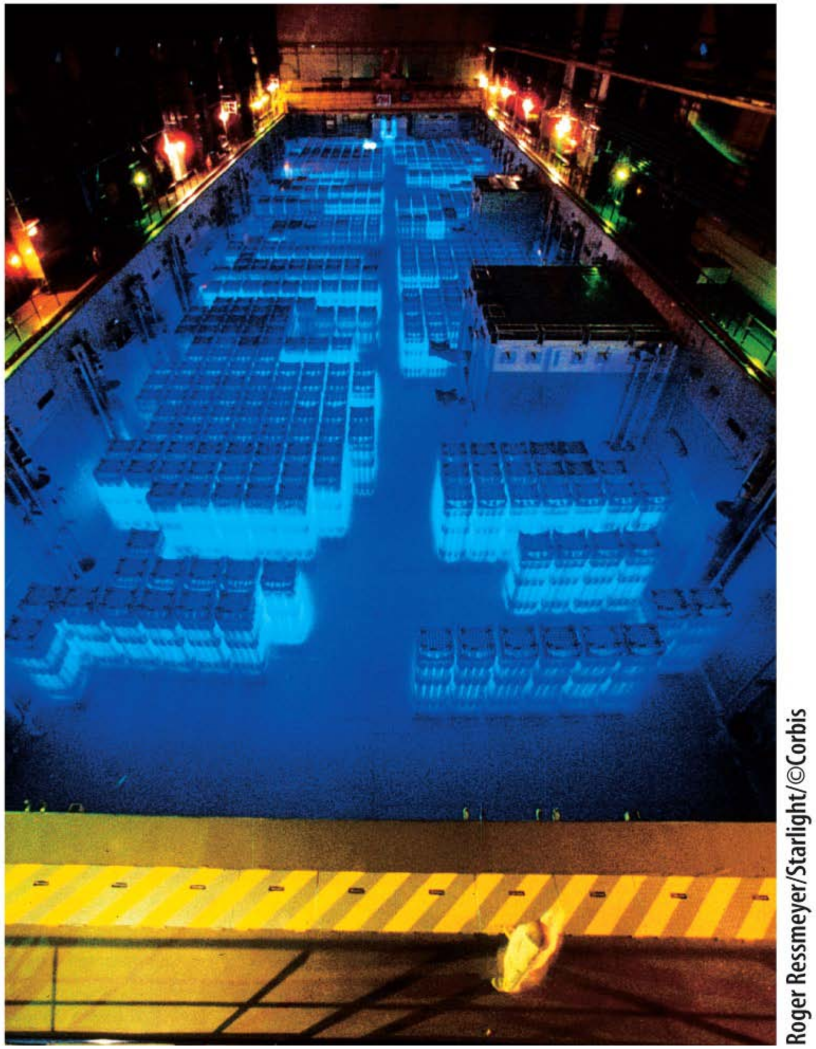
Martin Bond/Science Photo Library

Conventional Nuclear Reactors

- Main components of a reactor
  - Core—fuel and moderator
  - Control rods—control the rate of reaction or stop it
  - Coolant—remove heat
  - Reactor vessel
- Entire reactor is contained in a reinforced concrete building
- Most reactors now in use consume more fissionable material than they produce and are known as **burner.**

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





Conventional Nuclear Reactors

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.

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.

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 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 (uranium dioxide)—**are fabricated into strong ceramic pellets capable of withstanding operating temperatures and intense radiation in the reactor.

Pellets are loaded into hollow tubes (3–4 m long and less than 1 cm, or 0.4 in., in diameter). These tubes 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.**

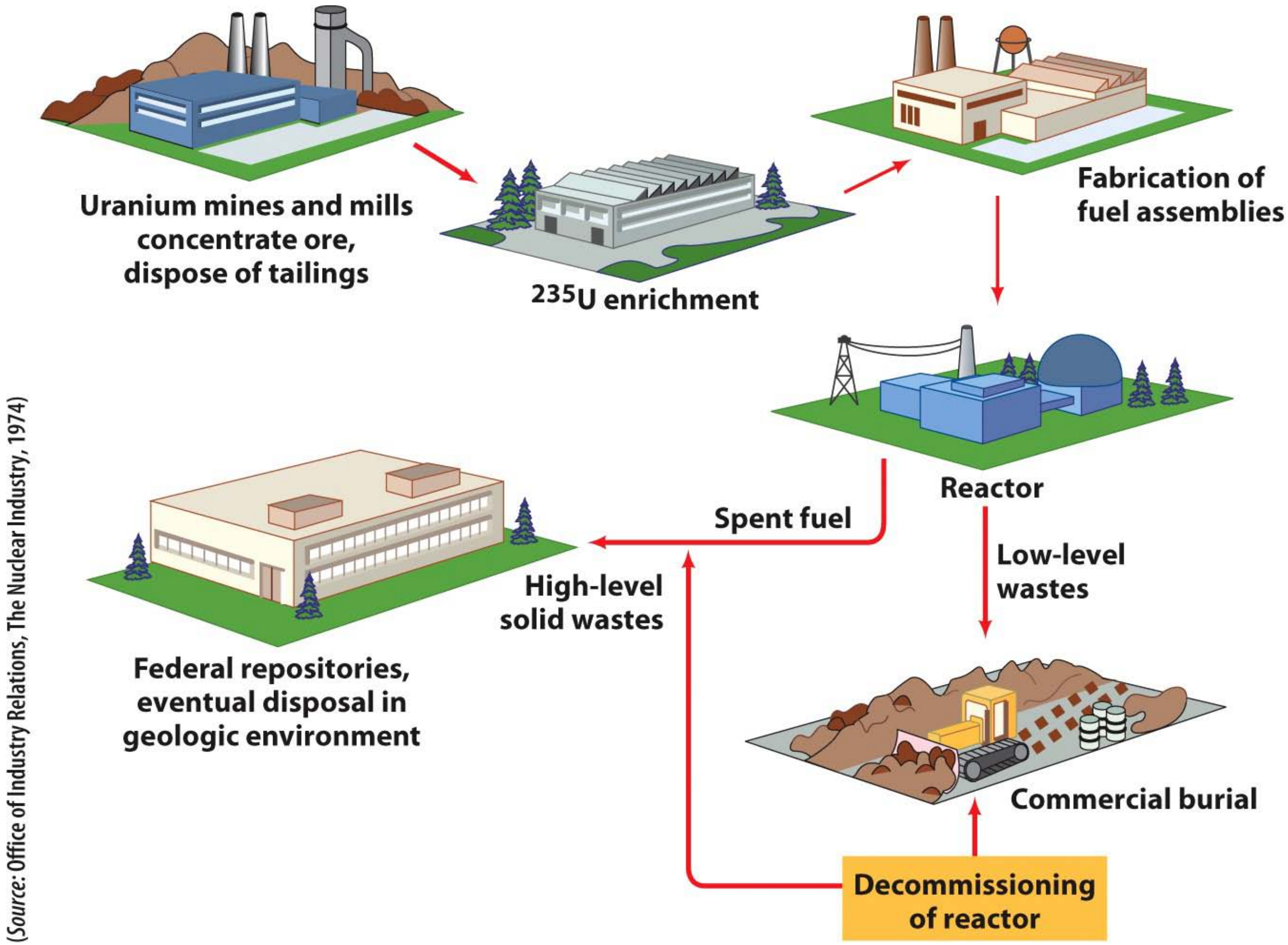
Control rods, which contain materials that capture neutrons, are used to regulate the chain reaction.

As the control rods are moved out of the core, the chain reaction increases; as they are moved into the core, the reaction slows.

Nuclear Energy and the Environment

- Nuclear fuel cycle includes
  - Mining and processing of uranium to controlled fission
  - Reprocessing of spent fuel
  - Decommissioning of power plants
  - Disposal of radioactive waste
- Throughout the cycle radiation can enter and affect the environment

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.



Problems with Nuclear Power

- Uranium mines and mills produce radioactive waste material that can pollute the environment
- U-235 enrichment and fabrication of fuel assemblies also produces waste materials
- Site selection and construction is controversial
- Power plant itself is the visible representation of past accidents or partial meltdowns

Problems with Nuclear Power

- Handling and disposal of waste
- Nuclear power plants have a limited lifetime
  - Decommissioning is expensive and uncertain
- Terrorists could collect plutonium for dirty bombs

Nuclear Radiation in the Environment

- Radioisotope—an isotope of a chemical element that spontaneously undergoes radioactive decay
- Affect environment by
  - Emitting radiation that affects other materials
  - Entering the normal pathways of mineral cycling and ecological food chains
  - We are exposed to natural background radiations from cosmic rays entering from space (2-4 mSv/y)
  - Radiation from rocks and soils (e.g granites) containing radioactive minerals delivers 03-1.2 mSv/y.
  - Radon gas in homes emission from certain geological settings.
  - Radiations we received from own bodies (1.35 mSv/y) from natural sources such as potassium-40 (an important electrolyte) and carbon-14.
  - Low level radiations from X rays etc (0.8-0.9 mSv/y)
  - Nuclear weapon testing 0.04 mSv/y
  - Burning of Fossil Fuels: 0.03 mSv/y
  - Nuclear facility workers: 3 mSv/y

Effects of Radioisotopes

- Explosion of nuclear atomic weapon does two types of damage
  - Directly from blast
  - Dispersal of radioactive isotopes
    - Fallout
    - Can enter ecological food chain
    - Biomagnifies in the food chain (e.g., reindeer moss, caribou, humans)

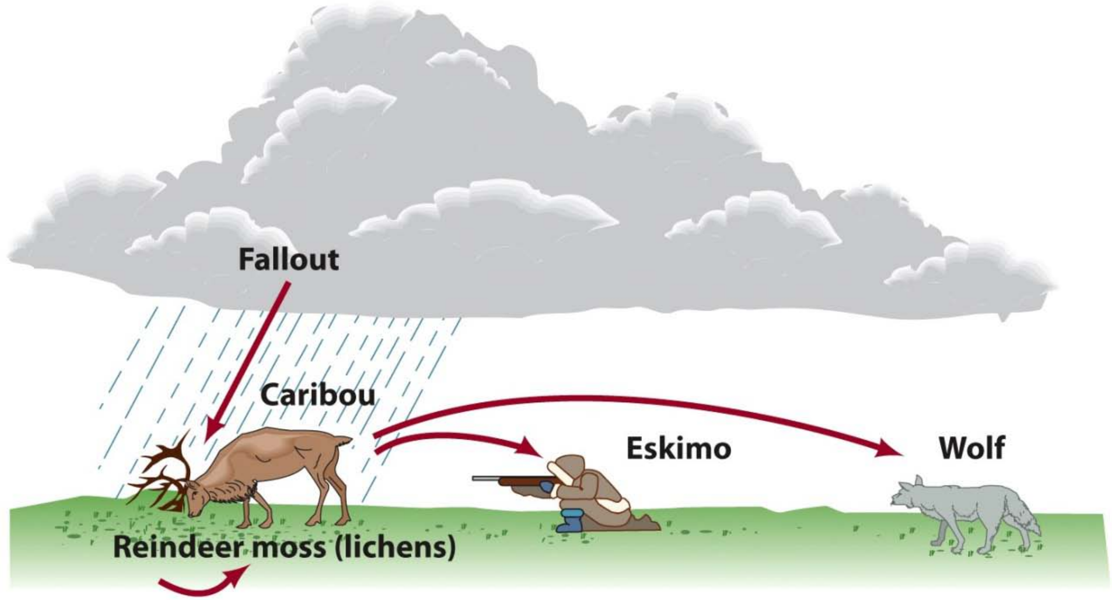
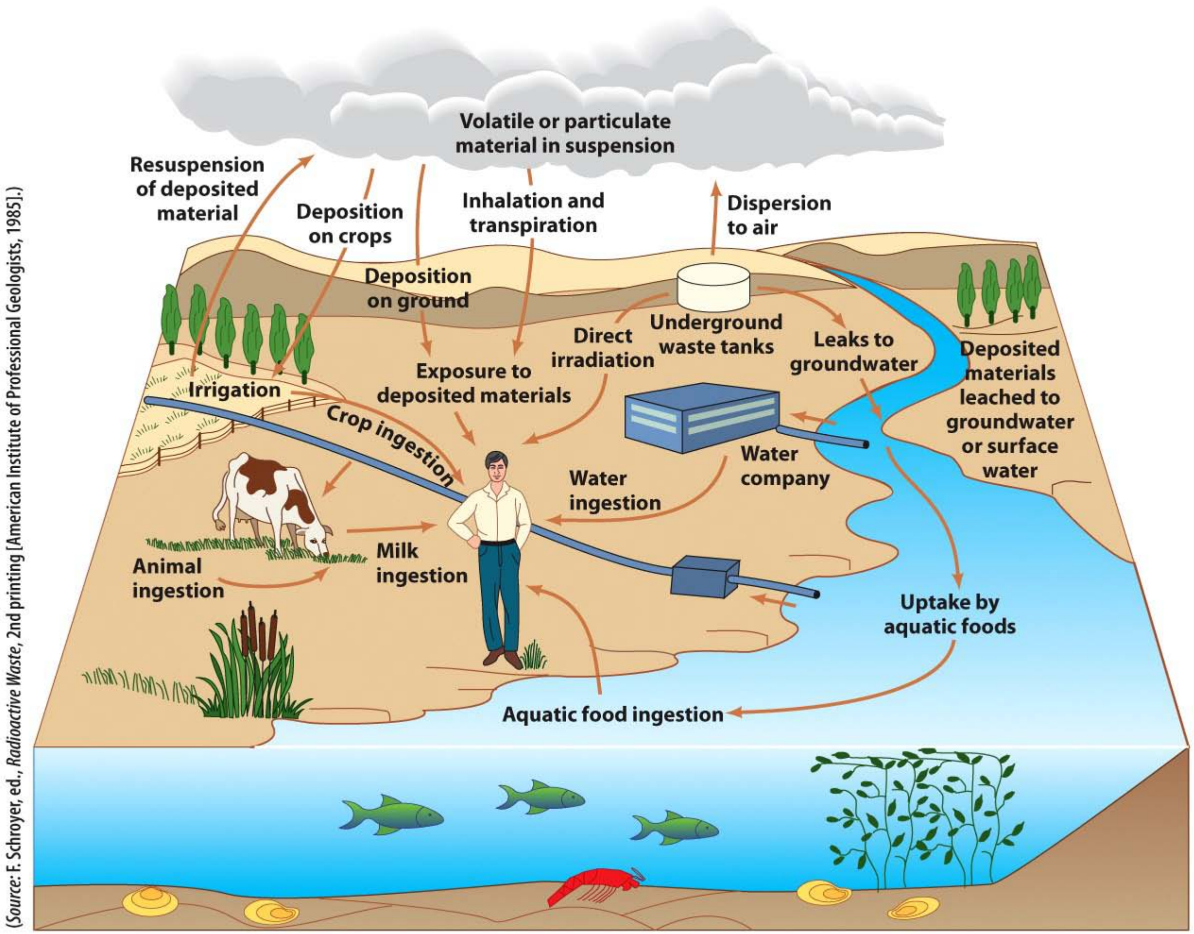


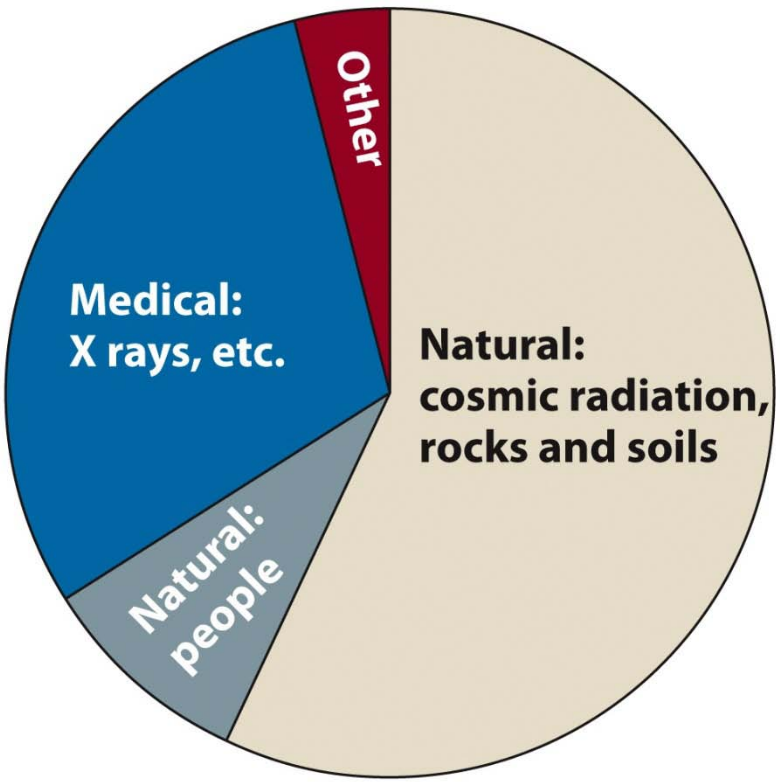
Figure 17.10 Cesium-137 released into the atmosphere by atomic bomb tests was part of the fallout deposited on soil and plants.
(a) The cesium fell on lichens, which were eaten by caribou. The caribou were in turn eaten by Eskimos.

How Radioactive Isotopes Reach People

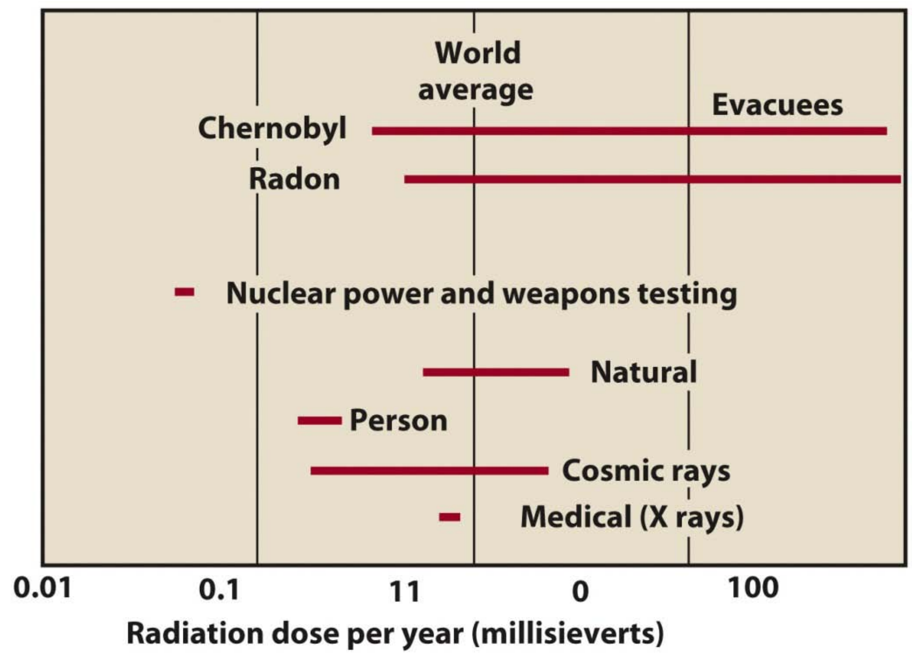


Sources and Doses of Radiation

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.).
(b) Range in annual radiation dose to people from major sources.



(*Source:* U.S. Department of Energy, 1999; New Encyclopedia Britannica, 1997. *Radiation* V26, p. 487)



(Source: Data in part from A.V. Nero Jr., "Controlling Indoor Air Pollution," Scientific American 258[5] [1998]: 42–48.)

Radiation Doses and Health

- At what point does an exposure or dose become a health hazard?
  - 5,000 mSv is considered lethal in 50% of people (LD-50)
  - 1,000-2,000 mSv sufficient to cause health problems
  - 50 mSv maximum allowed dose for workers in the industry (30 times average natural background)

Radiation Doses and Health

- 10-25 year delay between the time of exposure and the onset of disease
- Most scientists agree that radiation can cause cancer
  - They don't agree on relationship
  - Linear vs. some threshold level

Nuclear Power Plant Accidents

- Three well-known accidents
  - Three Mile Island
  - Chernobyl
  - Fukushima Nuclear Power Plant
  - Radiations can cause cancer and other health issues.
- 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.
- 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.
- Many of the women died of anemia or bone cancer.15 By 1924, dentists in New Jersey wer reporting cases of jaw rot; within five years radium was known to be the cause.

Three Mile Island

- Occurred March 28, 1979 near Harrisburg, PA
  - Malfunction of a valve resulted in partial core meltdown
  - Intense radiation released to interior of containment structure
  - Small amount of radiation released into environment

Three Mile Island

- Long-term chronic effects of exposure to low levels of radiation are not well understood
  - Effects of accident difficult to estimate
- Major impact of the incident was fear

Chernobyl

- Occurred April 26, 1986 in Chernobyl, Soviet Union
  - Worst accident in history of nuclear power generation
- Failure in cooling waters
  - Reactor overheated melting the uranium fuel
  - Explosions removed top of building
  - Fires produced a cloud of radioactive particles

Chernobyl

- 30 km zone surrounding Chernobyl evacuated
  - 115,000 people evacuated
  - 24,000 people estimated to have received radiation dose of 430 mSv
- Thyroid cancer increased in Belarus, Ukraine and the Russian Federation
- 4,000 deaths directly attributed to accident
  - Ultimately will be responsible for estimated ~16,000-39,000 deaths
- Trees and vegetation damaged

Igor Kostin/©Corbis

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

Fukushima Nuclear Power Plant

- Occurred Friday, March 11, 2011
  - 9+ offshore earthquake
  - Reactors automatically shut down per emergency protocols
  - Tsunami strikes the Fukushima facility
  - Tsunami overflows reactors
  - Cooling systems fail
  - Explosions result

Fukushima Nuclear Power Plant

- Results of disaster
  - People residing in the vicinity of the nuclear power plants were exposed to dangerous radiation levels
    - 1000s of people were evacuated from near the damaged nuclear power plants to a distance of approximately 30 km
  - Japanese people became very angry with the government and its response
    - Comprehensive evaluation of nuclear power in Japan is ongoing

Fukushima Nuclear Power Plant

- The Japanese catastrophe of 2011 could possibly have been avoided
  - Japanese scientists had suggested that large tsunamis could occur
  - Also that tsunami protection barriers may not have been large enough
  - Scientific findings not believed or taken seriously by government and nuclear power industry
    - Warnings were ignored, perhaps to save money

Fukushima Nuclear Power Plant

- The Japanese catastrophe of 2011 should be lesson to us all
  - We are vulnerable to natural processes
  - We need to heed potential warnings of events that happen *even* very infrequently
  - In the U.S., we should ensure that our reactors are safer by
    - Closely evaluating each reactor site for the possibility of flooding and damage to pumps and backup pumps that circulate cooling water

Figure 17.15 Tsunami waves inundate Japan in 2011, flooding towns and cities and nuclear power plants.

REUTERS/YOMIURI /LANDOV

Radioactive Waste Management

- By-products are expected when electricity is produced at nuclear reactors
- Two main categories as defined by The U.S. Federal Energy Regulatory Commission (FERC)
  - Low-level waste
  - High-level waste

Low-Level Radioactive Waste

- Low enough concentrations that it does not present a significant environmental hazard
  - If handled properly
- Includes variety of residual and solutions from processing
  - Solid and liquid waste, sludge and acids
  - Slightly contaminated equipment and materials such as tools, plastic, glass, wood and other materials

Low-Level Radioactive Waste

- Buried in near-surface burial areas
  - Where geologic and hydrologic conditions thought to limit migration
  - Three of the six closed due to leaks and finances
  - Creation of new sites has met with controversy
  - Question remains as to whether low-level radiation can be disposed of safely

High-Level Radioactive Waste

- Consists of commercial and military spent nuclear fuel
  - Uranium and plutonium derived from military reprocessing
  - Other nuclear weapons material
- Extremely toxic
  - Sense of urgency surround its disposal
  - Total volume of spent fuel accumulating

High-Level Radioactive Waste

- A comprehensive geologic disposal development program should have the following objectives
  - Identification of sites that meet broad geologic criteria
  - Intense subsurface exploration of possible sites
  - Predictions of future changes to sites
  - Evaluation of risk associated with various predictions
  - Political decision making based on risks acceptable to society

The Future of Nuclear Energy

- Advocates argue that nuclear power is good for the environment
  - It does not produce potential global warming through release of carbon dioxide
  - It does not cause acid rain
  - If breeder reactors are developed the amount of fuel will be greatly increased

Future of Nuclear Energy

- Breeder reactors
  - Designed to produce new nuclear fuel
  - Transform waste or low-grade uranium into fissionable material
  - Future of nuclear power if sustainability of fuel an objective

Fusion Reactors

- Involves combining the nuclei of light elements to form heavier ones
  - Heat energy is released
  - Source of energy in sun and stars
- In a hypothetical fusion reactor
  - Two isotopes of hydrogen injected into reactor chamber
  - Products include helium and neutrons

Fusion Reactors

- Several conditions necessary
  - Extremely high temperatures
    - 100 million degrees C
  - High density of fuel elements
  - Plasma must be confined
- Potential energy available if developed nearly inexhaustible
  - Many obstacles remain to be solved

Chapter Summary

- Nuclear fission is the process of splitting an atomic nucleus into smaller fragments
- As fission occurs, energy is released
- There are four major components of a fission reactor
  - The core
  - Control rods
  - Coolant
  - Reactor vessel

Chapter Summary

- Nuclear radiation occurs when a radioisotope spontaneously undergoes radioactive decay and changes into another isotope
- Three major types of nuclear radiation
  - Alpha particles
  - Beta particles
  - Gamma rays

Chapter Summary

- Each radioisotope has its own characteristic emissions
- Different types of radiation have different toxicities
- In terms of the health of humans and other organisms, it is important to know the type of radiation emitted and the half-life of that radiation

Chapter Summary

- The nuclear fuel cycle consists of:
  - Mining and processing uranium
  - Generating nuclear power through controlled fission
  - Reprocessing spent fuel
  - Disposing of nuclear waste
  - Decommissioning power plants when they become obsolete
- Each part of this cycle is associated with characteristic processes, all with different potential environmental problems

Chapter Summary

- Present burner reactors use uranium-235 as a fuel
  - Uranium is a nonrenewable resource mined from the Earth
  - If many more burner reactors were constructed, fuel shortages would result
  - Nuclear energy based on burning uranium-235 in light-water reactors is thus not sustainable
  - For nuclear energy to be sustainable, safe, and economical, breeder reactors need to be develop

Chapter Summary

- Accidents at nuclear power plants have shown
  - It is difficult to plan for the human factor
  - People make mistakes
  - Mankind 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 mankind can design much safer power plants where serious accidents are negligible

Chapter Summary

- Nuclear waste disposal a growing problem
- Consensus is that high-level nuclear waste may be safely disposed of in identified geologic formations
- 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

Chapter Summary

- Nuclear power is being seriously evaluated as an alternative to fossil fuels
  - Advantages
    - It emits no carbon dioxide
    - Will not contribute to global warming
    - Will not cause acid rain
    - Can be used to produce alternative fuels such as hydrogen
  - Disadvantages
    - Waste-disposal problems
    - Possibility of nuclear accidents
    - May be a path to nuclear weapons for some countries