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Enger & Smith

Chapter 10

Nuclear Energy

Nuclear Energy

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Outline

- The Nature of Nuclear Energy
- The History of Nuclear Energy Development
- Nuclear Fission Reactors
- Investigating Nuclear Alternatives
- The Nuclear Fuel Cycle
- Nuclear Concerns
- The Future of Nuclear Power

The Nature of Nuclear Energy

- The nuclei of certain atoms are unstable and spontaneously decompose. These isotopes are **radioactive.**
- Neutrons, electrons, protons, and other larger particles are released during nuclear disintegration, along with a great deal of energy.
- **Radioactive half-life** is the time it takes for half the radioactive material to spontaneously decompose.

The Nature of Nuclear Energy

- Nuclear disintegration releases energy from the nucleus as **radiation**, of which there are three major types:
  - **Alpha radiation** consists of moving particles composed of two neutrons and two protons.
    - It can be stopped by the outer layer of skin.
  - **Beta radiation** consists of electrons from the nucleus.
    - It can be stopped by a layer of clothing, glass, or aluminum.

The Nature of Nuclear Energy

- **Gamma radiation** is a form of electromagnetic radiation.
  - It can pass through your body, several centimeters of lead, or a meter of concrete.

- The **absorbed dose** is the amount of energy absorbed by matter. It is measured in grays or rads.
- The damage caused by alpha particles is 20 times greater than that caused by beta particles or gamma rays.

The Nature of Nuclear Energy

- The **dose equivalent** is the absorbed dose times a quality factor.
- When alpha or beta particles or gamma radiation interact with atoms, ions are formed. Therefore, it is known as **ionizing radiation.**
- Ionizing radiation affects DNA and can cause mutations.
  - Mutations that occur in some tissues of the body may manifest themselves as abnormal tissue growths known as cancers.

The Nature of Nuclear Energy

- Large doses of radiation are clearly lethal.
- Demonstrating known harmful biological effects from smaller doses is much more difficult.
- The more radiation a person receives, the more likely it is that there will be biological consequences.
- Time, distance, and shielding are the basic principles of radiation protection.
  - Water, lead, and concrete are common materials used for shielding from gamma radiation.

The Nature of Nuclear Energy

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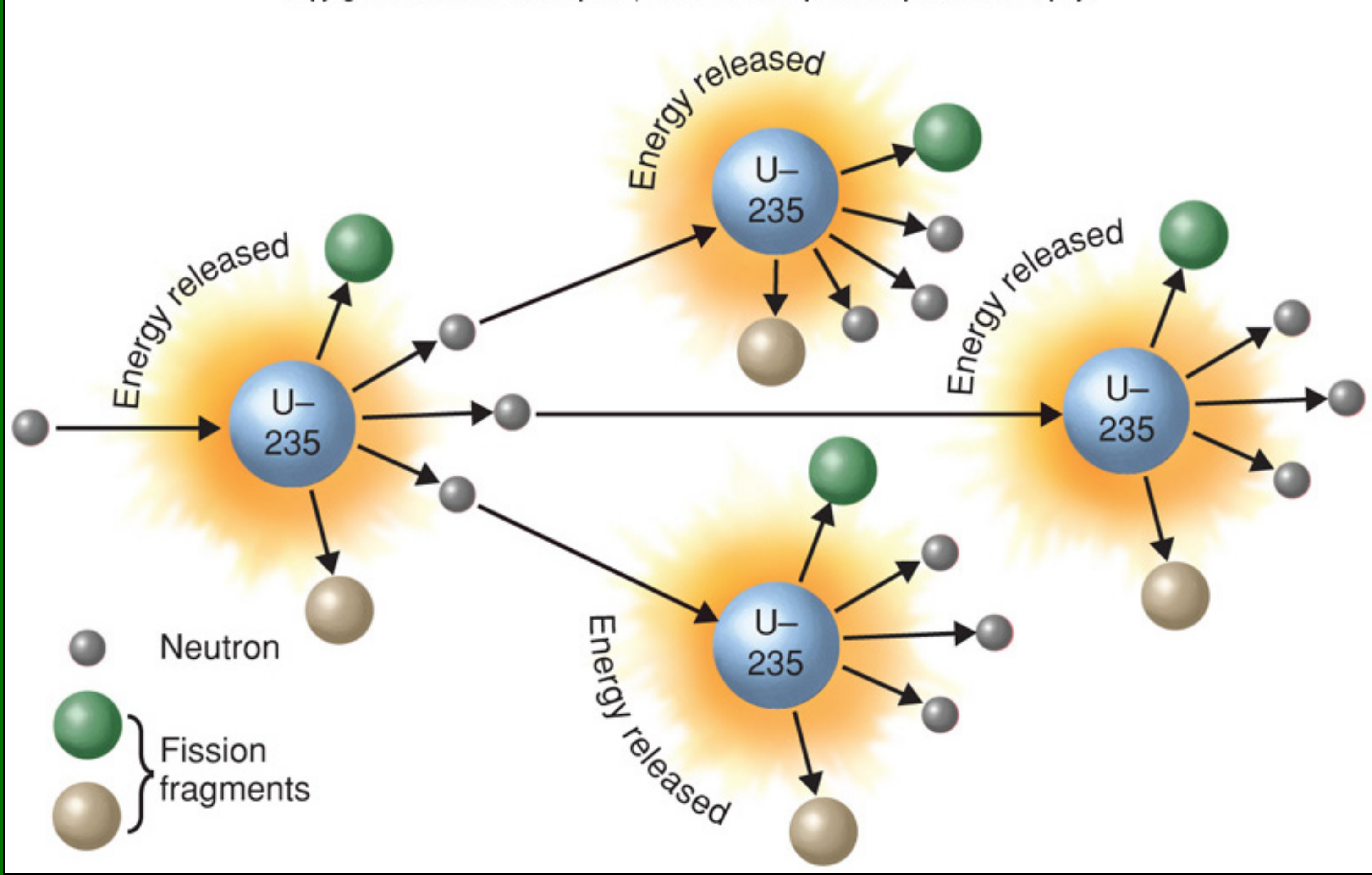
Protective equipment

The Nature of Nuclear Energy

- **Nuclear fission** occurs when neutrons impact and split the nuclei of certain other atoms.
- In a **nuclear chain reaction**, splitting nuclei release neutrons, which themselves strike more nuclei, in turn releasing even more neutrons.

The Nature of Nuclear Energy



Nuclear fission chain reaction

The Nature of Nuclear Energy

- Only certain kinds of atoms are suitable for development of a nuclear chain reaction.
  - The two most common are uranium-235 and plutonium-239.
  - There also must be a certain quantity of nuclear fuel (critical mass) for the chain reaction to occur.

The History of Nuclear Energy Development

- The first controlled nuclear chain reaction occurred at Stag Field in Chicago in 1942.
- That event led directly to the development of the atomic bombs dropped on the Japanese cities of Hiroshima and Nagasaki.
- Following WW II, people began exploring other potential uses of nuclear energy.
- The U.S. built the world's first nuclear power plant in 1951.

The History of Nuclear Energy Development

- In December 1953, President Dwight D. Eisenhower made the following prediction in his "Atoms for Peace" speech:
  - "Nuclear reactors will produce electricity so cheaply that it will not be necessary to meter it."
- Today's Reality:
  - Accidents have caused worldwide concern about the safety of nuclear power plants.
  - As of 2008 there are 439 operating reactors, and 36 under construction in 12 countries. 93 are in the planning stages.

Nuclear Fission Reactors

- A **nuclear reactor** is a device that permits a controlled fission chain reaction.
  - When the nucleus of a U-235 atom is struck by a slowly moving neutron from another atom, the nucleus splits into smaller particles.
  - More rapidly-moving neutrons are released, which strike more atoms.
  - The chain reaction continues to release energy until the fuel is spent or the neutrons are prevented from striking other nuclei.

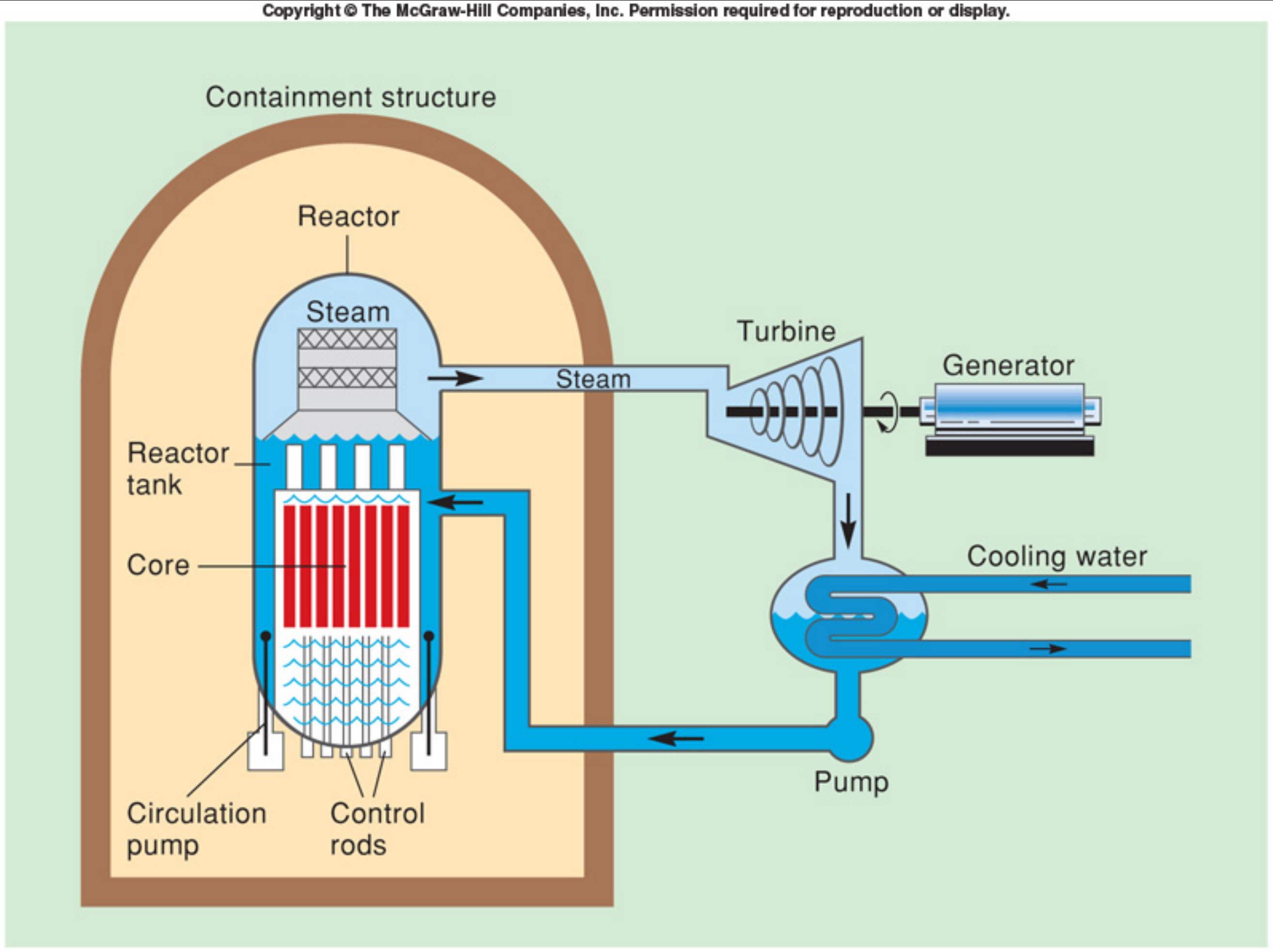
Nuclear Fission Reactors

- Control rods made of a non-fissionable material (boron, graphite) are lowered into the reactor to absorb neutrons and control the rate of fission.
  - When they are withdrawn, the rate of fission increases.
- A **moderator** is a substance that absorbs energy, which slows neutrons, enabling them to split the nuclei of other atoms more effectively.

Nuclear Fission Reactors

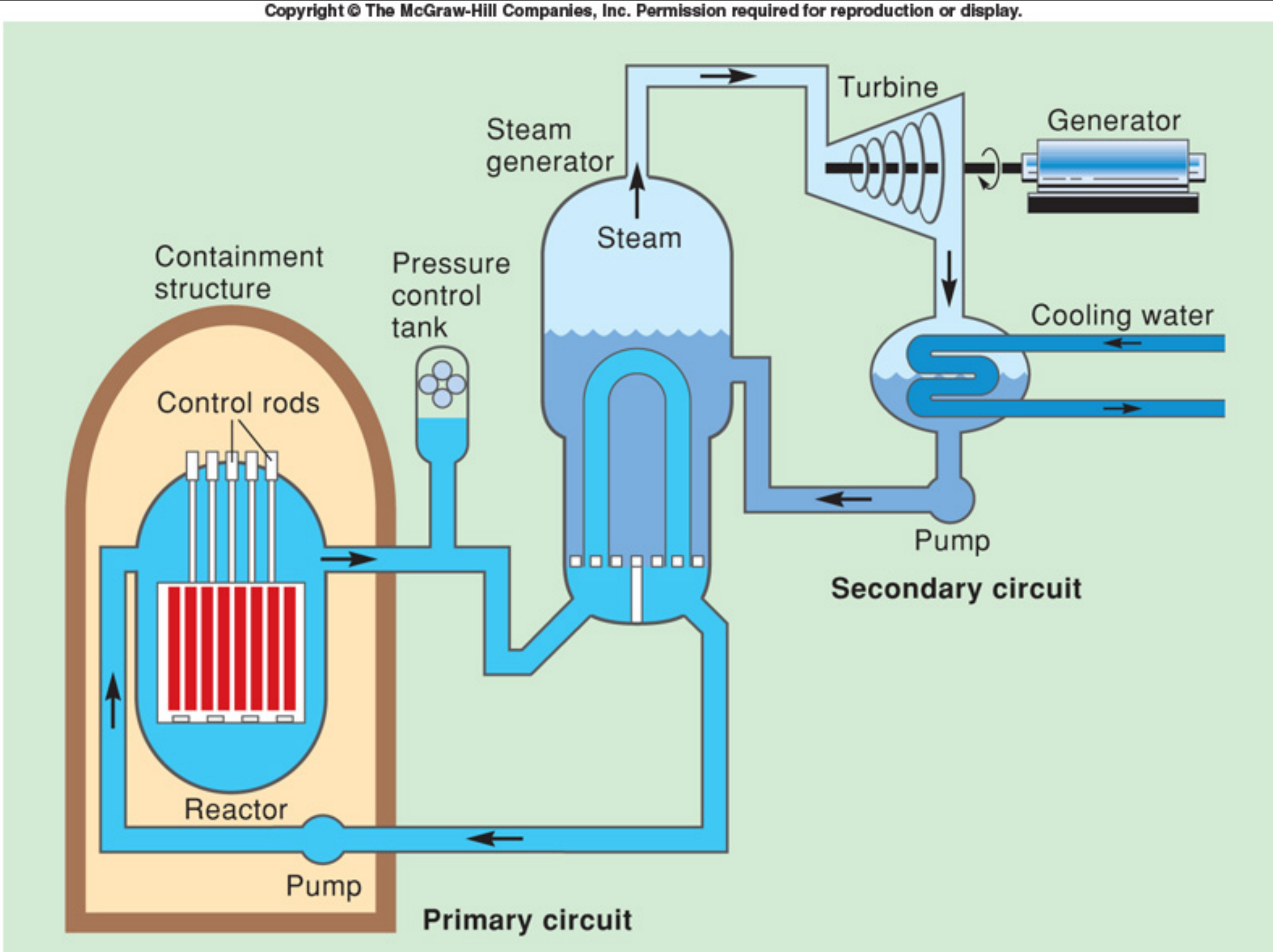
- In the production of electricity, a nuclear reactor serves the same function as a fossil-fuel boiler: it produces heat, which converts water to steam, which turns a turbine, generating electricity.
  - **The 3 most common types of reactors are:**
    - **20% Boiling-Water,**
    - **60% Pressurized-Water,**
    - **10% Heavy-Water.**
- Gas-Cooled Reactors are not popular, and no new plants of this type are being constructed.

Nuclear Fission Reactors



Boiling water reactor

Nuclear Fission Reactors

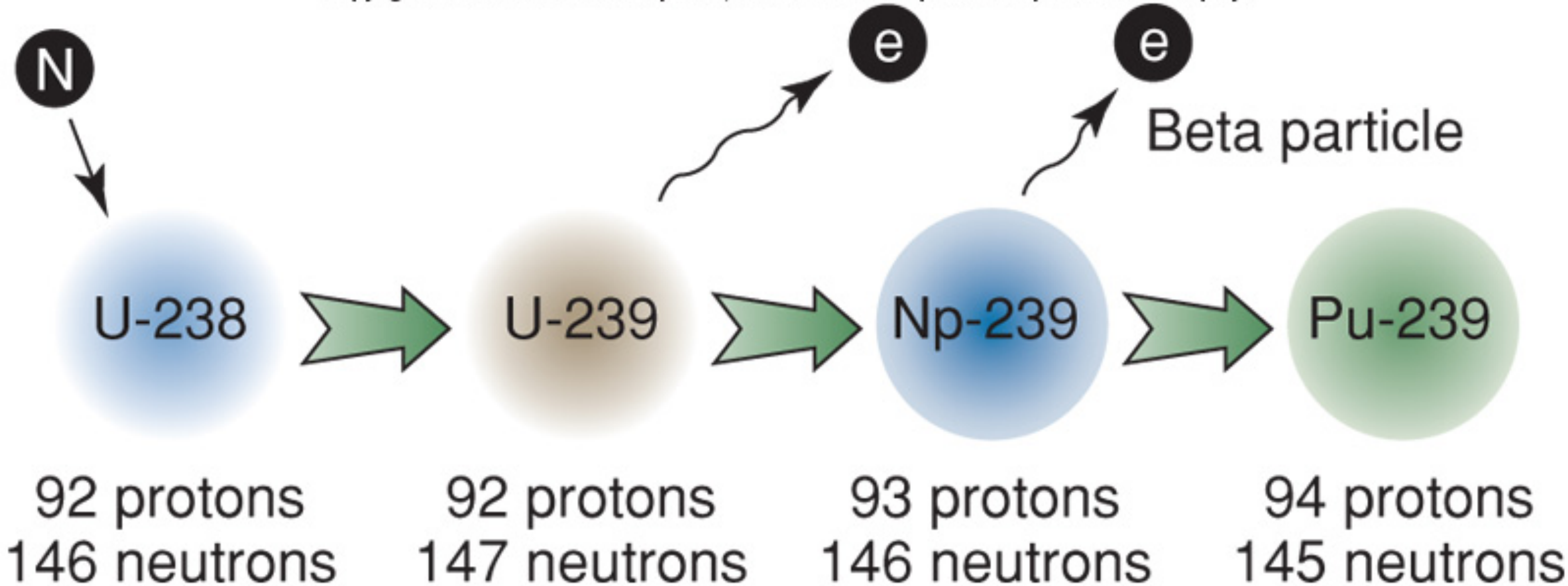


Pressurized-water reactor

Investigating Nuclear Alternatives

- **Breeder reactor**s produce nuclear fuel as they produce electricity.
- Liquid sodium efficiently moves heat away from the reactor core.
  - Hence they are called Liquid Metal Fast Breeder Reactors.
  - A fast moving neutron is absorbed by Uranium-238 and produces Plutonium-239
  - P 239 is fissionable fuel.
  - Most breeder reactors are considered experimental.
  - Because P239 can be used in nuclear weapons, they are politically sensitive.

Investigating Nuclear Alternatives



Formation of Pu-239 in a breeder reactor

Investigating Nuclear Alternatives

- **Nuclear fusion** is a process in which two lightweight atomic nuclei combine to form a heavier nucleus, resulting in the release of a large amount of energy.
- Fusion occurs in stars like our sun.
- It has been technically impossible to create conditions that would allow fusion to provide a reliable source of energy in the foreseeable future, and governments provide little funding for fusion research.

The Nuclear Fuel Cycle

- The nuclear fuel cycle begins with the mining of low-grade uranium ore primarily from Canada, Australia, and Kazakhstan.
- It is milled, and crushed and treated with a solvent to concentrate the uranium.
- Milling produces yellow-cake, a material containing 70-90% uranium oxide.

The Nuclear Fuel Cycle

- Naturally occurring uranium contains about 99.3% non-fissionable U^{238}, and .7% fissionable U^{235}.
  - It must be enriched to 3% U^{235} to be concentrated enough for most nuclear reactors.
  - Centrifuges separate the isotopes by their slight differences in mass.
  - Material is fabricated into a powder and then into pellets.
  - The pellets are sealed into metal rods (fuel rods) and lowered into the reactor.

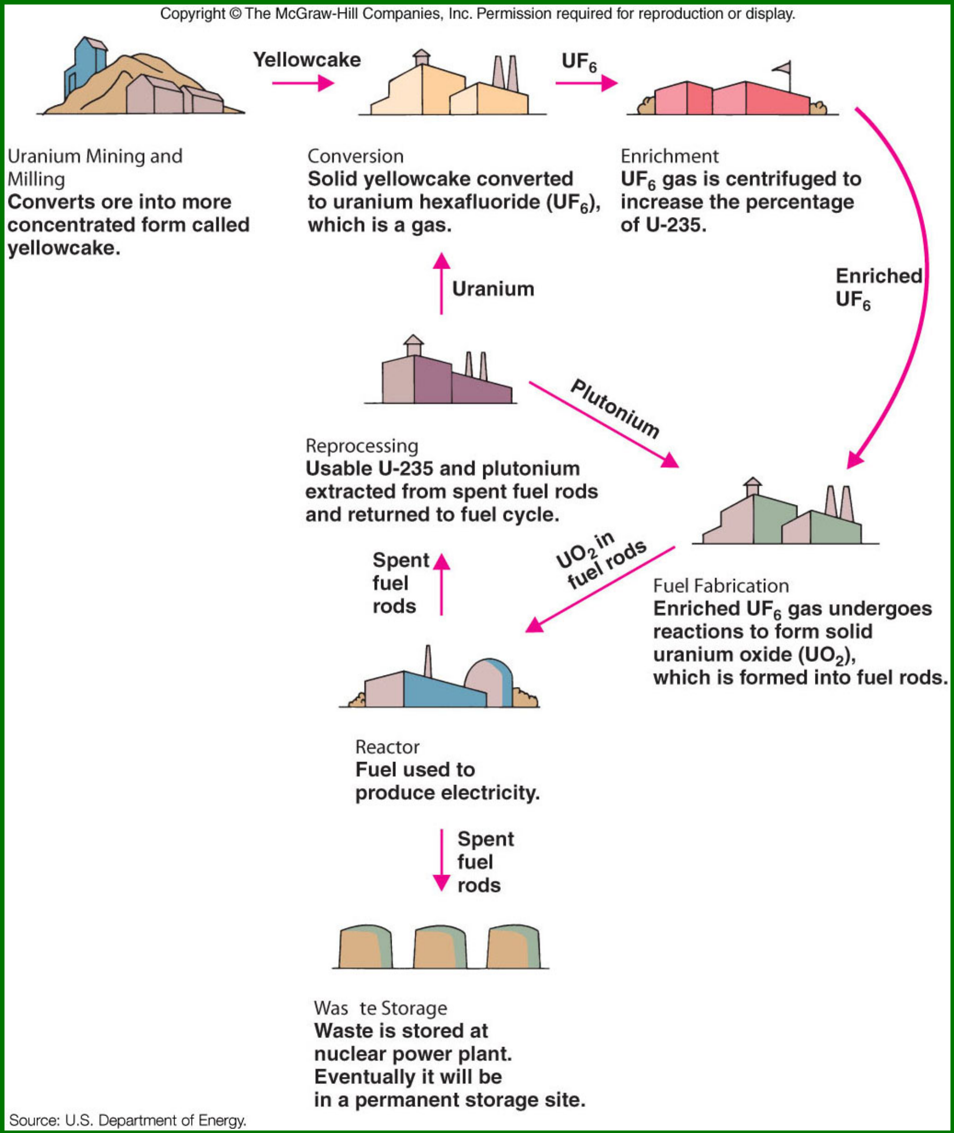
The Nuclear Fuel Cycle

- As fission occurs, U-235 concentration decreases.
- After about three years of operation, fuel rods don't have enough radioactive material remaining to sustain a chain reaction, thus spent fuel rods are replaced by new ones.
- Spent rods are still very radioactive, containing about 1% U-235 and 1% plutonium.

The Nuclear Fuel Cycle

- Spent fuel rods are radioactive, and must be managed carefully to prevent health risks and environmental damage.
- Rods can be reprocessed.
  - U-235 and plutonium are separated from the spent fuel and used to manufacture new fuel rods.
  - Less than half of the world's fuel rods are reprocessed.
- Rods can undergo long-term storage.
- At present, India, Japan, Russia, France, and the United Kingdom operate reprocessing plants as an alternative to storing rods as waste.

The Nuclear Fuel Cycle



Steps in the nuclear fuel cycle

The Nuclear Fuel Cycle

- All of the processes involved in the nuclear fuel cycle have the potential to generate waste.
- Each step in the nuclear fuel cycle involves the transport of radioactive materials.
- Each of these links in the fuel cycle presents the possibility of an accident or mishandling that could release radioactive material.

Nuclear Concerns

- Nuclear power provides over 16% of the world's electricity.
- However, many factors have caused some countries to reevaluate their commitment to nuclear power:
  - Accidents have raised questions about safety.
  - Use of nuclear material by terrorists.
  - Concern about worker and public exposure to radiation.
  - Weapons production.
  - Contamination and disposal problems.

Nuclear Concerns

- Reactor Safety
  - The Three Mile Island nuclear plant in Pennsylvania experienced a partial core meltdown on March 28, 1979.
    - It began with pump and valve malfunction, but operator error compounded the problem.
    - The containment structure prevented the release of radioactive materials from the core, but radioactive steam was vented into the atmosphere.
    - The crippled reactor was defueled in 1990 at a cost of about $1 billion.
    - Placed in monitored storage until its companion reactor reaches the end of its useful life.

Nuclear Concerns

- Reactor Safety
  - Chernobyl is a small city in Ukraine, north of Kiev.
  - It is the site of the world's largest nuclear accident, which occurred April 26, 1986.
    - Experiments were being conducted on reactor.
    - Operators violated six important safety rules.
    - They shut off all automatic warning systems, automatic shutdown systems, and the emergency core cooling system for the reactor.

Nuclear Concerns

Chernobyl

Nuclear Concerns

- Reactor Safety
  - In 4.5 seconds, the energy level of the reactor increased 2000 times.
  - The cooling water converted to steam and blew the 1102-ton concrete roof from the reactor.
  - The reactor core caught fire.
  - It took 10 days to bring the burning reactor under control.

Nuclear Concerns

- Reactor Safety
  - There were 37 deaths; 500 people hospitalized (237 with acute radiation sickness); 116,000 people evacuated.
    - 24,000 evacuees received high doses of radiation.
    - Children or fetuses exposed to fallout are showing increased frequency of thyroid cancer because of exposure to radioactive iodine 131 released from Chernobyl.

Nuclear Concerns

The accident at Chernobyl

Nuclear Concerns

- A consequence of the Chernobyl accident in particular has been a deepened public concern over nuclear reactor safety, and many countries halted construction of new plants.
- By 2008 there were 36 reactors under construction in 13 countries.
- An additional 93 are in the planning stages, including 12 in the United States.

Nuclear Concerns

- After Sept. 11, 2001, fear arose regarding nuclear plants as potential targets for terrorist attacks.
- Nuclear experts feel aircraft wouldn’t significantly damage the containment building or reactor, and normal emergency and containment functions would prevent the release of radioactive materials.
- Probably the greatest terrorism-related threat is from radiological dispersal devices (RDDs), or dirty bombs. They cause panic, not numerous deaths.

Nuclear Concerns

- Each step in the nuclear fuel cycle poses a radiation exposure problem.
- Prolonged exposure to low-level radiation increases workers' rates of certain cancers.
- Enrichment, fabrication, and transport of nuclear materials offer potential exposure hazards and risks of accidental release of radioactive materials into the environment.

Nuclear Concerns

- Producing nuclear materials for weapons and other military uses involves many of the same steps used to produce nuclear fuel for power reactors.
- The U.S. Department of Energy (DOE) is responsible for nuclear research for both weapons and peaceful uses.
- Historically, research and production dealt with hazardous chemicals and minor radioactive wastes by burying them, storing them in ponds, or releasing them into rivers.

Nuclear Concerns

- The DOE has become steward of a large number of sites that are contaminated with hazardous chemicals and radioactive materials.
- There are over 3000 contaminated sites containing hundreds of underground storage tanks, millions of 55 gallon drums of waste, and thousands of sites with contaminated soils.
- Several major sites have been cleaned up.
- Each year there are fewer sites, and those remaining are smaller.

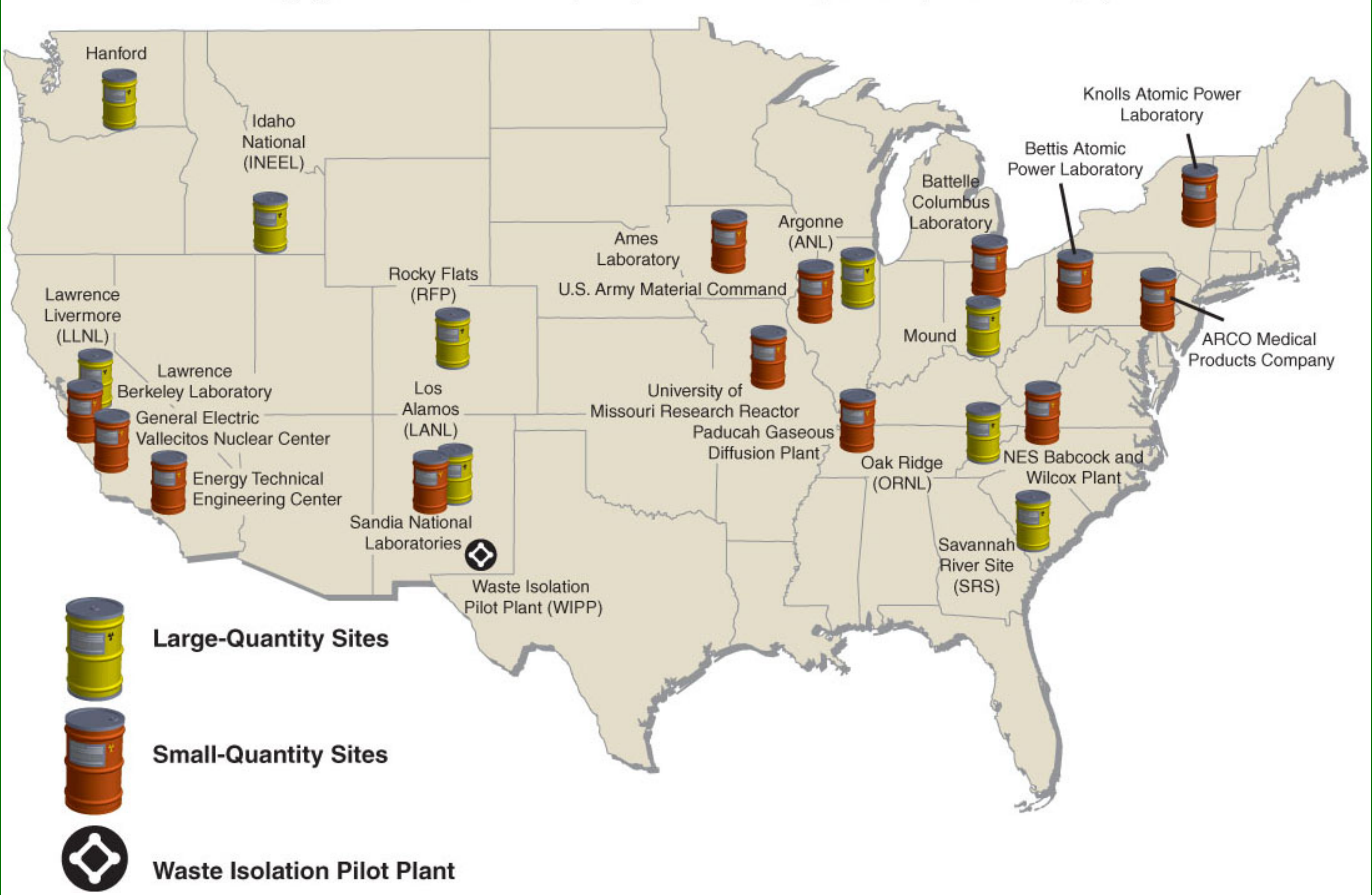
Nuclear Concerns

- There are four general categories of nuclear wastes:
  - **Transuranic wastes** are highly radioactive waste that contain large numbers of atoms that are larger than uranium with half-lives greater than 20 years.
  - **Uranium mining and milling wastes** have low levels of radioactivity but are above background levels.
  - **High-level radioactive wastes** are spent fuel rods and highly radioactive materials from the reprocessing of fuel rods.
  - **Low-level radioactive wastes** have low levels of radioactivity and are not classified into one of the other categories.

Nuclear Concerns

- Transuranic waste from former nuclear weapons sites is transported to the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM, which began accepting waste in March, 1999.
- Waste management activities of mining and milling waste include:
  - Building fences.
  - Putting up warning signs.
  - Establishing land use restrictions.
  - Covering the wastes with a thick layer of soil and rock to prevent erosion, windblown particles, and groundwater contamination.

Nuclear Concerns



Source: Nuclear Regulatory Commission.

DOE high-level radioactive transuranic waste sites

Nuclear Concerns

- Disposal of high-level radioactive waste is a major problem for the nuclear power industry.
  - In the U.S., about 30,000 metric tons of highly radioactive spent fuel rods are stored in special storage ponds at nuclear reactor sites.
  - There is no permanent storage facility, and many plants are running out of temporary storage.
  - Most experts feel the best solution is to bury waste in a stable geologic formation.

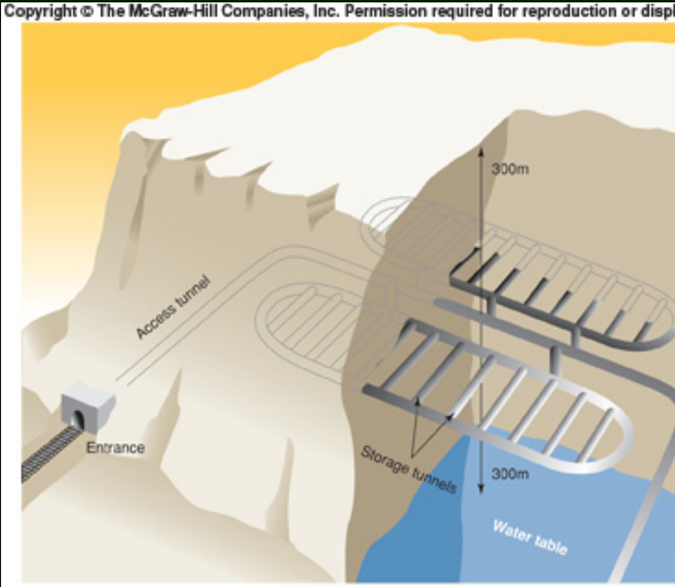
Nuclear Concerns

- The history of U.S. efforts to establish a repository for high-level radioactive waste is long and complicated.
  - 1982--U.S. Congress passed legislation for a high-level nuclear waste disposal site to be completed by 1998.
  - 1987--Several sites were considered and Yucca Mountain was selected for further study.
  - 1994-1997--A 5-mile U-shaped tunnel was constructed to study the suitability of the site.
  - 2002--Yucca Mountain was designated the nuclear repository.

Nuclear Concerns

- 2008--Department of Energy filed a license application with the Nuclear Regulatory Commission to construct a repository for spent nuclear fuel and high level radioactive waste at Yucca Mountain.
- 2017--Projected date for Yucca Mountain to begin accepting waste if the Nuclear Regulatory Commission approves the application.

Nuclear Concerns



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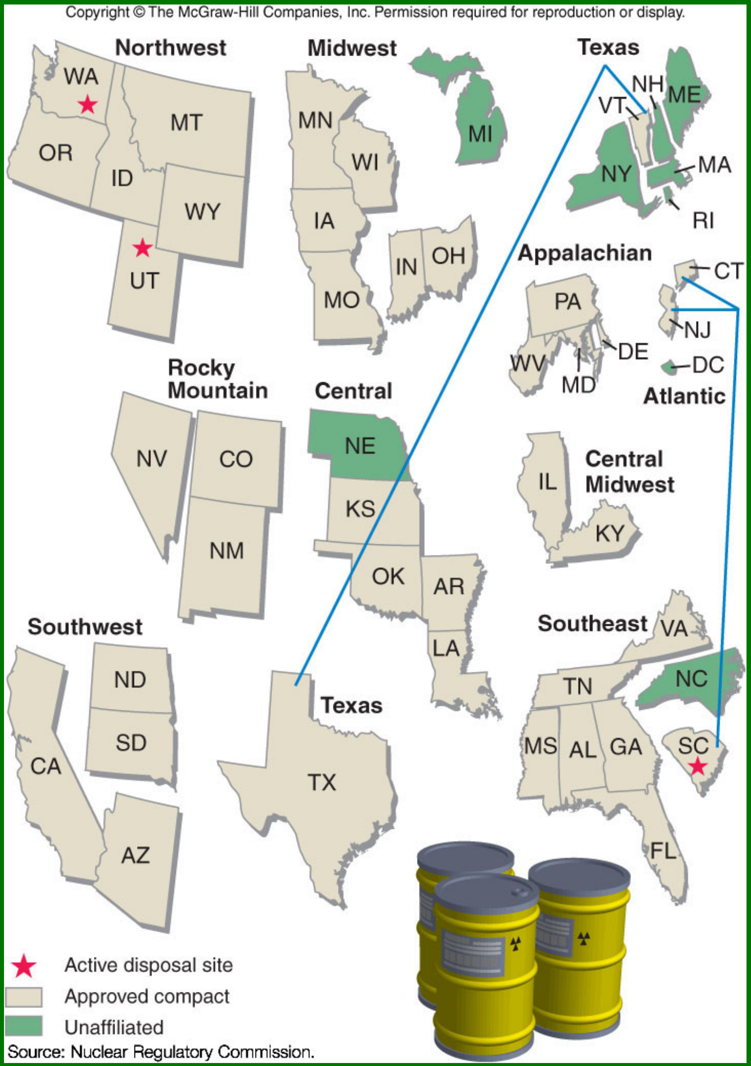
b: © AP Wide World Photos

High-level nuclear waste disposal

Nuclear Concerns

- Currently, the U.S. produces about 115,000 cubic meters of low-level radioactive waste annually.
  - It is presently buried in disposal sites in South Carolina, Washington, and Utah.
  - 1986 was the deadline for each state providing it's own storage sites.
  - Later states formed regional compacts where one state provided a disposal site.
  - Today many states do not have a permanent disposal site for low-level radioactive waste.

Nuclear Concerns



Low-level radioactive waste sites

Nuclear Concerns

- **Thermal pollution** is the addition of waste heat to the environment.
  - It is especially dangerous in aquatic systems.
  - To reduce the effects of waste heat, utilities build cooling facilities.

Nuclear Concerns

- The life expectancy of most electrical generating plants (fossil fuel or nuclear) is 30-40 years.
- Unlike other plants, nuclear plants are **decommissioned,** not demolished.
- Decommissioning is a 2-step process.
  - Stage 1 includes removing, properly disposing of or storing fuel rods and water used in the reactor.
  - Stage 2 is the final disposition of the facility. There are 3 options.
    - 1. Decontaminate and dismantle the plant as soon as it is shut down.

Nuclear Concerns

2. Secure the plant for many years to allow radioactive materials with a short half-life to disintegrate and then dismantle the plant. This should occur within 60 years.
3. Entomb the contaminated portions of the plant with reinforced concrete and place a barrier around the plant. Currently this option is only suitable for small research facilities.

- Over 90 nuclear power plants in the world have been shut down and are in various stages of being decommissioned.

The Future of Nuclear Power

- Environmental and economic issues have transformed into political stands where nuclear power is concerned.
- The potential for climate change has had major implications for nuclear power.
  - Because nuclear power plants do not produce carbon dioxide, many people have reevaluated the value of nuclear power as a continuing part of the energy equation.

The Future of Nuclear Power

- Many governments, setting their policy based on how their citizens vote, have declared themselves to be nonnuclear countries.

The Future of Nuclear Power

- Currently, there are 439 nuclear power reactors in 30 countries.
  - In 2006, they provided 16% of world's electricity.
- Currently, 36 reactors are under construction in 12 countries.
  - Most of the planned reactors are in Asia, where China, India, Japan, and South Korea plan to add 50 plants over the next 10-20 years.
  - Russia has plans for an additional 10 plants.
  - Electric utilities in the U.S. have requested approval for 12 new plants.

The Future of Nuclear Power

- Plant Life Extension
  - Most nuclear power plants originally had a normal design lifetime up to 40 years.
  - Engineering assessments have established many plants can operate much longer.
  - Extending the operating life of a plant reduces the cost of producing power because the decommissioning is delayed and no new power plant needs to be built to replace the lost capacity.

Summary

- Nuclear fission is the splitting of the nucleus of an atom.
- Various kinds of nuclear reactors have been constructed, and scientists are conducting research on the possibilities of using nuclear fusion to generate electricity.
- All reactors contain a core with fuel, a moderator to control the rate of the reaction, and a cooling mechanism to prevent the reactor from overheating.

Summary

- The nuclear fuel cycle involves mining and enriching the original uranium ore, fabricating it into fuel rods, using the fuel in reactors, and reprocessing or storing the spent fuel rods.
- Fuel and wastes must also be transported.
- Each step in the process presents a danger of exposure.

Summary

- Although accidents at Three Mile Island and Chernobyl raised safety concerns for a time, rising energy prices have stimulated increased building of nuclear power plants in many countries.
- Disposal of waste is expensive and controversial.
  - Long-term storage in geologically stable regions is supported.
  - Russia, Japan, and the UK operate nuclear reprocessing facilities to reduce future long-term storage needs.