21.2 Nuclear Reactors

SECTION OUTCOMES

- Analyze examples of Canadian contributions to a particular development of science and technology.
- Research the nature of existing fission reactors and the state of research into fusion reactors.

KEY TERMS

- critical
- subcritical
- supercritical
- thermal neutron
- moderator
- enriched uranium
- control rods
- primary coolant
- secondary coolant

Today's nuclear power reactors use uranium or plutonium as fuel. The heat produced by the fission reactions is used to boil water into steam which turns turbines. The turbines power electric generators. In this section, you will consider some requirements that must be met to operate a nuclear reactor. What sustains the fission reactions? What are the requirements for the fuel? How is the fission reaction controlled? How is the heat carried from the core of the reactor to a boiler? What happens to the fission products after the uranium has fissioned?

Nuclear Chain Reactions

Shortly after physicists discovered that bombardment of a certain isotope of uranium would cause the atom to fission and produce more neutrons, they realized that it might be possible to start a chain reaction. They reasoned that if more than one neutron is emitted when a nucleus fissions, those neutrons should be able stimulate more nuclei to fission. In 1942, under the leadership of Enrico Fermi, a team of physicists at the University of Chicago achieved the first self-sustaining chain reaction with uranium.

If one neutron from each fission event causes one more nucleus to fission, the reaction will be sustained at a constant rate. The fission process is said to be **critical** when these conditions are met. If fewer than one neutron from one event causes another — a condition called **subcritical** — the reactions will eventually cease. On the other extreme, if more than one neutron from each fission event causes another fission, the reaction rate will rise in a cascade of fissions. This condition is called **supercritical**. Figure 21.2 illustrates a nuclear chain reaction.

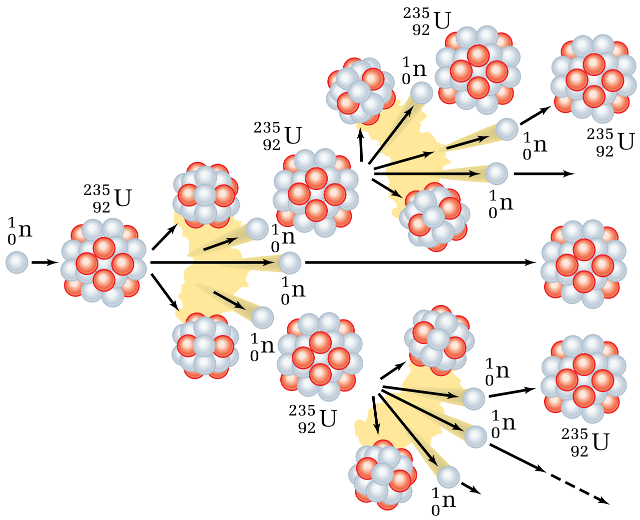


Figure 21.2 Neutrons emitted in each fission event are absorbed by another uranium atom and cause it to fission.

Fuel for Fission

Two nuclei that are likely to undergo fission are uranium-235 and plutonium-239. Plutonium-239 does not occur naturally but can be produced by bombarding uranium-238 with neutrons. Uranium-235 occurs in nature but in a very low abundance. Uranium from ore contains 99.3% uranium-238 and only 0.7% uranium-235. Both uranium-235 and plutonium-239 have a much greater probability of undergoing fission if the neutron they absorb is a slow neutron. The neutrons produced by the fission process, however, are fast neutrons. Slow neutrons have an energy of about 0.03 eV. They are usually called **thermal neutrons** because at their energy, they are in thermal equilibrium with gases in air around room temperature. Fast neutrons have energies between 10 and 15 MeV and must be slowed down before they can cause another fission.

How do you slow down a neutron? Since neutrons have no charge, they do not react with the electric fields around electrons and nuclei. The only types of interactions that neutrons can undergo are elastic collisions and absorption by nuclei. When your goal is to slow neutrons down so they will cause another fission reaction, you want to avoid substances that will absorb the neutrons. Elastic collisions provide the only way to slow the neutrons.

As you learned in Chapter 10, if a small object collides with a larger one in an elastic collision, it will bounce off with nearly the speed it had originally. So a good **moderator** — a substance that will slow down neutrons — should be as small or smaller than the neutron itself. Since there are no atoms smaller than a neutron, the best moderator should be hydrogen nuclei or protons. The simplest compound to handle that contains a large amount of hydrogen is ordinary water. However, ordinary water absorbs neutrons to a significant extent. The next larger atom relative to ordinary hydrogen is deuterium or ${}^{2}_{1}H$. Heavy water or deuterium oxide (D_2O) is used as a moderator in some reactors, as are the larger atoms beryllium and carbon in the form of graphite.

Table 21.1 compares some of the features of these moderators. The second row shows the average number of collisions that a neutron would have to undergo with that moderator to attain the best speed for absorption by uranium-235 or plutonium-239. The third row shows the chance that the moderator would absorb the neutron relative to heavy water.

Table 21.1 Characteristics of Neutron Moderators

Moderator	Ordinary water	Heavy water	Beryllium	Graphite
Collisions Required	18	25	90	114
Relative chance of absorption	560	1	16	6

PHYSICS FILE

Physicists measure what they call a "neutron cross section," which is an indication of how large atoms of various elements appear to neutrons. Cross sections really measure the chance that the atoms will absorb neutrons. In some early studies, researchers were astounded at the large cross section measured for a certain element. One physicist was said to have exclaimed, "That's as big as a barn!" Soon, the new unit for reporting neutron cross sections was named a barn. A barn is equivalent to 10^{-28} m^2.

MISCONCEPTION

A Nuclear Reactor Cannot Explode

Many people think that reactors the same as a nuclear bombs. They are not! There is not enough uranium in a reactor and it is not enriched enough to explode. The worst accident that a reactor can have is to heat up to such a high temperature that the reactor core will melt. Although this creates serious problems, it is nothing like a bomb.

As you can see from Table 21.1, heavy water is probably the best moderator, but it is quite expensive relative to the other moderators.

If any moderator other than heavy water is used in a reactor, it will be extremely difficult to sustain a chain reaction in natural uranium. This difficulty arises because only 0.7% of the uranium atoms are uranium-235, the fissionable isotope of uranium. Too many neutrons will be absorbed or will escape from the fuel assemblies before causing a fission reaction. Either plutonium would have to be used as fuel or the uranium must be **enriched uranium**. That is, the percent of uranium-235 must be increased. Since all isotopes of the same element react identically chemically, no chemical reactions can enrich the uranium-235. One common method involves heating a uranium compound to a temperature at which it will vapourize and allowing the gas to diffuse through special filters. The smaller uranium-235 will diffuse slightly faster than uranium-238. The process provides enough enrichment to use the uranium for fuel in reactors.

Control Rods

A chain reaction can be sustained, keeping the fission reactions at the critical level, by using heavy water as a moderator or by enriching the uranium fuel. How, then, do you control the rate of the fission reactions and prevent them from going supercritical? In the discussion of moderators, you read that some nuclei have a much greater tendency to absorb neutrons than others. Isotopes of two elements, cadmium and boron, have an exceptional ability to absorb neutrons. **Control rods** made of cadmium or boron are designed to be lowered into the core or withdrawn from the core to the point that they absorb exactly the right amount of neutrons so that exactly one neutron from every fission reaction causes one more fission reaction.

Coolants

The coolant is the link between the energy released by the fission reactions and the production of electric energy. The **primary coolant** runs through the core of the reactor, removing the heat from the fuel rods and carrying it away to a boiler as shown in Figure 21.3 on the following page. The primary coolant pipes run through the boiler and heat the water, converting it into the steam that drives the turbines. The water in the boiler is sometimes called the **secondary coolant**. Notice that the primary and secondary coolants never mix because the primary coolant is inside sealed pipes. Only heat passes from the primary to the secondary coolant.

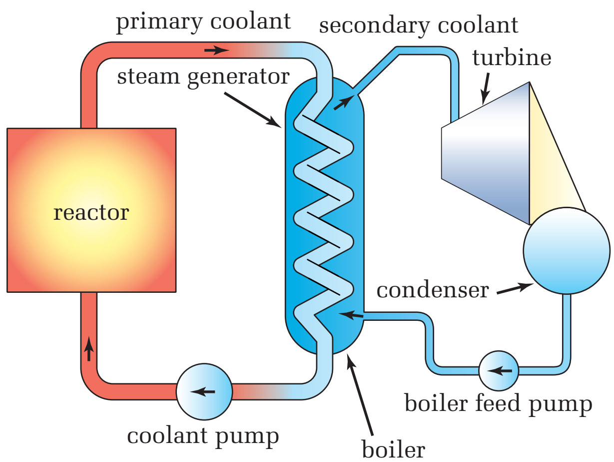


Figure 21.3 If the primary coolant picks up any contaminants in the reactor, they are not passed on to the secondary coolant because the two coolants never mix.

For a fluid to be a good coolant, it should have several important properties. Coolants should have a high boiling point, be non-corrosive, *not* absorb neutrons and become radioactive, be chemically stable in the presence of radiation and high temperatures, have good heat transfer properties, and pump easily. No single fluid could have all of these properties, so coolants are selected depending on each specific reactor design. Some of the common coolants are ordinary water, heavy water, organic liquids such as diphenyl, liquid metals such as sodium or a sodium potassium alloy, and even gases such as air, carbon dioxide, helium, nitrogen, and hydrogen.

Nuclear Waste

Up to this point, you have read little about the hazards of nuclear energy. What are the dangers and the hazards?

Reactor fuels, uranium or plutonium, are radioactive — but they are alpha emitters. You learned that alpha particles can do no damage as long as they are external to the body. When the fuel is encased in the metal rods, alpha particles cannot penetrate the walls of the rods. The problem lies in the fission products. The reason will become clear when you examine Figure 21.4. When a large nucleus splits into two nuclei roughly half the size of the parent nucleus, the smaller fission products have a neutron to proton ratio nearly the same as the large parent nucleus. However, stable nuclei the size of the fission products have neutron to proton ratios that are much smaller. As a result, the fission products lie far outside of the range of stability. They are therefore extremely unstable and very radioactive. The hazards of nuclear reactors lie in the potential release of these highly radioactive materials. The handling and storage of fission products must be carried out with extreme care.

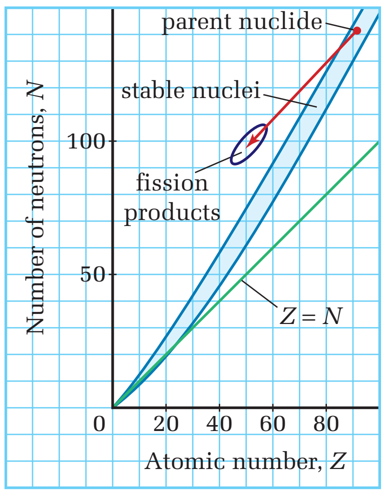


Figure 21.4 Fission products lie above the range of stability and are therefore mostly beta emitters.

CAREERS IN PHYSICS

Nuclear Safety Supervisor

Jennifer Noronha

In some ways, nuclear power is an appealing power source. Nuclear reactions create large amounts of energy from minimal material, and they generate none of the carbon dioxide and other emissions that cause acid rain and global warming. The products and reactants of nuclear reactions, however, are dangerously radioactive. Therefore, special measures are needed to protect nuclear power station employees from daily exposure to radiation. That is where Jennifer Noronha comes in. Noronha is the supervisor of Radiological Services at Darlington. Employee safety—especially from high radiation doses—is her first priority.

The Darlington Nuclear Generating Station is located 70 km east of Toronto. It uses a fuel of natural uranium to produce enough electricity to provide power for a city the size of Toronto. Noronha and her radiation protection team plan and implement safety programs that minimize the chance that employees will be exposed to radiation.

Station employees must undergo four weeks of radiation protection training. This training was designed by Noronha's department, based on an extensive investigation of radiation fields within the station, as well as a thorough evaluation of past safety programs and approaches. Through this training, employees learn how to measure existing dose rates with survey equipment, assess what kinds of tools and protective clothing are needed, and take appropriate action to lower radiation doses.

For example:

- Airborne hazards, such as tritium (present in radiated water vapour), can be reduced by running the station's dryer system. The dryer system catches the radiated vapour and dries it out of the air.
- Non-airborne radiation can be countered by shielding the affected area with lead blankets or sheeting material.

Noronha's strong mathematics skills were evident from an early age. When she moved to Canada from Kenya at age 11, she was immediately put ahead a grade. Her mathematics skills and her father's engineering profession were what propelled her toward engineering. Noronha earned her engineering physics degree from McMaster University. Her courses included general chemistry, biomedical theory, and nuclear theory. She worked as a commissioning engineer at Darlington during its start-up. She tested the station's safety shutdown systems and helped to bring the station's first reactor on-line. "It was pretty amazing," Noronha says. "At the time, it was still relatively new technology, and it was Canadian technology."

Noronha got her MBA from the University of Toronto in 1998. Soon after, she moved to her current position, which allows her to combine her people skills and technical expertise.

Going Further

1. Are you interested in the different safety concerns related to Canadian nuclear reactors, and the steps that are being taken to counter these concerns? Contact the Canadian Nuclear Safety Commission (CNSC) or explore their web site. (The CNSC is the Ottawa-based government watchdog for the use of nuclear energy in Canada.)

Canada's CANDU Reactor

Canada entered the nuclear industry in 1945 with the first controlled nuclear chain reaction outside of the United States. Canada has remained active in the nuclear industry and has developed one of the most respected designs for reactors in the world — the CANDU reactor. Several countries have purchased the CANDU reactor from Canada. The basic design of the reactor assembly is shown in Figure 21.5.

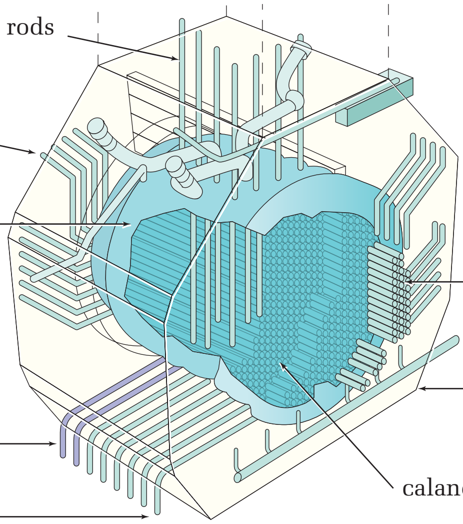
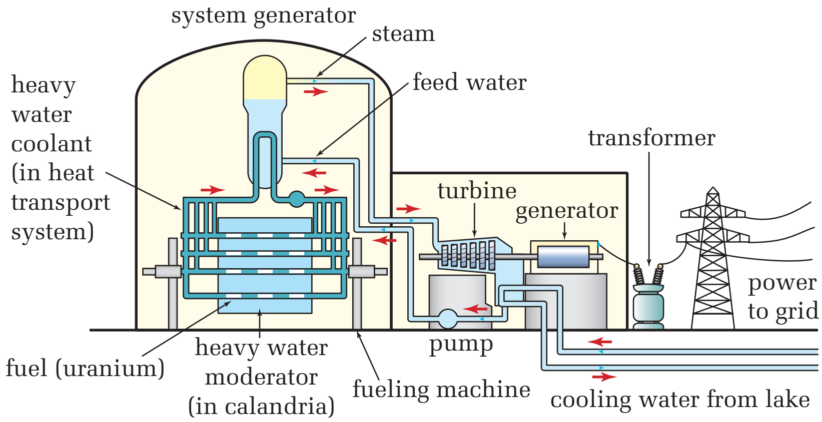


Figure 21.5 The reactor assembly of the CANDU reactor consists of horizontal fuel rods inside of a container called the calandria. The heavy water coolant and moderator runs through the reactor while control rods are inserted from above.

The CANDU reactor uses heavy water as both a moderator and a coolant, and can therefore use natural uranium as fuel. The fuel is made of uranium oxide pellets that are inserted into tubes made of a zirconium alloy. The tubes are arranged into fuel bundles that are about 0.5 m long and contain 22 kg of UO_2. One fuel bundle produces as much thermal energy as 400 t of coal. A bundle lasts about 17 months, after which new bundles are added to the calandria tubes. The spent bundle is pushed out the other end into a tank of water where it is stored. The CANDU reactor is unique in that the fuel can be replaced while the reactor is operating. Most reactors have vertical fuel tubes and must be shut down for refuelling.

Figure 21.6 on the following page shows how the reactor assembly is connected to the turbine and boiler. Take note of all of the levels of containment for the fuel. The zirconium alloy tubes containing the fuel pellets are sealed and placed inside of sealed calandria tubes. The calandria tubes are sealed in the calandria itself. The reactor building is designed to contain any potential leaks as well, and is separate from the turbine and generator room. Further safety features include the vertical control rods that will drop further into the reactor in the event of a problem. Also, the heavy water moderator can rapidly be drained to stop the chain reaction. These, along with many other safety features, make the CANDU reactor one of the safest currently operating in the world today.

Figure 21.6 The primary coolant runs, in sealed pipes, through a boiler which produces steam to turn a turbine. The turbine and generator are in a separate containment building.



Fusion Reactors

No matter how safe the design of a fission reactor, radioactive waste products are constantly accumulating and must be contained for hundreds of years. Fusion reactions do not produce radioactive waste. Why are fusion reactors not available? Although research has been ongoing in the development of fusion reactors for over 50 years, no one has been successful in sustaining a fusion reaction.

The most challenging obstacle is that temperatures of nearly 100 million degrees Celsius must be reached to produce atoms that are energetic enough to collide and undergo fusion. As well, no materials could contain gases at these temperatures. Several different approaches to containment have been attempted. The most promising approach being investigated today is containment in a magnetic field. A photograph of the inside of an experimental Tokamak fusion reactor is shown in Figure 21.7. Coils carrying large currents wrap around this chamber, generating a magnetic field inside. The magnetic field suspends the gases in which the reactions occur.

Figure 21.7 These workers are inspecting the inside of the experimental Tokamak fusion reactor at Princeton University.

One fusion reaction that holds promise is shown in Figure 21.8. A deuterium atom and tritium atom fuse to form a very unstable helium-5 atom that rapidly disintegrates into an atom of helium-4 and a neutron.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{5}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

In this reaction, 1 g of deuterium yields as much energy as 8 t of coal. This fusion reaction has been achieved in these experimental reactors but only sustained for about half a second.

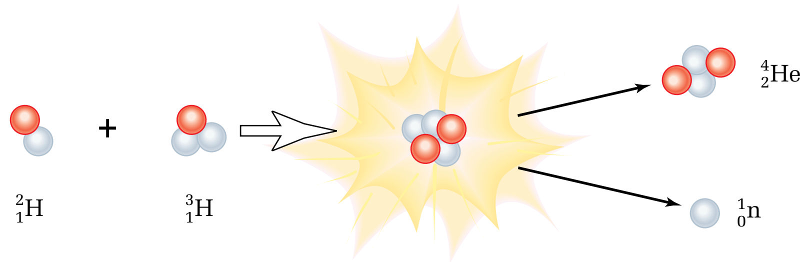


Figure 21.8 The helium nucleus has a much larger binding energy than either deuterium or tritium, thus large amounts of energy are released in the nuclear fusion reaction.

Fusion research is extremely expensive but some people feel that it is necessary. Fossil fuels pollute the environment and eventually will be depleted. Fission reactors continue to accumulate highly radioactive waste products. Fusion power would be clean and relatively safe and the oceans hold enough hydrogen isotopes to last hundreds of years. Fusion power might be society's greatest hope for energy in the future.

21.2 Section Review

1. K/U Explain what the terms critical, subcritical, and supercritical mean with respect to a nuclear chain reaction.
2. K/U What is a moderator and why is it necessary in the operation of a fission reactor?
3. K/U What is enriched uranium? Why is it necessary to produce enriched uranium?
4. K/U List four characteristics of a good coolant for a fission reactor.
5. C What creates the most serious potential hazard in the operation of a fission reactor?
6. MC It is often stated that it is impossible for a Chernobyl type accident to happen with a CANDU reactor. Do research to learn about the basis of this statement.
7. K/U Explain why fusion would be an appealing energy source.

UNIT PROJECT PREP

If you and your class carried out the Quick Lab on page 921, review the results of the survey and discussion. If you did not carry out the Quick Lab, think about how your perception of nuclear power generation has changed as you worked through this unit.

- Identify your bias. Do you believe that the hazards of nuclear power outweigh any benefits?
- Should environmental, economic, or social concerns take precedence in considering an issue that affects all three?