16.5: Nuclear Reactors

Nuclear submarine Figure 20.9.1

There are many applications of radioactivity. The applications range from scientific research in physics, medicine, and agriculture to industrial measuring, nuclear weapons, and electricity generation. The particular application shown in the photo is the USS *Newport News* nuclear-powered attack submarine. In terms of nuclear fuel supply, the USS *Newport News* leaves port with sufficient fuel to remain underwater for 20 years. In nuclear naval vessels, the nuclear reaction produces steam and the steam then runs the ship.

Fission Reactors

A nuclear reactor is a device in which a nuclear chain reaction is carried out at a controlled rate. When the controlled chain reaction is a fission reaction, the reactor is called a fission reactor. Fission reactors are used primarily for the production of electricity, although there are a few fission reactors used for military purposes and for research. The great majority of electrical generating systems all follow a reasonably simple design. The nuclear reaction boils water into steam, the steam is used to spin a turbine, and the turbine turns an electrical generator. After the water is turned into steam, the sequence in a fossil fuel generating plant and a nuclear generating plant are approximately the same. Of course, with the nuclear plant, the reaction chamber must be inside a containment building.

Fissionable Fuel

Naturally occurring uranium is composed almost entirely of two isotopes, uranium-238 (99%) and uranium-235 (1%). It is the uranium-235 that is fissionable (will undergo fission) and therefore, this is the uranium isotope than can be used for fuel in a nuclear reactor. For uranium to be used as fuel, the percent of uranium-235 must be increased to at least 3%. Uranium in which the U-235 content is more than 1% is called enriched uranium. Somehow, the two isotopes must be separated so that enriched uranium is available for use as fuel. Separating the isotope by chemical means (chemical reactions) is not successful because the isotopes have exactly the same chemistry. The only essential difference between U-238 and U-235 is their atomic masses; as a result, the two isotopes are separated by a physical means that takes advantage of the difference in mass.

Once the supply of U-235 is acquired, it is placed in a series of long cylindrical tubes called fuel rods. These fuel cylinders are bundled together with **control rods** (see diagram below) made of neutron-absorbing material. The amount of heat generated by the chain reaction is controlled by the rate at which the nuclear reaction occurs. The rate of the nuclear reaction is dependent on how many neutrons are emitted by one U-235 nuclear disintegration *and* how many strike a new U-235 nucleus to cause another disintegration. The purpose of the control rods is to absorb some of the neutrons and thus stop them from causing further disintegrations. The control rods can be raised or lowered into the fuel rod bundle. When the control rods are lowered all the way into the fuel rod bundle, they absorb so many neutrons that the chain reaction essentially stops. When more heat is desired, the control rods are raised so that the chain reaction speeds up and more heat is generated. The control rods are operated in a fail-safe system so that power is necessary to hold them up. During a power failure, gravity will pull the control rods down to shut off the system.

Schematic of a nuclear reactor Figure 20.9.2

U-235 nuclei can capture neutrons and disintegrate more efficiently if the neutrons are moving slower than the speed at which they are released. Fission reactors use a **moderator** surrounding the fuel rods to slow down the neutrons. Water is not only a good coolant but also a good moderator, so a common type of fission reactor has the fuel core submerged in a huge pool of water. This type of reactor is called a light water reactor or LWR. All public electricity generating fission reactors in the United States are LWRs.

Schematic of a nuclear power plant Figure 20.9.3

You can follow the operation of an electricity-generating fission reactor in the image above. The reactor core is submerged in a pool of water. The heat from the fission reaction heats the water, which is pumped into a heat exchange container. There the heated water boils the water in the heat exchanger. The produced steam is forced through a turbine that spins a generator and produces electricity. After the water passes through the turbine, it is condensed back to liquid water and pumped back to the heat exchanger.

Breeder Reactors

U-235 is the only naturally occurring fissile isotope, and it constitutes less than 1% of naturally occurring uranium. A **fissile** substance is a substance capable of sustaining a chain reaction of nuclear fission. It has been projected that the world's supply of U-235 will be exhausted in less than 200 years. It is possible, however, to convert U-238 to a fissionable isotope that will function as a fuel for nuclear reactors. The fissionable isotope is plutonium-239 and is produced by the following series of reactions:

$${}_{92}^{238}U + {}_{0}^{1}n \rightarrow {}_{92}^{239}U \rightarrow {}_{-1}^{0}e + {}_{93}^{239}Np \rightarrow {}_{-1}^{0}e + {}_{94}^{239}Pu$$

The final product from this series of reactions is plutonium-239, which has a half-life of 24,000 years and is another nuclear reactor fuel. This series of reactions can be made to occur inside an operating nuclear reactor by replacing some of the control rods with rods of U-238. As the nuclear decay process proceeds inside the reactor, it produces more fuel than it uses. It would take about 20 such breeder reactors to produce enough fuel to operate one additional reactor. The use of breeder reactors would extend the fuel supply a hundred fold. The problem with breeder reactors, however, is that plutonium is an extremely deadly poison. Furthermore, unlike ordinary fission reactors, it is possible for out-of-control breeder reactors to explode. None of the civilian nuclear power plants in the U.S. are breeder reactors.

Launch the PLIX Interactive below to start a chain reaction by causing a neutron to collide with a uranium atom:

Summary

- A nuclear reactor is a device in which a nuclear chain reaction is carried out at a controlled rate.
- The nuclear reaction boils water into steam, the steam is used to spin a turbine, and the turbine turns an electrical generator.
- It is the uranium-235 that is fissionable (will undergo fission) and therefore, this is the uranium isotope than can be used for fuel in a nuclear reactor.
- Uranium in which the U-235 content is more than 1% is called enriched uranium and can be used as fuel in a fission reactor.
- Once the supply of U-235 is acquired, it is placed in a series of long cylindrical tubes called fuel rods.
- These fuel cylinders are bundled together with control rods made of neutron-absorbing material.
- The purpose of the control rods is to absorb some of the neutrons and thus stop them from causing further disintegrations.
- The control rods can be raised or lowered into the fuel rod bundle. When the control rods are lowered all the way into the fuel rod bundle, they absorb so many neutrons that the chain reaction essentially stops.
- When more heat is desired, the control rods are raised so that the chain reaction speeds up and more heat is generated.
- The control rods are operated in a fail-safe system so that power is necessary to hold them up. During a power failure, gravity will pull the control rods down to shut off the system.
- It is possible, however, to convert U-238 to a fissionable isotope that will function as a fuel for nuclear reactors. This process is carried out in reactors called breeder reactors.
- None of the civilian nuclear power plants in the U.S. are breeder reactors.

Review

1. Nuclear power plants produce electricity through
   1. induced fission
   2. induced fusion
   3. beta decay
2. U-235 nuclei split when struck by
   1. a proton
   2. a neutron
   3. an electron
3. The most important difference between a nuclear power plant and a fossil fuel plant is
   1. the size of the generator.
   2. the shape of the generator.
   3. the fuel.
4. Which of the following will function as fuel in a fission reactor?
   1. hydrogen
   2. coal

3. all isotopes of uranium
4. only U-235

Explore More

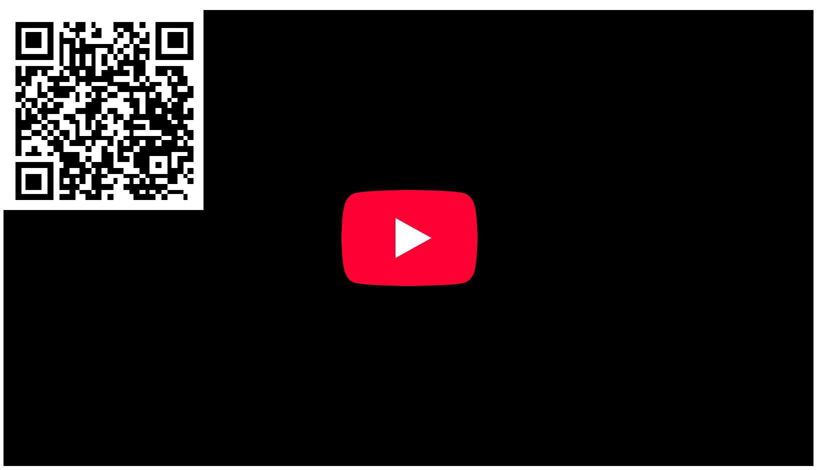
Use this resource to answer the questions that follow.

1. What does PWR stand for?
2. What do the control rods do?
3. Once the steam is generated, what is it used for?

Additional Resources

Study Guide: Nuclear Physics Study Guide

Video:



Real World Application: Just Cool It