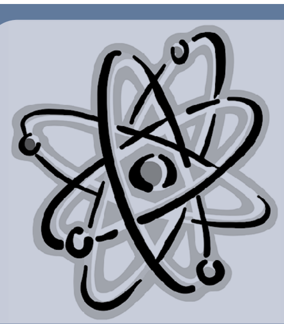


Harnessing Nuclear Energy

Students simulate a nuclear chain reaction and read about how a nuclear reactor works.

Grade Level: 5–8 (9–12)

Subject Areas: English Language Arts, Mathematics, Science

Setting: Classroom, outdoors, or large space

Time:
Preparation: One hour
Activity: Two 50-minute periods

Vocabulary: Atom, Boiling water reactor, Chain reaction, Containment building, Control rod, Coolant, Element, Enrichment, Fission, Fuel assembly, Isotope, Kinetic energy, Moderator, Neutron, Nuclear energy, Nucleus, Plutonium, Potential energy, Pressure vessel, Pressurized water reactor, Radiation, Radioactive decay, Radioactivity, Reactor, Uranium

Major Concept Area:

- Development of energy resources

Objectives

Students will be able to:

- explain how energy is obtained from nuclear fission;
- compare controlled and uncontrolled nuclear chain reactions;
- describe how a nuclear reactor uses nuclear energy to produce electricity; and
- formulate an opinion about using nuclear energy.

Rationale

Understanding how energy is obtained from nuclear fission and how it is used to produce electricity in a nuclear power plant teaches students how some of the electricity they use is produced.

Materials

- Copies of ***Nuclear Fission and Nuclear Chain Reactions***
- Scrap paper or small, light biodegradable objects such as popcorn
- Stopwatch or clock with second hand
- Marbles (for each group)
- Copies of ***How a Nuclear Power Plant Operates***
- Copies of ***Facts about Nuclear Energy*** (optional)
- Find additional resources related to this activity on keepprogram.org > Curriculum & Resources

Background

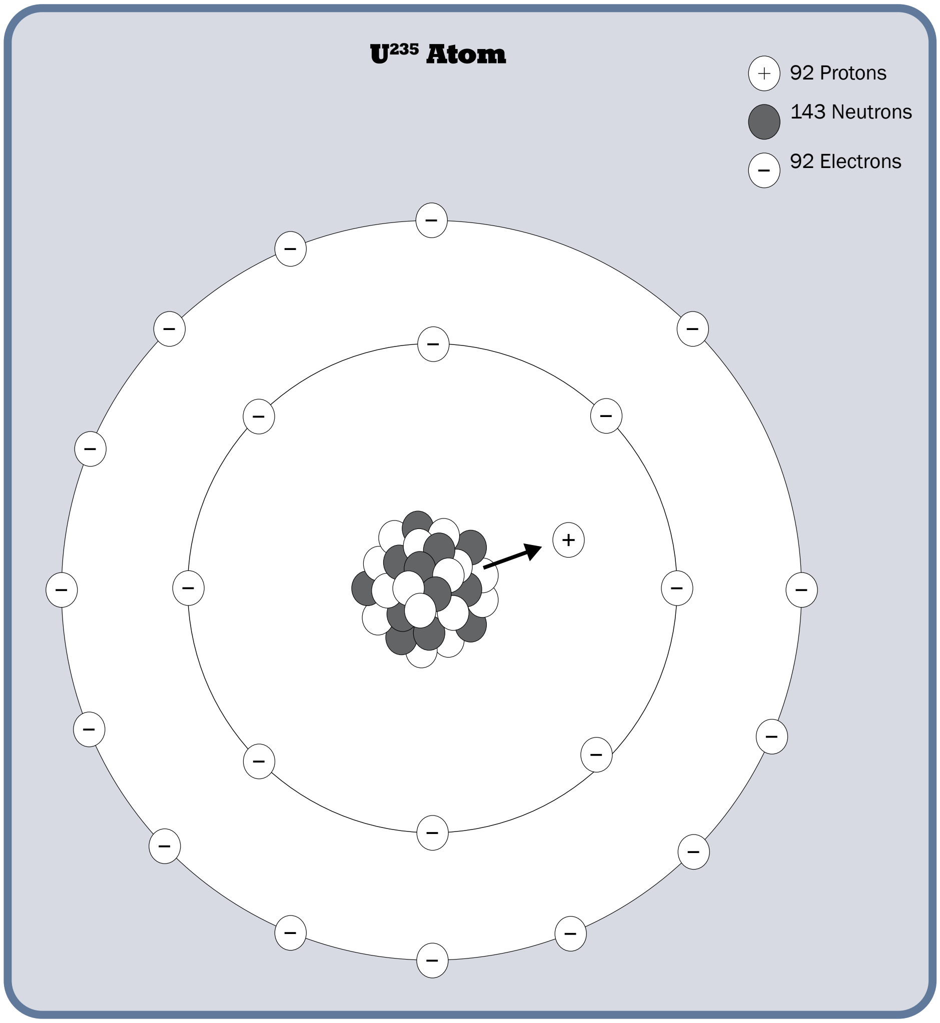
See the background information in ***Nuclear Fission and Nuclear Chain Reactions*** and ***How a Nuclear Power Plant Operates***. Additional information may be found in ***Facts about Nuclear Energy***.

Procedure

Orientation

Ask students what they know about nuclear energy. Record their comments on the board or elsewhere. Ask students to label each comment as “fact” (true), “fiction” (false), or “don’t know.”

Review basic atomic terms such as atom, nucleus, neutron, radioactivity, and molecule with the class. Draw a diagram of an atom on the board and have students identify its parts. You may want to draw a simplified version of a uranium-235 (U^{235}) atom, showing its nucleus surrounded by electrons. List the number of protons (92) and neutrons (143) by the nucleus, and the number of electrons (92) by the area where they orbit the U^{235} nucleus (see ***U^{235} Atom*** diagram).



Steps

1. Divide the class into pairs and have them read ***Nuclear Fission and Nuclear Chain Reactions*** and answer the questions (see ***Read and Explain Pairs*** for a suggested reading comprehension strategy). Select pairs to share their answers with the class. Encourage students to raise other questions about the readings.

2. Tell students they are going to model a nuclear chain reaction. Take the class outside or to a large open area. Inform students they each represent a U^{235} nucleus. Provide each student with two pieces of scrap paper and tell students to wad the paper into small balls (or give each student two kernels of popcorn). The paper balls represent neutrons.

3. Have students stand in three or four rows about an arm's length from each other. Tell them that you will start by throwing your paper wads into the air. Students who are hit by a paper wad have been bombarded with a neutron, and they must split off their own neutrons by immediately tossing their two balls of paper into the air. Students are to throw the paper wads randomly (not aiming at anyone).

4. Note the time and throw your papers into the air. When the paper balls stop flying, note the time again. Also count the number of students that did not "react" or who were not hit with paper.

5. Discuss controlled and uncontrolled chain reactions.
   - Uncontrolled reactions occur when fissionable material is concentrated and all of it reacts very quickly. This reaction produces a very high temperature all at once and results in an action much like an atomic bomb.
   - Controlled reactions last longer than uncontrolled reactions. They usually start small, speed up slowly, and reach a constant, sustained level of reaction.

6. Ask students if they think their paper-throwing demonstration represented a controlled or uncontrolled reaction. How would they arrange themselves to simulate a more controlled reaction? Have them collect the papers and try out their suggestions, and compare the results to the previous demonstration.

7. After students have returned to the classroom and to their seats, have them read ***How a Nuclear Power Plant Operates*** (see ***Read and Explain Pairs***). Select pairs to share their answers with the class.

Closure
Ask students to review their earlier comments about nuclear energy and to re-classify their comments as "fact," "fiction," or "don't know." Discuss whether their initial understanding was based on popular misconceptions about nuclear energy. Ask them how they would respond to such misconceptions in the future (see **Assessment**).

Assessment
Formative
- Did students work cooperatively to read the material?
- How accurately did students answer questions from the reading assignments?
- Can students demonstrate an uncontrolled and a controlled nuclear chain reaction using wads of paper?

Summative
Have students identify reasons why they would or would not want their electricity generated from nuclear energy. What else would they need to find out before making their choice?

Extension
An alternative to the paper throwing activity is to have students set up dominoes. Dominoes that are arranged close together when knocked over illustrate an uncontrolled reaction. Challenge students to set up the dominoes so that they simulate a controlled reaction.

Related KEEP Activities
Conduct the appliance survey in the activity "At Watt Rate?" to orient students how to use electricity in the home. Students can learn more about nuclear power plants in Wisconsin through the activity "Fuel That Power Plant." The activity "Advertising Energy" can be used to analyze public relations strategies employed by electric utilities. Follow this activity with "Dealing with Nuclear Waste." Further investigations of different types of resources can accompany this activity. Have students simulate electricity generation in "Electric Motors and Generators."

Credits
Activity adapted from New York Energy Education Project. "Harnessing Nuclear Energy" pp. 4–1 to 4–21 in *Fossil Fuels: Student Activities* from the New York Energy Education Project. Albany, N.Y.: The Research Foundation of the State University of New York on behalf of the New York Energy Project, 1985. Used with permission of the New York Science, Technology and Society Education Project (NYSTEP). All rights reserved

Activity adapted and diagrams of nuclear reactor, boiling water reactor and pressurized water reactor from U.S. Department of Energy. pp. 61–65, 69–72, and 94–95 in *The Harnessed Atom: Nuclear Energy and Electricity*. Washington D.C.: U.S. Department of Energy, 1986. DOE/NE-0072. Used with permission. All rights reserved.

Point Beach Nuclear Power Plant
Source: Nextera Energy Resources

Read and Explain Pairs

It's often more effective to ask students to read assigned material in cooperative pairs than individually. The expected criterion for success is that both members be able to explain the meaning of the assigned material correctly. The task is for the pairs to ascertain the meaning of each section and the assigned material as a whole (a "section" is text covering a specific topic and introduced by a section heading shown in bold type). The cooperative goal is for both members to agree on the meaning of each section, formulate a joint summary, and be able to explain their answer.

Here's How It Works

1. Assign a high reader and a low reader to be a reading pair, telling them what specific pages (passages) that you want them to read.
2. Students read all section headings for an overview.
3. Students silently read the first section and then take turns acting as summarizer and accuracy coach. They rotate roles after each section.
4. The summarizer outlines in her own words the content of the section to her partner.
5. The accuracy coach listens carefully, corrects any misstatements, adds anything that was left out, and explains how the material relates to something they already know.
6. The students then move on to the next section and repeat the procedure. They continue until they have read all assigned material. At that point, they come to an agreement on the overall meaning of the assigned material.

During the lesson, systematically monitor each reading pair and assist students in following the procedure. To ensure individual accountability, randomly ask students to summarize what they have read so far. Remind students that there is intergroup cooperation—whenever it is helpful, they should check procedures, answers, and strategies with another group, or if they finish early, they should compare and discuss answers with another group.

The Wisconsin K-12 Energy Education Program is supported through funding from

Wisconsin K-12 Energy Education Program (KEEP)
College of Natural Resources
University of Wisconsin-Stevens Point

Nuclear Fission and Nuclear Chain Reactions

Introduction

One of the greatest scientific discoveries of the twentieth century is that nuclei of uranium atoms can be split by neutrons to produce large quantities of energy. This process, called nuclear fission, brings to mind the large-scale production of electricity by nuclear power plants and large-scale destruction by nuclear weapons. In order to understand how nuclear fission can produce such large amounts of energy, we must begin by looking at uranium.

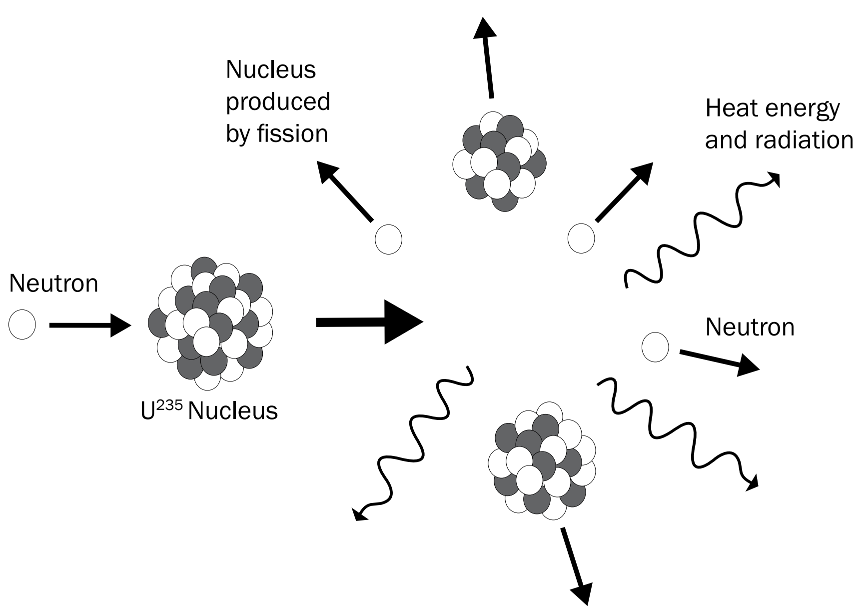
Characteristics of Uranium

Uranium is one of the elements found in nature. An element is a substance made entirely of the same kind of atoms, with each atom having the same number of protons and electrons. Every uranium atom has 92 protons in its nucleus and 92 electrons orbiting the nucleus. However, not every uranium atom is completely alike. Different uranium atoms have different numbers of neutrons in their nuclei. These variations of uranium atoms are called isotopes. Many other elements besides uranium have isotopes as well. The isotope of uranium used to produce nuclear energy is uranium-235 (abbreviated as U^{235}). It is called U^{235} because each atom has 92 protons plus 143 neutrons in its nucleus, which totals 235 protons and neutrons. Another important uranium isotope is uranium-238 (U^{238}), which has 92 protons and 146 neutrons in its nucleus (92 + 146 = 238). An atom of U^{238} has three more neutrons in its nucleus than an atom of U^{235} does. The forces that hold protons and neutrons together in uranium isotopes are unstable. When the forces that hold an isotope together are broken energy, in the form of radioactive gamma waves, similar to x rays, is released. Therefore, another characteristic of uranium is that it is radioactive.

Energy from Nuclear Fission

For nuclear fission to occur, the nucleus of a uranium atom has to be split somehow. This splitting is done with neutrons. Most neutrons travel at low speeds. Such neutrons have the right amount of energy needed to split U^{235}. On the other hand, only neutrons traveling at very high speeds have enough energy to split U^{238} nuclei, and they are rare. Therefore, fission occurs much more easily with U^{235} than it does with U^{238}.

A neutron colliding with a U^{235} nucleus splits it into two smaller nuclei of other elements and, depending on the nuclei that are formed, releases two or three neutrons. For example, a U^{235} nucleus might be split into the nuclei of the elements barium and krypton, and release three neutrons. Splitting another U^{235} nucleus might produce the elements lanthanum and molybdenum and only two neutrons. These and other elements produced by fission are radioactive.



Nuclear Fission and Nuclear Chain Reactions

When the total mass of the U^{235} nucleus before fission, plus the neutron that splits it, is compared to the total mass of the two smaller nuclei and the neutrons after fission, a small amount of mass is missing. This finding is true no matter what combination of nuclei and neutrons is produced. Where did the missing mass go? Einstein's famous equation $E = mc^2$ solves the mystery—the missing mass was converted into energy (see ***E = mc²: How Nuclear Fission Produces Energy***). The energy stored in the form of mass in the nucleus, plus energy stored in the bonds that hold neutrons and protons together, is called nuclear energy. This is a form of potential energy. The energy released after fission occurs is observed as motion of the split nuclei and neutrons (kinetic energy) and released heat (thermal energy).

E=mc²: How Nuclear Fission Produces Energy

To see how nuclear fission produces energy, let's look at one of the possible fission reactions for a single U^{235} nucleus. The reaction can be written as follows:

$${}_{0}n^{1} + {}_{92}U^{235} \text{ fi } {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1} + \text{energy}$$

A neutron (${}_{0}n^{1}$) hits a U^{235} nucleus, splitting it into a barium nucleus (${}_{56}Ba^{141}$) and a krypton nucleus (${}_{36}Kr^{92}$). Three neutrons ($3{}_{0}n^{1}$) plus a certain amount of energy are also released. When the total mass of the neutron and the U^{235} nucleus before fission is compared to the total mass of the barium, krypton, and three neutrons after fission, a small amount of mass turns out to be missing.

The amount of missing mass and the energy released by this reaction can be calculated. Since atomic nuclei are very small, it is more convenient to express their mass in units called atomic mass units (amu) rather than in pounds or kilograms (one amu is equal to one-twelfth of the mass of C^{12}, the most common form of carbon atom).

The total mass of the neutron and the U^{235} before fission is:

${}_{92}U^{235}$	=	235.04393 amu (atomic mass units)
${}_{0}n^{1}$	=	1.00867 amu
total	=	236.05260 amu

The total mass of the barium, krypton, and the three neutrons after fission is

${}_{56}Ba^{141}$	=	140.91436 amu
${}_{36}Kr^{92}$	=	91.92627 amu
$3\ {}_{0}n^{1}$	=	3.02601 amu
total	=	235.86664 amu

To find the decrease in mass, subtract the total masses of the barium, krypton, and three neutrons from the neutron and the U^{235}.

Decrease in mass	=	total mass before fission - total mass after fission
	=	236.05260 amu - 235.86664 amu
	=	0.18596 amu

Nuclear Fission and Nuclear Chain Reactions

$E=mc^2$: How Nuclear Fission Produces Energy Continued...

Next, use Einstein's equation $E=mc^2$ to calculate the amount of energy equal to the decrease in mass. To do this, the mass must first be converted from amu to kilograms.

$$0.18596 \text{ amu} \times \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ amu}} = 3.09 \times 10^{-28} \text{ kg}$$

The amount of energy produced is equal to m, the decrease in mass (in kilograms), multiplied by c^2, the square of the speed of light (in meters per second).

$$\begin{aligned} E &= mc^2 \\ &= (3.09 \times 10^{-28} \text{ kg}) \times (3 \times 108 \text{ meters/sec})^2 \\ &= (3.09 \times 10^{-28} \text{ kg}) \times (9 \times 1016 \text{ meters/sec}^2) \\ &= 2.78 \times 10^{-11} \text{ kg.meter}^2/\text{sec}^2 \text{ (and since 1 joule = 1kg.meter}^2/\text{sec}^2) \\ &= 2.78 \times 10^{-11} \text{ joules} \times \frac{1 \text{ Btu}}{1.06 \times 103 \text{ joules}} \\ &= 2.64 \times 10^{-14} \text{ Btu of energy per } U^{235} \text{ nucleus} \end{aligned}$$

Splitting one U^{235} nucleus produces 2.64×10^{-14} Btu of energy, an amount that can barely be measured. On the other hand, the amount of energy released by fission of one pound of pure U^{235} is extremely large. One pound of pure U^{235} contains 1.18×10^{24} atoms* of U^{235}. Assuming every atom undergoes fission according to the reaction given earlier, the energy released is:

$$\frac{2.64 \times 10^{-14} \text{ Btu}}{\text{atom of } U^{235}} \times \frac{1.18 \times 10^{24} \text{ atoms of } U^{235}}{\text{pound of } U^{235}} = 3.11 \times 1010 \text{ Btu per pound of } U^{235}$$

$$* \frac{453.59\cancel{g}}{1lb} \times \frac{1 \cancel{\text{mole } U^{235}}}{235g} \times \frac{6.02 \times 10^{23} \text{ atoms } U^{235}}{1 \cancel{\text{mole U235}}} = 1.18 \times 10^{24} \text{ atoms } U^{235}$$

This is equal to the energy contained in 1,244 tons (1,264 metric tons) of bituminous coal, 249,000 gallons (942,565 liters) of gasoline, or 2,600 tons (2,642 metric tons) of wood.

This amount is slightly smaller than the average amount of energy released by fission of one pound of U^{235}. Other fission reactions may produce nuclei like germanium, lanthanum, strontium, xenon, and zirconium instead of barium and krypton, along with only two instead of three neutrons. Producing different fission products yields slightly different amounts of energy per split U^{235} nucleus. When averaged, the energy produced by fissioning one pound of pure U^{235} is equal to 3.5×10^{10} Btu.

Nuclear Chain Reactions

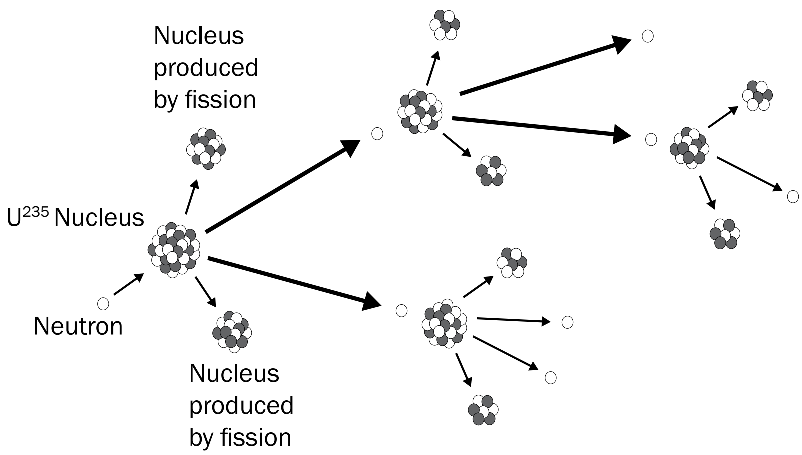
The energy released by a single U^{235} nucleus is too small to have any practical purpose. To produce a large amount of energy, a large number of U^{235} nuclei have to be split. This happens when neutrons released from a split U^{235} nucleus go on to fission other U^{235} nuclei. This reaction produces additional neutrons, which cause more fissions, which release still more neutrons to cause even more fissions, which release even more neutrons, and so on. The result is known as a chain reaction.

Nuclear Fission and Nuclear Chain Reactions

An uncontrolled chain reaction releases large amounts of energy quickly. This kind of chain reaction allows nuclear weapons to create large explosions. A controlled chain reaction releases energy more slowly and steadily. Nuclear power plants are designed to produce controlled chain reactions that release steady amounts of energy for producing electricity.

The average concentration of uranium in ore mined from Earth is about 0.11 percent; the rest of the ore is made up of other minerals. Of the total amount of uranium, 99.3 percent is U^{238} and 0.7 percent is U^{235}.

A chain reaction is not possible with such low concentrations of U^{235}, so the percentage of U^{235} needs to be increased. This is done by first using chemical processes that remove the uranium from the ore after mining, and then increasing the percentage of U^{235} in the uranium using a process called enrichment. In nuclear power plants, a mixture of three percent U^{235} and 97 percent U^{238} is used to produce controlled chain reactions. To produce uncontrolled chain reactions like those that occur in nuclear explosions, a mixture of 90 percent U^{235} and ten percent U^{238} is used.



Comparing the Energy from Combustion and from Nuclear Fission

The energy released by nuclear fission is much larger than the energy released by burning wood or fossil fuels such as coal, oil, and natural gas. For instance, one pound (.45 kg) of uranium with three percent U^{235} —the mixture used in nuclear power plants—has an amount of energy equal to about 41 tons (36.9 metric tons) of bituminous coal, 8,300 gallons (31,5401 liters) of gasoline, or 87 tons (78.3 metric tons) of wood.

Why is the energy from nuclear fission so much greater than from burning wood or fossil fuels? The nuclear bonds holding the neutrons and protons in the nuclei together are much, much stronger than the chemical bonds that hold the molecules in wood and fossil fuels together. The stronger the bonds, the more energy is stored in them. In addition, breaking nuclear bonds changes a small amount of the mass in a uranium nucleus into energy. Therefore, the nuclear energy stored in a uranium nucleus is much greater than the chemical energy stored in wood and fossil fuel molecules.

Nuclear Fission and Nuclear Chain Reactions

Questions

1. Two isotopes of the element carbon are carbon-12 (C^{12}) and carbon-14 (C^{14}). In what ways are the carbon isotopes the same? In what ways are they different?

2. Using marbles to represent protons and neutrons, describe what happens when a neutron splits a U^{235} nucleus.

3. Explain how energy is obtained from nuclear fission.

4. Why is a chain reaction needed to produce large amounts of energy from nuclear fission?

5. Why might a uranium mixture of 60 percent U^{235} and 40 percent U^{238} not be suitable for use in a nuclear power plant?

6. How many pounds of uranium are in one ton (2,000 pounds) of uranium ore? How many pounds of U^{235} are in one ton of uranium ore?

7. Why is the energy produced by nuclear fission of uranium so much greater than the energy produced by burning wood?

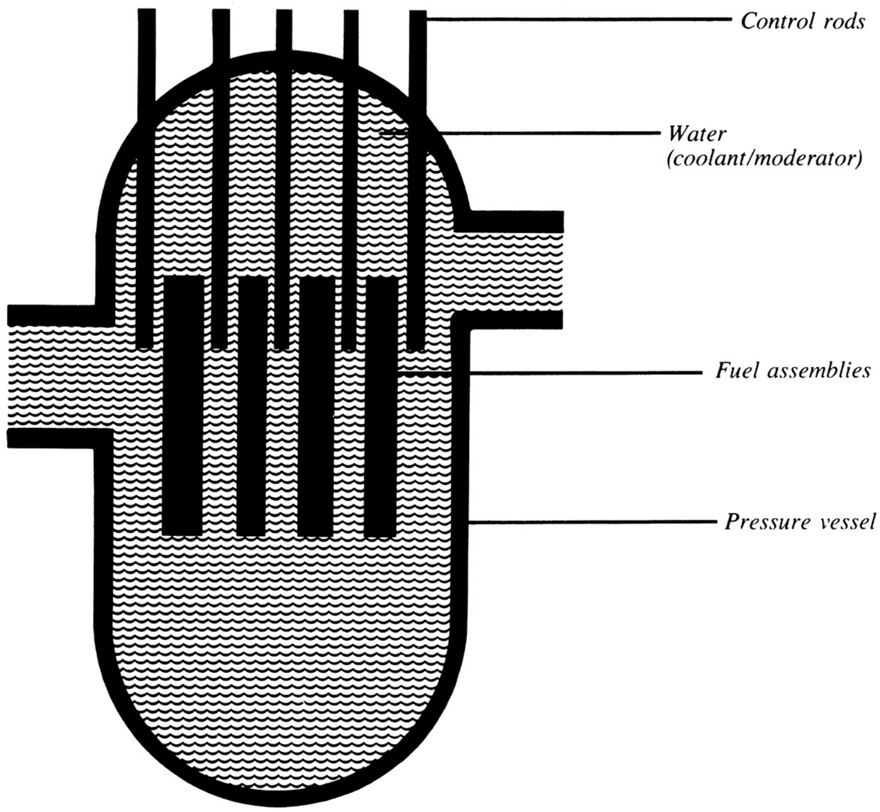
How a Nuclear Power Plant Operates

Introduction

Nuclear power plants, like power plants that burn fossil fuels, produce electricity by first boiling water to produce steam. The main difference between a nuclear power plant and other kinds of power plants is that at a nuclear power plant, the heat used to make the steam is produced by fissioning atoms, not by burning fossil fuels.

Nuclear Reactors

At a nuclear power plant, fission takes place in the reactor. The reactor is basically a machine that heats water. A reactor has four main parts:
(1) the uranium fuel assemblies;
(2) the control rods;
(3) the coolant/moderator; and
(4) the pressure vessel. The fuel assemblies, control rods, and coolant/moderator make up the reactor's core. The core is surrounded by the pressure vessel.



The Fuel Assemblies

Uranium made up of a mixture of three percent U^{235} and 97 percent U^{238} is the fuel used in a nuclear power plant. But we cannot just throw uranium into the reactor the way we can shovel coal into a furnace. Uranium must be enriched and formed into fuel pellets that are about the size of your fingertip. The fuel pellets are then stacked into hollow metal tubes called fuel rods, which keep the pellets in the proper position.

Each fuel rod contains about 200 fuel pellets and is 12 to 14 feet (3.6 to 4.2 m) long. However, a single fuel rod cannot generate the heat needed to make a large amount of electricity. So fuel rods are carefully bound together in fuel assemblies, each of which contains about 240 rods. The assemblies hold the fuel rods apart so when they are submerged in the reactor core, water can flow between them.

The Control Rods

Another important part of the reactor are the control rods. They are inserted from the top of the reactor core, and slide up and down between the fuel rods or fuel assemblies in the reactor core. Control rods regulate or control the speed of the nuclear reaction. These rods contain materials such as cadmium and boron. Because of their atomic structure, cadmium and boron absorb neutrons, but do not fission. The control rods work like

How a Nuclear Power Plant Operates

sponges by absorbing extra neutrons. When the control rods absorb neutrons that could otherwise hit uranium atoms and cause them to split, the chain reaction slows down.

The temperature in the reactor core is carefully monitored and controlled. When the core temperature goes down, the control rods are slowly lifted out of the core, and fewer neutrons are absorbed. Therefore, more neutrons are available to cause fission. This releases more energy and heat. When the temperature in the core rises, the rods are slowly lowered and the energy output decreases because fewer neutrons are available for the chain reaction. To maintain a controlled nuclear chain reaction, one neutron from each U^{235} atom that splits will cause another U^{235} atom to fission, while other neutrons are absorbed. Therefore, the number of fissioning atoms stays constant.

Temperature changes in the core are usually gradual. But if monitors detect a sudden change in temperature, the reactor would immediately shut down automatically by dropping all the control rods all the way into the core to absorb neutrons. A shutdown of this type takes only a few seconds and stops the nuclear chain reaction. This shutdown happens because the neutrons necessary to keep a chain reaction going are absorbed by the control rods.

The Coolant/Moderator

A third essential part of the reactor is the coolant/moderator. At most nuclear power plants in the United States, the coolant/moderator is nothing more than purified, treated water. Any material used for cooling is called a coolant. In nuclear power plants, the cooling water is also used to move the reactor's heat to places where it can be used to generate electricity. If the reactor is not cooled, the heat inside could damage the core. So it is necessary always to have coolant in the reactor core to keep it from getting too hot.

A moderator is a material that slows down neutrons. Just as a ball is more likely to be caught when it is thrown softly, neutrons are more likely to be captured and cause fission in U^{235} atoms when they are not moving too fast. Water is a moderator because it slows down the neutrons. Using water as the moderator allows enough neutrons to be captured by the uranium to permit a chain reaction to occur.

The Pressure Vessel

The fourth part of the reactor is the pressure vessel. The pressure vessel is enormous. Its walls are 9 inches (22.5 cm) thick, and it often weighs more than 300 tons (270 metric tons). The pressure vessel surrounds and protects the reactor core. It provides a safety barrier and holds the fuel assemblies, the control rods, and the coolant/moderator. The pressure vessel is located inside the containment building, which is made of thick concrete reinforced with thick steel bars.

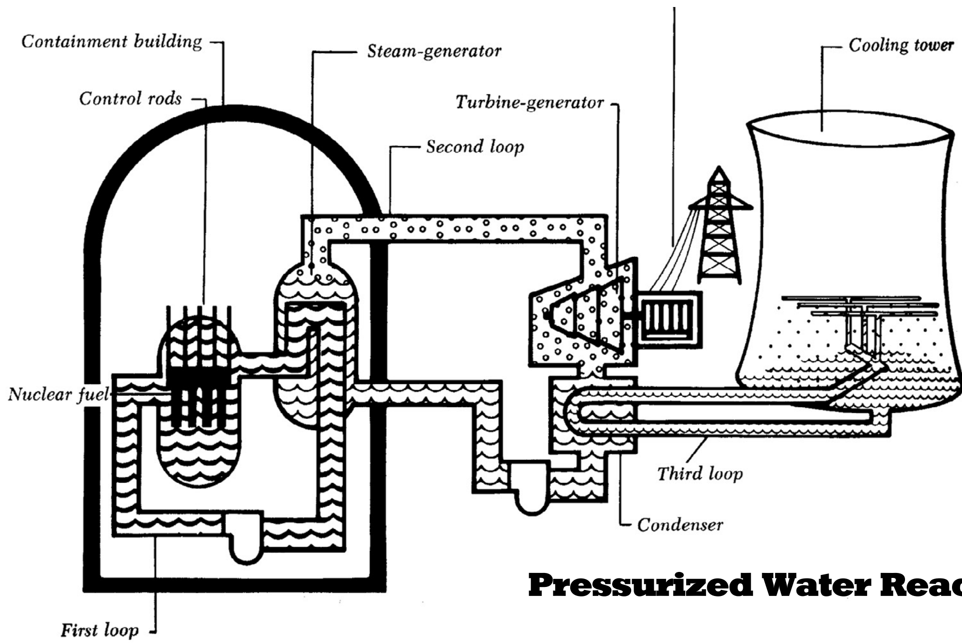
How a Nuclear Power Plant Produces Electricity

The reactor in a nuclear power plant converts nuclear energy into thermal energy (heat). The purpose of the other parts of the nuclear power plant is to convert the thermal energy produced by the reactor into electrical energy.

Because of the heat produced by the fission reaction, the coolant/moderator water that is circulated through the core becomes extremely hot. Generally, when water reaches 212 degrees F (100°C), it boils and turns into a gas called steam. Gas takes up more space than liquid. But inside certain kinds of reactors, there is only a limited amount of space, and the water cannot turn into steam. As a result, the water is under pressure, and it can be heated to 600 degrees F (316°C) and still remain a liquid. Because the water in the core is under enough pressure to remain a liquid, this type of reactor is called a pressurized water reactor, or PWR.

Pressurized water reactors have three separate systems of pipes, or loops, for moving heat. Water in these loops never mixes together. However, heat energy from one loop moves to another. In the first loop, pressurized water is

How a Nuclear Power Plant Operates



Pressurized Water Reactor

pumped through the reactor and then moved through extremely strong pipes that lead to several steam generators.

Inside the steam generators, the coolant/moderator water in the first loop flows through hundreds of pipes. Water from the second loop flows around these pipes. The first loop carries water that is 600 degrees F (316°C). Because heat flows away from heated surfaces toward cooler surfaces, the heat in the first loop transfers to the second loop. When water in this second loop takes on the heat from the first loop, it turns to steam. This is because water in the second loop is under less pressure.

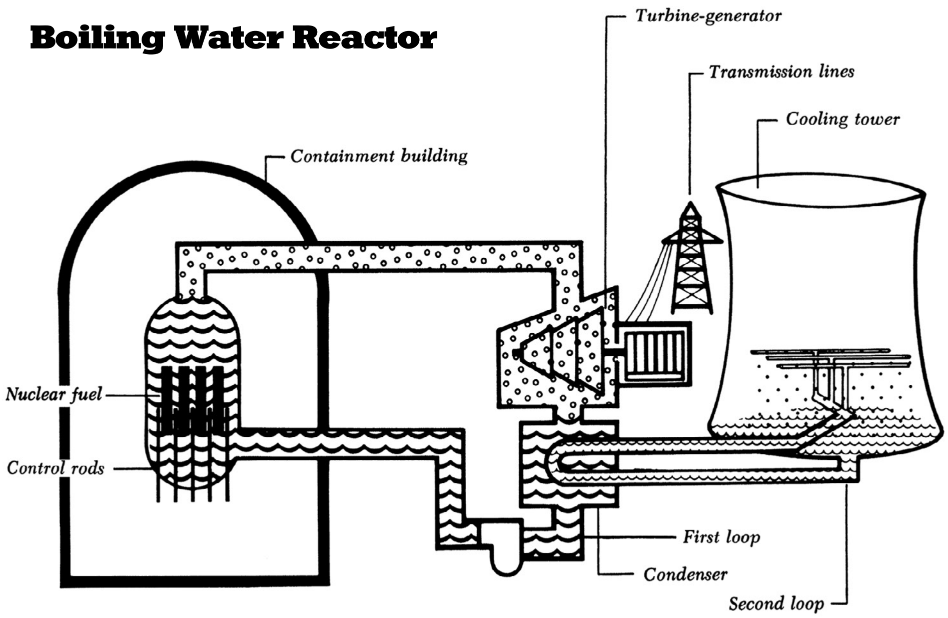
The second loop carries the steam to the turbine. A turbine is basically a pinwheel with many blades that are spun by steam. At power plants, turbines are attached to generators, which change the mechanical energy of the spinning turbine into electrical energy.

After turning the turbine, the steam in the second loop has lost most of its heat energy. It is cooled and turned back into water so that it can be used again in the second loop. This operation takes place in the condenser, which is located under the turbine. In the condenser, the steam in the second loop transfers some of its heat to the third loop. Again, heat is transferred from a heated substance to a cooler one. The third loop contains cooling water drawn from a large body of water such as a large river, lake, or ocean. The purpose of the third loop is to remove heat from the steam in the second loop. This heat is removed by placing the heated water back into the river, lake, or ocean. In cases where heated water may adversely affect the river or lake environment, or if a large body of water is not available, the heat is dissipated into the air by using large cooling towers.

Another common type of light water reactor is the boiling water reactor, or BWR. The main difference between a PWR and a BWR is that PWRs have three loops, while BWRs only have two loops. BWRs do not have steam generators. Instead, the water in BWRs boils inside the pressure vessel, and the steam is used directly to turn the turbine. In BWRs, the control rods come from the bottom instead of the top. It is important to remember that in both a PWR and a BWR, the water from one loop never mixes with water from another loop. Only the heat is transferred.

How a Nuclear Power Plant Operates

Boiling Water Reactor



Nuclear Power Plant Safety

The new elements formed in the nuclear reactor due to fission are radioactive and therefore potentially dangerous to human health. Preventing their release to the public is the most important part of reactor safety. Because of the danger that could result from overheated uranium fuel, there is great concern about the possibility of an accident in which coolant is lost. This is known as a loss of coolant accident, or LOCA. To handle a LOCA, reactors are designed to work in the following ways:

- The temperature of the uranium fuel is kept well below its overheating point.
- In PWR and BWR reactors, the coolant is the moderator (water), so any loss of coolant also means a loss of moderator. If the moderator is not there to slow the neutrons down, they cannot continue the chain reaction. When the reaction stops, heat is reduced.
- The control rods automatically move into place to absorb neutrons and stop the chain reaction when any abnormal situation is detected.
- An emergency core cooling system (ECCS) turns on to replace lost coolant by rapidly injecting cooling water.
- The reactor building itself (the containment structure) is designed to withstand high pressure inside and to contain the energy released during a LOCA from steam and hot gases.

Accidents have occurred in nuclear power plants in the United States, the most widely publicized one being the LOCA at the Three Mile Island (TMI) power station on March 28, 1979. The TMI accident seems to have been due to a faulty valve, a design error in a water level indicator, and human error. But the control rods did automatically shut down the chain reaction, or “scram” the reactor; the emergency core cooling system (ECCS) also operated as planned. The results were a damaged reactor core and a small release of radioactive gases into the atmosphere.

The accident at TMI did nothing to end the nuclear debate. Opponents of nuclear power said that TMI proved that nuclear technology is fundamentally unsafe and unsound. Advocates of nuclear power replied that the accident showed that even when a great deal goes wrong, a nuclear reactor’s redundant safety systems prevent the loss of control.

How a Nuclear Power Plant Operates

Questions

1. Explain how a nuclear reactor converts nuclear energy into electricity.

2. Give two reasons why the fuel assemblies hold the fuel rods apart.

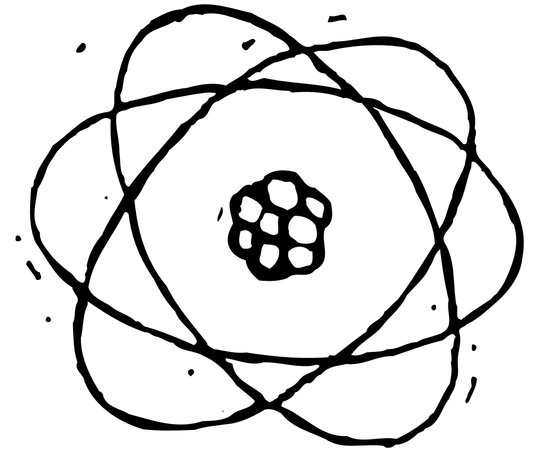
3. Compare the three-loop system of the pressurized water reactor (PWR) to the two-loop system of the boiling water reactor (BWR). Suggest advantages and disadvantages of using each system.

4. How is a nuclear reactor designed to keep uranium fuel from overheating?

5. Suppose a problem occurs in which some of the control rods in the reactor get stuck and won't go into the core when they are supposed to. The rest of the control rods are working properly but are only in the core part way. What can be done to keep the uranium fuel from overheating?

6. Using everyday objects, design or build a model of a nuclear reactor that includes fuel assemblies, control rods, a coolant/moderator, and a pressure vessel. (Hint: a coffee can could be used to represent the pressure vessel.) Use the model you designed or built to explain to the class how a nuclear reactor works.

Facts about Nuclear Energy



Introduction

A recent revival on the energy scene, nuclear energy is associated with the promise of vast quantities of energy. It is also associated with health issues and environmental problems due to radiation and nuclear waste disposal. Despite the controversy surrounding it, nuclear energy supplies a significant amount of electricity for Wisconsin, the United States, and the world.

Uranium

Mineral ores contain uranium in the form of uranium oxide. Two types of uranium atoms, called isotopes, are found in these ores: uranium-235 (U^{235}) and uranium-238 (U^{238}). Of these two, only U^{235} can undergo nuclear fission. However, 99.3 percent of naturally occurring uranium is U^{238} while only 0.7 percent is U^{235}.

Generally, foreign ores have a higher uranium content than those found in the United States. Ores found in the United States contain from 0.05 to 0.3 percent pure uranium. The uranium content of foreign ores ranges from 0.035 percent in southern Africa to 2.5 percent in northern Saskatchewan, Canada.

Nuclear Fission

Nuclear energy can be obtained by a process called nuclear fission (or simply "fission"). Fission occurs when a neutron splits the nucleus of a U^{235} atom into two smaller nuclei, releasing energy and additional neutrons. The extra neutrons then split other U^{235} nuclei, releasing still more neutrons that split more U^{235} nuclei, and so on. This process is called a nuclear chain reaction.

A nuclear chain reaction cannot take place using naturally-occurring uranium. Nuclear power plants use fuels with a mixture of 3 percent U^{235}; this fuel is produced from natural ores by an enrichment process. Nuclear fuel can produce immense amounts of energy. One kilogram of U^{235} can produce two to three million times the energy of one kilogram of coal.

Nuclear Power Plants

In a nuclear power plant, energy from nuclear fission is produced in the reactor. A nuclear reactor is made up of the fuel assemblies, control rods, a moderator, a cooling tower, and the pressure vessel.

The fuel assemblies, control rods, and cooling system make up the reactor's core. U^{235} in the fuel assemblies undergoes fission, releasing neutrons and large amounts of heat. Control rods are moved up and down between the fuel assemblies to absorb some of the neutrons, thereby regulating the rate of fission. A moderator, such as graphite, slows down the neutrons so that the fission reaction is more efficient. A coolant circulates through the reactor's core to remove the heat so that it can be used to make steam in another part of the plant. The steam spins a turbine connected to a generator that produces electricity.

The core is surrounded by the pressure vessel, which is located inside the containment building, a structure made of thick concrete reinforced with steel bars.

A special type of nuclear reactor called a fast breeder reactor converts U^{238} into plutonium (Pu^{239}) while also

Facts about Nuclear Energy

producing electricity. Because plutonium is fissionable, breeder reactors could greatly increase the amount of usable nuclear fuel. Breeder reactor projects were once considered in Germany, the United Kingdom, Japan, and the United States but research has since been discontinued due to the extreme risk in extracting plutonium and the cost of developing the reactors.

Electricity Production

There were 61 nuclear power plants with 99 reactors located in 30 states in 2016. Combined they produced 805.3 kWh of electricity in the United States in 2016, close to 20 percent of the nation's electricity. Nuclear power plant construction ceased in the late 1990's, but has rebounded and several new power plants are ordered and at the same time many existing plants have been extended to continue operations.

The United States has more nuclear capacity than any other country in the world. France has the second, Russia the third, and South Korea the fourth. In 2016, 63 reactors are under construction in 15 countries throughout the world, mostly in the Asian region. Nuclear power capacity worldwide has been increasing steadily.

Wisconsin utilities currently have two nuclear power units, both at Point Beach in Two Rivers, Wisconsin. These units produce about one-sixth of all electric power in Wisconsin. There are now 444 operable civil nuclear power reactors around the world.

Uranium Reserves

Uranium reserves are described in terms of how much it costs per pound to mine the ore. Ores with a high concentration of uranium cost less to mine than those with low concentrations. The U.S. Department of Energy estimates that there were about 66 million pounds of $30 per pound uranium reserves and 362 million pounds at up to $100 per pound uranium reserves in the United States in 2015. (Plutonium from decommissioned weapons can also be used as a nuclear fuel).

U.S. uranium deposits in 2014 were over 207,400 tons of uranium, which is 4 percent of the world reserves. Wisconsin, however, has no known reserves. Other countries with major reserves include Australia, Kazakhstan, Canada, Russia, and South Africa.

Mining and Processing Uranium

Most uranium ore is mined using surface mining, also called "open mining." At a mill near the mine the ore is crushed and ground and the uranium oxide is chemically extracted. This yields uranium concentrate, also referred to as yellowcake. The ore, rocks, and soil left over after mining and milling are called tailings. The tailings contain radioactive materials and must be buried.

Other types of mining include underground mining, in situ leach (ISL) mining (where fortified groundwater is pumped into the aquifer, dissolving the uranium from the host sand), and heap leaching.

Trucks or trains then ship the uranium concentrate to a chemical plant where it is converted into a gas. This gas is then enriched, which increases the amount of U^{235} in the uranium mixture from 0.7 percent to 3.5-5 percent.

After enrichment, the gaseous uranium compound is converted into ceramic fuel pellets. The pellets, which are the size of a fingertip, are sealed inside metal tubes called fuel rods. Each 12- to 14-foot fuel rod contains about 200 pellets. Fuel rods are bound together in assemblies, each containing about 240 rods. Trucks or trains transport finished fuel assemblies to a nuclear power plant.

Facts about Nuclear Energy

Other Uses

Nuclear energy is widely used in the military to power submarines and aircraft carriers. Nuclear power plants aboard naval vessels offer great reliability and allow ships and submarines to sail for long periods of time without refueling. Nuclear weapons use U^{235} or plutonium to produce nuclear explosions. Nuclear energy also has important uses in medical diagnosis and treatment.

Effects

Nuclear energy has some important benefits. Because large amounts of energy can be obtained from a small amount of U^{235}, some of the environmental effects of mining uranium for energy are not as great as they are for coal. Also, nuclear power plants do not produce air pollutants or release carbon dioxide (a cause of global climate change) into the atmosphere. Some experts believe that nuclear energy is better able to meet the world's growing demand for energy than fossil fuels or renewable energy resources.

The main disadvantage of nuclear energy is that uranium and the waste materials produced from nuclear fission are radioactive. Radioactive materials emit alpha and beta particles and gamma rays, which can harm living cells. Radioactive materials are present in the mining, production, and transportation of nuclear fuel; in the operation of nuclear power plants; and in nuclear waste. Transportation is one of the most serious concerns related to nuclear energy use. After the fuel is mined, it needs to be transported to the plant and after the fuel is spent, it is transferred to the storage site. Transporting the fuel many miles to a permanent storage site adds even more risk and complications. On a global scale, there is fear associated with countries exporting and importing fuel by sea and by air. All these operations must be designed and managed to protect the environment from the release of radioactive materials. This often requires expensive and complex technology.

Although nuclear power plants are designed with many safety protocols to prevent releases of radiation, accidents at the Three Mile Island power plant in the United States in 1979 and the Chernobyl plant in the Ukraine in 1986, as well as the Fukushima plant in Japan in 2011, increased public concern about their safety. Safer nuclear reactors have been designed and tested, and are being put into use today.

Radioactive waste is classified as one of the following: Exempt waste; very low-level waste, low-level waste, intermediate-level waste, or high level waste. Low-level waste, for example, contains a small amount of radioactivity within a relatively large amount of material. These wastes include tools, equipment, and protective clothing exposed to radioactive materials. They must be stored in steel drums and buried for several decades until their radioactivity decreases to a safe level. The U.S. government has burial sites for low-level wastes in Barnwell, South Carolina; Richland, Washington; Clive, Utah; and Andrews, Texas.

Nuclear fuel from power plants is an example of a high-level waste. These wastes are extremely hazardous and must be safely stored for thousands of years until their radioactivity decreases to a safe level.

New research in reusing radioactive wastes is being conducted. It may be feasible at some point in time to remove the uranium, plutonium, and minor actinides for recycling in a fast breeder reactor. Currently, however, this recycling of radioactive wastes is not available on a commercial scale.

In the U.S., no permanent storage site for high-level waste exists. Currently, all nuclear power plants in the U.S. store their spent nuclear fuel in steel-lined concrete pools. These are temporary facilities near the plant; some of which are nearly full. Storing wastes deep underground is the option most likely to be used in the near future. The wastes would be sealed in metal canisters and buried about half a mile underground in a

Facts about Nuclear Energy

location where earthquakes do not occur and contact with groundwater is avoided. (However, it is difficult to predict whether an underground site will be geologically stable for thousands of years). Yucca Mountain in southern Nevada has been the leading candidate for a permanent disposal site since the 1980s. Studies of the area have been conducted to ensure the repository would be safe and environmentally sound for a one-million-year period of waste isolation. No final decision has been made about use of the site as of 2017.

Outlook

Nuclear energy has some important benefits. Because large amounts of energy can be obtained from a small amount of U^{235}, some of the Reserves of uranium will last for the projected lifetimes of the world's current nuclear power plants. Because only a small fraction of uranium is U^{235} (0.7 percent), uranium reserves are only thought to be enough to last about 90 years. However, new technologies could potentially extend this outlook past 200 years supply.

The expense and complexity of nuclear power plants and concerns about radiation exposure, disposal, and long-term safe containment of nuclear wastes have led many people to oppose nuclear energy. On the other hand, nuclear energy does not add pollutants or carbon dioxide to the atmosphere. It can also meet the world's growing demand for energy. Nuclear energy will continue to be used to produce electricity in the near future, but its long-term fate is somewhat uncertain.

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Nuclear Power Plant Diagram