Radiation in Science

The uses of radiation in science and research are many and varied. Here are a few examples to consider.

Radiocarbon Dating

All living things have some radioactive carbon-14 in them. Because living things no longer take in carbon-14 when they die, we can measure the amount left in substances that once were living, such as wood, and figure out when the living thing died. Archaeologists and paleontologists use this measurement in their studies.

This technique, called *radiocarbon dating*, also is used in environmental studies to learn how Earth's climate has changed in the past and to help researchers predict how the global climate might change in the future. The carbon-14 technique is an essential tool in many fields including atmospheric science, oceanography, geology, and climatology.

Space Exploration

The Mars rover *Sojourner* used alpha particles to identify chemical elements in Martian rocks. An instrument on the rover bombarded selected rocks with alpha particles, then read the X-rays generated from the rocks. Because each chemical element produces a distinctive X-ray, the instrument could determine the composition of the rocks.

On many spacecraft, heat produced by the natural radioactive decay of plutonium (a metallic, heavy element) is converted to electricity to power the craft's onboard scientific instruments. This type of electrical power supply has been used in several U.S. space missions including *Viking* to Mars, *Voyager* and *Pioneer* to the outer planets, *Galileo* to Jupiter, and *Cassini* to Saturn.

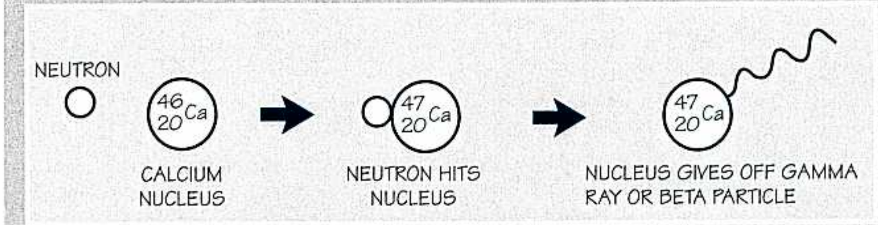
Neutron Activation

Shooting neutrons into stable atomic nuclei can make them radioactive, a process called *neutron activation*. When nuclei are activated, they get rid of the extra energy by giving off a beta particle or gamma ray.

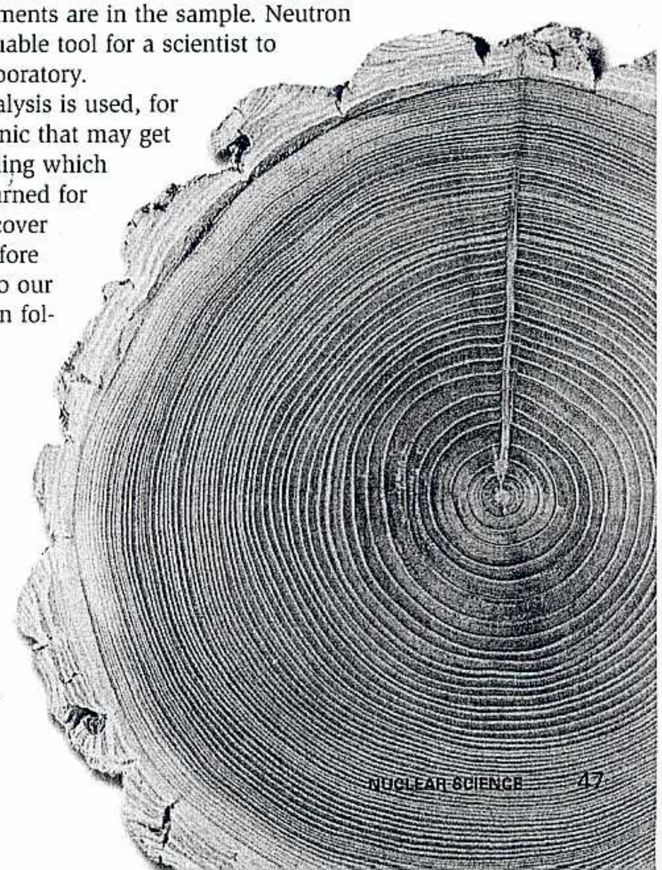
Gamma rays are not all alike. Some have more energy than others. The gamma ray given off from neutron activation of a calcium nucleus is different from a gamma ray given off from neutron activation of a gold nucleus. By looking for the gamma ray or beta particle that comes off from a sample, a scientist can tell which elements are in the sample. Neutron activation analysis is a valuable tool for a scientist to identify materials in the laboratory.

Neutron activation analysis is used, for example, for detecting arsenic that may get into fish we eat, or for finding which elements are in the coal burned for electric power. We can discover heavy metals in sewage before releasing the pollutants into our environment. Ecologists can follow the movement of tiny amounts of insecticides in the environment.

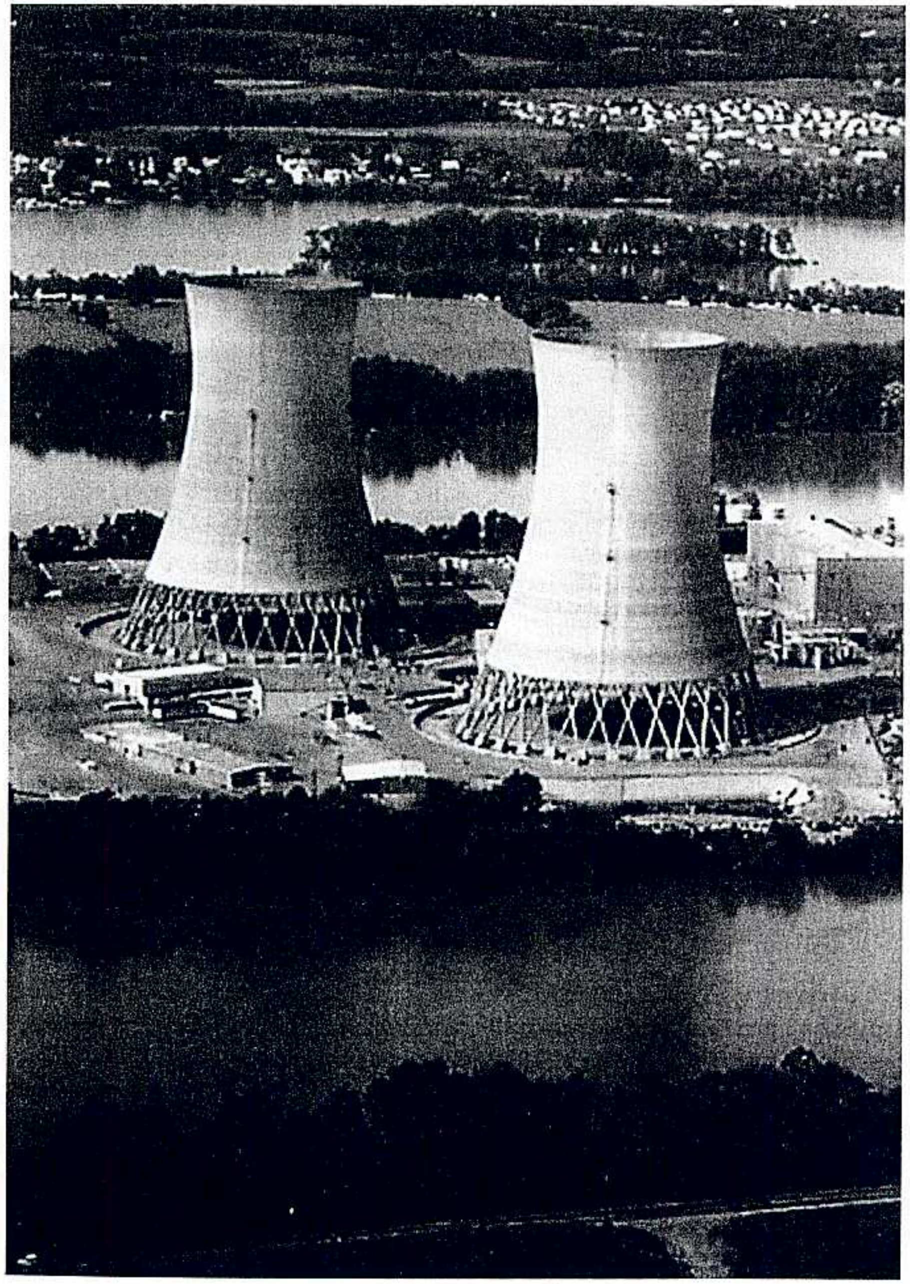
A single atom surrounded by a million others can be identified by neutron activation analysis—an extremely sensitive procedure. If you put 1/40 of a gram of salt in a gallon of water, you couldn't taste the salt. But neutron activation analysis could find it.



Elements can be identified by the radiation "fingerprint" they give off. (Atoms can be drawn in many ways. This pamphlet uses the form shown here, a circle with the symbol of the element, mass number, and atomic number. Electrons may or may not be shown. Electrons do not play an active part in nuclear reactions.)



Neutron activation allows scientists to measure the pollution that was in the air decades ago, when this tree was alive and growing.



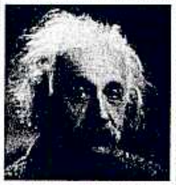
Splitting Atoms: Nuclear Energy

Almost everyone has heard of Albert Einstein's famous equation, $E = mc^2$. The equation is a short way of saying that matter can be changed to energy. To find out how much energy (E) you get from a mass of matter (m), you multiply by the speed of light squared (c^2).

If you do the math, you get a very big number because *c* is a very big number. The speed of light is 30,000,000,000 (30 billion) centimeters per second. If you square this number (multiply *c* times *c*), you get 900,000,000,000,000,000,000 (900 billion billion). So, how much energy do you get from changing matter into energy? One gram of mass (one dime) will make 900 billion billion *ergs* of energy. That is equal to the energy from about 700,000 gallons of gasoline.

In the early 20th century, however, Einstein's equation was not fully verified. No one yet knew how to convert mass to energy. The ideas and work of many other scientists would be needed to show how to do it.

An *erg* is a small amount of energy. A burning match will produce 10 million ergs.

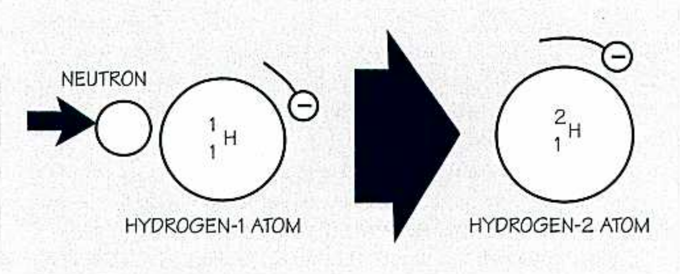


Albert Einstein (1879–1955), born in Germany, became interested in physics as a child playing with his father's compass. In 1905 at age 26, Einstein earned a doctorate and published four groundbreaking theories. His theory that light exists in "packets," or *photons,* won him a 1921 Nobel Prize. His special *theory of relativity* added time as a fourth dimension and controversially claimed that time and distance are relative to the observer. He also published his famous equation, $E = mc^2$, which explains that matter and energy are different forms of the same thing. At the end of his life, Einstein tried to create a *unified field theory* that would link together everything from subatomic particles to the universe as a whole. Today, some physicists still pursue Einstein's vision of a unified theory.

Neutrons as Atomic Bullets

By the 1930s, new discoveries were leading researchers in promising new directions. After James Chadwick discovered the neutron in 1932, scientists began shooting neutrons like bullets into atomic nuclei. The results of these collisions told researchers much about the properties of the nuclei.

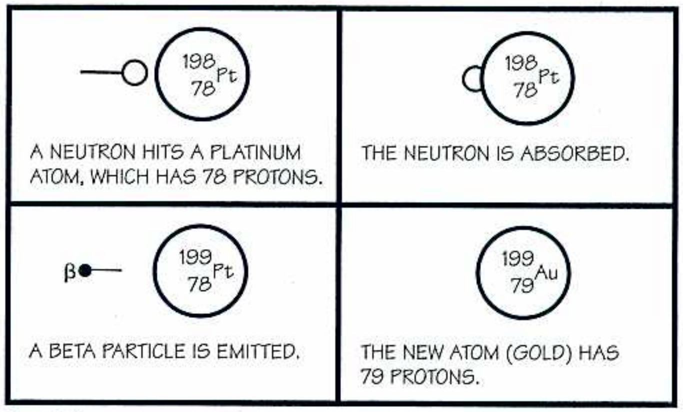
Two things can happen to an atom hit by a neutron. One possibility is that it will add one unit to the atom's mass number. When a neutron is added to the nucleus, the atomic number stays the same; only the mass number is changed.



A neutron can add one unit to an atom's mass number.

Sometimes, the neutron breaks down as it hits an atom. The breakdown produces a proton, which remains in the nucleus, and an electron (a beta particle), which flies out.

The second thing, therefore, that can happen to a nucleus when a neutron hits it is that it will give off a beta particle and the nucleus will now have one more proton than before. This adds one unit to the atomic number. If the atom gives off a beta particle after catching a neutron, one unit will be added to the mass number and one unit will be added to the atomic number, changing the atom into a new element. Enrico Fermi found that if you shoot an atom with a neutron, when the beta particle comes out, the atom always changes into the next heavier element.



By adding a proton, elements can be changed into different elements. The transformation of one element into another by a nuclear reaction is called *transmutation*.

What if you hit the heaviest known element, uranium, with a neutron? You could make a new, even heavier element. Fermi tried it. The uranium (element 92) disappeared, but no new element 93 could be found. Where did it go? What was going on?

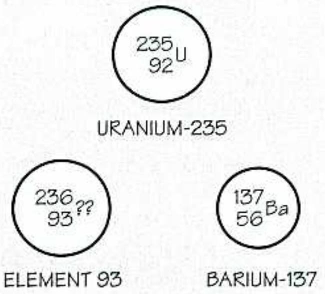
Enrico Fermi (1901–1954) was born in Italy and came to the United States to teach. He won the 1938 Nobel Prize in physics for discovering nuclear reactions set off by neutrons. In 1942, on a squash court at the University of Chicago, he conducted an experiment that led to the first controlled nuclear reaction and the start of the Atomic Age. Fermi became a leader among the physicists who worked on the Manhattan Project, the name given to the project created by the U.S. government in 1942 to develop the atomic bomb.

Splitting the Atom

In 1934, Fermi was trying to make element 93. When he shot neutrons into uranium, he got beta particles, as he expected. But when he tested for atoms of element 93, none were found.

In Germany, Otto Hahn and Lise Meitner worked on Fermi's problem. In 1938, Meitner left Germany because of political oppression. Fritz Strassmann joined Hahn, and they kept working. They continued shooting neutrons into uranium and looking for a new element about as heavy as uranium.

What they did find looked like barium. But uranium atoms have an atomic mass of around 238. The new element should be about the same mass. Barium is far too light, with a mass of 137. For uranium to change to barium, the uranium nucleus would have to break into large pieces.



Researchers looked for element 93 but found barium, which was too small to have come from uranium unless the uranium nucleus split when hit by a neutron.

Hahn and Strassmann wrote to Lise Meitner about their research. She concluded that when uranium is hit with a neutron, it must break in half. Dr. Meitner cowrote a paper on this idea in 1939. An American biologist, William Arnold, read the paper and decided to call the splitting of atoms *fission*—the word biologists used for the splitting of cells.

Lise Meitner (1878–1968) of Austria codiscovered the 91st element, protactinium, with Otto Hahn in Berlin in 1918. Her continued work with Hahn (and another scientist, Fritz Strassmann) led to the 1938 discovery of nuclear fission, the process by which an atom splits, releasing tremendous amounts of energy. Fission was later used in World War II to produce the atomic bomb, but Meitner refused to contribute to the creation of nuclear weapons. Element 109 was named meitnerium in her honor.

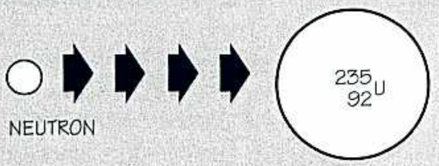
Otto Hahn (1879–1968) of Germany received a doctorate in chemistry and, working under Ernest Rutherford, discovered a new radioactive substance called radioactinium. In 1907, he began 30 years of research with Lise Meitner. Their work, with that of Fritz Strassmann, led to the discovery of nuclear fission, which won Hahn the 1944 Nobel Prize in chemistry. He campaigned against the use of fission to produce nuclear weapons.

Ernest Lawrence (1901–1958), born in South Dakota, taught physics at Yale, then took a job at the University of California at Berkeley. He invented the cyclotron, a circular type of particle accelerator that speeds up nuclear particles. This device later was used in cancer treatments and won him the 1939 Nobel Prize in physics. Lawrence made important contributions to the Manhattan Project, but he later discouraged atomic bomb testing.

Glenn T. Seaborg (1912–1999), born in Michigan, earned a doctorate in chemistry and taught at the University of California at Berkeley. Seaborg codiscovered plutonium, the element used to fuel some nuclear reactors and to make nuclear weapons. In 1951, the former Scout won the Nobel Prize for understanding the chemistry of plutonium and the nearby elements. With colleagues, he identified 10 new elements and more than 100 isotopes of different elements. From 1942 to 1946, he headed the Manhattan Project's plutonium research. Element 106 was named seaborgium in his honor.

How Fission Works

1. A neutron hits a uranium nucleus.



2. The nucleus stretches and bends.

3. The nucleus breaks, releasing two smaller parts called fission fragments, along with neutrons and lots of energy.

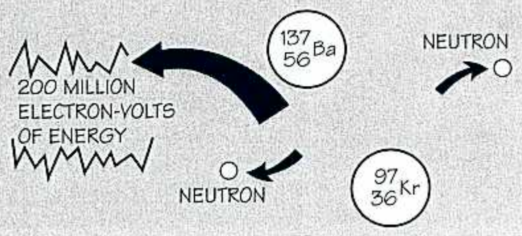


Diagram Nuclear Fission
Your drawing of nuclear fission should show the incoming neutron, the nucleus it hits, the nucleus splitting, and what is released: fission fragments, neutrons, and lots of energy.

Some atoms other than uranium-235 can be fissioned. Plutonium also can be split for energy.

Chain Reaction

Fission would not be useful for producing energy if we had to shoot each nucleus with a neutron to break it. That would use more energy than it would produce.

But each fission releases extra neutrons. These neutrons can be used to split other nuclei.

Fermi found that with the element he was using—uranium—slow neutrons hit nuclei better than fast ones did. Fermi used *moderators* to slow down the neutrons.

In December 1942, Fermi and a group of other scientists completed the first atomic *pile.* This was a stack of blocks of graphite containing uranium in carefully spaced lumps. The graphite was the moderator. Rods of cadmium in the pile soaked up neutrons before they could hit the uranium. These *control rods* kept the reaction from starting. Then, when the experiment ended, the rods would be used to stop the reaction.

Slowly, one by one, the rods were pulled out. The reaction started and then went faster and faster. The *chain reaction* was continuing on its own. Neutrons from one fission were causing more fissions. The world had entered the nuclear age.

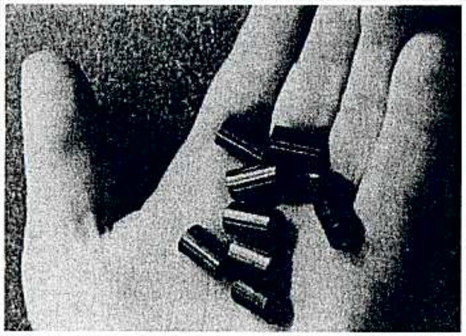
The stack of blocks Fermi used was called a nuclear pile. Modern devices for hosting chain reactions are called *nuclear reactors.* A *critical mass* of nuclear fuel is necessary to sustain a chain reaction. Too little fuel produces too few neutrons to keep the fissions going.

Neutrons are best slowed by low-mass atoms such as hydrogen, deuterium, or carbon (graphite). These make the best moderators.

Modern Nuclear Reactors

Today's nuclear reactors look much different from Fermi's pile of graphite, uranium, and cadmium, but the principles on which they work are the same. Reactors are used to produce and control nuclear energy. The energy released by splitting nuclei creates large amounts of heat. This heat can be used to make steam, and the steam spins turbines to generate electricity.

The energy in one uranium fuel pellet—the size of the tip of your little finger—equals the energy in 17,000 cubic feet of natural gas; 1,780 pounds of coal; or 149 gallons of oil. In American reactors the fissionable fuel is uranium-235 (U-235), a scarce isotope of uranium. U-235 is the only natural material that nuclear reactors can use to produce a chain reaction. Nuclei of the much more abundant U-238 isotope usually absorb neutrons without splitting.



A fuel rod consists of pellets of fuel inside a metal tube. Each of these uranium pellets has nearly the same energy as a ton of coal.

The reactor's *core* contains rods of nuclear fuel inside a tanklike structure called the reactor vessel. Control rods containing neutron-absorbing materials such as cadmium are pushed into the core or pulled out to slow down or speed up the chain reaction. The control rods also are part of the safety systems that prevent the chain reaction from going too fast.

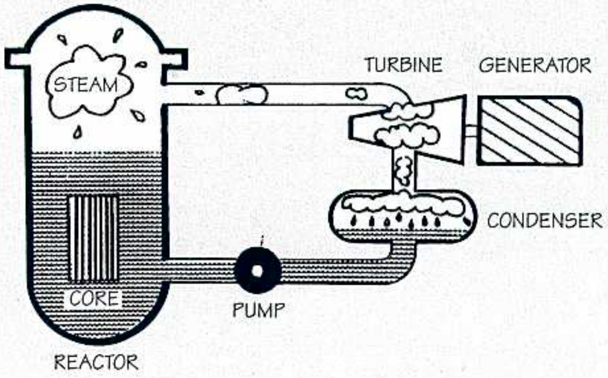
The moderator fills the spaces between the fuel rods. Most of today's nuclear reactors use water as a moderator.

Water also works to cool the core. It carries off the heat made by the chain reaction, transferring it to where it can be used to generate electricity. Water, therefore, is both a moderator and a coolant.

Kinds of Reactors

All commercial power reactors in the United States are *light water reactors.* They use light (ordinary) water as the moderator and coolant. Canadian reactors are *heavy water reactors.* They use heavy water, which has deuterium in place of ordinary hydrogen.

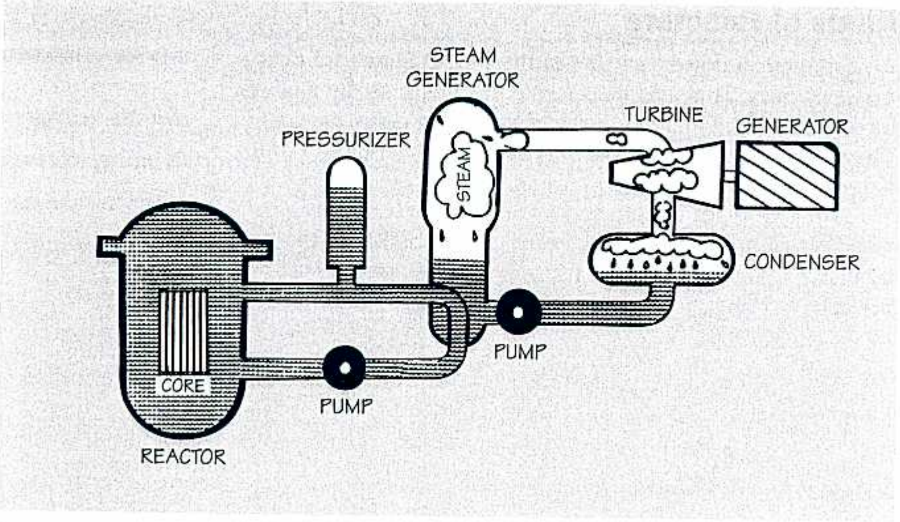
The two types of light water reactors are *boiling water reactors* and *pressurized water reactors.* The boiling water type boils the moderator water in the core, making steam inside the reactor vessel. Pipes carry the steam to the power plant's turbines and generators.



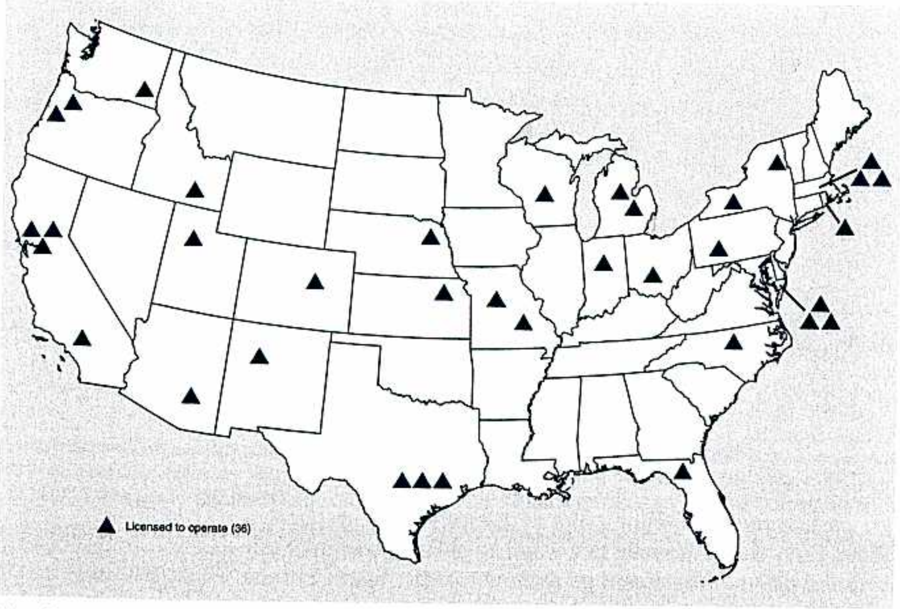
Boiling water reactor

Most nuclear plants in the United States use pressurized water reactors (PWRs). This type makes steam outside the reactor vessel. The water in the core is heated under extremely high pressure, which allows the water to heat without boiling far past its normal boiling point of 212 degrees Fahrenheit. Pipes carry this extremely hot water to steam generators outside the reactor. The steam generators transfer heat from the pressurized water to a separate supply of water, which boils and produces steam.

Nuclear energy is energy released when the nucleus of an atom splits (fission), joins with another nucleus (fusion), or disintegrates (radiation). "Nuclear energy" rather than "atomic energy" is the most exact name for the energy produced in a nuclear reactor.

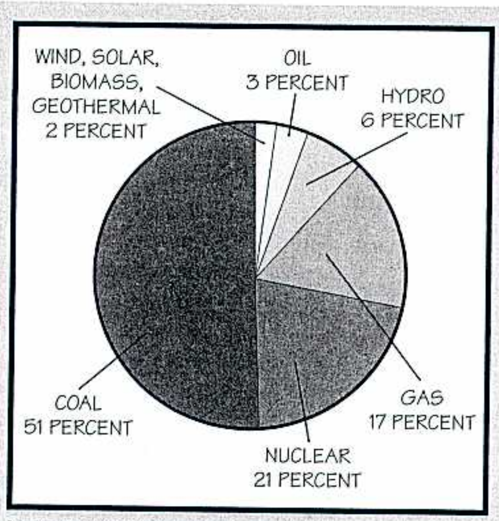


Pressurized water reactor (PWR)



As of 2004, 103 power nuclear reactors were operating in the United States. The 36 smaller reactors pinpointed above are located mainly at universities and other places where training and research are conducted.

Nuclear power—the second-largest source of electricity in the United States—supplies about 21 percent (one-fifth) of the nation's electricity each year. Unlike fossil fuels (coal, oil, and gas) burned to make electricity, nuclear power does not produce *greenhouse gases*—carbon dioxide and other gases that trap heat in Earth's atmosphere much as a glass greenhouse captures sunlight. Nuclear plants do not release solid pollutants such as coal ash and sulphur. However, used nuclear fuel produces dangerous radiation long after the end of its useful life. This *radioactive waste* must be safely stored and disposed of.



U.S. electricity by source

Radioactive Wastes

The fissioning of uranium-235 produces many radioactive isotopes, such as strontium-90, cesium-137, and barium-140. An especially dangerous nuclear-reactor byproduct is plutonium-239. Plutonium remains radioactive for thousands of years, and even in small amounts it can cause cancer.

Safely disposing of these radioactive wastes is a major issue in nuclear power. The current plan in the United States calls for depositing long-lived radioactive waste underground. In the meantime, nuclear power plants in the United States store used fuel and other wastes in pools of water at the plants.

Living next door to a nuclear power plant would expose you to less radiation than you would get in one round-trip flight from New York to Los Angeles.

Reactor Safety

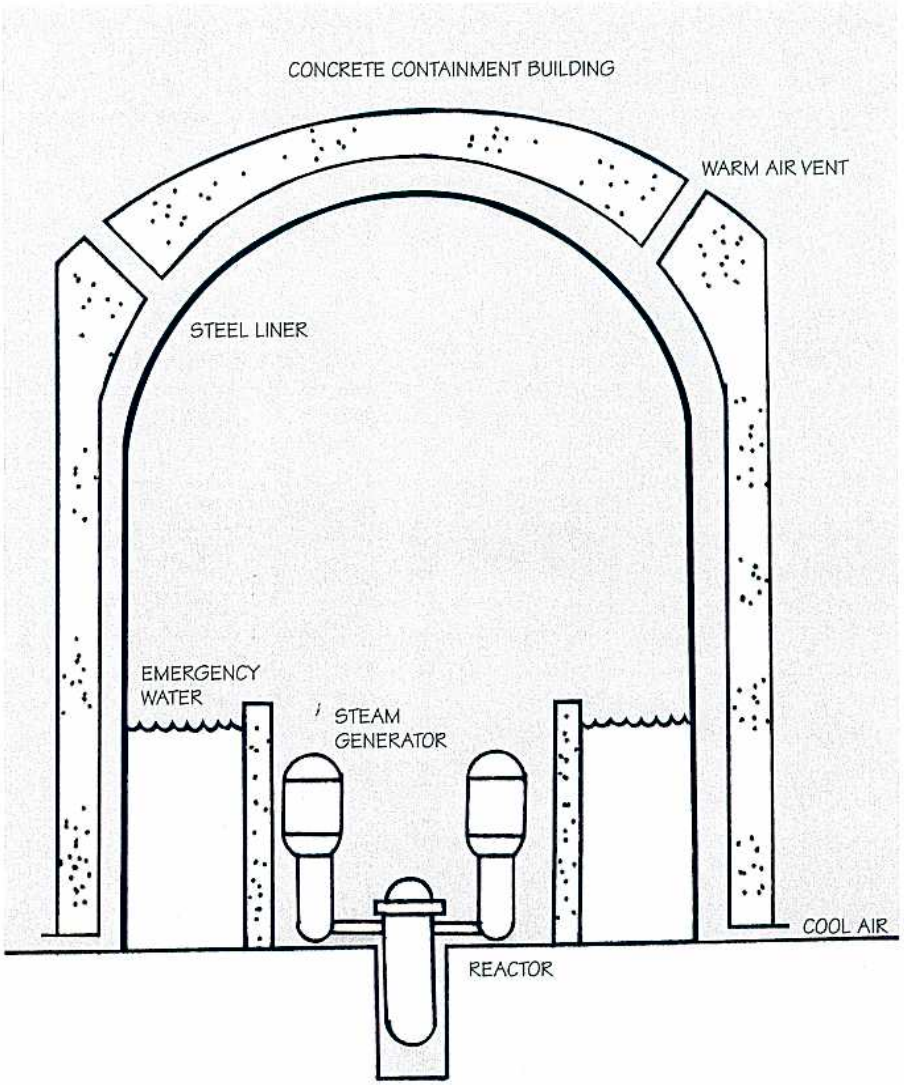
Nuclear power plants in the United States have emergency safety systems and backup systems that work automatically and immediately. Built-in sensors watch temperature, pressure, and water level. The sensors connect to systems that adjust or shut down the reactor if something is not working right. If cooling water leaks away, emergency cooling systems make up the water loss and keep the reactor from overheating.

Plants have physical barriers to keep radiation from escaping into the environment. Most of the radioactive by-products of the fission process remain locked inside the nuclear fuel pellets. The pellets are sealed inside strong metal rods. The fuel rod assemblies are enclosed in a steel reactor vessel with walls about 8 inches thick. The reactor vessel itself is in a massive, reinforced steel and concrete structure called the containment, with walls about 4 feet thick.

Nuclear Reactors as Factories

Besides generating electric power, a nuclear reactor also can be a kind of factory or manufacturing plant for making things radioactive. Most radioactive materials used commercially are made in nuclear reactors or cyclotrons. For example, hitting stable cobalt with neutrons in a reactor transforms the cobalt into a radioisotope—cobalt-60—that has been used to treat cancer and to sterilize medical supplies and consumer products.

Usually only one type of radioactive material can be produced at a time in a cyclotron, but a reactor can produce many different radioisotopes at once. After the materials are made, they are packaged and shipped to users nationwide, including hospitals, laboratories, universities, and manufacturing plants.



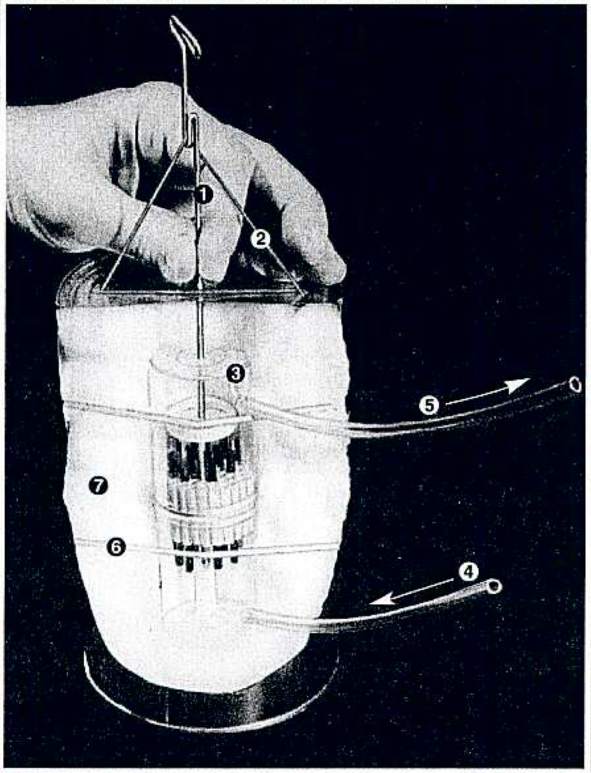
Nuclear reactors are housed in containment buildings with thick concrete floors and thick walls of steel or of concrete lined with steel. The concrete and steel are there to prevent radioactive materials from escaping into the air.

Make a Reactor Model

For optional requirement 4b, build this simple cross-section model of the pressure vessel for a pressurized water reactor. Lack of space prevents detailed instructions here, but by looking at the materials list and the labels on the photos, you should be able to make the model. Note the clever rubber band "scram" spring simulating the automatic shutoff system of a real reactor.

Materials Needed

- ☐ 1 large juice can
- ☐ 2 plastic pill bottles (about 2½ inches tall and 1½-inch diameter)
- ☐ 1 plastic pill bottle top (1-inch diameter)
- ☐ 1 wire coat hanger
- ☐ 13 soda straws (12 thin, one thick)
- ☐ 12 to 16 kitchen matches
- ☐ 2 6-inch swab sticks
- ☐ 2 6-inch pieces of ½-inch plastic tubing
- ☐ Rubber bands, cotton batting, assorted color marking pens
- ☐ Quick-drying glue

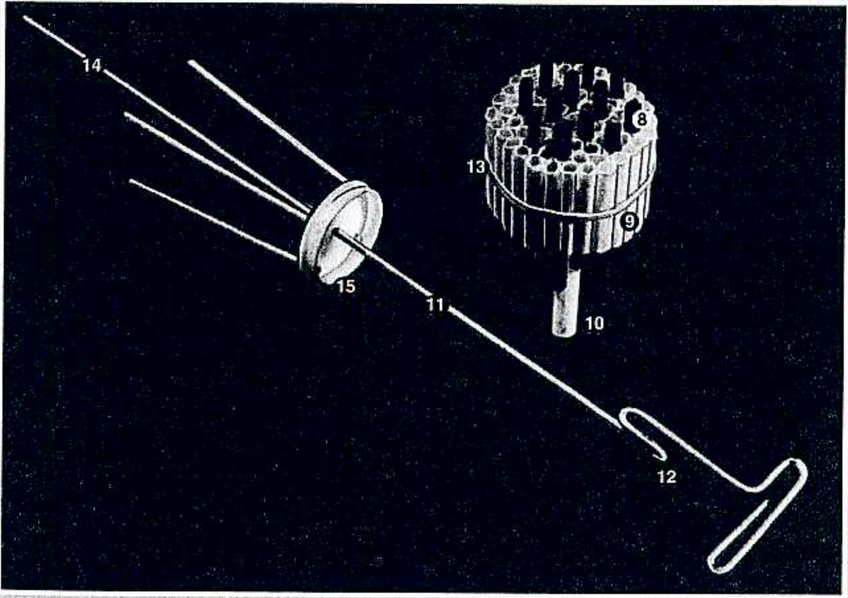


Completed Model

1 Control rods partially withdrawn
2 Rubber band scram spring
3 Pressure vessel
4 Cool water in
5 Hot water out
6 Rubber bands to hold vessel in place
7 Shielding

Reactor Controls

8 Fuel elements (matches colored red)
9 Core lattice (1-inch thin straws)
10 Channel for central control mechanism (thick straw cut to 3 inches)
11 Central control mechanism shaft (coat hanger wire)
12 Hook for rubber band scram spring
13 Rubber band
14 Control rods (swabsticks)
15 Soft plastic cap (1-inch diameter)



Thanks to Scouter Bob LeCompte, a former member of the Atomic Energy Commission (forerunner to the Nuclear Regulatory Commission), for the original design of this reactor model.

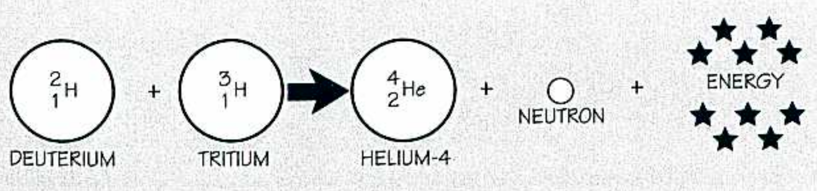
Fusion Research

Fission splits nuclei; *fusion* combines them. Tremendous amounts of energy are released when atomic nuclei fuse. The energy of the sun comes from the fusion of hydrogen nuclei to form helium. Experiments with ways to control nuclear fusion could result in virtually unlimited power from fusion reactors. While fission reactors split heavy elements (uranium and plutonium), fusion reactors join light elements (mainly deuterium and tritium, isotopes of abundant hydrogen).

The fuel for fusion is in the form of a *plasma*—a very hot gaslike mixture of ions. Fusion reactions take place when the plasma is hot enough, dense enough, and contained for long enough for the atomic nuclei in the plasma to start fusing together.

For nuclei to fuse, they must be going very fast. To go fast enough, they must be extremely hot. A great amount of energy is required to heat and create the plasma. Fusion reactors will be useful for producing electric power only if they can be made to produce more energy than they consume.

One promising fusion design uses extremely powerful laser beams to heat deuterium and tritium gas and turn it to plasma. Compressing the plasma fuel causes fusion.



The deuterium-tritium fusion reaction produces helium.

ITER

An experiment called *ITER* (Latin for "the way") aims to provide the know-how to build the world's first nuclear fusion plant for generating electricity. ITER is an experimental reactor based on the *tokamak* concept—a doughnut-shaped magnetic vessel in which conditions for controlled fusion reactions are created. The experiment will test all the main new features needed for a power plant fueled by hot plasma that is held in place (confined) by magnets.

Plans call for ITER to begin operating in 2014 and last for 20 years. Constructing and operating ITER will be an essential step in determining whether people can successfully use magnetic confinement of plasma for generating electricity in the 21st century. The project is an international collaboration of scientists and engineers from China, Europe, Japan, Korea, Russia, and the United States.