Energy
Skill Builders

Nuclear Reactor

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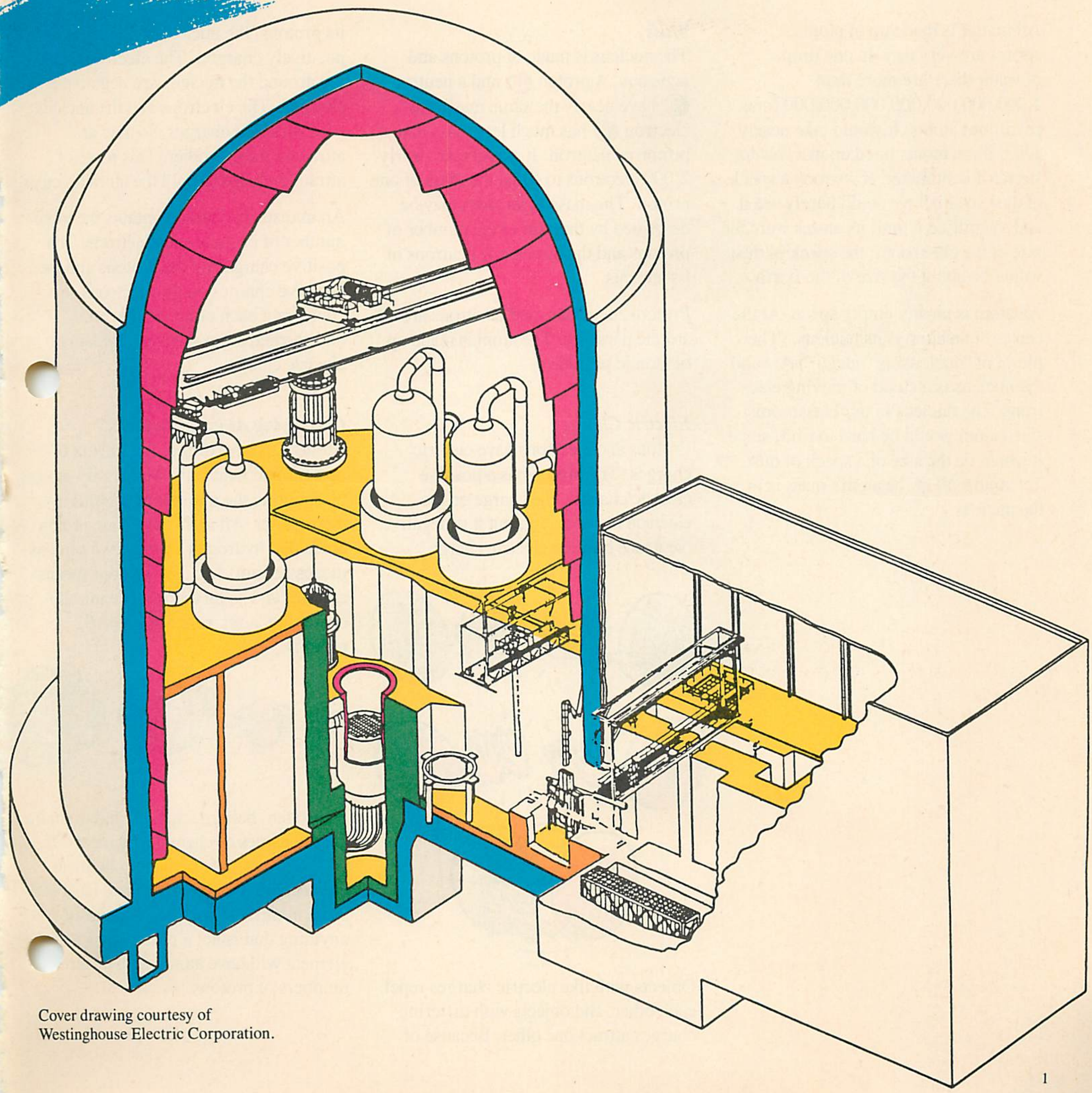

Cover drawing courtesy of
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Reviewing the Structure of the Atom

All matter is made up of atoms. Atoms are very tiny. In one drop of water there are more than 1,000,000,000,000,000,000,000 (one sextillion) atoms. It would take nearly 100 million atoms lined up in a row to stretch 1 centimeter. If we took a speck of dust so small we could barely see it and magnified it until its atoms were the size of the classroom, the speck of dust would be about the size of the Earth.

An atom is mostly empty space. At the center of an atom is its nucleus. (The plural of "nucleus" is "nuclei.") Around the nucleus is a cloud of moving electrons. The nucleus in our classroom-sized atom would be hard to find, since it would be the size of a speck of dust. Yet almost all of the atom's mass is in the nucleus.

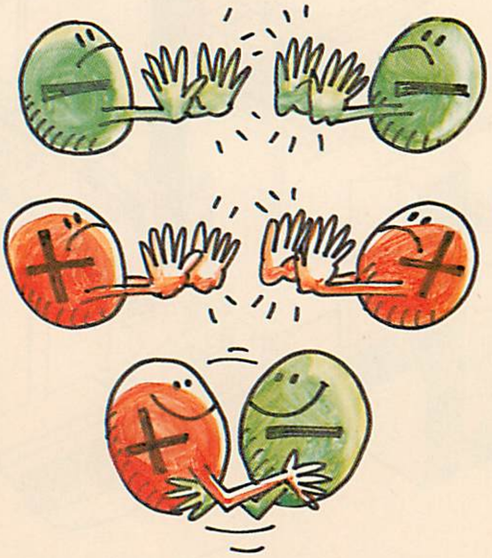
Mass

The nucleus is made of protons and neutrons. A proton ⊕ and a neutron ● have nearly the same mass. An electron ⊖ has much less mass than a proton or neutron. It would take nearly 2,000 electrons to equal the mass of one proton. The mass of an atom may be described by the sum of the number of protons and the number of neutrons in its nucleus.

Protons, neutrons, and electrons are all atomic particles. The atom is made up of atomic particles.

Electric Charge

Protons and electrons have electric charges. The proton has a positive electric charge. The charge on the electron is just as big, but it is negative. Neutrons have no electric charge.

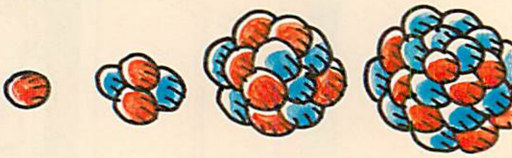


Objects with like electric charges repel each other, and objects with differing charges attract one other. Because of its protons, the nucleus of the atom is positively charged. The electrons moving around the nucleus are negatively charged. The electrons and the nucleus have different charges, so they are attracted to each other. This force of attraction helps to hold the atom together.

An undisturbed atom contains the same number of protons and electrons. The positive charges on the protons and the negative charges on the electrons counteract each other, so that an undisturbed atom seems to contain no electric charge.

Classifying Atoms: Elements

Atoms can have different numbers of protons and neutrons. We classify atoms by counting the number of protons in their nuclei. All atoms with one proton are called hydrogen atoms. Two protons means helium, . . . , six protons means carbon, and so on to the last naturally-occurring atom, uranium, with 92 protons.



Hydrogen, helium, carbon, and uranium are the names of chemical elements. If you have a sample of a pure chemical element, all the atoms in it will have the same number of protons. A piece of anything that is not a pure chemical element will have atoms with differe numbers of protons.

Classifying Nuclei: Isotopes

Two atoms can have the same number of protons but different numbers of neutrons. After we have classified atoms into elements by counting their protons, we can further classify them, into **isotopes**, by counting the number of neutrons in the atom. Atoms belonging to the same isotope have the same number of protons and also the same number of neutrons. The usual way of writing the name of an isotope is to write the name of the element followed by the number of protons plus neutrons, this: carbon-12, carbon-13, and carbon-14. The numbers indicate the sum of the number of protons and the number of neutrons in the atom's nucleus.


Carbon-12


Carbon-13

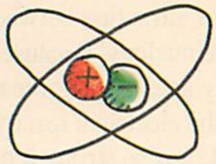

Carbon-14

Chemists want to know what element an atom is, because they study how atoms join together. The ways an atom can join with other atoms depend on the number of electrons it has, which is the same as the number of protons in its nucleus. Chemical reactions involve a change in what atom is joined to what other atom. The nuclei of atoms do not change in a chemical reaction.

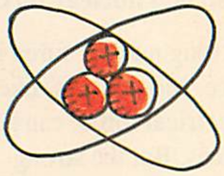
In a nuclear reaction, however, nuclei do change. Nuclear physicists need to ow what isotope an atom is, because in a nuclear reaction different isotopes of the same element behave differently.

1. Which diagram is closest to being a model of an atom?

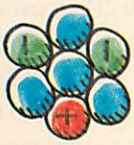
a.



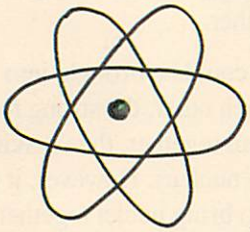
b.



c.



d.



2. What element does this nucleus represent?

3. Which of the following nuclei are isotopes of the same atom?

a.

b.

c.

d.

4. How many neutrons are in an atom of carbon-12?

5. A dime

a. is solid protons and neutrons.

b. is solid protons, electrons and neutrons.

c. has more than 1,000,000,000,000,000, 000,000,000,000,000 atoms.

d. is mostly empty space.

6. All the electrons in your body would weigh about as much as

a. your leg.

b. your head.

c. your right thumb.

d. one hair from your head.

Optional:

7. If all the atoms in a drop of water were put into a straight line, the line would stretch

a. one centimeter.

b. almost a kilometer.

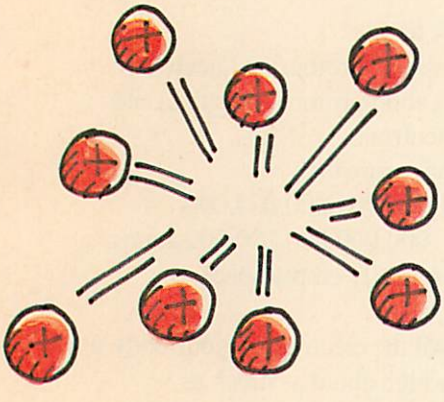
c. more than half way to the moon.

d. forever.

Energy from the Nucleus

The center of the atom, the nucleus, is a tremendous store of energy. In the last 50 years, we have learned how to tap this energy.

In the nucleus the positively charged protons are very close together. But objects with like electric charges repel each other. Every proton in a nucleus is repelling every other proton.

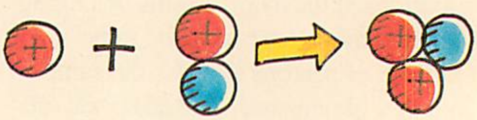


Why doesn't the nucleus fly apart? A different force must be holding it together, a force of attraction between the particles in the nucleus. Because the nucleus doesn't fly apart, this force must be stronger than the electrical force that it opposes. In fact, it is so strong it has been named the **strong nuclear force.**

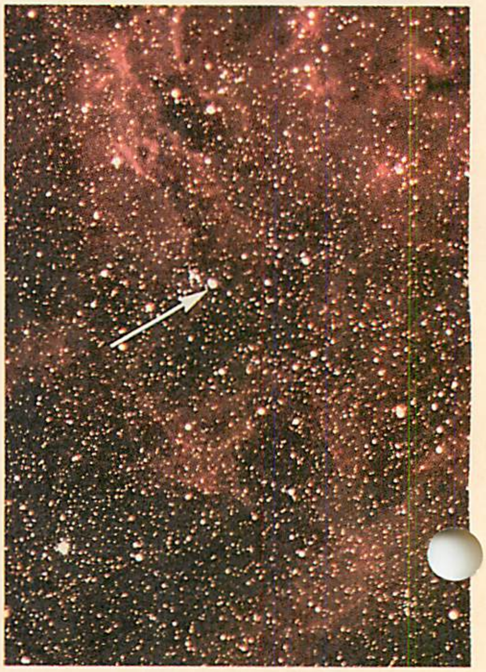
In one way the strong nuclear force is a very strange force. Most forces, like gravity or the electrical force, can act over great distances. But the strong force has a noticeable effect over only a very short distance, about the size of an atom's nucleus. Only when protons and neutrons are brought very close together can the attraction due to the strong force pull them together.

If small nuclei could be brought into contact with each other, the strong force would hold them together, thus making a new, heavier, nucleus. However, it is very difficult to bring nuclei together, because the closer they get the stronger the electrical repulsion between their positively charged protons is. It takes considerable energy to overcome this force and assemble protons and neutrons into a nucleus.

There is a place where enough energy can be found: in the center of stars. In the center of a star the temperature is millions of degrees. The higher the temperature is, the faster atoms move. Stars are made up mostly of hydrogen, the most abundant element in the universe. The hydrogen-1 and hydrogen-2 nuclei move so fast that electrical repulsion cannot prevent them from getting very close together. Then the **strong force** joins them together, to form a nucleus of helium-3. This is a nuclear reaction, because it involves the nuclei of atoms. The sun is a kind of nuclear reactor, a place where nuclear reactions take place.



In a star, helium-3 nuclei are then brought together to form other light elements such as carbon-12 and nitrogen-14. The energy needed to bring together all the protons against the electrical repulsions is called the **binding energy.** This energy is stored in the nucleus by the **strong force,** in the same way that

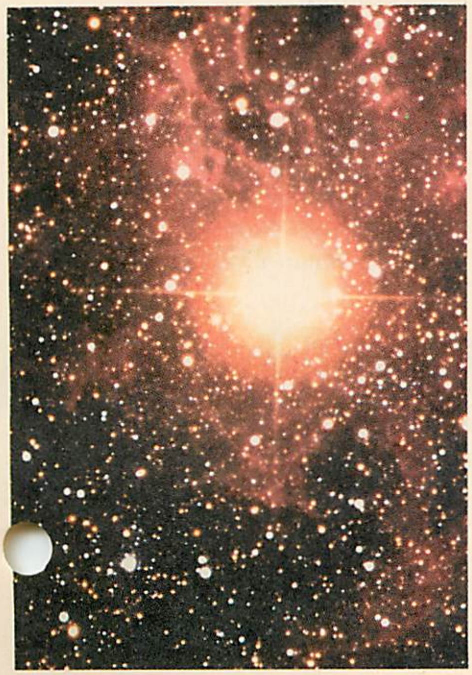


January, 1987

the force of gravity stores energy in water that has been lifted to the top of a hill.

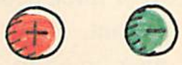
Even in the center of a star, there is not enough energy to form nuclei of heavier elements like silver-107, gold-197, lead-206, and uranium-238. They are formed under the enormous forces when stars explode as supernovas. In all, we have found about 90 elements in nature, and hundreds of isotopes.

The atoms around us are loaded with energy. Their nuclei are like jack-in-the-boxes, their protons ready to spring out. The strong force acts like a latch holding the door closed. We have found a way of getting out some of this energy from a few heavy isotopes, releasing the energy stored in them billions of years ago in a supernova.



February, 1987

1. Where is the strongest repulsion?

a. 

b. 

c. 

d. 

2. Why is it more difficult to join two carbon nuclei than two helium nuclei? The carbon nuclei

a. are negative.
b. are smaller.
c. have more protons.
d. are more affected by gravity.

3. Where is most helium made?

a. in the center of stars.
b. in supernovas.
c. in nuclear reactors.
d. in chemistry labs.

4. Why doesn't the **strong force** pull together the atoms of a penny?

a. the electrical force prevents it.
b. there is no such force.
c. the force's range is too short.
d. the force only attracts non-metals.

Optional:

5. The electrical force is an "inverse square" force. If the distance between two charges is reduced to 1/3 the original distance, the force becomes $(3/1)^2$, or nine times as much as the original force. By how many times as much will the force change if the distance becomes 1/10 as much?

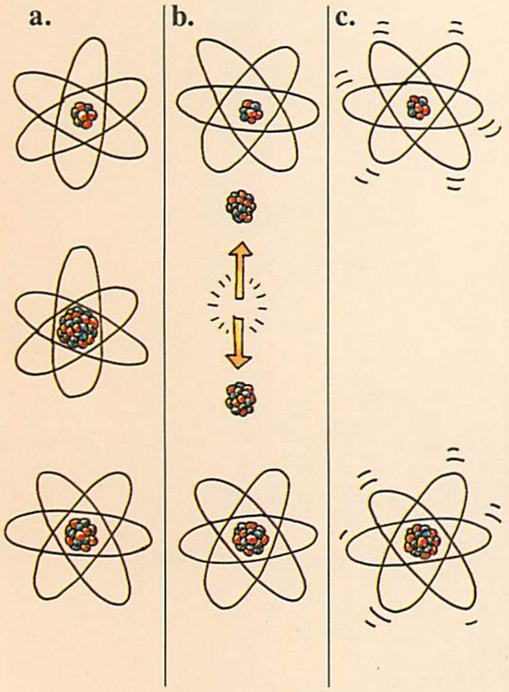
a. 10
b. 100
c. 1/10
d. 1/100

A Useful Nuclear Reaction

Fission

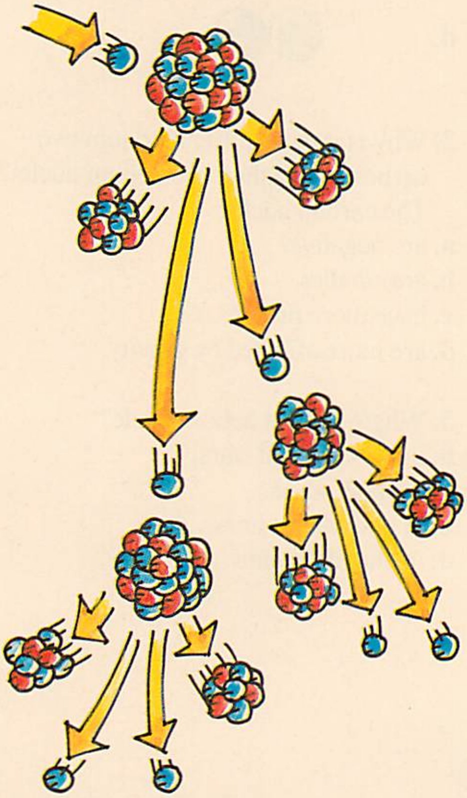
If a slow-moving neutron gets close enough to a uranium-235 nucleus, the nucleus can capture it. The nucleus still has 92 protons, so it is still uranium but it now has one more neutron. It is now a nucleus of uranium-236.

Uranium-236 is unstable. It soon splits, or **fissions,** into two smaller nuclei and two or three neutrons. Once these two new nuclei are out of the range of the strong force, the electric force of repulsion between them speeds them up to extremely high speeds, thousands of kilometers per second. But the new nuclei don't get far before they strike other atoms. When they do, they speed them up. By jostling the surrounding atoms, the fissioning of a nucleus raises the temperature of the surrounding matter.



Chain Reactions

The release of the two or three neutrons in fission is very important. These neutrons can make other uranium-235 nuclei fission, releasing more neutrons, and those neutrons can make other nuclei fission and so on. This process is called a **chain reaction.** The chain reaction can continue as long as uranium-235 nuclei and neutrons are present.



Because heat energy is produced whenever a nucleus fissions, a chain reaction is a continuous source of heat energy. In nuclear power reactors, this source of heat energy is used to generate electricity. But to harness this energy, we need more than just a lump of uranium-235.

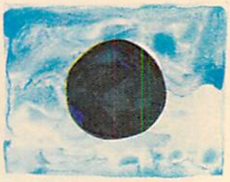
Slowing Down the Neutrons

The chance that a uranium-235 nucleus will capture an approaching neutron depends a lot on the speed of the neutron. Most fast neutrons just bounce off uranium-235 nuclei. A slow-moving neutron is thousands of times more likely to make a uranium-235 nucleus fission than a neutron moving at the speed of neutrons just released by fission.

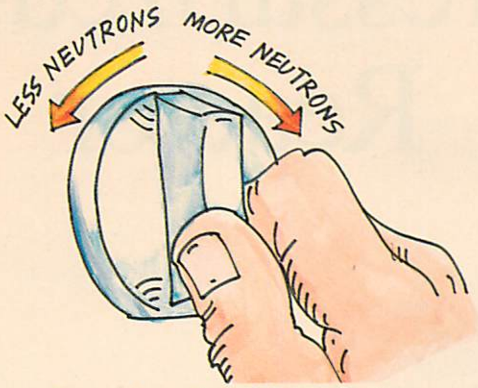
To increase the chance that a neutron released by fission will cause another fission, it must be slowed down. A neutron will slow down if it hits something; it slows down the most if it hits something with the same mass as itself. Protons have about the same mass as neutrons. The nucleus of a hydrogen-1 atom is a proton. Since two-thirds of the atoms in water are hydrogen, water is a good substance to use for slowing down neutrons.

A substance that is used to slow down neutrons in a reactor is called a **moderator.** The moderator and the uranium-235 must be arranged in a way that allows neutrons from a fission event to pass through water on their way to another uranium-235 nucleus.

Good



Not As Good



Making Sure There Are Enough Neutrons

Not every neutron released by a fission event will cause another nucleus to fission, for two main reasons. First, some neutrons happen to travel in directions that take them out of the fuel. They escape.

Second, many of the neutrons are absorbed by isotopes other than uranium-235. Nuclei in the steel and concrete of which the reactor is made can capture neutrons, so can the hydrogen-1 in the moderator. Even the fuel captures neutrons without fissioning. The uranium in ore is a mixture of two isotopes; less than 1% uranium-235, and the rest uranium-238. In reactor fuel the percentage of uranium-235 is increased to about 3%. Still, 97% of the uranium atoms in fuel are uranium-238, and uranium-238 nuclei capture neutrons without fissioning.

To make sure that at least one neutron from each fission causes another nucleus to fission, engineers add extra fuel to the reactor. The more fuel there is, the more uranium-235 nuclei surround any fissioning nucleus, making escape or capture by nonfissionable nuclei less likely.

Controlling the Chain Reaction

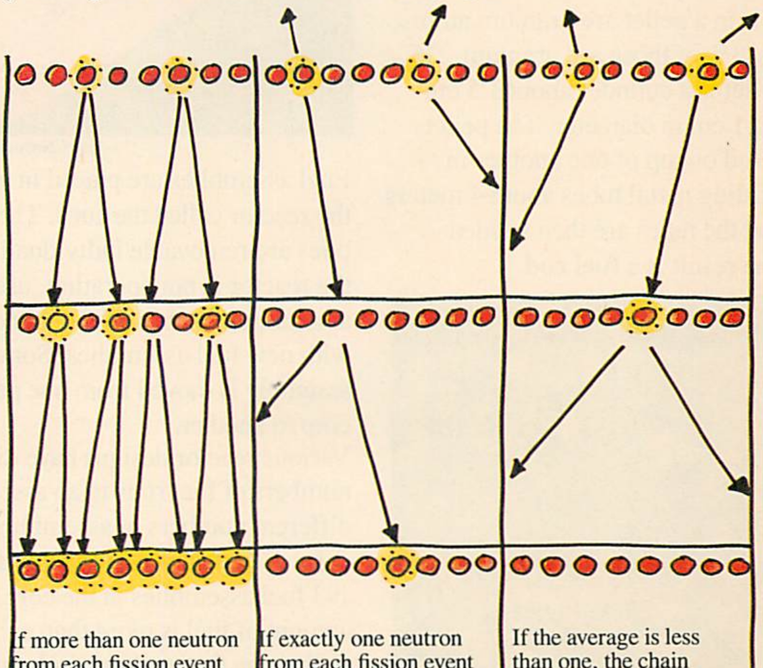
A heat source is much more useful if it can be controlled. Your kitchen stove would be much less useful if it had on/off switches instead of the knobs that change the amount of heat produced at the burner. In a nuclear power reactor, the amount of heat being produced depends on the number of nuclei that fission every second. The more fission events, the more heat. The number of fissions per second depends on the number of fissionable nuclei and on the number of neutrons shooting around between atoms.

The number of fissionable nuclei present – the amount of fuel – was decided when the reactor was designed; the operators cannot change that minute by minute. But if they can control the number of neutrons in flight, the rate at which heat is being produced can be controlled. (Neutrons in nuclei have no effect, only the free neutrons traveling between atoms.)

The number of neutrons in flight can be reduced by adding to the reactor some substances whose nuclei are good at capturing neutrons, but do not fission. Such substances are sometimes called "neutron poisons." We must also have a way of removing neutron poisons, in case we find we need more neutrons.

So the strategy for controlling the reactor is this: Start with so much fuel that, if no neutron poisons were present, there would be more than enough neutrons. Then add neutron poisons to get just the right number of neutrons in flight. To change the number of neutrons, put in or take out neutron poison. That allows us to start, stop, or adjust the chain reaction.

Your teacher may give you some questions to answer after reading these two pages.



f more than one neutron from each fission event makes another nucleus fission, the number of nuclei fissioning in each second will grow larger and larger. The power output would soon grow too large.

f exactly one neutron from each fission event makes another nucleus fission, the chain reaction will continue at the same rate. Steady power is produced.

If the average is less than one, the chain reaction will slow down and eventually stop.

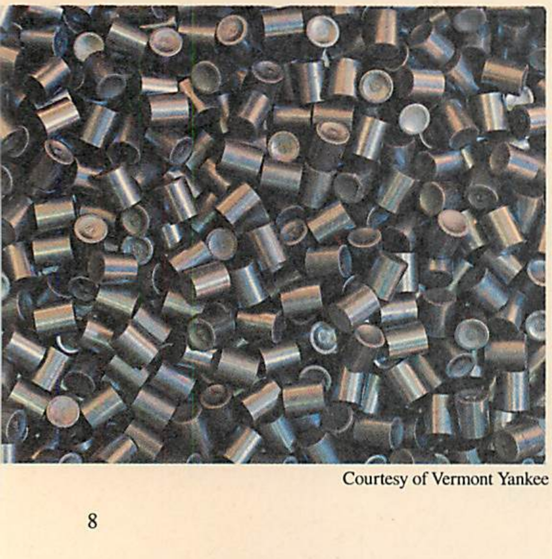
The Pressurized-Water Reactor

In the United States, the most common kind of power reactor is the pressurized-water reactor. (About a third of all U.S. nuclear power plants use another kind called a boiling-water reactor.) As their names suggest, in both types the heat is carried out of the reactor by water, just as water carries away heat in most automobile engines.

If you understand how a pressurized-water reactor works, you will find it easy to understand how a boiling-water reactor works. Later, the one big difference between them will be explained.

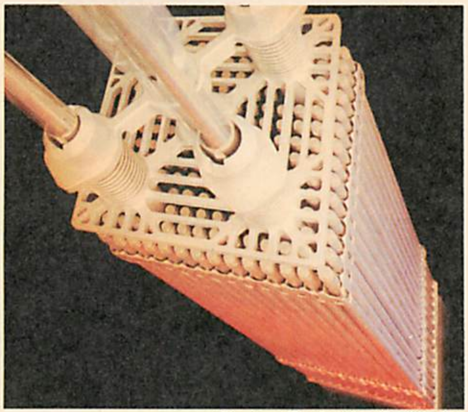
The Fuel

To make the fuel for a pressurized-water reactor, uranium dioxide is formed into small ceramic pellets. Less than half of the atoms in a pellet are uranium atoms, and only 3% of those are uranium-235. Each pellet is a cylinder about 1.5 cm high and 1 cm in diameter. The pellets are stacked on top of one another in tightly-fitting metal tubes about 4 meters long, and the tubes are then welded shut. The result is a **fuel rod.**



Courtesy of Vermont Yankee

The fuel rods are then grouped together to make a **fuel assembly.** Spacers support the fuel rods a few millimeters apart from each other in a 17 by 17 pattern, making a square about 20 cm by 20 cm. Of the 289 places, 264 are taken by fuel rods; the other spaces are used for instruments or to control the reactor. At the top of the assembly is a handle that is used to lift and lower the assembly. A single fuel assembly weighs about 660 kilograms.



Courtesy Combustion Engineering

Fuel assemblies are placed in a part of the reactor called the **core.** The assemblies are removable individually. When the reactor is not operating, used fuel assemblies can be lifted out and replaced with new fuel assemblies. Sometimes an assembly is moved from one part of the core to another.

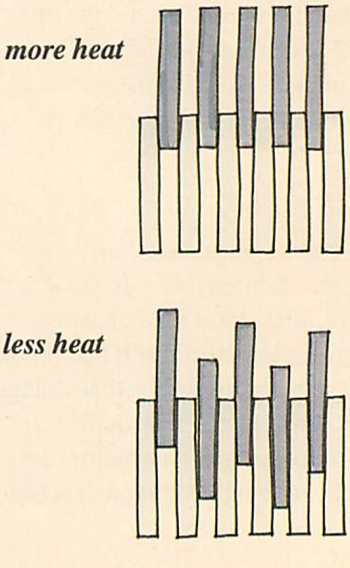
Various reactor designs have different numbers of fuel rods in an assembly and different numbers of assemblies in the core. A typical recent reactor design has 193 fuel assemblies in the core. This amount of fuel is more than enough fuel so that, on the average, each time a uranium-235 nucleus fissions one of the neutrons released will be captured by another uranium-235 nucleus.

Controlling the Number of Neutrons

To regulate the chain reaction, there must be a way of increasing and decreasing the amount of neutron-absorbing, non fissionable, nuclei in the core. To do this, metals that are neutron poisons, such as cadmium and silver, are made into shapes similar to fuel rods. In about a third of the fuel assemblies, 24 of the spaces that might have been occupied by fuel rods are taken by movable **control rods.**

Unlike fuel rods, control rods are fastened to machinery that can move them in or out of the core while the reactor is operating. The farther the control rods are pushed into the core, the greater the percentage of the neutrons in flight that are absorbed, so the fission rate slows down. As control rods are moved out of the core, the fission rate increases and the reactor heats up.

Some of the control rods have special equipment that can move them into the core very quickly. All the control rods



are held out of the core by electromagnets. If the electricity goes off, gravity automatically pulls the control rods into the core. With the control rods in the core, so many neutrons are absorbed that a chain reaction cannot continue, and the reactor stops. Every reactor has many more control rods than necessary to stop the chain reaction.

Moderation and Heat Transfer

The core is inside a large, sealed, steel container called the **pressure vessel.** The reactor pressure vessel is always kept full of water; the fuel assemblies and the fuel rods they hold are always sitting in water. The water serves three purposes.

First, the water acts as a moderator, slowing down the neutrons released by fission. A fast neutron leaves a fuel rod, is slowed down in the water, enters a fuel rod, and causes a uranium-235 nucleus there to fission.

Second, the water carries away heat. It serves as a **coolant**, a fluid that carries away heat. The fissioning of the uranium-235 nuclei makes the fuel rods get hot. The hot fuel rods heat the water. The shape of the long slender rods makes it easy for heat to be transferred from the fuel pellets to the water. At most, a fissioning nucleus will be only a few millimeters or so from flowing water.

Third, substances which are very good neutron-absorbers can be dissolved in the water. Usually boron-10 is used. Changing the amount of boron-10 in the water is a way of making long term adjustments in the number of neutrons in flight.

A pressure vessel is delivered to a reactor construction site. How can you tell that the vessel must be very heavy?

Courtesy of Baltimore Gas And Electric

1. About how many fuel pellets fit into a fuel rod?
a. 27
b. 267
c. 2,667
d. 26,667

2. One of the spaces in every fuel assembly is taken by a rod that contains only instruments, to measure such things as temperature. About how many instrumentation rods are there in the core?
a. 10
b. 50
c. 200
d. 1000

3. About how many fuel rods does a typical reactor have?
a. 260
b. 283
c. 50,000
d. 14,000,000

4. About how many fuel pellets are there in the core of a typical reactor?
a. 267
b. 60,000
c. 14,000,000
d. 140,000,000

5. Control rods are made of metals with nuclei that

____

neutrons, but do not

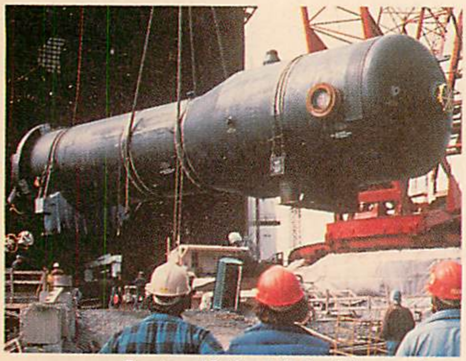
______________________________.

6. The number of neutrons from each fission event that causes another nucleus to fission must be greater than one (on the average) when the reactor is:
a. being started up.
b. being shut down.
c. turned off.
d. being refuelled.

Making Use of the Heat

In a pressurized water reactor, heat is moved from place to place by moving water, the reactor's coolant. The water flows in closed circles, or loops. The first loop runs from the core to a steam generator and back again. The second runs from the steam generator to a turbine and back again.

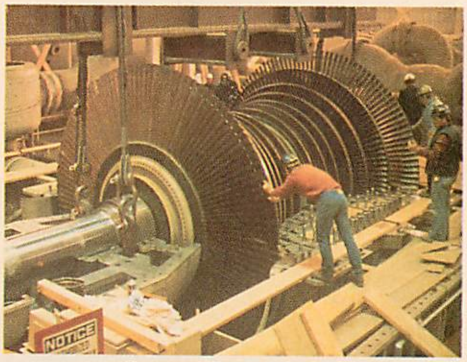
In the first loop, pumps (K) push water into the pressure vessel, past the fuel rods in the core, through a **steam generator** (O) and back to the core. More than 15,000 liters of water pass through the core each second. That's equal to the water in a small swimming pool every few seconds. As it moves through the core, the water gets very hot, but because it is under such high pressure it doesn't boil. The hot water then flows to the steam generator.



Courtesy of Seabrook Station Education Center

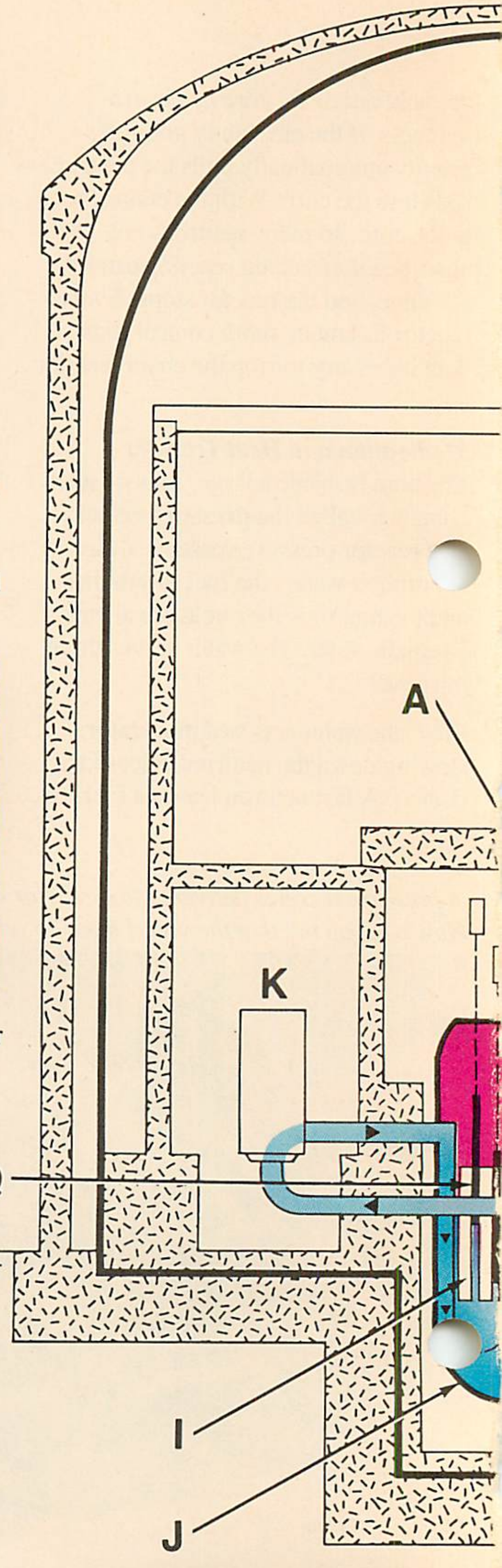
The steam generator is a heat exchanger. Both of the water loops pass through it, but the water in the two loops doesn't mix. Instead, heat from the hot water flows through the walls of the pipes to cooler water travelling in the second loop. The water in the second loop is under much less pressure, and the heat makes the low-pressure water boil. A pressurized water nuclear power plant can have two, three or four steam generators, all connected to one reactor pressure vessel.

The steam is piped to a steam turbine (D) that turns an electric generator (E). The used steam from the turbine is cooled and converted back to water in a condenser (N). The condenser is also a heat exchanger; in it heat passes from the steam to a third loop of water, which often comes from a river, lake, or ocean (G), and is returned to it (F). The steam turns back to liquid water and is pumped back to the steam generator.



Courtesy of Seabrook Station Education Center

The turbine-generator of a nuclear power plant is very similar to the turbine-generator in a gas-, oil- or coal-fueled power plant; it is the way of making the steam that is different.

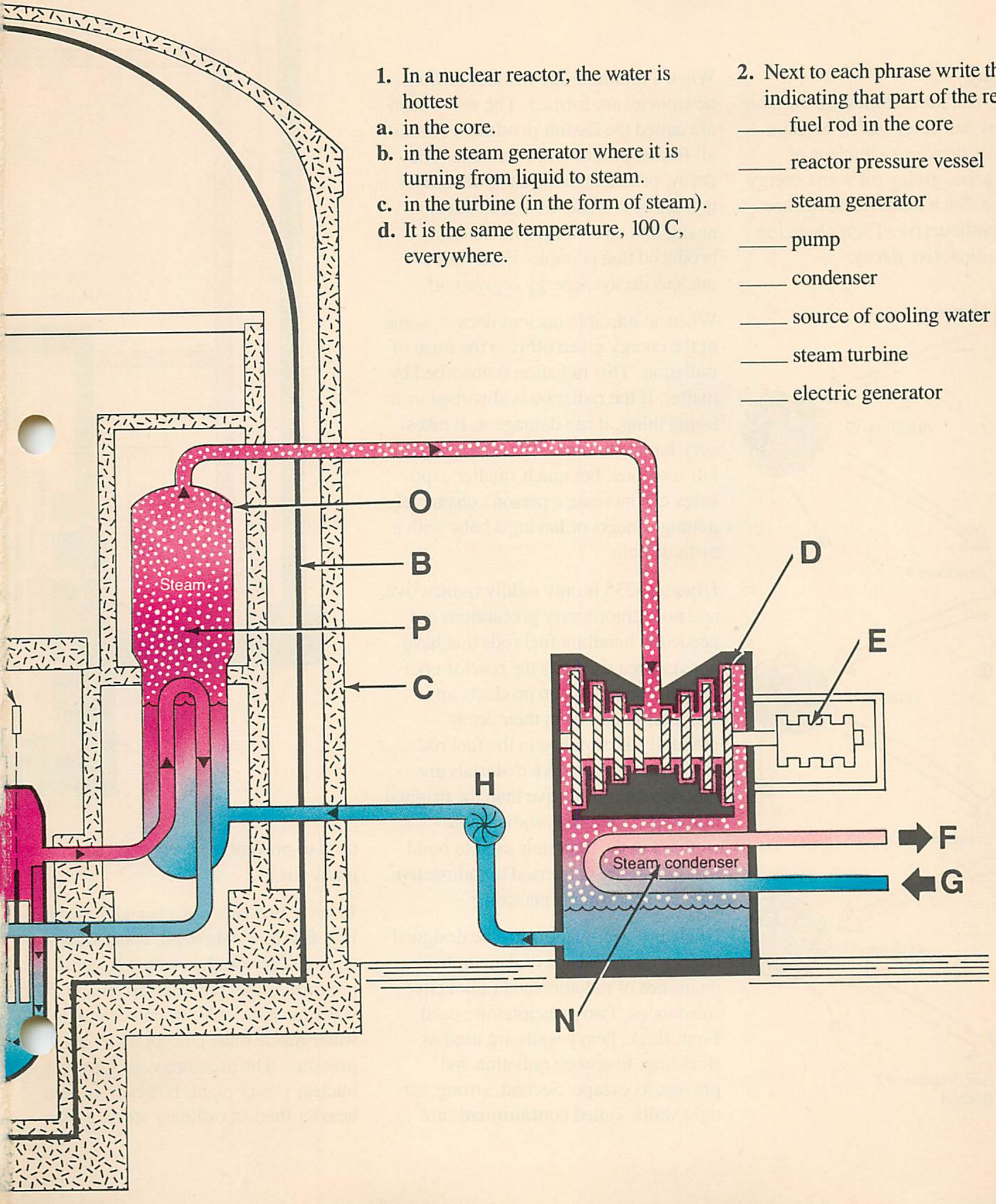


1. In a nuclear reactor, the water is hottest

a. in the core.
b. in the steam generator where it is turning from liquid to steam.
c. in the turbine (in the form of steam).
d. It is the same temperature, 100 C, everywhere.

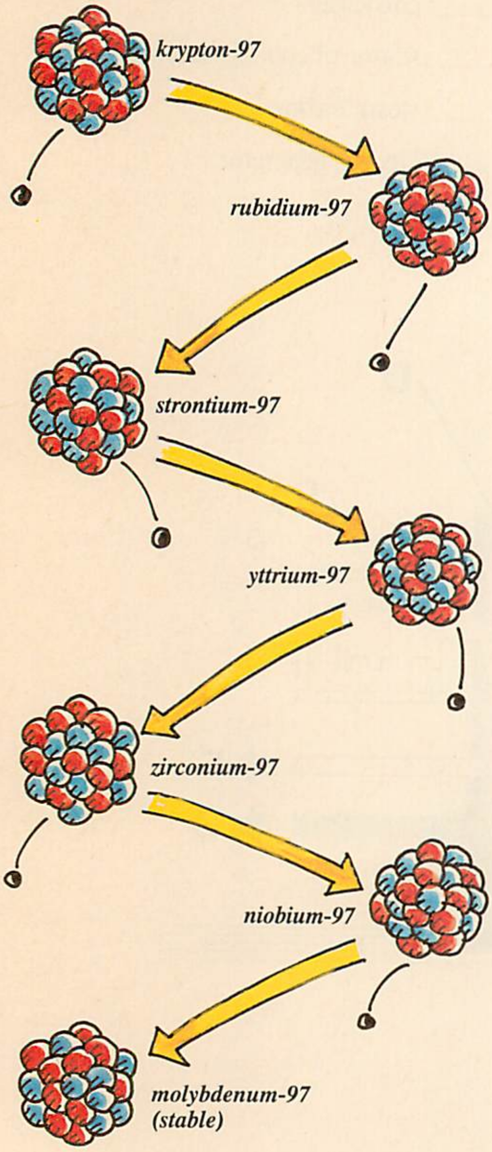
2. Next to each phrase write the letter indicating that part of the reactor.

____ fuel rod in the core
____ reactor pressure vessel
____ steam generator
____ pump
____ condenser
____ source of cooling water
____ steam turbine
____ electric generator



Containment

Radioactivity
The nuclei of some isotopes are unstable. Without any warning, such a nucleus can suddenly turn into a nucleus of another isotope, giving off some energy as it does so. Such unstable nuclei are said to be **radioactive.** Their changing is called **radioactive decay.**

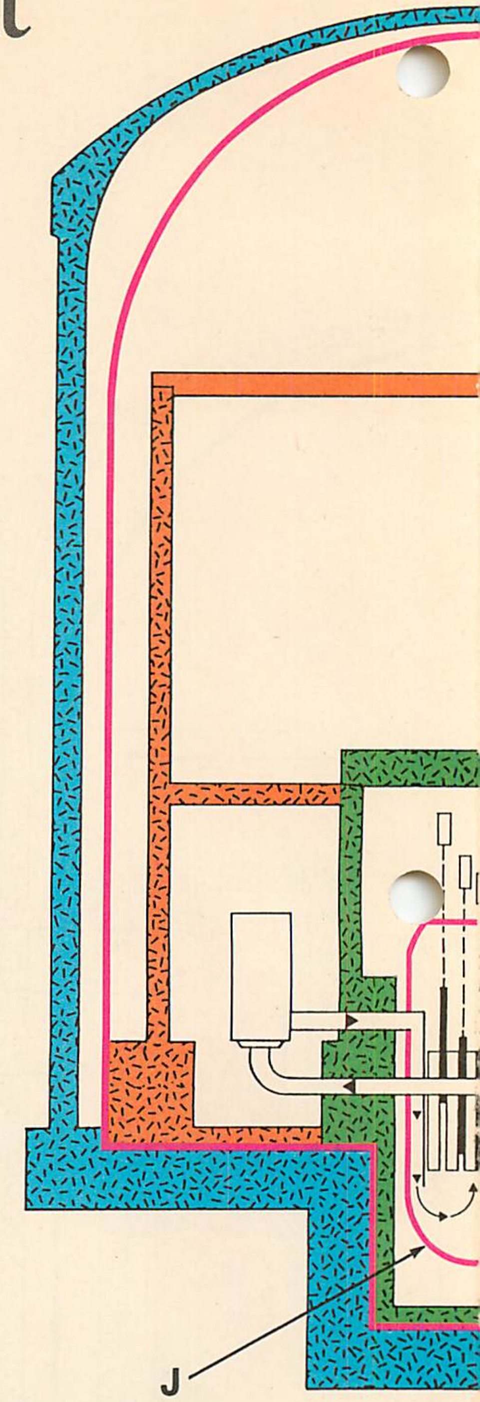


When a uranium-236 nucleus fissions, new nuclei are formed. The new nuclei are called the **fission products**. Almost all fission products are unstable. They decay, producing new daughter nuclei that are also unstable, which decay again, and so on until a nucleus is produced that is stable. Each time a nucleus decays, energy is given off.

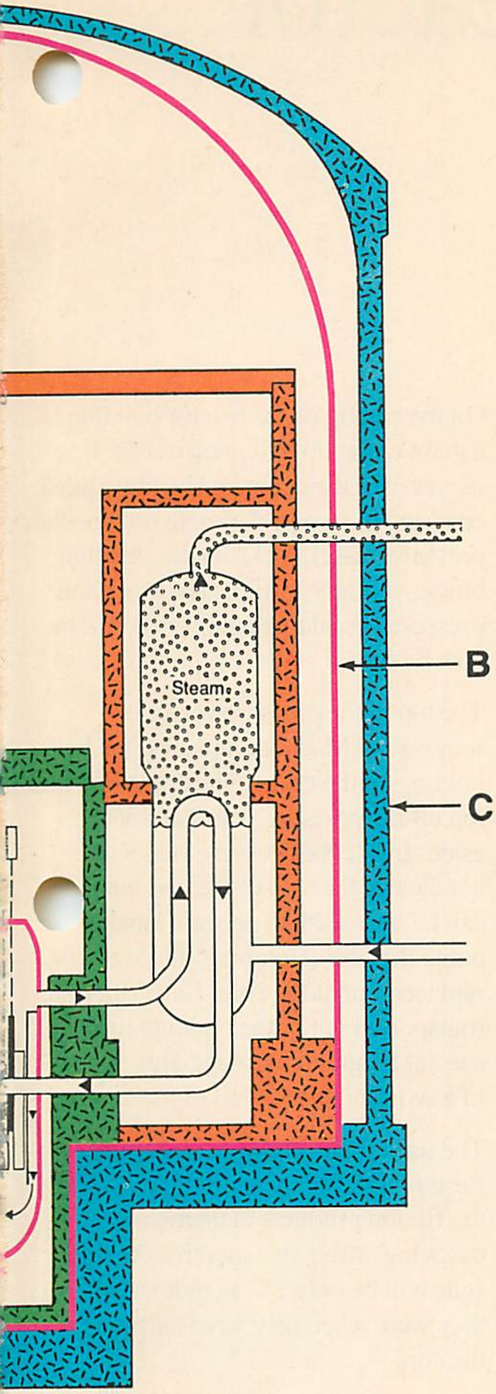
When an unstable nucleus decays, some of the energy given off is in the form of radiation. This radiation is absorbed by matter. If the radiation is absorbed by a living thing, it can damage it. It takes very large amounts of such radiation to kill someone, but much smaller exposures can increase a person's chance of getting cancers or having a baby with a birth defect.

Uranium-235 is only mildly radioactive, and no extraordinary precautions are needed in handling fuel rods that have not yet been used. As the reactor operates, however, fission products and daughter nuclei from their decay gradually accumulate in the fuel rods. These new radioactive materials are much more radioactive than the original uranium-235. (Also, some stable isotopes in the materials used to build the reactor are converted to radioactive ones by absorbing a neutron.)

Nuclear power plants must be designed to prevent the escape of dangerous quantities of radiation and radioactive substances. Two principles are used. First, thick, heavy walls are used as shielding, to absorb radiation and prevent its escape. Second, strong, airtight walls, called **containment**, are used to prevent the escape of radioactive materials.

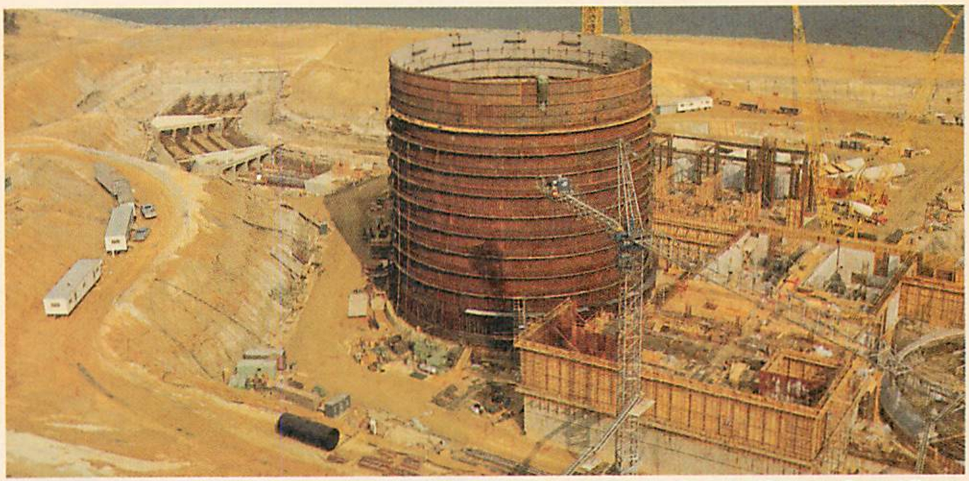


Reactor pressure vessels and the buildings that house them are enormously strong. The core lies within a sealed pressure vessel (J). Like all boilers, its walls must be very strong because the water inside must be kept under high pressure. The pressure vessel in a nuclear power plant, however, is even heavier than an ordinary steam boiler,



because of the need to minimize the chance of its rupturing and releasing the radioactive materials. Its walls are made of steel from nearly 15 cm to more than 20 cm thick.

Around the pressure vessel is a thick concrete wall. This wall acts as shielding, protecting workers by absorbing escaping neutrons from the chain reaction, and other radiation from the fuel and fission products.



Courtesy of Baltimore Gas And Electric

Next comes an airtight steel liner (B). If the pressure vessel or the pipes entering it should break, the escaping steam would be trapped inside the liner, which is strong enough to withstand a great deal of pressure.

Finally, the building's reinforced concrete outer wall (C) acts as shielding, and is also intended to withstand natural and man-made events like earthquakes, plane crashes, and terrorist attacks.

And That's Not All…

You now know all the major parts of a nuclear power plant, but other essential parts we have not mentioned. For example, there is a water purification plant that controls the composition of the water flowing through the core. There is the pressurizer, a device that keeps the water in the first loop from boiling. Altogether, a nuclear power plant is a very complex, sophisticated piece of equipment.

1. The steel walls of the pressure vessel are about as thick as

a. two pencils placed side by side.
b. this booklet is wide.
c. a newspaper is wide.
d. an automobile is long.

2. Between the outside of a nuclear power plant and the core of its reactor are at least

____

concrete wall(s) and

____

steel wall(s).

3. After it has been used in a reactor, a fuel rod will contain more chemical elements than it did when it was fresh. Why?

____

____

____

____

Operating the Reactor Safely

Starting and Stopping the Reactor

The reactor is operated by a crew in a control room. Instruments in the control room show measurements of water and steam temperature, pressure, flows, the number of neutrons in flight, and many other indications of what is happening at many points with the reactor.

To start the reactor, some of the neutron poison is removed from the circulating coolant. Then the control rods are slowly withdrawn, until the reactor comes to a stable low power and begins producing heat and steam. It takes about 36 hours to go from a complete stop to normal temperature and pressure. After that, small control rod movements change power level quickly.

Shutting down the reactor is easier than starting it up. Inserting the control rods all the way will reduce the chain reaction within seconds from 100% power to less than 3% power. Below the 3% level, the heat comes from the radioactive decay of the fission products and their daughters. The rate at which this heat is produced decreases continuously after the chain reaction is stopped.

Refueling

In the United States, nuclear power reactors are shut down every 12 to 18 months for refueling. A fuel rod must be replaced long before all the uranium-235 nuclei in it have fissioned, because some of the fission products (and daughters) that accumulate in the fuel rods are neutron poisons. By absorbing neutrons, the fission products tend to stop the chain reaction.

Courtesy of So. Calif. Edison/Photographer: Greg O'Loughlin

To refuel the reactor, the chain reaction is stopped and the reactor is allowed to sit for a while, to allow some of the more radioactive fission products to decay. The room in which the pressure vessel sits is flooded with water, which will act as extra shielding to protect the people refuelling the reactor.

On the ceiling of the reactor building is a giant crane travelling on tracks. It moves over the concrete shielding block covering the top of the room holding the pressure vessel, picks up the shielding block, and sets it aside. The top of the pressure vessel that holds the core can now be seen.

The top of the pressure vessel is removable. Machines unscrew the bolts holding on the cover. The crane lifts the top off the pressure vessel and sets it aside. Inside the pressure vessel, the handles on the tops of fuel assemblies can be now seen. A second, smaller crane lifts the assemblies that are to be replaced out of the core. Later, they are transported out of the building to a special temporary storage area in a rack in a swimming pool full of water.

The used fuel rods are stored in the pool for months, and sometimes years, while the fission products in them continue decaying. After five months, the fuel rods will be only 2% as radioactive as they were when they were taken out of the core.

Workers

There are many different jobs at a nuclear power plant, and they are filled by people with various backgrounds. Some have taken college courses on nuclear energy, but all are *trained* (and retrained!) by the company after they are hired. The operators are tested and certified by an agency of the federal government called the Nuclear Regulatory Commission. If the NRC is not satisfied with the performance of the reactor operators, it shuts the reactor down.

Many people who have never worked in a nuclear power plant wonder how safe the jobs are—mainly, they are afraid of exposure to radiation. One way of determining the safety of a job is to look at how many accidents workers have, how many days of sick leave they take every year, and how long they live. By such standards, working in a nuclear power plant is a safe occupation, much safer than mining or heavy construction.

Accidents

It is not possible for a nuclear power plant to explode like an atomic bomb. To make an explosion, the chain reaction has to build up very fast. Almost every neutron must cause another nucleus to fission, so very few neutrons can be allowed to escape or to be absorbed by non-fissionable nuclei. To make a weapon, the fissionable nuclei are concentrated in a very small space, with less than 10% non-fissionable nuclei. Chemical high explosives are needed to hold the fissionable material together long enough for the chain reaction to include as many nuclei as possible.

In contrast, less than 2% of all the nuclei in the core of a nuclear power plant are uranium-235. The fissionable nuclei are spread out, separated by many other kinds of nuclei, many of which are good neutron absorbers. Even if an uncontrolled chain reaction could occur in a pressurized water reactor, the fuel would simply melt and disperse. An atom bomb type of explosion could not occur.

Courtesy of South Texas Project

The most serious accidents that could happen in a nuclear power plant involve overheating of the core. Such an accident is called a loss-of-coolant accident, because the core can't overheat unless the coolant stops circulating through it. Circulation could be lost if a combination of pipes burst, for example. Conceivably, a dry, overheated core could melt through the pressure vessel. Hydrogen created by the high temperature could cause a chemical explosion, if it were ignited.

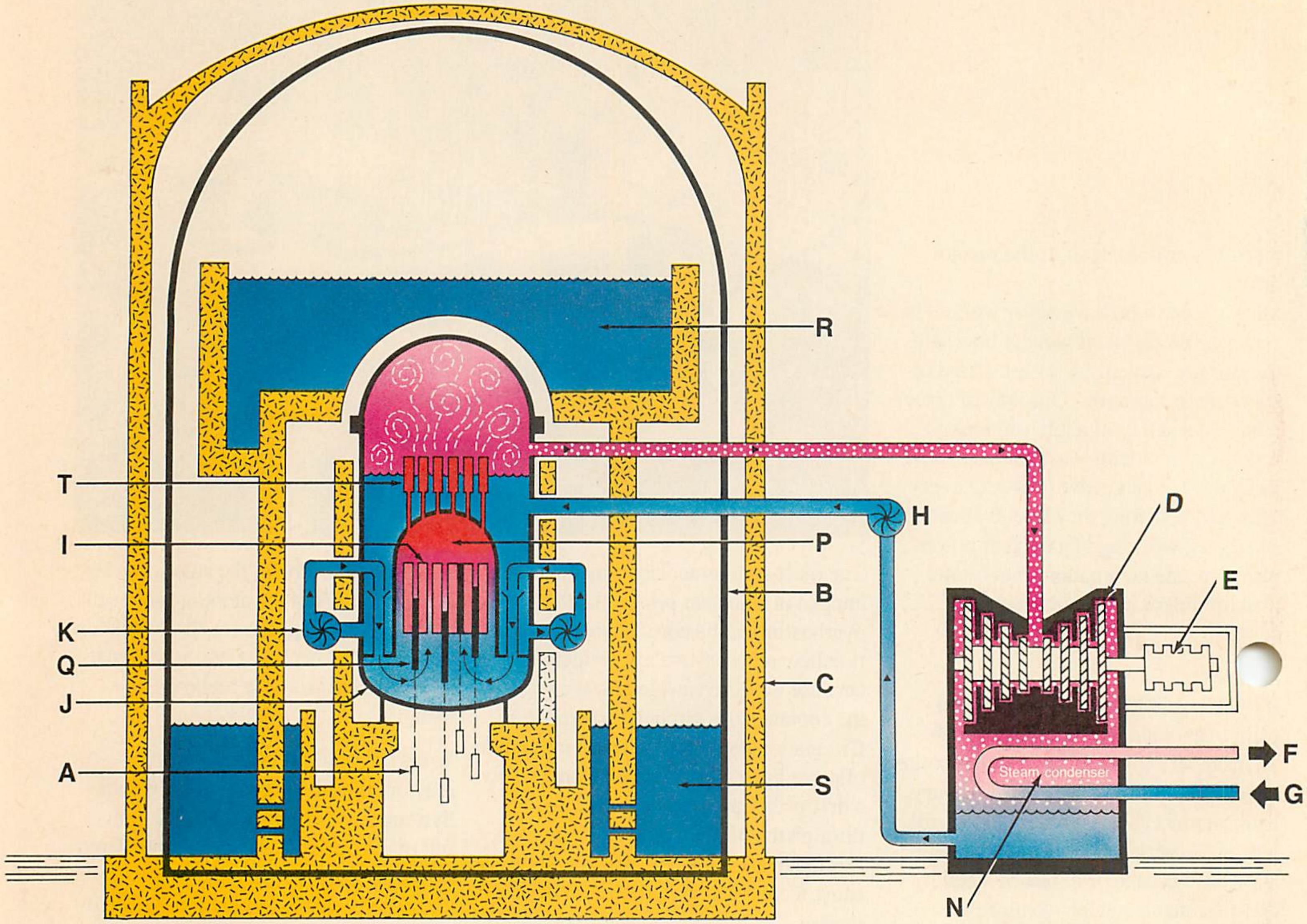
The reactor itself is designed to respond automatically to such an emergency, and the operators are also trained to respond. The response has two goals: to prevent damage to the core, especially the melting of fuel rods, and to prevent the release of material that would expose the public to radiation. Stopping the chain reaction is relatively easy. Losing the coolant itself tends to stop the chain reaction, because the coolant is also the moderator. The control rods drop in and neutron poisons are injected into the coolant. Even after the chain reaction stops, however, heat will continue to be produced in the core because of the decay of the fission products. Within ten seconds of shutdown, the amount of heat is less than 5% of the amount produced by fission at full power; with 15 minutes, less than 1%. Nevertheless, if this heat is not carried away the fuel rods will melt.

To carry away this heat, all power reactors have Emergency Core Cooling Systems: sets of pumps and reservoirs full of coolant completely separate from those that normally circulate water through the steam generators. A reactor has several different back-up safety systems, so that if one fails, another will be available. There must be several ways to correct or block any failure.

Safety Statistics

Although the public is very concerned about nuclear safety, studies show that the risk of large scale disaster from U.S. nuclear plants is far below other human caused events (airplane crashes, dam failure, fires, explosions, etc.) or natural events (hurricanes, earthquakes, floods). The amount of radiation a member of the general population presently receives from the nuclear industry is about 4% of the amount he or she receives from rocks or cosmic rays.

Boiling-Water Reactor



The boiling-water reactor is similar to the pressurized-water reactor except that it doesn't have a separate steam generator. The coolant is boiled within the pressure vessel, in the area just above the core, and is sent directly to the turbine.

Label the drawing using the following key:

_____=the reactor pressure vessel

_____=the steam turbine

_____=where the water is hottest

_____=where the fuel is

_____=the generator

_____=the control rods (in a BWR, they come up from the bottom)

_____=water pump

_____=containment

_____=shielding

_____=the condenser

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