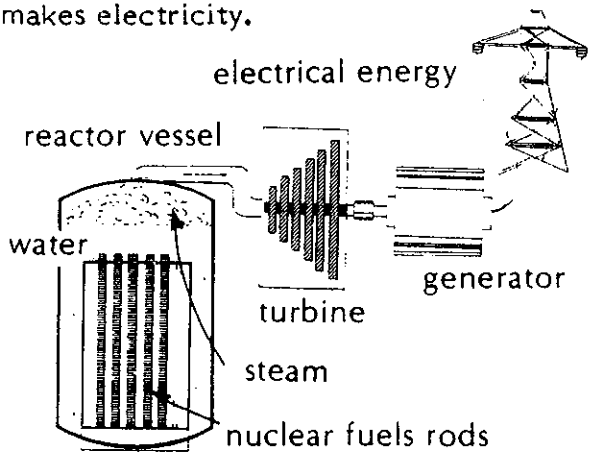
Worksheet C

How a Nuclear Reactor Works

From an energy standpoint, a nuclear reaction is really just another way to produce heat. That heat is used, in a nuclear power plant, to make electricity.

The nuclear reaction heats water to make steam. The steam turns the blades of a turbine, which spins a generator, which makes electricity.



But where does the heat of the nuclear reaction come from?

Nuclear Fuel

You have learned that nuclear energy is produced from a fission chain reaction. To have a chain reaction, you must have nuclear fuel. Nuclear fuel is matter containing atoms that will fission. In the United States, the nuclear fuel used is usually a mixture of uranium and other elements.

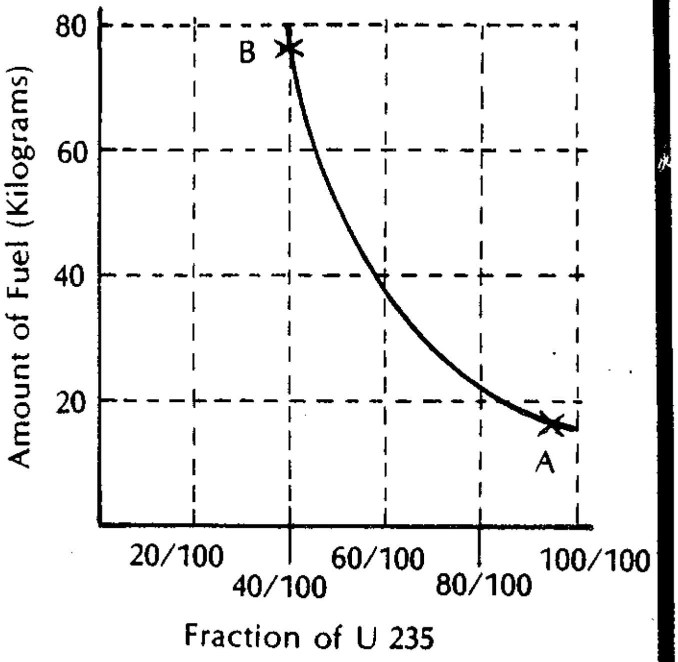
The fissionable part of the fuel is a form of uranium called U^{235}. U^{235} will fission if it is struck by slow neutrons. (There are other fissionable elements and other types of fission, but they won't be discussed here. Most reactors use the slow neutron fission of U^{235}.)

Critical Mass

To have a chain reaction you must have enough U^{235} atoms around for the neutrons to strike. The minimum amount of fuel needed for a chain reaction is called the critical mass. Without the critical mass, the reaction will never get going. A critical mass of fuel is needed because at least one neutron from each nuclear fission must cause another nuclear fission.

Now uranium fuel is a mixture of U^{235} with other kinds of uranium. And it's easy to see that the more U^{235} there is in the mixture, the easier it is to start a chain reaction and the less fuel you need to reach the critical mass.

Study the critical mass graph. The vertical axis shows the amount of nuclear fuel in kilograms. The horizontal axis shows the fraction of the fuel that is U^{235}. The curve shows the critical masses of uranium with different fractions of U^{235}. Notice that if a sample has a very high fraction of U^{235} (A), a small amount is enough for critical mass. If you have a lower fraction of U^{235}(B), you need more fuel to reach critical mass.



The Critical Mass of Uranium as a Function of Fraction of U^{235}

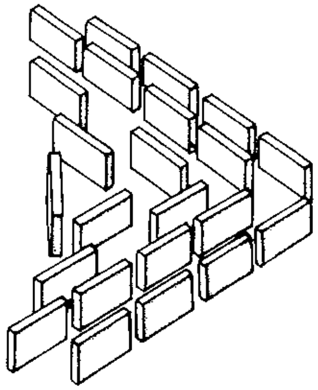
(From Ernest J. Moniz and Thomas L. Neff, "Nuclear Power and Nuclear-Weapons Proliferation," Physics Today, April 1978, p. 44.)

Worksheet B

Modeling Chain Reactions of Nuclear Fission

Let's see how a chain reaction works, and how chain reactions can differ.

A. An Uncontrolled Chain Reaction



(From Ronald M. Benrey, *Nuclear Experiments You Can Do...from Edison*, Thomas Alva Edison Foundation, Southfield, MI 48075, 1976, p. 11.)

Directions:

1. Take a box of dominoes, and set up the dominoes in the arrangement shown below.
2. Imagine that each domino is an atom of a fissionable element.
3. Start the fission reaction by tipping over the domino marked with the arrow.

Explanation: Notice that

1. The reaction starts small.
2. The reaction grows very rapidly.
3. The reaction stops only when all the dominoes have tipped over.
4. If you added more dominoes in the same pattern, the reaction would grow even more.

This uncontrolled reaction is like the reaction in an atomic bomb. The fissionable material is concentrated so that all of it will react very quickly. This produces a very high temperature all at once.

Now let's try a different kind of reaction, the kind you would have in a nuclear reactor.

B. A Controlled Chain Reaction

Directions:

1. This time you want a reaction that starts small, grows a little, stays at the same level for the rest of the reaction, lasts longer than the uncontrolled reaction, and stops when all the dominoes have tipped over.
2. Arrange the dominoes so that they will act as described above. (There are several possible arrangements.)
3. Tip over the dominoes to see if your chain reaction works.
4. Draw a diagram of your arrangement in the space provided.

Your Diagram

If you had 40 kg of fuel that was 40/100 U^{235}, would you have critical mass? What if it were 60/100 U^{235}?

In uranium as it is mined from the ground, only one atom of every 140 is uranium-235. Almost all the others are uranium-238. To get a larger fraction of uranium-235 atoms requires a process called "enrichment." It requires adding extra atoms of uranium-235, just like enriching bread means adding vitamins and minerals.

Effective operation of the nuclear reactors used in the United States requires that the uranium fuel be enriched so that 3 of every 100 uranium atoms are uranium-235. As you can see from the graph, this means that the critical mass is much more than 100 kilograms. In fact, each year about 27,000 kilograms of uranium fuel are replaced in each reactor. (And this is only one third of the total amount of uranium that each reactor contains.)

Because U^{235} is mixed with U^{238} in nuclear fuel, there is not enough concentrated fissionable material (U^{235}) in the fuel to explode like a nuclear weapon. On the other hand, uranium in a nuclear weapon is often concentrated much more.

Light Water Reactor Components

To have a nuclear fission chain reaction, then, you must have a critical mass of nuclear fuel. Of course, to produce useful energy, the reaction must happen in a controlled way. That is what the nuclear reactor is designed for: getting useful energy in a controlled way from a nuclear chain reaction. Here is how the reactor works.

The Fuel Rods

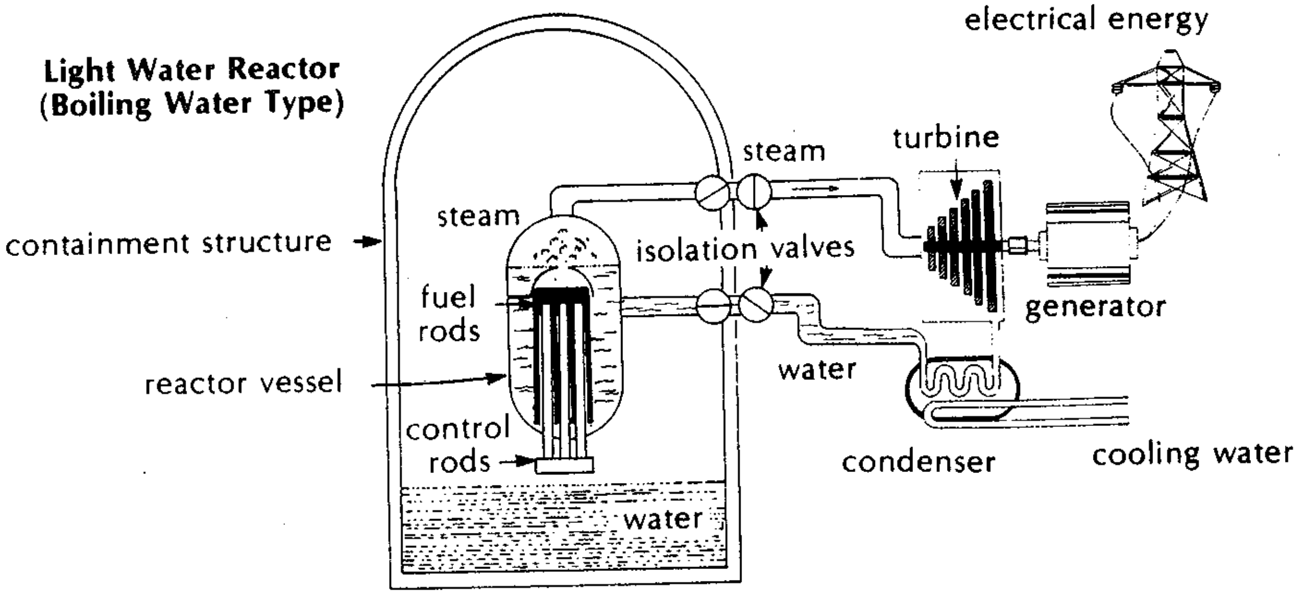
Nuclear fuel is produced in pellets, which are stacked in long rods. Thousands of fuel rods are suspended in the reactor.

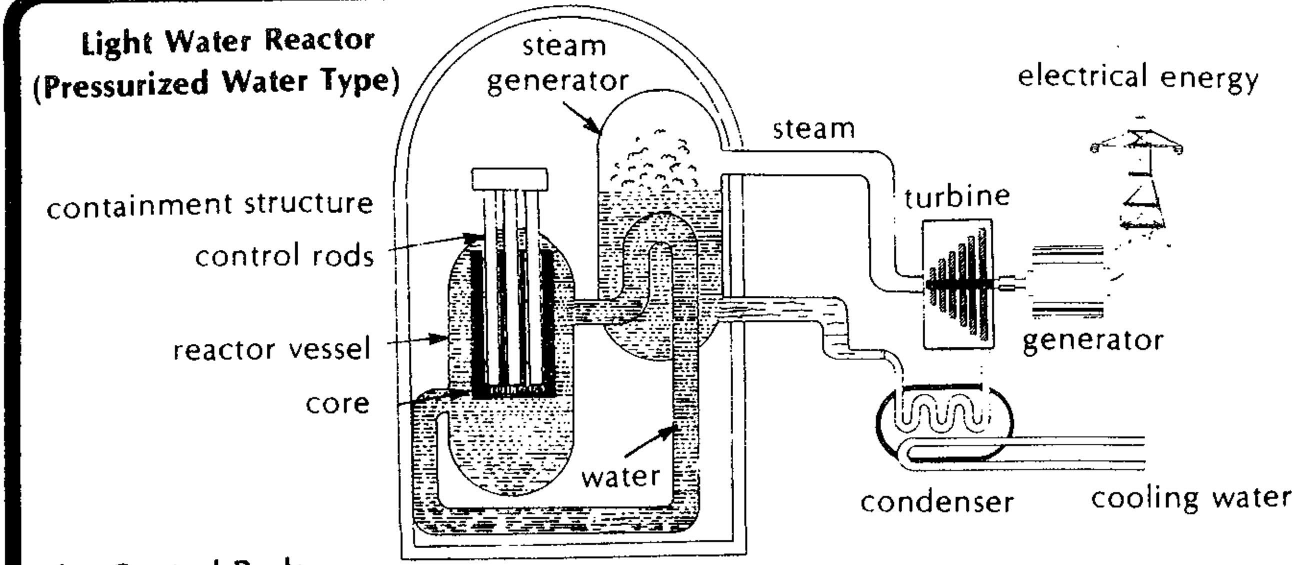
The Moderator

The reactor vessel is full of water, and the fuel rods are suspended in water. Why is this? When neutrons are released from the fission of a nucleus, they move very fast. But neutrons can fission nuclei of uranium-235 more easily when they move slowly. In a nuclear reactor something must be used to moderate the speed of the neutrons -- that is, to slow them down. This makes the chain reaction possible.

Most reactors now operating in the United States use water as a moderator. They use ordinary or "light" water. This is why they are called light water reactors (LWRs). (If you study other kinds of reactors you will learn about "heavy" water and graphite as moderators.)

Light Water Reactor (Boiling Water Type)





Light Water Reactor (Pressurized Water Type)

The Control Rods

The control rods are used, as their name suggests, to control the chain reaction. They contain elements like boron or cadmium, which can absorb neutrons. These rods are inserted between the fuel rods to absorb neutrons and control the reaction when necessary.

The Coolant

Finally, a nuclear reactor needs a coolant -- to take the heat generated by fission to where it can be used. In the light water reactor the moderator and the coolant are the same water. We use water both to slow down the neutrons and to absorb the heat of nuclear fission. Fission heats the water to make steam and the steam drives a turbine generator to generate electricity.

So the coolant converts fission energy to electricity. It also prevents the uranium fuel from becoming too hot. If this happened the fuel would melt and become a radioactive mass, which might damage or leak from the reactor.

Reactor Safety

The new elements formed during fission are radioactive and therefore potentially dangerous. Only a small fraction of these elements are gases, or would become gases if the fuel melted. Preventing the release to the public of these radioactive elements 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 for short. To handle a LOCA, reactors are designed to work the following ways:

1. The temperature of the uranium fuel is kept well below its overheating point.
2. In a light water reactor, the coolant is the moderator (water). So loss of coolant also means 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.
3. The control rods automatically move into place to absorb neutrons and stop the chain reaction when any abnormal situation is detected.
4. An emergency core cooling system (ECCS) turns on to replace lost coolant by rapidly injecting cooling water.
5. The reactor building itself (containment structure) is designed to withstand high pressure inside, and contain the energy released during a LOCA from steam and hot gases.

Worksheet A

The Breeder Reactor

Why Look for Another Type of Reactor?

In Activity 4, we studied the light water reactor. In this reactor, nuclear energy is released by using uranium as the fuel. However, this type of reactor can only use U^{235} as the fissionable material.

In natural uranium, U^{235} is present only in tiny amounts. After this fissionable material (U^{235}) has been used, it is gone for good. Furthermore, the supply of uranium in the world is limited. Therefore, if we continue to use U^{235} as the fissionable material to supply our energy demand, then sooner or later we will encounter the same problem we have now with oil: a shrinking supply of non-renewable fuel.

For this reason, another type of reactor has been developed that can produce power and at the same time make more fissionable materials than it uses. This type of reactor is called a breeder reactor.

How Does It Work?

When ${}_{92}U^{238}$ absorbs a neutron it will become ${}_{92}U^{239}$. This isotope of uranium will undergo beta decay to beome ${}_{93}Np^{239}$ which will undergo further beta decay to become ${}_{94}Pu^{239}$. This isotope of plutonium is fissionable and will undergo fission by absorbing neutrons. Accompanying each fission, more than two neutrons are liberated.

As you know, several things can happen to neutrons released by fission in a reactor. Some of these neutrons can be absorbed by coolant or control rods, or can escape from the core. Therefore, these neutrons can be considered as "lost". Like other types of reactors, breeder reactors also use at least one of these neutrons to evoke another fission. Therefore, self-sustaining chain reactions can be maintained and power can be produced.

What Makes the Breeder Different?

Unlike other types of reactors, a breeder reactor has a blanket of U^{238} surrounding the core. This blanket will absorb neutrons that would otherwise escape from the core or be absorbed by other materials. As already mentioned, by absorbing a neutron, U^{238} will become U^{239}. This isotope will undergo beta decay twice to become Pu^{239} which is fissionable.

The blanket around the core makes it possible to use at least one of the neutrons from each fission to produce Pu^{239}. Thus, for every one fissionable nucleus we use to generate power, we can produce at least one new fissionable nucleus. Therefore, a breeder reactor can generate power and at the same time produce more fissionable material (in the blanket) than it uses. This can then be used to make new fuel.

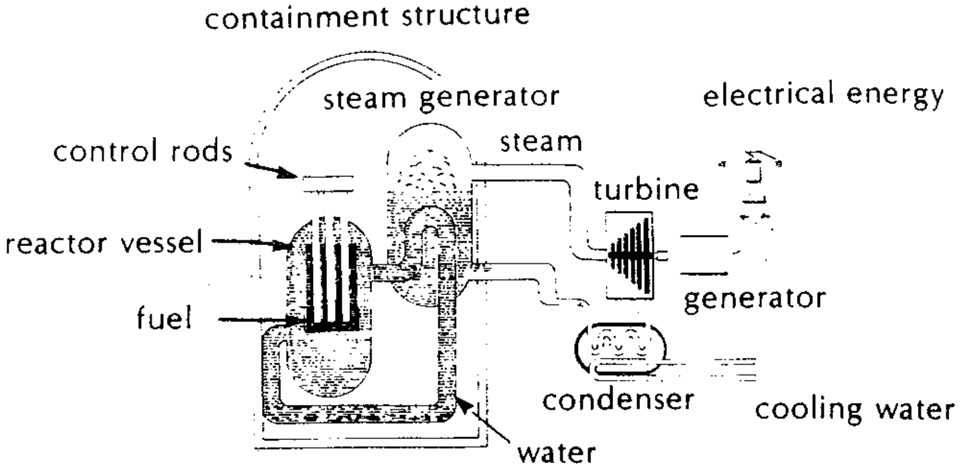
Why Doesn't This Happen in an Ordinary Reactor?

U^{235} tends to undergo fission by absorbing slow neutrons. For this reason, in an ordinary reactor, neutrons need to be slowed down before they can be used to fission U^{235}. Therefore, ordinary reactors have a moderator, "light water," which slows down neutrons.

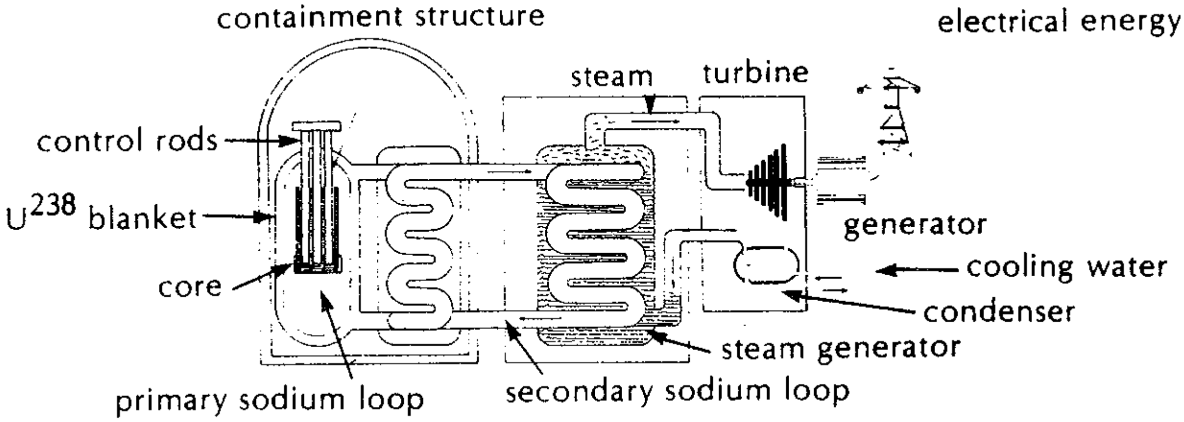
Pu^{239}, on the other hand, tends to undergo fission by absorbing fast neutrons. Therefore, a breeder reactor cannot have a moderator. In fact, a breeder reactor cannot have water as a coolant either, because the water would act as a moderator.

To see the differences between these two types of reactors, look at the following two diagrams. The Light Water Reactor (LWR) is an example of an ordinary reactor, while the Liquid Metal Fast Breeder Reactor (LMFBR) is a breeder reactor, as the name indicates. You probably notice two differences immediately.

Light Water Reactor



Liquid Metal Fast Breeder Reactor



What does the LWR use for a coolant/moderator? And what does the LMFBR use?

By using liquid sodium instead of water, the breeder allows more neutrons to be involved in the reaction. Sodium works as a coolant, but doesn't moderate. That is, it doesn't slow down or stop neutrons to the degree that water does. The result is that more fast neutrons are available.

What's more, the fuel in the breeder core is wrapped in a "blanket" of U^{238}. Many neutrons are absorbed by this U^{238}, resulting in U^{239} and plutonium.

Is That Good?

It depends on how you look at it. Certainly, from an energy standpoint, breeders are efficient. A breeder gets 60 to 70 times as much energy from uranium as a light water reactor does. But the safety question is important too. That's what the next reading is about.

To understand breeder reactors better, play the following game.

Worksheet B

The Plutonium Problem and Possible Solutions

We have learned how breeder reactors can produce power and at the same time produce fissionable materials. Do breeder reactors solve the problem of the limited supply of uranium? The answer is "yes." Unfortunately, though, the breeder may create other problems.

The plutonium-239 fuel made by the Liquid Metal Fast Breeder Reactor (LMFBR) presents two serious problems.

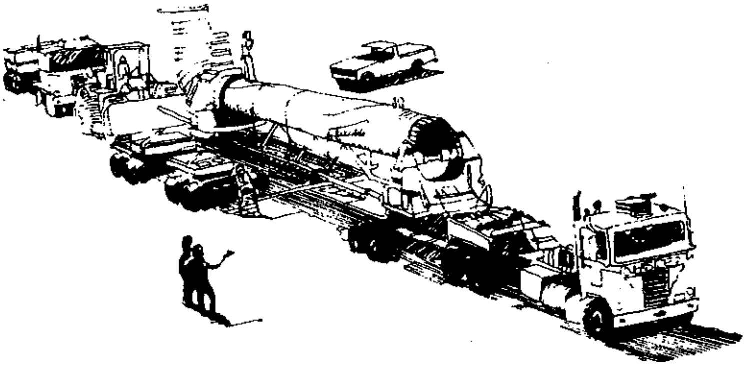
1. It can be used to make nuclear weapons.
2. If released into the environment, it is very hazardous to human health.

Plutonium in Nuclear Weapons

In light water reactor fuel, only about 3 of 100 uranium atoms are fissionable uranium-235, but over 15 of 100 fuel atoms in a LMFBR are fissionable plutonium-239. Furthermore, it is not as difficult to extract plutonium-239 from the fuel as it is to extract U^{235}. Plutonium and uranium are different chemical elements, so they can be separated by chemical processes. (This is not true for separating uranium-235 from uranium-238, because all uranium atoms have the same chemical properties.)

What this means is that the fissionable material in breeder fuel could be extracted to make bomb material. The plutonium in a breeder reactor is not completely ideal for making a nuclear weapon. This is because it is not pure plutonium-239. Other isotopes of plutonium are present as well. Nevertheless, the plutonium in a breeder reactor <u>could</u> be used by a highly skilled group of unauthorized people to make a nuclear weapon. This might cause nuclear weapons to <u>proliferate</u> (spread) to more groups and nations, including terrorist groups. Many nations (including 113 that do <u>not</u> have nuclear weapons) have in fact signed a treaty to oppose such nuclear proliferation.

One way to make the plutonium in breeder reactor fuel unattractive to would-be thieves is to mix some highly-radioactive isotopes with it. (These can be isotopes of fission products left in the "spent fuel" from a light water reactor.) This would make the plutonium "dirty," harder to handle, so it



would reduce the likelihood that the plutonium would be made into a nuclear weapon. But plutonium would still be a hazard to our health and environment.

Plutonium as an Environmental Hazard

Most isotopes of plutonium in reactor fuel give off alpha particles. Although alpha particles are stopped by the skin, inhaling plutonium dust allows alpha particles to do serious damage to the lungs. Inhaling as little as a quarter of a milligram of plutonium from reactor fuel is regarded as deadly.

A situation in which plutonium would be inhaled is very unlikely. Still, like other toxic materials, it requires planning to ensure that the hazard is minimized. The United States is not currently pursuing the development of the LMFBR. But our LWRs make more plutonium every day, and something will have to be done with it.

Advocates of breeder reactors argue that the best way to get rid of plutonium is to use it as a reactor fuel. Indeed, a majority of the nations participating in the International Nuclear Fuel Cycle Evaluation in March 1980 acknowledged the problems with plutonium but went on to support developing the LMFBR anyway. At the forefront of LMFBR development is France, with Great Britain and the Soviet Union not far behind.

Nuclear Energy Without Plutonium

The way to eliminate plutonium from the production of nuclear energy is to eliminate what "breeds" it, namely uranium-238. Two reactor designs do this, and both are being studied for further nuclear energy development. They are the <u>high temperature gas-cooled reactor</u> and the <u>light water breeder reactor</u>.

Both of these reactors use uranium-235 as their fissionable isotope. But instead of uranium-238 they contain thorium-232 (which, like uranium, also occurs in nature). Just as uranium-238 breeds fissionable plutonium-239, thorium-232 breeds fissionable uranium-233. In fact, after sufficient uranium-233 is bred it can be used instead of uranium-235.

Other Ideas

If you have completed this whole activity (and have been able to understand most of it) then you now know that nuclear reactors are not all the same. Besides the ones described here, there are still others: the Canadian CANDU (Canada Deuterium Uranium Reactor) the Swedish PIUS (Process Inherent Ultimately Safe) which is still on the drawing board, to mention two. Both LWRs and breeders come in various designs.

New reactor designs attempt to make nuclear energy more efficient and safe. Each design tries to address these public concerns:

1. that nuclear fuel and wastes pose problems for health and the environment,
2. that the supply of uranium is limited, and
3. that plutonium-239 can supplement our uranium supply, but it presents a special problem because of its potential use in weapons.