DOCUMENT RESUME

ED 242 501	SE 044 122
TITLE	Nuclear Power from Fission Reactors. An Introduction.
INSTITUTION	Department of Energy, Washington, DC. Technical Information Center.
REPORT NO	DOE/NE-0029
PUB DATE	Mar 82
NOTE	24p.
PUB TYPE	Guides - Classroom Use - Materials (For Learner) (051) -- Guides - Classroom Use - Guides (For Teachers) (052)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	Energy; Fuels; Instructional Materials; *Nuclear Energy; *Nuclear Power Plants; Nuclear Technology; Power Technology; Science Education; Secondary Education
IDENTIFIERS	PF Project

ABSTRACT

The purpose of this booklet is to provide a basic understanding of nuclear fission energy and different fission reaction concepts. Topics discussed are: energy use and production, current uses of fuels, oil and gas consumption, alternative energy sources, fossil-fuel plants, nuclear plants, boiling water and pressurized water reactors, the light water reactor fuel cycle, enrichment, reprocessing, the breeding process, breeder reactor design, the breeder reactor fuel cycle, and breeder reactors in the United States. Each topic is accompanied by an illustration or diagram to aid understanding. A section of additional information describes the history of nuclear power in the United States, and nuclear plants throughout the world. A glossary defines basic terms used to describe the fission process, the fuel cycle, and nuclear reactors. This pamphlet is suitable for use with secondary school students. (LP)

DOE/NE-0029

Nuclear Power From Fission Reactors

An Introduction

March 1982

The purpose of this booklet is to provide a basic understanding of nuclear fission energy and different fission reactor concepts.

U.S. Department of Energy
Assistant Secretary for Nuclear Energy
Washington, D.C. 20585

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Reprinted March 1983
Atomic Industrial Forum, Inc.
7101 Wisconsin Avenue
Bethesda, MD 20814

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Technical Information Center
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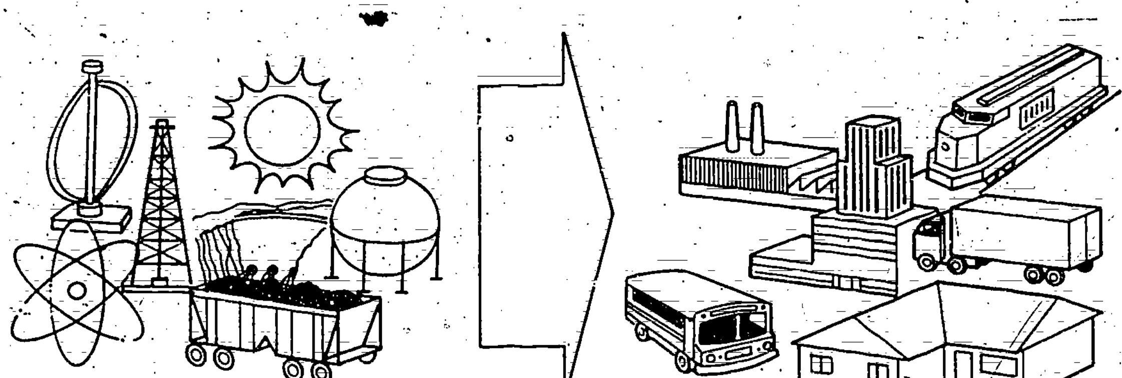
Energy Use and Production

Energy is an important element in nearly every aspect of daily living. It is vital to many of our needs, including heating and cooling, transportation, and electricity for lighting and to run machines.

The energy for these and many other uses is produced in many different ways. We get energy from fuels such as oil, coal, natural gas, and uranium. In addition, we can harness energy from the sun, running water, and the wind. Nuclear power is just one of many ways to produce energy. In order to understand its role, we can ask how it relates to other means of getting energy. In particular, we can look at the way in which we use our fuels today.

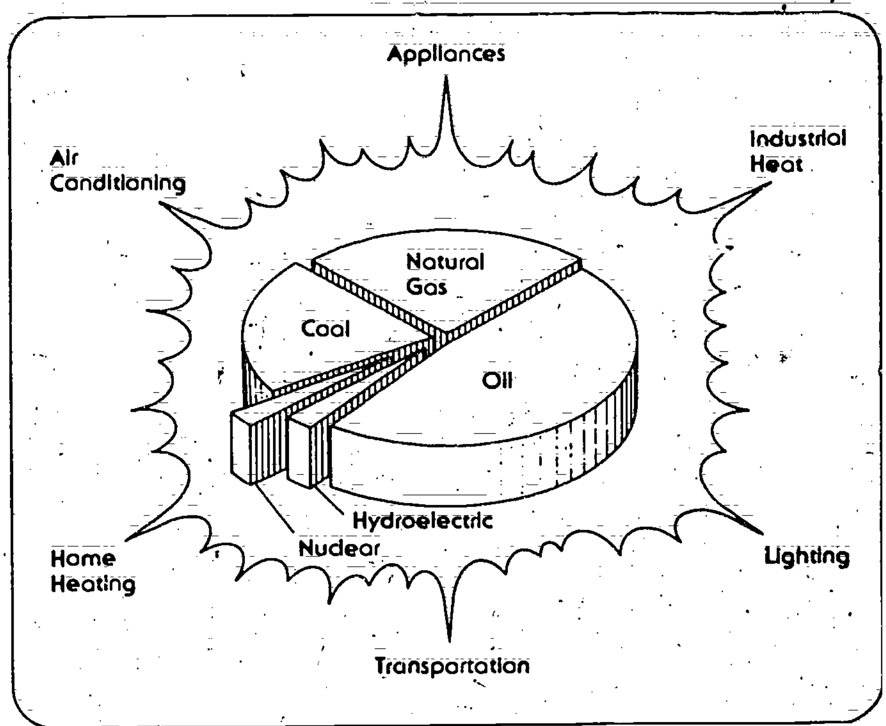


Sources of Energy

Uses of Energy

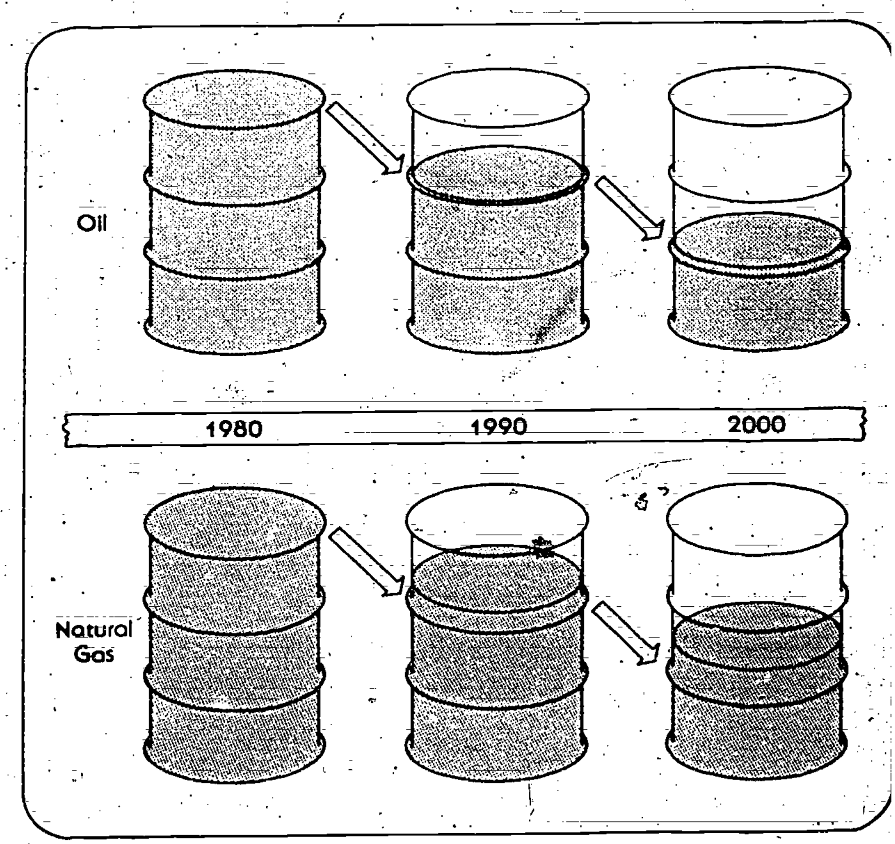
Current Use of Fuels

While there are many ways to produce energy, we do not use them all to the same extent. Some are not fully developed, while others are too expensive or of limited potential. In fact, most of the energy we use today comes from a few major sources--oil, natural gas, coal, uranium, and hydroelectric power. Two of these fuels, oil and gas, supply nearly three-quarters of the energy needs for the U.S.



Oil and Gas Consumption

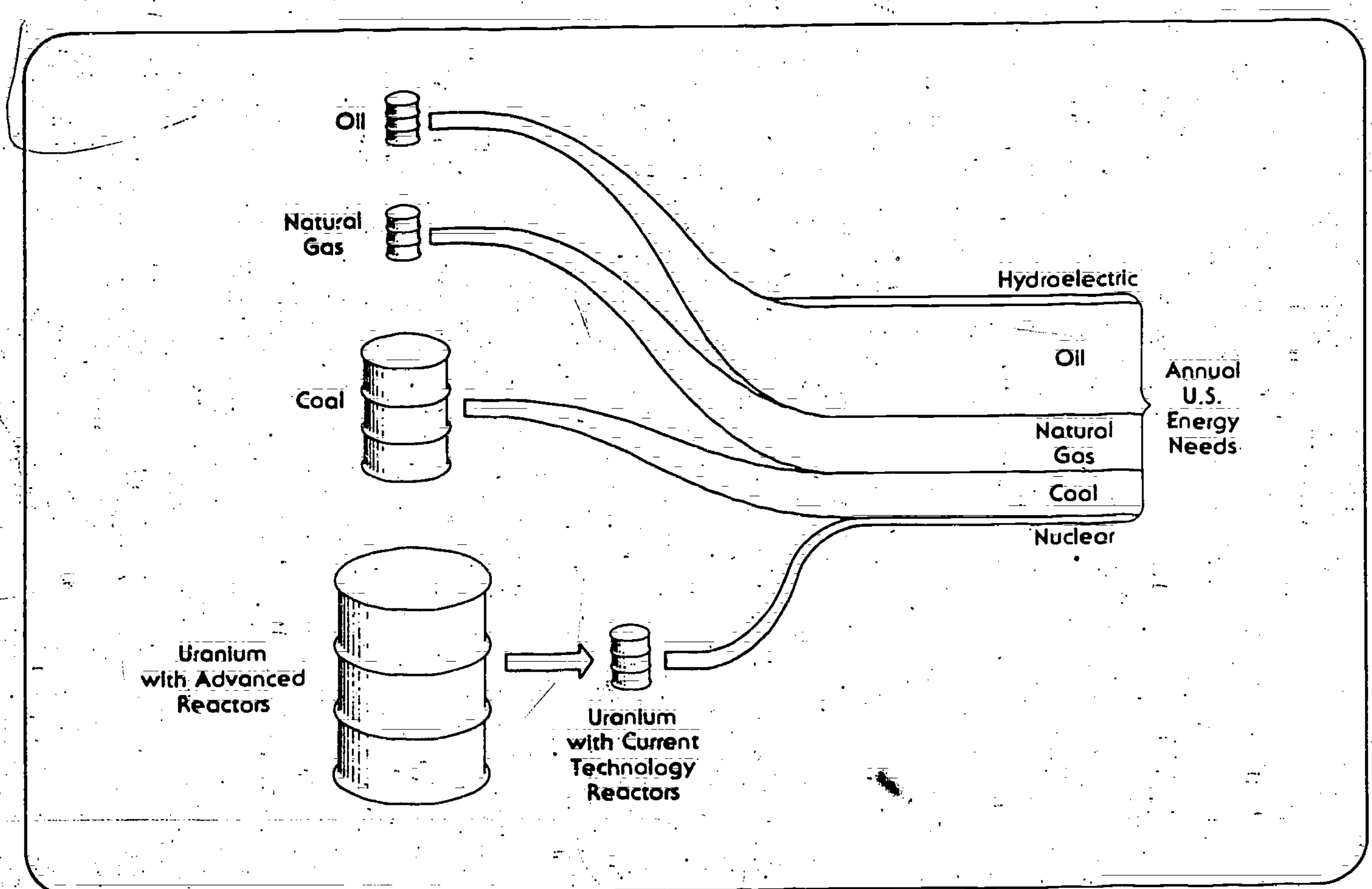
We know that the domestic supplies of oil and gas are limited. In fact, oil and gas deposits are being depleted rapidly. If we continue to use these fuels at the same rate we use them today, we will have consumed nearly one-quarter of all our oil and gas resources within the next ten years. If there are no significant new discoveries within 20 years, these valuable fuels will be half-way gone. Therefore, it is vital that we develop other energy sources that can replace oil and natural gas so that we may have a supply of energy for into the future.



Alternative Sources of Energy

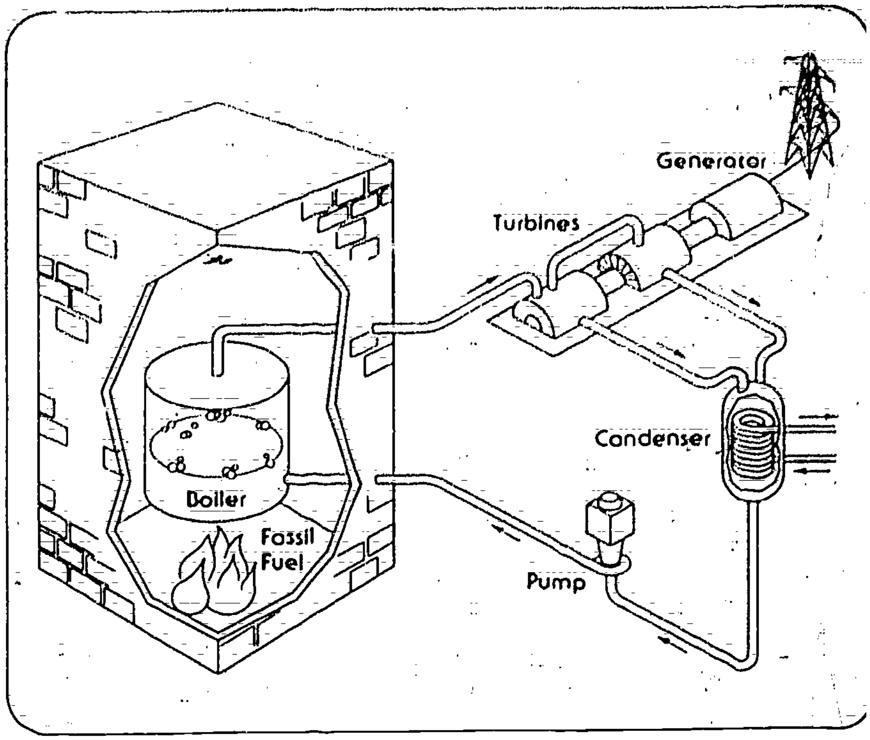
We are fortunate in the U.S. to have fuels besides oil and gas that can provide us energy for many years. As shown below by the size of the barrels, coal is a very large energy resource. The three fossil fuels--coal, oil, and natural gas--provide most of the energy used in the U.S.

Uranium, which is a nuclear fuel rather than a fossil fuel, can also produce energy. If used in today's reactors, uranium could provide as much energy as either oil or natural gas. In addition, if used in advanced reactors known as breeder reactors, the amount of energy obtained from uranium could be multiplied by a factor of 60.



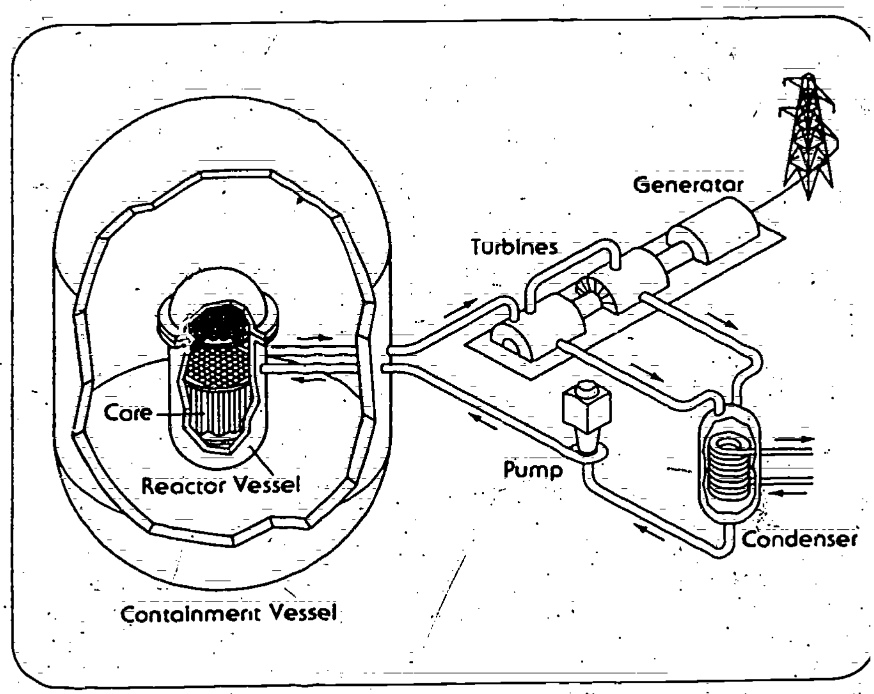
Fossil Fuel Plants

In conventional fossil plants, oil, coal, and natural gas can be burned to produce heat. Regardless of its source, the heat is converted into steam in a boiler. The steam expands as it passes through a turbine. This process drives a generator, which produces electricity. As steam leaves the turbine, it is condensed and returned to the boiler in the form of water.



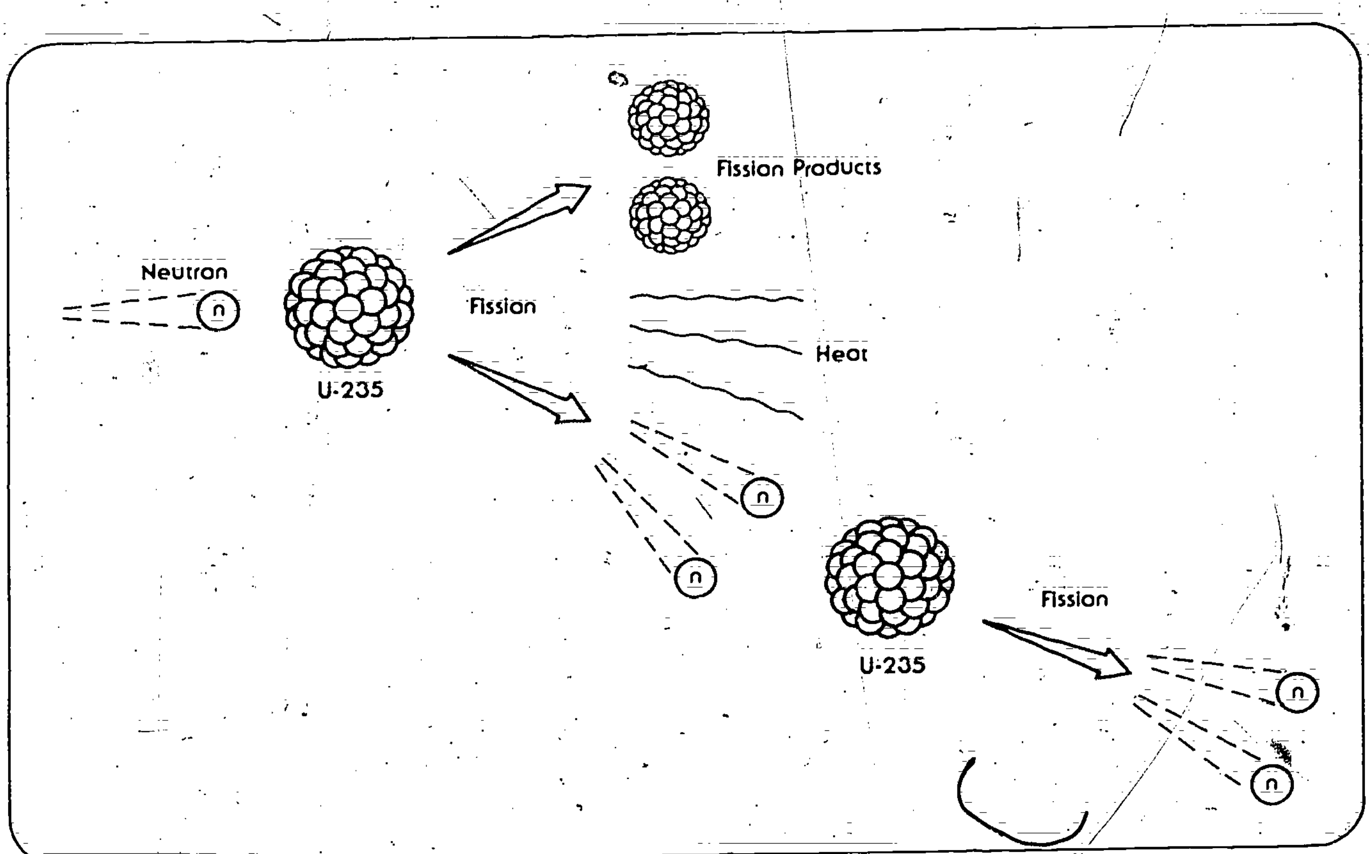
Nuclear Plants

In a nuclear plant, heat is also used to produce steam, which in turn is used to generate electricity. The main difference between a fossil plant and a nuclear plant is the source of heat. The heat in a nuclear plant is produced by a process called nuclear fission, which can occur in special types of nuclear fuel.



Nuclear Fission

The process of fissioning, or splitting, atoms can produce enough heat to generate electricity. Fission occurs readily in only a few elements, such as uranium and plutonium. One particular isotope of uranium, U-235, is commonly used in today's reactors. When a neutron strikes a uranium-235 atom, it is absorbed. This makes the nucleus of the U-235 atom unstable, and causes it to split into two lighter atoms called fission products. At the same time, energy in the form of heat is released along with two or three neutrons. The neutrons can strike other uranium atoms and cause additional fissions. The continuing process of fissioning is known as a chain reaction.

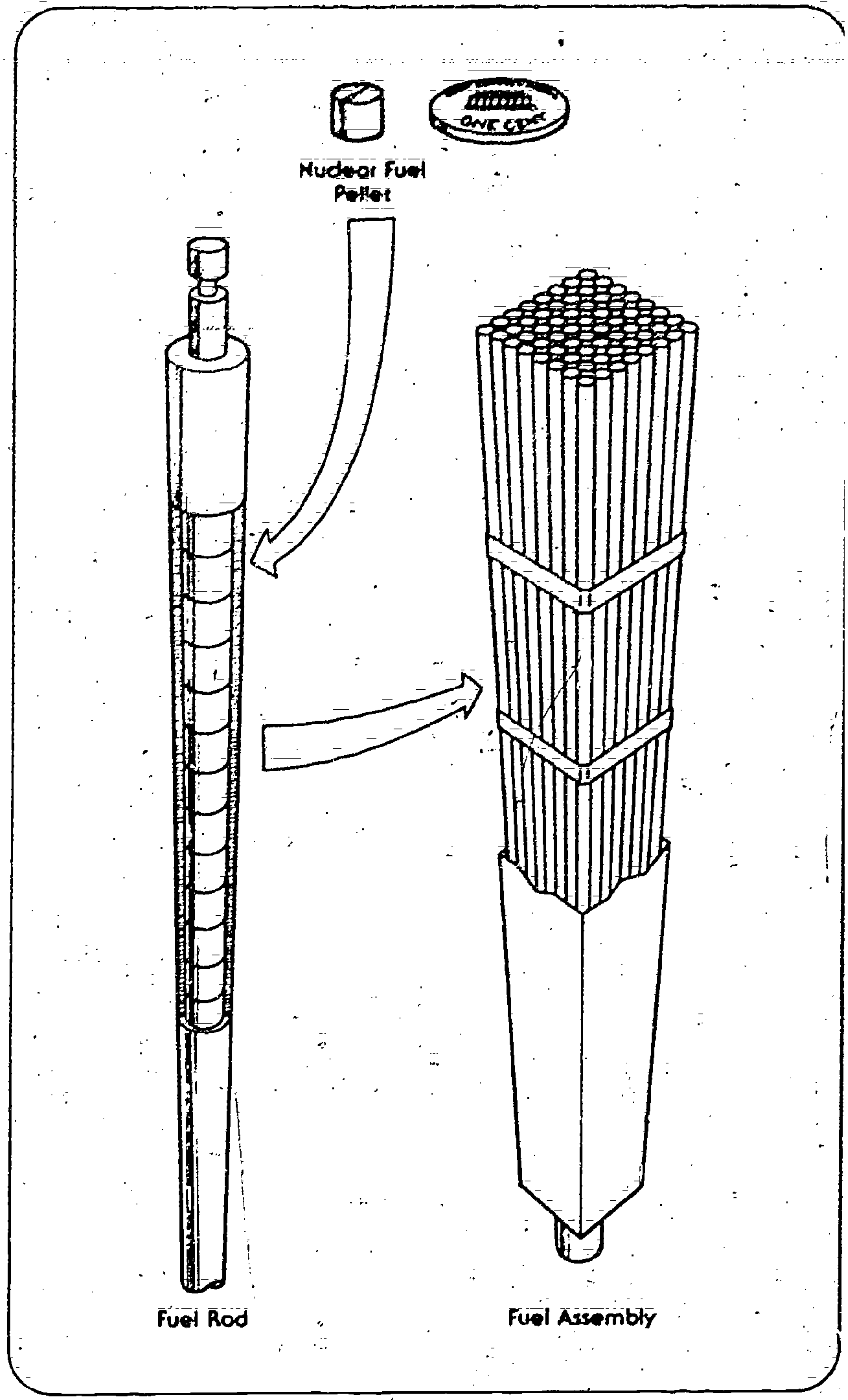


Nuclear Fuel

Only a few elements fission easily enough to be used as fuel in a nuclear power plant. Of these special materials, uranium is the most common fuel in today's reactors.

Any nuclear fuel, including uranium, must be processed through several steps before it can be used in a reactor. The fuel must first be carefully refined. It is then shaped into small cylinders known as fuel pellets. The pellets are less than 1/2 inch in diameter, but each one can produce as much energy as 120 gallons of oil.

Fuel pellets are stacked and sealed in hollow tubes about 12 feet long. The filled tubes are called fuel pins or rods. The rods are grouped together in bundles known as fuel assemblies. The fuel rods are carefully spaced in the assemblies to allow a liquid coolant to flow between them.



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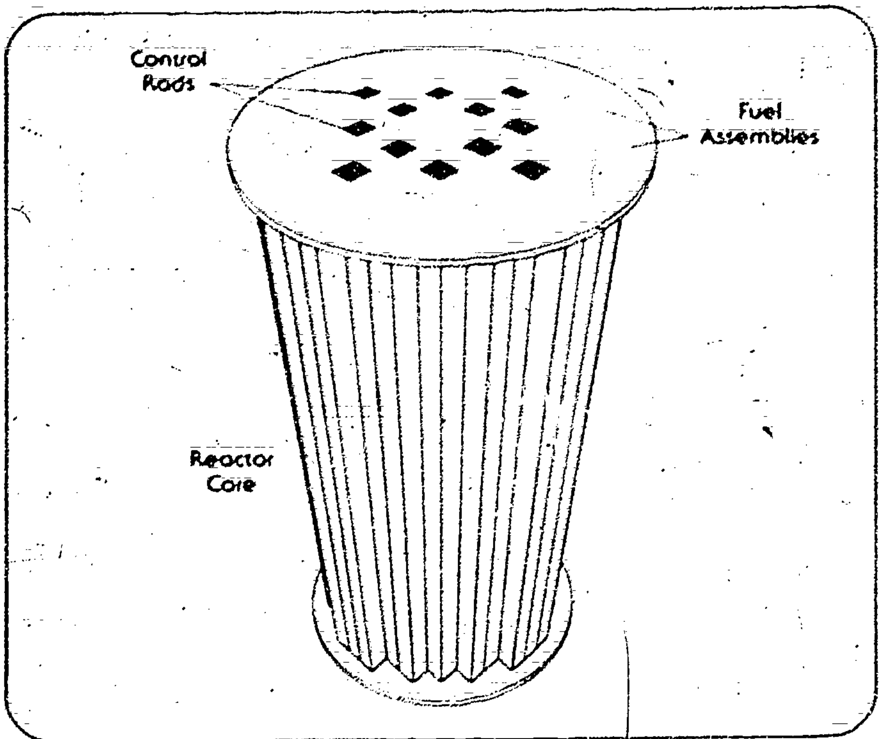
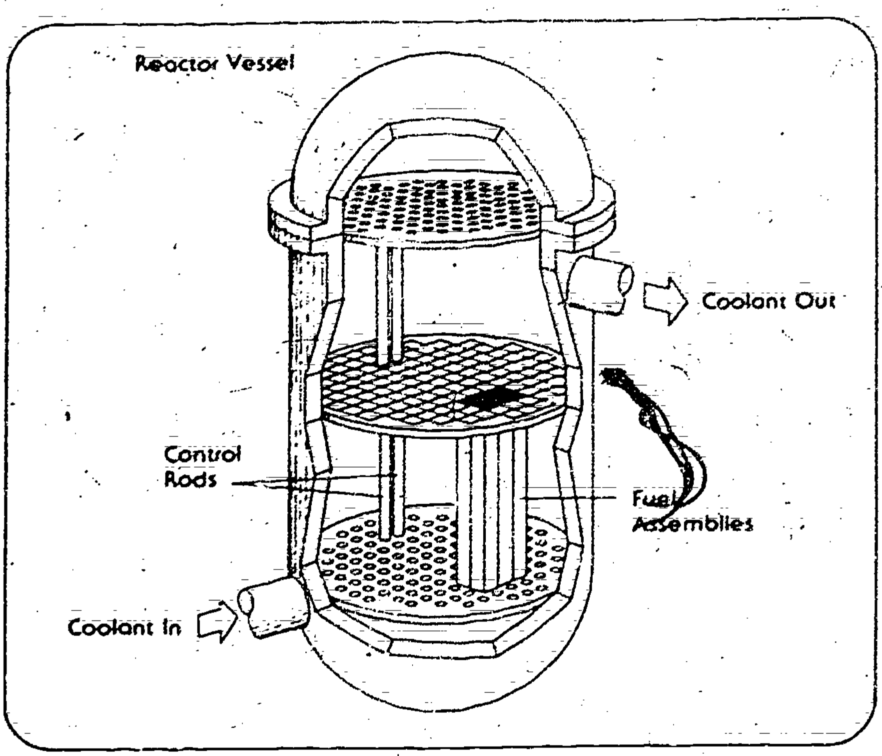


Reactor Core

Approximately 200 nuclear fuel assemblies are grouped together to make up the core of one reactor. Nuclear fuel in the core generates heat in a reactor just as coal or oil generates heat in a boiler.

Interspersed among the fuel assemblies are movable control rods, which are made of material that readily absorbs neutrons. When the control rods are inserted into the core, the nuclear chain reaction in the fuel assemblies is slowed down. This reduces the amount of heat produced by the core. When the control rods are withdrawn from the core, the chain reaction speeds up, and more heat is produced.



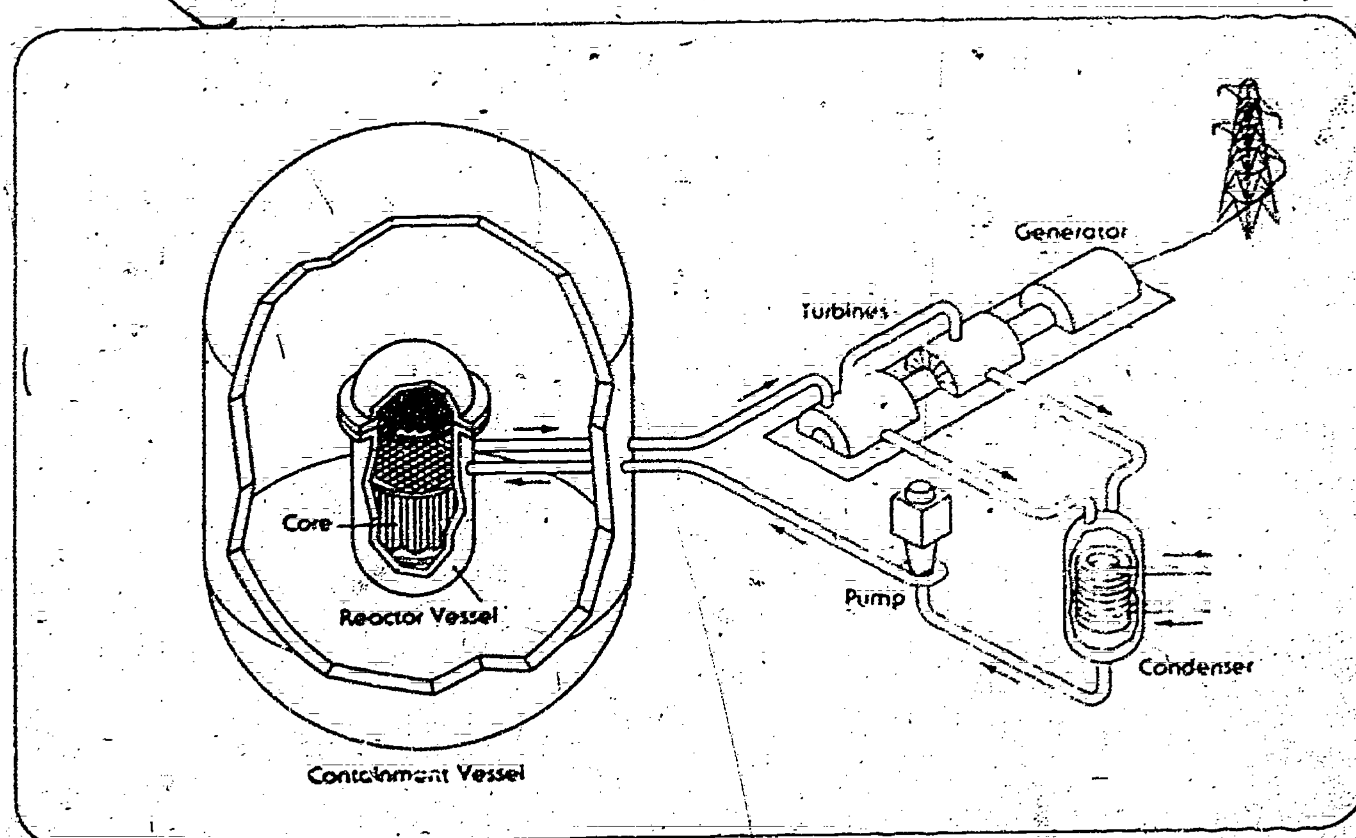
Reactor Vessel

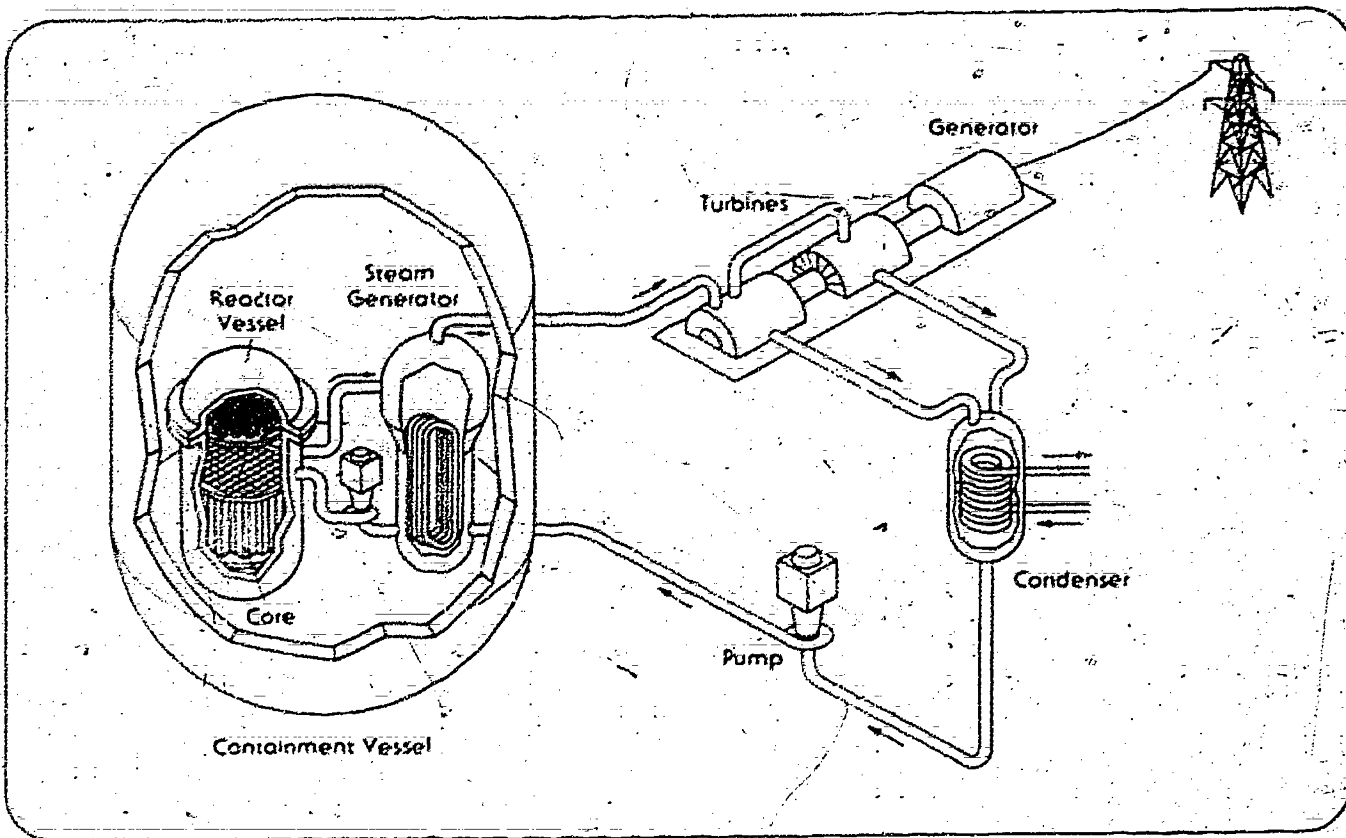
The entire reactor core, which contains fuel assemblies and control rods, is enclosed in a heavy stainless steel vessel. To ensure safety, the entire reactor vessel is housed in a reinforced concrete structure.

A liquid coolant is pumped into the reactor vessel through the core to remove heat. The coolant is then pumped out of the reactor vessel and is used to produce steam. Most of the nuclear power plants in the United States use water as a coolant. These plants are known as Light Water Reactors (LWR's).

Boiling Water Reactors

There are two distinct types of light water reactors in the U.S., and many of each type are built. In both reactors, fuel assemblies in the core are cooled by water, and the heated water is used to generate steam. In the Boiling Water Reactor (BWR), the pressure inside the reactor vessel is carefully controlled so that the water boils as it passes through the core. This reactor generates steam directly by the heat from the core, with no intermediate steps. This is known as a "direct cycle" system.





Pressurized Water Reactors

In the Pressurized Water Reactor (PWR), the pressure is kept high enough to prevent boiling, even though the water is very hot. In the PWR, the heated water from the core is pumped into a steam generator. At this point, the heat is transferred to another coolant system and steam is produced. The water from the core is circulated again and again through the primary loop without ever being converted into steam.

LWR Fuel Cycle

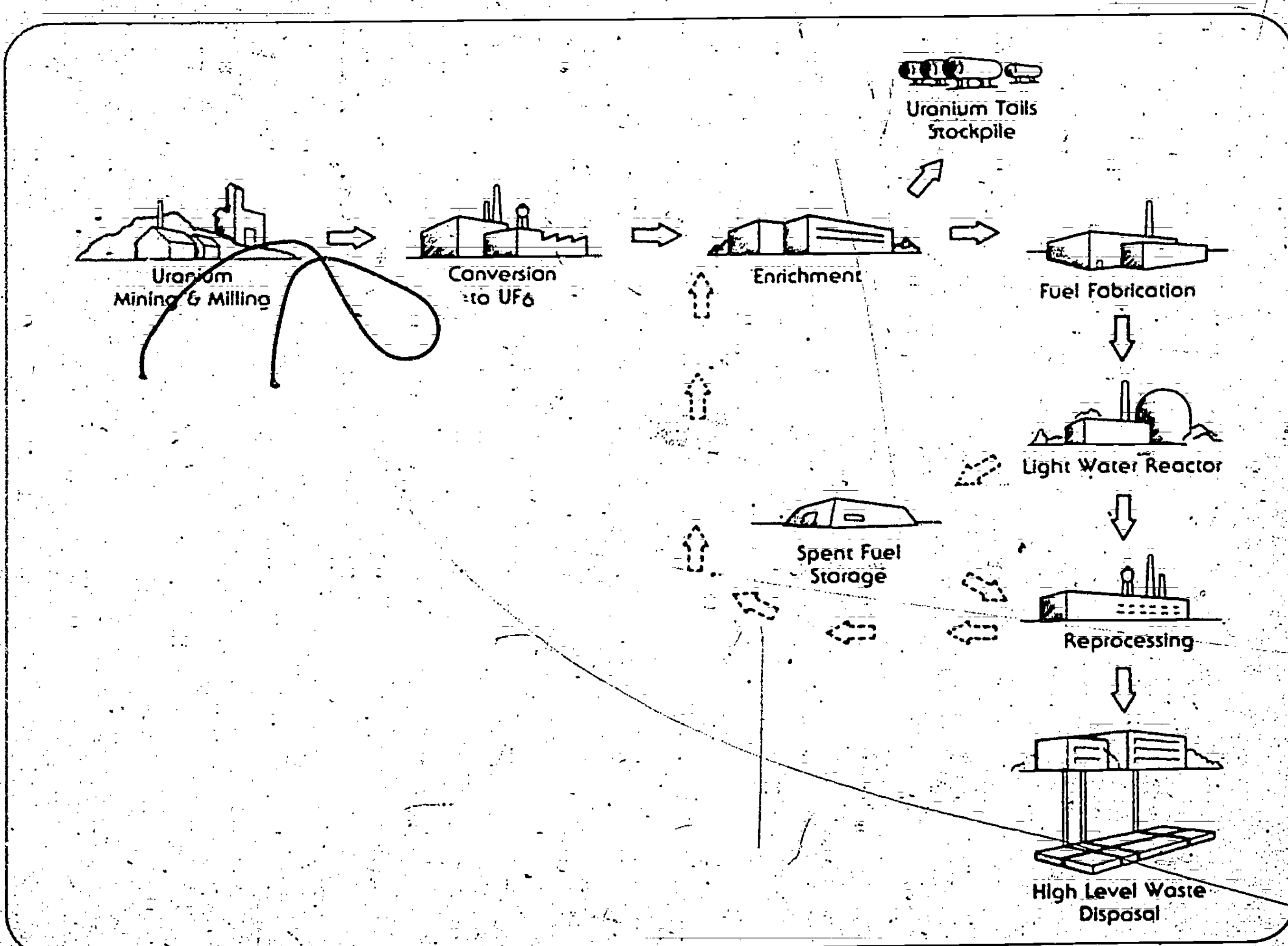
Light water reactors have been built in the U.S. for many years, and the industry that supplies equipment and services is well-established. However, it is not enough to build a reactor that produces heat and electricity. We must also be able to find and prepare nuclear fuel. In addition, we must handle fuel after it is discharged from the reactor. The fuel cycle represents all the elements that must be developed to have a complete nuclear power system.

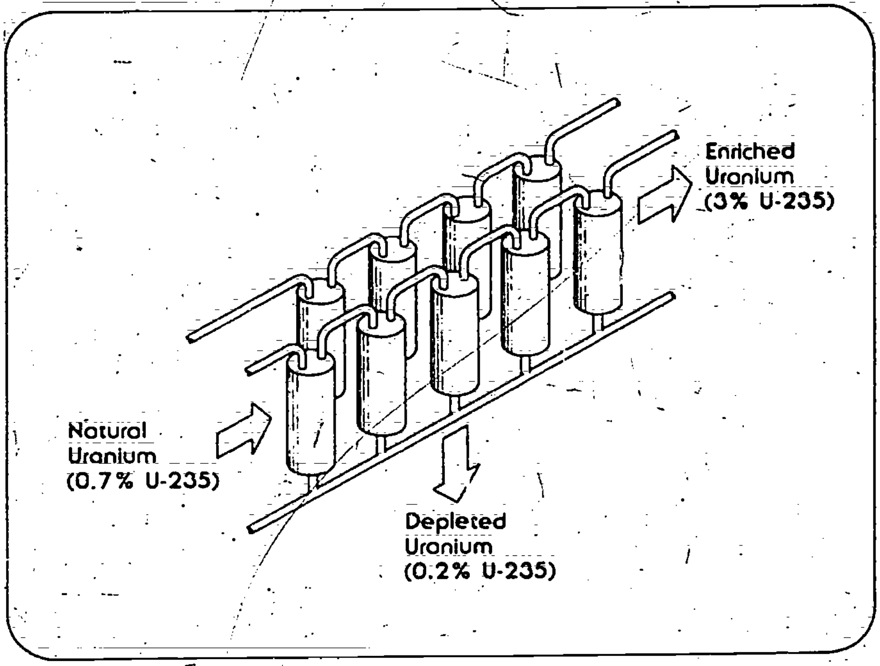
Mining uranium ore is the first step in the fuel cycle for light water reactors. After being mined, uranium is sent to a mill to be crushed and ground. The mill produces "yellowcake," which has a large concentration of the uranium compound U_3O_8.

Yellowcake contains, among other things, several isotopes or varieties of uranium. One such isotope is uranium-235, which is important because it fissions readily in a reactor. Uranium-238 is another isotope found in natural uranium, but it does not fission as easily. Unfortunately, natural uranium is composed primarily of U-238 and has less than 1% U-235. The concentration of uranium-235 can, however, be increased artificially. This is done by first converting the yellowcake to another chemical form and then processing it in an enrichment plant.

After uranium is enriched enough to be used in a reactor, it is fabricated into nuclear fuel elements. The fuel elements are grouped into fuel assemblies and placed in the core of a reactor. The fuel remains in the core and produces power for three to five years before it is removed.

After being discharged from the reactor core, nuclear fuel is cooled in a pool of water near the reactor. After it has cooled long enough to be handled easily, it may be shipped to another location. If it is shipped to a reprocessing plant, valuable fuel would be separated from radioactive waste. The waste material would then be stored safely and the fuel would be available to be used again. If reprocessing plants are not immediately available, it is possible that the spent nuclear fuel would be shipped to an interim storage facility.

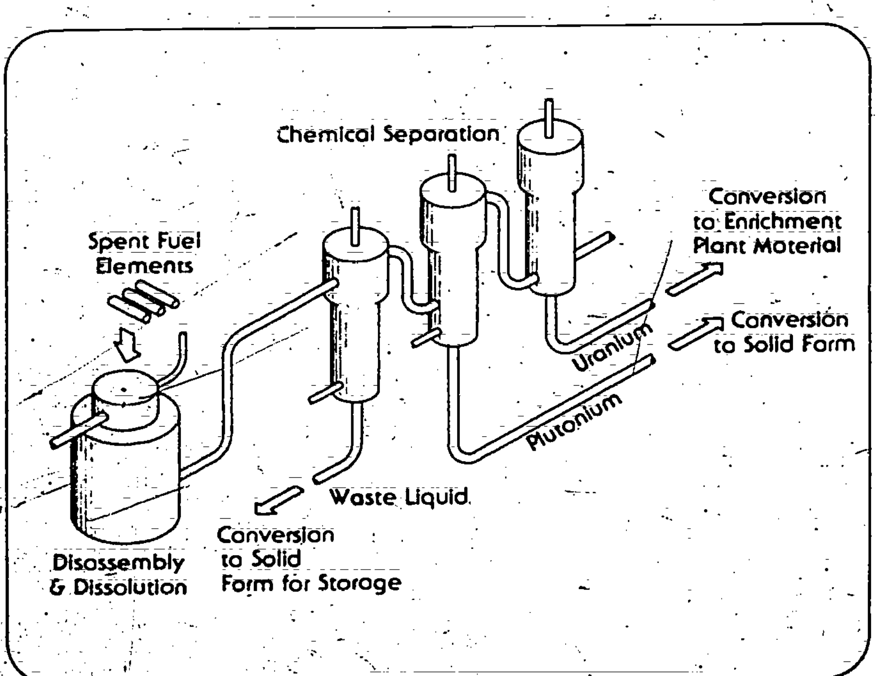




Enrichment

The process of enriching uranium is very sophisticated, but it accomplishes a simple purpose--it increases the concentration of the isotope U-235 in uranium. This is a necessary operation in the LWR fuel cycle, since natural uranium does not contain enough U-235 to run an LWR.

During the process of enrichment, natural uranium is fed into the enrichment plant. Only 0.7% of this uranium is U-235, while 99.3% is another isotope of uranium, U-238. The natural uranium is processed and split into two streams. One contains the concentrated uranium, which is usually about 3% U-235. This is sent to be fabricated for use in light water reactors. The other stream is depleted uranium, or "tails," which contains only 0.2% U-235. Since it is not usable in today's reactors, it is stored.



Reprocessing

Even after fuel is removed from a reactor, it still contains some usable nuclear material, such as uranium or plutonium. The usable fuel can be salvaged, however, only if it is reprocessed. This is a method of chemically separating valuable nuclear materials from radioactive waste material.

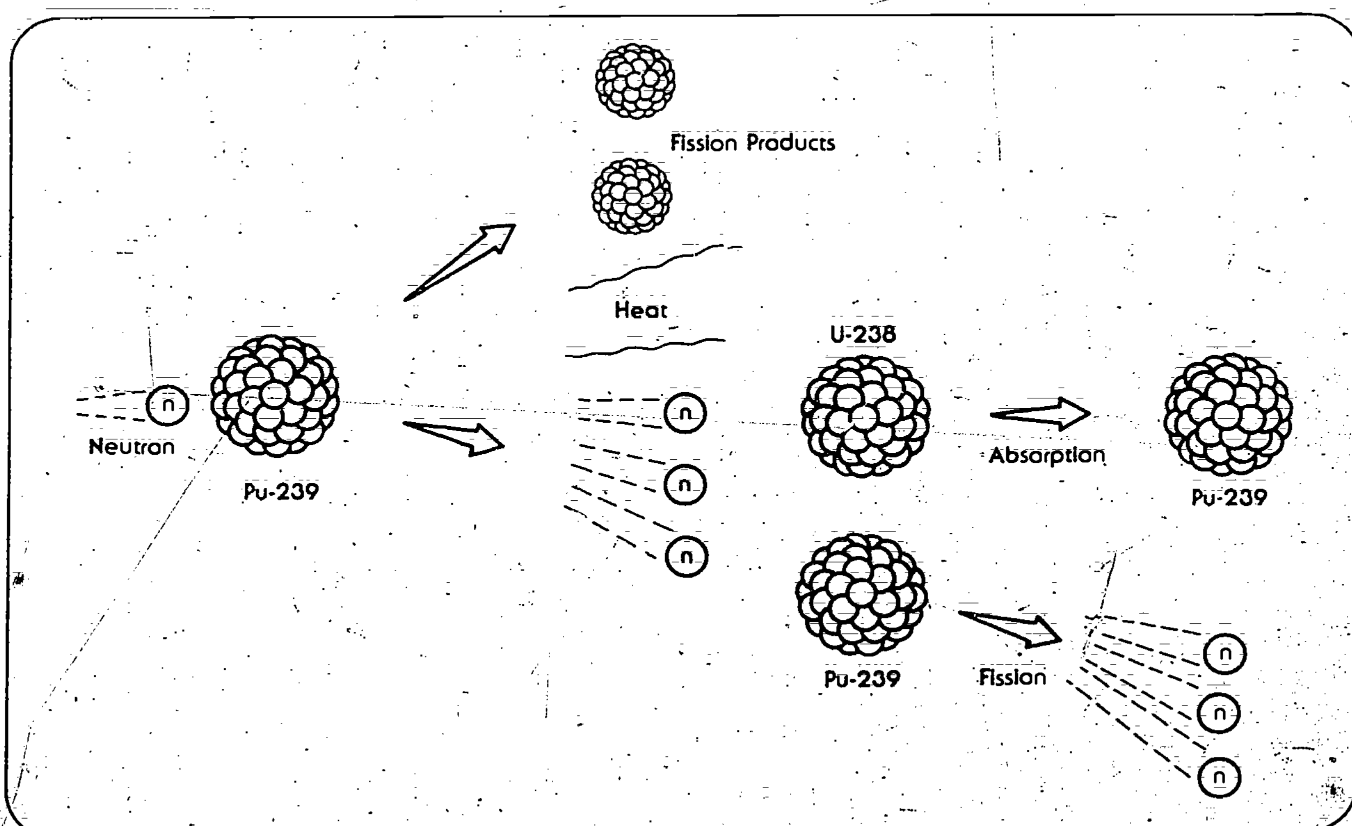
Nuclear material that is recovered during reprocessing can be reused many times. Uranium can be enriched again and used in light water reactors. Recovered plutonium would probably be stored until it could be used in advanced reactors.

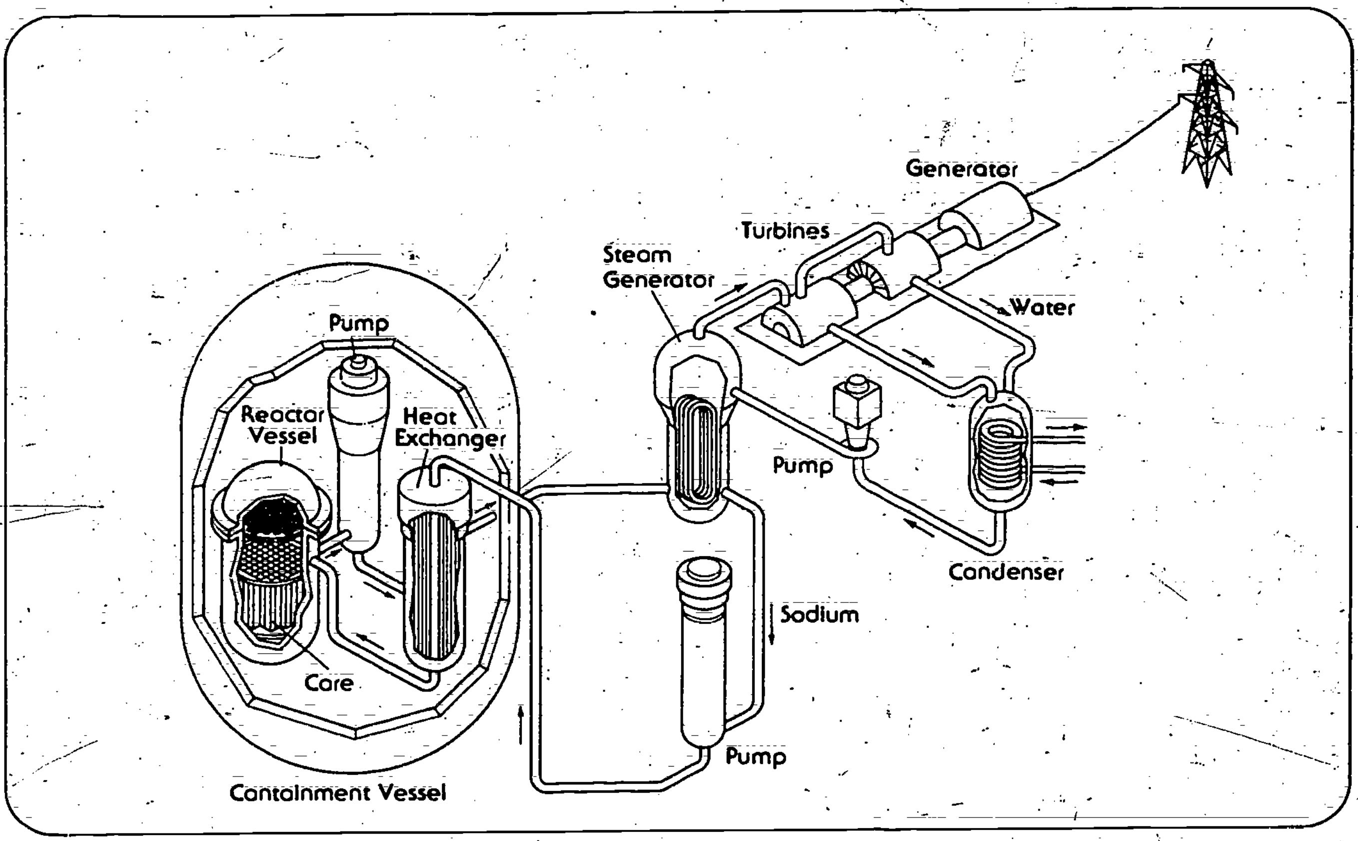
Waste material can be changed in form from a liquid to a type of glass and then buried so that it will not contaminate the environment.

The Breeding Process

The breeder reactor is able to get much more energy from uranium than a light water reactor because it uses it in a different way. In a light water reactor, the fission process depends primarily on U-235, which is found in small quantities in natural uranium. The breeding process depends on a different element, plutonium. When struck by a neutron, plutonium splits into two fission particles and releases heat and several neutrons. If these neutrons strike other plutonium atoms, the fission process can continue in a chain reaction. This is very similar to fission in a light water reactor.

But where do we get the plutonium to start the whole process? It does not occur in nature, and cannot be mined like uranium. Plutonium is, however, formed inside all nuclear reactors that use uranium as a fuel. This occurs when a U-238 atom is struck by a neutron. In general, this does not result in a fission. Rather, the atom of U-238 usually absorbs the neutron, and an atom of plutonium is created. This happens to some extent in light water reactors. Breeder reactors, however, are designed to enhance this effect. In fact, breeder reactors can create more plutonium than they consume.

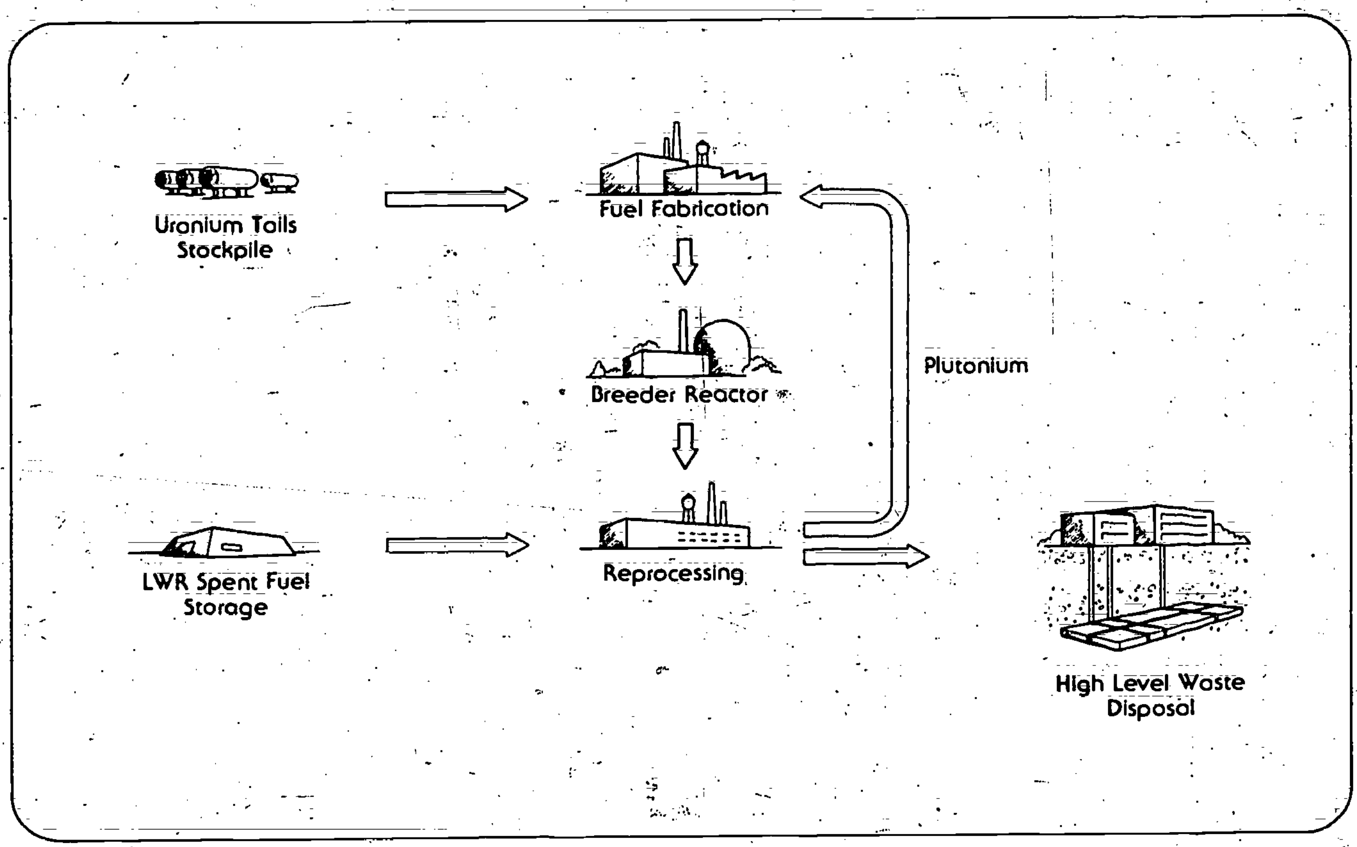




Breeder Reactor Design

The most common design for a breeder reactor uses liquid sodium as a coolant, rather than water. This type of reactor is known as a Liquid Metal Fast Breeder Reactor (LMFBR). Liquid sodium is an excellent heat transfer fluid, and it allows the LMFBR to be operated at high temperatures and low pressures. This produces a more efficient conversion of heat into electricity.

In a breeder reactor, liquid sodium is pumped through the core and into a heat exchanger. There heat from the core is transferred to another sodium coolant system. This second loop of liquid sodium is used to generate steam. Since the sodium in the secondary loop never passes through the core of the reactor, it does not become radioactive.



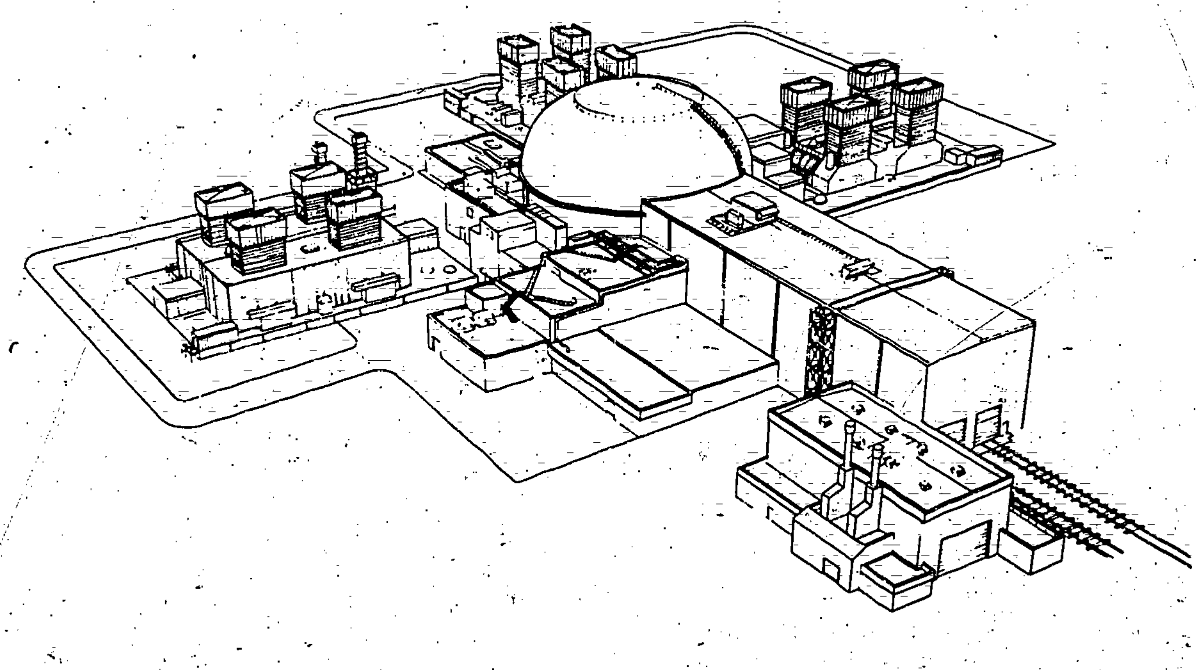
Breeder Reactor Fuel Cycle

The fuel cycle for the breeder reactor is different from the LWR fuel cycle. With the breeder reactor, there is no need to mine, convert, or enrich uranium, since it does not require high concentrations of U-235. The uranium that is used in the breeder reactor can be taken from the depleted stockpile produced by enrichment plants. This is useless in a light water reactor, but can be converted to plutonium and used as fuel in a breeder reactor.

In order to obtain plutonium to fuel a breeder reactor, it is necessary to reprocess nuclear fuel that has been removed from another reactor. Light water reactors produce some plutonium during normal operation, and the spent fuel from this type of reactor may be reprocessed to recover plutonium for a breeder reactor. In addition, fuel discharged from breeder reactors can be reprocessed and reused again and again.

Breeder Reactors in the U.S.

The objective of the U.S. breeder reactor program is to develop the technology to the point where the reactors may be built commercially. As part of this program, the U.S. built several experimental breeder reactors, starting in 1951. The most recent reactor to be completed is the Fast Flux Test Facility, which is used to test materials and fuels that may be used in future reactors. The next step is to complete the Clinch River Breeder Reactor, which is currently under construction. The final stage in developing the breeder reactor would be to construct a large-scale demonstration plant.



Fast Flux Test Facility

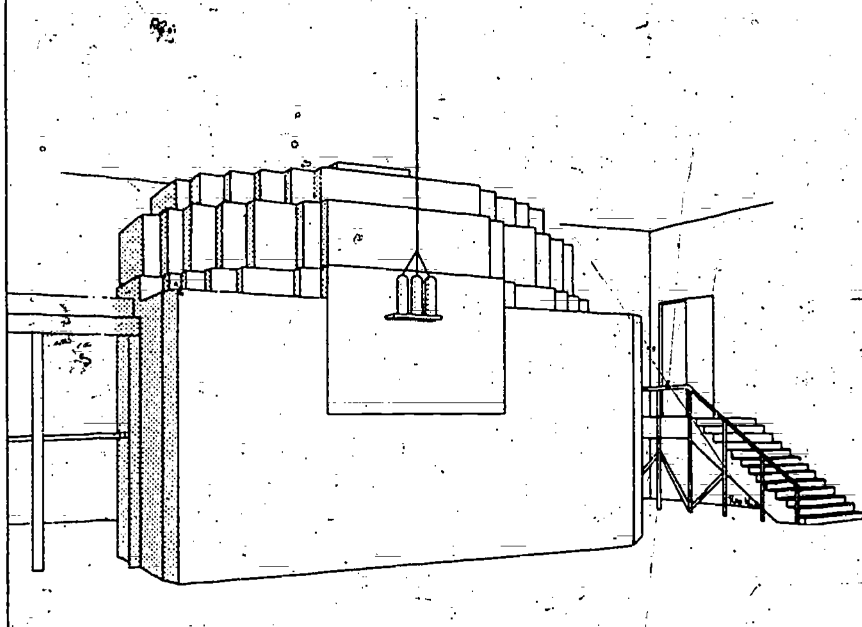
ADDITIONAL INFORMATION

History of Nuclear Power in the U.S.

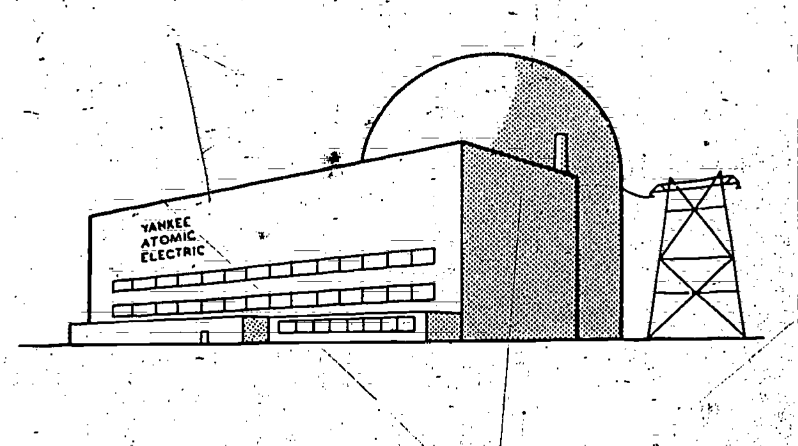
In December of 1942, a team of scientists, led by Nobel prize physicist Enrico Fermi, produced the world's first controlled nuclear chain reaction. The experiment took place at Stagg Field in Chicago in a simple reactor. This early nuclear research was directed toward developing weapons for use in World War II. However, the concept of using nuclear power for peaceful purposes was also important to the scientists. Fermi wrote, "We all hoped that with the end of the war, emphasis would be shifted decidely from the weapon to the peaceful aspects of atomic energy."

Shortly after World War II, the U.S. government began to develop civilian applications of nuclear power. By the mid-1950's, it was a goal of the government to demonstrate that nuclear power could safely produce electricity for use in the private sector. As a first step towards achieving this goal, the U.S. government developed the light water reactor, and commissioned the first one in 1957. This was the first reactor in the U.S. to provide electricity to the public.

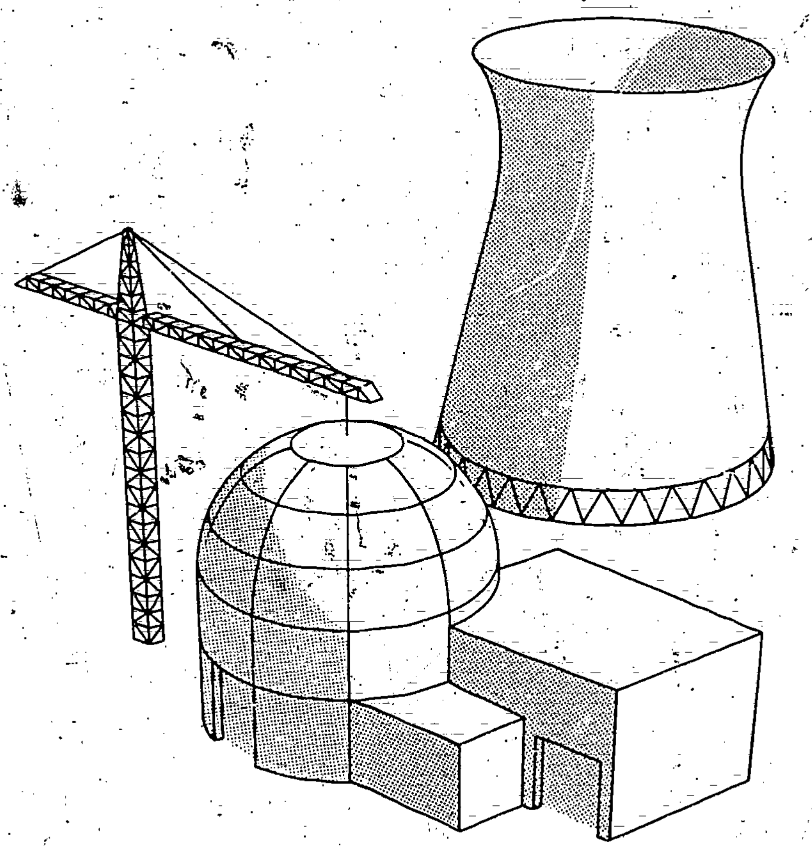
Although this first plant was entirely financed and constructed by the government, subsequent projects encouraged industry participation. Through cooperative efforts by government and industry, a series of reactors were constructed. These plants were the forerunners of today's commercial reactors. The first generation of light water reactors includes Dresden-1 in Illinois and Yankee Atomic Power Station in Massachusetts, which were commissioned in the early 1960's.



First Nuclear Reactor at Stagg Field



Early U.S. Power Reactor



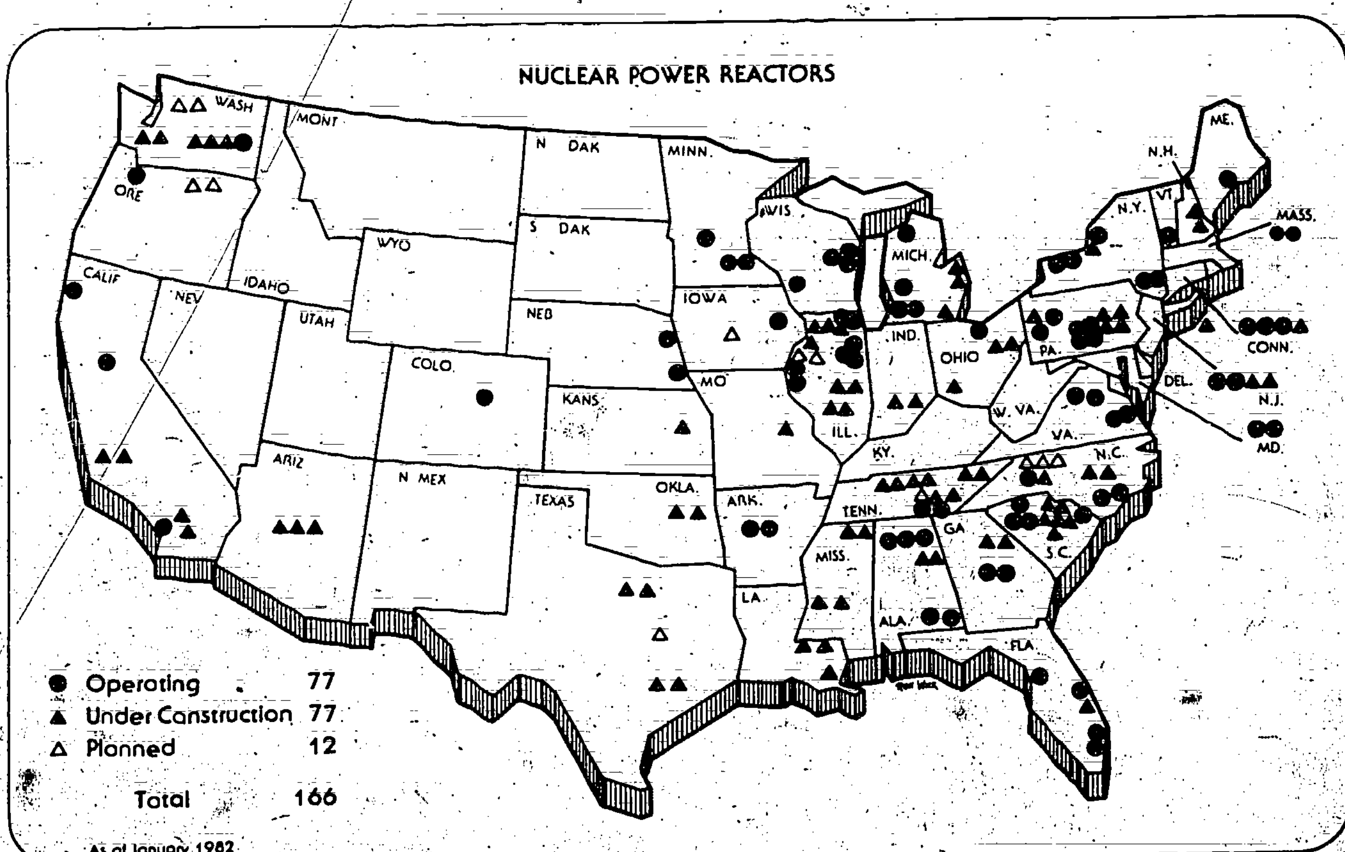
LWR Construction

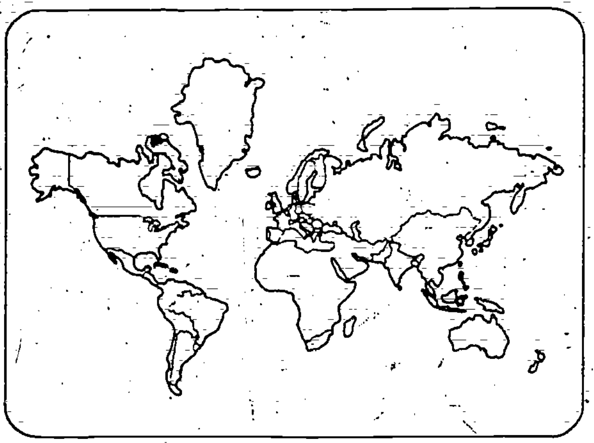
Throughout the development of the first nuclear power plants, an industry grew to meet the new demand for nuclear components and services. By the mid-1960's, a nuclear industry was sufficiently established that government assistance was no longer necessary to build a reactor. In 1963, the first order was placed for a reactor that did not involve government funds. This order opened the door for a large number of reactor sales in the late 1960's and early 1970's. In fact, within five years of the first order, the utilities had committed themselves to building nearly 77,000 MWe of nuclear generating capacity. By 1973, 56 reactors were operating, and today nearly 80 nuclear units are producing electricity.

Nuclear Reactors in the U.S.

In the past few years, nuclear reactors have provided steady and reliable power to many areas of the United States. Approximately 80 nuclear power plants are licensed to operate today, and these reactors provide 11% of all the electricity used in the U.S. In certain areas of the Midwest and Northeast, more than half of the electricity is produced by nuclear generating untis.

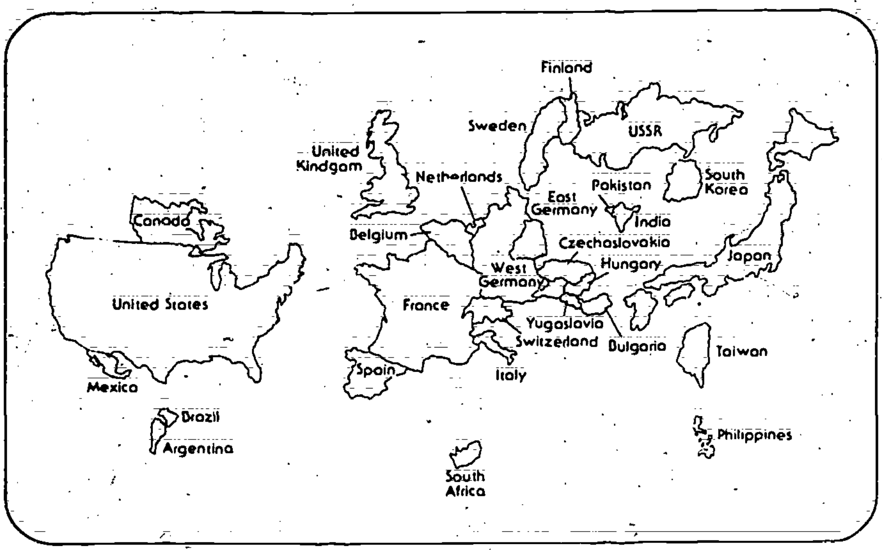
In addition to those plants in operation, another 80 nuclear units are being built and there are plans to construct even more reactors. When these plants are completed, more than 150 nuclear power plants will be operating in the United States.

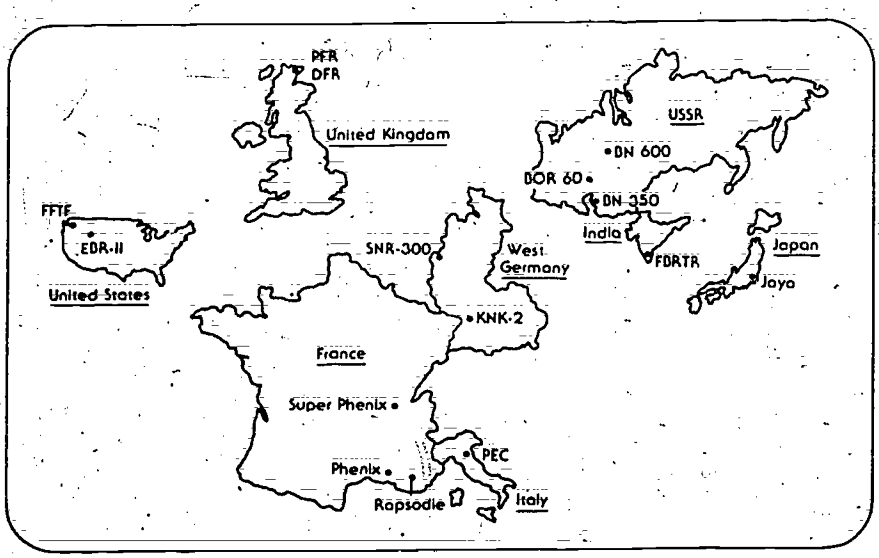




Nuclear Reactors Throughout the World

Nuclear power is an important source of electricity in many nations, as shown by these two maps. The upper map shows the traditional view of the world. In the map below, the area of a nation is proportional to the size of its nuclear program in 1985. It can be seen that the United States has the world's largest nuclear power program. Many other nations, such as France and Japan, plan to develop a large amount of additional nuclear generating capacity.





Breeder Reactors Throughout the World

A number of nations with large nuclear programs have invested in developing breeder reactor technology. France, the United Kingdom, and the Soviet Union have already completed demonstration plants; West Germany and Japan will soon follow. In the figure, the size of each country is determined by the size of the largest breeder reactor that will be operating in 1985.

DEFINITIONS OF BASIC TERMS

THE FISSION PROCESS

Neutron - A basic atomic particle that has no electrical charge. Neutrons and protons, which are positively charged particles, form the central portion of the atom known as the nucleus. Negatively charged electrons orbit the nucleus at various distances. The chemical and nuclear properties of an atom are determined by the number of its neutrons, protons, and electrons.

Fission - The process by which a neutron strikes a nucleus and splits it into two fragments. During the process of nuclear fission, several neutrons are emitted at high speed, and heat and radiation are released.

Chain Reaction - The continuing process of nuclear fissioning, in which the neutrons released from every fission trigger at least one other nuclear fission.

Fission Products - The two small atoms created when a nucleus fissions. The mass of the fission products is less than that of the original nucleus. The difference in mass is released as energy.

Isotopes - Atoms having the same number of protons, but a different number of neutrons. Two isotopes of the same atom are very similar and difficult to separate by ordinary chemical means. Isotopes can have very different nuclear properties, however. For example, one isotope may fission readily, while another isotope of the same atom may not fission at all.

Uranium - A metallic element found in nature that is commonly used as a fuel in nuclear reactors. As found in nature, it contains two isotopes--uranium-235 and uranium-238.

Uranium-235 - The less abundant uranium isotope, accounting for less than one percent of natural uranium. Uranium-235 splits, or fissions, when struck by a neutron. When uranium is used as a fuel in a nuclear reactor, the concentration of U-235 is often increased to enhance the fission process. For example, the fuel for light water reactors contains about 3% uranium-235.

Uranium-238 - The more abundant uranium isotope, accounting for more than 99% of natural uranium. Uranium-238 tends to absorb neutrons rather than fission. When it absorbs a neutron, the uranium atom changes to form a new element--plutonium.

Plutonium - An element that is not found in nature, but can be produced from uranium in a nuclear reactor. Plutonium fissions easily, and can be used as a nuclear fuel.

Fissile - Material composed of atoms which readily fission when struck by a neutron. Uranium-235 and plutonium-239 are examples of fissile materials.

Fertile - Material composed of atoms which readily absorb neutrons to produce fissionable materials. One such element is uranium-238, which becomes plutonium-239 after it absorbs a neutron. Fertile material alone cannot sustain a chain reaction.

FUEL CYCLE

Conversion - The chemical process by which uranium is prepared for treatment in an enrichment facility. The conversion process changes uranium from a solid oxide form to a fluoride gas.

Enrichment - The process by which the concentration of uranium-235 is increased. Generally, uranium is enriched from its natural concentration of less than 1% U-235 to about 3% U-235. This concentration of fissile material is suitable for use in a light water reactor.

Tails - A product of uranium enrichment that is composed of uranium with a very low concentration of U-235. While this material is of little use in a light water reactor, it can be converted to plutonium in a fast breeder reactor.

Fabrication - The final step in preparing nuclear fuel for use in a reactor. During fabrication, the fuel is shaped into small pellets and then stacked in thin metal tubes. The tubes, or rods, of fuel are carefully spaced within a metal grid before being inserted in a reactor.

Spent Nuclear Fuel - Material that is removed from a reactor after it can no longer sustain a chain reaction. Spent fuel from a light water reactor is composed primarily of uranium and contains some radioactive materials, such as fission products. Spent fuel also contains some valuable nuclear materials, such as uranium-235 and plutonium.

Reprocessing - A series of chemical steps in which valuable nuclear materials are extracted from spent nuclear fuel. The useful materials, including uranium and plutonium, can be used again as fuel in other reactors. The remaining waste materials are solidified and isolated from the environment.

NUCLEAR REACTORS

Nuclear Fuel - Nuclear material which fissions easily. The most common nuclear fuels are uranium and plutonium. The material is packed into long, thin tubes known as fuel rods which are arranged in a compact configuration. This allows a controlled chain reaction to occur.

Core - The region of a reactor in which the nuclear chain reaction is initiated, maintained, and controlled. Coolant is constantly circulated through the core to remove heat produced by the fission process.

Control Rods - Long, thin rods that are positioned among fuel rods to regulate the nuclear chain reaction. Control rods are composed of material that absorbs neutrons readily. They interrupt or slow down a chain reaction by capturing neutrons that would otherwise trigger more fissions.

Coolant - Fluid that is circulated through the core of a reactor to remove the heat generated by the fission process. Most reactors operating today used water as coolant, but some are cooled by liquid sodium. In reactors that have more than one coolant system, the fluid which passes through the core of a reactor is known as the primary coolant. It absorbs heat in the core and then transfers it to a secondary coolant system. The secondary system produces steam, which generates electricity.

Pressure Vessel - A heavy steel enclosure around the core of a reactor. It is designed to withstand high pressures and temperatures to prevent radioactive material from escaping from the core.

Containment Building - A thick concrete structure surrounding the pressure vessel and other reactor components. It is designed to prevent radioactive material from being released to the atmosphere in the unlikely event that it should escape from the pressure vessel.

Light Water Reactor - A general term that refers to all nuclear reators which use ordinary water as a coolant. This includes pressurized water reactors and boiling water reactors, which are the predominant reactors in the U.S. LWR's are generally fueled with enriched uranium, although they can operate with other nuclear fuels.

Pressurized Water Reactor - A reactor cooled by water that is kept at high pressure to prevent it from boiling. Primary coolant passes through the core of a PWR, and then transfers its heat to a secondary coolant system. Steam is produced from the heated water in the secondary system.

Boiling Water Reactor - A reactor cooled by water that is allowed to boil as it passes through the core. This coolant is used directly to produce the steam which generates electricity.

Fast Breeder Reactor - A reactor cooled by liquid sodium rather than water. In this type of reactor, the transformation of uranium-238 to plutonium occurs readily. Since plutonium fissions easily, it can be recycled and used as fuel for a breeder reactor. The conversion of uranium to plutonium is so efficient in an FBR that this reactor creates more fuel than it consumes.

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