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ABSTRACT

This booklet explains the basic technology of nuclear fission power reactors, the nuclear fuel cycle, and the role of nuclear energy as one of the domestic energy resources being developed to meet the national energy demand. Major topic areas discussed include: the role of nuclear power; the role of electricity; generating electricity with the atom; nuclear power and radiation; types of nuclear reactors (boiling-water, pressurized-water, and high temperature gas-cooled reactors); breeder reactors; nuclear fuel--mining to reactor; nuclear fuel--reactor to waste disposal; transporting radioactive materials; the economics of nuclear power; and nuclear electricity in other countries. A list of selected books, reports and articles, and films is included. (JN)

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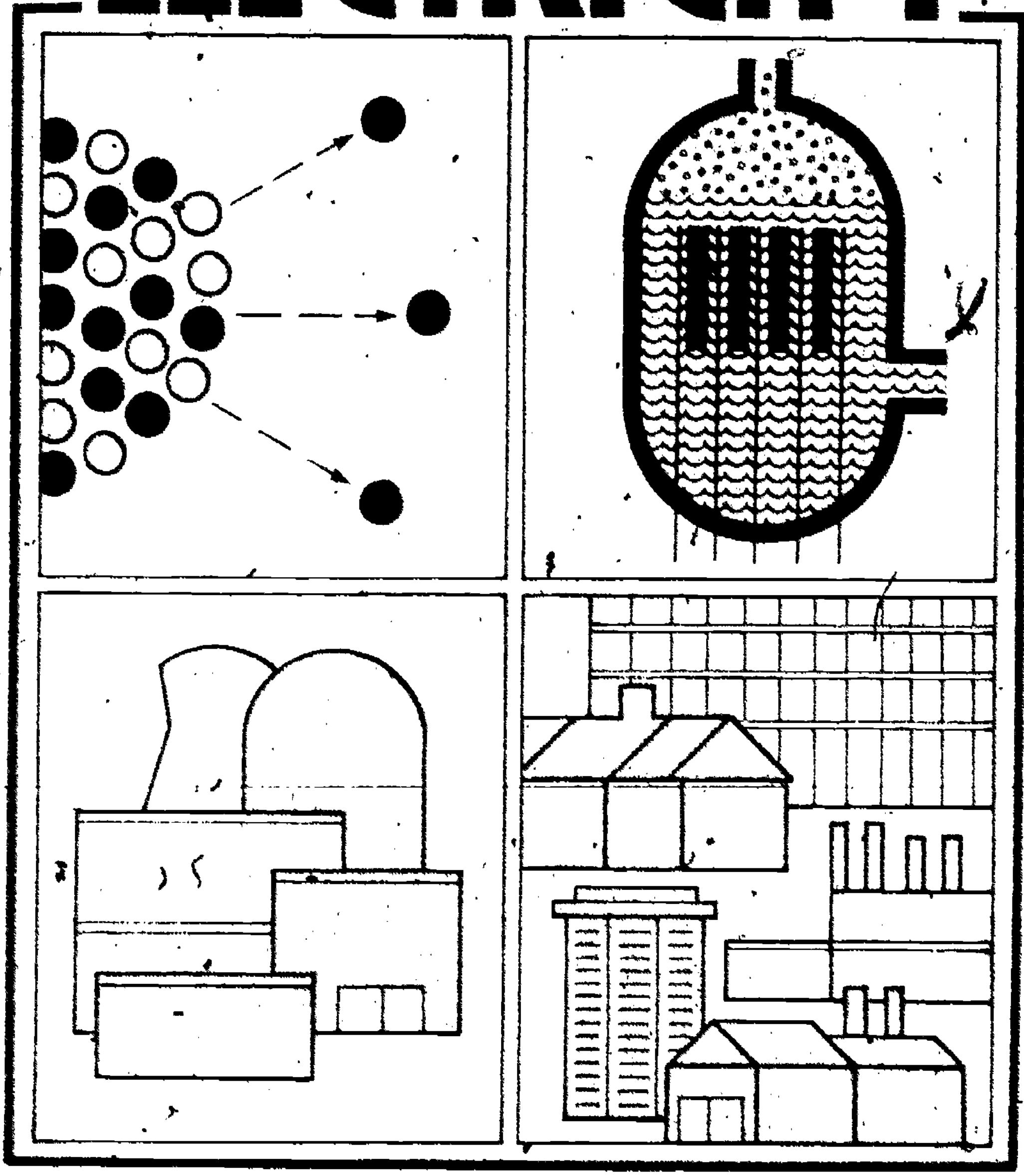
ATOMS TO ELECTRICITY



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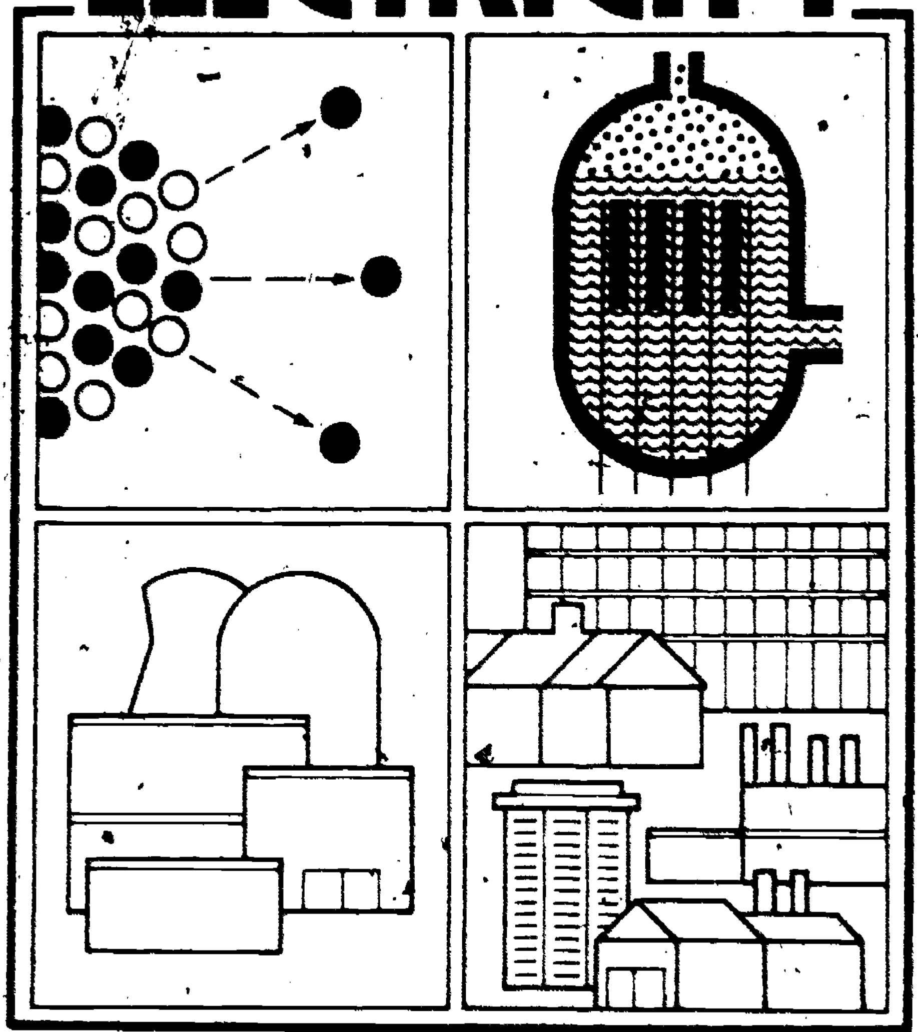

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Introduction

By the mid 1970s the United States and much of the rest of the world found itself in a serious, long-term energy crisis. Fuel costs had become much more expensive than they had ever been, largely because the most easily recovered oil and gas had already been depleted. Moreover, a major portion of the energy use in the United States was based on a potentially unreliable fuel source: imported oil. The security of the nation's economy now depended on decisions about energy prices and energy supplies made in other countries thousands of miles away.

Cutting back on U.S. dependence on imported oil, most experts agreed, required two actions: first, conserving energy, especially the use of oil, and second, relying more heavily on energy resources available in the United States. These changes have brought a new level of importance to the role of electricity in our national economy.

As Americans cut back on their direct use of oil, they turned to electric power to fill much of the gap. Electricity, which accounted for 25 percent of our national energy use in 1970, increased its share to over 30 percent by 1980. Many energy projections expect it to account for nearly 50 percent by the turn of the century.

As electric power has grown in importance, the number of potential fuel sources to produce it have declined. Large sites for hydroelectric plants have essentially been exhausted, and oil and gas have become too expensive to consider for new electricity generating stations. This means that the nation must rely almost totally on two energy sources—coal and nuclear energy—for new needs for electricity over the next few decades.

This booklet explains the basic technology of nuclear fission power reactors, the nuclear fuel cycle and the role of nuclear energy as one of the domestic energy resources being developed to help meet our national energy demand. Nuclear power accounted for some 12 percent of the U.S. electric energy supply in 1982. In the 1990's, it is expected to become second only to coal as a source of our electric power, almost doubling its present contribution to our national electricity supply.

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The Role of Nuclear Power

The Beginnings

On December 20, 1951, at a government laboratory in Idaho, man's ability to use an energy hidden in nature entered a new era. An experimental plant called the Experimental Breeder Reactor (EBR-I) generated enough electricity to light four 200-watt light bulbs (Figure 1). With that success, man had harnessed a new energy source that was neither mechanical, like the power of wind or falling water, or chemical, like the burning of coal, oil or gas. This electricity was created by nuclear energy.

The importance of this breakthrough was evident to scientists and energy experts around the world. Nuclear fission energy—the heat released when the nucleus of an atom "fissions", or splits into two small pieces—expanded human potential beyond the limits of such fuels as coal, oil, gas, and the renewable energy of hydropower. It offered the promise of abundant electricity at relatively low costs and of providing power without the environmental effects that accompany the burning of fossil fuels. Government officials, scientists, journalists, and industry leaders alike saw this development as the beginning of a new age—the "atomic age".

The Growth of Nuclear Power

During the 1950s, there was no shortage of inexpensive fossil fuels for electric generating plants, so there was little obvious need to develop an alternative fuel source. The first few nuclear powerplants were essentially demonstrations of the technology, co-sponsored by utilities and the U.S. Atomic Energy Commission (Figure 2).

In 1960, however, the first nuclear powerplant financed entirely by a utility, the Dresden 1 plant of Commonwealth Edison Company, began operating near Chicago. In the next six years 28 other utilities followed suit with a total of 38 new nuclear units. They were turning to nuclear for two reasons: to take advantage of the cost savings made possible by nuclear energy and, in some cases, to conserve fossil fuels. By the early 1970s utilities were announcing plans for new nuclear plants as frequently as for coal-fueled stations.

In the mid 1970s the rapid-growth era for new nuclear powerplants came to an end. The United States responded to the Mideast oil embargo and other shocks to its economy by using less energy than had previously been projected. The economic slowdown of the late 1970s and early 1980s further reduced energy demand. The 7 percent a year increase in electric power demand, which had remained essentially constant for over two decades, dropped to near zero in 1974. With minor fluctuations, the average annual growth since then has been about 3.5 percent, or half the rate of earlier years. Many utilities were hard-pressed to embark on large construction projects because of high inflation rates and even higher increases in fuel costs. Facing a slowdown in the growth of electricity

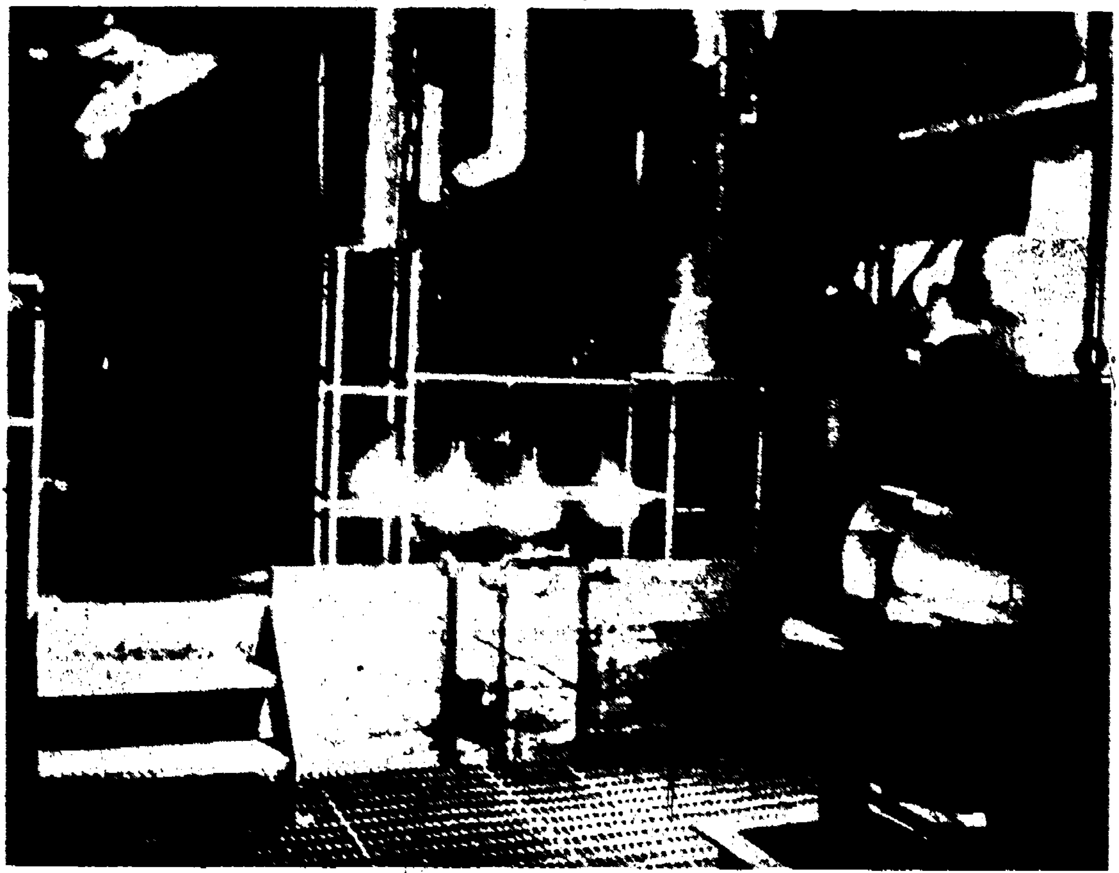

Figure 1. *On December 20, 1951, four electric light bulbs at the Atomic Energy Commission's (AEC) National Reactor Testing Station in Idaho were powered by this generator (right) which operated on heat from Experimental Breeder Reactor (EBR-I). (Credit: Argonne National Laboratory)*

demand, utilities began cutting back on their plans for additional generating units, both coal and nuclear.

Nuclear Power Today and Tomorrow

Today more than 80 commercial nuclear powerplants are licensed to operate in the United States (Figure 3). In 1982 nuclear power provided over 12 percent of the nation's electricity. Since electricity accounts for some 34 percent of the energy use in the country, nuclear power was the source of 4.3 pecent of the energy produced overall for the nation. The capacity of today's nuclear plants—about 65 million kilowatts—is equal to the size of the entire U.S. electric capability in the mid-1940's.

The role of nuclear power is particularly important in many regions of the country with high fossil fuel costs. In New England, where the principal alternative to

Figure 2: *The 60,000-kw Shippingport Atomic Power Station, Shippingport, Pennsylvania, was the first large-scale central-station nuclear powerplant in the United States and the first plant of such size in the world operated solely to produce electric power. The plant, a joint project of the U.S. Atomic Energy Commission and Duquesne Light Company, began operating in 1957. (Credit: Department of Energy)*

nuclear power is imported oil, nuclear energy provided nearly 35 percent of the total electricity generated in 1982 (Figure 4). In Virginia, nuclear power accounted for 46 percent; in New Jersey, 45 percent; in Nebraska, 48 percent; in Minnesota, 36 percent.

About 60 other nuclear units are under construction or being planned by the nation's investor-owned, government-owned and consumer-owned utilities. Assuming that they are completed in the 1990's, nuclear power will provide enough electricity to meet the electrical needs of about 20 percent of the U.S. population.

Beyond the approximately 140 plants operating or under construction, the outlook for nuclear power in the United States remains uncertain. The number of additional U.S. nuclear powerplants built in the next few decades will depend upon several factors:

- the overall need for new electric generating stations

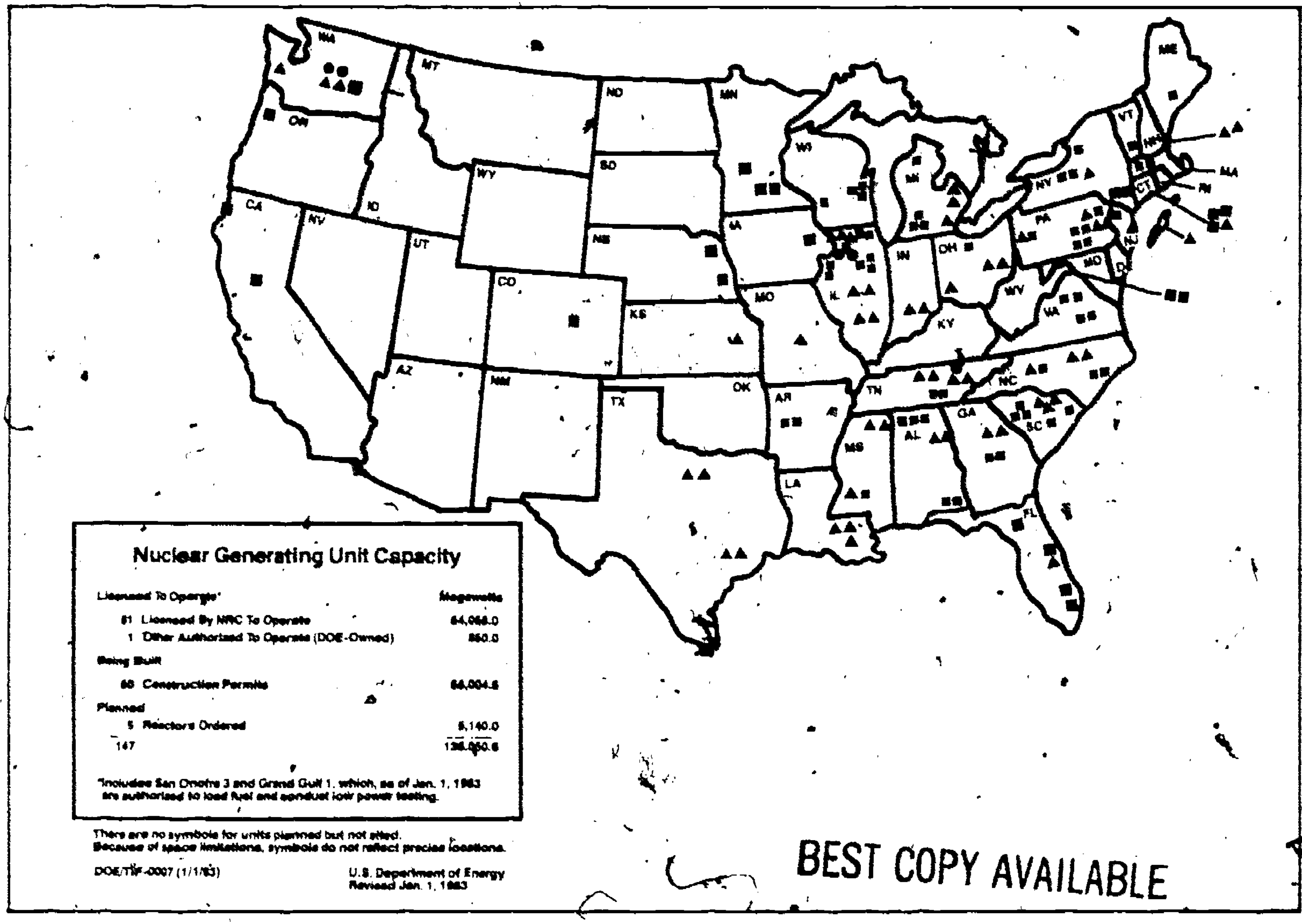

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Figure 3. *Commercial Nuclear Powerplants in the United States*

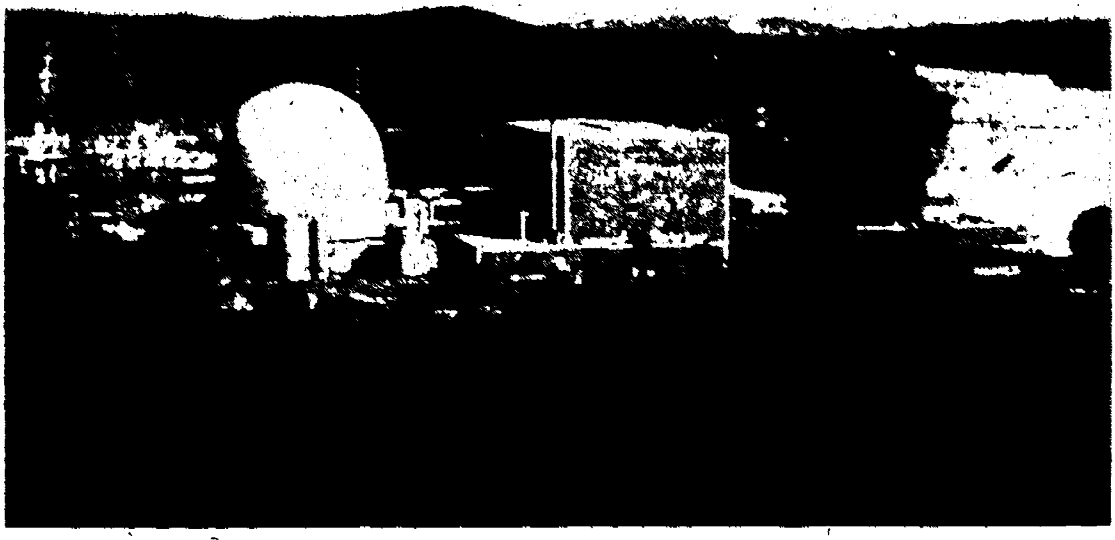

Figure 4. *Maine Yankee Nuclear Power Station set a record in July 1978 for the longest continuous operation of a nuclear powerplant: 392 days. During that run it generated 7 billion kilowatt hours of electricity, which is the equivalent of 13 million barrels of oil. The plant has the capacity to produce 825,000 kilowatts of electricity. (Credit: Maine Yankee)*

as a result of electrical demand growth as well as the need to replace old plants;

- the degree to which electric power will be used to substitute for oil and other fossil fuels;
- the ability of other resources—like coal, solar energy or other new technologies—to meet future energy demand; and,
- changes in the nuclear regulatory climate.

With 140 plants already in operation or under construction, nuclear power clearly represents a major energy source. It will be important to the U.S. economy for at least a generation into the future—and perhaps for much longer, depending on future energy and economic policies.

The Role of Electricity

Ever since Michael Faraday invented an electric generator in the early 1800s, the industrialized world has been using an increasing amount of its energy in the form of electricity. Faraday demonstrated that a wire loop that is rotating in a magnetic field will generate electricity—that is, the mechanical energy of its rotation can be transformed into electrical energy. The electrical energy can be transmitted to a motor that will reverse the process, transforming the electricity back into a useful mechanical energy.

Electricity, then, is not a *source* of energy, but a *form* of energy. It relies on basic energy sources—like falling water or heat from the burning of coal or other fuels—to spin a turbine (Figure 5). The turbine provides the mechanical energy that a generator converts into electricity. The electricity is "shipped" or distributed through transmission lines to homes, schools, hospitals, factories, office buildings and other customers.

Because electricity can easily be shipped considerable distances by transmission lines to big cities, small towns, and farm communities, and because the consumer finds electricity convenient for many purposes, the use of electricity has steadily increased. In fact, as a rule, it has grown far more rapidly in the past few decades than the overall use of energy.

Electricity and the Economy

Over a period of several decades, the development of the U.S. economy has been closely linked with the usage of electric power. Electricity demand steadily

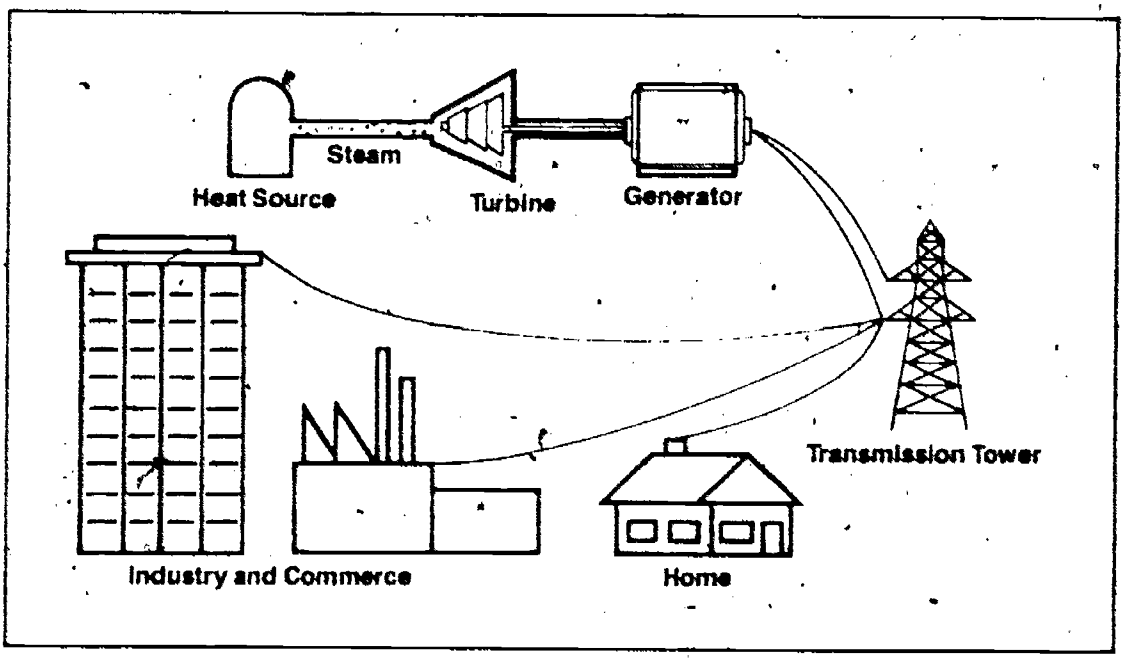

Figure 5. *Electricity: From Its Source To You*

Figure 6. *The H.B. Robinson Steam Electric Plant near Hartsville, S.C., produces electricity from both a nuclear unit (left) and coal-fired unit (right). (Credit: Carolina Power and Light Co.)*

increased much faster than the national economy—by some 70 to 80 percent—until our energy usage patterns began to change drastically in the early 1970s. Conservation programs and rising prices made Americans much more careful about their energy use. But ever since then, while the use of other energy forms has declined, the demand for electricity has continued to grow faster than the national economy by some 25 to 50 percent.

Electricity and the Consumer

Approximately one-third of the energy used in the United States goes into the generation of electric power. Of that electricity, about 40 percent is used in industry, about 35 percent in households, and 25 percent in stores and offices. All three segments of our economy have cut back on their use of every other energy form in the past decade, but they have increased their demand for electric power.

Trends in housing have dramatized this steady shift toward electricity. Until 1970 less than 8 percent of U.S. households were heated electrically. Since then the electric heat pump has increased the efficiency of electric heating and lowered the cost to the point that more than 50 percent of all the new homes in the past decade have been built with electric heating systems.

Many recent developments that we now take for granted depend on electricity—television, air-conditioners, stereo systems, computers and calculators, movies, home appliances, and even elevators, which made modern cities possible. Together they contributed to a demand for electric power that increased by some 50 percent even during the conservation-minded decade of the 1970s. With a growing emphasis on computer and other innovative technologies, the United States, like much of the industrialized world, is moving ahead into a new world of increased electrification.

Fueling the Powerplants

As recently as 1973, oil and natural gas were providing 35 percent of our national electric power supply. Over the past 10 years they have become increasingly valuable for other energy needs and increasingly expensive; their share of our electric power has declined to 20 percent. Our amount of hydroelectric power has remained essentially the same, and its share of electric generation over the last decade has declined slightly from 15 to 14 percent. The amount of coal that we are burning in powerplants has increased significantly, bringing coal's share of our electricity supply up to more than 53 percent. The source and fuel that has helped coal meet this rising electrical demand—growing in importance from four percent in 1973 to over 12 percent in 1982—is nuclear energy from uranium. (Figure 6)

Generating Electricity With the Atom

In concept a nuclear powerplant operates essentially the same way as a fossil fuel plant, with one basic difference: the source of heat. The reactor of the nuclear plant performs the same function as the burning of fossil fuel in other types of electric plants—it generates heat. The process that produces the heat in a nuclear plant is the fissioning or splitting of uranium atoms. That heat boils water to make the steam that turns the turbine-generator, just as in a fossil fuel plant. The part of the plant where the heat is produced is called the reactor core.

The Fission Process

What is the fission process that produces the heat in nuclear power plants? It starts with the uranium atom.

Atoms are made up of three major particles. (Figure 7)

- Inside the nucleus, which is the center of the atom, there are positively charged *protons*. The number of protons in the nucleus determines which family or element the atom belongs to: all hydrogen atoms have 1 proton, carbon has 6, uranium has 92, etc.
- The nucleus also contains uncharged particles known as *neutrons*. The number of neutrons in the nucleus identifies the specific member of the atom's family—or isotope. Different isotopes of the same element are designated by numbers after the element name that describe the total

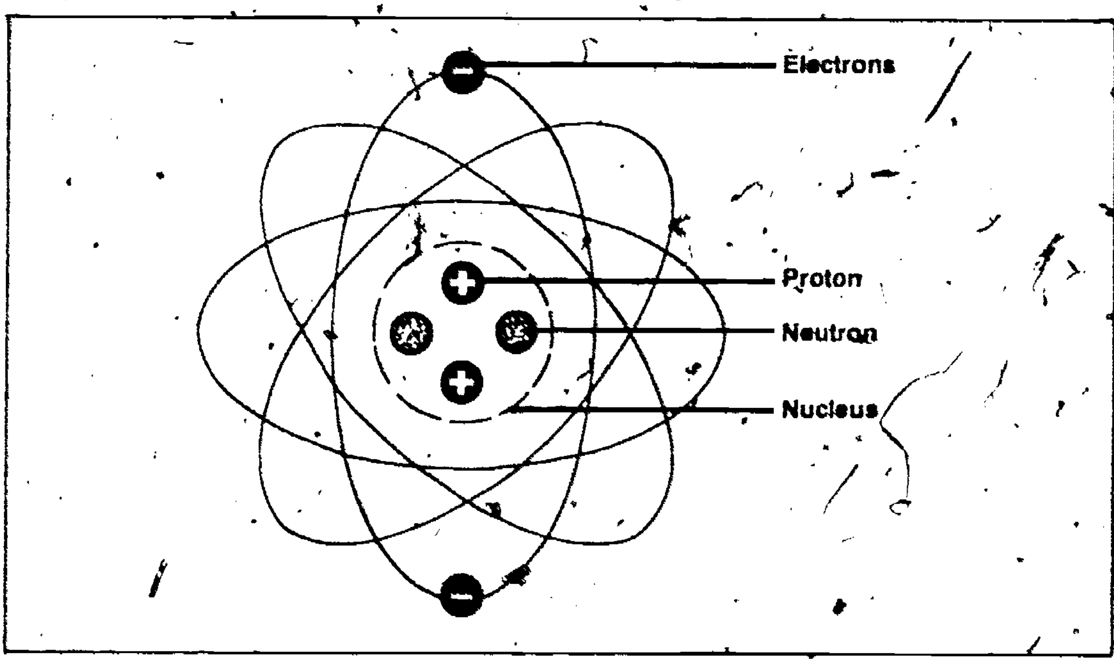

Figure 7. *The Components Of An Atom*

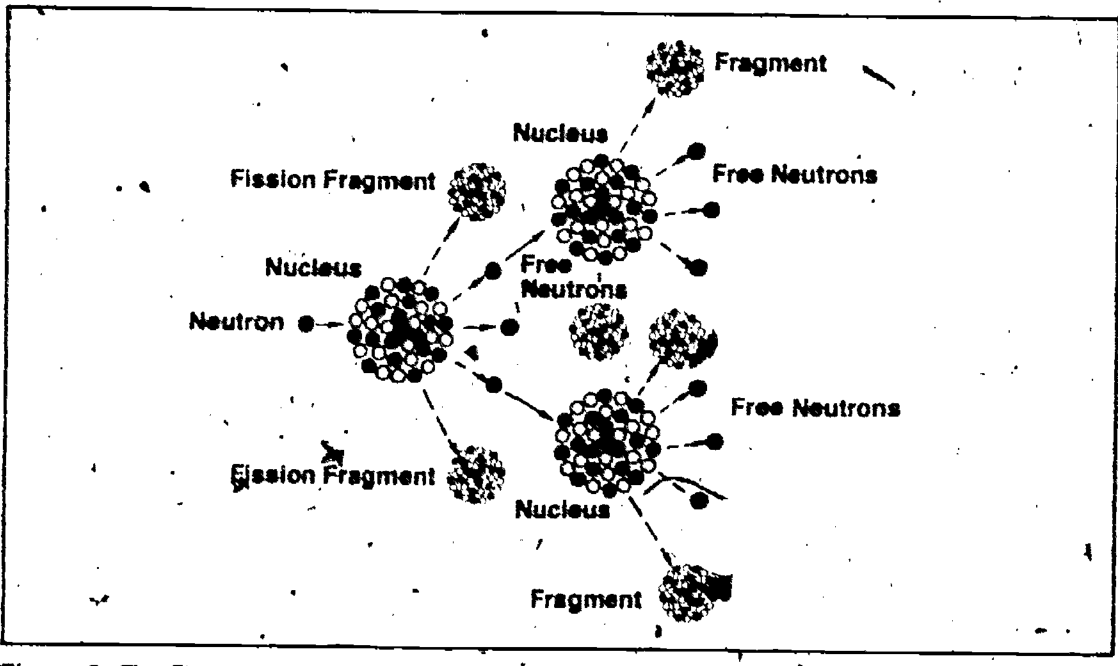

Figure 8. *The Fission Process*

number of protons and neutrons inside the nucleus. The carbon-12 atom, for example, contains six protons (which make it carbon) and six neutrons in the nucleus; the carbon-14 atom has six protons and eight neutrons. Though all isotopes of an element behave the same chemically, they can vary in other properties. Carbon-14, for example, is radioactive, making it a radioisotope.

- Circling around the nucleus of each atom are tiny negatively charged *electrons.* There are normally the same number of electrons as there are protons in the nucleus; otherwise the atom has a positive or negative charge and is said to be ionized.

Because the protons have a positive charge, they could be expected to repel each other. In fact, however, the particles in the nucleus are held together by what scientists call "nuclear binding energy."

It is possible to overcome that binding energy in some large atoms, such as uranium, causing them to split apart or fission. The fission process occurs when a neutron enters the nucleus of a fissionable atom (Figure 8). The nucleus immediately becomes unstable, vibrates and then splits into two fission fragments that are propelled apart at a high speed. The kinetic energy (energy of motion) of these fragments is transformed into heat as the fission fragments collide with surrounding atoms and molecules. This completes the nuclear fission process: the binding energy of the nucleus was released when the nucleus absorbed a free neutron, it was transformed into kinetic energy that propelled apart the two fission fragments, and their collisions with surrounding atoms transformed the kinetic energy into heat.

The process of mass actually turning into energy was anticipated by Professor Albert Einstein. His formula, $E = mc^2$, predicts that a small amount of mass (m) can be transformed into a large amount of energy (E), and that the amount of energy can be calculated by multiplying the mass times the square of the speed of light (c^2).

In addition to the fission fragments and heat, a fissioning nucleus also frees two or three additional neutrons. Some of these neutrons can strike other fissionable atoms, which release still other neutrons. These neutrons can, in turn, hit other fissionable atoms and continue the chain reaction. The rate at which these "free" neutrons are emitted is the key to sustaining and controlling a nuclear chain reaction.

Uranium Isotopes

The most common fissionable atom is an isotope of uranium known as uranium-235 (or U-235), which is the fuel used in most types of nuclear reactors that are being built today. Though uranium is quite common in nature, about 100 times more common than silver, for example, U-235 is relatively rare. When uranium is mined, it contains two isotopes: 99.3 percent is the isotope U-238 and only 0.7 percent is the isotope U-235. Before the uranium can be used as fuel in a nuclear powerplant, however, the 0.7 percent concentration of U-235 must be enriched to around a 3 percent concentration.

The most common uranium isotope, U-238, is not fissionable under most conditions. Interestingly, though, it is fertile—which means that when it absorbs a neutron, instead of fissioning, it is transformed into an atom that is itself fissionable. As neutrons from other fissions are absorbed by U-238, they cause nuclear reactions that convert U-238 to plutonium-239 (Pu-239), which is fissionable and can be used as fuel the same as U-235. As nuclear reactors operate, then, they are both using fuel by burning U-235 and *creating* fuel by transforming otherwise useless U-238 into Pu-239. As plutonium builds up, some of the fissions in a reactor come from the plutonium, when it in turn absorbs another neutron.

Nuclear Reactors

Nuclear reactors are basically machines that contain and control chain reactions while releasing heat at a controlled rate (Figure 9). In electric powerplants the reactors supply the heat to turn water into steam which drives the turbine-generator. The reactor core is basically composed of the following four elements:

- *The fuel.* The nuclear fuel is

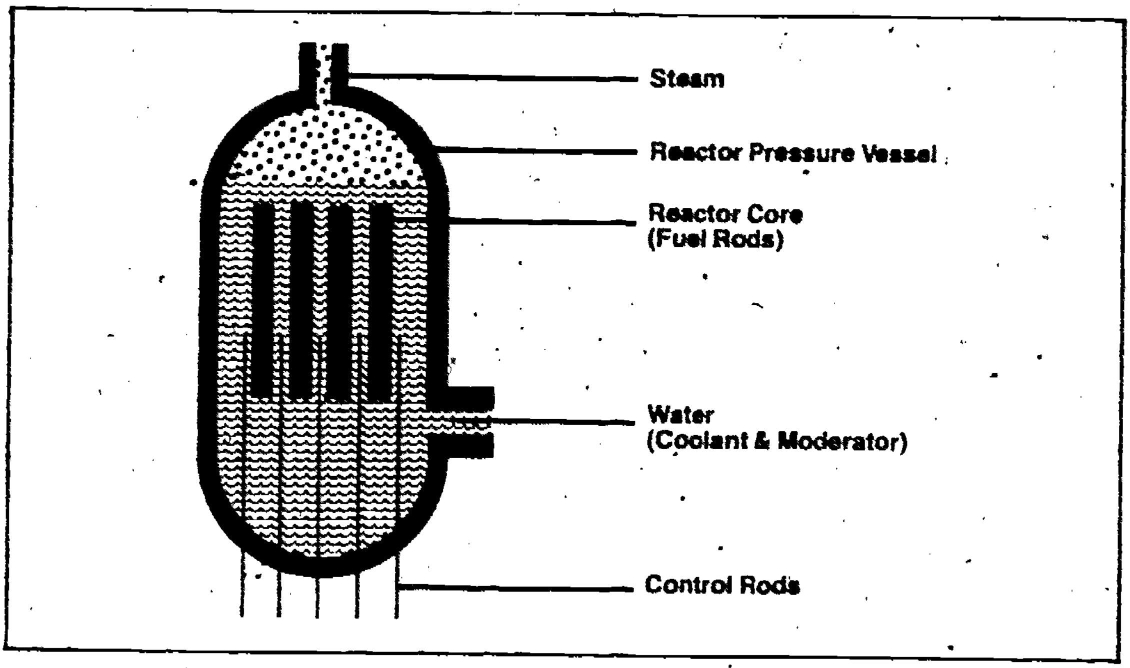

Figure 9. *Elements of a Nuclear Water-Cooled Reactor*

the heart of the reactor. In most U.S. reactors the fuel consists of pellets of ceramic uranium dioxide (UO_2) less than ½ inch in diameter and ½ inch long that are sealed in thousands of zirconium alloy tubes about 12 feet long. These tubes or "fuel rods" are arranged in a precise geometric pattern and placed vertically at the center of the reactor (Figure 10).

- *The control rods.* These rods have cross-shaped blades containing materials that absorb neutrons and are used to regulate the rate of the chain reaction. If they are pulled out of the core, the reaction speeds up. If they are inserted, they capture a larger fraction of the free neutrons and the reaction slows. The control rods are interspersed among the fuel assemblies in the core. Boron is a widely used absorber material.

- *The coolant.* A coolant, usually water, is pumped through the reactor to carry away the heat produced by the fissioning of the fuel. This is comparable to the water in the cooling system of a car which carries away the heat built up in the engine. In large reactors as much as 330,000 gallons of water flow through the reactor core every minute to carry away the heat. Most U.S. reactors are called light

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Figure 10. *The first fuel bundle at the Duane Arnold Energy Center being lowered into the nuclear reactor February 27, 1974. The 600-pound bundle is supported by a cable in the center. The cartridge-like posts ringing the reactor are the bolts for fastening the reactor vessel head in place. (Credit: Iowa Electric)*

water reactors (LWRs) because they are cooled by ordinary or light water.

- *The moderator.* Neutrons have a better chance of causing an atom to fission if they move considerably slower than their initial speed after being emitted by a fissioning nucleus. The material used to slow the neutrons down is called the moderator. Fortunately for reactor designers, water itself is an excellent moderator, so reactors can be moderated by the same water that serves as a coolant. The moderator is essential to maintain a chain reaction; if water is lost from the core, the chain reaction stops (though the residual heat must still be removed).

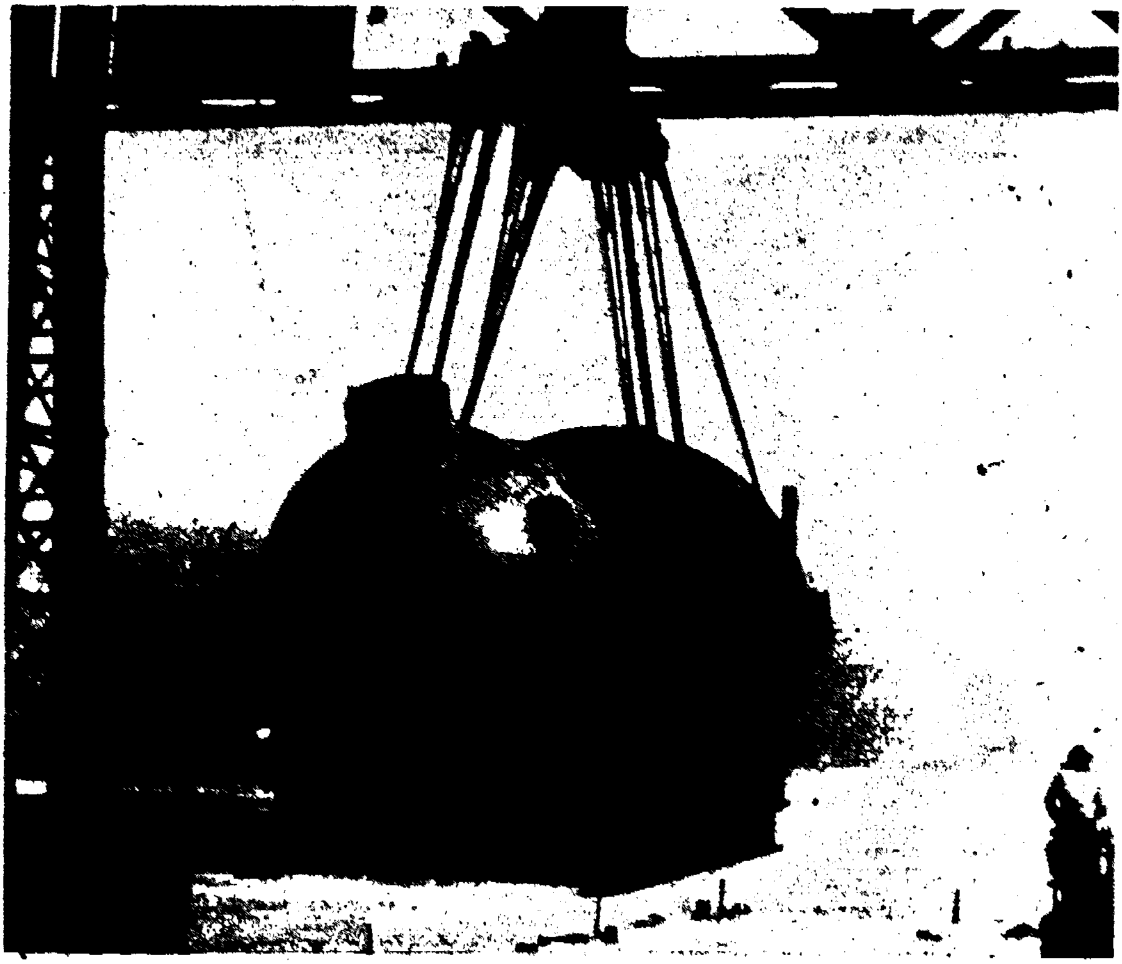

Figure 11. A 500-ton steam generator positioned on a barge for shipment to Arkansas Power and Light's nuclear power plant outside Little Rock. The barge trip covered 1,065 miles and took about two weeks. (Credit: Combustion Engineering)

Although engineering designs are quite complex, these four elements—the fuel, the control rods, the coolant and the moderator—are the basic components of a nuclear reactor. When the control rods are withdrawn, the uranium fuel begins to fission and release extra neutrons, the neutrons are slowed by the moderator so that they will continue the chain reaction, and the heat is carried away by the coolant.

The Nuclear Electric Plant

The reactor is the one unique element of the nuclear powerplant. The rest of the buildings and equipment are similar to other electric powerplants. Summarizing the process:

- Heat from the fission process turns water into steam;
- The steam flows into the

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turbine and turns a shaft to spin the generator and generate electricity, losing some of its heat and pressure in the process (Figure 11);

- The steam then moves to the condenser, where water flowing through cooling pipes chills it and condenses it back into water. This water—called "condensate"—is preheated, to make use of a bit more of the heat in the low-pressure steam, and fed back into the reactor to begin the cycle once again.

The water flowing through the cooling pipes, totally separate from the "condensate," is handled differently. Cooling water is necessary for all electric powerplants that make steam from a heat source, not just nuclear plants. For that reason, electric plants of many kinds are typically located near a river, lake or other body of water. The cooling water for the plant is pumped from the body of water through pipes to the plant where it cools the steam. In the process of cooling the steam, the temperature of the cooling water itself rises a bit. To dissipate this left over heat in the cooling water, many electric powerplants pump the water through a cooling tower or a specially-built pond. Then the water is fed back into the source it came from originally. At no time does the cooling water come into contact with the nuclear reactor or with radioactive materials.

Nuclear Powerplant Safety

In decisions to license, build and operate all nuclear powerplants, the subject of safety is of major importance. Operators of nuclear powerplants must demonstrate to the Nuclear Regulatory Commission (NRC)—the independent Federal agency responsible for licensing and regulating nuclear facilities—that each plant is designed and constructed with stringent safety features. Most of these safety features have one overall objective: to prevent or minimize the accidental release of radioactive material from the plant. Additionally, the routine operation of nuclear powerplants must also meet stringent safety requirements.

Since matters of safety are treated so seriously during the design, construction and operation of a nuclear electric plant by the utility, the nuclear industry and government regulators, experts consider it quite unlikely that any radioactive release could occur that would seriously affect public health and safety. Further, nuclear explosions are physically impossible: the uranium fuel with only a 3 percent concentration of fissionable atoms is in a form that cannot explode. While other kinds of equipment failure or operator errors are possible, radioactive materials would almost certainly be contained.

As of the end of 1982, the United States had accumulated over 700 reactor-years of operating experience with commericial nuclear

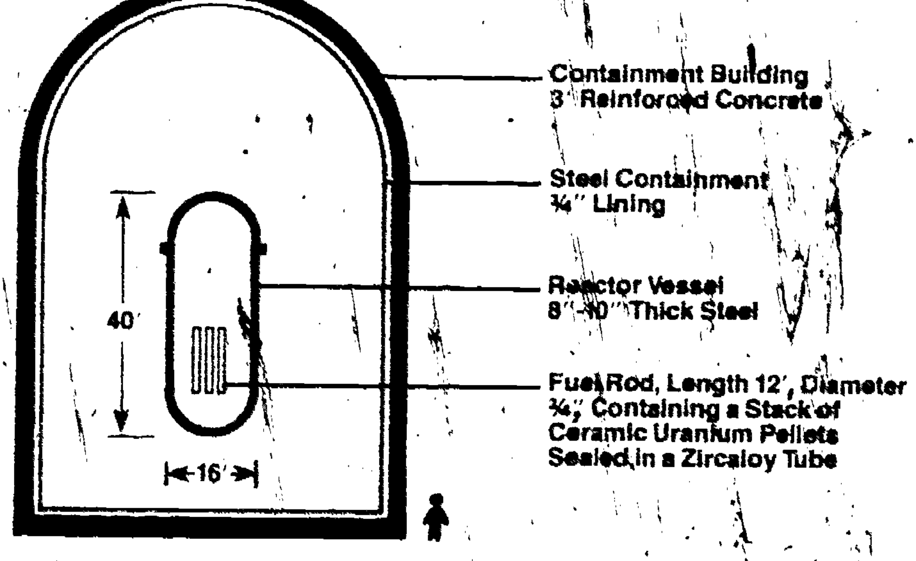

Figure 12. *Safety Barriers in a Nuclear Powerplant*

powerplants without a single loss of life to a member of the public.

Several barriers to trap and contain radioactive material are designed into every nuclear powerplant (Figure 12). They include:

- *Ceramic fuel pellets.* The uranium dioxide fuel material is pressed into pellets to provide a stable form.
- *Zircaloy fuel rods.* The tubes, or fuel rods, which hold the uranium fuel pellets are made out of a strong alloy of zirconium and tin called Zircaloy. They prevent the solid and gaseous fission products from spreading through the reactor system.
- *Reactor vessel.* Surrounding the core of fuel rods is a reactor vessel, made of carbon steel some 8–10 inches thick and lined with stainless steel. Reactor vessels measure about 40 feet in height and up to 16 feet in diameter, and they typically weigh some 400–800 tons (Figure 13).
- *Containment building.* As a final measure of protection, the entire reactor is surrounded by a massive concrete and steel containment building. It has the single purpose of preventing radioactive materials from reaching the environment in the event that piping systems inside should leak

Figure 13. *The reactor vessel for Unit 1 of the Shearon Harris Nuclear Powerplant in North Carolina being hoisted into the containment building in April 1980. (Credit: Carolina Power and Light)*

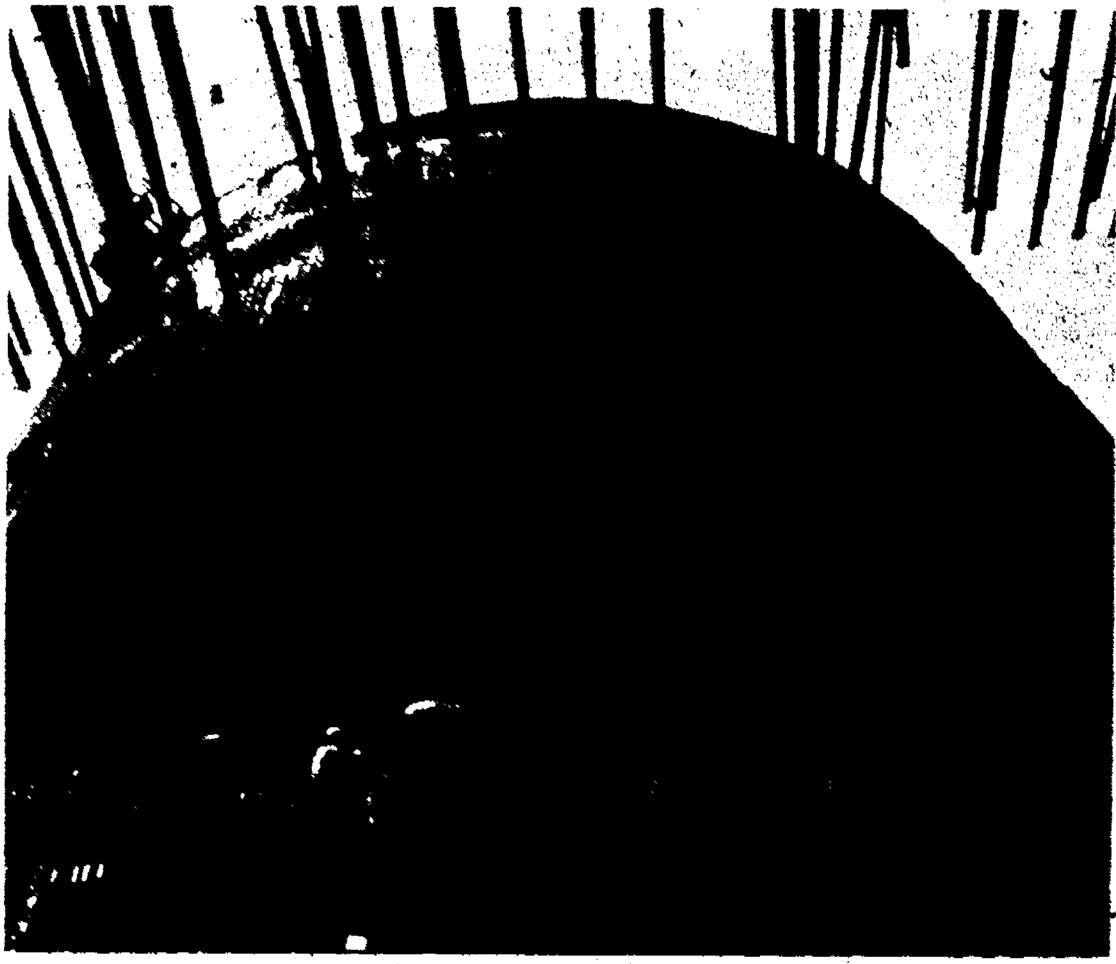

Figure 14. *Workers install reinforcement steel on the containment liner of Unit 1 of the Shearon Harris Nuclear Powerplant near New Hill, North Carolina. (Credit: Carolina Power and Light)*

or break. The concrete in the containment is typically about three feet thick, lined with 3/4 of an inch of steel (Figure 14). The containment building is designed to protect the reactor from being damaged by a direct hit by a large aircraft or tornado winds up to 300 mph.

In addition to these physical barriers, nuclear powerplants are designed and built with several safety systems and backup safety systems. The safety systems are to guard against malfunctions, mistakes and potential accidents. For example, the most extensively studied accident is called a "loss of coolant". If the reactor core is not constantly cooled, its tremendous rate of heat generation could melt parts of the core. Even after the control rods shut the reactor down there is still "decay heat" that requires some constant cooling. To protect against a loss of coolant, nuclear plants contain several back-up cooling systems that can be called on to cool the core if the primary cooling system should stop functioning.

With over 80 commercial nuclear plants licensed to operate in the United States, some for more than 15 years, there has never been an accident that has released a significant amount of radioactive materials to the environment. Recent scientific studies confirm that record, even for the 1979 Three Mile Island accident. That accident provided a considerable amount of information about the adequacy of nuclear power safety systems. Though the back-up cooling systems worked as designed and no radiation escaped through the reactor containment building (some was released from a nearby auxiliary building), the accident pinpointed that improvements were needed in operator training and in information displays in the control rooms. New Federal regulations and improved training and monitoring practices by the nuclear industry should help prevent a recurrence of the type of accident that occurred at Three Mile Island.

Further safety precautions are taken in the immediate vicinity of all licensed nuclear plants. For example, no homes are permitted within the boundaries of the site of the plant, which typically covers several hundred acres. Access to the site is also controlled. These security measures are to protect individuals from exposure to radiation or radioactive materials and to keep unauthorized persons outside the area.

Besides restricted public access to the site, public health is protected by programs that check for radiation releases. At the site boundary, monitoring and surveillance instruments are set up to measure whether any airborne radioactive materials are being released from the plant in the form of dusts, fumes, mists, vapors, or gases. These ongoing monitoring programs assure that indications of radiation levels remain within the public health standards and that corrective actions would be taken before the safety of the public is jeopardized.

Licensing, Building and Operating a Nuclear Powerplant

Only after receiving both a construction permit and an operating license from the NRC can a nuclear powerplant be brought into service in the United States. To issue these licenses, the NRC conducts detailed technical reviews of utility applications and must find that:

- constructing and operating the plant will not present undue risk to public health and safety;
- licensing the plant will not be harmful to national defense and security;
- the utility is technically qualified to design, construct and operate the proposed facility; and
- the project complies with the National Environmental Policy Act.

Figure 15. *Zion Nuclear Power Station is on Lake Michigan. (Credit: Commonwealth Edison Co.)*

The complete licensing and construction of a nuclear powerplant requires a lengthy series of licenses and permits from Federal, state and local government agencies. These permits and licenses determine where the plant can be located, whether the power is needed, and how excavation and construciton will be carried out. They also ensure the protection of local plant and animal life, and the preservation of land, air, and water from pollution (Figure 15).

Notices about legislation, regulations, and rules that affect nuclear powerplants are published in a government document called *The Federal Register.* These notices describe the type of action that is proposed and the government agency responsible for the action. Notices invite members of the public to comment, and they identify a contact who will provide additional information upon request. Copies of *The Federal Register* can usually be found in local libraries.

Utilities provide the NRC with extensive environmental and safety information as part of their license applications. They also are required to submit annual reports about the operation of the plants and special reports on occurrences out of the ordinary (Figure 16). These studies and reports are available for reading in the NRC's public document rooms in Washington, D.C., and other locations across the country, including at least one public document room in the area of every nuclear plant.

At important milestones in the planning and construction of new nuclear powerplants there are

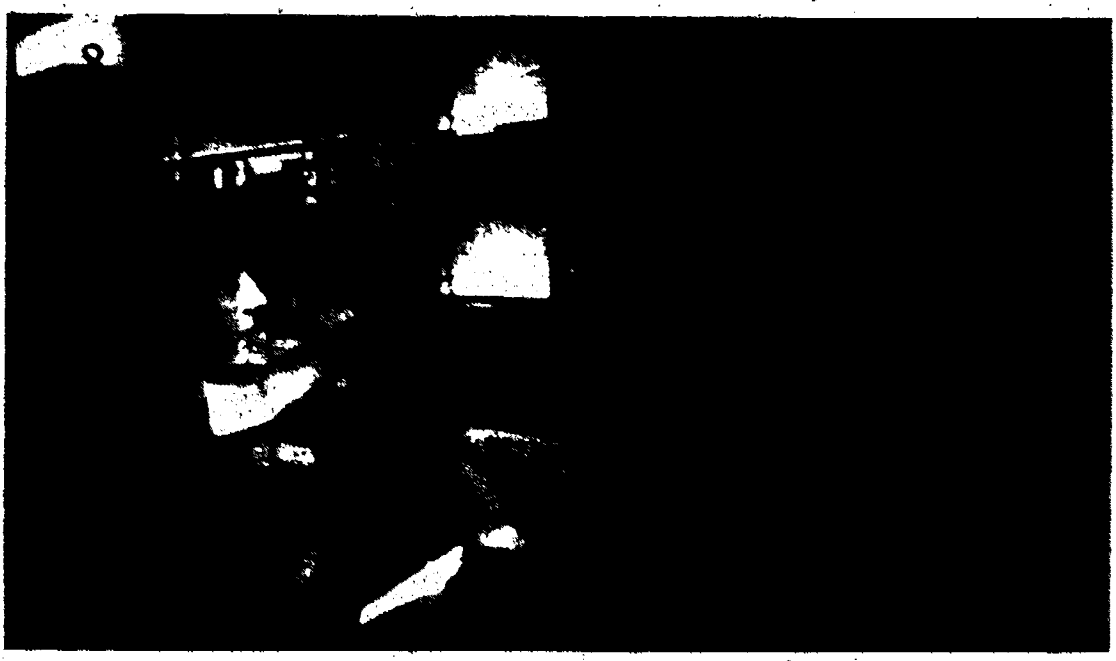

Figure 16. A technician takes a reading from the environmental monitoring system at the Crystal River Nuclear Plant in Florida. (Credit: Florida Power and Light)

opportunities for members of the public to voice their views and raise their questions and even to become a full participant as an "intervenor" in the proceedings. As an intervenor one is provided copies of all reports and applications and has the right to testify and question the government and industry witnesses before the Atomic Safety and Licensing Board, which conducts the hearings.

Building a nuclear powerplant requires a large number of specialists and skilled laborers. A project construction team includes nuclear engineers (specially trained to design and build the plant), civil, mechanical and electrical engineers, boilermakers, welders, pipefitters, carpenters and others. At the peak of construction activity more than 2500 workers are typically employed and high standards of quality are required.

Nuclear powerplants are designed and built to operate for 30–40 years. After the plant begins operating, more than 200 workers handle its everyday operation and maintenance. These workers include nuclear operators and supervisors, mechanical maintenance crews, instrument technicians, electricians, laborers, experts in radiation protection called health physicists, and a security guard force. When the plant shuts down once a year for refueling and major maintenance, this workforce may be supplemented for about two months with up to 500 workers.

The nuclear plant operators, working round-the-clock shifts, are responsible for the safe operation of the plant. To qualify as a nuclear plant operator, a person must go through extensive training and pass a detailed written examination. Those who qualify are issued a license by the NRC. The qualification process is much like the rigorous training one would undergo to become an airline pilot.

Nuclear powerplants that are being built today are considerably larger than those constructed in the early days of nuclear development. Electric generating stations are rated by the amount of electricity they can generate at their peak levels—usually expressed in terms of the kilowatt, which is 1,000 watts. The early demonstration plants were rated between 200,000 and 300,000 kilowatts. Most nuclear power units that have been completed in the past few years have a capacity of about 1-million kilowatts, and there is often more than one unit on a single plant site. A typical 1-million kilowatt powerplant will generate enough electricity to meet the commercial and residential needs of a city of some 560,000 people.

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Nuclear Power and Radiation

Nuclear powerplants are permitted by license to release to the atmosphere small amounts of radioactive materials which are virtually undetectable beyond the reactor site boundaries by even the most sensitive instruments. These small quantities are relatively insignificant when compared to the natural radiation that has always been a part of the earth's environment.

Natural radiation comes in the form of cosmic rays from the sun, and from naturally radioactive elements like potassium, radon, radium, and uranium that are scattered throughout our soil, building materials, food, even our air and water (Table 1). The average American receives about 100 millirems—a standard unit or radiation measurement—each year from natural radiation. In addition adult Americans receive an average of about 90 millirems a year from medical and dental X-rays and from other medical procedures.

Table 1. *Typical Sources of Radiation Exposure in the United States*

Source of Radiation	Average Radiation Exposure Per Person (Millirems per Year)
Medical X-rays	77
Cosmic rays from the sun (depending on altitude)	28
Naturally radioactive elements in air, water, and food	28
Naturally radioactive elements in soil and rocks	26
Medicines with radioisotopes	14
Fallout from weapons tests	5
Naturally radioactive elements in building materials	5
Dental X-rays	1
Luminous clocks	0.5
Nuclear powerplants and associated activities	0,3

Source: "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation", Committee on the Biological Effects of Ionizing Radiation, National Academy of Sciences, Washington, D.C., 1980.

Types of Nuclear Reactors

Just as there are different approaches to designing and building airplanes and automobiles, engineers have developed different types of nuclear powerplants. Several types are used in the United States: Boiling-Water Reactors (BWR), Pressurized-Water Reactors (PWR), and High Temperature Gas-Cooled Reactors (HTGR). PWRs and BWRs are generically called Light-Water Reactors (LWR). The electric generation process is essentially the same for all of them; the principal differences lie inside the reactor that produces the heat.

Boiling-Water Reactors (BWR)

About 30 of the nuclear plants in operation in the United States are boiling-water reactors, or BWRs (Figure 17). In a BWR the water that is heated by the core turns directly to steam in the reactor vessel, and the same steam is used to power the turbine-generator.

The water in a BWR is piped around and through the reactor core and is transformed into steam as it flows up between the elements of the nuclear fuel. The steam leaves the reactor through a pipe at the top, turns the turbine-generator, is condensed back to water, and is pumped back into the reactor vessel, beginning the process again (Figure 18).

Normally water turns to steam at a temperature of 212° Fahrenheit (100° Celsius). But at such a low temperature, steam—like a boiling tea kettle—contains too little energy to be used in a turbine-generator. To raise the temperature and the

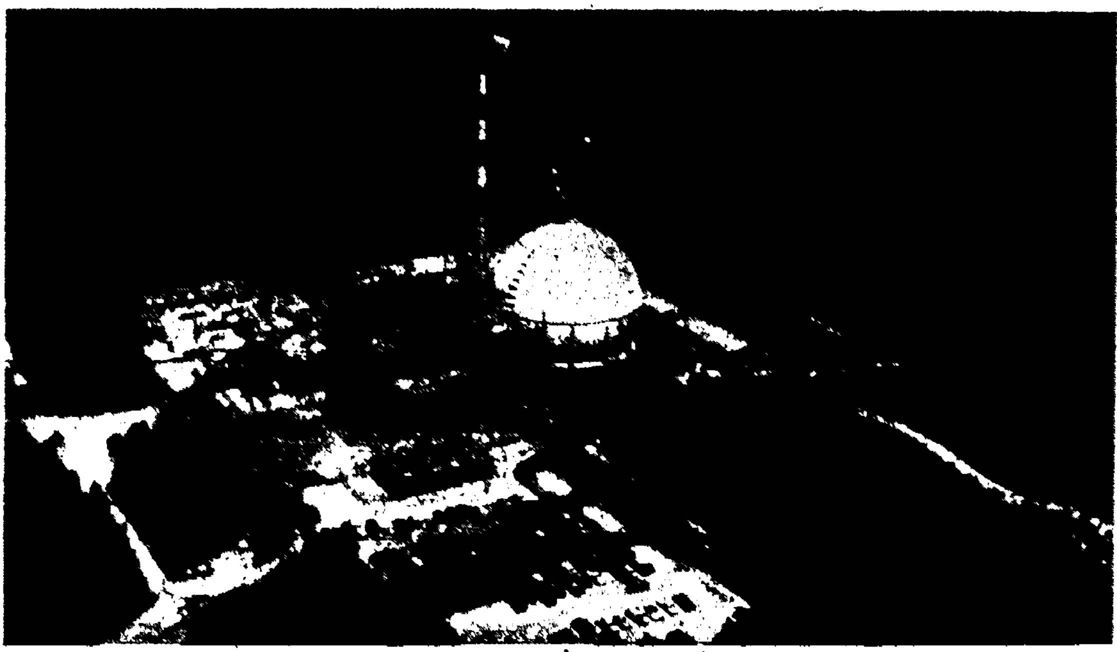

Figure 17. *Big Rock Point Nuclear Powerplant, a boiling-water reactor (BWR) plant in Michigan. (Credit: Consumers Power Company)*

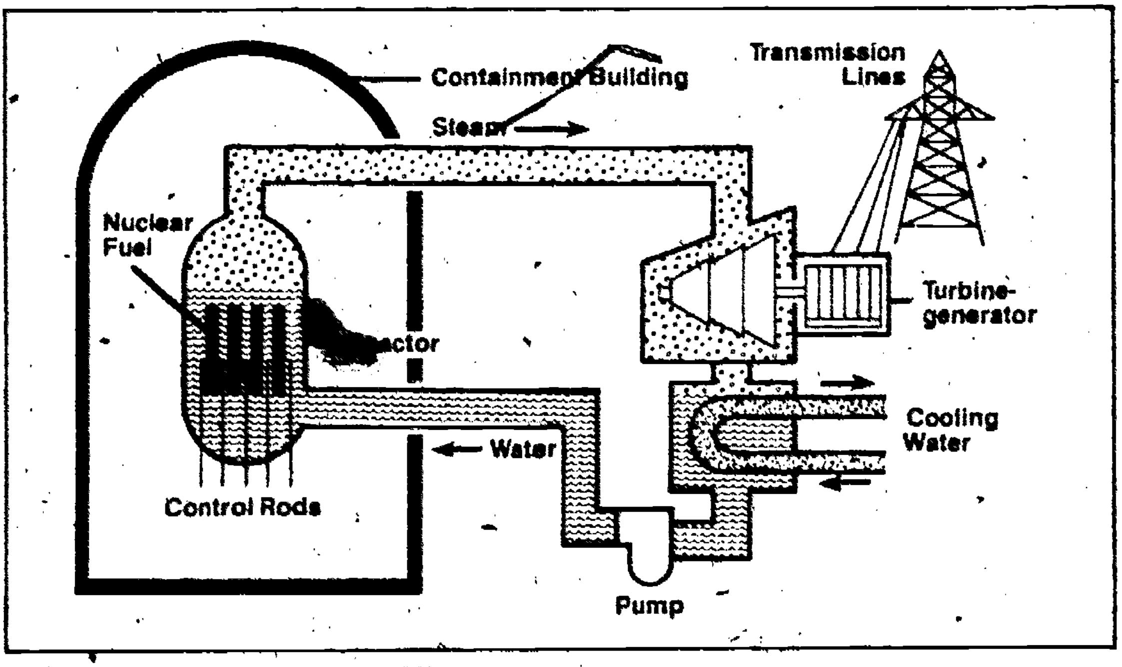

Figure 18. *Boiling Water Reactor (BWR)*

energy content, the water in a BWR is kept at a pressure of 1000 pounds per square inch (psi), instead of the normal atmospheric pressure of about 15 psi. Because of this added pressure, the water does not boil and turn to steam until it reaches a temperature of about 545° Fahrenheit (285° C). This higher temperature adds to the energy value of the steam in turning the turbine.

Pressurized-Water Reactors (PWR)

In a pressurized-water reactor (PWR) the water passing through the core is kept under sufficient pressure that it does not turn to steam at all—it remains liquid (Figure 19). Steam to drive the turbine is generated in a separate piece of equipment.

The PWR system is known as a double-loop because it involves two separate circuits of water—or loops—which never physically mix with each other. One is a primary loop; the other is called a secondary loop. The water that flows through the reactor, known as the "primary" loop, is pressurized to about 2250 psi. It heats to about 600°F (315°C) without boiling and leaves the reactor as a hot liquid. It is pumped through tubes in the steam generator. After transferring its heat in the steam generator to the secondary loop, the highly pressurized water in the primary loop is pumped back to the core to be reheated and continue with the process. The secondary water circulates around the tubes in the steam generator, picking up or "exchanging" heat from the primary loop. This heat exchange turns the

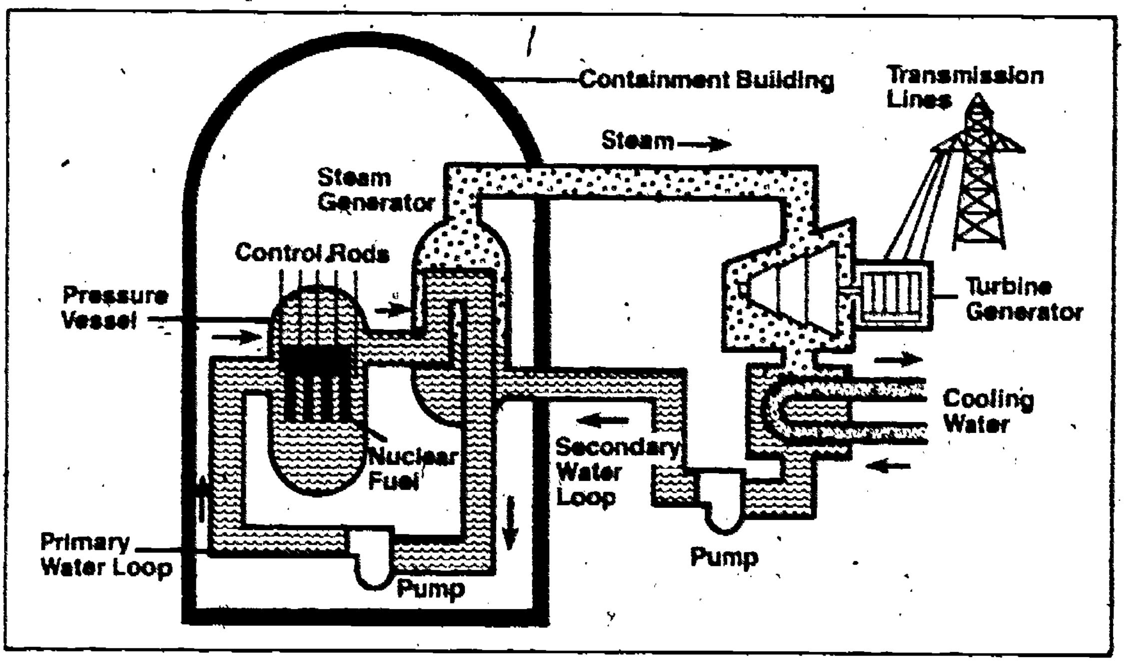

Figure 19. *Pressurized Water Reactor (PWR)*

secondary water to steam which flows toward the turbine at a temperature of about 500°F (260°C).

About 50 of the nuclear powerplants operating in the United States are pressurized-water reactors (Figure 20). PWRs are also used in nuclear submarines and other naval applications.

High Temperature Gas-Cooled Reactors (HTGR)

High temperature gas-cooled reactors (HTGRs) are also double-loop systems. (Figure 21). The principal difference is that the coolant in the primary loop—which flows through the core to carry away the heat—is not water, but a gas.

The gas used is helium, which is circulated through pipes in the primary loop by huge blowers. The gas, kept under a pressure of several hundred pounds per square inch, can achieve much higher temperatures than water. In some designs the gas can be heated to as much as 1400°F (760°C). As a result, the steam produced from water in the secondary loop, which powers the turbines, can have temperatures as high as 1000°F (538°C). This higher temperature leads to improved thermal efficiency—that is, more electric power is generated for the same amount of heat from the fuel.

Another major difference between gas-cooled reactors and water-cooled reactors is the moderator. As was explained previously in the description of reactor core elements, in water-cooled reactors the water serves as a moderator to slow neutrons and increase the likelihood of atoms fis-

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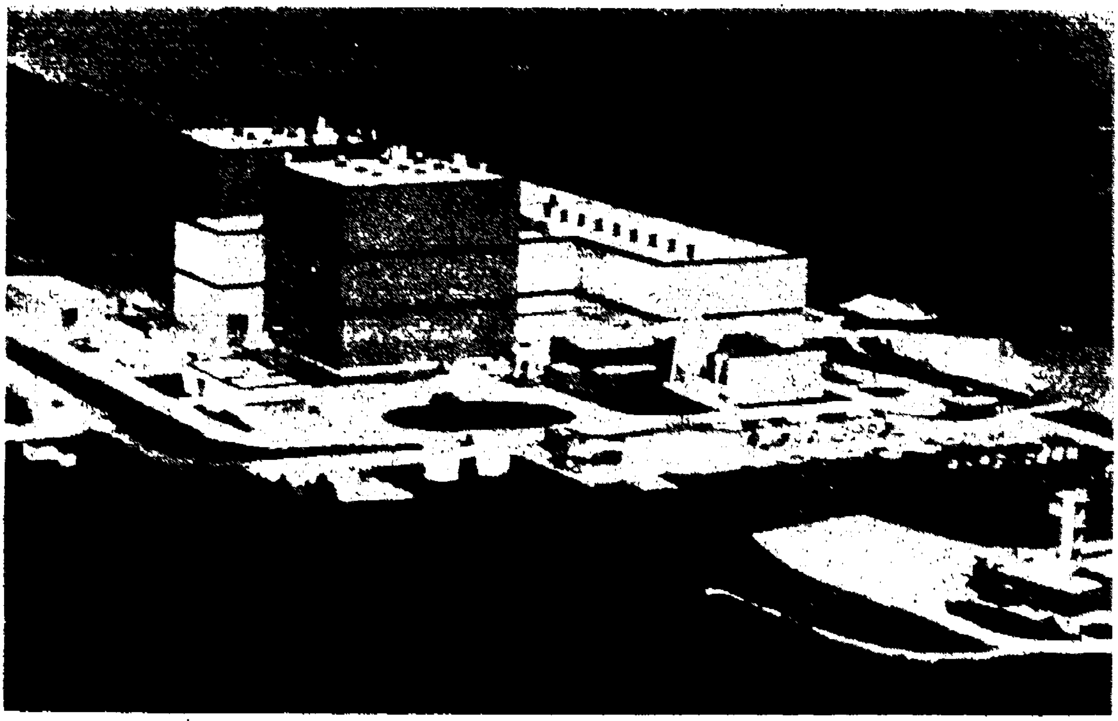

Figure 20. *Point Beach Nuclear Plant at Two Creeks, Wisconsin. The plant has two 497-megawatt pressurized-water reactors (PWRs). Unit 1 began operation in 1970, Unit 2 in 1972. (Credit: Wisconsin Electric Power Co.)*

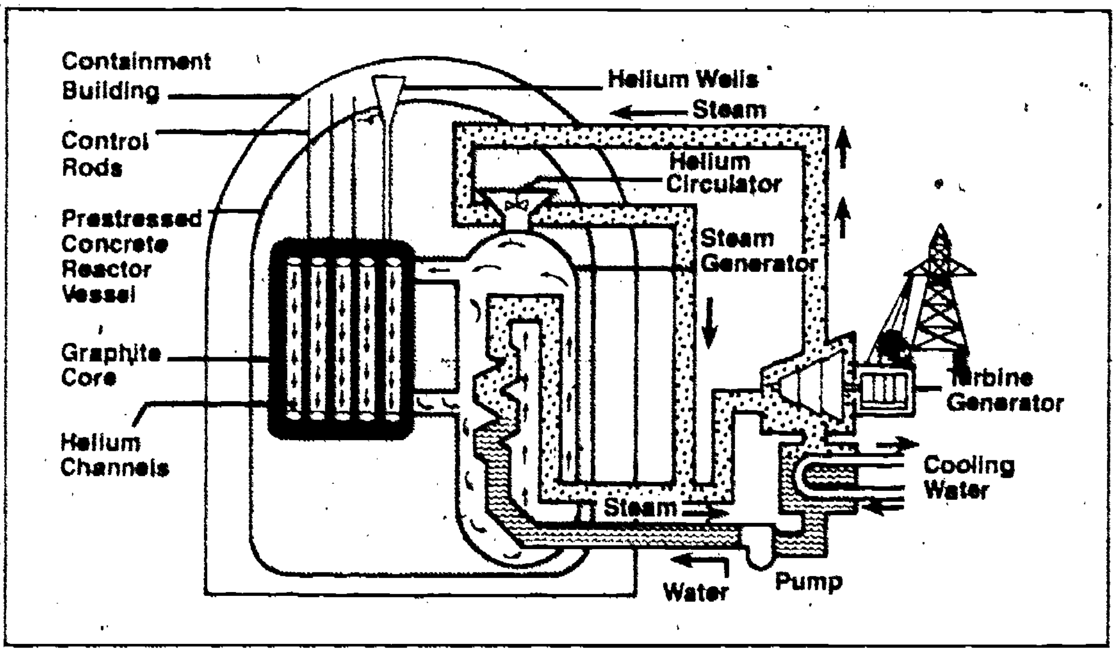

Figure 21. *High Temperature Gas-Cooled Reactor (HTGR)*

Figure 22. *Fort St. Vrain in Colorado is the first commercial high-temperature gas-cooled reactor (HTGR) to be built in the United States. It is also the first to use a prestressed concrete pressure vessel. (Credit: Public Service of Colorado)*

sioning. Gas, however, is not a satisfactory moderator because it is so much less dense. Therefore another material must be included in the core. The moderator in gas-cooled reactors is graphite, which can withstand the high temperatures of these systems. The fuel, uranium carbide particles, is distributed throughout the graphite in the core of an HTGR.

In the United States one gas-cooled reactor, Peach Bottom 1, operated as a demonstration plant in Pennsylvania for seven years. A commercial HTGR, Fort St. Vrain, has been operating in Colorado since 1979 (Figure 22).

Breeder Reactors

Scientists and engineers have been working for over three decades on breeder reactor technology. Breeder reactors are being developed which will greatly multiply the energy obtained from uranium by converting that finite energy resource into virtually an inexhaustible energy supply.

All nuclear powerplants produce new fuel while they are operating—extra neutrons are absorbed by U-238 atoms, which are then transformed into fissionable plutonium (Figure 23). Some reactors are designed to do this so efficiently that they actually produce more fuel than they consume and are called "breeder" reactors.

Breeder reactors are able to multiply the amount of energy available from uranium resources. By using the U-238—which exists in great quantities as an otherwise useless leftover from the uranium enrichment process—a breeder reactor will get 60 times as much usable energy from natural uranium as today's nuclear powerplants.

Several reactor types have the potential for breeding. The one that has been developed most thoroughly through experimental reactors and actual operating plants is cooled by circulating a liquid metal (sodium) through it. It is called the liquid metal fast breeder reactor, or LMFBR (Figure 24).

These reactors are different from the other designs discussed in this booklet in several ways:

- the neutrons released in the fission process are "fast," meaning they are not moderated, so they remain at high speed;

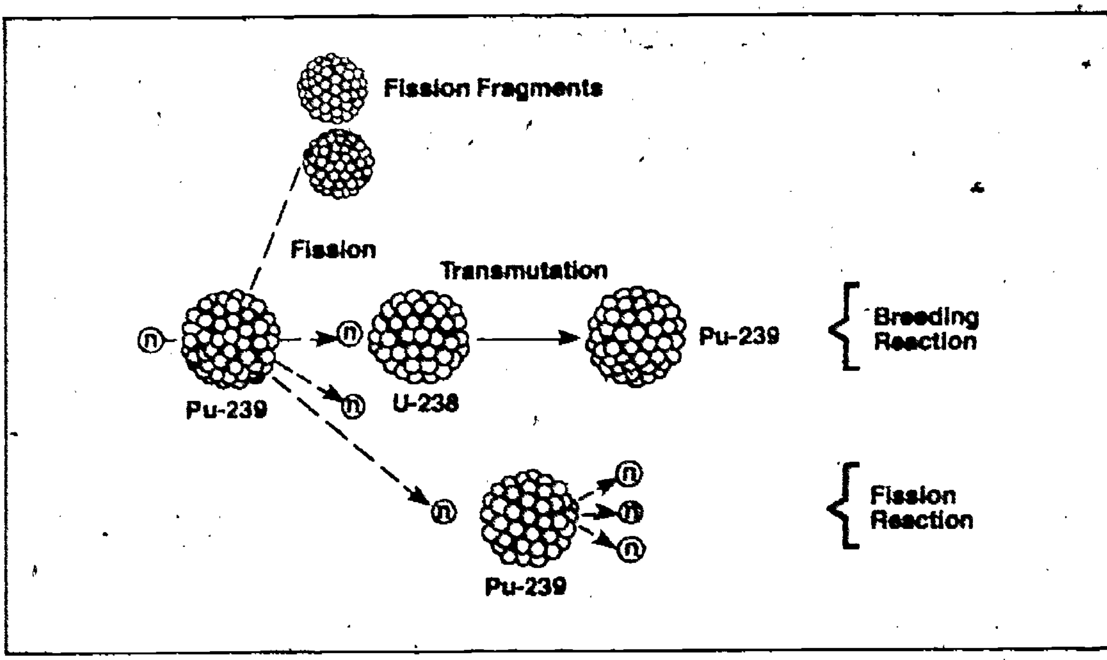

Figure 23. *The Breeding Process*

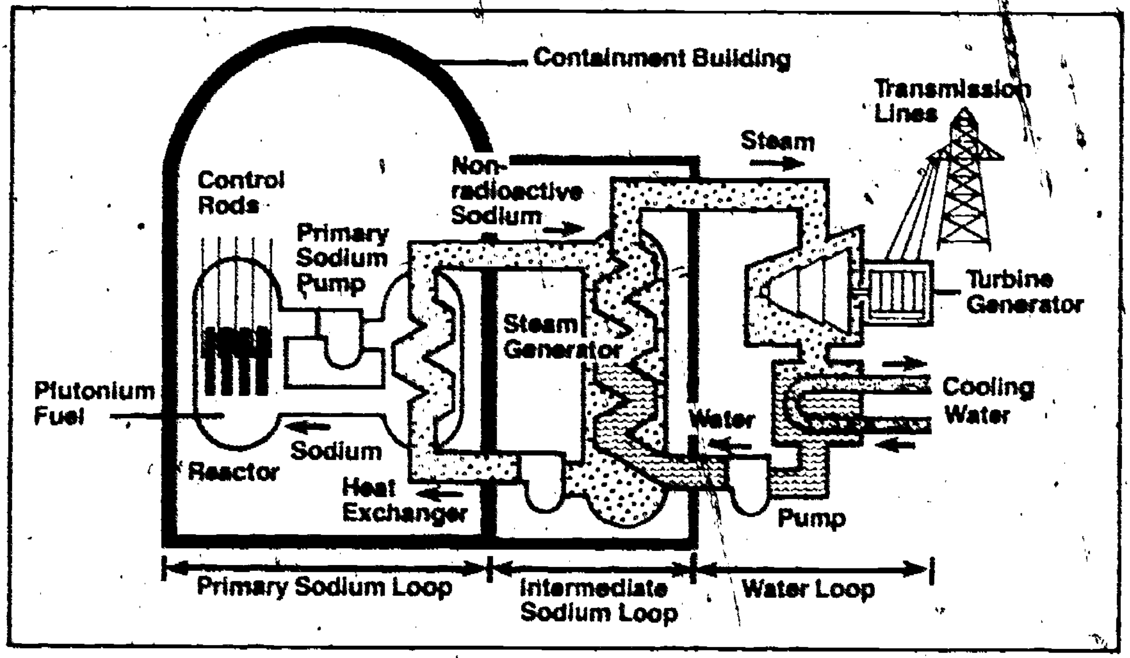

Figure 24. *Liquid Metal Fast Breeder Reactor (LMFBR)*

- the coolant is sodium in the form of a liquid metal—like mercury in a thermometer;
- the fuel is normally plutonium-239; and
- the design of the reactor incorporates uranium-238 as the fertile material.

Sodium is used as a coolant in the LMFBR because: it is an excellent heat transfer agent; it is inexpensive and available in high purity; it is not subject to irradiation damage; it is compatible with many construction materials; and it is easy to pump at the reactor operating temperature.

The liquid metal fast breeder powerplant is a three-loop system. Sodium would undergo a rapid chemical reaction if it comes into contact with water or steam. To keep the sodium that passes through the core (which becomes radioactive) from any potential contact with water, an intermediate heat-transfer loop also containing sodium separates the primary loop's radioactive sodium coolant from the water/steam loop.

In a liquid metal cooled breeder, sodium is circulated through the core and heated to about 1000°F (538°C). This sodium passes through a heat exchanger to transfer its heat to an intermediate sodium loop. The sodium in this secondary loop then moves to the steam generator where it heats water in a third loop to steam at about 900°F (482°C).

Several experimental breeder reactors have operated in the United States. In fact, the EBR-I produced the world's first electricity

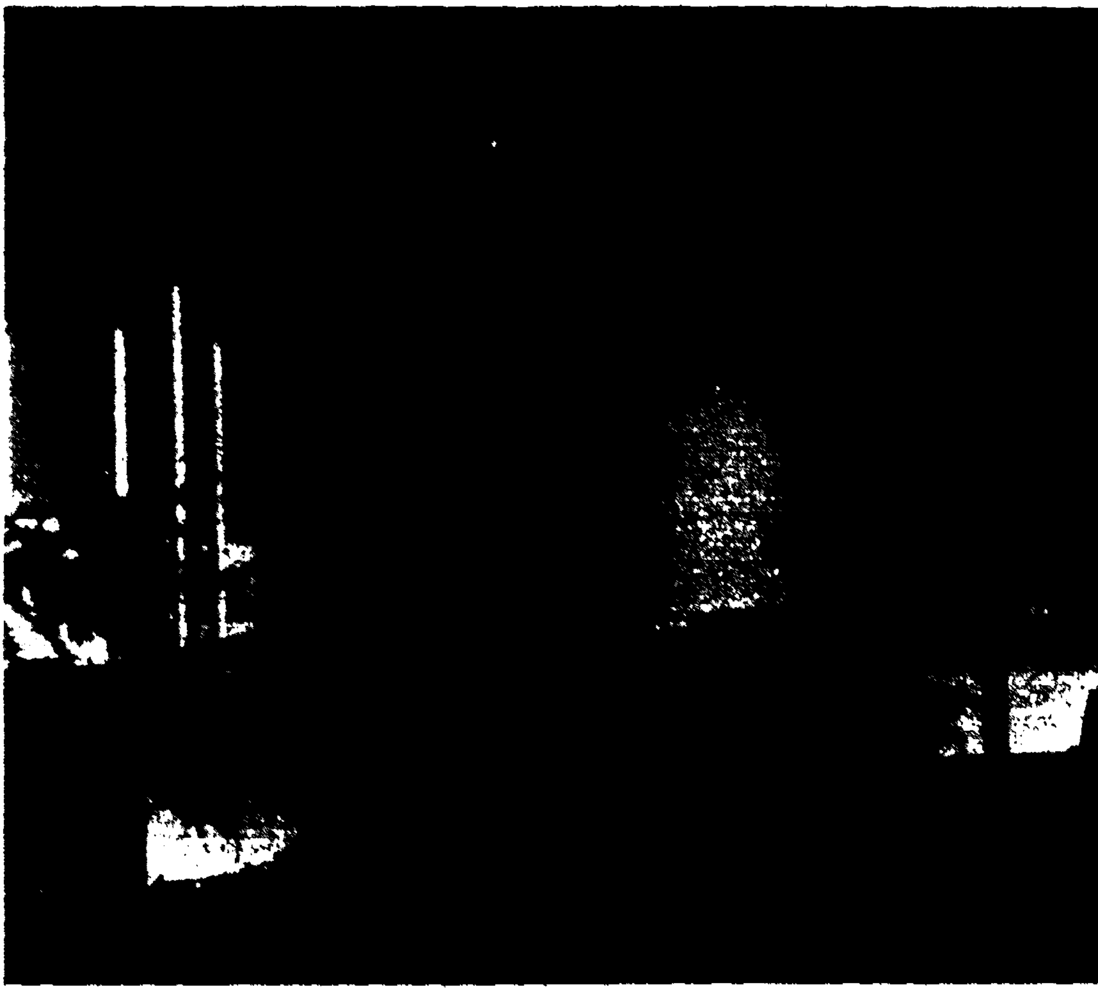

Figure 25. *The Experimental Breeder Reactor-II (EBR II), located at Idaho Falls, Idaho, has been in operation since 1963. (Credit: Department of Energy)*

generated by nuclear power in Idaho in 1951. Its successor, EBR-II, is still operating as a test reactor after almost 20 years, testing advanced reactor fuels and materials (Figure 25). A developmental commercial LMFBR, the Enrico Fermi Atomic Power Plant, operated in Michigan in the 1960's. Fuel failure caused the plant to be shutdown temporarily in 1966. After repairs, the plant resumed operations. High fuel cycle costs caused the plant to shut down in 1972, but not before its operation had helped to train personnel from France, Russia and Japan, who were later to develop fast reactor programs in their own countries. In 1980, the Fast Flux Test Facility (FFTF), a 400,000 kilowatt (thermal), sodium cooled, fast neutron flux reactor designed for irradiation testing of fuels and materials for the LMFBR program,

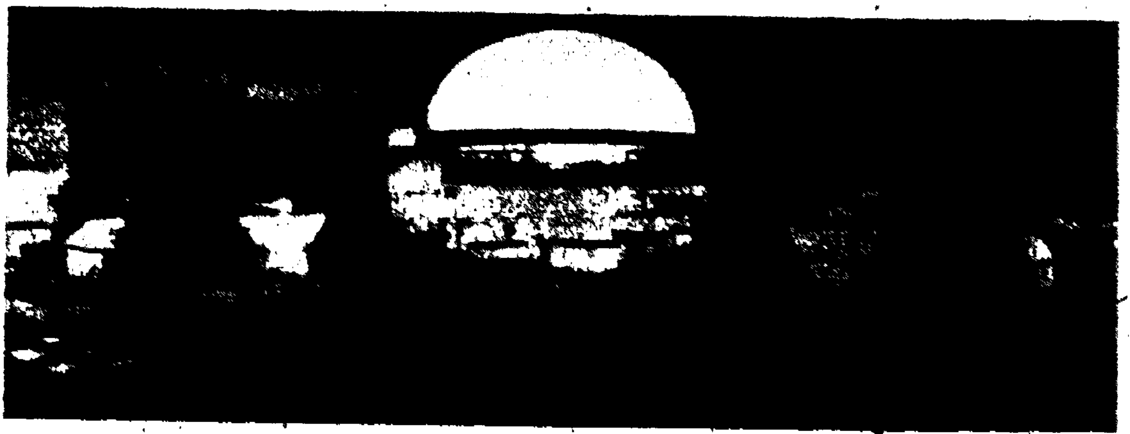

Figure 26. The Fast Flux Test Facility is designed specifically for the testing of breeder fuel and components. It began operation in February 1980. (Credit: Department of Energy)

Figure 27. Architectural concept of the Clinch River Breeder Reactor Plant. (Credit: Department of Energy)

began operating at the DOE Hanford Engineering Development Laboratory (HEDL) site in Richland, Washington, (Figure 26). A 375,000 kilowatt demonstration plant called the Clinch River Breeder Reactor (CRBR) has been under development in eastern Tennessee for several years with a combination of private and public funding (Figure 27).

France, the Soviet Union and Great Britain each have operating breeder reactors and are planning commercial-size 1 million kilowatt breeders in the near future. The French "Super Phenix" breeder (1.2 million kilowatts) is well along in construction and is expected to begin operating by 1984. The largest breeder now operating is the 600,000 kilowatt Beloyarsk plant in the Soviet Union. Breeders are also being developed in West Germany, India, Italy and Japan.

Nuclear Fuel: Mining to Reactor

Unlike fossil fuels, which can be burned in a power plant in virtually the same form in which they exist underground, uranium must go through a series of complex changes to become an efficient fuel for electricity generation. By the time it reaches the reactor the uranium fuel has been mined, chemically processed, isotopically enriched, and fabricated into fuel pellets, and in the process being transformed from a salt, to a powder, to a gas and finally to a dense ceramic.

Mining and Milling

Uranium is a fairly abundant element. It exists throughout much of the earth's crust and is even found in the world's oceans. The largest deposits of uranium ore that have so far been discovered are in

Figure 28. *Uranium ore is being carted from the Schwartzwalder underground mine in Golden Colorado. (Credit: Cotter Corporation)*

Table 2. *Comparative Fuel Requirements for Electric Powerplants**

Fuel	English Units	Metric Units
uranium	33 tons	30 metric tonnes
coal	2,300,000 tons	2,100,000 metric tonnes
oil	10,000,000 barrels	1,600,000 cubic meters
natural gas	64,000,000,000 cubic feet	1,800,000 cubic meters
solar cells	25,000 acres	10,125 hectares
garbage	7,000,000 tons	6,200,000 metric tonnes
wood	2–4,000,000 cords	4.6–9,800,000 metric-tonnes

Note: A 1-million kilowatt plant generates enough electricity for a city of 560,000 people.

*The annual fuel requirements of a 1-million kilowatt powerplant operating at 75 percent of its theoretical annual capacity.

the western United States, Australia, Canada, South Africa, and several other countries in Africa and South America (Figure 28).

Uranium in nature, however, is quite dilute, combined in small proportions with other elements to make up such minerals as pitchblende and carnotite. Natural uranium exists in an oxide form (i.e. chemically combined with the element oxygen) and typically amounts to only 0.1 to 0.2 percent of the raw ore. This means that a ton of ore mined from the ground yields at most only two to four pounds of uranium. But, uranium is more efficient than other fuel types (Table 2).

A crude uranium oxide is extracted from the ore at uranium mills that are generally located near the mines. The mills concentrate the uranium oxide by crushing the ore into fine sand-like particles which are then put through such separation and concentration processes as screening, flotation and gravity separation. The milling process leaves a large residue of liquid sludge called "tailings" which is allowed to dry and collected in piles within enclosures. The tailings contain the elements thorium and radium which are mainly by-products of the decay of U-238. Tailings are no more radioactive than the ore that was removed from the earth; but since the material has been brought to the surface and concentrated, it can pose a hazard unless covered by layers of earth or other forms of shielding to contain and stabilize it.

The uranium oxide extracted from the milling operation is further refined and purified in other chemical processes. This material, called yellow cake, is then combined with fluorine gas to be transformed into uranium hexafluoride gas (UF_6). In this form it is ready for enriching.

Figure 29. *In the U.S. Department of Energy's gaseous diffusion enrichment plant in Tennessee, uranium in the form of uranium hexafluoride gas (UF_6) is passed in stages through many porous barriers. More than 1,200 stages are needed to produce uranium enriched to 3.0 percent U-235. (Credit: Department of Energy)*

Figure 30. A technician is working through a laboratory glove box to make precise measurements of nuclear fuel pellets. The pellets are then inserted in pencil-thin tubes. (Credit: Department of Energy)

Enrichment and Fuel Fabrication

In the process of extracting the few pounds of uranium oxide that were present in the original ton of ore, impurities that would interfere with the fission process are chemically removed. But the uranium contains the natural proportion of isotopes: more than 99 percent is nonfissionable U-238, and only about 0.7 percent is the U-235 that can be used as fuel. Since a light-water reactor (LWR) requires that its uranium fuel contain about 3.0 percent U-235, the refined uranium must be enriched in its fissionable isotope.

Figure 31. *Loading the fuel at the McGuire Nuclear station in North Carolina. (Credit: Duke Power Co.)*

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Large-scale enrichment of uranium, which is one of the keys to most uses of nuclear energy, was made possible by the development of the gaseous diffusion process. Large gaseous diffusion plants owned by the U.S. Government make use of the fact that a U-238 atom is about 1 percent heavier than a U-235 atom because it contains three more neutrons (Figure 29).

To enrich uranium, the gaseous form (UF_6) is piped into a gaseous diffusion plant and pumped through barriers that have microscopically small holes, less than 1-millionth of a centimeter in diameter. Because the U-235 is slightly lighter than U-238, the U-235 passes through the holes more readily. Therefore, the gas that passes through a barrier in the diffusion plant has slightly more U-235 than natural uranium; the gas left behind has slightly less. After being pumped through a series of thousands of barriers, the end-product gas reaches the 3.0 percent enrichment level that is required for nuclear powerplants. The gas left behind has been stripped of its U-235 from 0.7 percent to less than 0.3 percent, and is known as depleted uranium. This depleted uranium cannot be used as fuel, but it has value as fertile material in breeder reactors.

After the uranium is enriched, it is chemically converted back into uranium oxide to be processed into fuel. The powdery oxide is compressed into small cylindrical pellets and loaded and sealed into metal tubes to form the fuel rods. Detailed inspection follows every step of this fabrication process (Figure 30).

These fuel rods, about 12 feet long, are grouped together in bundles known as fuel assemblies. The fuel rods are carefully spaced in the assemblies to allow a coolant to flow between them. The fuel assemblies are grouped together to make up the core of the reactor (Figure 31). The nuclear fuel fissions and generates heat in the reactor, just as burning coal or oil generates heat in a boiler.

Nuclear Fuel: Reactor to Waste Disposal

All operations involving radioactive materials—including nuclear powerplants, hospitals, research centers and industrial processes—create radioactive wastes that must be safely handled and disposed of. The radioactive wastes are created in several different forms, ranging from only slightly radioactive to intensely radioactive, and they are handled in different ways depending on their level of radioactivity, the amount of heat they generate, and other factors.

Handling Spent Fuel

A 1-million kilowatt nuclear powerplant typically contains about 100 tons of uranium fuel. Each year about one-third of the fuel—roughly 33 tons, or 60 of its fuel bundles—

Figure 32. *Technicians use an underwater periscope to inspect fuel assemblies in the spent fuel pool. (Credit: Wisconsin Electric Power Co.)*

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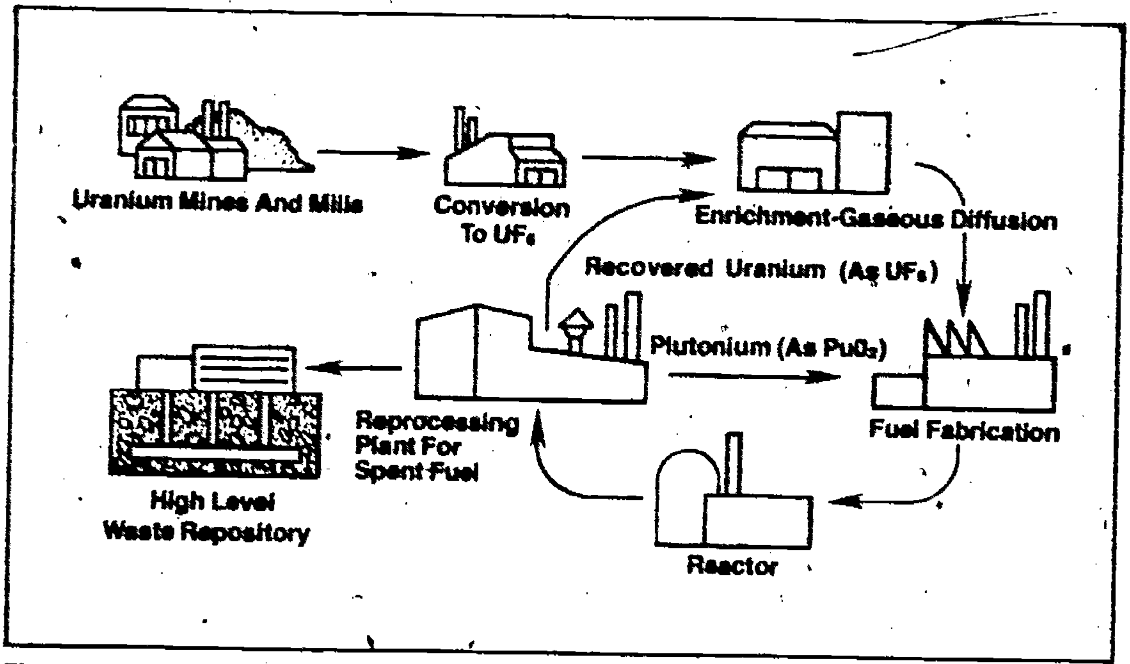

Figure 33. *The Nuclear Fuel Cycle*

must be removed and replaced. The used fuel is called spent fuel.

As the spent fuel rods leave the plant, they are physically similar to the new fuel rods that were originally installed. They are still composed largely of U-238, more than 94 percent by weight. The primary difference is that the U-235 that released its energy in the reactor created radioactive fission products and other long-lived radioisotopes. Though they represent a small proportion of the spent fuel, only 3.5 percent, they continue to generate heat and release radiation long after the fuel is removed from the reactor.

Most spent fuel from nuclear powerplants is stored in deep pools of water near the reactor (Figure 32). The water cools the fuel rods, to keep them from overheating, and it serves as an effective shield to protect workers from the radiation.

The level of radiation begins declining immediately, and within 10 years it has decayed by some 90 percent. Nevertheless, some fission products remain radioactive for many years. Storage of the spent fuel in pools near the reactors is a temporary measure, until the fuel is shipped to long-term storage, to permanent waste repositories, or to reprocessing plants.

Reprocessed Wastes

From the beginning of nuclear power use, it was assumed that the spent fuel would be chemically reprocessed to allow the still-usable fuel to be recycled and to concentrate the fission products into a smaller volume. (Figure 33). Fuel reprocessing technology has been developed and utilized in the United

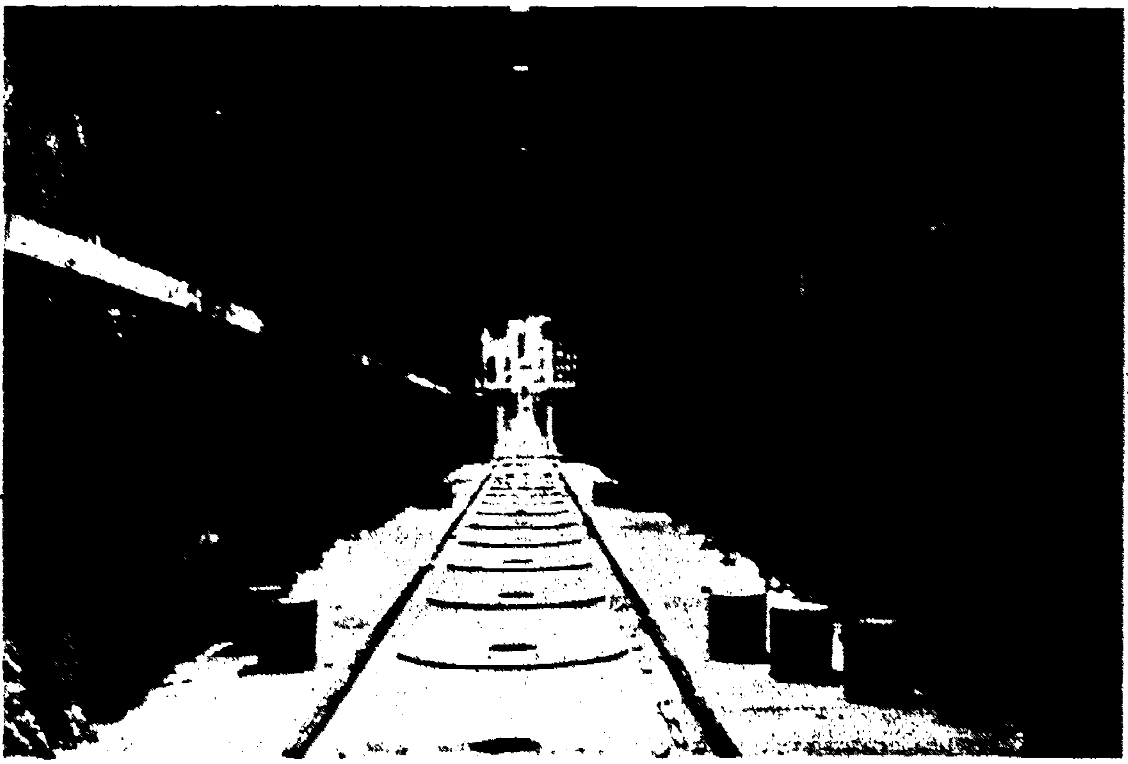

Figure 34. *The Climax Spent Fuel Storage Test is being conducted to evaluate the effects of storing spent reactor fuel in a crystalline rock formation 1,400 feet below the surface of the Nevada Test Site. (Credit: Atomic Industrial Forum)*

States. It is now being used in several other countries. After a moratorium on commerical reprocessing imposed in 1977, the United States Government and industry are now studying the circumstances and requirements under which resumption of reprocessing could be considered.

A reprocessing plant dissolves the fuel rods in acid and separates out the uranium and plutonium isotopes from the fission products and cladding. The uranium can be fabricated into fresh reactor fuel, and the newly created plutonium could be used in the advanced "breeder" reactor.

After the chemical reprocessing, the fission products exist in the form of a highly radioactive liquid. That liquid can then be turned into a solid that has a volume 80 percent less than the original spent fuel, thus requiring a smaller area for high-level waste disposal.

Handling and Disposing of High-Level Wastes

High-level waste (HLW) is nuclear waste with a relatively high level of radioactivity. HLW comes from the reprocessing step after nuclear fuel is removed from a reactor; it has come to mean also the spent reactor fuel assemblies if they are not reprocessed.

The goal of safe waste disposal is to ensure that essentially no radioactive material from the waste ever reaches man or his environment. The barriers that are designed to prevent the waste from reaching the environment include the form of the waste itself, its containers, the packing around them, and the physical protection of the permanent repository, such as a deep geologic formation (Figure 34).

The first assurance that radioactive waste will not move from its repository to the environment lies in its very form: one of the most likely forms—based on decades of research and experience in the United States and abroad—is a special glass compound, like Pyrex. This compound called "borosilicate glass", combines silicon (an ingredient of sand) with boron oxide and other elements; ordinary glassware contains a higher percentage of silicon and lime instead of boron

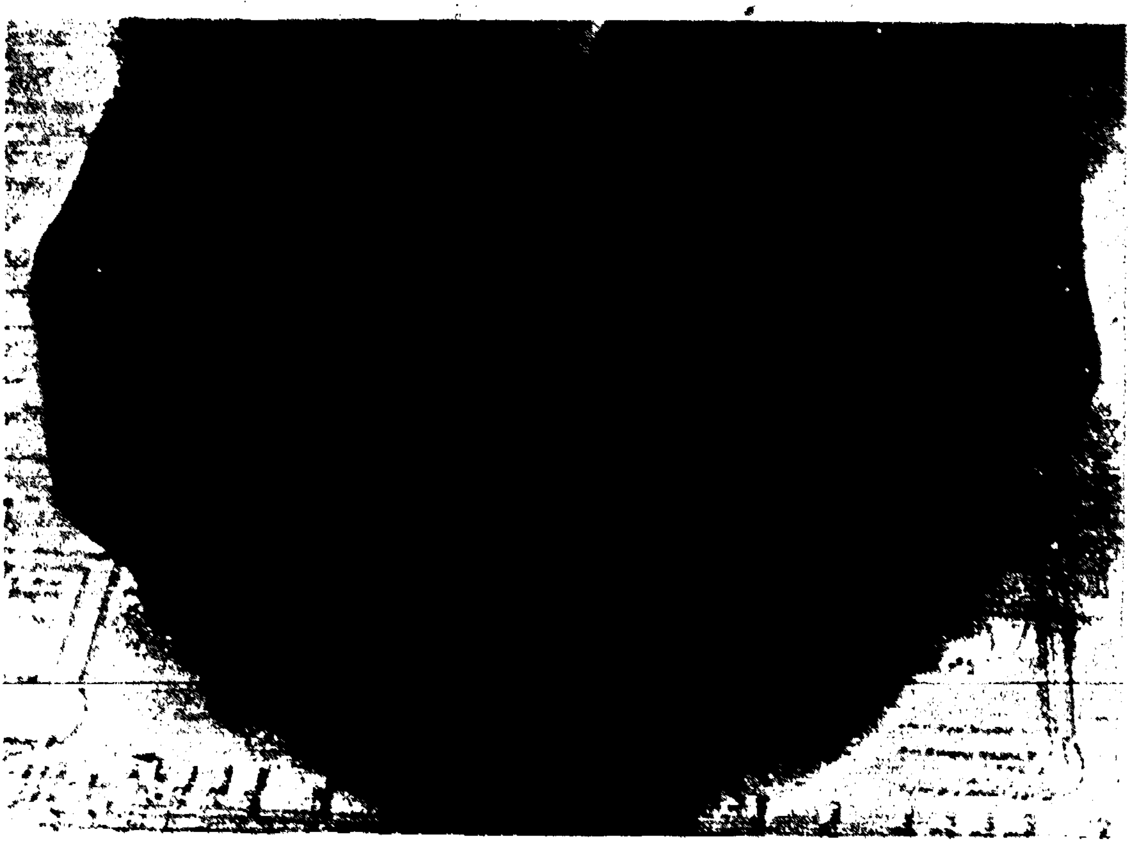

Figure 35. *Radioactive Waste from the nuclear fuel cycle can be immobilized in glass for handling and disposal. The simulated waste glass shown is comprised of 25 percent high-level waste-type material and 75 percent non-radioactive glass ingredients. The button on the left represents the annual quantity of high-level waste for one person if all U.S. electricity were produced by nuclear power. The cylinder at right represents an individual's lifetime quantity. (Credit: Department of Energy)*

oxide. In the borosilicate-glass form, the waste would be resistant to heat, chemical action, stress and radiation (Figure 35).

The solid waste could then be sealed in waterproof, corrosion-resistant steel containers about 10 feet long and one foot in diameter. The waste containers would then be encased in a series of protective wrappings, including cases of metal, ceramic or cement and buffers that would absorb water and other chemicals before they reached the container. These additional barriers would further isolate the radioactivity from the environment. About a dozen of these special canisters could hold all the high-level waste produced in a full-size nuclear powerplant in a year.

The Nuclear Waste Policy Act of 1982 spells out a procedure and timetable for the site selection, construction and operation of HLW repositories, the first one to be operable around the turn of the century. In addition to this strong commitment to permanent geologic disposal, it provides for a system of fees paid by utilities to fund waste disposal; a strong voice for States in the choice of siting; a limited, temporary federal storage program to alleviate near-term storage problems at powerplants; and a study of monitored retrievable storage as an interim step toward permanent disposal.

Handling and Disposing of Low-Level Wastes

Low-level wastes (LLW) contain relatively little of the radioactive transuranic elements. Most of this waste requires little or no shielding and no cooling and may be handled by direct contact.

Every organization that uses or produces radioactive materials generates low-level wastes. Industrial users that manufacture radiopharmaceuticals, smoke alarms, emergency exit signs, radium watch dials and other consumer goods produce low-level wastes consisting of machinery parts, plastics and organic solvents.

About half of the total low-level waste generated today is from nuclear powerplants. This includes used resins from chemical ion-exchange processes, filters and filter sludges, lubricating oils and greases, and detergent wastes from laundry operations and from decontaminating personnel and equipment. Most of this waste is processed and packaged for disposal at a specially designed waste facility.

The common method of disposing of low-level waste is to ship the wastes to a commercial disposal site where the containers of waste are buried in trenches. Low-level wastes are packaged in 55-gallon or 30-gallon metal drums, or high-integrity casks, and shipped by truck to the disposal site, in accordance with regulations set by the Department of Transportation and the Nuclear Regulatory Commission (Figure 36).

The dimensions of the trenches vary, depending on the soil and water conditions of the area. Typically, they might measure some 600 feet long, about 60 feet in

Figure 36. *A 55-gallon drum of solid low-level waste is loaded by crane into a trailer for shipment to a LLW disposal site. (Credit: Atomic Industrial Forum, Inc.)*

width, and 25 feet or more in depth. Each trench is filled with waste drums and crates to about two-thirds of the trench depth. Then several feet of soil and fill material are placed on top. When an entire trench has been completely back-filled in this manner, an impermeable "cap" of soil and sometimes compacted clay about 6 feet deep is sealed on top of the trench, creating a contour that sheds surface water.

After the trenches are filled and capped, their locations are outlined with permanent stone or metal markers which list the amount and type of radioactivity in the trenches below. Then the closed trench is seeded with grass to restore vegetation cover and prevent erosion. Site operators and regulatory agencies conduct regular surveys to determine radiation levels at open and filled trenches and around the site boundaries.

Changes in Low-Level Waste Policy

The current system for management of low-level waste evolved over a period of time when disposal capacity was available and costs were low. Disposal capacity is now limited to three sites: Barnwell, South Carolina; Beatty, Nevada; and Hanford, Washington. Two of the states have decided to cut back on the amount of waste they will accept from other states, and the Nevada facility is reaching its maximum capacity. Furthermore, the volume of wastes generated is on the rise despite improved volume-reduction techniques: in 1982 nearly 3 million cubic feet of low-level waste were shipped to commercial sites for disposal. Costs have risen as well, especially for transporting the waste as much as 3,000 miles to accommodate current volume ceilings at the existing disposal sites.

When Congress passed the Low-Level Waste Policy Act in 1980, it set in motion major changes in the national low-level waste disposal program:

- As of January 1, 1986, each state will be responsible for providing its own disposal facilities for low-level waste. That includes all fifty states and the District of Columbia.

- The most efficient method would be through regional compacts, which would provide a central disposal facility for several neighboring states. Congress must endorse the creation of each compact in advance and renew its approval every five years.

- After January 1, 1986, any state can refuse to accept low-level wastes from other states that are not members of its regional compact. Essentially, this means that a state must enter into a regional agreement, establish its own disposal facility, or stop generating low-level waste.

Vital services like electricity supply, medical diagnosis and treatment, and advancements made possible in research centers across the country depend on adequate low-level waste disposal capacity in the coming decades.

Transporting Radioactive Materials

Each year in the United States, some 500 billion shipments of commodities are made by truck, rail, barge, airplane, or other means. Of these about one in 5,000 contains material classified as hazardous. They include caustics and acids; toxic materials like pesticides and poisons; explosives, flammables, like gasoline and propane; corrosives; compressed gases; and radioactive materials.

Radioactive materials account for about two percent of all hazardous materials shipped. Half of these are radionuclides used in the practice of nuclear medicine. The rest are mostly radioisotopes used in industrial radiography, consumer products, and some industrial and scientific instrumentation. Radioactive materials involved in the operation of the Nation's nuclear powerplants account for only one quarter of one percent of all shipments of hazardous materials. (Table 3.)

The safety record of shipping radioactive materials is well-established. Only one-half of one percent of all accidents in the shipment of hazardous materials involves radioactive materials. (Table 4.) Most of the accidents involve small packages of low-level waste which contain little radioactivity. No deaths or serious injuries have ever been attributed to the radioactive nature of any materials involved in a transportation accident.

Since radioactive materials are subject to the same transportation hazards as any other freight, the regulations and procedures for ship-

Table 3. Annual Shipments of Nuclear Materials in the United States

Type of Material	No. of Shipments/Year
Exempt amount or limited radioactive level materials, e.g. smoke detectors, luminous signs or watches	700,000
Pharmaceutical and other medical sources, mainly radioisotopes used for diagnosis and treatment	910,000
Industrial radiation sources, including gauges to measure thickness of paper, portable x-ray devices	220,000
Nuclear materials used in the front end of the fuel cycle, including uranium, fresh fuels from fabrication plants, and a small amount of interplant spent fuel	200,000
Wastes from all industrial and medical sources other than nuclear powerplants	100,000
Nuclear powerplant wastes	50,000
Total	2,180,000

Source: Data courtesy of Robert Jefferson, Transportation Technology Center, Sandia National Laboratories; reprinted in "Understanding Radioactive Waste", Battelle Press, 1982.

Table 4. *Five-Year Total of Hazardous Materials Incident Reports* in the United States by Classification*

Classification	No. of Reports	Percent of Total
Flammable liquid	16,406	51.27
Corrosive material	10,672	33.33
Poisons, Class B	2,026	6.32
Flammable compressed gas	718	2.24
Oxidizing material	644	2.01
Nonflammable compressed gas	535	1.67
Miscellaneous and unknown	472	1.47
Flammable solid	183	0.57
Radioactive material	144	0.45
Explosives	122	0.38
Combustible liquid	69	0.21
Poisons, Class A	27	0.08
Total	32,018	100.00

*The figures in this table refer only to accidents that are reported to the Department of Transportation. Some events of each type fail to be reported.

Source: Department of Transportation Report DOT/RSPA/MTB-79/8; reprinted in "Understanding Radioactive Waste", Battelle Press, 1982.

ping them are governed by two thoughts: First, the methods for shipping radioactive materials from one location to another should minimize the chance that an accident will occur. Second, the radioactive materials should be packaged in such a way that no radiation will be released even if an accident should occur. Traditionally, the primary safety factor is the shipping container itself, which ensures against leakage and prevents accidents or sabotage.

Spent Fuel Shipments

Fuel assemblies are removed from the reactor after about three years. At this point, the used or "spent fuel" assemblies are highly radioactive. They are removed to storage pools of water near the reactor where they are held for a time to allow their radioactivity to decay and their heat to diminish before shipment. After a period of time, the spent fuel assemblies may

Figure 37. A large spent fuel rail cask. (Credit: Department of Energy)

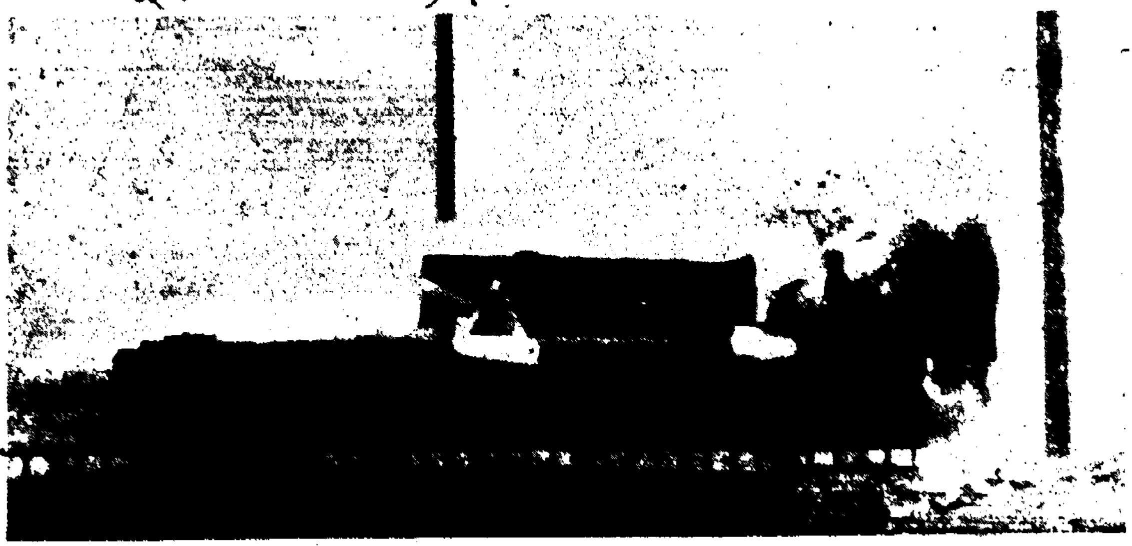

Figure 38. *To test the durability of a 22-ton container used to transport spent nuclear fuel, technicians at the Department of Energy's Sandia Laboratories in New Mexico mounted the cask on the bed of an expendable tractor-trailer. The rig was then loaded onto the Lab's rocket sled and slammed into a 10-foot thick concrete wall at 60 mph. Although the truck was totally demolished, the container suffered only a slight dent at one end but no part of the cask cracked open. A high-speed camera recorded the moment of impact and scattering wreckage immediately following. (Credit: Sandia Laboratories)*

be shipped in massive protective containers by truck or rail to a reprocessing facility (to extract still usable fuel), to a permanent disposal site, or to another storage pool.

Each nuclear powerplant annually produces the equivalent of approximately 25 truckloads or 10 railcars of spent fuel (Figure 37). Since 1964, over 4,000 spent fuel assemblies have been shipped from reactor sites to other locations, including two reprocessing plants. Today, however, there are no operational reprocessing plants or permanent disposal sites for commercial spent fuel, so such shipments are not taking place.

The shipping containers for spent fuel are rigorously designed, manufactured and tested—Figure 38 shows one cask design. In another cask design, the fuel assemblies are sealed into a water-filled stainless steel cylinder with walls one-half inch thick, clad with four inches of heavy metal shielding, enclosed by a shell of inch-and-a-half steel plate, surrounded by five inches of water, and encircled by a corrugated stainless steel outer jacket. The overall package measures 5 feet by 17 feet and weighs 70 tons.

The shipping cask is required by the Nuclear Regulatory Commission to withstand a series of accident conditions:

- a 30-foot fall on a flat, hard surface (as if the cask dropped from an overpass onto a concrete highway)

- a 40-inch drop onto a metal pin 6-inches in diameter (as if the cask hit a sharp corner of a bridge abutment)
- a 30-minute exposure to a fire at a temperature of 1475°F (as if a tank of gasoline ruptured in an accident and a fire ensued)
- complete immersion in three feet of water for eight hours (as if the cask rolled off into a creek along the highway)

The container must undergo these destructive forces in sequence with no breach of containment and with no significant reduction in shielding.

Road experiments designed to confirm the integrity of the spent fuel cask have been carried out and in all cases the safety requirements have been met or exceeded.

Transporting High- and Low-Level Wastes

Concentrated fission products, or high-level waste, are the most radioactive components of spent fuel. They result from reprocessing operations which can separate the radioactive waste from reusable fuel. When commercial reprocessing becomes available again and permanent waste disposal facilities begin operation in the United States, these wastes will be shipped to a permanent disposal site.

Before the high-level wastes from a reprocessing plant can be shipped, they will be transformed from a liquid to a solid. By solidifying the waste in canisters and placing them in shielded, hardened containers, the integrity of the wastes is assured under virtually all transportation conditions.

Low-level wastes contain small amounts of radioactive materials that generally do not require shielding during transportation. Most often they are shipped by truck in compacted solid form placed in sealed drums. A commercial nuclear reactor generates from 10 to 45 truckloads of low-level waste each year.

Shipping Procedures and Regulatory Responsibilities

The Department of Transportation (DOT) has general authority for regulating the transportation of hazardous materials, including radioactive materials. Its regulations include:

- packaging, marking and labeling radioactive materials shipments
- mechanical conditions for carriers and qualifications of carrier personnel
- loading, unloading, handling and storage

The Nuclear Regulatory Commission is responsible for licensing and regulating all commercial users and handlers of radioactive materials, including waste shippers and carriers.

Shipping procedures are designed to assure that radioactive materials are transported carefully. In shipping low-level waste, for example, truck drivers must meet basic mechanical knowledge of equipment and driving performance requirements, and are responsible for truck inspection and maintenance of vehicle logs. DOT requires that appropriate markers be placed on the truck to designate the potential radiation hazard of the kinds of waste carried. The transporter selects a specific route to the low-level waste disposal site before departure and notifies state authorities of the route chosen.

Shipments of spent fuel require further precautions. The NRC and local law enforcement agencies along the route are notified before each shipment. A communication center remains in touch with the transport vehicle and monitors its progress.

ERIC

The Economics of Nuclear Power

Do nuclear electric plants cost more than other types of powerplants, or do they save money for the electricity consumer? Surprisingly perhaps, the answer to both questions can be yes.

Just as you may spend more money for a car that gets better gas mileage, so that it actually saves you money over the life of the car, utilities spend more money to construct nuclear electric plants because the fuel costs are so much lower than for plants that burn coal. (Oil and natural gas have become too valuable and expensive to burn in new generating plants.) Because of the considerable difference in fuel costs, nuclear plants result in a savings to consumers in many parts of the country, particularly in areas like the Northeast that do not have coal mines nearby.

The cost of electricity from a generating plant is made up of three parts:

- the cost of fuel (coal, oil, gas or nuclear fuel) and the disposal of the residue (ash or nuclear waste);
- operation and maintenance costs (largely wages and salaries plus tools and equipment); and
- powerplant capital cost (cost of design, engineering, and construction including factory equipment, tools, interest on the capital, etc.)

Actual generating costs depend on several factors that can vary considerably: the location of the plant, the fuel choice, environmental protection equipment, and the length of time that it ~~takes~~ to build the plant. Perhaps most important of all, the costs depend on the time frame over which the plant was built. The higher interest and inflation rates of the past few years have raised the construction costs of nuclear and coal plants alike by some 15 percent a year, making new electric power stations much more expensive than those built a few years earlier.

Capital costs of electric generating plants are expressed in terms of dollars per kilowatt of installed capacity. For example, a 1,000-kilowatt plant that had a total capital cost of $500,000 would be described as costing $500 per kilowatt. In these terms alone, nuclear energy has always been on the expensive side. In the late 1960's nuclear plants were projected to cost about $150 per kilowatt, and coal plants about $120. After years of inflation, current projections for plants that would begin operating at the end of the 1980's estimate that nuclear electric plants would cost some $2,400 per kilowatt, and coal about $1,600. That means a 1-million kilowatt nuclear plant would cost about $2.4 billion, and a coal plant that size would cost some $1.6 billion by the time it could be completed.

Nuclear plants, however, begin saving money shortly after they go into service because of their lower fuel costs. While every utility system is a unique case, one of the most useful comparisons of nuclear and fossil costs can be seen on the

Commonwealth Edison electric system in the Chicago area. That utility has six large nuclear plants and six large coal plants of roughly the same size and dates of construction. In 1982 the electricity from the coal and nuclear plants cost about the same. The principal difference between them is the cost of the fuel. The fuel amounted to 54 percent of the total cost of the coal-generated electricity, but only 19 percent of the cost of nuclear power.

Although the differences are not necessarily this dramatic in all parts of the country, nuclear plants show a slight economic edge in total generating costs. Nationwide, nuclear plants generated electricity at a cost of 26 mills per kilowatt hour in 1981; for coal plants, the cost was 29 mills. Even though oil-fired plants are much less expensive to build than either nuclear or coal plants, the costs of the fuel itself make their electricity costs considerably higher.

Estimated costs of electricity from new powerplants in the future continue to show that both nuclear and coal will generate electricity at about the same cost but at a much lower cost than the alternative fuels such as oil. These projections depend on several unknowns—the future inflation rate, interest costs, regulatory processes, pollution control equipment, fuel costs, and demand for power.

It's important to remember that the current nuclear cost advantage is in comparison to coal plants built at the same time. As long as the United States is in a period of high interest, high inflation, rising fuel costs and lengthy regulatory processes, electricity from any new electric plant—whether nuclear or coal—will no doubt be more expensive than from older plants. This means that every new generating unit tends to raise the cost of electricity to consumers.

Utilities, electricity rate payers, and bond holders have an enormous investment in the nuclear powerplants that are now operating or being built. The steadily rising capital costs of electric plants are adding new pressures to electric utilities: instead of paying \$100–\$150 million for a 1-million kilowatt electric plant, as they did in the mid-1960's, utilities must now commit upwards of \$2 billion. The pressures associated with raising that much capital, paying the carrying charges, and seeking increases in electric rates to pay for these costs have steered many utilities away from a "build-and-grow" philosophy. Instead they are encouraging energy efficiency and conservation programs to slow down the rate at which they must build new central station generating plants.

Even with better managed growth in electric demand, more generating plants will most probably be required in most areas of the country. Why? Because the country's population continues to grow; old powerplants need to be replaced; the economy—which is extremely dependent on energy—continues to expand, even if not as rapidly as in the past; and many energy users are continuing to shift from direct oil use to other substitutes, including electricity. This anticipated increase will extend the need for new powerplants that generate electricity at a cost competitive with other available fuel sources.

Nuclear Electricity in Other Countries

In September 1956 two nuclear electric plants, Calder Hall 1 and 2, in Northern England began operation, becoming the world's first commercial nuclear generating station. Because of its dependence on imported oil, Great Britain turned to nuclear power earlier than other countries. The wisdom of this decision was dramatized when the Suez Canal crisis erupted only weeks after Calder Hall had started up. The UK presently has about 30 nuclear powerplants (gas cooled) in operation, generating 16.5% of the country's electricity in 1982.

Today most industrialized nations are operating or building nuclear plants for similar reasons—lack of enough locally owned fuel resources and concern over imported oil. Several nations—France, Switzerland, Sweden, Belgium, Taiwan, Finland, Japan, and West Germany—generate a larger proportion of their electricity from nuclear energy than does the United States.

As of March 31, 1983, the 220 nuclear plants operating in 24 countries outside the United States provided more than 9 percent of the world's electricity (Table 5). More than 360 other nuclear plants are under construction or being planned, which would bring the total nuclear generating capacity in other countries to some 440 million kilowatts—which is equal to the entire U.S. electrical capacity as recently as 1973.

Throughout the 1970s France conducted the world's most aggressive nuclear development program. France was relying on imported oil for more than 65 percent of her energy needs when oil prices quadrupled in the early 1970s. France turned to her one abundant energy resource, uranium, and developed a policy of "tout nucleaire"—or "all nuclear," vowing that no more coal- or oil-fired electric plants would be built. By the end of the decade France was operating 22 nuclear powerplants and bringing new ones into service at an average of one every two months (Figure 39). France's nuclear program is the third largest in the world after those of the United States and the Soviet Union and first in percentage of electricity needs satisfied by nuclear reactors. Nuclear energy is expected to provide more than 40 percent of France's electricity in the 1990s.

As of March 31, 1983, the Soviet Union was operating 40 nuclear electric plants and providing some 18 million kilowatts of capacity. The USSR expects to generate 10 percent of its electricity from nuclear power in 1985 and 25 percent in 1990.

Japan, which brought its first nuclear powerplant into service in 1966, now operates 25 (Figure 40). They provide 17 million kilowatts of capacity or about 12 percent of the nation's total electrical capability. One of its plants, Fukushima, is the largest nuclear generating facility in the world, with six reactors representing a total of 4.7 million kilowatts. By 1990 Japan expects to have increased its nuclear power program to 53 million kilowatts, or about 23 percent of the national electric capacity.

Table 5. *Nuclear Powerplants Outside the United States (as of March 31, 1983)*

Reactor Status	No. of Kilowatts	No. of Nuclear Units
In Operation	113,440,000	220
Under Construction	163,184,000	176
Planned	167,681,000	175
Total	444,305,000	571

Foreign Countries with Operating Reactors

Country	No. of Operating Units	No. of Units Under Construction
Argentina	2	1
Belgium	6	2
Brazil	1	2
Bulgaria	4	3
Canada	13	11
Czechoslovakia	2	10
Finland	4	–
France	32	34
Germany, Democratic Republic of	5	8
Germany, Federal Republic of	15	12
Hungary	1	4
India	4	7
Italy	4	3
Japan	25	14
Korea, Republic of South	2	7
The Netherlands	2	–
Pakistan	1	–
Spain	4	11
Sweden	10	2
Switzerland	4	1
Taiwan	4	2
Union of Soviet Socialist Republics	40	34
United Kingdom	34	8
Yugoslavia	1	–
Total	220	176

Source: International Atomic Energy Agency

Figure 39. *France and Belgium share equally the power generated by the Tihange-1 Nuclear Powerplant. Shown here during construction, the 970,000 kilowatt facility has been operating since 1975. Tihange is a PWR whose major components were manufactured in Europe. (Credit: Atomic Industrial Forum)*

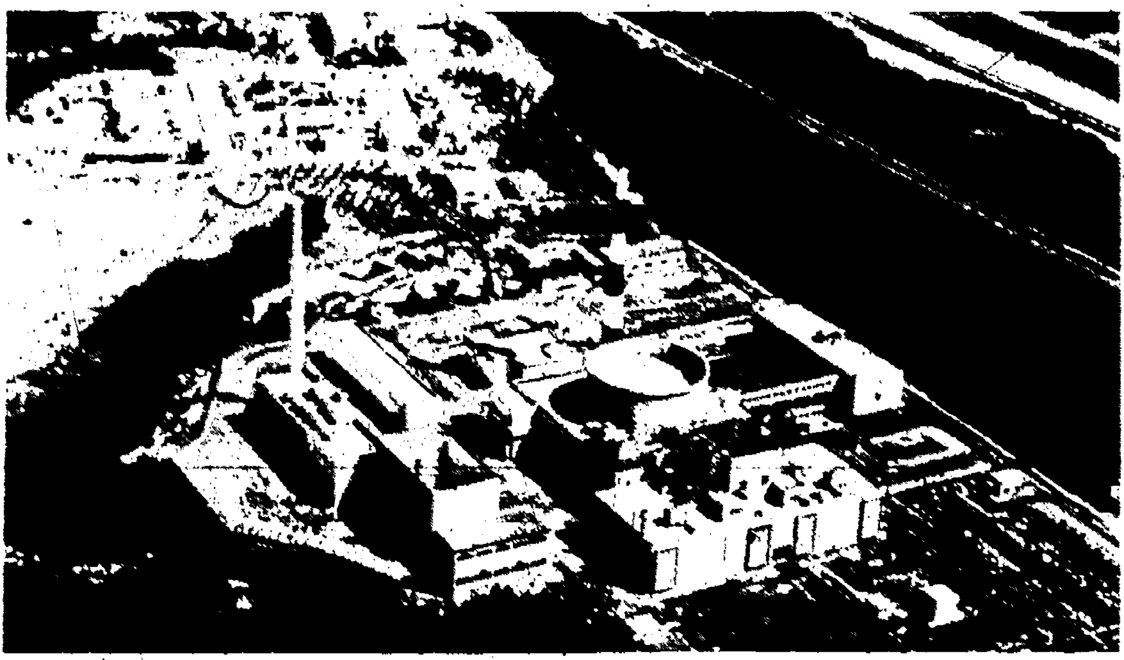

Figure 40. *The 100,000 kilowatt reactor, Joyo, near Mito, Japan, is a liquid metal fast breeder reactor which achieved criticality in 1977. Other facilities planned for the Japanese LMFBR program are the 300,000 kilowatt Monju prototype demonstration plant and a 1,500,000 kilowatt commercial plant. (Credit: Department of Energy)*

Conclusion

Electricity generated by nuclear energy has grown from a small experimental scale only 30 years ago to its current position as a significant component of the energy supply of the United States and most of the industrialized world. Because of the increasing costs of oil and natural gas, it is generally agreed that nuclear energy and coal are now the only two energy sources that are available economically for large new electric powerplants.

The future of nuclear power in the United States will depend largely on economic factors and energy policies yet to be determined. If the demand for electricity continues to increase as a result of economic growth, and if shifts from our heavy reliance on imported oil are necessary, nuclear energy offers the potential for centuries of electric power that does not further deplete our finite fossil fuel supply. Even the current level of nuclear plants in operation and under construciton around the country indicates that, as a minimum, nuclear energy will generate a significant share of our electric power until well into the 21st century.

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- *The Paradox of Plenty* (16 mm, color 22 minutes, 1977). This film features Don Herbert, also known as "Mr. Wizard," tracing the history of our energy sources. It focuses on the present choices for electric power generation—coal and uranium. Available for preview from The Magic Lantern, Carlton Center, 925 Penn Avenue, Pittsburgh, Pa. 15222.

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