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See also: Fisheries; Forestry; Forests; Hydroenergy; Oil and natural gas reservoirs.

Nuclear energy

Category: Energy resources

Nuclear power, an outgrowth of the development of the atomic bomb during World War II, once seemed to hold the promise of abundant, clean energy. However, it became controversial, and few new plants were constructed in the late twentieth century. Nonetheless, nuclear power is being revisited as a possible remedy for global warming because of its low greenhouse-gas emissions.

Background

The fission reaction that occurs in a nuclear reactor releases tremendous amounts of energy in the form of heat. This heat can be used to produce steam, and the steam can be used to drive an electric generator. It appears that uranium, the fuel for nuclear reactors, will far outlast oil and coal as a source of energy. However, concerns about the safety of nuclear reactors and about the disposal of used fuel and other wastes have slowed the pace of reactor development dramatically. In addition, nuclear power plants are usually more expensive to construct than coal- or gas-fired plants.

Scientific Principles and Historical Background

Naturally occurring uranium consists of 99.3 percent uranium 238 and 0.7 percent uranium 235. The nuclei of both of these isotopes contain 92 protons. Uranium-238 nuclei also contain 146 neutrons, while uranium-235 nuclei contain 143 neutrons. When a neutron strikes the nucleus of a uranium-235 atom, the nucleus splits roughly in half. Several neutrons and considerable heat are released. This process is called fission. The neutrons that are released can cause the fission of other uranium-235 nuclei, so the process continues in a chain reaction. The smaller nuclei that result from fission are called fission products. They are highly radioactive, and this radioactivity is accompanied by significant heat generation. When 1 gram of uranium fissions, it releases the same amount of heat as burning about 3 metric tons of coal or more than 12 barrels of oil.

In 1934, Enrico Fermi, working in Rome, was bombarding uranium atoms with neutrons. He expected the neutrons to be absorbed and new, heavier atoms to result. However, the chemical properties of the atoms he produced were not what he expected. Lise Meitner, Irène Joliot-Curie (the daughter of Nobel Prize winner Marie Curie), and Otto Hahn reproduced Fermi's experiments. They too were baffled by the results. Finally, Hahn realized what was happening: Instead of being absorbed into the uranium-235 nucleus, the neutrons were causing that nucleus to split roughly in half. The result was two lighter atoms rather than one heavier one. Because these researchers were working with very small quantities of uranium, they did not produce a chain reaction and did not detect the heat being released.

In 1939, William Laurence, a science reporter for *The New York Times*, asked Fermi and Niels Bohr, another famous physicist, whether a small quantity of uranium 235 could be used as a bomb as powerful as several thousand metric tons of trinitrotoluene (TNT). Fermi simply said, "We must not jump to hasty conclusions," but apparently Fermi and Bohr had already considered this possibility. On May 5, 1940, *The New York Times* carried a front-page story by Laurence under the headline "Vast Power Source in Atomic Energy Opened by Science."

Fermi apparently approached the U.S. Navy with his information, but it was not interested. Finally, in 1941, Albert Einstein signed a letter informing President Franklin Roosevelt of the possibilities of nuclear power, and the government finally took notice. Under Fermi's direction, the first nuclear reactor was built in an abandoned squash court under Stagg Field at the University of Chicago. This reactor consisted of tubes of naturally occurring uranium embedded in large blocks of graphite. On December 2, 1942, this reactor "went critical" for the first time. A reactor is said to be "critical" when the number of fissions in one second is the same as the number in each second that follows.

Fermi's reactor used naturally occurring uranium. However, bombs could not be built that way. There were two possible ways to build an atomic bomb: Either the uranium 235 could be separated from the uranium 238, or uranium 238 could be bombarded with neutrons and transformed into plutonium 239. Both uranium 235 and plutonium 239 fission easily when struck by neutrons. In these early days, separating uranium 235 from uranium 238 was very difficult, but it could be done. Transforming uranium 238 into plutonium 239 appeared to be the easier route. Large plutonium production reactors were build along the Columbia River near Richland, Washington, and by 1945, enough plutonium had been produced to build the bomb that destroyed Nagasaki, Japan. Ultimately, the separation of the two types of uranium proved to be somewhat easier than expected; the bomb dropped on Hiroshima, Japan, was built of uranium 235.

During the operation of the plutonium production reactors, that fact that large amounts of heat were produced by the fission reaction became obvious, and people began to think of ways to use this heat. This led to the idea of using reactors to generate steam to drive electric generators.

Nuclear Reactor Design

The electric generators and the steam turbines at a nuclear plant are similar to those at a coal-, oil-, or natural gas-fired plants. The difference lies in how the steam that drives the turbine is produced. Nuclear reactor fuel consists of uranium or plutonium oxide pellets contained inside zirconium tubes called fuel rods. These rods are arranged in a grid pattern, with space between them for coolant to flow. This part of a nuclear reactor is called the core. Movable control rods of neutron-absorbing material such as cadmium are used to regulate the fission rate in the reactor. The reactor core is housed in a strong steel container called the pressure vessel. Coolant flows into the pressure vessel, from which it flows through the core and absorbs the heat produced by fission. Then the heated coolant flows out of the pressure vessel and into other parts of the system. This heat is used to make steam. The cooling fluid can be a gas such as air or carbon dioxide, a liquid such as water, or a molten metal such as sodium. Nearly all electric power reactors in the United States are water cooled. There are two basic designs: pressurized-water reactors and boiling-water reactors.

In a pressurized-water reactor, water at very high pressure passes through the reactor core, the place where the uranium fuel is located. This water, which is called the primary water, absorbs the heat released by fission but does not boil because it is under such high pressure. After this very hot water leaves the reactor, it passes through a heat exchanger called a steam generator. In the steam generator, heat is transferred from the primary water to water at lower pressure. This lower-pressure water, which is called secondary water, boils as it absorbs heat from the primary water. The steam produced when the secondary water boils is used to spin the turbines that drive the electric generators, while the primary water returns to the reactor to pick up more heat. Both the reactor and the steam generator are housed inside a large, strong concrete structure called a containment building. The primary water, which becomes radioactive as it passes through the reactor core, never leaves the containment building; the secondary water, which does leave the containment building, is not radioactive. In 1987, there were sixty-nine operating nuclear power plants with pressurized-water reactors in the United States.

In a boiling-water reactor, about 10 percent of the water passing through the core is turned directly into steam. This steam leaves the reactor and goes directly to the turbines. No steam generator is required in this system, because steam is generated directly in the reactor. Because steam absorbs heat more slowly than

Types of Nuclear Reactors in Development

- Gas-cooled fast reactors
- Lead-cooled fast reactors
- Molten salt reactors
- Sodium-cooled fast reactors
- Supercritical water-cooled reactors
- Very high temperature gas reactors

liquid water, care must be taken to avoid the formation of too much steam in the reactor. This could lead to overheating of the uranium and damage to the core. As a result, a boiling-water reactor generates less power than a pressurized water reactor of the same core size. Many of the problems with pressurized-water reactor plants have been caused by the steam generators. Because boiling-water reactors do not have separate steam generators, these problems are eliminated. On the other hand, the steam from a boiling-water reactor is mildly radioactive, so the turbines and other equipment must be treated as radioactive material. This is not the case with a pressurized-water reactor. In 1987, there were thirty-eight power stations using boiling-water reactors in the United States.

Gas-cooled reactors have not been used much in the United States, but Great Britain has used them extensively. Commonly, carbon dioxide under high pressure is passed through the reactor core. Leaving the core, the carbon dioxide passes through a steam generator, where it heats and boils water to produce steam. This steam is used to drive the turbines. In a sense a gas-cooled reactor is similar to a pressurized-water reactor; however, the steam generators are quite different because the primary fluid is a gas rather than a liquid.

Some reactors are cooled by molten metals such as sodium. Because sodium melts at about 98° Celsius, it is a liquid at the temperatures found in a reactor system. Sodium conducts heat better than water does, so a sodium-cooled reactor can generate heat at a higher rate than a water-cooled one. On the other hand, sodium becomes highly radioactive as it passes through the reactor core, while water becomes only mildly radioactive. Also, sodium reacts violently with water, so great care must be taken to prevent leaks between the sodium reactor coolant and the steam being produced in the steam generator. Typical sodium-cooled reactors have three coolant loops. The primary sodium that flows through the reactor core transfers its heat to a secondary sodium loop in an intermediate heat exchanger. All this takes place inside the containment building. The secondary sodium flows to a steam generator that is outside the containment building. Here steam is produced to drive the turbines.

Molten metal-cooled reactors are also called fast re-

The San Onofre Nuclear Power Plant is located in San Diego County, California. (AFP/Getty Images) actors, a name which refers to the fact that the neutrons, which emerge from fission at very high speed, are not slowed down before they cause another fission. In water-cooled reactors the neutrons are slowed down a great deal; these reactors are called thermal reactors. Although fast reactors are potentially more efficient and economical than thermal reactors, thermal reactors appear to be safer. As a result, thermal reactors currently dominate the electric power generation business.

Another advantage of a fast reactor is that it can act as a breeder reactor. In a breeder reactor, some of the neutrons produced by fission go on to produce other fissions, but some of the neutrons react with uranium 238 and transform it into plutonium 239. Plutonium can be used to build bombs, but it can also be used in place of uranium 235 as reactor fuel. It is actually possible in a breeder reactor for the amount of plutonium produced to exceed the amount of uranium consumed. Therefore, the nuclear industry is not limited to using the 0.3 percent of natural uranium that is uranium 235; it can also use the uranium 238 after converting it into plutonium.

Many fast reactors are research reactors, but some countries have also used them for electric power generation. France has operated a fast breeder reactor for power generation, as have Russia and Kazakhstan. The Kazakhstan reactor was also used for water desalination. Russia is developing a small fast breeder reactor based on a submarine design that can use a variety of cooling agents, such as lead and bismuth, to be used to deliver electric power for remote areas.

The reactors described above are often labeled Generation I and II reactors. More advanced Generation III reactors are in operation in Japan and are under construction elsewhere. Third-generation reactors are more standardized than earlier reactors, speeding up the permitting process, and have longer operating lives, usually sixty years. They are also safer, with reduced possibility of core melt accidents. These reactors also are able to "burn" their fuel at a higher rate, reducing the waste. Many of the Generation III reactors in the planning and construction stages are light-water reactors, such as those under construction in South Korea and in Olkiluoto, Finland. The Olkiluoto reactor is often seen as a useful design and has been considered for adoption for some new U.S. reactors. Canada is developing two heavy-water designs based on the earlier CANDU-6 reactors. High-temperature gas-cooled reactors are also under construction, most of which use helium as a coolant. The Pebble Bed Modular Reactor, being developed in South Africa, also uses helium. Liquid-metal-cooled fast breeder reactors have been in operation since the 1950's, and several new designs are under development in Japan, Russia, and Italy.

Generation IV reactors are being developed by a consortium of several countries, including the United States, and are expected to be constructed by the late 2020's. Six different types of Generation IV reactors are under consideration; four are fast neutron reactors. The developmental process for Generation IV reactors got under way in 2002, when ten countries joined together to consider the development of six reactor types. These designs are still experimental and not all may be built, but they offer some intriguing possibilities.

Most of these reactors use uranium as fuel, although the lead-cooled fast reactors make use of depleted weapons-grade uranium and plutonium or thorium as fuel. The United States and the former Soviet Union began dismantling nuclear weapons in 1987. The weapons-grade plutonium is blended with uranium oxide into mixed oxide fuel that is suitable for use in power reactors. This approach has the advantage of decreasing the number of nuclear weapons as well as increasing the supply of fuel for power reactors. This mixed oxide fuel is used in Generation I and II reactors, but it may also be used to fuel more advanced reactors. Thorium has been considered as fuel for some of these new types of reactors, in part because it is far more common than uranium. India in particular has made the development of thorium as a fuel a major objective of its nuclear-power program. The fabrication costs for thorium fuel do not make it a feasible alternative to uranium, but this may change if the cost of uranium increases substantially.

Fusion

Fusion is an entirely different process from fission. Fission is the splitting apart of the nucleus of a uranium or plutonium atom. Fusion is the joining of two light atoms to form a heavier one. For instance, two hydrogen atoms can fuse to form a helium atom. The fusion reaction is also accompanied by the release of large amounts of heat. In fact it is the fusion reaction that generates the tremendous heat that stars give off. The potential of fusion to drive nuclear reactors is being explored, but there are significant problems involved.

An ordinary hydrogen atom has a nucleus composed of a lone proton, but there are two other forms of hydrogen. Different forms of the same element are called isotopes, and the isotopes of hydrogen are called deuterium and tritium. A deuterium nucleus contains a proton and a neutron, while a tritium nucleus contains a proton and two neutrons. Deuterium occurs naturally. Some of the hydrogen atoms in natural water molecules are actually deuterium. The deuterium in a cup of coffee could produce enough energy through fusion to drive a car for about a week of normal driving.

Fusion, like fission, was first used in weapons of war. In a hydrogen bomb one deuterium nucleus and one tritium nucleus fuse to make a helium nucleus, which is composed of two protons and two neutrons, plus a free neutron. Unlike deuterium, tritium is radioactive and does not occur in nature. It is commonly made in fission reactors by bombarding lithium atoms with neutrons. The deuterium-tritium reaction is one of the most promising for power-producing fusion reactors.

The most difficult aspect of fusion is that the fuel atoms must be heated to temperatures in the range of 100 million degrees Celsius in order to make the reaction occur at all. In 1989, there were newspaper reports of "cold" fusion—that is, fusion occurring at or near room temperature. However, these claims have not stood up under closer inspection. Although scientists have been able to produce the extremely high temperatures required for fusion, they have been able to maintain them only for very short times.

The biggest problem concerns how to contain the fuel at these temperatures. Certainly no material known could remain a solid at these temperatures. Instead, researchers have explored the use of magnetic fields or powerful laser light pulses to contain the fusion fuel. The magnetic confinement method uses a doughnut-shaped vacuum chamber with a very intense magnetic field inside it. The fuel is heated by passing an electric current through it until the required temperature is reached. Experimental fusion reactors that use magnetic containment are called tokamak reactors. The Tokamak Fusion Test Reactor at Princeton University in New Jersey is an example of this type.

Laser containment involves placing the fusion fuel in a pellet and illuminating the pellet with extremely powerful laser light. Details of pellet construction are highly classified. It is known that the laser light compresses the inner layers of the pellet while burning off the outer layers. As the inner layers are compressed, they heat up, and fusion begins. Each pellet reacts for only a small fraction of a second, so it is not clear how a sustained fusion reaction could be maintained in this way. The NOVA laser fusion facility at the Lawrence Livermore National Laboratory uses the laser containment approach.

Fusion remained in the experimental stages in the first decade of the twenty-first century. In the 1950's, researchers predicted that commercial fusion reactors were twenty years away. In the mid-1990's, commercial exploitation still seemed to be about twenty years away. Some experts believe that commercial fusion will not be achieved in the foreseeable future. The attraction of fusion is that its products are not radioactive. If fusion can be harnessed for the generation of electricity, the significant waste-disposal problems posed by fission can be eliminated. The United States, Japan, South Korea, Russia, China, India, and the European Union are part of the International Thermonuclear Experimental Reactor project directed toward building a workable fusion reactor. In 2005, the organization agreed to a site at Cadarache in southern France as the location for a reactor to demonstrate the feasibility of fusion. Even when completed, this reactor is unlikely to generate enough energy gain for use as a power plant. Thus, fusion power remains a long-term solution for world energy needs.

Reactor Safety and Nuclear Waste

One of the major factors limiting the development of nuclear power is concern about reactor safety. On March 28, 1979, there was a major accident in reactor number 2 at the Three Mile Island facility near Harrisburg, Pennsylvania. The accident began when one of the turbines stopped because of a minor malfunction. Although the fission reaction was stopped by the insertion of control rods very early in the accident, the uranium fuel continued to generate considerable heat because of the radioactive decay of the atoms produced when the uranium nuclei split. Water must continue to flow over the fuel rods long after fission stops in order to remove this heat. Through a series of errors by operating personnel at Three Mile Island, this flow of water was not maintained, and later, part of the core was not even submerged in water. As a result, much of the core overheated and melted. Although a core meltdown is a serious event, in this case, the exposure of people outside the reactor complex to radioactivity was negligible. Despite widespread concern over the Three Mile Island accident, one could argue that it demonstrated that pressurized-water reactors are actually quite safe. Such was not the public perception, however, and there were no new commercial reactor contracts signed in the United States between 1979 and 1996.

On April 26, 1986, a much more serious reactor accident occurred at the Chernobyl nuclear power station in Ukraine (at the time part of the Soviet Union). As a result of serious errors by operating personnel, the reactor went out of control. More and more fissions occurred every second, and the water could not carry away all the heat. Steam pressure built up until the reactor burst, and much radioactive material was expelled into the atmosphere. This radioactive material was detected as far away as Sweden. About 135,000 people were evacuated from the area around the reactor. Two people died immediately as a result of the bursting of the reactor. Another twenty-nine died of acute radiation poisoning within a short time. Estimates indicated that cancer deaths worldwide would increase by seventeen thousand over the fifty years following this accident as a result of the radioactive material released into the atmosphere; scientists have since revised this figure downward. The design of the Chernobyl reactor is very different from the pressurized- and boiling-water reactors used in the United States and most other countries. This accident seems to demonstrate that the type of reactor used at Chernobyl is not safe enough. In the United States, several government-owned reactors of a similar design were permanently shut down after the Chernobyl accident. These were plutonium production reactors rather than commercial electric power generation reactors.

Reactor safety is an important and a complicated issue that is difficult for nontechnical people to understand. Undeniably, nuclear reactors involve some risk, but so do other forms of power generation. Deciding what level of risk is acceptable is a difficult issue. Many people envision a reactor accident with large loss of life and conclude that the risk is unacceptable. Such an accident has not occurred with the types of reactors in use in the United States, but it cannot be completely ruled out. The third- and fourth-generation reactors under development are safer than present reactors, so that accidents such as Three Mile Island or Chernobyl are highly unlikely.

Because the new nuclei that form during fission are highly radioactive, the spent fuel that is periodically removed from the reactor must be handled with great care. The radioactivity is accompanied by considerable heat generation, and provisions must be made to remove this heat from the used fuel. It takes thousands of years for the radioactivity to diminish to safe levels, so used fuel must be stored in places that are expected to remain unaffected by earthquakes, hurricanes, and other natural disasters for a very long time.

Reactor plants are required to provide storage facilities for their own used fuel, but this is not a permanent solution. Although several national governments have been making plans for permanent, long-term storage of used fuel and other nuclear waste materials, technical and political problems have delayed the opening of such facilities. In addition to the used fuel, radioactive waste is created during the mining, refining, and processing of reactor fuel as well as from reactor operation. Although this waste is generally less hazardous than used fuel, provisions must be made for disposing of it safely. The United States has opened the Waste Isolation Pilot Plant near Carlsbad, New Mexico, to deal with certain types of these wastes. The United States has been building an underground disposal site for high-level radioactive wastes at Yucca Mountain, Nevada. However, in 2009, the Obama administration put the project on hold pending further safety analysis.

Reactors have a useful life of about forty years. Once a reactor is retired, provisions must be made to seal it permanently because many parts of the reactor will remain radioactive for a long time.

The Revival of Nuclear Energy

By the early twenty-first century, concerns with carbon dioxide emissions from coal- and oil-fired power plants and increasing energy demand had led many people to advocate the use of nuclear power. When the cost of carbon emissions from coal- or gas-fired power plants are taken into account, nuclear power becomes more cost-effective than before. Several nations are planning or building nuclear power plants, with some scheduled to be operational in the second decade of the twenty-first century. Even some Scandinavian countries that had turned against nuclear energy are returning to consideration of its use. All told, as of 2009, some forty reactors were under construction in eleven countries, with another one hundred planned to be operational by 2020; more than two hundred others were under consideration. Many of these reactors in the planning stages are in Asia. India, for example, had six reactors under construction that were expected to be completed by 2010, one of which is a prototype breeder reactor. China has eleven operating reactors and intends to quadruple its capacity by 2020. In 2009, the U.S. government agreed to provide up to $122 billion in loan guarantees for building twenty-one new reactors. The first stage of this project is projected to add seven reactors by 2015 or 2016 at a cost ranging between $5 and $12 billion.

Increasing costs for oil and coal, coupled with environmental concerns, have helped to drive a return to nuclear power. In some cases, the fuel costs for a nuclear power plant are one-third those of a coal-fired plant and one-quarter of a gas-fired plant. The typically long construction periods for nuclear power plants and the issue of nuclear waste disposal continue to keep overall costs high, however, especially in the United States and Western Europe. The continuing development of new types of reactors, sometimes labeled Generation IV reactors, should lead to more efficient operation of nuclear power plants, making nuclear electric power a feasible option in the future.

Research on and development of nuclear energy has been directed primarily toward electric power generation. By the late twentieth century, other uses were being developed. Desalination requires large amounts of energy, and some countries, such as Kazakhstan, have already made use of nuclear energy in this area. Electric power generation will remain the primary focus of nuclear energy in the future, but other uses are also being considered.

Edwin G. Wiggins, updated by John M. Theilmann

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