Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 11. Nuclear Energy

Future Energy:
Opportunities and Challenges

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11
Nuclear Energy

The Main Points

- **Power reactors based on nuclear fission are well-developed and now produce around 20 percent of America's electricity.**
- **Future reactor implementation faces concerns about the possible release of radioactive materials from a reactor accident or the possible escape of radioactive materials from nuclear waste.**
- **The safety record of currently operating U.S. reactors is good.**
- **There was an accident at Three Mile Island in Pennsylvania in 1979 caused by operator error. There was damage but no health consequences. Nevertheless, the accident led to a hiatus in the construction of new plants in the United States.**
- **There was an accident at the Chernobyl plant in the Ukraine in 1986. The accident occurred because of a design flaw and operator actions. There were major releases of radioactive materials. Chernobyl-type reactors are no longer being built.**
- **There was an accident at the Fukushima Dai-ichi nuclear power plant in Japan in 2011 caused by a tsunami that destroyed the emergency cooling system. Radioactive material was released into the environment.**
- **New reactor designs improve safety and reduce cost.**
- **Countries could build nuclear weapons, but independent terrorists could not.**
- **The only environmental impact of a properly operated nuclear reactor is waste heat.**

- **Uranium ore cost is a small component of nuclear power costs. Reactors could use large reserves of higher cost ore with little economic impact.**

- **Fusion reactors could produce essentially unlimited energy, but practical technology remains unavailable.**

11.1 Introduction

There is controversy about the capability and desirability of all energy supplies. Nuclear power tops the list in terms of the level of controversy. Nevertheless, nuclear power deserves to be considered for continued and expanded use because it is a non-polluting, economically competitive source of energy (and will be increasingly so if carbon emissions are taxed for fossil fuel plants in the future) that can be produced largely with U.S. domestic resources. Opponents of nuclear power think it is too expensive and/or they fear accidents at the power plants or the release to the environment of radioactive materials in the waste from nuclear plant operation. Those wishing to make an informed judgment about nuclear power must invest the time and effort required to understand the technical and economic issues.

11.2 Fission Reactors

Current (and near-term future) nuclear power plants employ the fission process, in which the nucleus of a heavy atom is split by a reaction with a neutron. The fuel used in this process is usually uranium, a rare, but economically recoverable material that is mined from the earth. The ore contains a mixture of two isotopes of uranium, 0.7 percent U235 and 99.3 percent U238. This naturally occurring mixture is called *natural uranium*. U235 is said to be fissile, meaning it readily undergoes fission. U238 can undergo fission when struck by a very high-energy neutron, but this is much less probable than fission in U235. U238 is said to be fissionable, but not fissile.

Most reactors require fuel with a higher percentage of U235 than occurs in natural uranium. A process called enrichment is used to increase the fraction of U235 in the mixture of uranium isotopes. Enrichment systems exploit the small mass differences between U235 and U238 to separate them. The currently favored method is gas centrifugation, in which a gas containing uranium is spun at a high rotational speed. The heavier material (U238) is thrown towards the outside of the spinning vessel (called a *centrifuge*). The gas near the center has a slightly increased concentration of U235.

A single centrifuge can yield only a small change in the relative amounts of U235 and U238 in the exit streams. Achieving significant changes in the relative concentrations requires a series of centrifuges (a cascade). Fuel for most nuclear power plants is enriched to U235 concentrations of 3 to 4 percent. (It should be noted that this enrichment level is inadequate for use in a nuclear weapon, for which almost pure U235 is required.)

It is possible to design a power reactor that can operate with natural uranium. This approach eliminates the need to enrich uranium. However, current natural uranium reactors require the use of heavy water as a moderator/coolant. (Later paragraphs will define the role of the moderator.) Heavy water (deuterium oxide) is a naturally-occurring, but very small, component of ordinary water. Deuterium is an isotope of hydrogen, differing from ordinary hydrogen by having a neutron as well as a proton in its nucleus. For use in a reactor, it must be separated from ordinary water. Thus, it is necessary to enrich water rather than uranium. The CANDU (Canadian Deuterium-Uranium) reactor is the only current power reactor design that uses natural uranium. CANDU reactors operate in Canada and other countries, but there are none in the United States.

A fission reaction yields the following products:

- Fission products. A fission reaction between an atom's nucleus and a neutron causes the atom to split into two or more smaller atoms. These fission products are radioactive. These, especially isotopes of strontium and cesium, create a radiation hazard in spent fuel.

- Neutrons. Two or three neutrons are produced in each fission reaction. The production of neutrons enables additional subsequent fission reactions and is the essential feature of a neutron chain reaction.

- Fission gamma rays (electromagnetic radiation released during fission).

- Energy. Energy appears because the total mass of the products resulting from fission is less than the total mass of the reactants (the nucleus that undergoes fission and a neutron). The amount of energy is given by Einstein's famous formula, $E=mc^2$, where m is the quantity of mass that is annihilated to produce energy. The energy appears as kinetic energy of the products (fission products and neutrons) and gamma ray energy.

In addition, non-fission neutron capture in uranium yields heavy elements called actinides. These materials, especially americium 241 and several isotopes of plutonium, contribute significantly to the radiation hazard in spent fuel, especially the long-term hazard.

The kinetic energy of the fission products and neutrons and the gamma ray energy degrade to heat energy as they interact with the materials in the reactor. This heat is usually used to make steam that drives a turbine in a power reactor. (Gas turbines can be used in gas-cooled reactors.) Steam may be produced by allowing water to boil in the reactor or by heating a liquid or gas stream in the reactor and subsequently using the heated liquid or gas to boil water in a heat exchanger called a steam generator.

A reactor must contain non-fuel materials such as structural material, coolant, moderator, metallic fuel cladding, and elements (such as oxygen) contained in compounds composing the fuel. All these materials absorb neutrons in a reactor. Since these non-fuel absorptions cause neither fissions nor conversion of fertile material into fissile material, a design objective is to minimize them by judicious selection of materials and arrangements.

The neutrons emitted in fission move at very high speed. Most reactor types include a moderator, a material that reduces the speed of the fission neutrons. Collisions between the neutrons and the moderator nuclei slow the neutrons without absorbing them strongly. (The exception is the fast breeder reactor in which the design favors fast neutrons.) The purpose of slowing the neutrons is that the probability of favorable events between neutrons and reactor core components (such as fission) is thereby increased relative to the probability of unfavorable events (such as non-fuel absorptions and leakage from the reactor). In those reactors that use either normal water or heavy water as a coolant, the coolant also serves as the moderator. Other reactor types employ a separate moderator material, such as graphite, in the reactor core.

A reactor may be designed in a way that causes temperature increases to slow the fission rate without requiring any actuation of the reactor control system. This feature, which greatly reduces the probability of an accident, is built into all U.S. reactors and will certainly be incorporated in future designs everywhere. (The Russian RBMK type of reactor did not have this feature, experienced an accident at the Chernobyl plant, and is no longer being built.) Control rods and safety shutdown rods provide control and safety shutdown capability. These rods contain strong neutron-absorbing materials. Insertion results in a reduction of the number of neutrons available for sustaining the chain reaction and slows or stops fission reactions.

Maintaining coolant flow even when the chain reaction shuts down is essential. Even after fission energy production ceases, the decay of radioactive material in the fuel continues to produce heat at a lower, but still significant, level. This energy, called *decay heat*, must be transferred to the coolant in order to prevent overheating and melting of core components. Reactors employ redundant emergency cooling systems to provide the coolant flow needed to remove decay heat. Nevertheless, emergency cooling failed when needed in the two accidents to date in light water reactors (Three Mile Island and Fukushima). Cooling is essential for the fuel rods in the reactor core. Cooling is also essential for the spent fuel rods that are stored in on-site pools until their level of radioactivity drops enough to permit dry storage.

The swarming neutrons and fission gamma rays, and the emissions from radioactive fission products, necessitate shielding of a power reactor. The spent fuel from a reactor contains fission products and actinides, some of which stay radioactive and harmful to humans for many years. They must be isolated and/or shielded to protect people from injury.

The U238, which constitutes 96 to 97 percent of the uranium loaded into most reactors (and 99 percent in CANDU reactors), also plays a role in plant operation. U238 can absorb neutrons, but only a small fraction of these absorptions results in fission. The great majority of the absorptions cause the U238 to be transformed into an isotope of plutonium, Pu239. Pu239, like U235, is readily capable of fissioning when struck by a neutron. That is, Pu239 is fissile. The production of useful Pu239 from useless U238 means there is a natural replenishment of useful fuel as the reactor operates. In a typical modern nuclear power reactor, about 40 Pu239 atoms are produced for every 100 fissions. Because U238 can be transformed into fissile Pu239, it is called a fertile material.

Nature also provides another potentially useful fertile material, thorium. Capture of a neutron by Th232 yields U233, a fissile isotope of uranium. Research reactors have been operated with thorium and U233. New thorium-U233 reactors, specifically molten salt reactors, are under consideration for future implementation. These reactors would permit exploiting the thorium resource in addition to the uranium resource for fueling reactors. It should be noted that starting a reactor that uses thorium requires blending the thorium with fissile material (U235 obtained by enrichment, Pu239 obtained from neutron capture in U238 in another reactor or U233 obtained from neutron capture in Th232 in another reactor).

It is even possible to build power reactors that produce more new fuel from fertile material than the fuel consumed. Recall that each fission reaction produces two or three neutrons. The average number of neutrons released is 2.5 or greater. One of these neutrons must cause a subsequent fission to maintain the chain reaction. This leaves at least 1.5 neutrons for capture in reactor materials or leakage from the reactor core. Judicious selection of reactor materials can result in one or more neutron captures in fertile material per fission event, resulting in the production of new fissile material. The result is the creation of as much or more new fuel from fertile material as is being consumed in fission reactions. Such reactors, called breeder reactors, are more complex than current-generation reactors. Prototype breeder reactors have been built and operated, but have not yet proved competitive with traditional designs.

Breeder reactors that produce Pu239 from U238 require a fast neutron spectrum. That is, moderator materials that slow neutrons are not used. Breeder reactors that produce U233 from Th232 can be operated with slow neutrons. That is, moderator material, such as graphite, is used to slow neutrons.

Reactors must be refueled when the fissile material is depleted and/or the material properties of the fuel degrade. New fuel is added, and the old, highly radioactive fuel is removed. The fuel may be reprocessed to recover valuable fissile material or stored.

11.3 Safety

The controversy about nuclear safety revolves around the possibility of releasing radioactivity into the environment because of a reactor accident or an accidental release of radioactive material from nuclear waste.

11.3.1 Safety Principles

When abnormal, safety-related events occur in a reactor, the response must have two essential features. These are rapid reduction of power generation by fission reactions and continued cooling of the fuel rods to remove heat produced by the decay of radioactive components in the fuel. Fuel rods in the reactor core and spent fuel in storage pools produce decay heat and must be cooled to avoid melting and the release of radioisotopes into the environment.

Inserting safety rods that contain strong neutron absorbers will stop fission power generation very quickly, but not instantaneously. A small amount of fission power generation persists for several minutes before it becomes insignificant.

Decay heat from the radioisotopes in the fuel necessitates continued cooling after a reactor is shut down. The rate of decay heat release after shutdown depends on the inventory of radioisotopes in the fuel at the time of shutdown. This inventory depends on the fuel composition and the length of time that the reactor has operated, but typical heat release rates are 0.4 percent of the reactor power that prevailed before shutdown after one day and 0.2 percent after one week. 0.2 percent does not sound like much, but a typical large power reactor with a capacity of 1,000 electrical megawatts produces around 3,000 megawatts of heat. 0.2 percent of full power for such a system is 6 megawatts, or around 20 million BTU per hour. This is a significant amount of power, which must be removed to avoid overheating and melting.

Emergency cooling in current reactors requires the operation of pumps powered by grid electricity (if available) or Diesel generators or batteries if grid electricity is unavailable. Loss of all sources of pump power is catastrophic.

Failure to keep the fuel rods cooled can lead to overheating and melting of the fuel's metallic cladding. Molten metal can react with water, producing hydrogen, an explosion hazard. Overheating also raises the pressure inside the reactor vessel and piping. It is necessary to maintain tolerable pressure levels by cooling and/or venting.

The popular media sometimes explain the decay heat problem by analogy to the cool-down of a hot oven, but this analogy is false. When an oven is turned off, there is no longer any heat addition. Cooling simply takes place via transfer of the stored thermal energy to the air around the oven. When a reactor shuts down, there is also stored thermal energy, but, in addition, there is ongoing production of decay heat. Ongoing heat production after shutdown is the issue in a reactor.

11.3.2 Reactor Accidents

There was a catastrophic accident at the Chernobyl nuclear power plant in the Ukraine in 1986. Because of an undesirable design feature and inappropriate operation, the plant experienced a runaway power transient, fuel failure, fire in the graphite used as a moderator, and release of radioisotopes into the environment, which caused sickness and death among those affected. Anti-nuclear individuals cite the Chernobyl accident as proof that nuclear power is unacceptably dangerous. Pro-nuclear individuals contend that Chernobyl was an anomaly that occurred because of the poor design methods and weak safety standards used in the former Soviet Union.

The Chernobyl reactor had a "positive power coefficient." This means a temperature increase following a power increase spontaneously and inherently causes an increase in the fission rate. Thus any power increase initiates further power increases unless constrained by operation of control action. This undesirable feature increases demands on the control system and increases the likelihood of a runaway chain reaction. Fortunately, nuclear engineers know conclusively how to design reactors with negative power coefficients. This means that a temperature increase following a power increase spontaneously and inherently causes a decrease in fission rates. Thus any power increase initiates subsequent power reductions, thereby stabilizing the reactor power. This feature reduces demands on the control system and eliminates the possibility of a runaway chain reaction. All reactors besides the Russian RBMK have negative power coefficients, and all future designs will certainly include this feature.

The design approach for U.S. reactors is to use multiple safety measures. The first is accident prevention by designing reactors to have inherent features that prevent or limit unsafe conditions (including negative power coefficients), by using redundant, highly reliable safety shutdown and cooling systems, and by requiring operating procedures that avoid safety challenges. Even though designers expect the accident prevention features to make accident probabilities vanishingly small, they incorporate containment as a second line of defense against the release of radioactive material. The fuel, its metallic sheath, and the reactor vessel and piping are designed to contain the fuel and fission products. Finally, the whole system is contained in a reinforced concrete structure that is designed to hold the radioactive materials should they escape from the vessel and piping.

The accident at Three Mile Island in 1979 occurred because workers ignored required procedures and operated the system improperly. The bad news was that cooling was lost, fuel melted, and radioactive materials escaped from the vessel and piping into the containment structure. The good news was the containment structure prevented gross release of radioactive material into the environment, though a small amount of radioactive gas was vented to the atmosphere. Three Mile Island was an event with major financial impact on its owner, but no direct impact on public health. (Some people may have experienced emotional illness because of the stress associated with the accident.) Three Mile Island revealed the crucial importance of safe operating procedures and adherence to those procedures. Nuclear power plants now operate under strict procedural rules, but, of course, continued vigilance is essential.

In March 2011, there was an accident at the Fukushima Dai-ichi plant in northeast Japan. The plant has six boiling water reactors. There was a massive earthquake in the ocean east of the plant. The reactor shutdown systems worked properly following the earthquake, stopping the fission reaction in all of the units that were operating. A few minutes later, a tsunami hit the plant, cutting access to off-site electrical power and wiping out the emergency cooling system. (The emergency power supplies were located where they were vulnerable to destruction by tsunami waves. Given the prior knowledge that the region was susceptible to tsunamis, this must be viewed as a major design error.) Decay heat and the loss of cooling ability led to fuel overheating, fuel melting, hydrogen production by metal-water reactions, hydrogen explosions, and the release of radioactive material. The Fukushima accident brings new uncertainty into the future of nuclear power. (In May 2011, Germany announced that it will shut down all of its nuclear plants.)

11.3.3 Radioactive Waste

The safety of radioactive waste is the second concern in the controversy over nuclear power safety. The waste is highly radioactive and very dangerous. However, the waste volume is small enough to make it feasible to implement extremely conservative handling procedures. For example, a typical large pressurized water reactor contains 193 fuel bundles in a reactor core that is 10 feet tall and 14.4 feet in diameter. The core volume is 1,628 cubic feet. The reactor is refueled every 18 to 24 months, with one-third of the fuel replaced with new fuel bundles at each refueling. So the volume of spent fuel removed at refueling occupies around 543 cubic feet. The volume of spent fuel is thus 272 to 362 cubic feet per year, depending on the frequency of refueling. The footprint of the spent fuel bundles (each 10 feet tall) is only 27 to 36 square feet per year. (This area is comparable to the floor area of a small closet.) Of course, a larger total footprint is required to provide cooling and shielding of the stored spent fuel, but it is clear the volume of spent fuel produced every year is quite small.

Reactor fuel cycles may be a once-through process, in which the spent fuel is stored, or a closed cycle process in which plutonium and uranium are separated from the spent fuel and mixed with new uranium or thorium for further use as fuel. Materials for recycling may also include fission products and actinides, which are included so they can be transformed into less dangerous elements by absorbing neutrons. Studies have evaluated the benefits of partitioning the fuel into streams composed of selected elements and then transmuting these elements by further exposure to neutrons. The transmuted elements have lower radioactivity and lower heat generation, thereby reducing design requirements for disposal facilities. Of course the separation and transmutation operations require special facilities and procedures. There is a trade-off between the cost of separation and transmutation and the benefits to disposal facilities. The current plan for waste handling in the U.S. is the once-through approach. Some other countries use the closed cycle process, and it is a possibility for future U.S. use.

The once-through fuel cycle uses a three-step approach. The first step involves storing the spent fuel in water-filled pools and, after adequate decay of the radioactive materials, in dry, shielded casks at the reactor site. During this step, most of the radioactivity dies off. The second step is transporting the spent fuel to a waste repository. Special high-strength containers will be used. (Anti-nuclear individuals feel that transporting nuclear material is too risky, regardless of the strength of the container. Pro-nuclear individuals say the containers are so over-designed that releases during transport are simply implausible.) The third step is burial in a waste repository. A repository for permanent storage of nuclear waste has one overriding design requirement: it must be highly improbable that isolation of the radioactive materials will ever be breached by human activity or natural causes. Human activities of concern for buried waste are mining and drilling. Natural causes of concern are contact with ground water, earthquakes, and volcanoes.

However, because there is currently no operating repository in the United States, only the first step in the once-through fuel cycle (on-site storage) is being practiced. A permanent repository site was selected at Yucca Mountain in Nevada. The Yucca Mountain facility has been under construction and testing for many years. Its originally scheduled opening date passed long ago, but Yucca Mountain's opening date is still indefinite, and it is not certain that it will ever open. (The Obama administration canceled work on Yucca Mountain. Whether this ruling will be reversed in the future is unknown,) On-site storage of spent fuel at reactor sites provides an acceptable short-term approach. Eventually there must be a permanent U.S. repository for the spent fuel.

In the closed-cycle approach, fuel is also is kept at the reactor site until most of the radioactivity has died away. The second step is to transfer the spent fuel to a reprocessing facility. This step raises the same issues as fuel transport in the once-through fuel cycle if the reprocessing facility is located away from the reactor site. At the reprocessing facility, the fuel material is chemically separated into two streams, a waste stream and a recycle stream. The waste stream is sent to a permanent storage facility. The recycle material is mixed with fresh uranium or thorium. Since the recycle fuel in current reactors is in the form of oxides of uranium and plutonium, it is called mixed oxide, or MOX, fuel.

There is disagreement among experts on whether the once-through or the closed cycle approach is superior.[1,2]

11.3.4 Accidents and Liability

The risk associated with nuclear power is a pervasive question for the nuclear utilities, the nuclear regulators, and the public. A method called probabilistic risk analysis (PRA) was developed to address the quantitative assessment of risk in nuclear power generation and other activities.

Accident risk is usually characterized by estimates of the probability that an accident will occur versus the consequences of that accident: illness and loss of human life, property damage, and rendering land unsuitable for human activities. In a PRA, the analyst attempts to identify all plausible accident scenarios, the probability that such an accident will occur and the consequences if the accident does occur. This undertaking is very complex. It is impossible to ensure every possible accident is included. Nevertheless, a carefully performed PRA provides a useful picture of the relative risk associated with various activities, even though the numerical results are subject to significant uncertainty.

Risk associated with large consequences is acceptable only if the probability of occurrence of an accident is low, and risk associated with accidents with a high probability of occurrence is acceptable only if the consequences are low. For example, history tells us that we can expect several major airline crashes per year, and the usual consequence is the loss of several hundred lives. The continued growth of air travel indicates that most people conclude that the risk is acceptable.

Probabilistic risk assessment finds that nuclear accidents have potentially large consequences, but accidents with extremely severe consequences have a low probability of occurrence. Of course accidents with less severe consequences are found to have a higher probability of occurrence. Also, it should be noted that an event having a low probability of occurrence does not mean that the event cannot occur. Any event with a non-zero probability can occur at any time. A low probability of an event only means that few events are likely in some time interval.

The possibility of accidents with large consequences raises questions about liability. If the worst possible nuclear accident were to occur, the financial liability would exceed the ability of any individual utility or insurance company to pay. The U.S. government has acted to help manage the liability for losses associated with a nuclear accident through the Price Anderson Act, which was enacted in 1957 and has been extended and revised several times since. The 2005 version (set to expire in 2025) has three main features:

- Owners of individual nuclear facilities must buy insurance to cover liabilities of up to $300 million.

- To provide for liabilities exceeding $300 million, all owners of nuclear facilities must contribute up to $111.9 million each to a fund to be used for compensation if, and when, losses occur. In 2011, the commitment for 104 nuclear power plants was $12.2 billion.

- If claims exceed the funds available from insurance and the industry fund, Congress can either increase the liability of the nuclear industry or provide federal funds.

This program, like other issues related to nuclear power, is controversial. Critics say the Price Anderson Act is an unfair subsidy for nuclear power. Proponents say the Act is a wise, low-risk government policy that supports an industry that operates for the good of the country.

11.4 Energy Costs and Environmental Impacts

Cost and environmental impact, as well as safety considerations, will dictate the future role of nuclear power. Costs consist of capital costs and operating costs. Capital costs are the ongoing debt service of the money borrowed to build the facility. Operating costs are the ongoing costs for fuel, maintenance, repairs, etc. In a nuclear plant, the capital costs are a much larger fraction of total power costs than in fossil fuel plants. Since capital costs persist whether the plant is operating or idle, it is desirable to run a nuclear power plant at full power as much as possible. Plants that operate at constant power are called base-load plants. Of course, other plants in the system must change power levels continuously in response to changing power demands in the electrical grid. These plants are called load-following plants. The need for adequate load-following capability influences the required ratio of load-following plants to base-load plants in a system. There must be enough load-following plants to handle any demand changes experienced by the system. Therefore, the number of base-load nuclear plants in a system is constrained by load-following considerations.

The average cost of electricity currently produced in U.S. nuclear plants is 3 to 5 cents per kilowatt-hour. Experts predict future costs of nuclear electricity. Predicted costs in two recent publications are 2 to 12 cents per kilowatt-hour[3] and 4.2 to 6.7 cents per kilowatt-hour[4]. The range of values in these estimates reflects the uncertainty in predictions of future costs.

Capital costs account for over 50 percent of nuclear energy cost, fuel accounts for around 19 percent, and operation and maintenance account for the rest. Fuel cost includes ore cost, processing cost, enrichment cost, and fabrication cost. Ore cost contributes only about 5 percent to total power cost. Since nuclear electricity costs are quite insensitive to the price of ore, the penalty for the use of lower grade and higher cost ore is a small contributor to total energy cost. Lower grade ores expand the uranium resource for use in nuclear plants.

The environmental impact of a properly operated nuclear power plant consists entirely of the waste heat dumped into the atmosphere or into bodies of water. There are no gaseous emissions, so there is no contribution to the greenhouse effect.

11.5 Proliferation

There is concern that the widespread use of nuclear power will increase the likelihood of acquisition of materials for weapons by rogue states or terrorists. A nuclear weapon requires almost pure U235 or Pu239. Pure U235 can be obtained only by enriching a U235-U238 mixture. Power reactor fuel enrichment is no more than 4 percent. Consequently, weapons material requires enrichment, whether starting with natural uranium (0.7 percent U235) or reactor fuel (4 percent U235). Diversion of reactor fuel to obtain raw material for enrichment to weapons grade is not a viable option for terrorists because enrichment facilities are too large, too expensive, and too hard to conceal.

Spent reactor fuel contains Pu239 as a result of neutron captures in U238. Pu239, like U235, is suitable for making a nuclear weapon. Plutonium can be separated from other materials in the spent fuel by chemical processing, so enrichment is not required. However, the chemical processing requires special heavily shielded facilities, and, furthermore, the plutonium contains other plutonium isotopes besides Pu239. These isotopes decrease the potential of the plutonium from spent fuel for use as weapons material. Obtaining weapons-grade plutonium from spent fuel is also not a viable option for terrorists.

The overall conclusion is that power reactors do not provide a viable means for illegal and clandestine acquisition of weapons material. The real concern is that highly concentrated radioactive waste material might be stolen and mixed with conventional explosives to make a so-called "dirty bomb." However, this too requires that perpetrators have the shielded facilities required to handle the radioactive material.

Of course, sovereign countries can choose to develop nuclear weapons. The major nuclear powers (the United States, Russia, the United Kingdom, France, and China) generally discourage development of nuclear weapons by other countries and encourage the signing of non-proliferation agreements. Nevertheless, some nations have undertaken weapons development programs. Most have canceled their programs, but some have successfully developed weapons (India, Pakistan, Israel, and North Korea). There is continued concern that nations with nuclear weapons will use them if they come under the control of an aggressive leader or if they become desperate in a war. There is also concern that poor, but nuclear-capable countries will sell weapons to terrorists. Monitoring, diplomacy, and sanctions are means by which limitations are placed on countries with nuclear weapons capabilities or ambitions. There is also the possibility of the use of military force to halt a nuclear weapons development program.

11.6 Reactor Design Evolution

Because of the controversy about the use of nuclear energy, it is important to understand how the nuclear power industry evolved as well as the technology on which it is based. Lessons learned from the past should help guide future decisions about nuclear power in the United States.

The evolution of commercial nuclear power is often described in terms of different generations, each characterized by the dominant reactor designs for that generation. Reactors currently being built in some parts of the world are Generation III designs. Work is under way on future designs that constitute Generation IV. Generation V systems are radically new, highly speculative designs that are being investigated for possible use in the distant future.

11.6.1 Generation I Reactors

The first nuclear reactor, designed by Enrico Fermi and built at the University of Chicago in 1942, served to demonstrate the feasibility of operating a system based on uranium fission (see Figure 11-1). The success of the "Chicago Pile" led to the construction of reactors in Oak Ridge, Tenn., and Hanford, Wash., whose purpose was to produce Pu239 for nuclear bombs by transforming U238 into Pu239 by neutron capture. Additional reactors for producing weapons material were subsequently built at the Savannah River Site near Aiken, S.C.

Figure 11-1. The Chicago Pile (courtesy of U.S. Dept. of Energy)

Following the initial focus on producing a nuclear bomb, interest developed in using nuclear fission reactors to produce useful energy. The U.S. government, through the Atomic Energy Commission, embarked on a reactor development program. The first nuclear electricity in the U.S. was produced with a small generator and used to power a light bulb at the Experimental Breeder Reactor, EBR-1, in Arco, Idaho in 1951. In 1954, the U.S. Congress removed the ban on nuclear activities by non-government organizations.

The first successful application of a nuclear reactor for energy production was military: the propulsion plant for the USS *Nautilus*, a submarine commissioned in 1955. The *Nautilus* used a pressurized water reactor supplied by Westinghouse to the Navy. The success of the Nautilus led to the construction and operation of the first U.S. land-based power reactor, the Shippingport 60 MW reactor in Pennsylvania, commissioned in 1957. Shippingport was the prototype of the large pressurized water reactors that were built subsequently in the U.S. and other countries. Another power reactor that was to be the prototype of large-scale commercial reactor systems was the 200 MW Dresden boiling water reactor, commissioned in Illinois in 1960.

Pressurized water reactors (PWRs) and boiling water reactors (BWRs) became the dominant types to be built in a massive power reactor construction boom in the U.S. and several other countries in the 1960s and 1970s. However, in the late 1950s and early 1960s, many different reactor types were considered for development into commercial systems. This included sodium cooled fast reactors, gas-cooled reactors, sodium-graphite reactors, aqueous homogeneous reactors, molten salt reactors, and organic moderated reactors. Much time and money was consumed in designing and building prototypes of all of these reactor types, but eventually all were abandoned in the U.S. (though China is building gas-cooled reactors, and some other types are still candidates for future implementation in the U.S. and elsewhere).

Reactors built in the early years (through the early 1960s) are usually referred to as Generation I reactors.

11.6.2 Generation II Reactors

Generation II reactors are the large commercial reactors (typified by PWRs and BWRs) built in the U.S. and elsewhere in the 1960s and 1970s. Most of these reactors are still operating and are producing about 20 percent of America's electricity. Power reactors were built by four U.S. companies for operation by utility companies. Westinghouse, Combustion Engineering, and Babcock and Wilcox offered pressurized water reactors (PWRs), and General Electric offered boiling water reactors (BWRs). Over 100 plants, some capable of delivering over 1000 megawatts of electricity, were built in the United States. In retrospect, it is amazing that nuclear power went from jubilation at powering a light bulb in 1951 to supplying 20 percent of America's electricity in about 25 years. It is now clear that in this rapid deployment, great strides were made, but some seeds of future problems were also planted.

Pressurized water reactors were built in greater numbers in the U.S. than boiling water reactors. Figure 11-2 shows the main components of a PWR. The uranium, in the form of uranium oxide pellets, is contained in tubes made of a zirconium alloy. These fuel rods are assembled into bundles for installing in the reactor. Water flows through the reactor and around the fuel rods to extract the heat from the fuel. The maximum water temperature is around 625°F (330°C), and the pressure is around 2200 pounds per square inch (152 bar). The heated water passes through piping into tubes inside the steam generator before returning to the reactor via piping. A second stream of water flows around the outside of the tubes of the steam generator where boiling occurs. The resulting steam flows to a turbine that drives an electrical generator. Exhaust steam from the turbine passes through a condenser and a series of reheaters before re-entering the steam generator. The reactor coolant loop (the primary loop) and the secondary loop are closed systems. There is no contact between the water in the separate loops. Control and safety rods enter empty spaces in the fuel bundles from above.

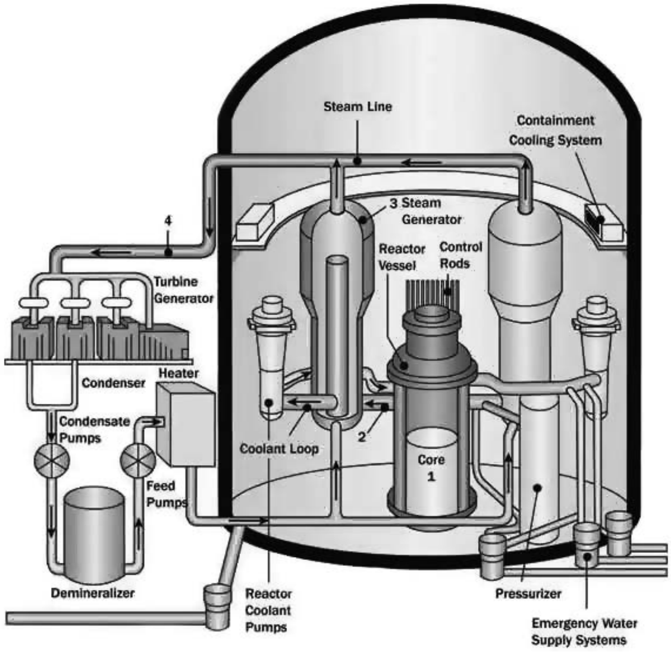

Figure 11-2. A Pressurized Water Reactor
(courtesy of U.S. Nuclear Regulatory Commission)

A number of boiling water reactors were also built in the United States. The main components of a BWR are shown in Figure 11-3. As in PWRs, uranium oxide pellets are stacked inside zirconium alloy tubes that are assembled into bundles. Water flows through the reactor to extract heat from the fuel rods as in a PWR, but in a BWR, the water boils inside the reactor core. The maximum water temperature is around 515°F (268°C), and the pressure is around 1,100 pounds per square inch (76 bar). The steam produced passes directly to a turbine. Exhaust steam from the turbine passes through a condenser and a series of reheaters before returning to the reactor vessel. Hydraulically-driven control and safety rods enter empty spaces in the fuel bundles from below.

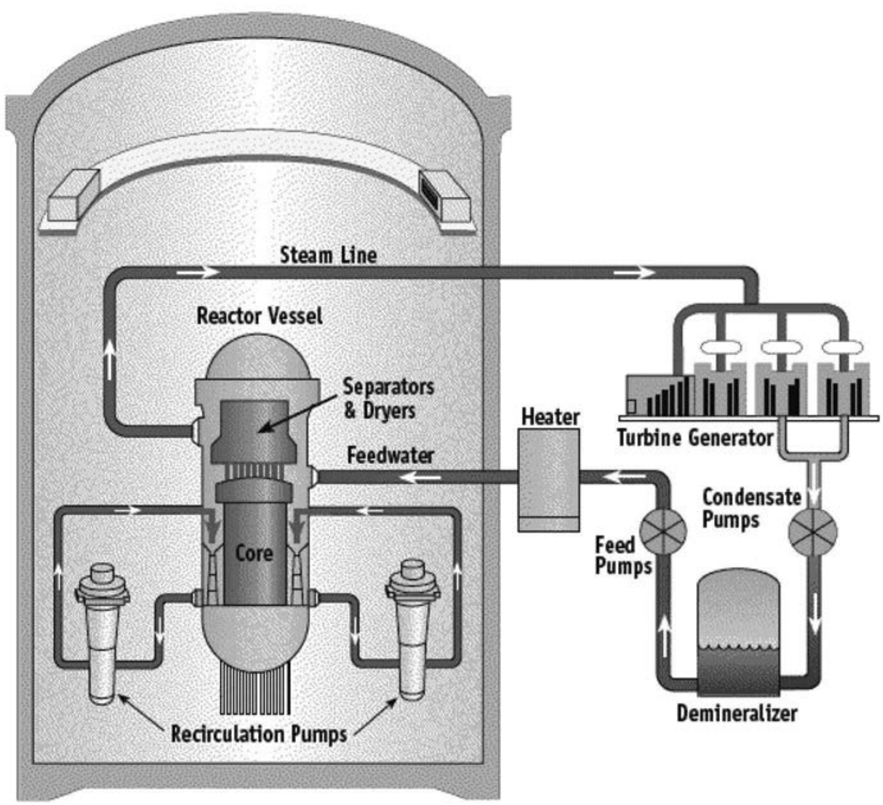

Figure 11-3. A Boiling Water Reactor (courtesy of U.S. Dept. of Energy)

PWRs and BWRs are designated as light water reactors (LWRs) to distinguish them from reactors that use other coolants.

Other power reactor types were developed and deployed in other countries. These include:

- CANDU: Canada developed the CANDU reactor, which uses natural uranium fuel and heavy water as a coolant and moderator.
- GCR: Gas-cooled reactors using carbon dioxide or helium coolant and graphite moderator have been built and operated, mostly in Britain and, more recently, in China.
- FBR: Several sodium-cooled fast breeder reactors have been operated, though their mission has been more to test the concept than to provide competitive electricity.
- VVER: This is the Russian version of the PWR. It has similarities and some significant differences from western PWRs.
- RBMK: The RBMK is a graphite-moderated, water cooled reactor of Russian design. It is known to have severe stability problems, which unfortunately manifested themselves in the Chernobyl accident. RBMK reactors are no longer being built.

In the rush to build U.S. power reactors, there was little focus on standardization. Not only did the four suppliers provide different designs, each vendor supplied custom designs to suit specific customers. It went so far that concerns about a possible design-specific problem that might cause regulators to shut down all of the reactors led to the construction of reactors from different vendors on a single site. This lack of standardization caused longer and more costly construction, longer and more costly regulatory review, fewer benefits of experience shared between operators of a reactor type, restrictions on staff transferability, and increased spare parts inventory requirements. The result was more expensive, less reliable, and less safe plants than would have occurred with standardization.

One might also argue that the nuclear industry demonstrated excessive hubris during the rapid deployment of large power reactors. Certainly, there was too little emphasis on training of reactor personnel, too few restrictions on operating procedures as needed to enhance safety, too little emphasis on safe and effective maintenance, and too little oversight. These factors contributed to the accident at the Three Mile Island PWR in 1979. Basically, operators performing work on a reactor subsystem ignored written procedures and caused a loss of coolant to the reactor core, with subsequent partial melting of the fuel. Operator error (exacerbated by poor reactor design) also caused the Chernobyl accident in The Ukraine in 1986.

All new power reactor construction in the U.S. stopped after Three Mile Island. Major new efforts have focused on improving the safety and reliability of existing reactors. Just as it appeared that a rebirth of nuclear power was about to begin, the Fukushima accident occurred. This event will certainly stall new reactor construction, at least temporarily. Nevertheless, work has started in the U.S. on completion of several reactors for which work was previously suspended, and construction of several new reactors has been approved.

11.6.3 Generation III Reactors

New designs, called Generation III reactors, have been developed. They are evolutionary improvements over Generation II reactors. Features of Generation III reactors include:

- Standardized designs that expedite licensing, reduce capital cost, and reduce construction time
- Passive safety features that reduce the need for the actuation and proper operation of engineered safety systems
- Longer intervals between refueling achieved by the use of higher fuel enrichment and burnable poisons (materials that absorb neutrons, but whose strength declines along with fuel consumption)

- Ability to operate with mixed oxide fuels
- Simpler designs that expedite construction and operation

Designs under consideration for Generation III include small and medium power plants. This is a major departure from the Generation II preference for large reactors with capacities of 1,000 megawatts or greater. The small and medium plants have generation capacity of less than 700 megawatts. The designs focus on the simplifications and safety enhancements that are possible with smaller sizes. Small and medium plants can employ greater shop fabrication and delivery of components to the plant site instead of the extensive on-site fabrication used for Generation II reactors. The plants have lower inventories of radioisotopes and are easier to cool in the event of an accident.

The number of reactor vendors has grown since the Generation II era. Companies have left the nuclear reactor business, companies have merged, companies have been bought by other companies, and new companies have appeared. This growth has good features and bad features. The good part is that competition will drive each vendor to make a better product. The bad part is that though each vendor might offer a standardized design, there is no standardization between vendors, causing concern about the possible recurrence of Generation II problems if several vendors compete in the same market.

11.6.4 Generation IV Reactors

Work is under way to develop reactor designs for possible construction in the future. Currently, six concepts are under consideration. The objective is to achieve improved safety, improved proliferation resistance, reduced waste, and reduced cost. Generation IV reactor designs provide higher temperature operation than current designs. Higher temperatures can enable higher thermodynamic efficiencies in electricity production and can provide process heat for processes such as the high-temperature electrolysis of water to produce hydrogen. The designs under consideration include new concepts and the resurrection of some older concepts that previously failed to reach commercialization. The plan is to have the designs ready for implementation around the end of the first quarter of the twenty-first century.

The Generation IV reactor concepts currently under consideration are:

- Very High Temperature Reactor (VHTR): The VHTR uses helium coolant that flows through a core consisting of graphite impregnated with fuel particles.

- Supercritical Water-Cooled Reactor (SCWR): The SCWR is an outgrowth of current light water designs. It operates at much higher temperatures and pressures than current light water reactors.

- Molten-Salt Reactor (MSR): The MSR is a fluid-fuel reactor. Fuel is dissolved in a molten salt that flows through a graphite core. The MSR concept permits continuous processing to remove fission products and add fresh fuel, but this is accomplished at the cost of complex plumbing and materials handling.

- Gas-Cooled Fast Reactor (GCR): The GCR is a breeder reactor that uses helium gas to carry the heat from fuel elements comprising the reactor core.

- Sodium-Cooled Fast Reactor (SFR): The SFR is a breeder reactor the uses liquid sodium to carry heat from fuel elements comprising the reactor core.

- Lead-Cooled Fast Reactor (LFR): The LFR is a breeder reactor that uses liquid lead to carry heat from fuel elements comprising the reactor core.

A successful Generation IV program must avoid the mistakes of the past. There will be trade-offs between giving each concept a fair chance and avoiding wasting money on concepts with little or no potential for commercialization.

11.6.5 Generation V Reactors

Generation V reactors are speculative concepts that may be suitable as successors to Generation IV systems. It is too early to identify leading candidates, their technical feasibility, or their economic competitiveness. It will be many decades before Generation V deserves or receives serious consideration.

11.7 Nuclear Fuel Supply

Like fossil fuel, uranium needed to fuel nuclear reactors is a finite resource that must be extracted from the earth or the seas. Unlike energy production with fossil fuels, energy production with uranium is quite insensitive to raw material cost. The expenditure for uranium ore is responsible for only about 5 percent of total energy cost for a nuclear power plant.

The World Nuclear Association[5] reports that in 2009, the U.S. had 0.2 million metric tons of remaining uranium that is recoverable for $130 per kilogram ($60 per pound) or less. The estimate for the world resource is 5.4 million metric tons for $130 per kilogram or less. Reserve estimates change periodically as new information becomes available, but these figures give a picture of the resource.

The uranium requirement in a current reactor with an output of 1,000 electrical megawatts is around 200 metric tons of natural uranium per year. Estimated U.S. reserves will support 1,000 reactor years of operation, and world reserves will support 27,000 reactor years (based on ore costing no more than $130 per kilogram and 1000 MWe reactors). Current nuclear power reactors in the U.S. produce power at a rate of about 100,000 MWe, requiring about 20,000 metric tons of natural uranium per year. It is known that huge amounts of lower grade uranium ores exist. These reserves could increase nuclear energy capacity manyfold with small increases in energy cost.

Reducing the quantity of uranium needed is achievable with closed cycle operation and/or the use of breeder reactors. These approaches would also result in a manyfold increase in nuclear energy capacity.

Resource availability is a factor in decisions about future deployment of nuclear power reactors, but because of the small contribution of ore cost to total power cost, it is not a limiting factor.

Obtaining uranium ore requires mining and milling operations performed with special precautions. Uranium ore contains radioactive radon gas as well as uranium. Radon exposures during mining operations are known to result in health problems. Careful ventilation is now used to minimize exposures to miners. Also, residues from the mining and milling operations contain radon and other radioactive materials that must be isolated from the environment. Government regulations now specify requirements for miner safety and for safe disposition of mining and milling residues.

11.8 Fusion

Fusion energy, like fission energy, relies on a process in which mass is converted into energy according to Einstein's famous formula, $E=mc^2$. In the fission process, heavy nuclei break apart upon reacting with a neutron, producing lighter nuclei whose collective mass is less than the combined mass of the fissile nucleus and the neutron. In the fusion process, two light nuclei join together to produce a heavier nucleus whose mass is less than the collective masses or the two reacting nuclei.

When fissile material and neutrons are brought together, fission proceeds readily. Fusion, however, is a different story. Since the nuclei in a fusion reaction are both positively charged, they repel one another. For a fusion reaction to occur, the reacting nuclei must overcome the repulsive force. One way to overcome the repulsive force is to heat the reacting nuclei to give them adequate kinetic energy. The required temperatures are in the millions of degrees. At these temperatures, the reacting materials are in the fully ionized, or plasma, state.

The light materials suitable for undergoing fusion are deuterium (D), tritium (T) and helium-3 (^3He). All of these are isotopes of common materials. Deuterium is an isotope of hydrogen, and it occurs naturally in ordinary hydrogen. Ordinary hydrogen consists of one part deuterium to 6,700 parts hydrogen. Hydrogen has one proton in its nucleus. Deuterium has one proton and one neutron. Tritium, with one proton and two neutrons, does not occur in nature, but it can be produced with appropriate nuclear reactions. Tritium can be produced by a reaction between a neutron and lithium-6, a naturally-occurring isotope of lithium. Helium-3 is an isotope of helium that does not occur naturally and is difficult to produce.

The fusion reactions are:

1. $D+D \rightarrow {}^3He+n+\text{energy}$

and

$D+D \rightarrow T+p+\text{energy}$

(Both reactions have equal probability.)

2. $D+{}^3He \rightarrow \alpha+p+\text{energy}$

3. $D+T \rightarrow \alpha+n+\text{energy}$

where

n = neutron
p = proton
α = alpha particle

The D, D and D,^{3}He reactions are less favorable than the D,T reaction because the D,D reaction suffers from low reaction probabilities, and the D,^{3}He reaction suffers because of the unavailability of ^{3}He. The D, T reaction is the most attractive, but it requires a supply of tritium. Fortunately, tritium can be produced in-situ by capturing neutrons from the D, T reaction in a lithium blanket around the reactor volume.

Two types of fusion device are under development: the magnetic fusion reactor and the inertial fusion reactor.

In the magnetic fusion reactor, the idea is to contain the plasma using magnetic force to "bottle" the high-energy nuclei. A magnetic fusion reactor based on the D, T reaction would consist of a high temperature reaction zone surrounded by a lithium blanket used to produce the necessary tritium with leakage neutrons from the reaction zone. A superconducting magnet around the blanket keeps the nuclei from leaving the reaction zone. Among the numerous engineering challenges in a magnetic fusion reactor are achieving material properties suitable for withstanding high temperature and high radiation, achieving a magnetic force field that properly contains the plasma, and extracting energy from the fusion reactor for useful purposes. Great progress has been made in understanding the science, but a device that produces more energy than it consumes has not yet been built.

In an inertial fusion device, the idea is to induce high temperatures and high reactant densities by bombarding small fuel pellets with a high energy laser or particle beam. This compresses and heats the pellet, thereby overcoming the repulsive forces between atoms. Each pellet acts like a small fusion bomblet. Rapid pellet injections and implosions produce continuous power.

11.9 Nuclear Energy in the Future

Previous sections have given a brief overview of nuclear energy and the main issues relevant to future deployment. It is clear that nuclear technology is capable of displacing significant quantities of fossil fuel used for generating electricity. Most, if not all, of the resources for building and operating nuclear power plants are available domestically in the United States. Whether this capability is used depends on allaying safety concerns, allaying proliferation concerns, and achieving economic competitiveness.

The 2011 accident at Fukushima certainly increased concerns about reactor safety and reduces the prospects for a return to growth in nuclear power, but it must be remembered that every energy source has its own drawbacks.

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Exercises

11-1. Nuclear energy results from the conversion of mass into energy. How does this relate to the principle of conservation of energy?

11-2. According to Einstein, the energy released during conversion of mass into energy is given by $E=mc^2$ where E = energy (in ergs) released, m = mass (in grams) annihilated, and c-speed of light = 3.1×10^{10} cm per second. Calculate the energy released by annihilation of one gram of matter. Express the result in ergs, BTUs, and kilowatt-hours. (Note: 1 kilowatt-hour = 3.6×10^{13} ergs.)

11-3. One watt of power is produced by 3.1×10^{10} fissions per second. How many atoms of fissile material must be consumed per second to produce one megawatt? How many grams of U235? (Note: there are 1.42×10^{26} atoms per gram of U235.)

11-4. When this book was written, the Yucca Mountain facility had been canceled, and there was no facility for permanent storage of nuclear waste. Use the Internet to find the current status of plans and facilities for permanent disposal.

11-5. Nuclear power plants produced about 20 percent of America's electricity in the early twenty-first century. If the energy from nuclear plants had been produced in coal-burning plants, how much carbon dioxide would have been released into the atmosphere per year? How significant is this?

11-6. The Fukushima nuclear plant accident in Japan occurred during the preparation of this book. What is the current estimate of the consequences (health effects, financial loss, property damage)? What effect has it had on plans for new nuclear plants in the U.S.?

11-7. Why did the safety system fail at Fukushima? Was the failure due to a design flaw or operator error?