Chapter 3.
What are the faults of nuclear power plants?

This chapter describes the basic structure of nuclear energy technology, from past to present. It explains the current aversion to "nuclear power plants."

Military use and peaceful use

The start of the relationship between the nuclear energy technology and human societies was a very unfortunate one. The discovery of nuclear fission (1938) happened on the eve of the Second World War. The completion and use of the atomic bomb occurred in 1945. After the war, nuclear power reactors were developed for the propulsion of submarines and aircraft carriers. Nuclear-powered ships can remain active for a year or more without refueling. Accordingly, the nuclear submarine has become such a formidable weapon that now nobody discusses its abolition. An intense competition in nuclear submarine development erupted in the mid-1950s.

Development placed little priority on economics and relentlessly pursued performance and reliability. In the early stages of development, the General Electric Company conducted sea trials of a submarine carrying a liquid-metal (sodium) cooled reactor in the U.S. The light-water (ordinary water) cooled reactor—especially the pressurized water reactor—became firmly established as the military reactor. The source of the pressurized water reactor is *steam power technology* of the Industrial Revolution. The light-water reactor was also used as a civilian reactor. It continues to be used as the conventional civilian reactor.

The preliminary examination of nuclear reactors for peaceful utilization began at Cambridge University around 1941, at Chicago University around 1943, etc.. Nuclear power was given a boost in 1953, when U.S. president Dwight Eisenhower made an "Atoms for Peace" speech at the United Nations. In 1955, the UN organized the International Atomic Energy Agency (IAEA) at the first International Conference on the Peaceful Use of Atomic Energy. In the 1950s and 1960s, nuclear reactors were being developed all over the world.

The mechanism of light-water reactors

Currently, about 80% of the nuclear reactors around the world are of the light-water-cooled type (*light-water reactors).* This name is familiar to the public, and nuclear power is discussed as if this were the almost only type of nuclear reactor. It is unreasonable to make an anti- or pro-nuclear conclusion based only on this type of reactor, since there are many possibilities of other type's reactors .

Let us look at light-water reactors (LWR) in some detail and then discuss alternatives.

All of the present-day thermal power plants are based on steam technology. Various designs that could link this technology with nuclear fission equipment have been attempted. One method places nuclear fuel into thin-walled metal tubes whose ends are welded tight. The heat generated in the fuel is cooled by water flowing outside the tubes. The heated water, thus obtained, drives a steam turbine and produces electric power.

Two methods of construction are employed. One is the *pressurized water reactor* (three-fourths of the world's LWRs) in which the water is not boiled inside the reactor. Rather, the water is circulated outside the reactor to a heat exchanger whose secondary water is boiled. By contrast, Japan uses the *boiling water reactor*, adopted by Tokyo Electric Power Company, Chubu Electric Power Company and others. It is a simple design. The steam generated in the reactor drives the turbine directly, as shown in Figure 3.1.

The schematic view of the reactor is shown in Figure 3.2. The reactor vessel is made of low-alloy steel, about 17-cm thick and lined with pressure-resistant stainless steel to withstand 73 atmospheric pressures.

The *core* (the central part) is loaded with ten thousands of fuel rods. As seen in the design specifications in Table 3.1, the fuel rod—the heat source—is composed of a thin-walled tube of zirconium alloy (inside diameter about 1 cm) filled with cylindrical pellets (compacted uranium oxide powder). Dozens of these fuel rods are packaged together as fuel assemblies, which are used to move fuel in and out of the core, as the fuel is consumed by fissioning.

During operation, the fuel rod serves as the heat source of nuclear fission to heat and boil the surrounding water. The schematic view and the major specifications of the newest boiling water reactors (Kashiwazaki-Kariwa Unit No. 6 and 7 of Tokyo Electric Power Co.) are shown in Figure 3.3 and Table 3.1. These reactors were developed with the cooperation of Toshiba, GE and Hitachi. Though further explanations are not given, Figure 3.3 and Table 3.1 should be useful as references.

When light water is used as both the coolant and the moderator (explained later), a nuclear fission chain reaction does not occur if the concentration of U-235 in the fuel is lower than 3-4 %. Accordingly, an enrichment of natural uranium is required to raise the naturally occurring concentration of 0.79% to 3 or 4%.

In the early days of enrichment, the *gas diffusion separation method* was used. Gas diffusion separation applies the difference in the speed of two different gas molecules (uranium hexafluoride: UF_6) when they pass through a narrow slit; the molecule composed of U-235 is faster than that composed of the heavier U-238. The *centrifugal separation method* of uranium enrichment is more economical and widely used; it causes heavier molecules (with U-238) to gather in the peripheral part of a swiftly rotating cylinder.

Control rods maintain a constant power output. A *control rod* is composed of materials that are good neutron absorbers. By moving them in and out of the core, the number of neutrons participating in the nuclear reactions is controlled so that the core power output is kept constant. When a reactor is operated for long periods, the nuclear fuel burns up and the subsequent fuel shortage causes a decline in power. An excessive quantity of fuel is loaded before the operation starts. In the early stages of operation, a somewhat large number of neutrons are absorbed by several hundreds of control rods to offset the power of the loaded fuel and keep the reactor power constant.

Major problems of light-water reactors

Because the light-water reactor is simple in principle, it is in widespread practical use. Now, however, most of the developed countries are ready to abandon it. Why?

The answer is that, although it is faithful to the “principle of thermal power plants” it runs against the “principle of nuclear power plants".

The following sections point out its major weaknesses, and present countermeasures.

(1) The nuclear fuel pellet is *solid* and it is sealed.

Because the nuclear fuel pellet is put into a thin fuel cladding, the following problems arise. Both fuel pellet and cladding are damaged from radiation exposure and become transformed—although within allowable design limits.

To remove the used fuel along with the "cinders"—the fission products, the reactor operation must be stopped to take out the fuel rods, disassemble them and perform chemical treatments such as dissolving and extraction. The gases generated (fission products) become highly pressurized because they are sealed in the cladding tubes. The pressure creates the risk of gas ejection if the tube is broken, and the strong neutron absorption by gases causes a decline in reaction efficiency. These problems arise from the fact that the fuel pellet is *solid* (This is addressed again in Chapter 5). Further, manufacturing cost becomes significant owing to the complex and precise design, as seen in Figure 3.2.

(2) Refueling and fuel shuffling require a heavy workload.

One hundred to two hundred control rods inserted into the core at the beginning of the operation suppress reactions. As the burn-up proceeds, they are gradually withdrawn to compensate for the degraded nuclear reaction ability (reactivity). This procedure decreases reaction efficiency by wasting neutrons in the control rods. Furthermore, the degraded fuel assemblies must be repositioned (shuffled) or refueled every one or two years. Compared to burning firewood, *repositioning (shuffling)* corresponds to repositioning a partially burnt log to a place where it would burn better. *Refueling* corresponds to replacing an old log, which, even if not completely burnt, has lower combustion efficiency.

(3) Light-water reactors lack flexibility of operation.

When a reactor is shut down, its startup is sometimes difficult. During the shutdown process, gases produced from fission—such as xenon—readily absorb neutrons and hinder nuclear reactions. In addition, fluctuations in the thermal output cause change of temperature distribution in the solid fuel. The output fluctuations should be avoided because they cause early fuel degradation. Furthermore, the high investment cost and high interest cost of nuclear power plants provide an incentive to operate them at full power. Because of this, they are used as the base-load power plants (supply base electricity at full power), rather than following the power demand. Fossil fuel fired power plants and hydroelectric power plants follow the fluctuations in demand. This will be discussed again in Chapter 7.

(4) Light-water reactors are unsuitable as small reactors.

Refueling and shuffling (2) require special machines, operational maintenance and inspection work. Accordingly, the size of the reactor must be large enough to cover costs, enhance efficiency and remain economical. Although industrialized countries with a large-scale electricity supply can afford large reactors, economical small reactors are indispensable in non-industrialized countries (Chapter 7). In addition, large reactors often have to be constructed far from centers of consumption (such as cities). Thus, long-distance electricity transmission could double the consumer cost.

(5) Water is used as both coolant and moderator.

Water's defect as a medium of energy transmission (the coolant) is that it cannot be used at high temperatures. Water pressure increases at high temperatures and, from the design perspective, it is desirable to avoid high pressures. The large amount of heat generated from the nuclear reaction cannot be extracted effectively, and converting the heat to electricity can reduce the efficiency of to 33%. Thus, light-water reactors waste up to two-thirds of the generated heat, causing heat pollution. Furthermore, radiation decomposes water and generates hydrogen. This decomposition creates the risk of explosion. Materials corrosion from high-temperature, high-pressure water is a difficult problem (see below). Some method for avoiding water in the core could circumvent many problems.

(6) Light-water reactors generate transuranic elements in the uranium fuel and cause corrosion.

The transuranic element plutonium can be used to make atomic weapons, and countermeasures for nuclear non-proliferation and nuclear terrorism are serious problems. Discussions on this point will be presented in Chapters 6 and 10.

Stainless steel containing 20-40 % nickel and chromium is used for the reactor vessel walls and other components. This stainless steel alloy is different than ordinary steel. Before the development of light-water reactors, the use of stainless steel in water boilers was prohibited. In the stainless steel vessel walls of light-water reactors, deformation from thermal stress can cause stress corrosion and fractures several centimeters long. This was the reason for the prohibition. Strong neutron irradiation can cause the stainless steel to become brittle and generate cracks. Accordingly, the combination of stainless steel and high temperature water is not desirable at all. Carbon steel is not a good substitute because it is easily oxidized. It produces radioactive corrosion products that flake off and scatter easily. Thus, there is no choice but to use stainless steel.

Reactors are easy to design if the rules are followed

The principles of the nuclear fission energy power generation are simple and clear. However, the following paragraphs explain that light-water reactors (LWRs) are not faithful to these principles.

In every nuclear reaction, neutrons play the major role. Although the electrical charge is not related to the reaction process, the neutron's predicted behavior is simple while entailing a lot of computation. It requires calculating where a neutron enters at a given speed, collides with a nucleus, is absorbed at a given probability, induces a nuclear reaction, or is repelled. These are ideal jobs for computers.

Before designing an ideal reactor, it is necessary to consider the following three questions and find answers to them. Thinking after the fact does not promise a good reactor (the LWRs fall short of an ideal reactor, especially relative to A and C below).

A) Both the nuclear fuel and the vessel materials are affected by radiation damage from nuclear reactions. What kind of radiation-resistant materials should be selected for the nuclear fuel and vessel?

B) The nuclear reaction heat must be transformed into electricity. What kind of energy transformation technology should be applied?

C) During the nuclear reaction, the initial nuclear fuel materials change into various elements and chemical compounds. Because these chemical changes imply fuel degradation, the reaction products must not interfere with the reactions. What kind of chemical treatment should be adopted for this purpose?

Let us think about these basic questions, consider a solution for the typical LWR problems (1)～(6) explained above, and construct the ideal nuclear energy power plant.

A. Selection of radiation-resistant materials for nuclear fuel and reactor vessels

A reactor should be composed of nuclear fuels and vessel materials that are resistant to the radiation generated from nuclear reactions. If solid fuel sustains radiation, it changes to other materials or generates gases (from chemical changes), and deteriorates during operation. Vessel materials can experience degradation, change, and rupture. If nuclear fuel is a gas or a liquid, the solvent gas or liquid also sustains radiation. For the reason described in B, it is necessary to select elements (Table 3.2) that absorb "slow- (low- energy) thermal neutrons" poorly.

In summary, it is important that the chosen element does not induce much nuclear reaction except for fission. If bombarded with neutrons, the selected elements should not cause a change in the shape and properties of the nuclear fuel or vessel materials (apart from the temperature rise).

Another point relates to the state of the material.

Generally, materials are categorized as gas, liquid, or solid.

First, a stable gas is usable for almost all purposes except vessel materials. A gas whose molecule is composed of one atom (helium and argon) is more convenient because the molecule cannot be broken. Helium gas has excellent heat conductivity. However, because helium's molecule is small, it is difficult to confine it under high-pressure and prevent leakage. Gases naturally have low density, low heat capacity and high-pressure capability.

Solids pose a more complex problem because radiation breaks their crystalline structures. The related phenomena and behaviors are so complex that we cannot predict what will happen unless irradiation experiments are conducted under actual conditions. Experiments and post-experiment analysis require special facilities and great capability, effort, and money. Apart from these effects of irradiation damage, the post chemical treatment (removal) of elements generated from nuclear chemical reactions become extremely difficult even if the quantity is small. Almost all these difficulties originate from the solid's lack of fluidity. This was pointed out in problem (1) of LWRs. Although only the disadvantages of solids have been presented here, it is clear that reactor equipment requires solid structural materials and vessel materials.

Liquids lie between solids and gases because of their fluidity, high density and general low pressure. They are broadly divided into four categories: (a) inorganic liquids such as water and ammonia; (b) organic liquids such as alcohol, benzene, and PCB; (c) liquid metals; and (d) molten-salts.

Problems with (a) and (b) relate to their component molecules. The molecules are not stable at high temperatures; they deteriorate from decomposition or polymerization because of irradiation damage.

The liquid metals (c) are composed of metal atoms and generally have no molecules to be broken. However, they are chemically reactive.

Molten-salts (d) are "liquefied salts." Because a salt is an aggregate of two kinds of positive and negative ions, it is also called an "*ionic liquid*". The popular table salt (sodium chloride, NaCl) is a mixture of equal numbers of sodium cations (Na^+) and chloride anions (Cl^-) at temperatures above its melting point (800°C). With a stable electric neutrality and intense thermal movement, it is impervious to radiation. It is also chemically stable.

Accordingly, (c) and (d) are suitable candidates, but the risk of vessel corrosion is considerable. Molten-salt, the most promising liquid, will be discussed in detail in Chapter 5.

B. Technologies of energy transformation

Having considered the materials, the next task is choosing the method of power production for the reactor. In principle, it is possible to generate power from the electric charges of the nuclei (or the charged particles generated by fission) by converting the momenta of the high-speed atoms or elementary particles into electricity. However, these methods have not worked well enough for practical use. Let us assume that heat is carried away from the high temperature nuclear fuel by coolants (thermal agents)—such as helium gas, water, liquid metal, or molten-salt—to produce steam for turbine power. In other words, let us assume that we use *steam power technology* of the conventional type while attaining the best thermal efficiencies consistent with economic considerations.

After narrowing down technological conditions, we still have many selection decisions relating to the nuclear fuel material, the shape and composition of fuel, and the coolant. Nuclear fuel alternatives to U-235 of the present reactors can also be considered,

Furthermore, we must think about the "neutron-deceleration (slowing down) material" as an important component of fission reactors.

What does the "neutron slowing-down process" mean?

Because the *neutron slowing-down process* is an important concept for understanding *criticality* and behavior peculiar to nuclear reactions, the author would like to comment on it here at some length.

Even a small quantity of nuclear fuel can easily produce criticality. This is evident from the description of the natural fission reactor (Oklo) and the careless criticality accident at Tokai-Mura (JCO—Japan Nuclear Fuel Conversion Company, 1999).

The fission of U-235 generates neutrons whose mean energy is about 2 MeV immediately after generation. A neutron of this energy flies so fast that it is very hard to make it collide with neighboring uranium atoms. However, if the neutrons are slowed down to less than 1eV, the reaction becomes easier by a factor of tens or hundreds. Slow neutrons, whose energy equalizes with its surrounding nuclei at room temperature, are called "*thermal* neutrons." From the viewpoint of slow neutrons, the nucleus of U-235 looks like a huge wall tens (or hundreds) of times as large as they are. They easily collide with it, are absorbed, and cause nuclear fission. This situation is schematically shown on the right side of Figure 2.3.

Water and organic liquids are most suitable for slowing neutrons. Therefore, reprocessing and fuel fabrication plants that use water and organic liquids are extremely dangerous! In the old days, human error caused tragic accidents from the slowing-down effect. This happened at Tokai-Mura. No one can believe that a group of engineers had been working for 20 years in Japan's most advanced nuclear technology area, Tokai-Mura, without any understanding of the criticality danger. The day after the Tokai-Mura criticality accident, my French friend asked me, "Was it terrorism?" One can only conclude that adequate instruction about criticality was lacking in Japan.

The fact that fission reactions easily develop from slowed neutrons is not only convenient but preferable because the critical mass—the required quantity of nuclear fuel—becomes smaller.

Accordingly, almost all reactors are designed to use slowing-down materials (*moderators*) and are called *thermal (neutron) reactors* because their neutrons have been slowed to thermal energy levels.

Materials composed of atoms with a *light* nucleus are suitable as moderators. When a neutron collides with a heavy nucleus, it rebounds with almost the same speed as if it hit a wall. However, if the nucleus is light, the neutron is slowed down from transferring considerable energy to the light nucleus.

Think of billiard balls: when a moving ball collides with a stationary ball, the latter jumps ahead, and the speed of the former becomes nearly zero. The hydrogen nucleus (a proton) is a substance that has almost the same mass as a neutron. Thus, a compound rich in hydrogen is a good moderator. However, as seen in Table 3.2, hydrogen reacts with neutrons by absorbing them, and therefore cannot produce more fission reactions. Preferred materials will have the next lightest nucleus but less neutron-absorption ability (such as deuterium—a hydrogen atom with one proton and one neutron); next is helium, then beryllium, and carbon. Water, organic substances, heavy water (water composed of deuterium instead of hydrogen), and graphite (almost pure carbon) are important as practical moderators.

Neutrons play the leading role in nuclear energy reactions.

The key to "building a good reactor" is utilizing precious neutrons well. Neutrons are used efficiently when they induce the next fission and are absorbed by fertile materials (U-238 and Th-232) in order to regenerate nuclear fuel. The use of neutrons for fuel regeneration avoids their leakage from the reactor and wasted absorption by the control rods and reactor materials.

Wasted neutrons generate problematic radioactive substances (wastes) and result in reduced reaction efficiency and the burden of waste disposal.

It has been explained that LWR nuclear reactions use control rods that absorb neutrons. The absorption and the waste of neutrons by control rods might seem inevitable, but this is not true. Control rods are required when solid nuclear fuel is used. The reactor proposed here does not require control rods under normal conditions. This will be explained in Chapter 7.

C. Approach to chemical treatment

The nuclear reactor is a nuclear chemical reaction facility, a chemical plant. Although the quantity is small, the nuclei of the fuel change into other substances. The generated substances must be chemically treated so that they do not interfere with the nuclear reaction. Otherwise the fuel becomes degraded (neutron poison) and the reaction efficiency is reduced. This fact should have been more widely recognized in the age of the *civil commercial plant* development (as distinct from the age of the nuclear submarine development race). The consumption of nuclear fuel per generated heat is several hundreds of thousands times smaller than that of fossil fuel! Reactors are designed as *electromechanical facilities* in which the nuclear fuel rods are treated as electric heat sources.

For chemical treatment, fuel rods have to be taken out of the core at the time of refueling and sent to a reprocessing plant. This work is inefficient and dangerous: the reactor must be shut down, dangerous radioactive materials (including plutonium) must be treated outside the reactor, and reprocessing must be performed. If the reactor had been viewed as a chemical plant, a safer and more efficient treatment method might have been chosen. This is indeed deplorable! However, it is not too late to remedy the situation. With an awareness of past mistakes, a "better nuclear power plant" should now be developed. Selecting materials with a design philosophy suited to the basic nature of the chemical plant will advance this work.

However, to build a *better* nuclear power plant, it is insufficient to consider only the operation, maintenance, and fuel treatment of the chemical plant.

The "nuclear fuel cycle system," encompassing all activities around the reactor—from fuel gathering and transportation to waste treatment—should be optimized. It should be made as simple, rational, and economical as possible. The requirements regarding the site, buildings, personnel, transportation route, quantity, and quantity of waste, and work hours should be minimized. In addition to these obvious factors, the harmful influence on society should be minimized. The objective should be a new energy industry that contributes to society, even if indirectly.

Peaceful use of nuclear energy: the gas-cooled reactors

Here, let us briefly summarize the history of the industrial development of thermal power reactors.

The easiest combination for early nuclear reactors was gas coolant, graphite moderator, and natural uranium fuel. Although gas becomes highly pressurized, it is easy to handle because it is fluid, like liquids, and does not change its state from liquid to gas. Carbon dioxide (CO_2) is a particularly good thermal agent with a large thermal capacity. As a moderating material, graphite is easily obtainable in its pure form and does not easily react with neutrons, as shown in Table 3.2. Moreover, it is an excellent high-temperature material because of its high melting point (about 4,000˚C), high thermal capacity, high heat conductivity, high strength, and moderate resistance to radiation damage.

With this combination of materials, the reactor can be made critical using natural uranium. This is very advantageous for a reactor because uranium enrichment is not required..

After World War II, the United Kingdom experienced harsh energy resource constraints and social and economic difficulties. Nevertheless, it tried to bring the gas-cooled reactor into practical use. Staking its national destiny and prestige as a technologically advanced country, the U.K. opened the Calder Hall reactor in 1956. Japan imported the design as the Tokai Unit No.1 plant. Although the plant had an excellent operational record, it was uneconomical. Its cost was high, owing to low power density, and its efficiency for converting thermal energy to electricity was low. This was due to the relatively low operational temperature (at high temperatures, graphite reacts with carbon dioxide). It is no longer operating in Japan.

The future of the gas-cooled reactors

Since the days of early gas-cooled reactors, improved coolants (helium) have assisted the development of high-temperature gas-cooled reactors in various countries, including Japan. However, gas-cooled reactors have serious weak points. For example, the production cost of the nuclear fuel is high. The fuel, whose particles are about one millimeter in diameter, are embedded in graphite "balls" (pebbles, several centimeters in diameter) or graphite blocks. The fuel particle material is made of oxide or carbide coated with multiple layers of carbon and silicon carbide. The low thermal power density of the core leads to a high core volume per unit power output and inevitably increases the size of the high-temperature, high-pressure reactor vessels. There is a need for mitigation against the possible introduction of high-pressure water from the steam generator into the core.

Two improvements have recently been proposed for the high temperature gas-cooled reactor to make it both safe and economical.

One (a) is to stop electric power generation and utilize the high temperature (~ 1000˚C) directly as industrial heat. The production of hydrogen for fuel cells is an example. Direct industrial utilization in form of heat results in less energy loss than to convert the generated heat from fission to electricity. Germany studied this prospect and the JAERI (Japan Atomic Energy Research Institute) is now actively promoting it. The other improvement (b) is the concept of a "small high temperature gas-cooled reactor with gas turbine," in which direct turbine power generation (using helium gas) improves efficiency. L. M. Lidsky of MIT (Massachusetts Institute of Technology) and others proposed this concept, and it is attracting interest. One safety benefit relates to its small size. In the event that helium cooling is lost, natural radiation cooling can be established (at sufficiently small power). Coating the layers of fuel prevents the fuel from getting too hot and reduces the possibility of emitting fission product gases.

However, even this idea has some difficulties. In the first place, concerning (a), there are limitations in the direct utilization of heat. Though direct use is highly efficient because conversion to electricity is not required, there are some restrictions. The reactor and the factory where the thermal energy is used must be close together. This will limit its application to special purposes. Energy in the form of electricity, which is easily transported and usable for any purposes in remote places, is far easier to use.

As for (b), the 100-MWe high-power helium gas turbine generator has not yet been proven. Handling helium gas is difficult, and this weighs heavily on the development and economics of the gas turbine. (It is not easy to confine helium in a vessel. This is clear from the fact that helium is used to detect gas leakage from highly tiny failure of vessels.) In addition, safety is doubtful even if the facility is physically destroyed inducing the fire of core. Further, the multi-layer fuel particles form gas-tight barriers that are so durable that they cause difficulty and expense in their manufacture and during chemical processing. The radioactivity of carbon adds to the difficulty. If thorium is used, its radioactivity makes reprocessing of solid fuels even more difficult. It means abandoning a closed nuclear fuel cycle, if the fuel assembly is discarded after use.

During the next century, establishing a sound, large-scale nuclear fuel cycle (fuel is circulated and reused) is indispensable. Squandering fuel and associated materials after one use will make the resources insufficient for wide scale use and remain the radio-waste problem. This last point is the main reason that the gas-cooled reactor cannot be wholeheartedly supported for global application. It contradicts the idea that the power reactor should be a chemical plant. It would gradually contradict the design philosophy even idealistic as a solid-fuel reactor itself. The future reactors must be capable of deployment worldwide on a large scale.

Heavy-water cooled and light-water cooled reactors

The possible reactor types after the gas-cooled reactor were the following possibilities.

Coolant: heavy water or light water; moderators: heavy-water or graphite; fuel: natural uranium.

What are the merits of these types? Because hydrogen atoms absorb neutrons well, the light water (ordinary water, H_2O) changes into heavy water (water in which the hydrogen is replaced by deuterium, D). If light water is used as the moderating material, the reaction efficiency is reduced because of the neutron absorption reaction. However, if heavy water is used as the moderating material instead of light water, the neutron efficiency increases. The neutron absorption rate of heavy water is 600 times smaller than light water, and criticality becomes attainable even with natural uranium. Canada was quick to develop the heavy water reactor. Canada took advantage of the cheap, large-scale production of heavy water as a by-product of the water electrolysis industry using hydropower. This type of reactor is used in Canada and other countries, including India and South Korea.

A similar type of reactor can use light water if the uranium enriched (3-5 %). The first successful power plant of this type was completed by I. V. Kurchatov at the Soviet Union's first atomic power city in Obninsk. It combined the following:

Coolant: light water; moderator: graphite; fuel: slightly enriched (5%) uranium alloy. However, its use was disallowed for safety reasons outside of USSR, and, since Chernobyl, it will be phased out even in Obninsk. Almost all of the ensuing reactors in the former Soviet Union were improved versions of this type.

Nowadays the most widely used reactor in the world is the light-water-moderated, light-water-cooled power reactor with a simpler combination:

Coolant and moderator: light water; fuel: slightly enriched (3-5 %) uranium (mainly oxide).

About 80 % of the nuclear reactors in the world, including Japan, are of this type. The LWR was originally developed by the U.S. for submarines and then converted to civilian use. In the early stages, it had a reputation for good economics. Many small-scale electric utilities in the U.S. were trying to benefit by introducing this reactor. They constructed about 100 LWR plants in about ten years. Seeing this, Japan hurried to introduce them.

This type of reactor is fairly good. France finally adopted it and made it the standard. France improved the economics by standardizing the model. It deployed more than 50 pressurized water reactors all over the country. These reactors supply over 75 % of domestic demand and export electricity to neighboring countries. Switzerland, while abolishing nuclear power plants locally, invests public funds in French nuclear power plants.

However, experience has shown this type to be far from ideal. Although it can be used for at least 30 to 50 years, the following problems must be solved: safety improvement; better fuel utilization; wastes; and proliferation of plutonium. Without solutions to these problems, this type of reactor has no future for greatly expanded worldwide deployment.

Can the fast breeder reactors sustain the future?

So far, we have discussed thermal (slow neutron) reactors. However, another type of reactor has a different concept for using neutrons. It is called the "fast (neutron) reactor" or "fast breeder reactor." Its fission neutrons do not slow down very much. The Japanese prototype reactor "MONJU" belongs to this type. A sodium leakage accident occurred at MONJU in 1995. While this leakage, and one in France, were big media events, the programs were shut down mainly for economic reasons: the projected cost of this kind of reactor is much higher than LWRs.

The number of neutrons generated per fission is about 2.3, as illustrated in Figure 2.3. If one neutron continues the chain reaction and another replenishes the nuclear fuel lost from fission, the residual neutrons breed additional nuclear fuel, as seen in Figure 6.2. Because the fast reactor does not use moderating material, the number of absorbed neutrons is reduced, and many neutrons become available to breed nuclear fuel.

However, this type uses liquid metals as coolant (sodium). Liquid metals do not slow down neutron speed nearly as much as materials specially chosen to be good moderators. However, liquid metals have a high ability to remove heat. The reactor design, technology development, and economics are difficult problems for the fast breeder. About 40 years ago, Japan developed fast breeders as a national project. Kazuo contributed to the project, which is the foundation of liquid-sodium coolant technology in Japan. Nowadays almost only Japan continues aggressively developing fast breeder reactors.

The fast breeder reactor has the following four problems.

i) To become the main energy source in the world, the breeding rate is too slow.
This will be discussed in Chapter 8 with an explanation of the necessity for fast breeders.

ii) The fast breeder is not safe enough. A technologically more unreasonable design is required than the thermal reactor and sodium is used.

iii) The large-scale utilization of plutonium poses problems. The fuel to be bred is plutonium. Large-scale utilization is necessary for the fast breeder reactor to mitigate global warming. This requires at least several tens thousand tons of plutonium. The countermeasures against its proliferation and nuclear terrorism become big problems.

iv) Economics is a problem. Nuclear fuel reprocessing and nuclear waste treatment (based on the sodium technology and plutonium utilization) become expensive. Thirty years ago the cost of nuclear power generation was considered flexible. It was supposed that further cost reduction would accompany technical improvements. Nowadays, however, people are less optimistic. The economics of the fast reactor is much more problematic. Some people argue the necessity of fast breeders from the uranium resource depletion point of view. Essentially, uranium resources are *infinite, much more if a breeding cycle would be realized.* However, it is more likely that uranium-rich countries will monopolize it owing to the strong localization of uranium. Breeding development is necessary to rationalize the technology. However, a fission breeding power reactor is a technological mistake, as will be explained in Chapter 8.

Industrialized countries have abandoned fast reactor development after 50 years of enormous investment. Even the Japanese government, which had strongly supported its development, finally withdrew support in August 2000. The present fast reactor budget in Japan is less than it had been. If investment is continued for the next several decades, surely some useful results will be produced (for example, utilization for space development). However, what will happen to Japan and the world in the meantime? We have little time left.

Over 400 LWRs continue to operate over their lifetime. However, we should proceed with conviction and due haste to *shift to better nuclear reactors.* The next steps to achieve better nuclear reactors will depend on a rational design approach discussed in this book. It will also depend on scientists, engineers, and workers, with the support of society to make decisions and carry out the work.

All types of the reactors discussed in this chapter use *solid nuclear fuel.* Actually, all the 436 nuclear power reactors operated in the world use solid nuclear fuel. From time to time it has been explained that there are many technical problems associated with *solid* fuel. This will be discussed in Chapter 5. Liquid fuel reactors will be better reactors.