Chapter 8.
Breeding nuclear fuel

For solving problems associated with preserving the global environment, population explosion and poverty in this century, it is urgent to secure a large amount of nuclear energy. The vital factor for securing nuclear energy is breeding nuclear fuel.

Nuclear technology as the leading energy technology: Necessary conditions

To achieve the leading role, nuclear energy must realize the following three prerequisites, as indicated in Figure 1.2 (D):

1. An enormous amount of energy generation is required—some 500-1000 times as much as in the past (about two billion kW-years). The maximum installed capacity will be about ten billion kW.

2. The power-generating capacity must be increased rapidly (doubling every ten years) and developed globally. Otherwise, this effort will result in a negligible reduction of atmospheric CO$_2$. Nuclear fuel must replace fossil fuel as soon as possible for solving global environmental problems.

3. The growth will begin to slow around 2060 and the total capacity will start to decrease around 2080, as solar energy technology rises.

All of these conditions must be satisfied. This statement seems severe. However, there is no room for compromise because the annual emission of carbon dioxide into the atmosphere will increase until around 2065, when it will reach twice the present level and level off, as shown in Figure 1.2 (C). A failure to develop a large nuclear energy industry is unacceptable regardless of difficulty, in the author's opinion. Indeed, these measures may not be sufficient; we may also have to promote energy conservation, carbon taxation, and expanded use of solar energy. The situation is extraordinarily serious.

This new nuclear industry will have to supply half of the world's energy. This implies the creation of a gigantic industry of the order of thousands (or tens of thousands) of trillions of yen. This assertion is likely to evoke alarm from nuclear energy experts who might say, “Just think how much we have invested for developing the uranium-plutonium fuel cycle to the present level! Do you mean you are going to do it all over again?” We understand their feelings, but our answer is “no.” We no longer need much development funding.

Carrying out the fast breeder reactor program, which the Japanese government advocates, will probably take several trillions of yen and dozens of years. Worldwide development is not feasible because the anticipated plutonium dissemination makes it unfavorable. In contrast, the thorium molten-salt reactor program requires only a fraction of the money required for the fast breeder program. Because of safety and economic advantages, a new industry of the order of ten thousand trillion yen can be developed worldwide.

Further, it is important that an elaborate infrastructure has already been established around nuclear power plants. If this existing investment is fully utilized, a smooth transition can be expected, as indicated in (A) or (D) of Figure 1.2. This is further illustrated in Figure 10.1 in Chapter 10.

This revitalization of nuclear industry will not disadvantage anyone. We believe that this project will be welcomed by all.
Doubling every ten years

Rapid industrial development, equivalent to the doubling of power generation every ten years, occurred in the petroleum and natural gas industries. These leading energy sources have been changing.

The private sector brought about this change. Economic advantages guided it. The future nuclear industry must also depend on the vitality of private industry. In the past, the nuclear industry advanced too rapidly and created social disruption. Enormous military investments in nuclear science and technology worldwide promoted the utilization of nuclear energy. The excessively rapid growth led to the accidents of Three Mile Island and Chernobyl, as indicated by the curve in Figure 1.2 (A). This resulted in the present nuclear power stagnation. The industry was not driven by private-sector vitality.

The future gigantic industry of thorium utilization will contract and retreat immediately after reaching its peak, as shown in Figure 1.2 (A). This is an important point. This period of retreat can be utilized to dispose of radioactive waste, the last remaining problem. This point will be addressed again at the end of this chapter.

Why “breeding” is necessary?

A rapid expansion of power generation requires enormous breeding of the necessary “kindling charcoal” (fissile nuclides). Without breeding, the supply of fissile nuclides cannot keep up with the rapid development of reactors.

Fissile nuclides (nuclides that fission easily) are in limited supply. The only fissile nuclide of natural uranium is U-235 (0.7% by content). If neutrons produced from the fission of U-235 are adequately absorbed by U-238 (99.3% of all natural uranium), fissile nuclides Pu-239 and Pu-241 can be bred in quantities greater than the U-235 consumed, as indicated in Figure 6.2.

Causing the fertile material Th-232 (nearly all natural thorium) to absorb neutrons allows U-233 to be bred in quantities greater than the fissile nuclides consumed. Fissile nuclides for producing these neutrons may be U-233, U-235, Pu-239, or Pu-241, as indicated in Figure 6.2.

However, it is not desirable to breed the fissile nuclides Pu-239 and Pu-241 from U-238. Plutonium is a crucial material for nuclear weapons and the object of enormous security. In addition, it is a nuclear waste and very difficult to handle. Nevertheless, when the goal is nuclear fission energy, breeding is indispensable.

How can we manage breeding effectively?

When power generation and breeding are performed in the same core, it appears logical to develop “breeder power reactors,” regardless of the resource used—uranium or thorium. Among uranium-plutonium nuclear fuel cycles, the Liquid-Metal Fast Breeder Reactor (LMFBR) is exemplified by MONJU in Japan. Among thorium-uranium nuclear fuel cycles, the Molten-Salt Breeder Reactor (MSBR) developed by ORNL of the U.S. is the best example. However, 50 years after the initial development, breeding and power generation in the same reactor have not been successful. The authors considered MSBR the best 20 years ago, but recently realized that the idea of breeding while generating power is unsuccessful. The reasons are shown below.

Insufficient breeding ability

It has become clear that the breeder power reactor cannot double its power
generation in ten years, satisfying conditions (1) and (2). Even after 50 years of investment by industrialized countries around the world, no prospective commercial reactors can double their power generation in fewer than 30 years. If the Super-Phoenix (the proposed French 1200 MWe fast breeder reactor) were used, it would take about 100 years.

Although the MSBR has an effective fuel doubling time of about 20 years and surpasses the fast breeder reactor in all aspects, its performance is insufficient. The minimum global requirement demands that power generation double every ten years. This is still not enough. Unless the design performance doubles every six or seven years, the power generation system cannot be doubled every ten years.

Nevertheless, reactors like the MSBR are economically unfeasible, because the fission process is neutron poor, as shown in Table 4.1.

**Larger complex reactors and high generation cost**

Simpler than the breeder reactor, even the LWR is unable to compete with a fossil fuel plant in cost. If a breeder reactor aims at higher breeding performance by increasing the neutron efficiency, it inevitably becomes a large, complex, and expensive power reactor. When the preparation of the nuclear fuel breeding cycle (including chemical processing) is considered, the power generation cost clearly increases.

In addition, the world’s developing countries require small reactors. If small power reactors with a low breeding performance are considered, the doubling time of the system becomes much longer. This rules out worldwide use of breeder reactors.

**Unfavorable development cost and time**

This consideration is almost the same as (b) and involves difficult problems. In conclusion, there are no prospects for practical use of breeding in the 21st century. Almost all countries have stopped development, mainly for the reason of low economic competitiveness.

**Technical difficulties of Molten-Salt Breeder Reactor**

One serious disadvantage of the MSBR is the core graphite replacement every four years. To enhance breeding performance, the loaded fuel must be burnt as fast as possible to shorten the fuel generation. Subsequently, the neutron irradiation damages the graphite. The replacement of graphite is hard work because it entails opening the lid of the reactor vessel under high temperature (to avoid solidification of molten-salt) and under conditions of strong radiation. The problem of graphite replacement reduces the advantage of liquid nuclear fuel.

Furthermore, the MSBR requires a continuous chemical processing facility in the primary fuel-salt system to separate the bred U-233. To be sure, the MSBR is superior to the LMFBR from the perspective of continuous chemical processing. In the FBR, after removal from the core, the radioactive burnt solid fuel assemblies must be stored for at least a year before the bred plutonium is separated by chemical processes. After a year or more, the plutonium is fabricated into solid nuclear fuel and transported. Thus, a lot of time is required to process the spent nuclear fuel of FBRs.

Though the continuous chemical processing facility of MSBR is an advantage, it is also a disadvantage. The technical development of the reprocessing facility is much more difficult than the reactor. For chemical processing, the fuel salt must undergo
frequent oxidation and reduction. Consequently, the chemical neutrality of the salt cannot be maintained, and this makes it difficult to protect the vessel materials from corrosion. Because these facilities are expensive, the reactor would tend to be large to absorb the cost. Nevertheless, the doubling time is 20 years, as noted above.

**What are the effective methods of breeding?**

This raises the question of what to do about breeding. FUJI-II is adequate for power generation. Perhaps it is better to build a separate facility exclusively for breeding.

Let us investigate major nuclear reactions useful for breeding. The important point is to obtain as many neutrons as possible. Nuclear fission, DT fusion, and nuclear spallation are three candidates for neutron producing reactions. Comparisons of their major characteristics are shown in Table 4.1.

From the standpoint of neutron acquisition, the nuclear spallation reaction is excellent and the fusion reaction is considered the second-best candidate. It can be seen from this table that the fission reaction is not good at breeding and that it is difficult to build a good breeder using this reaction.

Accordingly, the important point is how to use the spallation reaction for breeding.

As explained in Chapter 4, spallation is a nuclear reaction in which hydrogen nuclei (protons) accelerate to 1000-3000 MeV and collide with heavy nuclei to produce many neutrons. This is a very complex reaction. Let us explain this process by using Figure 8.1, which was prepared by Uhlich Laboratory (Germany).

A nucleus can be considered a droplet of protons and neutrons. If a high-energy proton collides with a heavy nucleus, the proton enters the nucleus and raises its temperature (the nucleus becomes excited). The collision results in the *evaporation (emission) of many neutrons*. This is the main reaction. In addition, other reactions such as the generation of mesons, partial destruction of the excited nucleus, and fission induced by fast neutrons also produce neutrons. If a 1000-MeV proton is injected into the pure thorium metal, about 40 neutrons are generated on the average.

The neutrons generated from reactions of thorium nuclei in the molten-salt are then absorbed by the surrounding thorium nuclei, and U-233 nuclear fuel is bred.

Here, the system should be designed so that the bred U-233 is used in FUJI and the nuclear fuel cycle circulates smoothly. More specifically, Flibe-based molten salt should be used throughout the whole system. A simple molten-salt nuclear fuel cycle that limits intermediate processes (separation and extraction) should be constructed.

**Proposal of Accelerator Molten-Salt Breeder**

A system fulfilling the above requirements has been invented. The *Accelerator Molten-Salt Breeder (AMSB)* was invented by K. Furukawa at JAERI (Japan Atomic Energy Research Institute) with the cooperation of his friends, the late Kineo Tsukada and Yasuaki Nakahara [Furukawa et al., J.Nucl. Sci. & Tech., Vol.18 (1981) P.79-81].

This system contains *a high-current proton accelerator and a molten-salt breeding facility*, as shown in Figure 8.2. AMSB has the facility to treat heat-accompanying reactions such as nuclear fission. However, its primary purpose is breeding, not power generation. The generated electricity is used mainly for operating the accelerator.
The high-current proton accelerator accelerates the proton beam (a flux of current), which is equivalent to 200 milli-amperes to 1000 MeV (a billion electron volts). A one milli-ampere accelerator has already been operating for 30 years at Los Alamos National Laboratory, and the development for a ten milli-ampere-class model has started in Japan. We are expecting that in 20 years, the Accelerator Molten-Salt Breeder will produce nuclear fuel for FUJI. By then, plutonium will be used as the initial fuel. (See Chapter 7 for the discussion on plutonium.) As for the accelerator, a simpler, more industrial and economical method of proton acceleration should be developed, even if the proton velocity is not uniform.

This proton beam is injected into the molten-salt target in a cylindrical vessel (molten-salt breeding facility), as shown in Figure 8.2. The cylindrical vessel has a diameter of 4.5 m and a depth of about 7 m. In the upper part of the molten-salt is a whirlpool with a depth of about 50 cm. The proton beam is injected a little off the center of the whirlpool. This is because the flow velocity is slow at the center, disadvantageous for dispersing generated heat. The nuclear reactions occur most actively in a region about one meter below the surface of the molten-salt.

The composition of the target salt is similar to the Flibe-based molten-salt nuclear fuel, which use in FUJI-II and others. However, the concentration of thorium is increased to enhance the spallation reactions with protons. In this method, neutrons are produced in the target salt, and nuclear fuel (U-233) is thereby generated from thorium in the same salt. Because the generated neutrons are blanketed by the thorium in this salt, it is called a target/blanket salt. The molten-salt protects the structures from radiation damage. New materials development is not needed, unlike nuclear fusion where materials development is a major problem.

This molten-salt is the only material that is irradiated, including fast particles; there is no radiation damage, and heat removal is not necessary. The substances generated are naturally mixed and diffused, so there is no worry about local accumulation of reaction products as in the case of solid targets. Regarding the proton injection window in the upper part of the vessel, we will use the Russian gas curtain method [ref.] instead of the solid window. Thus, other than development of the accelerator, there are no major problems standing in the way of utilization. In addition, the practical behavior of target/blanket salt should be examined in detail.

The concept of the Thorium Molten-Salt Nuclear Energy Synergetic System

We have laid the groundwork. The nuclear power generation system that satisfies requirement (D) of Figure 1.2 has been named the Thorium Molten-Salt Nuclear Energy Synergetic System (THORIMS-NES). This system follows the three principles described below.

The first principle-----use of molten-fluoride-salt nuclear fuel, instead of a solid fuel

Because a reactor is a kind of chemical engineering facility, one principle acknowledges the liquid as the working medium. Here, the Flibe-based fluorine molten-salt is used. It has three functions: nuclear reaction, heat transport, and the medium for chemical process. The technical basis of the reactor using this salt was established by ORNL (U.S.). In addition, its physico-chemical (electrochemical) properties are predictable.

The second principle-----use of thorium instead of uranium

By making natural thorium (Th-232) absorb neutrons, the fissile material U-233 is generated and used as the nuclear fuel. Few transuranic elements (such as
plutonium) are generated from thorium. The thorium resource is abundant and will
never be monopolized, in our opinion.

The third principle — a complete nuclear fuel breeding cycle combining the
nuclear fuel breeding facility and the power reactor

The ideal "breeding power reactor" concept was disappointing. The fast breeder
reactor and the Molten-Salt Breeder Reactor (developed by ORNL 30 years ago) are
destined to be large, complex, expensive, and perhaps insufficient in breeding
performance. Thus, they cannot be developed globally. To satisfy more than half the
world's electricity demand, a power station must be simple, safe, economical, and
small. To minimize the fluctuations in performance and the management of
materials transportation and treatment, the power reactor should be self-sufficient
in nuclear fuel. The power reactor FUJI and the AMSB (as a nuclear fuel breeding
and manufacturing plant) combine to complete the THORIMS-NES. This will
constitute the simplest nuclear fuel cycle without neutron waste and provide energy
to the world.

The facilities composing the total system are as follows.

(i) Molten-salt power plants (sited near cities)

These are FUJI-II-based plants such as U-233-fueled FUJI-U-233 and Pu-fueled
FUJI-Pu. The generating capacity can be varied with the purpose. It is advisable to
standardize two or three types of reactors with power output of no more than 500
MWe and to install several reactors (for modular plants), as required. This type of
reactor is suited to small plants.

(ii) Accelerator Molten-Salt Breeder (located at regional centers)

Because this is a large plant, it should be installed at 20-50 regional centers
distributed around the world. The plants will share the handling and management
of nuclear materials, specialists, and special auxiliary components.

(iii) Chemical processing, reactor component dismantling, and waste processing
plant (located at regional centers)

These processing and dismantling plants are systematically controlled in each
regional center as in the case of (ii).

The related facilities interact symbiotically and comprise the THORIMS-NES.

First, Flibe-based molten-salt nuclear fuel, which may also include plutonium, is
conveyed to the power reactor FUJI and loaded after the adjustment of chemical
compositions. The reactor is operated and electricity is generated. As a rule, two
power reactors are installed in each power plant to substitute for each other in case
of failure. It is assumed that a single unit represented by a regional center will have
a total power generation capacity of about 100 GWe (nearly the present total electric
capacity in Japan) to two or three times that capacity. After the end of the service
life, FUJI is dismantled and the reactor vessel, components of the primary system,
and the nuclear fuel are transported to the regional center.

Spent molten-salt nuclear fuel is recovered and then processed with fluorine gas.
All uranium components are separated in the form of uranium fluoride gas. This
uranium fluoride is added to the salt taken from the AMSB and sent to FUJI again
as molten-salt nuclear fuel. After the removal of uranium, some fission products in
the molten-salt are harmful. They are separated by chemical processing and
reserved for future incineration. Harmless fission products are left in the salt
without separation.

The residual salt, consisting of the fluorides of lithium, beryllium, and thorium
(plutonium), is added to the salt tank of the AMSB. As in the power reactor FUJI,
the salt in the AMSB goes slowly back and forth between the salt tank and the breeding facility. The concentration of U-233 in the salt of the breeding facility is kept nearly constant by adding the above residual salt for dilution.

When part of salt is pumped from the accelerator-driven reactor, the fission products left in the salt are pumped with it. This salt goes back to the power reactor FUJI as part of the fuel salt. The fission products gradually lose radioactivity within the nuclear fuel cycle while they are circulating between the accelerator-driven reactor AMSB and the power reactor FUJI. Chemical separation processes are intentionally kept at a minimum level, because they only increase the quantity of slightly contaminated low-level radioactive waste.

Incineration of radioactive waste

Let us provide a more detailed explanation of the treatment of the radioactive elements generated from fission, as seen in Table 8.1.

Of the fission products with a half-life longer than 30 years, the A- and B-groups, shown in Table 8.1, remain dissolved in the fuel salt. These fission products are gradually incinerated while they are circulating in the fuel-salt cycle, as explained above. In particular, elements in the A-group absorb thermal neutrons in the salt and become stable, contributing to more effective incineration. The fast neutrons in the AMSB incinerate the radioisotopes in the B-group. The metallic radioisotopes in the C-group, which do not dissolve in the salt, are collected by chemical processing, put in a graphite cask, sunk in the pool of the AMSB, and incinerated by fast neutrons. If the incineration were carried out aggressively, a commensurate amount of neutrons used for incinerations would become unavailable for fuel breeding.

Because the power reactor FUJI and the AMSB are designed for flexible performance, the incineration does not cause trouble for the reactor operation. However, it is undesirable to incinerate when neutrons are very precious—namely, when the curve of Figure 1.2 (D) is rapidly rising. It is advisable to separate and store some radioisotopes until the time of phase-out (around 2075).

At the beginning of this phase-out period, considerable radioactive waste from LWRs will have accumulated. It is possible to incinerate this waste in the power reactor FUJI and the AMSB. In the phase-out period, a surplus of nuclear fuel (such as U-233) will become available, and this surplus must be consumed or incinerated. The neutrons produced from the fission of these fuels can be used to incinerate nuclear wastes, so two birds can be killed with one stone.

It is clear that fluorine molten-salt is the best medium for these operations. If spent solid uranium (or plutonium) fuel is processed with fluorination by using the FREGATE method [ref.], the waste turns into fluorides and is easily treated. This means that a problem of tens of thousands of years is reduced to one of hundreds of years.

Necessary resources and waste

In the THORIMS-NES, small amounts of transuranic elements (plutonium) are produced, and the contamination of waste by these elements is slight. The amount of high-level waste, including nuclear materials, can be greatly reduced, and most of the other radioactive waste is easily incinerated. Thus, the remaining problem is the disposal of materials that are slightly radio-activated from neutron absorption.

Table 8.2 lists the materials required for the synergetic system to produce a combined power generation of a trillion kilowatt-years, as shown in Figure 1.2 (D).
These figures have a broad margin and can be reduced further. For reference, the figures corresponding with MSBR of ORNL are also shown.

Thorium resources are abundant. Although the 1.2 million tons of thorium can be further reduced, this remaining volume corresponds to a cube whose sides each measure 100 meters. Furthermore, these materials are chemically stable compounds.

The required amounts of the fuel salt materials are, at most, 0.6 million tons of lithium, 0.2 million tons of beryllium, and 2 million tons of fluorine. All these materials form stable chemical compounds and are easily convertible to a vitrified solid.

The amount of active carbon is 2.4 million tons. Because the radioactivity of the adsorbed radioactive gases is attenuated in fifty or sixty years, the quantity of wasted active carbon will be reduced to one tenth or one hundredth of that amount by reuse.

Most of the contaminated graphite surface (0.1 millimeter) that is ground off can be reused. At any rate, graphite is stable and easily stored.

In theory, the nickel-based structural material (Hastelloy-N) can be handled after one year of radioactivity cooling. It can be reused as reactor material after vacuum melting. However, nearly all of the Hastelloy-N listed in the table will remain, because the half-life of niobium 94 (produced by addition of 2% niobium to the nickel) is 20,000 years.

The total amount of low-level radioactive waste will be small and the necessary maintenance and chemical processing will be minimal. In addition, contamination by transuranic elements will be extremely low and can be reduced economically by dehydration, incineration, and chemical processing. In Japan, a low-level radioactive waste (3 million drums) burying center is being prepared at Rokkashyo-mura, Aomori prefecture the radioactivity of these wastes becomes negligible after 300 years, no additional facility will be required even if many new nuclear plants are built.

If power generation of a trillion kilowatt-years is done with coal, about 1.7 trillion tons of ash will be generated (two or three cubes whose sides each measure 10,000 meters). A transition from fossil fuel to nuclear energy means a reduction of the quantity of fuel transportation from the level of a trillion tons per year to ten million tons a year—a reduction of five digits. Although this offers a large economic benefit, if molten-salt fuel is substituted for solid nuclear fuel, nuclear fuel transportation could surely be reduced by at least another digit.

This new type of nuclear energy industry would help to prevent nuclear weapon technology proliferation between countries and the abuse of nuclear technology by terrorists. This problem will be discussed in Chapter 10.