Next-generation Nuclear Reactor Systems for Future Energy

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OVERVIEW: It is essential to develop systems for nuclear recycling to solve global environmental problems and create a sustainable energy supply for the future. Although the ultimate nuclear energy system for Japan would be one that uses Pu (plutonium) recycling based on FBRs (fast breeder reactors), the development of such FBR systems requires a certain period of time. A shift from the current LWR (light water reactor) systems needs to be done step by step through a transition period. We propose an interim nuclear energy system for this transition period, which consists of an RMWR (reduced moderation water reactor), i.e. a Pu recycling reactor based on LWR technology and an advanced reprocessing system, the FLUOREX (hybrid process of fluoride volatility and solvent extraction), which is a hybrid reprocessing method utilizing the fluoride volatility for U (uranium) and solvent extraction for Pu. An RMWR and FLUOREX fuel recycling system is a promising option for a sustainable energy supply in this century.

INTRODUCTION

IT is essential to first cope with the problem with energy to make it sustainable with limited global resources, while overcoming the trilemma of the population explosion, massive consumption of resources and energy, and global environmental pollution.

Therefore, we believe the recycling of U (uranium) resources, that is, the utilization of Pu (plutonium), is essential to Japan, for us to deal simultaneously with environmental issues and energy security.

Here, we describe our plans for nuclear reactors and a fuel recycling system for the next generation.

NUCLEAR ENERGY IN THE FUTURE

Overall System Outline

The ultimate nuclear system that we should aim at for in Japan is Pu recycling system based on FBRs (fast breeder reactors). This system is required for safety, economy, and reliability as well as solving

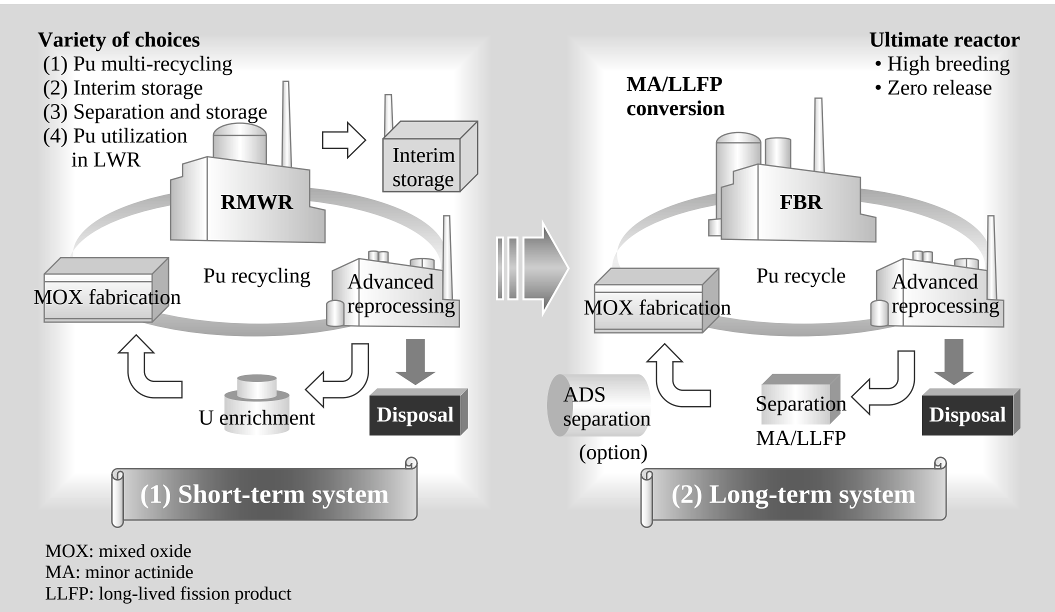


Fig. 1—Nuclear Systems in Future. Future nuclear systems will shift to the long-term ones based on FBR, through flexible short-term nuclear systems based on multiple Pu recycling by RMWR and advanced reprocessing.

energy and global environmental issues. The challenges, time and cost involved in development are huge in such cutting-edge systems.

Also, the development platform must be flexible so that it can be modified based on changing social circumstances and customers' needs.

Therefore, we believe such an ideal nuclear system cannot be developed with a single plan but the step-by-step (i.e. plan-do-check) by gradually enhancing system performance.

Since there are unforeseen circumstances in developing fuel recycling and establishing the technologies for this, and the reactor must be developed in accordance with these technologies, the best plan would be a two-stage strategy for a flexible short-term nuclear system, and then a long-term system, which would achieve the final goal.

The outlines are summarized in Fig. 1

Nuclear System in Short Term

It is important for a short-term system to be flexible in fuel cycling and economical as well as safe and reliable based on proven technologies with the present LWRs (light water reactors). Examples of expected alternatives are as follows and illustrated in Fig. 2.

(1) Alternative 1

Pu recycling: this is the target for nuclear power systems and a suitable combination of reactor technology and fuel cycling technology can ensure multiple recycling.

(2) Alternative 2

Pu utilization in LWRs: the previous use of Pu in LWRs would play an important role in establishing recycling systems and make it possible to burn surplus Pu.

(3) Alternative 3

Interim storage of spent fuel: this needs to be a well-thought-out plan to increase flexibility in fuel recycling.

(4) Alternative 4

Radioactive isotope separation and storage: U, which represents 95% of spent fuel, is separated from remaining radioactive isotopes and is stored independently for more efficient storage management.

In fact, there is no clear choice from the alternatives, but a combination could first be used to develop a Pu recycling option. As technological developments for any of the alternatives involve a certain time and cost, it is important to produce one reactor and make fuel recycling system more flexible to meet various demands by society.

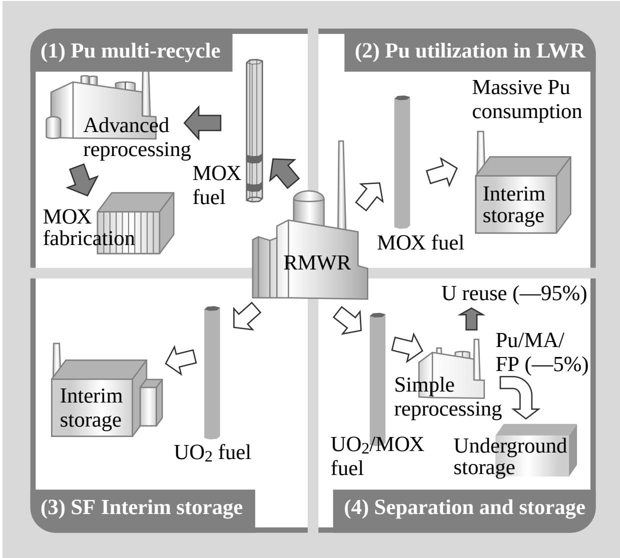


Fig. 2—Alternatives to Fuel Cycling with RMWRs.
RMWR is capable of coping with a variety of choices in a nuclear fuel cycle.

To achieve these, we propose an RMWR (reduced moderation water reactor) and an advanced reprocessing system based on fluoride volatility technology "FLUOREX (hybrid process of fluoride volatility and solvent extraction)," as a short-term solution and a fuel recycling system that is very flexible and has the potential meeting various energy needs. The details are described in the next and other sections.

Long-term Nuclear System

As U235, as well as fossil resources, is expected to run out in the long term, we need to depend more on energy extracted from Pu and to become involved in recycling this. Nuclear energy not only provides energy security but also alleviates concerns on radioactive waste.

Fast breeder reactor with a sodium coolant should be the main alternative to such requirements. However, it is still necessary to have a wide selection of choices including water-cooled reactors and gas-cooled reactors.

RMWR DEVELOPMENT

Flexibility in Core and Fuel Design

RMWR is basically compatible with the current BWR (boiling water reactor) plant system and only fuel assemblies and control rods are replaced in the new design. This provides a variety of core performance in:

(1) Pu burning and conversion (Pu recycle),

(2) Pu burning only, and

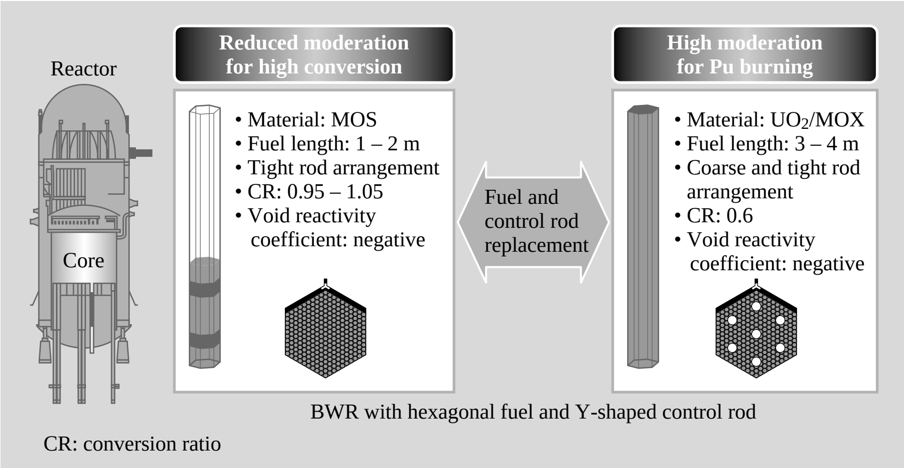
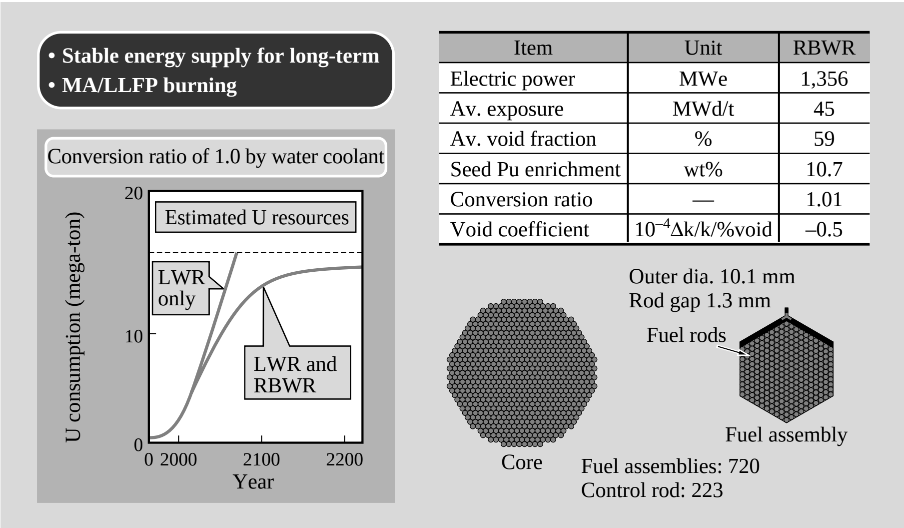


Fig. 3—Flexibility of RMWRs in Core and Fuel Choice.
By alternating fuel and the control rod, the reactor system can be made compatible with a reduced moderation core and a high moderation core.



Item	Unit	RBWR
Electric power	MWe	1,356
Av. exposure	MWd/t	45
Av. void fraction	%	59
Seed Pu enrichment	wt%	10.7
Conversion ratio	—	1.01
Void coefficient	$10^{-4}\Delta k/k/\%$void	–0.5

Fig. 4—Typical RMWR Concept (RBWR).
Fuel rods are arranged tightly with a hexagonal fuel lattice configuration, and this is ideal for reduced moderation.

(3) High U burning.

Fig. 3 shows the typical idea behind an RMWR offering flexibility in fuel replacement.

Fast neutrons in Pu recycling are requested for greater conversion, and the process of neutron moderation is removed to produce core “reduced moderation.” The cross section of fuel assembly is either square or hexagonal and the effective fuel length is between 1 and 2 m. The fuel rod is arranged hexagonally and the rod gap is between 1 and 1.5 mm.

In high U burning and Pu burning, the core becomes “highly moderated” and uses thermal neutrons for the fission reaction. The effective fuel length is increased to about 3.7 m and the rod gap widens to between 3 and 4 mm. Moreover, some water rods are used to increase neutron moderation to the level of the current BWRs.

Even when Pu is unavailable, such reactors can produce power by using U fuel in a configuration with a high moderation core. This reactor system’s compatibility is one of the benefits of the BWR-based RMWR concept.

The fuel rod in the assembly is arranged hexagonally to remove water effectively as a moderator and to maintain sufficient cooling capabilities. However, both a hexagonal fuel assembly and a square fuel assembly are possible for RMWRs.

A typical example of an RMWR with a hexagonal fuel assembly is the RBWR (resource-renewable BWR)[1] (see Fig. 4). The control rod for the RBWR is Y shaped to be compatible with the hexagonal fuel assembly. This hexagonal configuration in an RBWR is preferable with tight rod arrangement to achieve a higher conversion ratio. A conversion ratio of more than 1.0 would be ideal to sustain a nuclear energy supply.

The other example of an RMWR is a high conversion BWR[2] based on the ABWR-II system[3]. The concept is outlined in Fig. 5. This reactor has square fuel assemblies and fewer modifications to core

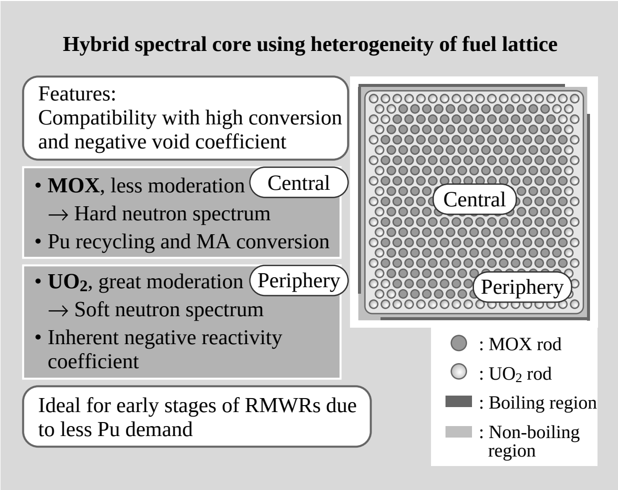


Fig. 5—Typical RMWR concept (ABWR-II Type).
Hybrid fuel made of Pu and U reduces the initial amount of Pu and is ideal for the early stages of RMWR construction when Pu supply is limited.

components from the current BWR, although the conversion ratio is slightly less than 1.0. It is easy to install this type of RMWR in the stages of introduction where Pu supplied from the LWR is limited, because it requires less Pu due to partial use of UO_2 rods in fuel assembly. Moreover, it is possible to be comparatively safe due to the negative void reactivity coefficient, which is an advantage of BWRs.

Impact on Fuel Cycle

Taking RMWRs based on the ABWR-II system in Fig. 5 as an example, we expect they will be introduced in 2030 and LWRs will be replaced by RMWRs as they reach the end of their usefulness. This means that it will take about 100 years to replace all LWRs with RMWRs; however, the total consumption of U is only 6% of total natural U reserves in the world. After that, although consumption will continue to increase gradually. This is expected to reach 1.5 million t in 2200, which is 10% of the total natural U reserves in the world.

Therefore, it is possible to sustain nuclear energy without running out U resources, if we introduce RMWRs in the 21st century as a short-term option and FBRs are introduced by 2100.

As previously discussed, RMWRs are based on the technological achievements with the current LWRs, and this will lead to highly sustainable and cost competitive energy in the 21st century.

DEVELOPMENT OF ADVANCED REPROCESSING TECHNOLOGY

In the short-term, when LWRs are replaced by RMWRs, it is best for recycled U to be used in LWRs after re-enrichment or to store it temporarily until demand increases. Pu should be reused as MOX (mixed oxide) fuels in RMWRs or FBRs in future. In U re-enrichment, temporary storage and MOX fabrication technologies, both the U and MOX products should have low activation with high decontamination.

The solvent extraction or Purex process is used worldwide to extract very pure U and MOX fuels as well as in the Rokkasho Reprocessing Plant of JNFL (JAPAN NUCLEAR FUEL LIMITED) under-construction. However, the costs are high.

The fluoride volatility process was not developed until the 1980s and it is superior in separating of U through a simple process. We combined these two processes and a hybrid process, FLUOREX process[4)–

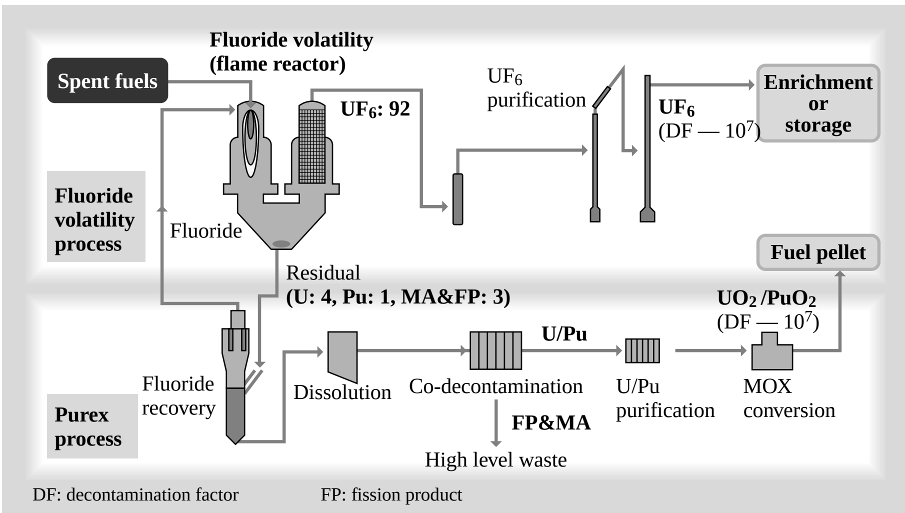


Fig. 6—Diagram of FLUOREX Process.
FLUOREX is a hybrid process involving fluoride volatility and solvent extraction and is ideal for the cost-effective reprocessing of spent fuels.

[6]), has been developed, where the fluoride volatility process is used to purify U and the Purex process is used to purify U and Pu mixtures.

Extremely pure U and MOX fuels are recovered in the FLUOREX process and this is compatible with the current sintered-pellet fuel-fabrication process. It is also cost effective.

The FLUOREX process is described in Fig. 6. More than 90% of the U, which is most of the spent fuel, is extracted efficiently with the compact facilities for the fluoride volatility process and is purified with a decontamination factor of 10^7 using NaF absorbers. Less than 10% of the remainder containing U, Pu and FP is dissolved in the solvent, and U and Pu mixture is extracted by the Purex process. The purity of MOX fuels obtained by this process is not different from that obtained by the current Purex process.

CONCLUSIONS

To ensure sustainable energy overcoming environmental issues with excess release of CO_2 (carbon dioxide), it is essential to use nuclear energy as well as other natural energy sources.

Although Pu recycling based on FBRs is a final goal to achieving this, it cannot be achieved in a single stage. We proposed an RMWR system for the short term and FBR for the long term. The advanced recycling system with the FLUOREX process is compatible with a variety of fuel cycles that are expected to be introduced in the future.

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