Nuclear Fuel Cycle Technologies for Future Low-carbon Society

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OVERVIEW: Establishing a nuclear fuel cycle that can recover usable fuel material from spent nuclear fuel so that it can be reused in a nuclear reactor is essential to meet objectives such as securing the long-term availability of an energy source that emits almost no CO_2 and improving Japan's very low level of energy self-sufficiency. The Monju prototype fast breeder reactor was restarted on May 6, 2010 and this will be accompanied by the planned completion in the future of the Rokkasho Reprocessing Plant, an interim storage facility for spent fuel, and other associated facilities. Discussions regarding the construction of a second reprocessing plant are expected to start during the 2010 financial year. It is anticipated that a demonstration fast-breeder reactor will be completed around 2025 and the introduction of commercial fast-breeder reactors will take place around 2050 provided economic and other requirements have been satisfied. In addition to its involvement in reprocessing, Monju, interim storage, and other such projects, Hitachi is also working on the development of future technologies such as fast breeder reactors and advanced reprocessing with the aim of creating a low-carbon society in the future.

INTRODUCTION

RISING international concerns about climate change have led to a growing number of countries showing an interest in nuclear power which can generate electricity without emitting any CO_2 (carbon dioxide), the gas implicated in global warming. Although other energy sources such as photovoltaic and wind power also emit no CO_2 in the generation process, they are characterized by requiring a large area of land and being dependent on weather conditions.

The level of energy self-sufficiency in Japan is approximately 18% if nuclear energy is treated as

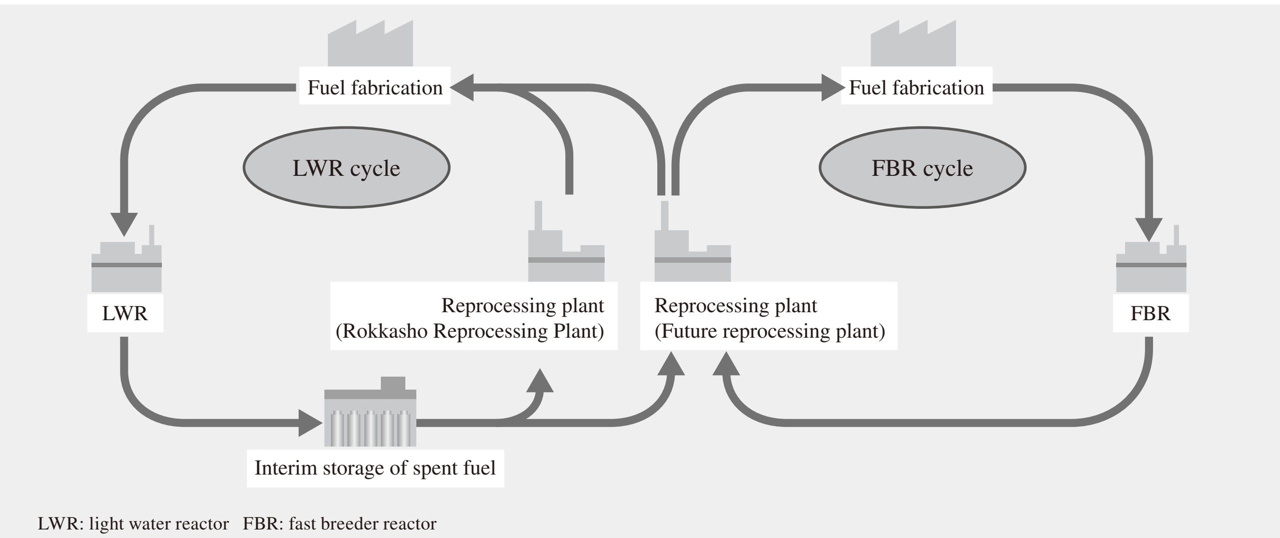

Fig. 1—Overview of Nuclear Fuel Cycle.
The plutonium recovered by reprocessing spent fuel from LWRs is currently recycled in LWRs and in the future will be recycled in FBRs. Future use of the FBR cycle will ensure long-term security of supply for nuclear energy.

a domestic source and only 4% otherwise, making it very low compared to many other countries. In particular, because these other energy sources include oil for which Japan relies on the Middle East for approximately 90% of its imports, an improvement in energy security is desirable.

Japan also relies on imports for all of the uranium fuel used for nuclear power. World uranium resources are finite and therefore it is essential to establish a nuclear fuel cycle that can extend by a factor of 10 or more the number of years of uranium reserves remaining (currently estimated as being enough for about 100 years). France, Russia, India, China, and South Korea are also aiming to establish a fast breeder reactor cycle.

This article describes current trends in the nuclear fuel cycle field in Japan and overseas together with Hitachi's involvement in the fuel cycle and the state of its technology development (see Fig. 1).

FUEL CYCLE TRENDS IN JAPAN AND OVERSEAS

Hitachi's activities in the fuel cycle business include the research and development and commercialization of interim storage of spent fuel, reprocessing of spent fuel, FBRs (fast breeder reactors), and radioactive waste management.

Currently, spent fuel from the LWRs (light water reactors) used to generate electricity in Japan is stored in a pool at the power station and some is transferred to the storage pool at Japan Nuclear Fuel Limited's Rokkasho Reprocessing Plant at Rokkasho Village in the Kamikita District of Aomori Prefecture. An off-site interim storage facility is also to be constructed in Mutsu City in Aomori Prefecture.

The current status of LWR spent fuel reprocessing is that a total of about 1,140 t of fuel was reprocessed at the Tokai Reprocessing Plant operated by the Japan Atomic Energy Agency in the period between September 1997 and March 2010. Meanwhile, the Rokkasho Reprocessing Plant with a maximum annual capacity of 800 tU is currently under construction and is due for completion in the near future. The Rokkasho Reprocessing Plant has a life of 40 years and investigations regarding the construction of a second reprocessing plant to succeed Rokkasho are scheduled to commence during the 2010 financial year.

The FBRs operated by the Japan Atomic Energy Agency are the Joyo test reactor and the Monju prototype reactor, with the Monju facility restarted on May 6, 2010. Research and development of commercial-scale FBRs is also underway and a demonstration reactor targeted to commence operation in 2025 is being designed with commercial reactors in mind.

Provided certain prerequisite conditions can be satisfied, it is expected that commercial FBRs will start to be introduced from around 2050. This coincides with the second reprocessing plant commencing operation and means that the plutonium recycled from this plant can be used to introduce FBRs. To this end, research and development aimed at the transition from LWRs to FBRs is underway with the Ministry of Economy, Trade and Industry and the Ministry of Education, Culture, Sports, Science and Technology taking central roles.

There are a number of different techniques for radioactive waste processing that have either already been put into practical use or are under development. Commercial disposal of low-level waste is already in progress at the low-level radioactive waste disposal center in Rokkasho Village and the search is now on for potential sites for the disposal of high-level waste.

France, Russia, India, China, and South Korea are also, like Japan, aiming to introduce fast breeder reactors around 2020, and India and China in particular have grand plans to construct several dozen fast breeder reactors by 2050. South Korea, which is prohibited from reprocessing under the Korea-US Atomic Energy Agreement, is also working on researching and developing its own fast breeder reactor fuel cycle. The USA has also restarted fuel cycle research and development with the aim of reducing the storage requirements for the large quantities of spent fuel from LWRs.

INTERIM STORAGE OF SPENT FUEL

The Recyclable-Fuel Storage Center (see upper image in Fig. 2) of the Recyclable-Fuel Storage Company located in Mutsu City in Aomori Prefecture and scheduled to start operation in 2012 applied for an establishment permit in March 2007. Hitachi plans to supply metal casks used for both transportation and storage which it developed itself and which are produced under an integrated quality management and assurance program. Hitachi is also testing the practicality of transport equipment to be used at the center[1]. The functions of the metal casks are to provide sufficient strength, seal integrity, prevention of criticality, shielding, and heat dissipation and their safety and reliability have been confirmed through testing that included dropping a one-third scale model from a height of 9 m. Other ways in which Hitachi is supporting Japan's first interim storage project include support for safety audits at the center. Hitachi is also manufacturing the metal storage casks (see lower image in Fig. 2).

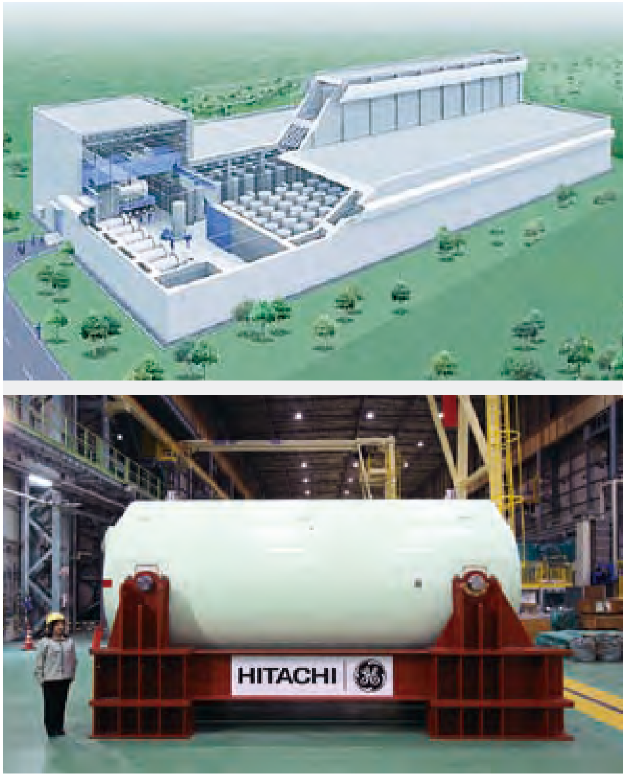

Fig. 2—Recyclable-Fuel Storage Center and Actual-size Cask.
The Recyclable-Fuel Storage Center to be constructed in Mutsu City in Aomori Prefecture (top) (photograph courtesy of Recyclable-Fuel Storage Company) and a metal storage cask produced by Hitachi (bottom).

REPROCESSING

Rokkasho Reprocessing Plant

One of Hitachi's roles at the Rokkasho Reprocessing Plant is as the construction coordination company responsible for managing construction of the separation building and low-level liquid waste treatment building in the main facility, and the other role is as lead contractor for the design, manufacture, installation, and commissioning of various equipment including a shearing and dissolver off-gas treatment facility, high-level liquid waste processing facility, acid recovery facility, and low-level liquid waste processing facility (see Fig. 3).

To ensure that the equipment can perform its required functions and operate safely and reliably, it has been tested in a series of trials using different materials whereby each trial gets progressively closer to the actual operating conditions. These trials tested the functions, performance, and other characteristics of each item of equipment and consisted of the "water operation tests" run from April 2001 which used water, steam, and air, the "chemical tests" run from November 2002 which used chemicals that did not include any radioactive materials, the "uranium tests" run from December 2004 which used uranium, and the "active tests" run from March 2006 which used spent nuclear fuel.

Fig. 3—Rokkasho Reprocessing Plant.
View of the Rokkasho Reprocessing Plant site (photograph courtesy of Japan Nuclear Fuel Limited). The plant has a maximum annual reprocessing capacity of 800 tU and utilizes technology from France, the UK, Germany, and Japan.

The active tests for the main facilities are largely complete and have confirmed that the equipment for which Hitachi is responsible can deliver the required performance.

Development of the Next-generation Reprocessing Technology

Hitachi has been developing the FLUOREX (fluoride volatility and solvent extraction) method, a reprocessing technology which combines the fluoride volatility process and solvent extraction process[2], and which is intended for use at reprocessing facilities during the transition period from LWRs to FBRs.

Fig. 4 shows the development test facility for the FLUOREX process. The FLUOREX reprocessing system uses a fluorination process to separate out the majority of the uranium in spent fuel from LWRs (which is approximately 95% uranium) so that the subsequent solvent extraction process can be made smaller and the recovered uranium reused. In the fluorination process, a purification process using adsorbing materials separates the volatile UF_6 (uranium hexafluoride) from the impurity elements

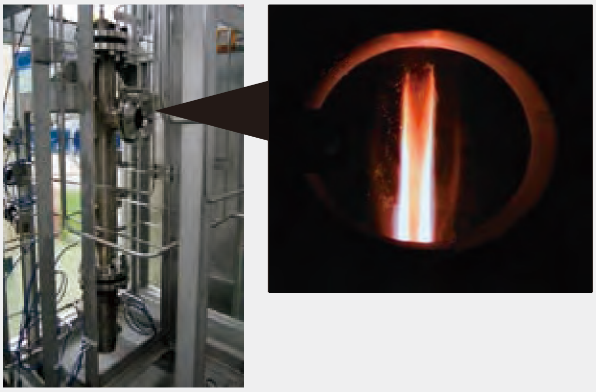

Fig. 4—Development Test Facility for FLUOREX Method.
The FLUOREX (fluoride volatility and solvent extraction) method uses a fluoride volatility process to separate and recover most of the uranium contained in spent nuclear fuel from LWRs as high-purity UF_6. The solvent extraction process is then used to recover a high-purity uranium and plutonium mixture from the fluorination residue. The photographs show the test facility for the fluoride volatility process and fluorination in action.

as a gas which can be recovered as high-purity UF_6. Because most elements other than uranium are non-volatile, they remain in the fluorination residue in solid form. This residue is passed through an oxide conversion (fluorine recovery) process, dissolved, and then the solvent extraction process is used to separate and recover the uranium and plutonium mixture from the other elements with a high level of purity.

The research and development of the FLUOREX method was funded by the Ministry of Economy, Trade and Industry and the Ministry of Education, Culture, Sports, Science and Technology, and undertaken in cooperation with institutions in Japan and overseas. Its practicality was confirmed through fluorination testing which included use of a flame reactor and testing that, although conducted on a small scale, used actual spent fuel. Further development aimed at commercializing the process is ongoing.

Development of Flexible Fuel Cycle Systems

Hitachi is also involved in the research and development of the FFCI (flexible fuel cycle initiative) fuel cycle system concept for the transition period[(3)].

In the transition period from LWRs to FBRs, reprocessing facilities must process spent fuel from both LWRs and FBRs and supply fuel to both types of reactor. In particular, because the initial load of plutonium required when commissioning FBRs is recovered from LWR spent fuel, flexibility in the fuel cycle, including the reactor and fuel fabrication steps, is very important. FFCI first extracts the bulk of the uranium from LWR spent fuel and then, if the introduction of FBRs is on schedule, the remaining material is inserted directly into the FBR cycle. Alternatively, if the FBRs are delayed, the material is instead placed in temporary storage for use when the FBRs commence operation.

Under the FFCI, LWR reprocessing extracts the uranium only whereas recovery of plutonium and uranium and FBR fuel fabrication are performed as part of FBR reprocessing. This enables shrinking the

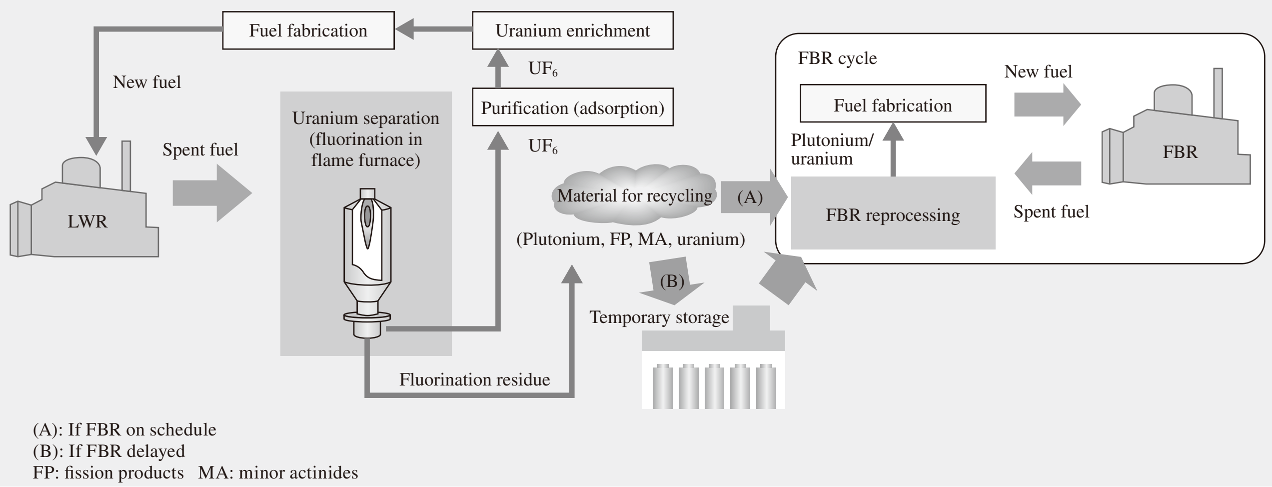

Fig. 5—Process Flow of FFCI Using Fluoride Volatility Method.
Most of the uranium contained in spent nuclear fuel from LWRs is separated and recovered as a high-purity fluoride (UF_6). Also, depending on the progress of introducing FBRs, the fluorination residue (material for recycling) can either be used immediately in FBR reprocessing to recover a uranium and plutonium mixture or placed in temporary storage. The temporary storage option allows the FFCI (flexible fuel cycle initiative) program to adapt flexibly to any changes in the pace of FBR introduction.

size of the LWR reprocessing facilities and effectively reducing the quantity of LWR spent fuel.

The development of FFCI is also being undertaken as government-funded research. The potential uranium separation techniques available for use in FFCI include the solvent extraction, crystallization, precipitation, and fluoride volatility methods. Fig. 5 shows the process flow of an FFCI system that incorporates the fluoride volatility method.

FBR

Monju Prototype FBR

The Japan Atomic Energy Agency's Monju prototype FBR has been shutdown since an accident in December 1995 involving a sodium leak in the secondary cooling system during test operation at partial output. Since this accident, the plant has been through a comprehensive safety inspection, safety investigations covering a range of areas including countermeasures to sodium leaks, permitting (approval for changes to the design and construction), and the Special Committee to Investigate and Survey the Safety of Monju held by Fukui Prefecture. Having obtained the agreement of the local population, work on upgrading the facility started in earnest in September 2005 and was completed in May 2007. Tests to confirm the appropriateness of this work were completed in August 2007 and tests to confirm that the equipment has been maintained in the same sound condition it had prior to the sodium leak accident were completed in August 2009 with the operation restart in May 2010. Fig. 6 shows a view of the Monju plant.

Fig. 6—Monju Prototype FBR.
A view of the Monju plant (photograph courtesy of the Japan Atomic Energy Agency). With an output of 280 MWe, Monju is the first FBR in Japan to be capable of generating electricity and has a reactor that is intermediate in size compared to a commercial reactor.

In summary, the upgrade work consisted of: (1) replacement and removal of temperature sensors used in the secondary cooling system, (2) improvements relating to the sodium leak, and (3) improvements to the blowdown performance of the evaporator (one of the steam generation systems). Hitachi's role was part of the sodium leak improvements (2) and included conversion of primary drain valves to electrical operation, the installation of insulation in the secondary chamber walls and ceiling, and the installation of a comprehensive leak monitoring system. During the subsequent confirmation tests, work done by Hitachi included preparing test designs and evaluating the results, especially for the primary cooling system which Hitachi had supplied.

Development of Technology for Demonstration FBR and Commercial FBR

Hitachi's involvement so far has covered design and research for a demonstration reactor, investigation of commercial reactor concepts, and the development of specific technologies for the reactor core and safety, structure and ability to withstand earthquakes, heat flow, materials, equipment, sensors and control, and so on. Based on this experience together with Hitachi's experience in the development, manufacture, installation, and maintenance of actual systems, mainly relating to the primary cooling system at Monju, Hitachi has an active role in technical developments involving fields such as equipment, heat flow, and materials and structures, and also in the study of system concepts aimed at improvements such as making the equipment smaller and more integrated. The objective is to start operation of a demonstration reactor around 2025 and a commercial reactor around 2050.

RADIOACTIVE WASTE MANAGEMENT

Radioactive Waste Processing

Hitachi has developed technologies for processing the radioactive waste from nuclear power stations, reprocessing plants, and similar facilities that include solidification to allow the waste to be safely buried and waste inspection technologies for ensuring its safety. These technologies are currently in use.

Hitachi has developed a solidification technology called "in-drum solidification" that increases the amount of radioactive waste in liquid or powder form that can be contained, and produces solid material with strength, porosity and other characteristics that comply with the standards for land-based disposal. This technology is expected to enter practical use in the near future. Hitachi has also developed a continuous mixing facility for solid radioactive waste which uses simpler equipment than the mortar-mixing batch process used in the past.

Hitachi has also developed and commercialized a waste inspection technology for radioactive waste that has been stabilized in a drum which uses a technique called the "spectral correction method" to measure the level of radioactivity and can non-destructively determine the type and volume of radioactive waste from outside the drum. The equipment has already been installed at four plants.

To deal with the aging of radioactive waste processing equipment that has been in use for several decades, work is also in progress on replacing equipment that has deteriorated with age, substituting out-of-production parts, and other maintenance.

Radioactive Waste Disposal

As a step toward the development of technology for the disposal of TRU (trans-uranium) waste, Hitachi has been working with Taiheiyo Consultant Co., Ltd. since 1999 on research commissioned by the Radioactive Waste Management Funding and Research Center as part of the Investigation into Geological Disposal Technologies (Technologies for Disposal of TRU Waste) program under a grant from the Ministry of Economy, Trade and Industry. This work includes the development of ultra-sonic inspection techniques that can be used for the detection of cracks, voids, and other defects and crack length measurement as part of quality management in the production of HSULPC (high strength and ultra low permeability concrete) containers for disposing of TRU waste.

It was confirmed that the fixed-angle/tip-echo and the TOFD (time-of-flight diffraction) methods could detect the cracks and measure their length in small HSULPC test pieces.

In the field of geological disposal of high-level radioactive waste, Hitachi also received assistance between 2004 and 2007 from the Ministry of Economy, Trade and Industry's Innovative and Viable Nuclear Energy Technology Development Project to work with relevant institutions and universities on the development of technology for geological microchemical probes able to perform down-hole measurement of bedrock water quality and material migration characteristics in boreholes. Tests at a deep borehole belonging to the Japan Atomic Energy Agency were carried out in January 2008 during which the world's first successful simultaneous in-situ measurements of bedrock diffusion coefficient and distribution coefficient were made at a depth of approximately 112 m[4].

CONCLUSIONS

This article has described the current trends in the nuclear fuel cycle field in Japan and overseas together with Hitachi's involvement in the fuel cycle and the state of its technology development.

A nuclear renaissance is underway around the world as demonstrated by the renewal of interest in nuclear power and the nuclear fuel cycle in the USA after a 30-year hiatus and the moves by India and China to use nuclear power generation to satisfy the growing demand for energy. As a base-load energy source that is not affected by weather conditions and can significantly reduce emissions of CO_2, the gas implicated in global warming, the expectations for nuclear power are great. In Japan with its very low level of energy self-sufficiency compared to many other countries, nuclear power generation and the nuclear fuel cycle are extremely important because of their ability to lessen the country's dependence on overseas resources.

In the future, Hitachi will continue to contribute to solving environmental and energy problems through technology development and the manufacture of highly reliable equipment with safety and security as its top priorities.

REFERENCES

(1) M. Shimizu et al., "Hitachi's Activity for Development of Interim Spent Fuel Storage (1), (2)," Proceedings of The 16th Pacific Basin Nuclear Conference, Aomori, Japan (Oct. 2008).

(2) Y. Kani et al., "New Reprocessing System for Spent Nuclear Reactor Fuel Using Fluoride Volatility Method," Journal of Fluorine Chemistry, 130, pp. 74-82 (2009).

(3) T. Fukasawa et al., "Transition Period Fuel Cycle from LWR to FBR," Proceedings of Global 2009, Paper 9129, pp. 2626-2632, Paris, France (Sep. 2009).

(4) T. Oe et al., "Development of Micro-Chemical Probe for Geological Environment Diagnosis," 2008 Fall Meeting of the Atomic Energy Society of Japan, M14-M18 (Sep. 2008) in Japanese.

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