Nuclear Fuel-Cycle Technologies for a Long-Term Stable Supply of Energy

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OVERVIEW: The nuclear fuel cycle consists of uranium enrichment, fuel fabrication, nuclear power generation, the storage and reprocessing of spent fuel, management of radioactive waste and the decommissioning of facilities. A variety of technologies have been developed for the Rokkasho reprocessing plant that will start operation in 2005 and for advanced reprocessing in the future. The latter technologies include a fluoride volatility process. Hitachi has also been developing technologies in other nuclear fields to establish a safe and rational fuel-cycle system in Japan. All of the technologies developed are available for utilization elsewhere in the world.

INTRODUCTION

FIG. 1 shows a nuclear fuel-cycle system that includes both light-water reactors (LWRs) and advanced reactors such as fast-breeder reactors (FBRs). A policy of closing the nuclear fuel cycle is indispensable for Japan, with its lack of energy resources, to become more self-reliant in the supply of energy. Uranium, as an imported energy resource, currently supplies more than 30% of electricity in Japan, but its recognized deposits worldwide will only last for about 70 years. The recycling of recovered uranium and plutonium greatly enhances the efficiency of utilization of nuclear fuel. Plutonium, in particular, can be considered a national resource that is independent of supply by import. Japan thus needs to close the nuclear fuel cycle by successfully starting up a commercial reprocessing plant in the beginning of 21st century. This will assist in ensuring a stable and reliable supply of energy and in safely managing the radioactive waste generated by other facilities in the cycle. Sustainable development and improvement of LWR fuel-cycle is especially important because of the delay of FBR industrialization. Hitachi is contributing to the establishment of this closed nuclear fuel cycle by developing a variety of technologies, some of which are introduced in this article.

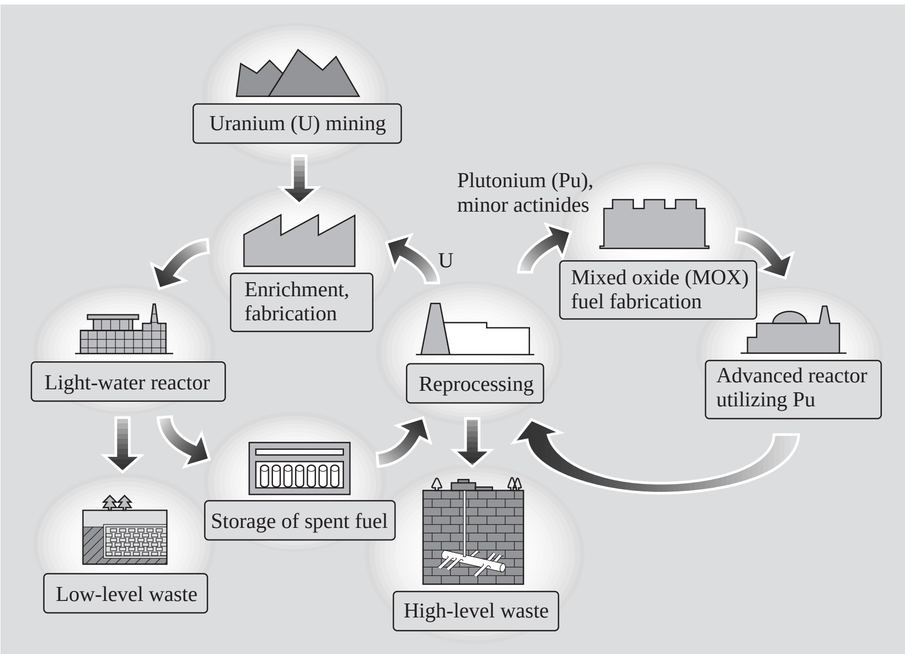

Fig. 1— A Closed Nuclear Fuel-Cycle System Is Japan's Policy for Securing an Energy Supply That Is Stable over the Long-Term.

DEVELOPMENT OF REPROCESSING TECHNOLOGY

State of Construction at Rokkasho Reprocessing Plant

Japan Nuclear Fuel Limited (JNFL) is constructing a commercial reprocessing plant in Rokkasho village, Aomori prefecture. When it is completed, in July 2005, the plant will be able to handle 800 t of waste every year. Over 60% of the main facilities had already been constructed, as scheduled, by April 2001 (Fig. 2).

Hitachi manages facilities for the separation of uranium, plutonium and fission products and for the treatment of low-level liquid waste, and is proceeding with the design, manufacture, and installation of equipments for the treatment of dissolution off-gas, high-level liquid waste and low-level liquid waste and for the recovery of nitric acid. An iodine-removal tower made of zirconium, one of the main items of equipment for off-gas treatment, was installed in autumn of 1998. This tower is the result of the development of an iodine adsorbent, zirconium (Zr)/stainless steel (SUS) explosion-junction method, and of techniques for the manufacture and welding of zirconium equipment, developed with a bench-scale model. An annular vessel for interim liquid storage was installed in summer of 1999 and apparatus for the concentration of high-level liquid waste was installed in autumn of 2000 (Fig. 3). This apparatus is one of the most important items in the reprocessing plant and its performance has been confirmed by nuclide-removal tests, and tests of the corrosion-resistant SUS with actual corrosive solutions.

JNFL concluded safety agreements on the receipt of spent fuel at the reprocessing site with Aomori prefecture and Rokkasho village in October of 2000, and with six neighboring communities in November of 2000. The first loads of spent fuel were transferred from Tokyo Electric Power Company's Fukushima-Daini Nuclear Power Station and from other sites to the spent fuel receipt and storage facility in December of 2000. Hitachi was in charge of constructing this facility.

Fig. 2— Construction of Rokkasho Reprocessing Plant, a Commercial Facility for Ensuring a Stable Supply of Electricity, Is Now at Its Peak Level of Activity.

Fig. 3— Installation of Apparatus for the Concentration of High-Level Liquid Waste; Corrosion-Resistance Techniques Were Gathered on a Worldwide Scale for Application to This Waste-Reduction Vessel.

Advanced Reprocessing Technology

The FBR is able to greatly increase the efficiency of utilization of uranium, but its commercialization will take longer than had been expected. We must thus consider, for use in the near future, an economical and transparent LWR fuel-cycle system which allows the recycling of MOX (mixed oxide) fuel. Such a system can be largely based on existing technologies and thus be quickly established. The reprocessing technology should also be applicable to the FBR fuel cycle. Considering these factors, Hitachi commenced

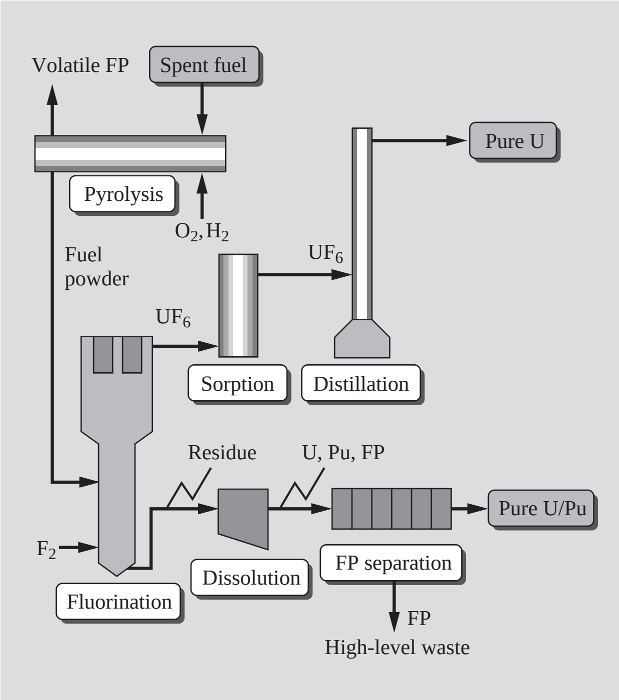

Fig. 4— Typical Flow of Fluorex Reprocessing; Pure Uranium and MOX Are Recovered by a Simple Process.

development of an advanced reprocessing technology named Fluorex, a hybrid process in which fluoride volatility and solvent extraction are applied. The Fluorex process has several variants and a typical flow is shown in Fig. 4.

Spent fuel from LWRs is about 94% uranium, 1% plutonium, and 5% fission products (FP). The key point in the MOX recycling system for LWRs is the efficient separation of these elements into three parts: MOX for fuel fabrication, the bulk of the uranium for re-enrichment, and FP as waste. A number of research projects worldwide, from the 1950s to the 1980s, showed the great possibilities of the fluoride volatility process for the easy separation of spent fuel components into these three parts and the difficulty of getting pure MOX after separation for conventional fuel fabrication facilities. A fluoride volatility process has been applied to remove most of uranium from spent nuclear fuels before purification of the mixture of plutonium and residual uranium by solvent extraction from the FP. It is then easy to purify the removed uranium by conventional adsorption and distillation methods. Several countries had stopped development of fluoride volatility reprocessing methods by the late 1970's due to the difficulty of isolating pure plutonium with a high recovery ratio. This difficulty can be overcome by improving the process to recover dirty plutonium or to adopt Purex method for plutonium purification. The latter approach was selected for our method of Fluorex reprocessing, to avoid the difficulties experienced in the past (Fig. 4).

Spent fuel from thermal reactors will be sheared and their cladding material will be removed by a pyrolysis method, such as the Airox process. Fluorination and purification of most of the uranium can be easily achieved by applying the fluoride volatility method in a compact facility. About 10% of the residues, including the plutonium, can be treated by the well-established Purex method. This means that it is possible for the facility to be about 1/10 that of a conventional Purex facility with the same processing capacity. Pure uranium hexafluoride does not require a conversion facility and is suitable for direct transfer to the re-enrichment stage (LWR recycle again), and for storage over a certain period, in simple storage facilities, for use in the FBRs of the future. A pure plutonium/uranium product can be obtained by solvent extraction without separating the plutonium and uranium, and this is suitable for the fabrication of conventional MOX fuel and for interim storage. Another option for treating fluorination residues (plutonium/uranium + FP) is to store them in a compact facility with an adequate cooling system until the FBR era becomes a reality. Such a storage facility will have to store plutonium/uranium + FP that has less than 1/10 of the volume of the spent fuel.

Fluorex reprocessing is possibly economical and proliferation resistant, satisfies the needs of the LWR fuel cycle for the near future, and is also applicable to

Fig. 5— This Fluorex Experimental Apparatus Is Used to Confirm the Method's Compatibility, Safety and Waste Generation.

the FBR fuel cycle. The experimental apparatus shown in Fig. 5 has been constructed to confirm the practical capabilities of Fluorex reprocessing.

DEVELOPMENT OF OTHER TECHNOLOGIES FOR THE CYCLE

Uranium Enrichment

The cascade equipment of the centrifugal enrichment plant now operated by JNFL in Rokkasho was prepared by Hitachi. A facility for the treatment of spent centrifuges has also been constructed at JNC's Ningyo site, by Hitachi, for the decontamination centrifuges and reduction of waste volumes. Construction, completed in 1999, was the result of a roughly 20-year technological development effort, in cooperation with JNC. Hitachi made a similar contribution, in terms of technological development, to the JNFL's Rokkasho enrichment plant. Laser uranium enrichment technology has been developed by Laser Atomic Separation Engineering Research Association of Japan and Hitachi has prepared the enriched uranium recovery system.

Storage of Spent Fuel

Spent fuel generated from LWRs in Japan will be stored for a while before reprocessing. The storage facility, to be situated away from the reactors, will enter service around 2010. The dry metal cask, which has had long experience, will be adopted for the transportation of spent fuel to this facility. Hitachi has been developing high-capacity casks, economical concrete casks, and vault systems. Fig. 6 shows a typical dry metal cask concept for both transportation and storage, the reliability of which has been checked by experiments on its thermal conductivity, mechanical, sealing, and shielding properties. It was found to be suitable for commercialization. For the thermal conductivity experiments, a radially precise model apparatus was prepared (Fig. 7) and the temperature distribution from the heater which simulates the spent fuel was measured.

Waste Management

Technologies for the management of waste from nuclear power, reprocessing, and other facilities in the fuel cycle have been developed to reduce the volume of wastes and thus reduce the cost of their disposal, to solidify the wastes for safety of disposal, and to treat the waste to minimize the release of nuclides to the environment. Typical volume-reduction technologies include the super-concentration solidification of borate wastes rather than the conventional drying-powdering-pelletizing or bitumen solidification and graphite inductive-heating melt techniques. Super-concentration solidification of borate wastes in a cement achieves a higher reduction ratio than conventional methods. A graphite inductive-heating melt technique is able to reduce the possibility of steam explosion and attain a compact facility. A high-performance cement was developed as a solidification technology that satisfies the standards for land disposal in terms of strength, porosity, and the distribution of nuclides. This was achieved by the addition of carbon fiber and nuclide-adsorbents materials and by other measures. Hitachi has developed a system that decomposes organic impurities by applying ozone and

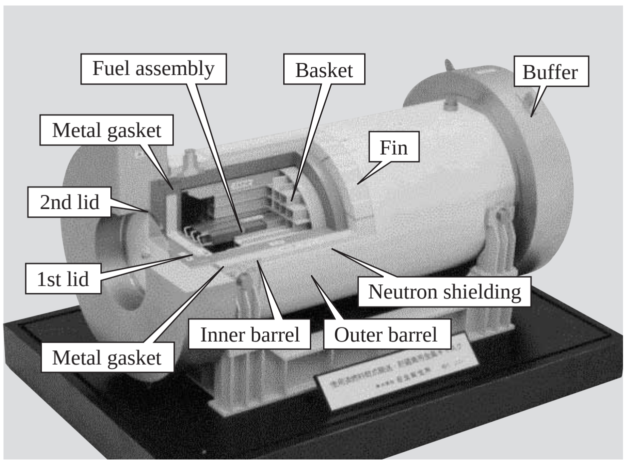

Fig. 6— The Dry Metal Cask Concept for Storage and Transportation of Spent Fuel Features Dry Sealing and Radiation Shielding.

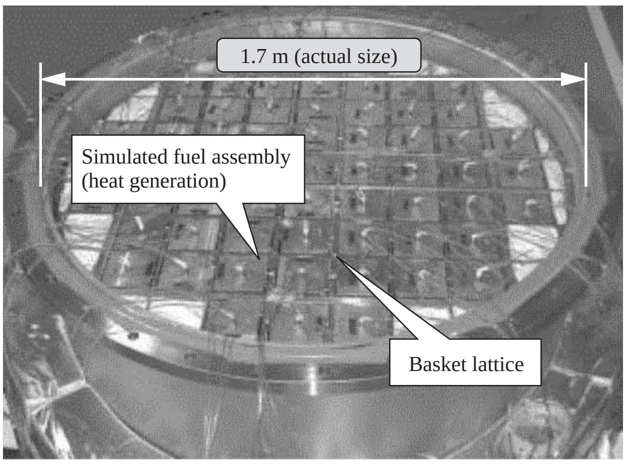

Fig. 7— The Experimental Apparatus Used in Thermal Conductivity Experiments on the Dry Metal Cask Is of the Cask's Actual Radial Size; A Heater Simulates the Spent Fuel.

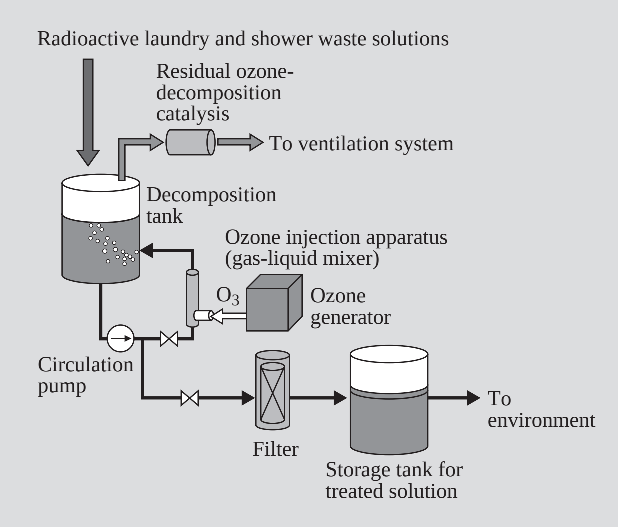

Fig. 8— In the Ozone Decomposition System for Liquid Waste Treatment, Ozone Is Supplied to the Circulation Line, Residual Ozone Is Catalytically Decomposed and Radioactive Crud Is Removed by Simple Filtration.

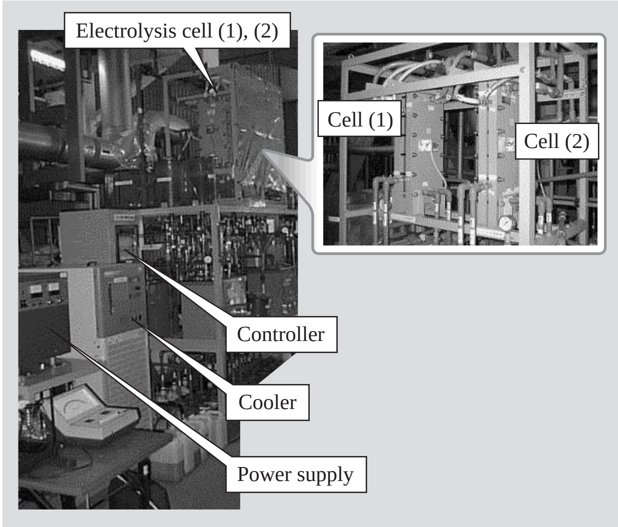

Fig. 9— The Electrolytic System for Recovering Acid from Decontamination-Waste Solution Applies an Electrolysis Cell with Ion-Exchange Membranes to Efficient Recovery Hydrochloric Acid.

removes crud materials from laundry/shower-drain waste solutions. The ozone decomposition method is used to disinfection and deodorize the water as a general service. The developed system, as shown in Fig. 8, adopts continuous ozone supply for the waste-tank circulation line. This allows the application of this method to laundry-drain solutions with higher concentrations of organic impurities. Organic components like detergents and human filth can be decomposed to carbon dioxide by ozone. Radioactive solid components can be removed by a simplified filter. Secondary waste is then reduced to less than 1/20 of the volume from a conventional activated-charcoal system.

Decommissioning

Decommissioning is currently attracting much interest due to the termination of the Tokai-1 reactor of the Japan Atomic Power Company (JAPCO) in March 1998, the plan for the termination of the JNC's advanced thermal reactor Fugen in 2003, and the fact that Japan's first LWRs have been in operation for 30 years. Decommissioning can be carried out by using existing technologies. Advanced technologies have, however, been developed for much safer and economical decommissioning in terms of nuclide measurement, safety analysis, decontamination, remote dismantling and waste management. Waste minimization during decommissioning is especially important. A typical example of a reuse system for decontamination-waste solution is thus introduced here. Hitachi is proceeding the development of a decontamination method with a high decontamination factor that is mainly based on the use of hydrochloric acid, and of a method for reducing waste by recovering recyclable materials from spent decontamination solution. Electrolysis of the waste solution is able to recover 75% of the hydrochloric acid with a nuclide content 1/1,000th that of the waste solution. This has been demonstrated by experiments using a small apparatus with the membrane surface area of 30 cm^2 and the capacity of 500 m*l*/h (Fig. 9). The results showed higher levels of performance than the target values, including a waste volume-reduction ratio of 1/10. The applicability of the system to actual decommissioning has thus been demonstrated.

Advanced Reactors

The liquid-sodium-cooled FBR is the main topic here. Hitachi is the first company in Japan to tackle the development of sodium equipment and has been cultivating techniques for the treatment of liquid sodium. The experience thus gained has provided the basis for Hitachi's contribution to the construction of the JNC's experimental FBR Joyo and prototype FBR Monju, and to the reconstruction of the primary cooling system of Joyo as part of its Mark-III project. Hitachi designed and manufactured the equipment for experiments in extinguishing sodium fires used in the sodium-handling training facility of the JNC's FBR

Fig. 10— The Sodium Fire Experimental and Extinguishment Equipment Is Used for Observation of Sodium Combustion and Training in Using the Special Fire Extinguisher (photo from JNC).

training center in Tsuruga city, which opened in May 2000. This equipment allows the state of sodium combustion to be observed from outside by rotating the air flow in the center of the equipment room and avoiding the adhesion of sodium aerosols to the inner window surface. The room, 8 m in diameter and 6-m high, is now extensively used for extinguishment training (Fig. 10). Design technology and equipment have been also developed for JAPCO's demonstration FBR project by using high-temperature sodium-test facility[3,4]. The demonstration FBR project is succeeding as a study of the feasibility of the FBR and related fuel cycles, and will help JNC and electric-power companies to establish the safer and more economical FBR concepts.

Design study of reduced moderation LWR has been developed as a progressive one, which utilizes light water and steam bubble coolant same as usual boiling water reactors and achieves higher conversion ratio than usual LWRs.

CONCLUSIONS

The states of development of reprocessing and other fuel-cycle technologies has been presented in this article. Activity in this field will increasingly prosper as the start-up of the commercial reprocessing plant approaches. Hitachi will continue to apply its comprehensive power to the development, in cooperation with electric-power companies, of the required technologies in order to ensure the continuous and stable supply of cheap electricity. Several developed technologies have already been applied in actual plants and can now be offered for use elsewhere in the world, as will technologies under development as they become available.

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