Current Status and Prospects of Nuclear Fuel Cycle Development in Korea

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1 Introduction

The safe and peaceful use of nuclear energy is vital to the welfare of the nation's economy, environment and the development of technology. Korea has been pushing an aggressive nuclear-industry development program over the past three decades in an effort to overcome its vulnerability to world oil and natural gas markets. By drafting a comprehensive and practical atomic energy policy, Korea aims to ensure that atomic energy is used for the right purpose in the most efficient way. Now, Korea controls one of the largest and most advanced nuclear industries in Asia, operating 20 nuclear reactors nationwide that generate 40 percent of the country's electricity. By 2015, 10 more nuclear power plants are expected to be completed, when it will supply about 46 percent of the nation's electricity.

Considering the sharp rise in the prices of gas and oil and the increasing global efforts to reduce carbon dioxide emissions from all energy sectors, nuclear technology has the potential to become an industrial growth engine for Korea. Being a country lacking natural resources, the primary objective of policymakers has been to diversify energy sources to secure an economical and stable supply of energy. Overcoming the high-level of dependency on energy imports, mostly oil, and improving the country's energy security has been an important concern. The basic doctrine of the nation's nuclear energy policy is centered on the safe usage of atomic energy in accordance with nature, and respect for life. Principal objectives of nuclear energy policy are as follows; acquiring advanced safety system for the peaceful usage of atomic energy and ensuring the people's trust on safety so that nuclear energy is sustainable, contributing to a steady energy supply as a major energy resource under continued development, winning global competitiveness in a nuclear reactor and proliferation-resistant nuclear fuel cycle technology, expanding usage of atomic energy in various medical, agricultural, industrial sectors, and activating basic and advanced atomic energy research and contributing to overall scientific development.

The government expects nuclear-power to become the major energy source by 2015. A permanent storage for radioactive wastes needs to be established by 2008 at the latest, as existing facilities has limited storage capacity. The government tried to find a location to build the waste dumpsite in the face of resistance from some residents and opposition from environmental groups. Last year, the government assures that high-level nuclear waste such as spent fuel will not be stored in the new site. Storage will be restricted to low- and intermediate-level radioactive wastes from the power plants. The local governments of the four vying locales submitted their intent to house the controversial site a few months ago, despite protests from environmental groups. Recently, the southeastern city of Gyeongju won a vote to host the nation's first nuclear waste dumpsite with the highest voter approval among four competing cities. It is the first of such plebiscite votes to take place on a government project since a new voting law took effect last year. Nearly 90 percent of residents in Gyeongju voted in favor of the project. The plebiscite brings an end the to the government's hunt for a nuclear power waste site that began in 1986.

As the nuclear industry has been expanded, the demand for the nuclear fuel cycle service has continuously increased in Korea. While the ultimate policy of the back-end fuel cycle is still under consideration in Korea, the related research is towards developing a proliferation-resistant fuel cycle technology to reuse the spent fuel for the effective management of the accumulated spent fuel in a proliferation-resistant way. Extensive studies on the innovative fuel cycle technologies are being carried out at the Korea Atomic Energy Research Institute (KAERI) in order to find an effective solution for the back-end of the fuel cycle. These studies include the DUPIC (Direct Use of spent PWR fuel in CANDU reactors) program, the Advanced Spent Fuel Conditioning Process (ACP) program, the pyrometallurgical partitioning and transmutation program, and the high-level waste disposal program.

2 Advanced Nuclear Fuel Cycle Technology Development

For an ambitious long-term perspective in the Korean nuclear power program, the effective management of spent fuel remains a challenge for the future of the nuclear industry. The premises for developing the fuel cycle technologies are to secure and strengthen the sustainability, proliferation resistance, environmental safety, and economic competitiveness of the future nuclear energy systems.

2.1 DUPIC technology development

The DUPIC fuel cycle is a unique spent nuclear fuel management technology that can be implemented in Korea, which is considered to be an intermediate measure to recycle spent PWR fuel directly into the CANDU reactors. This technology is to directly fabricate the CANDU fuel from the spent PWR fuel through a dry thermal/mechanical process without any separation of the stable fission products and transuranic elements. Due to the high radioactivity of the fuel material, all the manufacturing processes should be performed remotely in a highly shielded facility. Even if the remote fabrication and handling of DUPIC fuel causes technical challenges, there is an advantage for enhancing the proliferation resistance by no intentional separation of the fissile isotopes and fission products from the fuel fabrication processes, difficulties of a physical access and diversion of material, and a self-contained processing facility.

Spent PWR fuel is first disassembled and then decladed mechanically to retrieve the fuel material. The irradiated fuel material is treated by repeated cycles of an oxidation and a reduction, named the OREOX (Oxidation and Reduction of Oxide Fuel) process, to make the irradiated fuel material resinterable. Once the resinterable powder feedstock is prepared, the remaining fabrication steps are similar to the conventional CANDU fuel fabrication process, i.e. powder treatment, compaction, sintering, end cap welding and bundle assembling. Since all the fabrication processes should be performed in a shielded facility throughout the whole process, a designated remote fabrication laboratory, called the DUPIC Fuel Development Facility (DFDF), was established in 2000 by refurbishing an existing hot cell at KAERI.

A comprehensive research and development program has been implemented at KAERI to experimentally verify the DUPIC fuel cycle concept with international cooperation with Canada, USA and the IAEA. In Phase II entitled "Experimental Verification Program", which was carried out at a full momentum until 2001, the proliferation resistant dry process was developed for the direct recycling of spent PWR fuel in the CANDU reactors. Following the small-scale hot cell experiments at the Post Irradiation Examination Facility (PIEF) to characterize the DUPIC powder/pellet using actual spent PWR fuel, a major DUPIC fuel fabrication campaign was started in 2000 to fabricate the DUPIC fuel pellets and the elements. KAERI has successfully fabricated several DUPIC fuel elements in a remote manner at DFDF. The performance evaluation through the irradiation tests at the HANARO research reactor and post-irradiation examination has also been performed. The DUPIC fuel cycle is internationally known to be the most representative example of the proliferation-resistant fuel cycle technology.

Though the key DUPIC technologies have been developed, it is too early to launch the commercialization of the DUPIC fuel based on the laboratory-scale technology. However, it is thought that there should be no technical problems to develop the commercial DUPIC technology once the fuel fabrication technology and its performance are demonstrated through a practical use of the DUPIC fuel. The pilot-scale technical verification program including the fabrication of DUPIC bundles, their performance evaluation and in-depth analysis on the compatibility and economics is being suggested to the government by KAERI.

2.2 Advanced conditioning process development

The ACP program has been under development at KAERI since 1997. The principal efforts for developing a pyroprocess are given to the electrolytic reduction of oxide fuel and an electrorefining, targeting the reduction of the volume, heat load and the toxicity of the spent fuel. The main concept is to reduce the spent oxide fuel into a metallic form in a high temperature molten salt, as an intermediate step for the conditioning of the spent fuel for an eventual disposal and for a recycling and transmutation in a GEN-IV fast reactor. It includes several process steps such as an air voloxidation of the oxide fuel pellets, electrolytic reduction of the oxide fuel powder in a $LiCl\text{-}Li_2O$ molten salt bath, and a smelting of the reduced metal powder.

The first step of the ACP is the air voloxidation of an UO_2 oxide pellet to produce U3O8 powder. This is to increase the reaction rate at the subsequent reduction step and to remove the volatile fission products from the spent fuel. The U_3O_8 powder produced is introduced into a molten salt bath for converting the spent fuel oxides to base metals. Early activities for developing the reduction process focused on the conventional Li-reduction process. However, since 2001 an electrolytic reduction technology has evolved as a new innovative approach, which then replaced the Li-reduction process. In the process, the spent oxide fuel serves as the cathode of the cell in which the metal ions are reduced to the base metal, and the oxide ions are oxidized at an inert anode to produce oxygen gas, which then is vented from the cell. The new concept has advantages over the Li-reduction process such as a simplicity of the process systems, reduction of the molten salt waste and an increase of the reduction yield. Through the experimental verification of the process, a reference procedure was established.

The laboratory scale mock-up tests were carried out successfully with a scale of 20 kgU/batch. The laboratory scale demonstration facilities of 20 kgHM/batch have been installed in a hot cell this year. Based on the experimental and operational results using these facilities, the engineering scale demonstration facilities of 100 kgHM/batch will be designed and installed by 2012.

2.3 Pyro-partitioning process development

The pyro-partitioning technology development aims at the application to the GEN-IV reactor systems as the recycling and transmutation methods for closing the fuel cycle. KAERI has been conducting an R & D project on the partitioning and transmutation (P&T) of long-lived radionuclides since 1997.

The study for the partitioning is focused on the development of a pyroprocessing based on an electrorefining of actinides because it is a kind of proliferation-resistant technology, where all the transuranic metals are separated together as a mixture. In order to achieve the above objective, a study on pyro-partitioning at KAERI is being carried out in three phases. Phase I (1997 ~ 2000) was mainly focused on the concept of a fluoride molten salt reactor proposed by LANL. Accordingly, the target of the research was to review and to obtain basic technologies on pyroprocessing such as an electrowining and a reductive extraction, using fluoride molten salt. However, in Phase II (2001 ~ 2003), the concept of pyroprocessing was changed from a fluoride based molten salt reactor into a chloride based metallic fuel proposed by ANL, with the purpose of using a metal ingot produced from the ACP process. During Phase II, the goal of the research was to obtain the key technologies of pyroprocessing such as a uranium electrorefining and a cathode process.

As for a treatment of the spent molten salt, the oxide fuel reduction process as well as the pyro-partitioning process is to generate the molten salt wastes. The treatment process of the salt waste is being studied now. Some characterizations such as the free chloride content, chemical durability by a 7-day PCT, etc., were performed for the salt-loaded zeolite sample. Main activities performed during Phase II are as follows; installation of laboratory scale equipment (throughput: 100 gU/batch) for a uranium electrorefining and for a salt distillation, exanimation of the experimental conditions such as the optimum current density applicable in an operation, initial uranium concentration, separation factor of the uranium from the rare earth, and the salt distillation behavior, and basic study on the immobilization of the molten salt in zeolite 4A by an ion exchange.

Based on the results of Phase II, a scale-up of the electrorefining process (1 kgU/batch) has been carried out to verify the experimental conditions during Phase III. Also, Phase III contains activities on the conceptual design and process modeling of high-throughput electrorefining. The tasks to be performed are to develop the high-throughput electrorefiner, integrated salt distillation equipment, and electrowinning process to recover U/TRU from chloride molten salt without the problems of cadmium liquid cathode.

2.4 High-level waste disposal technology development

KAERI initiated R&D activities on high-level waste (HLW) disposal technology given that it will be required for long-term consideration of the nuclear energy strategy regardless of fuel cycle options. A three-step 10-year R&D program was launched in

1997 to develop a reference geologic repository system for HLW by 2006. The program has now entered into its third year of the last step (2002~2006) in preparation of the KRS (Korean Reference Disposal System).

The R&D program has been carried out in four different areas: repository system development, performance/safety assessment, geoscientific environmental research, and performance validation of the proposed HLW disposal system. The current design of a repository to accommodate spent nuclear fuel from 28 nuclear power plants needs a quite significant repository area of 6~7 square kilometers. The potential host rock, crystalline rock, has fractured networks and major water conducting features which require closer look in the process of site selection. So, the key issues are on the safety of a repository even though in technical level it can be resolved by enhanced engineered barriers and innovative designs.

The results carried out by 2002 have been combined together to develop a reference repository concept. The third phase study to refine technologies on the performance assessment and to develop the Korean repository concept has been continued.

2.5 Decontamination and decommissioning activities

Two decommissioning projects are carried out at the KAERI, one for the Korea research reactors, KRR-1 and KRR-2, and another for the uranium conversion plant (UCP). The project was launched for the decommissioning of the reactors in January 1997 with the goal of a completion by 2008. The work scopes during the reactor decommissioning project are the dismantling of all the facilities and the removal of all the radioactive materials from the reactor site

The decontamination and decommissioning (D&D) technology of the long-term R&D project funded by Korean government has been carried out intensively since 2001 by KAERI in order to develop the D&D technologies not only to apply to the decommissioning projects for two research reactors, uranium conversion facilities and decommissioning waste management, but also to cope with the decommissioning of nuclear power plants in the country in the future.

3 International Collaboration

3.1 Collaboration with the US through the I-NERI program

In 2001, the parties agreed to launch the International Nuclear Energy Research Initiative (I-NERI) program to cooperate in the development of nuclear technologies. The first I-NERI program in the field of the nuclear fuel cycle area was initiated in 2003. Currently, four I-NERI projects are being performed in connection with the Advanced Fuel Cycle Initiative (AFCI) program.

Development of the structural materials to enable the electrochemical reduction of spent oxide nuclear fuel in a molten salt electrolysis

This joint I-NERI project with ANL of the USA was initiated in January 2003 with a three-year term program. The principle objectives of this study are to assess and select candidate materials, and to develop new candidate material systems (e.g., functional barrier coatings) for service in the electrochemical reduction process vessel.

Development of the voloxidation process for the treatment of spent LWR fuel

The voloxidation process could be used as a head-end treatment step for the pyrochemical treatment process. It was agreed that the two parties will conduct joint experiments in a U.S. DOE laboratory with actual spent LWR fuel for the purpose of measuring the efficiency of the recovery of the volatile fission products and transmutation products (Xe, Kr, I, H^3, Tc, and C^{14}). Independent experiments will also be conducted for the development of various trapping concepts for immobilizing the volatiles released in the course of the voloxidation treatment. Additionally, process cycles will be developed that optimize the particle size of the oxidized fuel and the degree of the fuel cladding separation. This project has been carried out as one of the I-NERI projects by KAERI (Korea), and ANL and ORNL (USA) since June 2004, and is planned for a three-year research.

Alterative methods for the treatment of TRISO fuel

A 3 year I-NERI project related to the Tristructural Isotropic (TRISO) fuel treatment was launched in June, 2004. KAERI's partner is ANL in USA. The KAERI ACP and the U.S. DOE AFCI have been developing transmutation strategies for separating and transmuting the transuranic and long-lived fission products contained in spent nuclear fuel. Coated particle TRISO fuel is one of the inventories to be treated.

Material corrosion performance testing and benchmarking in lead alloy loops

An accelerator driven system and/or a critical reactor can perform a transmutation. Lead-alloy (Pb-Bi and Pb) is used as a coolant material for both systems. Since KAERI is working on both the Accelerator-Driven System (ADS) and the Lead-Cooled Fast Reactor (LFR), a 3-year I-NERI project related to lead-alloy was launched in June 2004. KAERI's partner is LANL in US. LANL is working on lead-alloy within the work scope of the AFCI and GEN-IV LFR coolant and materials projects. KAERI and LANL will collaborate on several important aspects of the material testing and coolant chemistry control.

3.2 MEGAPIE program

KAERI joined the MEGAPIE project in 2001 for the experimental study of Pb-Bi. MEGAPIE is the one megawatt proton beam irradiation test of the Pb-Bi target. PSI, CEA, CNRS, FZK, ENEA, SCK.CEN, KAERI, JAERI and DOE are members of the MEGAPIE project. Now the Pb-Bi target is at the stage of fabrication. The most significant problem in handling Pb-Bi is corrosion. Therefore, KAERI built a static Pb-Bi corrosion test facility and performed experiments using it in 2003 and 2004. KAERI will complete the construction of a Pb-Bi corrosion loop in 2005.

4 Concluding Remarks

The sharp rise in the prices of gas and oil and the increasing global efforts to reduce carbon dioxide emissions from all energy sectors, nuclear technology has the potential to become an industrial growth engine for Korea. She continues to perform R&D activities in a search of an optimal option for the spent fuel management with a long-term perspective of nuclear power utilization.

While the ultimate policy of the back-end fuel cycle is still under consideration in Korea, the related researches are towards developing the advanced fuel cycle technology to reuse the spent fuel in an effective and proliferation-resistant way. Recently, Korea has been focusing her efforts on the pyroprocess technology development, by targeting the reduction of the volume, heat load and toxicity of the spent fuel and an application to the GEN-IV reactor systems as the recycling and transmutation methods for closing the fuel cycle. The pyroprocess development plan will be harmonized with the schedule of the GEN-IV reactor system development.