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Technological Change of Nuclear Fuel Cycle in Korea
: The case of DUPIC

TAE JOON LEE*

Korea Atomic Energy Research Institute, 150, Deokjin-dong, Yousung-ku, Taejon, 305-353, The Republic of Korea
*Corresponding author: Tel: +82-42-868-2149; Fax: +82-42-861-7521
E-mail address: tjlee@kaeri.re.kr

Abstract

This paper describes how Korea has been successfully carrying out the DUPIC project for the development of the nuclear fuel cycle. To enhance energy security, the DUPIC is a response to the challenge faced by Korea's nuclear energy program. First of all, indigenous technological capabilities have played a significant role in finding an alternative technological trajectory for proliferation resistance as well as energy economics and in solving innovative and complex technological problems. While being supported by a long-lasting national commitment, the implementation of DUPIC has also depended upon the domestic techno-economic validity in association with energy security, market condition and the industrial demand of spent fuel management.

Keywords: nuclear fuel cycle policy, technological capabilities; international politics, DUPIC, Korea

1. INTRODUCTION

Korean nuclear power development has been inextricably linked to the enhancement of energy security for national economic development and industrialisation. First, Korea has very small energy resources. Major domestic energy resources such as anthracite coal and hydropower are not sufficient to cope with the ever-increasing energy demands. The only domestic fossil fuel is anthracite coal of a low calorific value, below 4,000 kcal/kg. Proven anthracite reserves are estimated to be 1.5 billion tons - about half of this is economically recoverable. Hydro electric potential is about 3,000 MW. Even though hydropower had been successfully exploited by the mid-1970s, it is assessed to be marginal in terms of the total energy demand. Moreover, uranium deposits are identified as low grade which is not worth exploiting economically (Ha, 1982; Choi, 1996). Secondly, Korea has tried to reduce its fossil fuel dependency on foreign countries. In addition to the huge amounts of foreign currency needed for oil imports and storage, this source of fossil energy has been regarded as insecure in terms of the uncertainty of the world oil well locations and possible international struggles or conflicts. So, Korea has concluded that it is not feasible to use fossil fuels as a long-term strategy to achieve a stable energy supply. Thus, Korea has pursued the idea of so-called 'diversification of energy resources' to develop alternatives. In line with this energy policy, the government has introduced and enlarged nuclear power generation. [1] At the present time, Korea plans to run 28 nuclear power plants(NPPs) by 2010 including 18 NPPs currently in operation and 2 NPPs under construction.

Due to very weak energy security, Korea has been particularly interested in the development of the back-end of the nuclear fuel cycle (BNFC). It has been strongly motivated to take advantage of the potential energy in spent nuclear fuel and to make it a domestic energy resource. While nuclear power production could proceed worldwide in the short- and medium-term for around 50 years at current levels of use without BNFC, in principle spent nuclear fuel could be used for the peaceful purpose of energy production 70 times more efficiently with BNFC than with a typical once-through cycle (IAEA, 1997).

According to IAEA (1997):

> "...... recycling plutonium from reprocessed spent fuel in thermal reactors as mixed oxide fuel and the introduction of fast breeder reactors to also convert non-fissionable uranium into plutonium would increase the energy potential of today's known uranium reserves by up to 70 times, enough for more than 3000 years at today's levels of use.' (p. 41)

Thus, this breeding characteristic has seemed highly attractive to Korea and influenced its national energy policy. Therefore, BNFC development for reproducing nuclear energy has been considered as an important way to meet the increasing domestic energy demands in line with the national economic growth and to reduce the energy dependency on foreign countries. Due to the high risk of proliferation of nuclear technology and material for a military purpose, however, the reuse of spent nuclear fuel in non-nuclear weapon countries (NNWs) has been strictly restricted under international political intervention, such as export control, prior consent and international political influence, especially as exercised by the United States.[2]

Nevertheless, Korea has developed a BNFC project, i.e. DUPIC (Direct Use of spent PWR fuel in CANDU). By the middle of 2000, Korea succeeded in designing and fabricating the prototype DUPIC pellet using spent nuclear fuel on a laboratory scale. With US permission, Korea used spent fuel discharged from Korea's PWRs (Pressurised Water Reactors) and carried out technological activities of BNFC for the first time. How have these things happened in Korea? From the perspective of technological development of BNFC in NNWs, this research aims primarily at exploring the question of how Korea has been successfully carrying out the DUPIC project and what sorts of elements have been dynamically involved in the project.

2. Creation of the DUPIC Project

2.1 Socio-economic Environment and Project Creation

Alongside the nation's economic growth, energy demands had been increasing. Total energy consumption increased from 12,012 TOE in 1965 to 56,296 TOE in 1985 with an annual average growth rate of 8.0 %. In particular, electricity consumption reached 50,732 kWh in 1985 - eighteen times higher than in 1965. The proportion of electricity in final energy increased from 1.9 % in 1965 to 9.3 % in 1985.Thus, the role

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[1] For oil importing nations, the energy security benefit of nuclear power derives from the diversification of energy resource dependence (Poneman, 1982; Lönnroth and Walker, 1979; Potter, 1982).

[2] For better understanding about the international political intervention regarding the issue of nuclear non-proliferation, see LEE & Yang (2003).

of electricity had become more important in the energy demand and supply structure of the country. As energy demand, and especially for electricity, increased, the role of nuclear power also expanded. By the end of 1989, nine commercial NPPs were operating producing 50.1 % of the total electricity generated in Korea (MOER and KEPCO, 1990).[3] In this situation, as the localisation of conventional CANDU fuel succeeded and the Korean CANDU plant achieved high performance operations in the late 1980s, it was recommended that the nuclear fuel cycle utilising PWR spent fuel for CANDU be developed from 2006 to 2015 and a liquid metal reactor be introduced as a very long-term option (Aju University, 1989 cited in Kang, 1991).[4] By the second half of 1987, KAERI (Korea Atomic Energy Research Institute) supplied the total number of natural uranium fuel bundles needed for the Wolsong unit 1 (KAERI, 1987; Suk and Jung, 1992).[5] The CANDU plant achieved a high operation performance, greater than 90 percent of its availability.[6] Hence, Korea reviewed the expansion of the CANDU nuclear power plants along with PWRs and began to study how to make effective use of this combination of PWR and CANDU reactors.

The option of a PWR-CANDU liaison fuel cycle was also supported by the anti-nuclear movement in Korea. As nuclear power had been increasing, Korea began to be faced with the serious problem of spent nuclear fuel accumulation. Despite the national commitment to nuclear power development, there was no definite policy on the long-term management of nuclear radwaste, including spent nuclear fuel. As a result, the amount of spent fuel discharged from nuclear power plants had been steadily increasing and accumulating at nuclear power plant (NPP) sites along with low and medium level radioactive waste (LMLW). By the end of 1989, 1,143 tons of spent nuclear fuel and 4,920 kilolitres of LMLW were being stored at NPP sites. With respect to spent nuclear fuel, the national storage capacity was expected to be filled by the end of 1997 (MOER and KEPCO, 1990). In 1986, the Korean government established a national system for the management of nuclear waste. Under the supervision of MOST (Ministry of Science and Technology), KAERI was entrusted with the total management of LMLW and spent nuclear fuel. In 1988, the Korean government decided to build an underground repository for low and medium level radwaste to be completed by the end of 1995, and a centralized Away From Reactor (AFR) interim storage facility for spent fuel on the same site by 1997. This AFR facility was for the storage of 3, 000 tons of spent nuclear fuel (MOER and KEPCO, 1990). However, this government plan fell behind schedule because the government could not locate a site for the underground repository and AFR storage facilities. This was mainly due to the public opposition to nuclear facilities. In the late 1980s, an anti-nuclear movement emerged in Korea along with democracy movements. The public began to debate about nuclear environmental problems and safety. Residents near existing and would-be nuclear sites were reluctant to have nuclear facilities, including nuclear power plants, near their homes, although they did not object in principle to nuclear power expansion (Park, 1989). Finally, public acceptance had

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[3] On the other hand, world oil and uranium supplies were stable in the late 1980s and this trend was estimated to continue in the near future. World oil and uranium prices were 13.69 US $/bbl and 15.30 US $/lb uranium, in 1988 (MOER and KEPCO, 1990).

[4] It resulted from the study of 'The Outlook and Developmental Strategy of Nuclear Energy for the Early 21st Century in the Republic of Korea' (Kang, 1991).

[5] 5100 CANDU fuel bundles (100 MTU) were required to operate 670-MWe class of CANDU plant like Wolsong Unit 1 for one year (KAERI, 1987).

[6] In particular, the plant reached a world record, 98.4% of availability in 1986 (MOER and KEPCO, 1999)

become a significant factor in the nuclear power programme in Korea. Under these circumstances, KAERI began in 1986 to investigate possible sites for an underground repository and an AFR interim storage facility and had selected three candidates by early 1988. As a result of public opposition to the construction of these facilities, however, the site investigation was suspended in March 1989 without any decision being made about the sites for the storage of nuclear waste (MOER and KEPCO, 1990). As the nuclear waste management project was not proceeding, using PWR fuel in the CANDU reactors became an attractive option to reduce the amounts of spent nuclear fuel. Then, Korea began to discuss with the US the concept of a Korean BNFC project.

2.2 Feasibility study under US political consent

Before contacting the US, Korea held discussions with Canada for the development of the Korean PWR-CANDU liaison fuel cycle. In the 8th Republic Of Korea - Canada Nuclear Joint Co-ordinating Committee in 1990,[7] Korea and Canada discussed the idea of a dry (heating and mechanical) non-separation process to reuse spent PWR fuel in a CANDU reactor. In the 13th Joint Standing Committee on Nuclear and Other Energy Technology between the government of the Republic of Korea and the government of the US (JSCNOET) in May 1991,[8] Korea suggested an international collaborative R&D project between Korea, Canada and the US to develop the PWR-CANDU liaison fuel cycle without the chemical processing of spent PWR fuel. As a follow up to this meeting, Korea, Canada and the US met in Ottawa in June 1991 and agreed to carry out the R&D project for the PWR-CANDU liaison fuel cycle by international collaboration between the three countries. At the meeting, DUPIC (Direct Use of spent PWR fuel in CANDU) was chosen as the name of the fuel cycle and Korea received US approval for the feasibility study of the DUPIC. Thus the Korean technological initiation in BNFC commenced with US political approval in July 1991. Between September and October 1991, the three countries discussed the overall content of the project and division of responsibility for each country. The US joined the project by participating in the development of the DUPIC safeguards system. Since then, all the technological activities of DUPIC had been internationally available at least twice a year through project review meetings (KAERI, 1997a). In November 1991, Korea received formally the US government approval for the implementation of the project (KAERI, 1997a). Despite US political approval for the overall project, the Korean BNFC project had to agree with the US government with respect to the core technology for the project.

In conducting the feasibility study, the phase I of the project, Korea first reviewed alternative technologies for the major DUPIC fabrication process in terms of product quality and project efficiency. Korea compared the reconfiguration method with the refabrication technologies. In the interests of product quality, Korea selected refabrication. After assessing the pros and cons of vibropack and OREOX as refabrication technologies, [9] Korea finally selected the OREOX (Oxidation and REduction of OXide fuel) technology for technological learning efficiency (see Table 1).

[7] After Korea and Canada signed an agreement for nuclear cooperation between the two countries in May 1975 in the course of importing the first Korean CANDU reactor from Canada. Korea and Canada agreed to form the committee in September 1982. (KAERI, 2000c).

[8] JSCNOET has run since 1977. After the Korean reprocessing project was discontinued, Korea and the US agreed to establish the JSCNOET for nuclear cooperation as an organisation to proceed the nuclear cooperation of peaceful purposes between Korea and the US in August 1976. The first meeting of JSCNOET was held in July 1977.

[9] For further information of vibropack, please see Skiba *et al.* (1993).

However, the decision to use OREOX had to be approved by the US. When Korea and the US discussed technology options for DUPIC including OREOX, the reconfiguration and vibropack, Korea pointed out the problem that the reconfiguration of the inhomogeneous composition in nuclear fuel would result in a safety problem. Korea also explained the licensing problem of the vibropack process. Korea argued that although vibropack had the advantage in maintaining the homogeneity of fuel composition, it was difficult to get a licence for construction and operation of the fabrication facility or plant from the regulatory body. So far as the CANDU reactor was concerned, no matter what process was used, DUPIC fuel must meet the design requirement and the technical specification of CANDU-type fuel, in particular CANFLEX. Otherwise, the construction and operation of a DUPIC facility would require new licences, which would be another major task and would greatly affect the efficiency of the DUPIC project. As a result, the US agreed to OREOX which was chosen as the major fabrication technology for DUPIC fuel in June 1992.

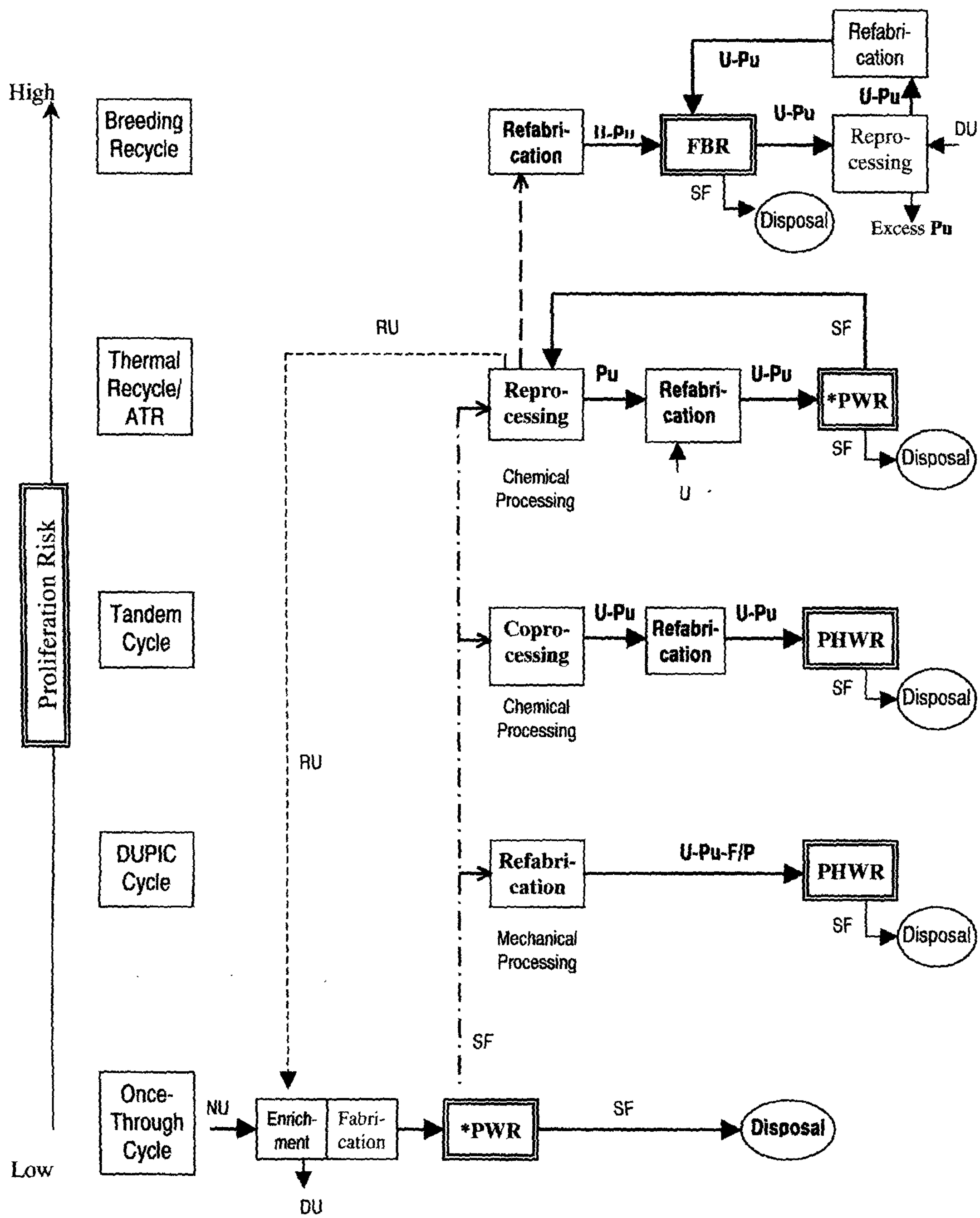
Table 1 Technical difference between reconfiguration and refabrication

Reconfiguration	Refabrication	
	vibropack	OREOX
Do not dismantle SF by mechanical process	Dismantle spent fuel but do not take heat treatment process	Needs to dismantle spent fuel and to treat heat process
Inhomogeneous fuel Composition	Homogeneous fuel composition	Homogeneous fuel composition
	Not satisfying the reference CANDU-type fuel design criteria	Satisfying the reference CANDU-type fuel design criteria
	Licensing problem	Technical complexity and difficulty that needs remote control technology in hot cell

2.3. Identification of technical feasibility

In persuading the US about the technical aspects of DUPIC, in February 1993 technical feasibility was studied while focusing on the optimal fabrication technology, proliferation resistance, energy recycling effect, compatibility of DUPIC fuel with the CANDU reactor, and the ability to safeguard. The most distinctive characteristic of DUPIC is its proliferation resistance in terms of product and process. Unlike other recycling technologies, such as the reprocessing and tandem fuel cycles, refabrication does not involve any process of chemical separation of sensitive nuclear material that might be diverted to make a nuclear weapon (see Figure 1). Thanks to no separation of fission products, the fresh DUPIC fuel has almost the same high level of radioactivity as the spent PWR fuel. This high radioactivity of product and process for the fresh DUPIC fuel enhances proliferation resistance. From recovering of the spent fuel material to reloading into the CANDU reactor, by virtue of this high radioactivity, all the stages in the DUPIC fuel cycle protect against any clandestine access to this sensitive nuclear material.[10] Thus, both the product and process of DUPIC are highly proliferation-resistant.

[10] In 1994, the US National Academy of Science suggested the concept of the "Spent Fuel Standard" as a criterion in disposing of excess plutonium. It was concerned with the risk of recovery of the plutonium, 'that is to make this plutonium roughly as inaccessible for weapons use as the much larger and growing



(Figure 1) Proliferation risk and material flows of nuclear fuel cycles[11]

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quantity of plutonium that exists in spent fuel from commercial reactors' (NAS, 1994: 13). The rationale behind the concept is that the hostile conditions of spent fuel by virtue of heat and radiation barriers could represent a benchmark for the management of plutonium while preventing any clandestine access to plutonium (Berkhout, 1998; Ko and Kim, 2000). A US DOE study more recently stated the spent fuel standard as a technical option 'to make plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in spent fuel from commercial reactors' (DOE, 1996, cited in Berkhout, 1998).

[11] Author re-arranged the data of Ko and Kim (2000) in the order of proliferation risk. Legend: F/P-fission products; NU-natural uranium; DU-depleted uranium; RU-reprocessed uranium; SF-spent fuel; FBR-fast breeder reactor; PHWR-pressurized heavy water reactor; PWR- pressurized heavy water reactor.

The direct refabrication process of DUPIC is sequentially composed of the OREOX process and the CANDU-type fuel fabrication process. The OREOX process is a powder preparation process to produce resinterable powder feedstock for DUPIC fuel pellets without any chemical separation of spent PWR fuel. Because DUPIC fuel is modelled on CANFLEX fuel, the rest of the process is similar to the CANFLEX fuel fabrication process except for the fact that the whole process is carried out in a highly radioactive hot cell (KAERI, 1997a; Ko and Kim, 2000; Yim *et al.*, 2000).

In order to confirm the compatibility of the DUPIC fuel with the CANDU reactor while maintaining reactor safety, KAERI established a reference fuel composition and refuelling scheme for the DUPIC fuel. The reference composition of DUPIC fuel should be determined to reduce the effect of the heterogeneous composition of the spent PWR fuel. Because more fissile concentration is related to the safety of the conventional CANDU reactor in which four or eight fuel bundles are loaded at one time, the fuelling scheme should be changed in order not to violate the design and operation criteria of the conventional CANDU reactor. KAERI identified a two-bundle shift refuelling scheme. KAERI also established reference enrichment, i.e. 1.0 wt % of U-235 and 0.45 wt % of Pu-239 to achieve a comparable advantage in DUPIC core performance against a natural uranium core while utilising spent PWR fuel as much as possible (Choi and Yang, 1999). With respect to out-core compatibility, Korea found DUPIC fuel could be loaded in the CANDU reactor by retrofitting the conventional CANDU reactor.

In using this reference DUPIC fuel composition with a two-bundle shift refuelling scheme, the DUPIC fuel cycle would save more than 25 % of the natural uranium resources, and reduce overall spent fuel accumulation by two-thirds per unit of electricity generation compared with the once-through fuel cycle (Yang and Park, 1997). Moreover, the DUPIC fuel cycle was analysed to produce an average burn-up of 15.5 MWd/kgU in CANDU on the basis of spent PWR fuel with an average burn-up of 42.5 MWd/kgU while the discharge burn-up of the relevant DUPIC fuel in CANDU was calculated to be 18 MWd/kgU for a lower burn-up case (35 MWd/kg U in PWR) and 13 MWd/kgU for a higher burn-up case (50 MWd/kg U in PWR). This means that the DUPIC fuel cycle would produce 37 % more power than the once-through option with the same amount of uranium. With this burn-up value, the combination ratio between PWR and CANDU reactors for a mass balance of the DUPIC cycle is analysed to be 3.0 on average while it was calculated to be 2.5 for a lower burn-up case and 4.8 for a higher burn-up case.

2.4 Absorptive capacity for complex and innovative technology

Contrary to the advantage of nuclear non-proliferation resistance of the refabrication technology, however, the highly radioactive process characteristics make the process and product technology more difficult and complex than the tandem fuel cycle. Therefore, special equipment and facilities need to be developed to deal with this radioactive material, such as remote control technologies and a hot cell facility. In addition to its complexity, DUPIC is an innovative technology in the application of conventional technologies for the development of a new product. Although the basic idea to use spent PWR fuel in CANDU was the same as in the Tandem project, the non-separation technology in recycling spent PWR fuel for CANDU was the innovative feature of DUPIC. Refabrication technology was researched in the mid 1960s in ORNL at the level of identifying a technical concept. OREOX itself was developed on a laboratory scale in Atomic International in the early 1960s and was known as AEROX. The AEROX was not developed for the CANDU reactor but for PWR and FBR by reenriching PWR spent fuel. However, refabrication technologies, including AEROX, were not developed further for commercialisation.[12]

KAERI decided to conduct such complex and innovative technology with its absorptive capacity. Korea accumulated the basic design capability for a conventional reprocessing fuel cycle through the conceptual study of reprocessing technology in the 1970s. Through the conceptual study of the Tandem project in the early 1980s, Korea also accumulated the basic design capability for various PWR-CANDU liaison fuel cycles. With this elementary design capability, Korea was able to understand the technical mechanism of the PWR-CANDU liaison fuel cycle as well as the conventional reprocessing fuel cycle. Even though Korean technological capabilities (TCs) in BNFC were limited to an elementary design capability without any experience of a detailed design and fabrication, this enabled Korea to define the innovative DUPIC fuel concept and to carry out the feasibility study. Korea had also accumulated TCs to design and fabricate conventional fuel for the CANDU and PWR, which had resulted from the localisation of CANDU fuel and PWR fuel in the 1980s, and the development of CANFLEX in the 1990s. Design and fabrication capabilities for CANDU-type fuel could be applied to DUPIC after the OREOX process with the exception of the high radioactive content. Technical information about spent PWR fuel acquired through the PWR fuel localisation project could be used for DUPIC fuel design. Moreover, the design capability to analyse and design the reactor core, accumulated through the introduction of CANDU reactors (Wolsong unit 1 and 2) were applied to DUPIC for analysing the compatibility of DUPIC fuel with the CANDU reactor.

3. Development of Prototypical DUPIC Fuel

3.1 International collaboration for prototypical technological learning

In April 1993, Korea, Canada and the US agreed to carry out the second phase of the international joint R&D project for DUPIC fuel cycle development. Korea established its technology strategy to develop indigenous TCs building for prototype DUPIC fuel on a laboratory scale. In phase II, the project aimed to accumulate experimentally design and fabrication capabilities to the extent that Korea produced prototype DUPIC fuel bundles and verified performance of the fuel by 2002 (NRPAC, 1996). Although Korea had the TCs to carry out the conceptual study, the absorption of advanced technology was required to develop such complex technology as DUPIC. Thus, international collaboration became the major organisational structure for laboratory scale TCs building. While technology transfer through international collaboration was a major way of learning, KAERI assembled various technologies that were developed through in-house and international collaborative R&D. In addition to the acquisition of technological information, joint R&D was performed as an effective way of learning in absorbing advanced technology for indigenous TCs building.

International collaboration for design and fabrication of DUPIC was conducted with AECL, Canada. Through joint R&D with AECL, KAERI began to develop design and fabrication technology for DUPIC in a hot cell.For the development of a safeguards system for the DUPIC cycle, KAERI collaborated with DOS and LANL of the US. The US LANL (Los Alamos National Laboratory) developed a technology to measure the

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[12] It was not so much a technological matter as an industrial and political matter. In the 1960s, in the US, various reactor and fuel cycles were researched. Among them, PWR and its fuel cycle quickly became the dominant technologies in the 1960s. Moreover, as the US non-proliferation policy was enhanced in the late 1970s, technological change using spent nuclear fuel was not significantly made in the US and refabrication technologies were no longer developed.

amount of plutonium for the MOX process. The LANL safeguards technology was used in a glove box, not in a high radioactive environment like a DUPIC hot cell. However, the underlying scientific principles could be applied to DUPIC. KAERI and LANL carried out the development of material accounting systems for DUPIC safeguards including DSNC (DUPIC Safeguards Neutron Counter) and ICS (Intelligent Containment Surveillance).Remote control technology had been developed by joint R&D between KAERI and US ORNL (Oak Ridge National Laboratory). For the conceptual design of remote control technology and hot cell, Korea collaborated with ORNL. However, objections were raised by the US government to technology transfer from ORNL.

3.2 Technological response to international political intervention

In introducing remote control technology for DUPIC, Korea came into conflict with the US. In order to manufacture and test DUPIC prototype fuel, about 30 types of equipment such as mechanical decladding, pellet loading, etc. needed to be developed and installed in the shielded facility. This equipment has to be operated and maintained remotely. Because Korea had little experience in developing or operating remote-control technology for the purpose of dealing with highly radioactive nuclear fuel, it was decided to introduce foreign technology. In June 1994, KAERI contracted with ORNL for a six-week training in remote control technology, including practical training, as well as provision of technical information (KAERI, 1997a). After the training, KAERI decided to carry out an international collaborative project with ORNL for the conceptual design of DUPIC fuel development equipment, focusing on remote control technology as one sort of core fabrication technology for DUPIC. KAERI and ORNL agreed to the technology transfer for the conceptual design in January 1995. However, in the course of negotiating with ORNL, the US DOS opposed the transfer of ORNL technology for the DUPIC project by considering DUPIC as a sort of sensitive technology. Through the JSCNOET in May 1995 and the DUPIC project review meeting in June 1995, Korea made efforts to persuade the US that remote control technology for DUPIC was not sensitive technology because the DUPIC process did not involve separating plutonium and uranium from spent nuclear fuel. As a result of Korea's technological effort, the joint R&D between KAERI and ORNL was approved by the US DOE and formally began in July 1995. Up to July 1996, KAERI carried out the conceptual design for nine types of remote-control fuel manufacturing and test equipment including a hot cell facility with US ORNL technical support (KAERI, 1997a).

3.3 Korean nuclear policy and national support for DUPIC

Since the agreement between Korea and the US for cooperation concerning the peaceful uses of nuclear energy in 1956, safeguards obligations have been applied to Korean nuclear activities on a bilateral basis. As the International Atomic Energy Agency (IAEA) took over bilateral safeguards, the application of the US-administered safeguards to supplies of US-origin in Korea pursuant to the 1956 agreement was transferred to the IAEA by a trilateral agreement between Korea, the US and the IAEA in January 1968 (KAERI, 1997b). After the NPT launched in 1970, the Korean parliament ratified the treaty in March 1975. Then, the agreement between the government of the Republic of Korea and the IAEA for the application of safeguards in connection with the NPT was signed in October 1975 and came into effect in November 1975 (KAERI, 1990). Following the safeguards agreement, the Ministry of Science and Technology (MOST) established State's System of Accounting for and Control of nuclear material (SSAC) to verify that all nuclear material subject to the safeguards are used for peaceful uses only. Since then, Korea has been using the SSAC system for its nuclear facilities while undergoing IAEA inspection. (Park *et al.*, 2001). The government has also made continuous efforts to improve its safeguards system in recording and reporting any inventory changes of nuclear material (Choi, 1996).

Coupled with the end of the Cold War, in the early 1990s Iraqi and North Korean nuclear programmes led to the reinforced international safeguards system, i.e., 'Programme 93+2'. In association with this international effort, Korea and the IAEA held the first Joint Review Meeting on Safeguards Implementation in Korea In 1991. Since then, Korea and the IAEA have discussed annually the result of safeguards implementation in Korea and possible cooperation between the two sides through the meetings (Park *et al.*, 2001). In particular, President Roh declared the Korean government's denuclearization policy on 18 November 1991. With its explicit intention of nuclear transparency and international credibility regarding Korean nuclear activities, he announced that Korea shall not test, manufacture, possess, store, deploy and use nuclear weapons. He also declared that Korea shall not possess nuclear reprocessing and uranium enrichment facilities while undergoing the IAEA safeguards inspection (Park, 1992). In coping with the strengthened international safeguards regime, Korea established the Technology Center for Nuclear Control (TCNC) in KAERI in April 1994, with a view to not only enhancing nuclear transparency in its nuclear energy utilization but also improving the preparation for the IAEA inspections of domestic nuclear facilities and materials (Choi, 1996; Yoon *et al.*, 2001). Moreover, nuclear materials and facilities subject the IAEA safeguards have been continuously increasing in Korea owing to the active expansion of nuclear power capacity.[13] With the domestic SSAC expertise accumulated for about 25 years, therefore, a national inspection system (NSI) was introduced for the effective and efficient implementation of national and IAEA safeguards (Park *et al.*, 2001). The Atomic Energy Act was amended to provide the legal basis for the national inspections in December 1994 and came into force in January 1995. After providing detailed requirements and guidelines for NSI, MOST entrusted TCNC in KAERI as the formal technical body with national safeguards implementation in November 1996 (Yoon *et al.*, 2001). From the second half of 1997, national inspections have been carried out by officials from MOST with technical assistance of TCNC. In 2000, a total of 148 national inspections had been carried out in 32 nuclear facilities including 12 PWRs, 4 CANDUs, 10 research facilities, and four fuel fabrication plants. Korea carried out 463 PDIs (person-days-of-inspection) while IAEA performed the same number of inspections with 351 PDIs during 2000 (Park *et al.*, 2001).

On the other hand, in 1992 the Korean government established a national long-term nuclear R&D programme to the year 2001 to develop conventional technologies further. This programme aimed at developing a wide range of technologies needed to pursue peaceful uses of nuclear energy and also at building a foundation of national energy self-sufficiency through the development of nuclear power generation technologies. Furthermore, in 1994, the Korean government established its 'Long-term Nuclear Policy Directions toward 2030' to present the long-term national vision and basic policy directions regarding nuclear energy and its utilization. The importance of

[13] By 1975, the IAEA safeguards were applied to only two nuclear facilities, TRIGA Mark-II and III research reactors. By 2000, 32 nuclear facilities were under the IAEA safeguards inspection (Park *et al.*, 2001).

DUPIC was included as one of the objectives of this policy as follows: 'To establish ... non-proliferating nuclear fuel cycle technology through systematic research and development of nuclear energy.' As part of the national R&D programme and nuclear policies, DUPIC was supported by the government.

3.4 US prior consent for the use of spent PWR fuel in DUPIC

Because the utilisation of spent PWR fuel for DUPIC is classed as an alteration to the form and content of nuclear material of US origin, it requires US prior consent according to Article VIII.C of the 1974 Agreement for Cooperation between the Government of the United States of America and the Government of the Republic of Korea concerning Civil Uses of Atomic Energy. When Korea applied for US prior consent, the US asked Korea for the Official Facility Attachments (OFA) from IAEA and the details of the planning for the use of spent PWR fuel in DUPIC, including the testing and manufacturing of DUPIC fuel.[14] The hot issue for prior consent is concerned with 'alteration of form or content' of nuclear material. Reprocessing and Tandem projects were liable for US prior consent because they involved chemical alteration. DUPIC does not involve the chemical alteration of nuclear material. However, it needs to crush spent fuel and alter its form and content, known as a physical alteration. Therefore DUPIC also needed US prior consent. Apart from the irradiation test to improve the performance of conventional nuclear fuel, DUPIC is the only technological project to have received US prior consent.

In February 1998, KAERI submitted design information about DUPIC test and fabrication facilities in order to receive the OFA from the IAEA, and finally received the OFA on 15 December 1998. KAERI requested US prior consent for physical alteration of spent nuclear fuel and submitted the US government technical report and the OFA from August 1998.[15] Then KAERI had discussions with the US concerning the detailed plan for the use of spent PWR fuel for DUPIC. As a result of the Korean efforts, the US gave prior consent for the use of spent PWR fuel for the test and fabrication of DUPIC fuel in March 1999.[16] Korea and the US signed a Joint Determination agreement for the use of irradiated fuel of US origin in April 1999. The US agreed that Korea could use 50 kg of spent PWR fuel for the fabrication of DUPIC fuel and 1 kg for the testing of the fuel.

3.5 Laboratory TCs building of prototype DUPIC fuel

DUPIC technology is concerned with the transformation of spent PWR fuel into a CANDU-type DUPIC fuel product by a direct refabrication process. In the laboratory phase of development of the prototype DUPIC fuel, technological learning focused on the development of the design and fabrication of a new product. Fabrication technology was researched to develop a new product rather than process technology to reduce production costs. Product technology for DUPIC fuel consisted mainly of identification of the chemical composition of a fissile material and fabrication of the fuel structure. Design of the DUPIC product was concentrated on a reference composition of fissile material to produce electric power because the mechanical structure of DUPIC is identical to CANFLEX for which TCs had been accumulated in Korea (see Table 2).

[14] Since September 1993, IAEA has attended the project review meetings of DUPIC (KAERI, 1997a).

[15] Before finalising OFA, KAERI submitted the draft of OFA that was under discussion between Korea and IAEA.

[16] As Korea received approval to use spent PWR fuel with both the IAEA OFA and the US prior consent, IAEA safeguards inspection for the DUPIC project began in March 1999 (KAERI, 2000a).

However, due to the difference in fuel composition between the natural UO2 of CANFLEX and OREOX-UO2 of DUPIC, [17] the reference fuel composition was researched to satisfy in-core compatibility while increasing DUPIC core performance. KAERI established the reference fissile composition to be 1.0 wt% of U-235 and 0.45 wt% of Pu through computer analysis.

Table 2 Technical specification of homogeneous DUPIC fuel bundle

Criteria	DUPIC bundle
Fuel bundle	
- Length (mm)	495.30 +/- 0.75
- Diameter (mm)	102.50 (max)
- Weight (kg)	23.2
- No of elements	43 (8 larger and 35 smaller pins)
Fuel element/pellet	
- Outer diameter (mm)	13.50 (larger pin), 11.5 (small pin)
- Cladding material	Zircaloy-4
- No of pellets	29-31
- Pellet material	OREOX-UO2

(Source: KAERI, 1997a: 126-130)

Although KAERI accumulated the fabrication capability in CANDU-type fuel, DUPIC fabrication technology was also developed for the design and construction of hot cell facilities using remote control technology because of the high radioactivity of the product and fabrication process. KAERI designed fabrication conditions for the DUPIC fuel and developed the DUPIC hot cells by 1999. The hot cells in IMEF (Irradiated Material Examination Facility) and PIEF (Post-Irradiation Examination Facility) of KAERI were selected and refurbished for the DUPIC fuel fabrication facility on a laboratory scale. The IMEF hot cell is used to fabricate DUPIC fuel while the PIEF hot cell is used for the characterisation testing of DUPIC fuel powder and pellets. In the highly radioactive hot cell, all material replacement and equipment operations have to be carried out remotely outside the hot cell. A great deal of remote control equipment for fabrication had been developed and installed in the DUPIC fuel development facility (DFDF) by the end of 1999. With the design established and the DFDF constructed, about fifty DUPIC pellets were successfully fabricated from spent PWR fuel by April 2000. The irradiation testing of DUPIC fuel was scheduled at the HANARO research reactor in KAERI in 2000 for the evaluation of the performance and fuel behaviour of the DUPIC fuel.[18] After the development of a DUPIC fuel bundle, the accumulated capabilities will lead to the scale-up of the process technology, i.e. pilot plant.

As long as DUPIC is an innovative and complex R&D project, there is no existing safeguards technology that can be directly used for the DUPIC fuel cycle. Therefore Korea has to develop safeguards capabilities for the purpose of the verification of safeguardability of the DUPIC fuel development facility. The DUPIC safeguards system consists of a nuclear material measurement system, a near real time accountability

[17] OREOX-UO2 means that DUPIC fuel powder is made of UO2 from spent PWR fuel through OREOX.
[18] Before the actual DUPIC fuel test, the simulated DUPIC fuel[18] was developed and used for irradiation test HANARO from August 1999 to October 1999 (KAERI, 2000b). The experience and result of the simulated fuel test was intended to be used in the real fuel test.

system and a built-in containment and surveillance system (KAERI, 2000a). By the end of 1999, a DSNC (DUPIC Safeguards Neutron Counter) had been developed as a nuclear material measurement system. The DSNC was used for DFDF after IAEA authorisation in 1999 while the other two were still under development (Ko and Kim, 2000).

4. Factors for the development of DUPIC

4.1 Role of technological capabilities

By the late 1980s, Korea had accumulated basic design capabilities of BNFC and commercial design and fabrication capabilities in FNFC. Without fabrication experience of the BNFC, Korea learned the elementary design capabilities up to understanding the technical mechanisms involved in the contemporary technologies for reprocessing and co-processing fuel cycles in the early 1970s and 1980s. As for the FNFC area of DUPIC, Korea succeeded in the localisation of CANDU fuel and PWR fuel during the 1980s. Korea accumulated TCs to design and fabricate conventional CANDU fuel, which could be used for the design and fabrication capabilities for the DUPIC fuel pellet and assembly. In addition, TCs accumulated in the PWR fuel localisation projects provided DUPIC with data on spent PWR fuel. TCs to analyse and design the reactor core, accumulated through the introduction of CANDU reactors (Wolsong unit 1 and 2), were also applied to the DUPIC project for analysing the compatibility of DUPIC fuel with the CANDU reactor.

These TCs were shown to have contributed to creating the DUPIC project. The existing TCs helped in exploring and conceptualising a new technology trajectory to mitigate international political intervention and, at the same time, to cope with the domestic energy security problem. Following an assessment that there was no technological solution to both the domestic and international problems involved in the conventional BNFC technologies, including reprocessing and co-processing, Korea found a new innovative technical concept. This innovative concept was to apply the conventional refabrication technology to the synergistic PWR-CANDU liaison fuel cycle on the basis of domestic nuclear power plant portfolios. The technological trajectory of this innovative technology was directed mainly to the improvement of proliferation resistance while maintaining the energy recycling demand. Without adequate TCs, Korea was unable to locate such an innovative trajectory. DUPIC does not separate any nuclear material from spent nuclear fuel and is recognised as a highly proliferation-resistant technology. In terms of its energy recycling effect, the DUPIC fuel cycle carries some advantage of saving more than 25 % of natural uranium compared with a once-through uranium cycle. The indigenous TCs also made the technical path of the project clearer by convincing the US that there was no clandestine motive for the DUPIC project, which contributed to gaining US political approval for the use of OREOX technology for the DUPIC. Moreover, the TCs were important to satisfy US export control policy in receiving US government approval for the technology transfer of remote control technology from US ORNL.

On the other hand, the advantage of proliferation resistance becomes disadvantageous for the development of product and process technologies, the safeguards system and fuel loading for the DUPIC cycle. In return for maintaining a high proliferation resistance, all the fabrication process had to be performed in a heavily shielded hot cell by remote control technologies from the stage of R&D to commercial production. In addition, this innovative fuel cycle demanded a new safeguards system that could not be bought off the conventional technology shelf. The hostile condition of

DFDF is a significant barrier to the development of the DUPIC safeguards system, especially in terms of nuclear material accountancy. Although it was developed with internationally collaborative R&D, such complex technology was successfully being developed mainly by the in-house technological efforts made during the project. The accumulated safeguards capability was able to promote nuclear transparency of the DUPIC project, which contributed to reducing international anxiety about the proliferation risk of the DUPIC fuel cycle. Thus TCs contributed not only to programming the optimal technology trajectory of BNFC for coping with international political intervention and domestic energy needs, but also implementing the innovative and complex project.

4.2 Role of domestic techno-economic factors with national commitment

Although TCs are shown to have been the most important factor in reducing international political intervention, it is not possible to say that the accumulated TCs were the main reason for reducing the conflict between the weak developing country and the strong advanced country in developing such sensitive technology as BNFC. What other elements then were involved in the continuation of the DUPIC project? In answering this question, this paper examines the domestic socio-economic factors surrounding the DUPIC project. As a result of empirical analysis, the following domestic socio-economic factors were related to reducing international political intervention, given the proliferation resistance of the DUPIC fuel cycle: the fundamentally weak energy security; adequate product market; industrial problems related to the management of spent fuel. First, the fundamentally weak energy security against high increasing energy demand continuously supported the Korean rationale of TCs building in BNFC. The energy-poor country needed to use imported energy resources effectively, i.e. uranium, and to improve its energy security. In addition, since the late 1980s, global environment problems have been under discussion and international regulations have been put in place to reduce fossil fuel use. As a result, nuclear power has been likely to be reintroduced in some countries and newly introduced in other countries, and uranium prices will increase. Then such energy-poor countries as Korea would be significantly affected in their development of a sustainable national economy. Second, DUPIC has been driven by market demands. Korea had a unique portfolio in its nuclear power reactors, including PWRs and CANDUs, in the course of expanding nuclear power capacity. By 1999 when the DUPIC prototype fuel rod was first developed, Korea was operating 16 NPPs with a combination of 12 PWRs and 4 CANDUs. The increasing domestic PWR and CANDU nuclear power capacities offered an adequate market for DUPIC fuel. PWR capacity was about three times as much as CANDU. Considering that spent PWR fuel collected from three PWR is used to make the DUPIC fuel loaded into one CANDU, the ratio of PWR versus CANDU in terms of plant capacity offered an ideal combination for the DUPIC fuel. Lastly, so far as spent fuel management is concerned, Korean was extremely keen to undertake the DUPIC project. The temporary storage had nearly reached its capacity and the national efforts to find interim storage sites had been unsuccessful due to public objections to nuclear power facilities. Use of DUPIC technology would reduce the stock of spent fuel. The Korean spent fuel management problem might be significant in the eyes of the US. In order to remove the possibility of military abuse, all the spent fuel could be in theory returned to the US. But this was not practically possible. The US had not found monitored retrievable storage (MRS) for its own radwaste, including spent fuel. Thus, DUPIC fuel cycle was considered to be very beneficial.

In addition to these socio-economic factors, long-lasting government efforts clearly demonstrated so-called nuclear transparency. Since 1975, the Korean government had made continuous efforts to improve its safeguards system with regard to nuclear material for the effective and efficient implementation of national and IAEA safeguards. While Roh's declaration in 1991 renouncing possession of enrichment and reprocessing facilities has been said to produce an impasse in the nation's nuclear power development,[19] this paper argues that the declaration contributed to Korea's access to spent nuclear fuel for the DUPIC project coupled with the techno-economic features of the DUPIC cycle concerned. By the declaration, Korea proclaimed its explicit intention to provide the nation's nuclear transparency, especially in the area of BNFC, which was likely to result in the US permission for Korean BNFC activity.[20] Moreover, The Technology Center for Nuclear Control (TCNC) was established in KAERI in April 1994. The objective of the TCNC was to improve the preparation for the IAEA inspections of domestic nuclear facilities and materials. Therefore, the mission-oriented and systemic performance of the TCNC to implement national safeguards was likely to increase transparency regarding Korea's nuclear energy utilization and in turn contribute indirectly to nuclear non-proliferation in the DUPIC cycle.

5. Conclusion

The DUPIC project has been running in Korea since 1991. The further expansion of CANDU as well as PWR power plants to cope with the sharp increase in electricity demand motivated the BNFC project to use spent PWR fuel in CANDU. Anti-nuclear activities related to nuclear facilities induced additional interest in the PWR-CANDU liaison fuel cycle as a way to reduce the amount of spent fuel. Influenced by these domestic social and economic factors, Korea has carried out the DUPIC project with a technology strategy towards indigenous TCs building from a laboratory scale. However, the two-sided nature of the BNFC technology meant that domestic technological activity for TCs building in the weak developing country was seriously influenced by the international political intervention of the strong advanced country. From a perspective of non-proliferation to prevent horizontal nuclear proliferation by banning sensitive material and technology, US political intervention was involved in the Korean DUPIC project.

Through the dynamic process under international political-economic environment, indigenous technological capabilities played an important role of searching for an optimal solution to cope with US political intervention and, at the same time, satisfy domestic economic needs. It was also required to develop the innovative and complex technology linked to the high radioactivity of the process and product. However, TCs alone were not sufficient. Given that the technology trajectory was exploited by domestic TCs, the weak energy security and adequate market condition contributed to further mitigation of US political intervention along with domestic industrial demand for spent fuel management. In addition to these economic factors, the government's commitment is also analysed to increase the nation's nuclear transparency. These factors were integrated to contribute to obtaining US prior consent over the use of spent PWR

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[19] Kim (1992) argued that 'with the November 8 Declaration in 1991 renouncing possession of enrichment and reprocessing facilities, the nation's atomic energy industry will remain crippled.' (p 253)

[20] According to Steinberg (1994), by the early 1990s, it is evaluated as follows: 'With the notable exception of North Korea, there are few indications of proliferation in Asia. Taiwan, Indonesia, South Korea, and other potential proliferators have apparently decided against pursuing nuclear weapons.' (p 129)

fuel for DUPIC in 1999 and the continuance of the DUPIC project. By the middle of 2000, Korea had accumulated design, fabrication and safeguards capabilities on a laboratory scale. As a result, the DUPIC fuel pellet was successfully developed and irradiation tests on DUPIC fuel were conducted at HANARO in KAERI in order to confirm the performance of the product.

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