CURRENT STATUS AND FUTURE PROSPECT OF CANDU FUEL RESEARCH & DEVELOPMENT IN KOREA

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ABSTRACT

The current status and future prospect of CANDU fuel R & D in Korea is always subjected to the consideration of domestic and international environments concerning nuclear safety, nuclear waste, non-proliferation and economy in favor of the arguments from public acceptance, international environments, and utilities. Considering that, at the end of 2000, the procurement of additional CANDU units at the Shin Wolsong site was decided not to proceed, the current and future CANDU fuel R & D would be oriented to the safety and economy of fuel and reactor operations rather than the national strategy of nuclear fuel cycle and reactor programs in Korea. Therefore, the current CANDU advanced fuel R & D programs such as CANFLEX-NU fuel industrialization, CANFLEX-0.9% SEU/RU fuel R & D, and DUPIC fuel cycle development in a laboratory-scale will be continued for the time being as it was. But the R & D of CANDU innovative fuels such as CANFLEX-1.2% ~ 1.5 % SEU fuel, thorium oxide fuel and DUPIC fuel would have some difficulties to continue in the mid- and long-term if they would not have the justifications in the points of the non-proliferation, economic and safety views of fuel, fuel cycle and reactor.

1. INTRODUCTION

In Korea, sixteen nuclear power plants with 12 PWRs and 4 CANDU[1]-PHWRs are now in operation with a total installed electric-generation capacity of 13, 716 MWe, which accounts for about 27 % of the domestic installed electric-generation capacity in Korea.

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[1] CANDU®(Canada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited(AECL).

As shown in Table 1, the installed electric-generation capacity of the 4 CANDU-PHWRs is 2,779 MWe, where it shall be noted that, at the end of 2000, the Korea Electric Power Corporation (KEPCO) decided not to proceed with the procurement of additional CANDU units for Shin Wolsong site. Today, the nuclear industries in Korea are faced with several key challenges to achieve the highest levels of safety, to pursue acceptable waste management option to the industry and general public, to operate within varying political climates, and to tackle all of these within a cost regime competitive with fossil fuel generated electricity.

Since the period of the late 1970s, nuclear fuel design and fabrication technologies have been engaged as one of the important R & D activities in Korea. This paper describes the current status of CANDU fuel R & D in Korea. It also describes the future prospect of CANDU fuel R & D by taking into account "nuclear safety", "nuclear waste", "non-proliferation", "economy", and "not to proceed with the procurement of additional CANDU units" in favor of the arguments from public acceptance, international environments, and utilities.

2. DOMESTIC AND INTERNATIONAL ENVIRONMENTS

Taking into account the domestic and international environment concerning non-proliferation in the Peninsula of Korea, some product development guidelines of the CANDU advanced fuel R & D may be summarized as [1]:

① enhancement of reactor and fuel safety and operation margin,
② reduction of annual production rate of spent fuel volume,
③ no involvement and no use of enrichment and reprocessing technologies in Korea,
④ to be compatible with existing reactor without major change of hardware,
⑤ improvement of economics by means of reduction of fuel cycle and/or reactor operating costs.

These guidelines for fuel and fuel cycle R & D in Korea have been and will be applied not only for the CANDU advanced fuel R & D but also for the R & D of PWR fuel and others.

The CANDU power plants as shown in Table 1 will be operated at least by the mid of this century, because Wolsong #2, #3, and #4 could be decommissioned by around the year

2048, which is taken account into the initial licensing life time of 30 years and the life time extension of 20 years.

Based on a commercial consideration, KEPCO decided, at the 2000 December, that the procurement of additional CANDU units was not to proceed for the Shin Wolsong site.

3. CURRENT STATUS AND FUTURE PROSPECT OF CANDU FUEL R & D IN KOREA

As presented in the 4th International Conference on CANDU Fuel, Pembroke, Canada, 1995 October, a strategical projection of CANDU fuel R & D programs in Korea would be summarized as shown in Figure 1. For the time being, the existing R & D programs of CANDU advanced fuel such as CANFLEX(CANDU Flexible fuelling)-NU(Natural Uranium) & -SEU(Slightly Enriched Uranium)/RU(Recovered Uranium from spent fuel) and DUPIC(Direct Use of PWR spent fuel in CANDU) fuel cycle would be continued as it was. In the next couple years from the late part of 2001, the Korea Institute of Science & Technology Evaluation and Planning (KISTEP) will outline the mid- and long-term CANDU fuel R & D programs for the next 20 years from 2002. KISTEP was established on 1999 February with its main missions of surveying, analyzing, and evaluating Korea's national R & D programs.

3.1 37-Element Fuel

At the end of 1996, Korea's nuclear energy industrial structure was reformed as a follow-up to Korea's national policy, and so KAERI's commercial activities of CANDU fuel fabrication and PWR fuel design transferred to the Korea Nuclear Fuel Company (KNFC). In the KEPCO Nuclear Fuel Co. Ltd. (KNFC), a CANDU fuel fabrication plant with a fuel production capacity of 400 tons of uranium per year was constructed in cooperation with GEC. Since 1998, KNFC has commercially produced all the locally needed CANDU fuel, and also paid attention to improve the productivity by developing advanced manufacturing technologies such as an advanced method of Zr-Be brazing, ECT(Eddy Current Test) for the detection end cap weld discontinuities, and so on.

3.2 CANFLEX 43-Element Fuel

Since the early 1990's, the Korea Atomic Energy Research Institute (KAERI) and the Atomic Energy of Canada Limited (AECL) have pursued a collaborative program to develop, verify, and prove the CANFLEX[2] 43-element fuel bundle design. The CANFLEX [2] fuel bundle enables the introduction of advanced fuel cycles such as SEU, RU and other fuel cycles into CANDU reactors. The bundle assembly and its critical-heat-flux (CHF) appendages offer higher operating and safety margins than current fuel and the potential of reactor power uprating, which would further increase the economic competitiveness of the CANDU reactor, while maintaining full compatibility with operating CANDU reactors. It enables a higher power to be realized before CHF occurs, leading to a net gain in critical channel power (CCP) typically of 6 to 8% over the existing 37-element NU fuel. The greater element subdivision and the use of two element sizes lower the peak linear-element rating. Therefore, it is well suited for the use of advanced fuel cycles, particularly those that can attain high fuel burnup.

The fuel has been verified through extensive testing by KAERI and AECL and has been critically reviewed under a Formal Design Review. The compatibility of the fuel type with existing reactor systems has been proven through a demonstration irradiation of 24 CANFLEX-NU bundles in the Pt. Lepreau Generating Station (PLGS) at New Brunswick, Canada between September 1988 and August 2000 [3].

3.2.1 CANFLEX-NU Fuel

As a prime example of the results that can be achieved through collaborative ventures between Canada and Korea, KAERI and AECL have, since 1991, jointly developed CANFLEX-NU fuel which could likely counterbalance the adverse effects of ageing within the CANDU heat transport system.

KAERI prepared the CANFLEX-NU fuel design report for use of CANFLEX

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[2] CANFLEX® (CANDU Flexible Fuelling) is a registered trademark of Atomic Energy of Canada Limited(AECL) and Korea Atomic Energy Research Institute(KAERI).

bundles in Korea and submitted it to the Korea Institute of Nuclear Safety (KINS) on 1996 July, to obtain approval of the fuel design and fabrication method, as part of the Korean licensing process. This approval was obtained from the Korean Government, Ministry of Science and Technology (MOST) at 1999 August 6. Following the approval of CANFLEX-NU fuel design and fabrication method in Korea as well as the successful demonstration irradiation of CANFLEX-NU fuel in PLGS, a 3-year industrialization program for the use of CANFLEX-NU fuel in a CANDU-6 Wolsong reactor has been jointly conducted by the Korea Electric Power Research Institute (KEPRI) and KAERI since 2000 November. This KEPRI and KAERI joint R & D program will be conducted by 2003 November. A demonstration irradiation of 24 CANFLEX-NU fuel bundles in Wolsong Unit 1 is expectantly started in the late part of 2001, which is detailed in Reference [4]. The decision on full-core conversion of CANFLEX-NU fuel in Wolsong Unit 1 will be processed in this program.

3.2.2 CANFLEX-SEU/RU and Other Advanced Fuels

KAERI and AECL agreed a joint CANFLEX-SEU fuel development program in 1996 September in order to prepare for the introduction of advanced fuel cycles such as SEU including RU, as an economical alternative to natural uranium and also a fuel for existing or future CANDU reactors. The prime objective of this joint program is the small-scale demonstration irradiation in a CANDU power reactor of 20 to 100 bundles of CANFLEX-0.9 % Equivalent SEU, followed by selective post irradiation examination of selected irradiated bundles. This is a necessary prerequisite to a full-scale conversion to CANFLEX-SEU. The program includes the necessary analysis and out-reactor tests. Also, in parallel with the agreement on AECL/KAERI joint CANFLEX-SEU fuel development program, a cooperative program was agreed between KAERI and British Nuclear Fuels Plc(BNFL) in 1996 November, as a similar cooperative agreement between AECL and BNFL, to complete the development and proof testing of recovered uranium fuel for CANDU reactors. The three Parties, KAERI, AECL and BNFL have implemented the three agreements to create one joint cooperative program.

0.9 % or 1.2 % SEU fuel would increase fuel burnup and hence reduce the quantity of spent fuel produced by a factor of 2 or 3 compared with NU fuel [5]. The SEU fuel

would reduce uranium requirements per unit energy by about 24 % and so improve uranium utilization, and would also reduce CANDU fuel cycle costs by 20 to 30% compared with NU fuel. RU offers similar characteristics and benefits as 0.9% SEU. The total amount of RU produced from reprocessing operations in Europe and Japan is around 25,000 tons with additional quantities from reprocessing in the former Soviet Union [6]. It is anticipated that RU can be obtained at very attractive price, because some utilities pay for the storage of the RU. Security of supply is not an issue, as SEU of equivalent enrichment can be substituted. The technical feasibility of using RU as a fuel cycle option for CANDU reactors in Korea has been studied to show the overall evaluation and identification of the potential benefits, risks, and costs associated with the use of the fuel to a CANDU-6 utility [7]. This feasibility study indicated that the use of RU in CANDU reactors has beneficial environmental and economical impacts on overall fuel cycles. Anticipating the advantages of the use of 0.9 % SEU or RU of the fuel cycle option for CANDU reactors in Korea, the CANFLEX-0.9% SEU/RU fuel development program is scoped into three Phases as follows.

In Phase 1 from 1997 July to 200 March, the overall evaluation and identification of the potential benefits, risks, costs associated with the use of 0.9% SEU or RU to CANDU-6 utility, and the overall possibility to satisfy the licensing issues described in Korea Safety Review Guideline [1] have been shown to provide a rationale for the justification of the R & D efforts on it for the advanced fuel cycle of CANDU reactors in Korea.

In Phase 2 from 2003 April to 2006 March, the detailed fuel design, reactor physics, thermalhydraulics, and safety analyses, proof testing, and code validations will be performed to lead the small-scale demonstration irradiation in a commercial power reactor. Topical Reports on the fuel design and fabrication method will be licensed as a part of the Korean Licensing process. But this task will not be fully completed in Phase 2.

In Phase 3 from 2006 Arpil to 2010 March, the remaining workscope will be completed. If the results obtained from Phases 1 and 2 show sufficient merit of the use of RU of the advanced fuel cycle option for CANDU reactors in Korea, then a business case including a small-scale demonstration of CANFLEX-RU fuel in a Wolsong CANDU-6 reactor will be started in Phase 3 for which the business workscope would be drafted.

Activities [1] would include the preparation of all safety and licensing documentation for irradiation of 20 to 100 bundles in a CANDU-6 reactor, including interaction with the Korean licensing authorities, and fabrication of those bundles in KNFC.

In Phase 3, it is expected that a CANFLEX advanced fuel equal to and/or higher than 1.2 % equivalent SEU fuel cycle will be briefly assessed and reviewed to reduce the annual production rate of spent fuel volume from CANDU reactors in Korea as much as that from PWRs in Korea. This assessment will include the overall evaluation and identification of the potential benefits, risks, and costs associated with the use of 1.2% ~ 1.5% SEU to CANDU-6 utility, and the overall possibility to satisfy the licensing issues described in Korea Safety Review Guideline [1]. Also, it will review the option of extending the U-235 indefinitely through the use of fuel cycles based on the thorium in Korea. If the assessment indicates CANFLEX-1.2% ~ 1.5% SEU fuel to be feasibly justified to continue the R & D, the SEU fuel will be developed for the next around 10 years from 2011. The R & D efforts of CANFLEX-1.2% ~ 1.5% SEU fuel will be more clearly justified, if CANDU NG (Next Generation [8] is introduced in Korea just after the last nuclear power plant of KNGR (Korean Next Generation Reactor) #4 in the long-term construction plan of Korean nuclear power plants.

3.3 DUPIC Fuel Cycle

Considering that PWR spent fuel contains enough fissile materials to be burned in CANDU reactors, DUPIC [9] involves converting the PWR spent fuel into CANDU fuel by a thermal-mechanical dry process without any wet chemical processing. DUPIC fuel cycle technology is currently under development by KAERI and AECL in cooperation with the US Department of State and the International Atomic Energy Agency (IAEA). Including the additional energy extracted from the fuel in a CANDU reactor, the potential benefits of the DUPIC fuel cycle in comparison with conventional wet reprocessing and with respect to uranium utilization and spent fuel arising are:

① proliferation resistance due to the non-separation of uranium, plutonium and fission products during the fabrication process,

② a smaller amount of radioactive waste from processing, due to the nature of dry processing,

③ savings of uranium resources due to the efficient uranium utilization - the DUPIC fuel cycle could reduce the natural uranium requirements by about 25% compared with the direct disposal fuel cycle, and

④ a significant reduction in spent fuel arising – a three-fold reduction in the quantity of spent fuel arising per unit electricity generation, compared with direct disposal fuel cycle.

The DUPIC fuel cycle is being developed in a phased approach. Phase I was a feasibility study, which was conducted between 1991 and 1993, to conceptually evaluate several possible DUPIC fuel fabrication processes. Among several fabrication options, the OREOX (Oxidation/Reduction of Oxide fuel) process was selected as the optimum DUPIC fuel fabrication method for further study [10], and its safeguardability was judged to be achievable.

Phase II, which is currently under way from 1994 to 2002, is focused on demonstrating that DUPIC fuel can be fabricated using the OREOX process on laboratory scale, and on assessing the fuel performance by irradiating the fuel in research reactors. Both KAERI and AECL are developing the fuel fabrication technology and also assessing the reactor physics and the fuel element performance. The DUPIC fuel performance will be experimentally verified by conducting the following activities:

① fabrication of several DUPIC pellets and elements from spent PWR fuel in KAERI

② evaluation on the performance of DUPIC fuel by the irradiation tests at HANARO research reactor in KAERI

③ development of safeguards equipment and technology for the fabrication of several DUPIC pellets and elements

④ evaluation on the compatibility of the DUPIC fuel with existing CANDU reactor.

KAERI is developing the safeguard methods through international collaboration with Los Alamos National Laboratories (LANL) in USA and with the IAEA. In 1999, KAERI completed preparations for hot cell equipment, refurbishment of a hot cell for the fuel fabrication, and the verification of safeguards equipment. Using about 1 kg of spent PWR fuel, a characterization study on DUPIC powder and pellets has successfully been performed in a hot cell of PIEF (Post Irradiation Examination Facility) in KAERI.

Subsequently, KAERI has fabricated three DUPIC fuel mini-elements with 50 pellets at the remote fuel fabrication laboratory in IMEF (Irradiation Materials Examination Facility). For a in-core fuel performance evaluation of the DUPIC fuel elements, the KAERI-made DUPIC elements have been irradiated in the HANARO research reactor for about 2 months since 2000 May. These mini-elements had been burned out up to 43 MWh/kgHe by irradiating with an average linear power of about 50 kW/m. Some data obtained from the post-irradiation examinations of the irradiated DUPIC fuel at PIEF and IMEF in KAERI indicated that the microstructure of the DUPIC pellets is quite similar to that of a CANDU-6 fuel pellets irradiated with a linear power of 73 kW/m[11]. In the Spring of 2001, KAERI also fabricated another three DUPIC fuel mini-elements which have been irradiated in the HANARO reactor since 2001 May. These fuel elements with an estimated maximum-linear power of 49.0 kW/m will be irradiated up to 290 MWh/kgHE.

The scope of DUPIC fuel cycle R & D for the next five years from 2002 April will be planned in the late part of 2001 by KISTEP. KAERI's DUPIC fuel cycle R & D team issues Korean PWR spent fuel management, national energy security through reuse of spent fuel, non-proliferation of nuclear fuel cycles, and self-reliance in fuel technology to continue the laboratory-scale R & D of the fuel cycle in KAERI:

① remote fabrication of prototypical DUPIC elements and bundles from spent PWR fuel
② DUPIC fuel performance evaluation by the irradiation tests in HANARO research reactor
③ development of computer programs for the evaluation of DUPIC fuel performance
④ development of safeguards equipment and technology for remote fabrication of prototypical DUPIC elements and bundles
⑤ evaluation on DUPIC fuel licensing for the use in existing CANDU reactors.

KAERI's DUPIC fuel cycle R & D team also claims the following activities to be continued for the mid- and long-term as the periods from 2006 to 2015:

① remote fabrication of prototypical DUPIC elements and bundles from spent PWR fuel
② small-scale demonstration irradiation of DUPIC fuel bundles in a CANDU-6 reactor
③ development of safeguards equipment and technology for the mass production of DUPIC fuel
④ design and construction of a pilot plant for the DUPIC fuel manufacturing

⑤ construction of DUPIC fuel handling facility at a CANDU-6 reactor site
⑥ licensing of DUPIC fuel for the use in a existing CANDU-6 reactor
⑦ development of a dry process technology for the mass treatment of PWR spent fuel

4. CONCLUDING REMARKS

The current status and future prospect of CANDU fuel R & D in Korea is always subjected to the consideration of domestic and international environments concerning nuclear safety, nuclear waste, non-proliferation and economy in favor of the arguments from public acceptance, international environments, and utilities. The R & D of CANDU fuel and fuel cycles such as the 37-element bundle, CANFLEX fuel, and DUPIC fuel cycle for the four Wolsong CANDU-6 power reactors in commercial operation and expectantly future CANDU reactors in Korea have been actively and successfully conducted so far since 1980. Considering that, at the end of 2000, the procurement of additional CANDU units in Shin Wolsong site was decided not to proceed, the current and future CANDU fuel R & D in Korea would be oriented to the safety and economy of fuel and reactor operations rather than the national strategy of nuclear fuel cycle and reactor programs in Korea. Therefore, the current CANDU advanced fuel R & D programs such as CANFLEX-NU fuel industrialization, CANFLEX-0.9%SEU/RU fuel R & D, and DUPIC fuel cycle development in a laboratory-scale will be continued for the time being. But the R & D of CANDU innovative fuels such as CANFLEX-1.2% ~ 1.5 % SEU fuel, thorium oxide fuel and DUPIC fuel would have some difficulties to continue in the mid- and long-term if they would not have the justifications in the points of the non-proliferation, economic and safety views of fuel, fuel cycle and reactor. The R & D efforts of the CANDU innovative fuel would be more clearly justified if CANDU NG as an example would be introduced in Korea just after KNGR #4 which will be constructed for the period of 2007 to 2014 as shown in the long-term construction plan of Korean nuclear power plants.

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Table 1. Current Status of CANDU Power Plants in Korea

Reactor Name	Reactor Type	Capacity (MWe)	Reactor's Manufacturer	T/G Manufacturer	Commercial Operation
Wolsong #1	CANDU-PHWR	679	AECL	NEI/PARSONS	April, 1983
Wolsong #2	CANDU-PHWR	700	AECL	KHIC/GE	June, 1997
Wolsong #3	CANDU-PHWR	700	AECL	KHIC/GE	July, 1998
Wolsong #4	CANDU-PHWR	700	AECL	KHIC/GE	Sept., 1999

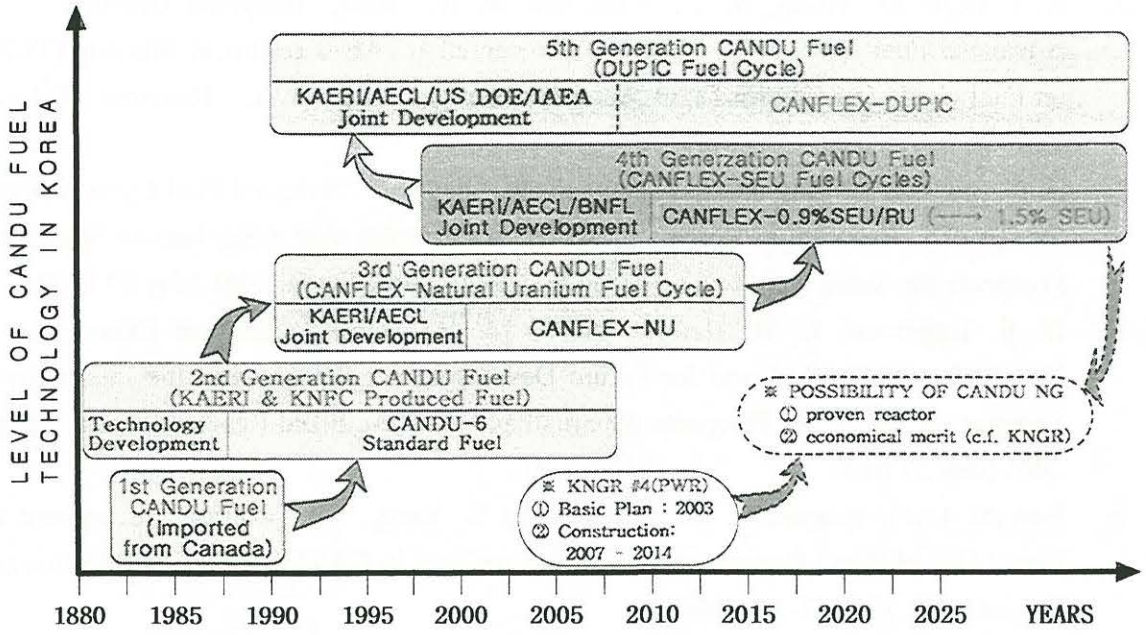

Figure 1. Strategical Projection of CANDU Fuel R & D Programs in Korea