KOREA'S CANDU FUEL R & D PROGRAM

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ABSTRACT

As the first R & D activity led to the nuclear fuel industrialization in Korea, KAERI had successfully developed the CANDU-6 fuel bundle in the period of 1981 to 1986 and has commercially produced more than 35,000 fuel bundles for the use in Wolsong Unit 1 since 1987. The commercial production of the CANDU-6 fuel in KAERI will be terminated on the end of 1997 and KNFC will take over the mission of CANDU-6 fuel production with a capacity of 400 tons of uranium per year from 1998.

In 1992 June, KAERI's long term nuclear R & D program as a national R & D program for the enhancement of nuclear energy development in Korea was established with the approval of Korea Atomic Energy Committee. Subsequently, the KAERI's CANDU fuel R & D projects have been intensively carried out to develop CANDU new fuel such as CANFLEX and DUPIC in which KAERI's advanced CANDU reactor development project also interested. For CANFLEX fuel development : (1) 1992~1998, CANFLEX-NU fuel bundle is being developed jointly by AECL and KAERI. The bundle is expected to provide a fuel bundle format that is more appropriate to the specific needs of CANDU advanced fuel cycles than CANDU-6 fuel bundle; (2) 1996 ~ 2001, CANFLEX-SEU and -RU fuel will be developed to reduce the CANDU fuel cycle cost. For DUPIC fuel development to improve fuel utilization in the next century, (1) 1991~1993, the feasibility study was performed to determine the most promising method of recycling the PWR spent fuel in CANDU; (2) 1993~2000, the study for the experimental verification of the performance of DUPIC fuel by manufacturing and testing of prototypical DUPIC fuel is conducted in cooperation with AECL and US DOS.

To support these CANDU fuel R & D program, KAERI develops the R & D facilities: (1) 1993~1997, a steady state CANDU fuel irradiation loop will be installed at HANARO research reactor; (2) 1997~2001, a transient state CANDU fuel irradiation loop will be installed at HANARO research reactor; (3) 1993 ~ 2000, the preparation of IMEF hot cell facility and development of process equipment are under way for the DUPIC fuel fabrication; (4) Beside these facilities, KAERI also makes recently an attempt on feasibility investigations to have a critical assembly test facility for fuel reactivity tests as well as a loop for CHF tests of CANDU fuel bundle.

1. INTRODUCTION

In Korea, ten nuclear power plants, 9 PWRs and 1 CANDU-PHWR , are currently in operation with a total installed generation capacity of 8,616 MWe which accounts for about 29 % of the domestic installed generation capacity. The current status of Korea's nuclear power plants as of 1995 September is shown in Table 1. In 1995, these nuclear power plants have taken charge of around 34 percent of total annual generation of electric power in Korea. In addition, seven nuclear power plants, 4 PWRs and 3 CANDU-PHWRs, are under construction in Korea. Consequently, Korea will operate 17 nuclear power plants with the total capacity of more than 15,000 MWe by 2001. Beside these nuclear power plants, Korea tentatively plans the construction of additional nine units, 6 PWRs and 3 CANDU-PHWRs for the start-up of 2002 to 2006, and would decommission Kori Unit 1 in 2004, as shown in Table 2. In the year of 2006, 19 PWRs and 7 PHWRs will be operated in Korea. Following the Korea's expected economical growth and energy consumption increase in the future, the nuclear program will remain in the coming 30 years at least as significant as it is today.

Along with the active nuclear power program, the development of nuclear fuel technology has been carried out as a part of the localization of the fuel cycle technology in Korea. In this regard, KAERI (Korea Atomic Energy Research Institute) and KNFC (Korea Nuclear Fuel Company) successfully produce the commercial fuel for the use in CANDU-PHWR and PWRs in Korea, respectively.

As the first R & D activity led to the nuclear fuel industrialization in Korea, KAERI successfully developed the CANDU-6 fuel bundle in the period of 1981 to 1986 and has commercially produced more than 35,000 fuel bundles for use in Wolsong Unit 1 since 1987. In 1992, the Korean Government decided the commercial project of the CANDU fuel production to be transferred from KAERI to KNFC because KAERI is a public organization to do the atomic energy research and development and KNFC is a commercial fuel production company. Subsequently, the commercial production of the CANDU-6 fuel in KAERI will be terminated on the end of 1997 and KNFC will take over the mission of CANDU-6 fuel production with a capacity of 400 tons of uranium per year from 1998.

Also in 1992 June, KAERI's long term nuclear R & D program as a national R & D program for the enhancement of nuclear energy development in Korea was established with the approval of Korea Atomic Energy Committee. As detailed in the following sections, the KAERI's CANDU fuel R & D projects have been intensively carried out to develop CANDU new fuel such as CANFLEX (CANdu FLEXible fuelling) and DUPIC (Direct Use of spent PWR fuel in CANDU) and to develop the R & D facilities such as the fuel irradiation loop in KAERI's HANARO research reactor and IMEF hot cell facility.

2. DEVELOPMENT AND FABRICATION OF CANDU-6 FUEL BUNDLE

Since late period of 1970s, nuclear fuel design and fabrication technologies have been engaged as one important part of KAERI R & D activities. KAERI began the project to develop the design and fabrication technologies of CANDU fuel in 1981 and succeeded in the production of the prototype fuel bundles in 1983. In 1981 to 1982, a Hot Test Loop facility was designed and constructed for the hydraulic tests of CANDU fuel bundles with KAERI's own manpower and technology.

In 1983 and 1984, KAERI performed a series of out-of-reactor tests to evaluate and guarantee the performance and safety of the KAERI's prototype fuel bundles and also to show the compatibility of the fuel bundles with CANDU-6 reactor design. At this period, KAERI successfully completed the tests of the pressure drop, strength, refuelling impact, cross flow and endurance of the bundles using the Hot Test Loop, where the test and evaluation methods were very conservative. All the out-of-reactor test results indicated that the prototype fuel bundles were not only met to the CANDU-6 reactor's hydraulic requirements but also compatible with the primary heat transport system and fuel handling system.

Keeping abreast with the development of the CANDU Hot Test Loop, in 1982, KAERI made the Fuel Verification Agreement with AECL to perform the in-reactor performance test of KAERI's prototype fuel bundles under CANDU-6 reactor condition. Based on the Agreement, two KAERI made fuel bundles were irradiated in the U2C loop of NRU reactor and examined at the AECL Chalk River Hot Cell Laboratory during the period of 1983 and 1984. One of the bundles was filled with 1.58 % slightly enriched UO_2 pellets, and the other was assembled with natural UO_2 pellets. As the results of this NRU irradiation test, AECL and KAERI experts jointly concluded that the bundles performed similarly to Canadian made fuel subjected to the same power history since no significant deviations from normal irradiated CANDU-6 fuel were revealed by surpassing their target burnups.

These results of the in- and out-reactor tests led to carry out the demonstration irradiation test of KAERI made fuel bundles in Wolsong Unit 1 in which the 48 KAERI made fuel bundles were irradiated during 1984 and 1985, and demonstrated the excellent performance with the satisfaction of the discharge burnup and power output requirements without showing any defects. This successful demonstration irradiation of the prototype CANDU-6 fuel bundles in the commercial reactor made to decide commercial scale production of CANDU fuel in KAERI. In 1986, KAERI fabricated 360 fuel bundles and also expanded the production capacity of the research facility to do the commercial scale fuel production for Wolsong Unit 1 from 1987. Up to date, KAERI has commercially produced more than 35,000 fuel bundles for use in Wolsong Unit 1 since 1987. In KNFC site, a CANDU fuel fabrication plant with a capacity of 400 tons of uranium per year is under construction in cooperation with GEC in order to supply the fuel to Wolsong site's CANDU reactors from 1998. At that time, the KAERI production of about 48,000 CANDU-6 bundles as an uranium weight of 900 tons will be accumulated.

3. CANFLEX FUEL DEVELOPMENT

Just after the successful completion of the CANDU-6 fuel R & D including the demonstration irradiation in Wolsong Unit 1, KAERI conducted a CANDU-6 advanced fuel development project between 1987 and 1990. This project focused to develop a CANDU-6 high burnup fuel bundle for the reduction of the fuel cycle cost as well as for the improvement of fuel utilization, where the fuel bundle was intended for use with either NU or any of the enriched fuels in the existing or new CANDU reactors. While, in 1989 and 1990, AECL and KAERI conducted a joint study [1] on the potential for use of CANFLEX fuel in CANDU reactors to identify the advantages and incentives for using CANFLEX with both natural uranium (NU) and various enriched fuels, including slightly enriched uranium (SEU), recovered uranium (RU) and so on. Based on the results of the AECL /KAERI joint study as well as of the KAERI CANDU-6 advanced fuel development project, KAERI concluded that the CANFLEX advanced fuel bundle have wide application in current and future CANDUs. It is intended to be the optimal carrier for the extended burnup cycle for advanced fuel cycles for CANDU power reactors and is intended to permit economic savings associated with improved uranium utilization and reduced spent fuel volume. Subsequently, KAERI expanded the domestic CANDU fuel R & D project into an international program, "AECL/KAERI Joint CANFLEX Development Program (JCDP)" on February 1991.

The prime objective of the JCDP is to complete the development and proof testing of the CANFLEX fuel bundle to permit the use of slightly enriched uranium and other advanced fuel cycles in CANDU power reactors. It is intended that the product of the program will be a fuel bundle developed, tested, and ready for large scale demonstration in a CANDU power reactor [2]. In this paper, the status of the JCDP will not discuss in details because AECL CANFLEX Program Coordinator will present a AECL/KAERI joint paper of "Bringing the CANFLEX Fuel Bundle to Market" in this Conference. This joint paper describes the CANFLEX bundle, the development and testing programs set up to demonstrate its capabilities, plus the results obtained to date in those programs, and also outlines some of the analysis being planned to support a small-scale demonstration irradiation in a CANDU-6 reactor. However, as the following statements, it would be worth to mention KAERI's long term nuclear R & D program approach to the industrial use of CANFLEX fuel in Korea.

In Korea, it is recognized that CANDU provides the utilities and countries operating CANDU plants with a range of short, medium and long term strategic advantages. Paramount among these advantages are competitive economic performance, operational flexibility, safety and fuel cycle flexibility. CANDU can use many low fissile contents fuels, including natural uranium, and other advanced fuel cycles such as SEU and RU. In the longer term, CANDU can utilize Korea's abundant thorium reserves as fuel. This CANDU fuel cycle flexibility ensures long-term energy security by providing diverse fuel cycle option.

Concerning the range of the medium and long term fuel cycle strategy, the KAERI's CANFLEX fuel R & D project has been divided into the two categories, CANFLEX -NU and -SEU(& -RU) fuels which are maybe called respectively as the third and fourth generation CANDU fuels with respect to Korean development level of CANDU fuel technology as shown in Fig. 1. Tables 3 and 4 outline the project for the developments of CANFLEX-NU, -SEU and -RU fuels, respectively. Korean nuclear industrial community and KAERI expect that the CANFLEX-NU fuel will be successfully developed under the AECL and KAERI Joint CANFLEX Development Program. Also, they are hopeful that the CANFLEX-SEU (& -RU) fuel will be continuously developed by AECL and KAERI jointly. Particularly the

HANARO in-reactor fuel irradiation test loop as stated in Section 5 is strongly expected to support the irradiation study of CANFLEX-SEU (&-RU) fuel as CANDU high burnup fuel.

KAERI has actively made efforts not only to develop the CANFLEX fuel bundle but also to demonstrate the small-scale irradiation of CANFLEX-NU fuel in Wolsong Unit 1 for the proof testing of the CANFLEX fuel bundle in CANDU power reactor and then ultimately to do the full loading of CANFLEX fuel in Wolsong CANDU-6 reactors. KAERI and AECL have jointly presented the CANFLEX program three times to the owner of Wolsong reactors, KEPCO (Korea Electric Power Company), and one time to KINS (Korea Institute of Nuclear Safety) which is the atomic regulatory body in Korea since 1992. Also, KAERI has used to report and/or present the KAERI status of CANFLEX program to MOST (Ministry of Science and Technology), KEPCO and KINS. Therefore, KEPCO has recognized that the use of CANFLEX fuel will reduce the peak heat ratings for a given bundle power, provide better fuel performance at the higher burnup, and provide greater flexibility of fuel element internal design through the use of natural or slightly enriched uranium or other advanced fuel cycle for optimization of uranium supply-demand imbalance in the future. Also, KEPCO recently recognized the economic advantage for the use of CANFLEX fuel in Wolsong reactors, providing Table 5 of CANFLEX-NU, -SEU and -RU fuel cycle costs with respect to the CANDU-6 standard fuel. This CANFLEX economic evaluation was based on KEPCO input data of uranium, conversion, enrichment and fabrication costs. So, these circumstances encourage KAERI very much to do the demonstration irradiation of CANFLEX fuel bundles in Wolsong Unit 1.

In Korea, there are two steps of Government's licensing for the irradiation of a new fuel in a commercial nuclear power reactor according to Korean Atomic Law and Regulations, which is independent on the scale of irradiation: (1) the fuel manufacturer shall obtain the Government's fuel design approval before the manufacturing of the fuel for the irradiation, by submitting the application documents with the report of fuel design and description of fuel fabrication process ; (2) the owner of the power reactor shall obtain the Government's fuel loading license before the irradiation, by submitting the application documents with the safety analysis report, report of fuel test results, nuclear design report, validation report of computer codes used in the safety analysis. Regarding the small scale demonstration irradiation of CANFLEX-NU fuel bundles in Wolsong Unit 1, all the administrative and technical documents for the Government's design approval as well as all the technical documents for the fuel loading license are being prepared by KAERI, and so to do the applications, hopefully, by around 1996 March. Based on this schedule, therefore, KAERI expects the CANFLEX-NU fuel development project including the small scale demonstration irradiation of the fuel in Wolsong Unit 1 to be sucessfully completed until 1998.

4. DUPIC FUEL DEVELOPMENT

Considering that the PWR spent fuel contains large enough fissile elements to be burned in CANDU reactor, DUPIC is the concept of reusing spent PWR fuel in CANDU reactor by fabricating fuel through thermal-mechanical processes. The potential benefits of the DUPIC fuel cycle comparing with the conventional wet reprocessing are : (1) proliferation resistance due to the non-separation of all the uranium, plutonium and fission products with high radioactivity along the fabrication processes, (2) the small amount of radioactive waste due to its nature of dry processing. Moreover, it will reduce the spent fuel to be disposed by utilizing spent PWR fuel and the high burnup in CANDU, and will improve uranium resource utilization being in harmony with the Korean electric power generation strategy of combining the PWR and CANDU reactors.

A feasibility study as the Phase I research program was performed to evaluate the characteristics of fuel and processes and to determine most promising way of DUPIC fuel cycle from 1991 to 1993 in cooperation with AECL and US DOS. The evaluation criteria were reactor physics, fuel performance, fabrication and handling, waste management, and ability of safeguards, licence and retrofit to CANDU. Among seven DUPIC options, OREOX (Oxidation and REduction of OXide fuel) process was selected as a most promising method in the view points of homogeneity of the characteristics of fuel produced by OREOX process which is favorable in terms of physics, fuel performance and licensability.

In OREOX process, the PWR spent fuel will be decladded, and the fuel meat is treated by successive oxidation and reduction to produce the resinterable powder for the DUPIC fuel fabrication. During this process, most of gaseous and volatile fission products will be removed. Then, the DUPIC fuel will be manufactured through the powder/pellet route similar to the conventional CANDU fuel fabrication.

Following the feasibility study, the Phase II research program for the experimental verification of DUPIC fuel was started in tripartite cooperation between KAERI, AECL and USA in 1993 [3]. Its main objectives are to manufacture several prototype DUPIC fuel and test them in a research reactor to verify their performance. The major activities and milestones are shown in Table 6. The DUPIC fuel will be fabricated using currently available hot cells in KAERI, such as PIEF (Post Irradiation Examination Facility) and IMEF (Irradiated Materials Examination Facility), and the prototype fuel will be irradiated in HANARO. To meet the objectives, the wide scope of technologies in the areas of reactor physics and safety analysis, fuel manufacturing and quality control, hot cell facility preparation, radioactive waste treatment, and safeguards technique shall be developed.

The parametric analyses of DUPIC fuel cycle, selection of the optimum fuel composition and its effects on the fuel performance and safety are studied in cooperation with AECL[4]. The off-gas treatment during fuel manufacturing and stabilization of radioactive waste are the one of the important areas for the technology development. The safeguards system and nondestructive accounting technology are developed. Moreover, the OREOX process, manufacturing process and equipment developments and fuel performance analysis can be considered as crucial areas for the success of the DUPIC project.

The key step of DUPIC fuel development is the experimental verification of the OREOX process which will convert the PWR spent fuel meat into powder feedstock for the fabrication of high quality DUPIC pellet. As a preliminary experiment, KAERI has prepared simulated PWR spent pellets, and treated them with several cycles of oxidation and reduction. The simulated DUPIC pellets were then fabricated from the powder feedstock. Based on the results, it was tentatively concluded that the reliable DUPIC pellets with high sintered density can be produced by utilizing powder milling process after oxidation and reduction steps. However, it requires the accumulation of more experimental data and confirmation by the actual test with PWR spent fuel.

All the DUPIC fabrication campaigns shall be performed in remote operational manner at hot cells. The development of the process technology and equipment to be practical use in the campaigns is another important aspect of DUPIC fuel development. Some of the fabrication and quality control processes shall be modified to fit in remote operation and improved for the elimination of radioactive hazards and wastes. Even though KAERI has no a lot of experiences in the precise operation of hot cell equipment, the prototype DUPIC fuel will be successfully fabricated by utilizing the process automation and robotics technology developed for other remote operations. The major process equipment are conceptually designed now, and are going further on the development for the manufacturing and testing.

The DUPIC is a new conceptual CANDU fuel. It is not easy to find the closely-relevant technical information and nuclear data which will be used for the evaluation of DUPIC fuel performance. The experimental data for the behavior of various fission products in OREOX process and irradiation of DUPIC fuel are collected and analyzed. The details of the test irradiation and evaluation methods will be established.

5. R & D FACILITIES FOR THE FUEL DEVELOPMENT

To support these CANDU fuel R & D projects, KAERI develops the R & D facilities such as the irradiation test loops of HANARO research reactor in KAERI and DUPIC hot cell facility of IMEF (Irradiated Material Examination Facility). These facility development projects are also being progressed under KAERI's long term nuclear R & D program.

In 1993 to 1997, a steady state fuel irradiation loop facility with two in-pile sections for the CANDU and PWR fuel irradiation tests is scheduled to be constructed at HANARO of which initial criticality reached on 1995 February 8. The in-pile section for CANDU fuel irradiation tests will be manufactured for the irradiation of, at least, one CANDU-6 type fuel bundle with the nominal power of 800 kW under the nominal outlet coolant pressure of 10 MPa and the nominal outlet coolant temperature of 310 ^oC, where the average thermal neutron flux of 1.26×10^{14} n /(cm^2-sec) is expected for irradiation of a 4 % enriched uranium fuel bundle. The items of CANDU fuel irradiation study in the loop experiments are shown in Table 7. This irradiation loop system is being designed in cooperation with DAEWOO Engineering Company in Korea, Stone & Webster Engineering Corporation and Battelle Pacific Northwest Laboratories in USA. In 1995 January, the structural supports for the in-pile sections was completely installed in the research reactor. This HANARO steady state fuel irradiation loop will be operated by 1997 July. So, on the occasions of the HANARO operation as well as on the expectation of the fuel irradiation facility operation in 1997, the loop utilization programs up to the year 2001 have been comprehensively established for the CANFLEX-SEU and -RU and DUPIC fuel developments, which are described in KAERI document [5]. KAERI is hopeful that foreign countries join the KAERI's fuel irradiation program or use the irradiation and post irradiation examination facilities.

Also as one of the KAERI's long term nuclear R & D programs, a transient state CANDU fuel irradiation loop will be installed at HANARO research reactor from 1997 to 2001, in order to study the effects of power cycling on fuel integrity and material properties.

The PIEF at KAERI has been operated since 1987. This facility is adequately provided with PWR spent fuel storage in pool (up to 12 PWR assemblies) and dismantling. The small hot cells adjacent to the pool have been in use for PIE purposes such as fuel rod cutting and sample analyses. Considering the satisfactory operation experiences of the PIEF, not much difficulties are expected in using it for DUPIC purposes. As another hot cell facility at KAERI, IMEF is currently under test operation adjacent to HANARO at neighboring location to the PIEF. The IMEF was originally designed to complement technical functions of the PIEF in support of the HANARO operation. As this facility consists of sizable hot cell lines, some part of the hot cell spaces can be used, in principle, for remote fabrication of DUPIC fuel by refurnishing of some relevant equipment. In the M-6 cell as so-called the DUPIC cell in the IMEF, the DUPIC fuel fabrication process equipment for the oxidation/reduction, pelletizing, element and bundle fabrications, waste management and safeguards, which are under development, will be completely installed and operated until 2000.

For the industrial use of CANFLEX-SEU, DUPIC fuel and other advanced fuel cycles in CANDU power reactors, it is believed that the reactor physics and thermalhydraulic characteristics of the fuels shall be well established by means of validated computer code calculations and/or experimental data, as done for CANDU natural uranium fuel. So, KAERI takes a growing interest in the test facilities of reactor physics and thermalhydraulics and then makes recently an attempt on feasibility investigations to have a critical assembly test facility for fuel reactivity tests as well as a Freon Loop for CHF tests of fuel assembly.

6. SUMMARY AND CONCLUSIONS

In 1981 to 1986, KAERI successfully developed the CANDU-6 fuel bundle, which was the first R & D activity led to the nuclear fuel industrialization in Korea. So far, KAERI has supplied more than 35,000 fuel bundles to Wolsong Unit 1 since 1987. The commercial production of the CANDU-6 fuel in KAERI will be terminated on the end of 1997 and KNFC will take over the mission of the fuel production with an annual capacity of 400 tons of uranium from 1998.

In 1992 June, KAERI's long term nuclear R & D program as a national R & D program for the enhancement of nuclear energy development in Korea was established with the approval of Korea Atomic Energy Committee. Subsequently, the KAERI's CANDU fuel R & D projects have been intensively carried out to develop CANDU advanced fuel and their related experimental facilities and equipment:

1) Development of CANFLEX fuel to improve the operational safety and fuel cycle cost.
   (1) 1992 ~ 1998, CANFLEX-NU fuel bundle is being developed jointly by AECL and KAERI. The bundle is expected to provide a fuel bundle format that is more appropriate to the specific needs of CANDU advanced fuel cycles than CANDU-6 fuel bundle.
   (2) 1996 ~ 2001, CANFLEX-SEU and -RU fuel as CANDU high burnup fuel will be developed to reduce the CANDU fuel cycle cost as well as to reduce the volumetric production rate of spent fuel.

2) Development of DUPIC Fuel for the improvements of uranium utilization , the reduction of volumetric production rate of spent fuel and proliferation resistance as a prospective nuclear fuel cycle in future.
   (1) 1991 ~ 1993, a feasibility study resulted to determine the most promising method of recycling the PWR spent fuel in CANDU
   (2) 1993 ~ 2000, the study for the experimental verification of the performance of DUPIC fuel by manufacturing and testing of prototypical DUPIC fuel is being conducted in cooperation with AECL and US DOS. The international joint research project between KAERI, AECL and USA will provide the valuable database to experimentally verify the performance of DUPIC fuel and to evaluate the usefulness of the DUPIC fuel cycle in practice.

3) Development of R & D facilities and equipment to support the CANDU fuel R & D projects.
   (1) 1993~1997, a steady state fuel irradiation loop is being installed at HANARO.
   (2) 1997~2001, a transient state fuel irradiation loop is scheduled to be installed at HANARO.
   (3) 1993 ~ 2000, the preparation of IMEF hot cell facility and development of process equipment are under way for the DUPIC fuel fabrication.
   (4) Beside these facilities, KAERI also makes recently an attempt on feasibility investigations to have a critical assembly test facility for fuel reactivity tests as well as a loop for CHF tests of CANDU fuel bundle.

These CANDU fuel R & D projects are also incorporated with KAERI's advanced CANDU reactor development project, and will be led to the Korea's expected economicical growth and energy consumption increase in future. Also, Korea is really hopeful that the R & D results will be contribute the enhancement of the peaceful nuclear energy development in the World.

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Table 1. Current Status of Korea's Nuclear Power Plants as of September 1995

Reactor Name	Reactor Type	Capacity (MWe)	Manufacturer		Commercial Operation*
			Reactor	T/G	
Kori # 1	PWR	587	WH	GE	1978 April
Kori # 2	PWR	650	WH	GE	1983 July
Kori # 3	PWR	950	WH	GE	1985 Sept.
Kori # 4	PWR	950	WH	GE	1986 April
Wolsong #1	CANDU	679	AECL	NEI/PARSONS	1983 April
Wolsong #2	CANDU	700	AECL	KHIC/GE	(1997 June)
Wolsong #3	CANDU	700	AECL	KHIC/GE	(1998 June)
Wolsong #4	CANDU	700	AECL	KHIC/GE	(1999 June)
Yonggwang #1	PWR	950	WH	WH	1986 Aug.
Yonggwang #2	PWR	950	WH	WH	1987 June
Yonggwang #3	PWR	1000	KHIC	KHIC/GE	1995 March
Yonggwang #4	PWR	1000	KHIC	KHIC/GE	(1996 March)
Yonggwang #5	PWR	1000	KHIC	KHIC	(2000 June)
Yonggwang #6	PWR	1000	KHIC	KHIC	(2001 June)
Ulchin #1	PWR	950	FRAMATOME	ALSTHOM	1988 Sept.
Ulchin #2	PWR	950	FRAMATOME	ALSTHOM	1989 Sept.
Ulchin #3	PWR	1000	KHIC	KHIC/GE	(1998 June)
Ulchin #4	PWR	1000	KHIC	KHIC/GE	(1999 June)

* Dates in brackets are the expected date for commercial operation of the reactors under construction in current.

Table 2. Power Reactors Planned Tentatively up to 2006 in Korea

Reactor Name	Reactor Type	Capacity (MWe)	Commercial Operation
KNU #19	**PHWR**	700	2002 June
KNU #20	PWR	1000	2002 June
KNU #21	PWR	1000	2003 June
KNU #22	**PHWR**	700	2003 June
KNU #23	PWR	1000	2003 Oct.
KNU #24	PWR	1000	2004 June
KNU #25	PWR	1000	2005 June
KNU #26	PWR	1000	2006 June
KNU #22	**PHWR**	700	2003 June
Kori # 1	PWR	587	2004 (Decommissioning)

Table 3. KAERI's CANDU Fuel R & D Program for the Development of CANFLEX-NU Fuel

Work Scope	Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Fuel Design	- Fuel Design	◄	─	─	►						
	- Performance Analysis		◄	─	─	►					
	- Fuel Design Manual				◄	►					
	- Products and Materials Specifications			◄	─	►					
	- Test Specifications				◄	►					
Reactor Physics	- Full Core Analysis	◄	─	─	─	►					
	- Transition Core Analysis				◄	►					
	- Physics Manual				◄	►					
Thermalhydraulics	- Full Core Analysis			◄	─	─	►				
	- Transition Core Analysis					◄	►				
Safety Analysis	- Generic Evaluation of Full Core Loading in Wolsong # 1	◄	─	─	─	─	►				
	- Reload Transition Safety Analyis				◄	─	►				
Fuel Fabrication	- Fuel Fabrication for										
	a) Hydraulic Tests	◄	─	─	─	►					
	b) Fuel Handling Tests					◄►					
	c) NRU Irradiation Tests										
	d) ZED-2 Reactivity Tests					◄►					
	e) Demo Irradiation in Wolsong # 1						◄	►			
In - Research Reactor Tests	- NRU Irradiation & PIE Tests at AECL						◄	►			
	- ZED-2 Reactivity Tests at AECL					◄	►				
Out-of-Reactor Tests	- CHF Tests at AECL		◄	─	─	─	►				
	- Fuel Handling Tests at AECL					◄►					
	- Hydraulic Tests at KAERI			◄	─	─	►				
Licensing	- Documentation					◄	►				
	- Government Design Approval						◄►				
	- Licensing for Demo Irrad. in Wolsong # 1						◄►				
Demo Irradiation in Wolsong # 1	- Demo Irradiation in Wolsong #1							◄	►		
	- PIE at KAERI									◄	►

Table 4. KAERI's CANDU Fuel R & D Program for the Development of CANFLEX-SEU (& -RU) Fuel

Work Scope	Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Fuel Design	- Bundle Optimization and Fuel Design	◄	─	─	►						
	- Performance Analysis		◄	─	─	►					
	- Fuel Design Manual				◄	─	►				
	- Products and Materials Specifications			◄	─	►					
	- Test Specifications				◄	►					
Reactor Physics	- Full Core Analysis	◄	─	─	─	►					
	- Transition Core Analysis				◄	─	►				
	- Physics Manual				◄	►					
Thermalhydraulics	- Full Core Analysis			◄	─	─	►				
	- Transition Core Analysis					◄	►				
Safety Analysis	- Generic Evaluation of Full Core Loading in Wolsong Rx.	◄	─	─	─	─	►				
	- Reload Transition Safety Analyis				◄	─	►				
Fuel Fabrication	- Technology Development	◄	─	─	►						
	- Fuel Fabrication for										
	a) Hydraulic Tests		◄	─	─	─	►				
	c) HANARO Irradiation Tests		◄	─	─	►					
	d) Reactivity Tests					◄►					
	e) Demo Irradiation in Wolsong Rx.						◄	►			
In - Research Reactor Tests	- HANARO Irradiation & PIE Tests		◄	─	─	─	─	►			
	- Reactivity Tests						◄►				
Out-of-Reactor Tests	- Scoping and Qualification CHF Tests		◄	─	─	─	►				
	- Scoping and Qualification Hydraulic Tests at KAERI		◄	─	─	►					
Licensing	- Documentation					◄	►				
	- Government Design Approval						◄►				
	- Licensing for Demo Irrad. in Wolsong Rx.						◄►				
Demo Irradiation in Wolsong Rx.	- Demo Irradiation in Wolsong Rx.							◄	►		
	- PIE at KAERI									◄	►

Table 5. Relative Fuel Cycle Costs of CANFLEX-NU, -SEU and RU with respect to the CANDU-6 Standard Fuel

Fuel Type	CANDU-6 37-Eleemnts 0. 71 % NU	CANFLEX 43-Elements 0. 71 % NU	CANFLEX 43-Elements 0. 9 % SEU	CANFLEX 43-Elements 1. 2 % SEU	CANFLEX 43-Elements RU (0.9 %)
Relative value of the fuel cycle cost	1.00	1.04	0.87	0.73	0.46

Note: All the input costs provided by KEPCO is used for this cost evaluation, where the fabrication cost of CANFLEX 43-element fuel is assumed to be 16.2 % higher than that of CANDU-6 37-element fuel..

Table 6 : Outline of the Experimental Verification Program of DUPIC

WORK SCOPE	YEAR	1994	1995	1996	1997	1998	1999	2000	Remarks
Fuel Element fabrication & verification	- Fabrication process development	↔							AECL & KAERI
	- Element fabrication		↔	↔					
	- Element irrad. test				↔	↔			
	- PIE						↔		
	- Performance evaluation						↔		
Fuel Bundle fabrication & verification	- Fabrication process development	↔	↔	↔					KAERI
	- Bundle fabrication				↔	↔			
	- Bundle irrad. test					↔	↔		
	- PIE.							↔	
	- Performance evaluation							↔	
Reactor physics & safety analysis	- Selection of optimal fuel composition	↔	↔						AECL & KAERI
	- Mechanical integrity analysis	↔	↔	↔					
	- Physics analysis			↔	↔	↔			
	- Safety analysis					↔	↔	↔	
Safeguards development	- Material control and accounting system development	↔	↔	↔					KAERI & USA
	- Measurement technology	↔	↔	↔	↔				

Table 7. Items of Irradiation Study in the Loop Experiments

1. Fuel	UO_2 (SEU and RU); DUPIC,
2. Fuel design	Cylindrical pellet, Hollow cylindrical pellets, Dished end cylindrical pellets, Pellets with variations of density, grain size, chamfer, land width and dish depth, Elements with variations of diametral and axial gaps.
3. Sheath	Zircaloy-4 tube with graphite coated or non-coated on the inner surface.
4. Bundle design	Proof tests of fuel bundles with brazed bearing and spacer pads, welded or brazed button, and optimized element configuration
5. Metallurgy	Fabrication techniques, Creep rates, Corrosion effects
6. Coolant chemistry	Crud formation and deposition, Gas formation, PH control; Corrosion decontamination; Fuel defects, Hydriding, etc
7. Heat transfer	Critical heat flux correlations (dryout tests), Pressurized water, boiling water fog and steam modes of cooling, internally ridged pressure tube, etc.

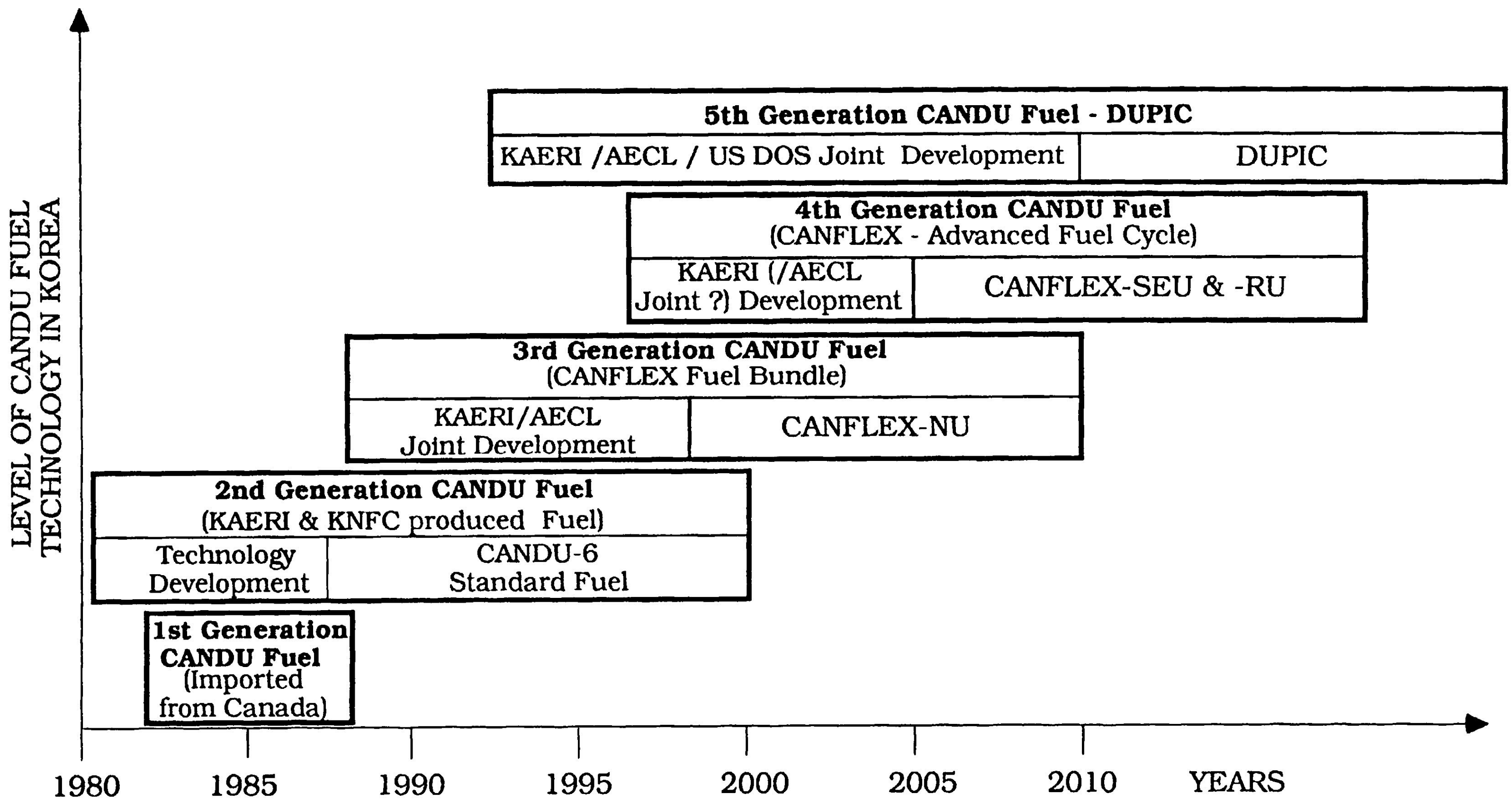

Fig. 1 Strategical Projection of CANDU Fuel R & D Programs in Korea