PHWR ADVANCED FUEL R & D FOR THE 21ST CENTURY IN KOREA

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ABSTRACT

As the first CANDU-PHWR nuclear power plant in Korea, Wolsong Unit 1 has been successfully operated since 1983. The CANDU installed electric-generation capacity was about 50 % of the installed electric-generation capacity of nuclear power plants in Korea in 1983 but then decreased to less than 10 % of the total installed nuclear electric-generation capacity by 1996. This CANDU installed electric-generation capacity has recovered to about 20 % of the total installed nuclear electric-generation capacity in 1999, because Wolsong Units 2, 3 and 4 have been placed into commercial operation in 1997, 1998 and 1999, respectively. This indicates that CANDU reactors are not the majority of nuclear power plants in Korea.

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. As one of the early R & D activities leading to nuclear power industrialization in Korea, the project to develop the design and fabrication technology of CANDU-6 37-element fuel had been successfully carried out from 1981 to 1987 by KAERI. Just after the successful completion of the 37-element fuel R & D, KAERI has developed a CANDU-6 advanced fuel. The key targets of the development program are safety enhancement, reduction of spent fuel volume, and economic improvements, using the inherent characteristics and advantages of CANDU technology.

The CANFLEX and DUPIC R & D programs have been conducted under Korea's Nuclear Energy R & D Project as national mid- and long-term programs since 1992. As the second of the CANDU R & D products in Korea, the CANFLEX-NU fuel has been jointly developed by KAERI and AECL. The fuel has demonstrated its irradiation performance in a Canadian commercial power reactor, Pt. Lepreau Generating Station since 1998 September.

The RU(SEU) and DUPIC fuels are expected to be developed continuously until about the year 2010 for their use in CANDU reactors. Beside these fuel cycles, SEU, LWR/PHWR synergism (RU, MOX, TANDEM) and Th could be also considered for CANDU fuel cycles in the 21st century, because CANDU fuel cycle flexibility arises naturally from excellent neutron economy, on-power fuelling, and simple fuel design. The advanced fuel cycles can be utilized in the CANFLEX 43-element fuel bundle. However, the CANDU-PHWR advanced fuel R & D for the 21st century in Korea shall take into account "nuclear safety", "nuclear waste", "non-proliferation" and "economics" in the favor of the arguments from the public, international environment, and utilities.

1. INTRODUCTION

Korea is unique among nations in having both PWR and CANDU-PHWR reactors. In Korea, sixteen nuclear power plants with 12 PWRs and 4 CANDU-PHWRs are now in operation with a total installed generation capacity of 13,716 MWe, which accounts for about 27 % of the domestic installed electric-generation capacity in Korea. The nuclear power plants produce 100,315 GWh electricity, which is about 40 % of the total generated electricity in Korea. The installed electric-generation capacity of the four CANDU-PHWRs is 2,779 MWe, which accounts for about 20 % of the total installed generation capacity of the Korean nuclear power plants. Beside these operating nuclear power plants, 4 PWRs are now under construction which will have a total installed generation capacity of an additional 4,000 MWe.

As shown in Figure 1, the CANDU electric-generation capacity was more than 30 % of the total nuclear electric-generation capacity in Korea for the period from 1983 to 1985, but had decreased to less than 10 % of the Korean nuclear electric-generation capacity by 1996. This ratio of CANDU electric-generation capacity to the Korean nuclear electric-generation capacity has slightly recovered to about 20 % in 1999 due to the commercial operations of Wolsong Units 2, 3, and 4. Therefore, it is certainly recognized that CANDU-PHWR reactors are not the majority of nuclear power plants in Korea. But they have produced significant electricity to contribute to Korea's economic growth as well as to satisfy the need for energy since 1983. Korea can therefore exploit the natural synergism between the two reactor types to minimize overall waste production, and maximize energy derived from the fuel, by burning the spent fuel from its PWR reactors in CANDU reactors.

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 past and current activities of CANDU fuel R & D leading to nuclear power industrialization in Korea. It also describes the CANDU fuel cycle options in connection with CANDU advanced fuel R & D for the 21st century in Korea, by taking into account "nuclear safety", "nuclear waste", "non-proliferation" and "economy" in favor of the arguments from public acceptance, international environments, and utilities.

2. ACTIVITIES OF CANDU FUEL R & D IN KOREA

2.1 37-Element Fuel

As one of the early R & D activities leading to nuclear power industrialization in Korea, the project to develop the design and fabrication technology of CANDU-6 37-element fuel had been successfully carried out from 1981 to 1987 by the Korea Atomic Energy Research Institute (KAERI) [1]. KAERI commercially produced and supplied more than 45,000 37-element fuel bundles to Wolsong Unit 1 from 1987 to 1996. In the course of the commercial production of the 37-element fuel bundles since 1987, KAERI has improved the design and fabrication of the 37-element bundle components, such as end-pellets and bearing pads. KAERI's commercial fuel manufacturing activity was transferred to the Korea Nuclear Fuel Company (KNFC), according to Korea's reformed nuclear energy industrial structure at the end of 1996 as a follow-up to the national policy.

2.2 43-Element CANFLEX-NU Fuel

Just after the successful completion of the 37-element fuel R & D, KAERI has developed a CANDU-6 advanced fuel [2]. The key targets of the development program were safety enhancement, reduction of spent fuel volume, and economic improvements, using the inherent characteristics and advantages of CANDU technology. As a national project for more incentive, efficient and active development of nuclear energy, Korea's Nuclear Energy R & D Projects as mid- and long-term programs have been operated by the Korea Ministry of Science and Technology since 1992. For example, KAERI has successfully carried out the CANFLEX (CANDU Flexible Fuelling) [3] and DUPIC (Direct Use of spent PWR Fuel in CANDU) [4] fuel development programs under the national R & D project.

As a prime example of the results that can be achieved through collaborative ventures between Canada and Korea, KAERI and Atomic Energy of Canada Limited (AECL) have, since 1991, jointly developed CANFLEX (CANDU Flexible Fuelling), to facilitate the use of various advanced fuel cycles in CANDU reactors. This new bundle, CANFLEX design [3], provides greater subdivision of the fuel than other CANDU fuel bundles, having 43 elements with two pin sizes. The increased number of elements and the use of two element sizes reduce the peak element rating by up to 20 % compared with a 37-element bundle operating at the same bundle power output The lower fuel rating in the CANFLEX bundle facilitates the adoption of extended burnups in CANDU reactors that are necessary for the economic use of various attractive fuel cycles Also, the lower fuel rating reduces the consequences of most design-basis accidents. The CANFLEX design also uses critical heat flux (CHF) enhancing appendages, which enable a high power to be realized before CHF occurs, leading to a net gain in the critical channel power typically of 6 to 8 % over the existing 37-element fuel. These two features provide larger operating margins and thus great operating flexibility in existing CANDU reactors, and will allow higher burnups.

The CANFLEX fuel bundles are presently undergoing demonstration irradiation in the CANDU-6 PHWR power plant at Pt. Lepreau in New Brunswick, Canada [5]. In September 1998, eight CANFLEX-NU bundles were loaded into a low-power channel Q20, and eight CANFLEX-NU bundles were loaded into a high power channel, S08, using the standard fuelling eight-bundle shift, where eight fresh-fuel bundles replace eight irradiated bundles on-line. In March 1999, channel S08 was refuelled with eight more CANFLEX-NU bundles, at which time four CANFLEX-NU bundles were discharged into the fuel bay and were shown to be successfully irradiated in the reactor.

Once the CANFLEX-NU fuel successfully demonstrates irradiation in a power reactor, KEPCO (Korea Electric Power Cooperation) and KAERI will more intensively discuss the use of CANFLEX-NU fuel in Wolsong Unit 1. If the fuel is introduced into the CANDU reactor at the Wolsong site, production of CANFLEX-NU will be transferred from KAERI's nuclear fuel R & D activities to the KNFC (Korea Nuclear Fuel Company) at the KAERI site.

2.3 CANFLEX-0.9 % Equivalent SEU(RU) Fuel [6]

As one of the CANFLEX fuel development programs in KAERI, RU (Recovered Uranium from spent nuclear fuel) fuel development for CANDU reactors is an international collaboration between KAERI, AECL and BNFL(British Nuclear Fuels plc). The use of recovered uranium (RU) in CANDUs is an excellent example of the environmental 3R's (Reduce, Reuse, Recycle) as applied to global nuclear energy use. RU fuel offers a very attractive alternative to the use of natural uranium (NU) and slightly enriched uranium (SEU) in CANDU reactors, because fuel economy is expected to improve even more through the use of RU. RU, with about 0.9 % ^{235}U enrichment, results in an average discharge burnup of about twice that of NU in a CANDU reactor, thereby increasing resource utilization and reducing fuel requirements. The ^{235}U isotope would be burned down to low levels of 0.2 % to 0.3 % in CANDU reactors, compared with the burned down levels of 0.8 % to 1.0 % in LWRs ; thus there would be no economic incentive for further recycling of this material. Spent fuel volumes and fuelling costs are reduced. Therefore, the use of RU in CANDU reactors potentially offers economic, environmental and public acceptance benefits on both the front-end and back-end. These benefits all fit well with the PWR-CANDU fuel cycle synergy. RU also offers greater flexibility in reactor and bundle designs and a power uprating capability. RU fuel can be packaged in the CANFLEX fuel bundle, since the full benefits of the use of RU in CANDU reactors are achieved through the provision of enhanced margins in the bundle design.

The use of RU in Korean CANDU reactors is not dependent on reprocessing Korean spent LWR fuel; RU, like NU and SEU, is a nuclear fuel commodity available from several sources. The cumulative quantity of RU projected to arise by the year 2000 from the reprocessing of spent oxide fuel in Europe and Japan will approach 25,000 te. This quantity would provide sufficient fuel for 500 years of CANDU-6 reactor operation. Security of supply is, therefore, not an issue, and in addition, SEU of equivalent enrichment can always be substituted for RU. It is anticipated that using RU in CANDU reactors will provide improvements in fuel cycle economics.

For the use of RU in CANDU reactors before the year of 2010, the detailed fuel design, reactor physics, thermalhyduraulic, and safety analyses, proof testing, and code validations will be performed in the R & D phase for 2000 April to 2006 March. This work will lead to a small-scale demonstration of irradiation in a commercial power reactor, if the overall evaluation and identification of the potential benefits, risks, and costs for the RU fuel are shown by 2000 March.

2.4 DUPIC Fuel Cycle

Considering that spent PWR fuel contains enough fissile materials to be burned in CANDU reactors, DUPIC[4, 7] involves converting the spent PWR fuel in CANDU fuel by a thermal-mechanical dry process without any wet chemical processing. DUPIC fuel cycle technology is currently under development at KAERI in cooperation with AECL, the US Department of State and IAEA (International Atomic Energy Agency). The potential benefits of the DUPIC fuel cycle in comparison with conventional wet reprocessing are:

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

(2) a smaller amount of radioactive waste due to the nature of dry processing.

KAERI, AECL and the US Department of State have examined several possible DUPIC fuel cycles. These include converting the spent PWR rods into CANDU fuel bundles with or without double cladding; vibratory packing of milled PWR pellets into fresh CANDU sheaths; and thermal-mechanical processing of the spent PWR pellets to form sinterable CANDU pellets. All options were judged to be technically feasible, and the last option, called "OREOX (Oxidation/Reduction of Oxide fuel) was chosen for further study [7]. The current technical feasibility study of the tripartite cooperation involves fabricating elements and bundles, to confirm technical feasibility of the process, to optimize the process, and to obtain technical information that would enable an economic comparison to be made with alternate technologies [8]. AECL has successfully fabricated DUPIC fuel pellets at the Whiteshell Laboratories for irradiation tests. The required fabrication and test facilities for the main fabrication campaign are being prepared in KAERI.

The existing R & D facilities including the hot cell facilities of the PIEF (Post-Irradiation Examination Facility), IMEF (Irradiated Material Examination Facility), HANARO research reactor and other laboratories in KAERI will be utilized with minimum modification for the fabrication of prototypical fuel. Equipment has been commissioned for additional fabrication development work in the PIEF to fabricate some DUPIC pellets using spent Korean PWR fuel. From the end of this year, several DUPIC fuel pellets and elements will be fabricated. KAERI plans experimental irradiation testing of the DUPIC fuel in the HANARO research reactor. This R & D of the DUPIC fuel cycle will be continued in the next century, if the overall compatibility of DUPIC fuel with current operating CANDU reactors in Korea is successfully shown by the end of 2000, thereby minimizing the necessary hardware modification of the reactors.

2.5 CANDU Advanced Fuel Cycle Options for the 21ST Century in Korea

The once-through natural uranium fuel cycle has served Korea well, and it continues to do so. However, fuel cycle considerations are not static in time. Korea is now technically far more advanced than when it first embarked on its ambitious nuclear program. At sometime in Korea's industrial development, the incentives for using natural uranium fuel in CANDU reactors may be outweighed by the advantages of adopting a different fuel cycle.

Slightly Enriched Uranium (SEU) [9,10]: SEU would reduce the quantity of spent fuel produced in CANDU reactors, and this may be positively viewed by the public. 0.9 % or 1.2 % SEU fuel would increase the efficient fuel burnup by a factor of 2 or 3 compared with natural uranium fuel, and hence reduce the quantity of spent fuel produced by the same factor. SEU would further improve uranium utilization. A reduction of about 25 % in uranium requirements per unit energy is achieved for enrichments between 0.9 and 1.2 %. Uranium utilization is an important consideration in Korea, a country that has few indigenous uranium resources and that has a keen strategic interest in energy self-reliance. Enrichments between 0.9 % and 1.2 % also reduce CANDU fuel-cycle costs by 20 ~ 30 % compared with natural uranium fuel.

CANDU/PWR Synergism [9,10]: Korea is a unique country having both PWR and CANDU reactors. Korea can therefore exploit the natural synergism between the two reactor types to minimize the overall spent fuel production, and maximize energy derived from the fuel, by burning the spent fuel from its PWR reactors in CANDU reactors. This synergism can be exploited by the use of several fuel-cycle alternatives such as RU and DUPIC as mentioned above, mixed oxide $(Pu,U)O_2$ fuel (MOX) and the TANDEM fuel cycle. The possibility of recycling the MOX fuel or TANDEM fuel from reprocessed PWR fuel back into CANDU reactors for energy self-sufficiency is enabled with the CANDU/PWR two-reactor system.

Thorium fuel cycle [11]: ^{235}U, currently being used in PWR, BWR and CANDU reactors, is a finite resource. One way of extending the ^{235}U indefinitely is through the use of fuel cycles based on thorium. The thorium fuel cycle in CANDU reactors [9] provides long-term assurance for nuclear fuel supplies, using a proven, reliable reactor technology. Those same CANDU features that provide fuel-cycle flexibility also make possible many thorium fuel cycle options. There are 2 broad classes: recycling options, in which the ^{233}U is recycled into fresh fuel; and the once-through-thorium (OTT) cycles, where the rationale for the use of thorium does not rely on recycling the ^{233}U (but where recycling remains a future option).

3. DISCUSSION AND CONCLUSIONS

As a country lacking natural resources, Korea has actively made the development of nuclear energy a national priority to fill economic growth needs and satisfy increasing energy consumption in the future while ensuring self-reliance of energy supply. The nuclear program of Korea will remain in the next century at least as important and vital as it is today. Along with the active nuclear power program, strong arguments against nuclear energy have been brought into the domestic and international environments: "Nuclear safety" and "nuclear waste" have been mainly argued by the public; "Non-proliferation" has been always emphasized in the international environment; and "economics" has been firstly considered by utilities. The CANDU-PHWR advanced fuel R & D and cycle options for the 21st century in Korea shall take into account nuclear safety, nuclear waste, non-proliferation and economics in favor of the arguments from the public, international environment, and utilities. It will be relatively straightforward to face the issues of nuclear safety, nuclear waste and economics in the arguments from the public and/or utilities, compared to face the issues of the non-proliferation.

If the political and non-proliferation considerations in the Korean peninsula lead to the decision to reprocess the Korean spent PWR fuel, then the resultant recovered plutonium could be mixed with depleted uranium to form MOX fuel for CANDU reactors. The resultant recovered uranium without re-enrichment could be burned as-is in CANDU reactors. In the TANDEM fuel cycle, the uranium and plutonium from PWR spent fuel are co-precipitated without separation. Only the fission products, and higher actinide isotopes, are removed. This fuel cycle uniquely takes advantage of the fact that the fissile component in spent PWR fuel (about 1.5 %) can be used directly in PHWRs, without readjustment of the enrichment. Fuel burnup in the fuel cycle would be about 25,000 MWd/kgHE. Since proliferation resistance would be enhanced by the high radioactivity of the fresh fuel, the DUPIC fuel cycle offers a very high degree of proliferation resistance as mentioned above.

With this PWR/CANDU synergism, MOX, RU, TANDEM and DUPIC fuels have advantages for improving natural uranium utilization, reducing enrichment requirements, and reducing the amount of spent fuel for ultimate disposal. However, the international environment generally considers that conventional reprocessing which produces plutonium does not offer proliferation resistance. Therefore, the MOX fuel development in Korea has not been allowed in the international environment. But, AECL and KAERI jointly investigated TANDEM fuel cycle in the mid-1980s. At that time, the international environment did not continuously allow the fuel cycle R & D, even though the co-precipitated product of recovered uranium and plutonium can not be divested to weapons. It was believed that the co-processing still did not offer a higher degree of proliferation resistance. In connection with the PWR/CANDU synergism in Korea, only the DUPIC fuel cycle has been studied to date from the early-1990s in the international collaboration between KAERI, AECL, the U.S. Department of State, and IAEA, because it does offer a very high degree of proliferation resistance along with high radiation fields of fresh fuel. Here, the economy and high radiation fields of DUPIC fresh fuel have been argued within the nuclear industrial community in Korea.

Without consideration of the PWR/CANDU synergism in Korea , the use of SEU or RU in CANDU reactors have a beneficial impact on the arguments form public, international environment and utilities in Korea on nuclear safety, nuclear waste, non-proliferation, and economics. The SEU or RU fuel can be utilized in the CANFLEX-43 element bundle. The use of SEU in Korean nuclear reactors has already been proved in favor of the arguments for its use in PWRs. The use of RU in Korean CANDU reactors would also be satisfied in favor of the arguments, because RU is an equivalent enriched SEU except for the minute contents of ^{232}U and ^{236}U and traces of transuranic elements which remain in RU.

If a proven, reliable reactor technology is successfully developed, the thorium fuel cycle in CANDU reactors would provide assurance of long-term nuclear fuel supplies in Korea. But, according to the arguments of non-proliferation in the international environment, the recycling options, in which the ^{233}U is recycled into fresh fuel, would not be allowed, because the higher degree of proliferation resistance would be not offered by the recycling processes.

As discussed above, Korea has not successfully utilized the PWR/CANDU synergism and so has limited the scope of CANDU advanced fuel R & D due to the consideration for non-proliferation in the international environment. This constraint will be continued into the 21st century in Korea, as long as the political and non-proliferation considerations in the Korean peninsula do not lead to the decision to reprocess Korean spent PWR fuel. Therefore, CANFLEX-RU and –SEU fuels are expected to be commercially available in the first 25 years of the 21st century in Korea. In this period, Korea must develop advanced fuel and fuel cycle technologies with a high degree of proliferation resistance, not only to fully utilize the advantages of PWR/CANDU synergism, but also to resolve the issue of spent fuel storage in Korea. At the same time, the international environment shall offer and guide a proper degree of proliferation resistance to reduce, recycle and reuse the spent fuel as applied to global nuclear energy uses.

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Table 1. Current Status of Korea's Nuclear Power Plants as of September 1999

Reactor Name	Reactor Type	Capacity (MWe)	Manufacture		Commercial Operation*
			Reactor	T/G	
Kori #1	LWR	587	WH	GEC	April, 1978
Kori #2	LWR	650	WH	GEC	July, 1983
Kori #3	LWR	950	WH	GEC	Sept., 1985
Kori #4	LWR	950	WH	GEC	April, 1986
Wolsong #1	CANDU-PHWR	679	AECL	NEI/PARSONS	April, 1983
Wolsong #2	CANDU-PHWR	700	AECL	KHIC/GE	June, 1997
Wolsong #3	CANDU-PHWR	713	AECL	KHIC/GE	July, 1998
Wolsong #4	CANDU-PHWR	713	AECL	KHIC/GE	Sept.,1999
Yonggwang #1	LWR	950	WH	WH	Aug., 1986
Yonggwang #2	LWR	950	WH	WH	June, 1987
Yonggwang #3	LWR	1000	KHIC/KAERI/CE	KHIC/GE	March, 1995
Yonggwang #4	LWR	1000	KHIC/KAERI/CE	KHIC/GE	March, 1996
Yonggwang #5	LWR	1000	KHIC/KAERI/KOPEC	KHIC/GE	(Dec., 2001)
Yonggwang #6	LWR	1000	KHIC/KAERI/KOPEC	KHIC/GE	(Dec., 2003)
Ulchin #1	LWR	950	FRAMATOME	ALSTHOM	Sept., 1988
Ulchin #2	LWR	950	FRAMATOME	ALSTHOM	Sept., 1989
Ulchin #3	LWR	1000	KHIC/KAERI/ABB-CE	KHIC/GE	Aug., 1998
Ulchin #4	LWR	1000	KHIC/KAERI/ABB-CE	KHIC/GE	June, 1999
Ulchin #5	LWR	1000	KHIC/KAERI/ABB-CE	KHIC/GE	(Feb., 2004)
Ulchin #6	LWR	1000	KHIC/KAERI/ABB-CE	KHIC/GE	(Feb., 2005)

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

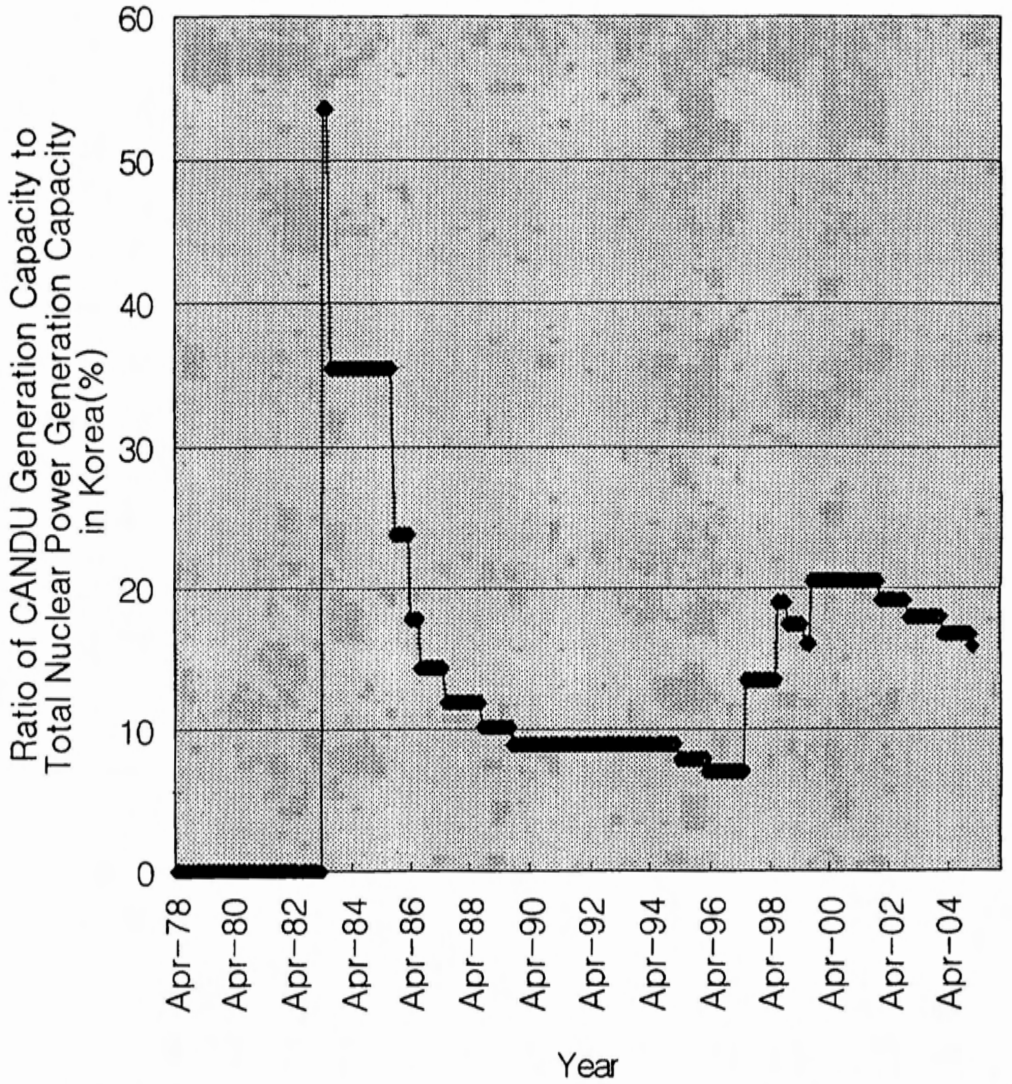

Figure 1. Trace of CANDU Generation Capacity for the Last 20 Years in Korea