研究論文

Analysis on DUPIC Fuel Cycle in Aspect of Overall Radioactive Waste Management†

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The DUPIC (Direct Use of spent PWR fuel In CANDU) fuel cycle is an advanced nuclear fuel cycle option, an alternative to the once-through fuel cycle, proposed in the early 1990's by Korea. It has the benefits of not only saving natural uranium but also substantially reducing the amount of spent fuel because of its synergetic effect expectable from burning PWR spent fuel again in CANDU reactor by direct fuel refabrication without separation of pure plutonium. In the present study, evaluations were made for the DUPIC fuel cycle, compared to the once-through cycle, about several issues such as a fabrication process of the DUPIC fuel, secondary radioactive wastes generated, mass flows, decay characteristics of the DUPIC spent fuel, and resource savings and environmental benefits. Impacts of three scenarios of DUPIC fuel cycle were evaluated when these are applied to Korea, compared to the once-through cycle, in reducing the amount of required natural uranium and spent fuel waste produced in Korea, based on the nuclear power capacity projected until 2030. Then, the optimized fuel cycle strategy in Korea was proposed from the view point of the optimization for the mass balance of DUPIC fuel cycle.

Keywords: DUPIC, once-through, fuel cycle, PWR, CANDU, spent fuel, Korea

DUPIC(Direct Use of spent PWR fuel In CANDU)核燃料サイクル（以下 DUPIC）は、ワンススルー核燃料サイクルの対案として 90 年代初頭に韓国から提案された新しい核燃料サイクルである。DUPIC は PWR 使用済燃料からプルトニウムを分離することなく直接再成形加工して、それを CANDU 炉で新燃料として再利用する軽水炉・重水炉連係核燃料サイクルである。それによって、所要天然ウラン量を減少させられるばかりではなく、使用済み燃料の量を減らすことができる。本研究では、DUPIC 燃料製造工程、２次廃棄物量、物質流量、DUPIC 使用済み燃料の線源強度、長期毒性などの崩壊特性、ウラン資源節約および環境への影響の減少などをワンススルーと比較し評価を行った。なお、2030 年までの韓国の原子力発電設備容量を予測して、いくつかのシナリオの DUPIC サイクルを適用した場合、天然ウラン所要量、使用済み燃料の発生量などのサイクル諸量について、適用しない場合と比較評価を行った。そして、DUPIC サイクルの物質バランスの観点から韓国の最適サイクル戦略を提案した。

Keywords: DUPIC、ワンススルー、燃料サイクル、PWR、CANDU、使用済み燃料、韓国

1. Introduction

One of the advanced fuel cycle options considered, as an alternative to the once-through fuel cycle, is the DUPIC fuel cycle; this reuses spent fuel from a light water reactor in a heavy water reactor, using a direct refabrication method without separating fissile materials. The DUPIC fuel cycle offers attractive possibilities not only of saving natural uraniumfuel for CANDU, but also of a substantial reduction in the amount of spent fuel compared to the once-through cycle. The main purpose of the DUPIC fuel cycle is to conserve uranium fuel, while at the same time reducing the volume of radioactive waste.

A feasibility study on the DUPIC fuel cycle concept was initiated in the early 1990's by Korea, as a joint evaluation program with Canada and the US. The conclusion of earlier studies have led to a subsequent program on experimental verification of the DUPIC concept, also in a tripartite cooperation framework with Canada and the US. Korea is unique in operating both PWR and CANDU and so has the potential for linking the two reactor types by the DUPIC fuel cycle[1-13]. The basic idea of the DUPIC fuel cycle is to burn the remaining fissile materials of the spent fuel from PWR, which still contains approximately 1.5 % of fissile material, twice that of natural uranium, in a heavy water reactor. For CANDU reacotors, which normally use natural uranium as the fuel, PWR spent fuel has plenty of fissile materials left for excellent utilization. Figure 1 illustrates basic concepts of the DUPIC fuel cycle and the once-through cycle.

The present study evaluates for the DUPIC fuel cycle, compared to the once-through cycle, about several issues such as a fabrication process of the DUPIC fuel, secondary radioactive wastes generated, mass flows, decay characteristics of the DUPIC spent fuel, and resource savings and environmental benefits. Impacts of three scenarios of DUPIC fuel cycle are evaluated when these are applied to Korea, compared to the once-through cycle, in reducing the amount of required natural uranium and spent fuel waste produced in Korea, based on the

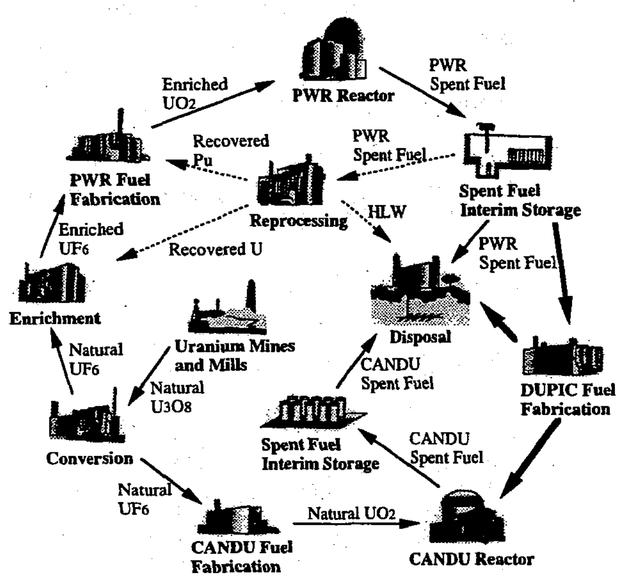

Fig.1 Basic Concept of the DUPIC Fuel Cycle and the Once-Through Cycle

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nuclear power capacity projected until 2030. Then, the optimized fuel cycle strategy in Korea is proposed from the view point of the optimization for the mass balance of DUPIC fuel cycle.

2. DUPIC Fuel Fabrication

Korea Atomic Energy Research Institute (KAERI) conducted a feasibility study on the DUPIC fuel cycle with Atomic Energy Canada Limited (AECL) and the US partner in early 1990's. KAERI and AECL have investigated seven options to refabricate PWR spent fuel into fresh CANDU fuel involving only the dry processing and have concluded that all options were technically feasible but OREOX(Oxidation and REduction of OXide fuel) process was recommended as the most promising option due to its homogeneous fuel characteristics[5].

Fig. 2 shows a schematic representation of the OREOX process[6]. The spent fuel has clad removed and repeatedly undergoes oxidation and reduction at high temperatures until a complete powder is formed, this is then compacted and sintered to produce DUPIC fuel pellets. During this process most of the volatile and semi-volatile fission products (Xe, Cs, Ru, Kr, I, etc.) are removed, but medium- and low-volatility fission products remain in the fuel, as do the uranium, plutonium, and minor actinides. Structural wastes such as non-fuel bearing hardware and fuel cladding of the PWR spent fuel would be one of the major sources of radioactive waste, and would be compacted or cemented into a container for disposal. Volatile and semi-volatile fission products would be collected by suitable adsorbents or cold traps. Recovered semi-volatiles would be immobilized together in a borosilicate glass waste form with the spent UO_2 scrap for waste disposal. Recovered krypton would be bottled for storage and the other recovered volatiles would be combined and immobilized in cement as low level waste[5].

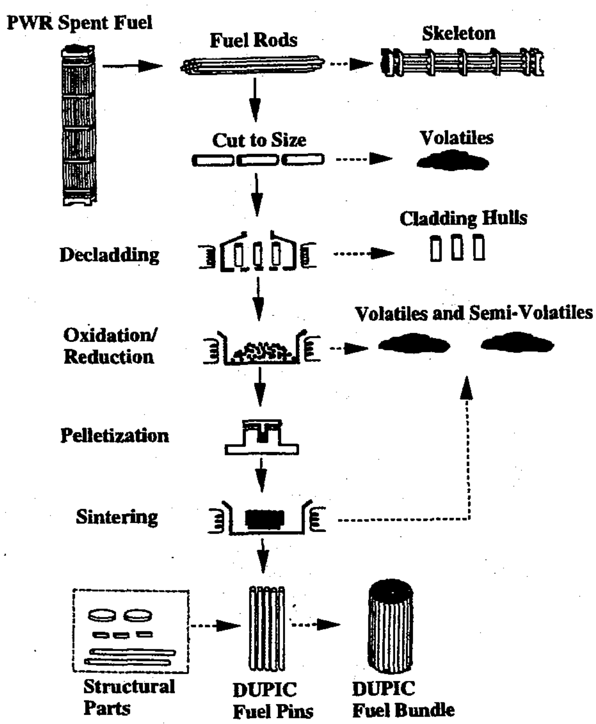

Fig.2 The DUPIC Fuel Fabrication Process and Radioactive Waste Source

The OREOX process does not produce a pure or partially pure plutonium product. Material in the DUPIC fuel cycle contains plutonium but in a form essentially similiar to the spent fuel. Further processing would be necessary to recover plutonium from a diverted material. Therefore, the DUPIC fuel cycle is unattractive for diversion when compared with conventional reprocessing.

The OREOX process is similar to the AIROX(Atomics International Reduction Oxidation) process, which is a pyrochemical process developed by Atomic International for recycling LWR spent fuel which would retain most of the fission product inventory in reconstituted fuel assemblies. For use in LWR, the AIROX-processed fuel must be blended with additional fissile material. However, for CANDU reactors, which normally use natural uranium as the fuel, the OREOX-processed fuel need not be blended with any additional fissile material[14-16].

3. Secondary Radioactive Waste Management

Most radioactive wastes from the DUPIC fuel fabrication processes are of solid and gaseous forms with practically no liquid waste. Solid wastes consist mainly of structural hardware of PWR spent fuel assembly generated from disassembling and decladding processes. Gaseous wastes consist of volatile and semi-volatile fission products and include any forms of particulate.

Table 1 compares the volumes and types of radioactive wastes generated at the reprocessing plant, MOX fuel fabrication plant and DUPIC fuel fabrication plant[17-19]. Total secondary radioactive wastes generated are 0.68 m^3/tHM in the DUPIC fuel cycle, while those are 2.37 m^3/tHM for conventional reprocessing and 3.7 m^3/tHM for MOX fuel fabrication plant. The total quantity of secondary radioactive wastes generated in the DUPIC fuel fabrication facility is less than that of

Table 1 Comparison of Types and Quantities of Radioactive Wastes Generatedat the Reprocessing Plant, MOX and DUPIC Fuel Fabrication Plant (Unit: m^3/tHM)

Waste Classification	Reprocessing[a)]	MOX Fuel[b)] Fabrication	DUPIC Fuel Fabrication
HLW	0.12	-	0.10
ILW	0.95	2.3	0.17
LLW	1.30	1.4	0.41
Total	2.37	3.7	0.68

a): Actual Values in 1993 at UP3 Plant
b): MELOX Plant

conventional reprocessing and MOX fuel fabri-cation process because there is no generation of liquid wastes in the OREOX process.

4. Mass Flows

For the analysis of mass flows for the DUPIC fuel cycle, a 950 MWe PWR and a 700 MWe CANDU are chosen as reference reactor systems. In consideration of the current trend toward higher burnup, both nominal (35000 MWd/t) and high (50000 MWd/t) burnups are taken as base burnup cases for PWR spent fuel, the corresponding initial enrichments are 3.5 and 4.4 w/o. Irradiation conditions of PWR and DUPIC fuels are summarized in Table 2. Irradiation conditions of natural uranium CANDU fuel are also given. PWR spent fuel cooled for 10 years and of 35000 and 50000 MWd/t burnup (referred to below as PWR35 and PWR50) produces fresh DUPIC fuel which, when spent, has a burnup of 19000 and 14000 MWd/t respectively (referred to below as DUPIC19 and DUPIC14) [9,10].

No bad effect on the safety parameters for DUPIC fresh fuel loaded core were reported in Ref.[9]. The refueling rate of the DUPIC fuel in a CANDU reactor is calculated assuming that the fuel bundles are irradiated under the average reactor power and the burnup interval is uniform for the fuel bundles in the core. Based on the refueling rate in a CANDU reactor, the annual mass flows of a PWR and a CANDU reactor for the DUPIC fuel cycle and the once-through cycle are given in Table 3. The equivalent number of PWR units for DUPIC19 and DUPIC14, which could supply the fuel material required for one CANDU at full power, are 1.7 and 3.3, respectively[9].

Table 2 Irradiation Conditions for the DUPIC Fuel Cycle and the Once-Through Cycle

Parameter	PWR35	PWR50	DUPIC19	DUPIC14	CANDU
Enrichment (w/o of Fissile)	3.5	4.4	1.6	1.5	0.7
Discharge Burnup (MWd/t)	35	50	19	14	7.3
Specific Power (MW/tHM)	40.2	40.2	25.5	25.5	25.5

Table 3 Comparison of Annual Mass Flows for the DUPIC Fuel Cycle and the Once-Through Cycle

Parameter	PWR35	PWR50	DUPIC19	DUPIC14	CANDU
Power (MWe)	950	950	2315	3835	700
Feed (tHM/y)	23.0	16.1	38.1	53.1	97.8
Discharge (tHM/y)	23.0	16.1	38.1	53.1	97.8

5. Decay Characteristics of the DUPIC Spent Fuel

The fresh DUPIC fuel is assumed to be fabricated from PWR spent fuel that has been cooled for 10 years after discharge from the reactor. In the DUPIC fuel fabrication, i.e., OREOX, process, volatile and semi-volatile fission products are released. In the present study, it is assumed that 100 % of krypton, ruthenium, xenon, iodine, and cesium and, in addition, 10 % of zirconium, antimony, barium, and lanthanum are removed[13]. Therefore, the fresh DUPIC fuels are constituted with 18 actinides and more than one hundred fission product nuclides. Calculations to simulate the irradiations of the DUPIC fuel cycle and the once-through cycle are performed using the ORIGEN2 code[20].

Fig. 3 shows a schematic representation of the DUPIC fuel cycle and the once-through cycle considered in the present study. The quantities interested are normalized to a measure of annual electrical energy benefit (MWey). Energy-benefit normalization seems a proper way to compare different fuel cycles[21,22].

For the comparative disposal safety assessment of spent fuels from the DUPIC fuel cycle and the once-through cycle, transuranics (TRU) mass inventory, radioactivity, decay heat, and neutron emission of spent fuel 10 years after discharge for both cycles are compared in Table 4. The total amount of TRU from the DUPIC spent fuel, compared to that from the PWR spent fuel of the once-through cycle, is decreased by about 30 % for the nominal and high burnup cases. This is mainly due to the decrease in the fissile plutonium which is fissioned in the CANDU reactor. For DUPIC spent fuel, there is a notable increase in the amount of curium compared to the PWR spent

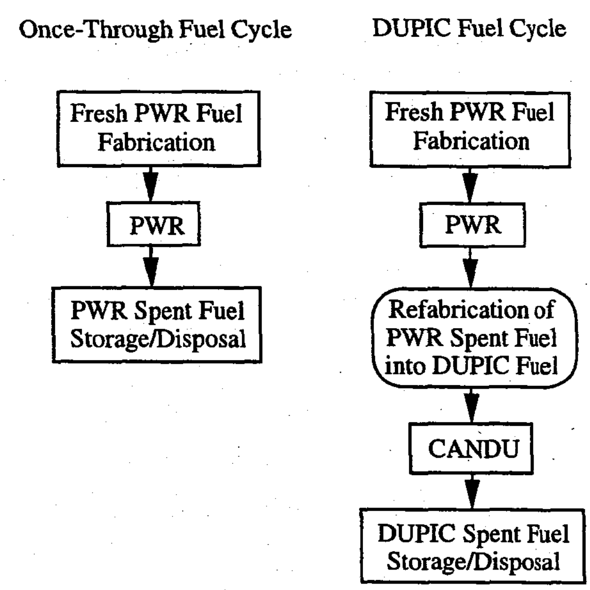

Fig. 3 Comparison of the DUPIC Fuel Cycle and the Once-Through Cycle Considered in the Present Study

of the once-through cycle, of about 250% and 50% for the nominal and high burnup cases, respectively. The increased curium, mainly Cm-244 with relatively short half-life, could give rise to a strong radiation and heat source in DUPIC spent fuel. The total radioactivity of the DUPIC spent fuel, compared to that of the PWR spent fuel of the once-through cycle, is decreased by about 40 % and 50 % for the nominal and high burnup cases, respectively. The total decay heat of the DUPIC spent fuel, compared to that of the PWR spent fuel of the once-through cycle, is decreased by about 20 % and 30 % for the nominal and high burnup cases, respectively. The substantial reduction in radioactivity and decay heat of spent fuel is to some extent due to the released volatile and semi-volatile fission products in the process of the DUPIC fuel fabrication. The total neutron emission of the DUPIC spent fuel is increased, compared to that of the PWR spent fuel of the once-through cycle, by about 220 % and 60 % for the nominal and high burnup cases, respectively. This is mainly because of the increased amount of curium of the DUPIC spent fuel. The difference in total neutron emission between the nominal and high burnup cases is due to the different rate of curium production in the two cases.

In Fig. 4 the toxicity from ingestion as a function of decay time is shown for a number of radionuclides contained in spent fuel for the DUPIC fuel cycle and the once-through cycle. In calculating the toxicity maximum permissible concentrations (MPC) are taken from Appendix B, Table 2, Column 2 in Ref.[23] which are calculated to produce an effective dose equivalent of 50 millirem/y. Although hundreds of isotopes are present in spent fuel, only a few of them are important in spent fuel disposal. Values of MPC of actinides and fission products taken into account in this study together with half-lives are given in Table 5[23,24]. Reduction in toxicity of the DUPIC fuel cycle relative to the once-through cycle is small during the short term because of the presence of large quantities of curium, which has a relatively short half-life. Later, the difference in toxicity is increased because of the decrease in the TRU inventory.

Table 4 TRU Inventory, Radioactivity, Decay Heat, and Neutron Emission Rate or the DUPIC Fuel Cycle and the Once-Through Cycle

Parameter	PWR35	PWR50	DUPIC19	DUPIC14
(g/MWey)				
Np	1.20E+01	1.30E+01	9.00E+00	1.10E+01
Pu	2.11E+02	1.80E+02	1.39E+02	1.26E+02
Am	1.40E+01	1.50E+01	1.00E+01	1.20E+01
Cm	4.00E-01	1.00E+00	1.40E+00	1.50E+00
Total	2.37E+02	2.09E+02	1.59E+02	1.50E+02
(Bq/MWey)				
HM	7.62E+13	7.66E+13	4.14E+13	4.29E+13
FP	2.93E+14	2.83E+14	1.64E+14	1.35E+14
Total	3.69E+14	3.60E+14	2.05E+14	1.78E+14
(W/MWey)				
HM	5.15E+00	7.29E+00	8.50E+00	1.00E+01
FP	2.31E+01	2.32E+01	1.37E+01	1.16E+01
Total	2.86E+01	3.05E+01	2.22E+01	2.16E+01
(n/s/MWey)				
(alpha,n)	1.48E+05	2.15E+05	2.56E+05	3.01E+05
Spontaneous	4.55E+06	1.00E+07	1.49E+07	1.61E+07
Total	4.70E+06	1.03E+07	1.51E+07	1.64E+07

* HM, FP and Spontaneous mean heavy metals, fission products and spontaneous fission neutron emissions, respectively.

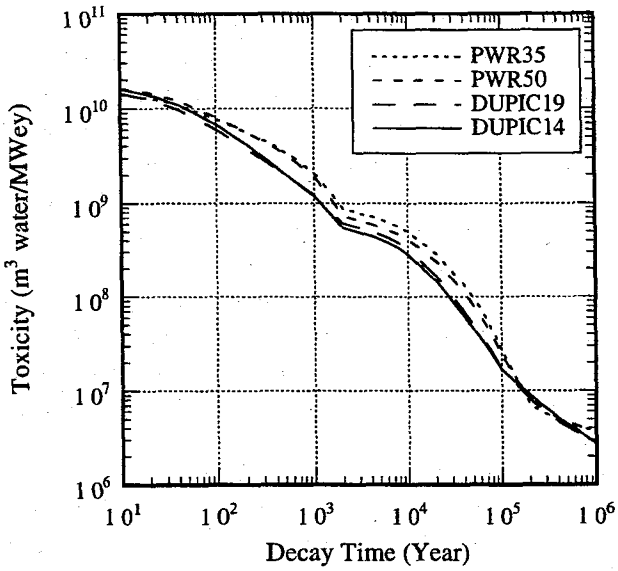

Fig. 4 Toxicity of Spent Fuel for the DUPIC Fuel Cycle and the Once-Through Cycle

Table 5 Properties of Actinides and Fission Products of Interest in Spent Fuel

Nuclide	Half-Life (Year)	MPC (Bq/m^3)
Pb-210	2.23E+01	3.70E+02
Ra-226	1.60E+03	2.22E+03
Th-229	7.30E+03	7.40E+02
Th-230	7.54E+04	3.70E+03
Pa-231	3.28E+04	2.22E+02
U-234	2.46E+05	1.11E+04
U-235	7.04E+08	1.11E+04
U-236	2.34E+07	1.11E+04
U-238	4.47E+09	1.11E+04
Np-237	2.14E+06	7.40E+02
Pu-238	8.77E+01	7.40E+02
Pu-239	2.41E+04	7.40E+02
Pu-240	6.56E+03	7.40E+02
Pu-241	1.44E+01	3.70E+04
Pu-242	3.75E+05	7.40E+02
Am-241	4.33E+02	7.40E+02
Am-242m	1.41E+02	7.40E+02
Am-243	7.37E+03	7.40E+02
Cm-243	2.91E+01	1.11E+03
Cm-244	1.81E+01	1.11E+03
Cm-245	8.50E+03	7.40E+02
Cm-246	4.80E+03	7.40E+02
Sr-90	2.81E+01	1.85E+04
Tc-99	2.13E+05	2.22E+06
I-129	1.57E+07	7.40E+03
Cs-137	3.02E+01	3.70E+04

6. Resource Savings and Environmental Benefits

There are several benefits from the DUPIC fuel cycle compared to the once-through cycle. Among them are resource savings and environmental benefits due to the reduction of natural uranium required and spent fuel arisings.

Based on Fig. 3 for the DUPIC fuel cycle and the once-through cycle, benefits from the DUPIC fuel cycle are compared in Table 6. In the calculation of the amount of required natural uranium, conversion and fabrication losses of 0.5 % and 1 %, respectively, are assumed. The enrichments of U-235 of natural uranium and depleted uranium in reprocessing are assumed to be 0.71 % and 0.25 %, respectively[25]. Uranium mining and milling wastes arisings are based on a uranium ore of 0.4 %[26].

The required annual amount of natural uranium, the amount of spent fuel arisings and the uranium mining and milling wastes produced for the DUPIC fuel cycle, relative to the once-through cycle, is reduced by about 30 % and 20 % for the nominal and high burnup cases, respectively.

7. Nuclear Power Capacity Projection in Korea

To evaluate the impact of the DUPIC fuel cycle in Korea, the nuclear power capacity in Korea is projected until 2030. Until 2010, the nuclear power capacity is projected from the government energy supply target decided in December 1995[27]. The Korean nuclear power capacities of PWR, CANDU and total are predicted to increase to 23.6, 2.8 and 26.3 GWe, respectively, by the year 2010. After 2010, the nuclear power capacity is projected until 2030 using the data in Ref.[28]. Table 7 and Fig. 5 show the nuclear power capacity in Korea projected until 2030. It is assumed that increasing rates of electric power in Korea are; the years 2011 to 2015:2.2 %/year, the years 2016 to 2020:1.7 %/year, the years 2021 to 2025:1.0 %/year, and the years 2026 to 2030: 0.5 %/year. It is also assumed that the nuclear power fractions in the total electric power capacity in Korea are 35 %, 37 %, 39 % and 40 % in the year 2011, 2012, 2013 and after 2014.

Table 6 Comparison of Mass Flows for the DUPIC Fuel Cycle and the Once-Through Cycle

Parameter	PWR35	PWR50	DUPIC19	DUPIC14	CANDU
Natural Uranium Required (kg/MWey)	173.2	154.4	118.1	126.1	139.7
Spent Fuel Produced (kg/MWey)	24.2	16.9	16.5	13.8	139.7
Uranium Mining & Milling Waste (t/MWey)	43.1	38.4	29.4	31.4	34.8

Before evaluating the impact of the DUPIC fuel cycle in reducing the amount of required natural uranium and spent fuel waste produced in Korea, three scenarios for the reactor deployment are assumed. First and second scenario assume that the ratio of PWR and CANDU in terms of power capacity by the year 2030 are 3:1 and 5:1, respectively. Third scenario assumes that there are no construction for CANDU reactor after the year 2011. Table 8 shows the postulated nuclear power capacity in Korea projected until 2030 with the above assumptions. A 30 years lifetime is assumed for both PWR and CANDU reactor. Until 2030 the Korean nuclear power capacity of PWR, CANDU and total would be increased to 30.9, 10.3 and 41.2GWe, respectively, for first scenario, 34.3, 6.8 and 41.2 GWe, respectively, for second scenario, and 41.2, 0.0 and 41.2 GWe, respectively, for third scenario.

Table 7 Nuclear Power Capacity in Korea Projected Until 2030

Year	Nuclear Power (GWe)	Nuclear Fraction (%)
2000	13.7	26.0
2010	26.3	33.1
2020	38.2	40.0
2030	41.2	40.0

Table 8 PWR, CANDU and Total Nuclear Power Capacity in Korea Projected Between the Years 2010 and 2030

	First Scenario(GWe)			Second Scenario(GWe)			Third Scenario(GWe)		
Year	PWR	CANDU	Total	PWR	CANDU	Total	PWR	CANDU	Total
2010	23.6	2.8	26.3	23.6	2.8	26.3	23.6	2.8	26.3
2020	32.6	5.7	38.2	33.3	4.9	38.2	36.1	2.1	38.2
2030	30.9	10.3	41.2	34.3	6.8	41.2	41.2	0.0	41.2

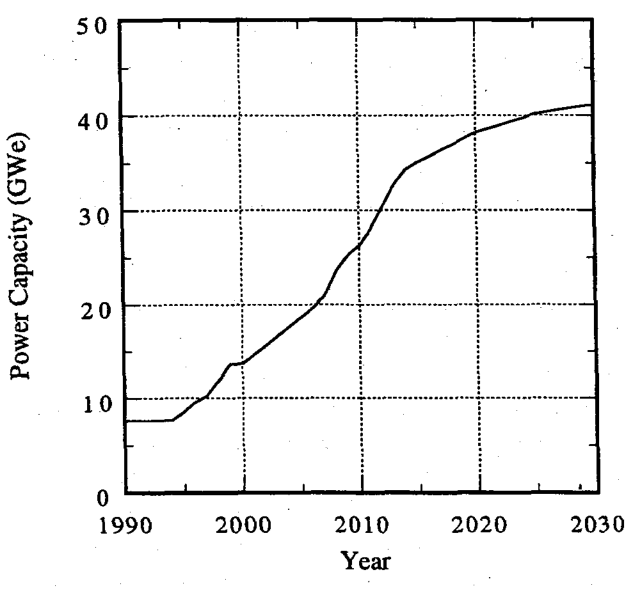

Fig. 5 Nuclear Power Capacity in Korea Projected Until 2030

8.Impact of the DUPIC Fuel Cycle in Korea

In evaluating the impact of the DUPIC fuel cycle in reducing the amount of required natural uranium and spent fuel waste produced in Korea, the following reactor characteristics are assumed: a PWR burnup of 35000 MWd/t until 1999 and 50000 MWd/t after 2000, while the burnup of CANDU using natural uranium as fresh fuel is taken to be 7300 MWd/t[9,28]. The DUPIC fuel cycle is assumed to be adopted from the year 2010[29]. It is assumed that the 10 years cooled PWR spent fuel is used as the fresh fuel in CANDU reactor for the DUPIC fuel cycle. If the inventory of the 10 years cooled PWR spent fuel is out, PWR spent fuel more than 10 years cooled is used.

Table 9 and Fig. 6 show the amount of required natural uranium accumulation in Korea, projected between the years 2000 and 2030 for the DUPIC fuel cycle and the once-through cycle. Total amount of required natural uranium accumulation in Korea at 2030 in the first, second, and third scenario would be 156.5, 155.1, and 151.5 kt, respectively, for the once-through fuel cycle, but 129.8, 133.3, and 143.0 kt with the DUPIC fuel cycle adopted from 2010. Required amount of natural uranium accumulation in Koreaat 2030 in the first, second, and third scenario for the DUPIC fuel cycle relative to the once-through cycle is reduced by 17 %, 14 % and 6 %, respectively. The accumulated amount of spent fuel in Korea from PWR, CANDU and total as of 1992 are 0.95, 0.89 and 1.84 kt, respectively, in Ref.[28]. With these data and the projection of nuclear power capacity, the amount of accumulated spent fuel in Korea between the years 1992 and 2010 is projected in Table 10. The amount of accumulated spent fuel at 2010 from PWR, CANDU and total would be 5.5, 6.6, and 12.1 kt, respectively.

Table 11, Fig. 7 and Fig. 8 show the amount of accumulated spent fuel in Korea, projected between the years 2000 and 2030 for the DUPIC fuel cycle and the once-through cycle. Total amount of accumulated spent fuel at 2030 in the first, second, and third scenario would be 41.4, 38.6, and 30.5 kt, respectively, for the once-through fuel cycle, but 23.0, 23.4, and 24.4 kt with the DUPIC fuel cycle adopted from 2010. Total amount of accumulated spent fuel in Korea at 2030 in the first, second and third scenario for the DUPIC fuel cycle relative to the once-through cycle is reduced by 45 %, 39 % and 20 %, respectively. The amount of accumulated PWR spent fuel at 2030 in the first, second, and third scenario would be about 16.8, 17.2, and 18.2 kt, respectively, for the once-through fuel cycle, but 7.6, 9.3, and 15.2 kt with the DUPIC fuel cycle adopted from 2010. The amount of accumulated PWR spent fuel in Korea at 2030 in the first, second, and third scenario for the DUPIC fuel cycle relative to the once-through cycle is reduced by 55 %, 46 % and 17 %, respectively. In Fig. 8, it is noteworthy that the amount of accumulated PWR spent fuel in Korea is decreasing since the year 2027 in first scenario.

Table 12, Fig. 9 and Fig. 10 show the amount of accumulated TRU included in spent fuel in Korea, projected between the years 2000 and 2030 for the DUPIC fuel cycle and the once-through cycle. The amount of accumulated Pu included in spent fuel at 2030 in the first, second, and third scenario would be about 268, 259, and 234 t, respectively, for the once-through fuel cycle, but 185, 190, and 207 t with the DUPIC fuel cycle adopted from 2010. The amount of accumulated Pu included in spent fuel in Korea at 2030 in the first, second and third scenar-

Table 9 Amount of Natural Uranium Required in Korea Projected Between the Years 2000 and 2030

		Once-Through Cycle(kt)			DUPIC Cyele(kt)		
	Year	PWR	CANDU	Total	PWR	CANDU	Total
	2000	1.68	0.59	2.27	1.68	0.59	2.27
First Scenario	2010	28.08	6.48	34.57	28.08	5.89	33.97(1.7%)
	2020	74.44	15.83	90.27	74.44	5.89	80.33(11.0%)
	2030	123.92	32.54	156.46	123.92	5.89	129.81(17.0%)
Second Scenario	2010	28.08	6.48	34.57	28.08	5.89	33.97(1.7%)
	2020	74.94	15.14	90.08	74.94	5.89	80.83(10.3%)
	2030	127.40	27.75	155.14	127.40	5.89	133.29(14.1%)
Third Scenario	2010	28.08	6.48	34.57	28.08	5.89	33.97(1.7%)
	2020	77.78	11.22	89.00	77.78	5.89	83.67(6.0%)
	2030	137.11	14.34	151.45	137.11	5.89	143.00(5.6%)

* In the parenthises are decreasing rates of total values due to DUPIC fuel cycle.

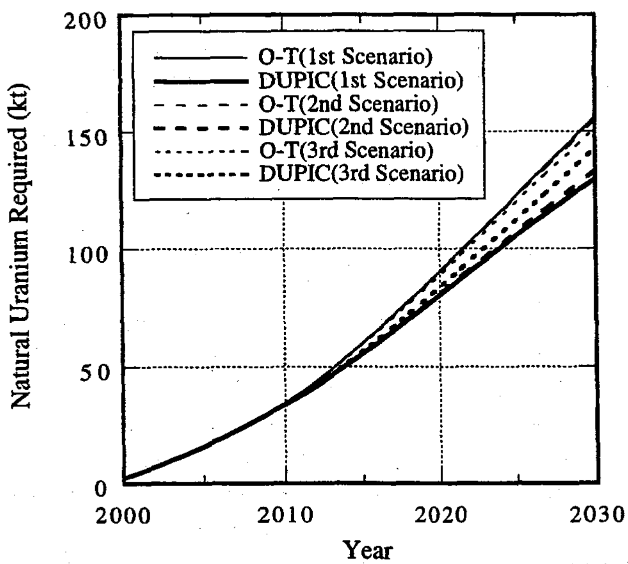

Fig. 6 Amount of Natural Uranium Required in Korea Projected Between the Years 2000 and 2030

Table 10 Amount of Spent Fuel Accumulated in Korea Projected Between the Years 1992 and 2010

Year	PWR (kt)	CANDU (kt)	Total (kt)
1992	0.95	0.89	1.84
2000	2.60	2.58	5.18
2010	5.54	6.59	12.13

Table 11 Amount of Spent Fuel Accumulated in Korea Projected Between the Years 2010 and 2030

	Year	Once-Through Cycle(kt) PWR	CANDU (Nat.U)	Total	DUPIC Cyele(kt) PWR	CANDU (Nat.U)	CANDU (DUPIC)	Total
First Scenario	2010	5.54	6.59	12.13	5.38	6.19	0.16	11.73(3.3%)
	2020	11.08	13.03	24.11	7.67	6.19	3.41	17.27(28.4%)
	2030	16.79	24.65	41.44	7.60	6.19	9.20	22.99(44.5%)
Second Scenario	2010	5.54	6.59	12.13	5.38	6.19	0.16	11.73(3.3%)
	2020	11.13	12.57	23.70	7.92	6.19	3.22	17.33(26.9%)
	2030	17.17	21.39	38.56	9.32	6.19	7.85	23.36(39.4%)
Third Scenario	2010	5.54	6.59	12.13	5.38	6.19	0.16	11.73(3.3%)
	2020	11.45	9.90	21.35	9.56	6.19	1.89	17.64(17.4%)
	2030	18.24	12.27	30.51	15.20	6.19	3.03	24.42(20.0%)

* In the parenthises are decreasing rates of total values due to DUPIC fuel cycle.

Table 12 Amount of Transuranics Accumulated in Korea Projected Between the Years 2010 and 2030

	Year	Once-Through Cycle(t) Pu	MA	TRU	DUPIC Cyele(t) Pu	MA	TRU
First Scenario	2010	81	8	89	79	8	87(2.2%)
	2020	164	18	182	134	17	151(17.0%)
	2030	268	32	300	185	27	212(29.3%)
Second Scenario	2010	81	8	89	79	8	87(2.2%)
	2020	163	18	181	134	17	151(16.6%)
	2030	259	32	291	190	28	218(25.1%)
Third Scenario	2010	81	8	89	79	8	87(2.2%)
	2020	156	19	175	139	18	157(10.3%)
	2030	234	33	267	207	31	238(10.9%)

* MA = Np + Am + Cm
TRU = Pu + MA
In the parenthises are decreasing rates of TRU values due to DUPIC fuel cycle.

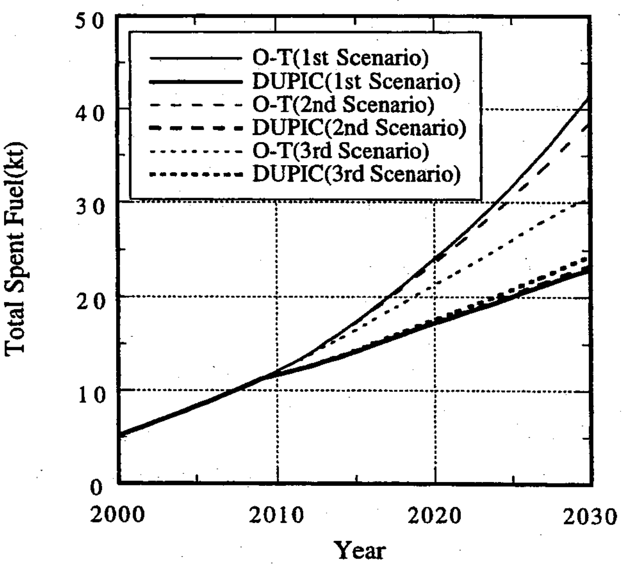

Fig. 7 Amount of Total Spent Fuel Accumulated in Korea Projected Between the Years 2000 and 2030

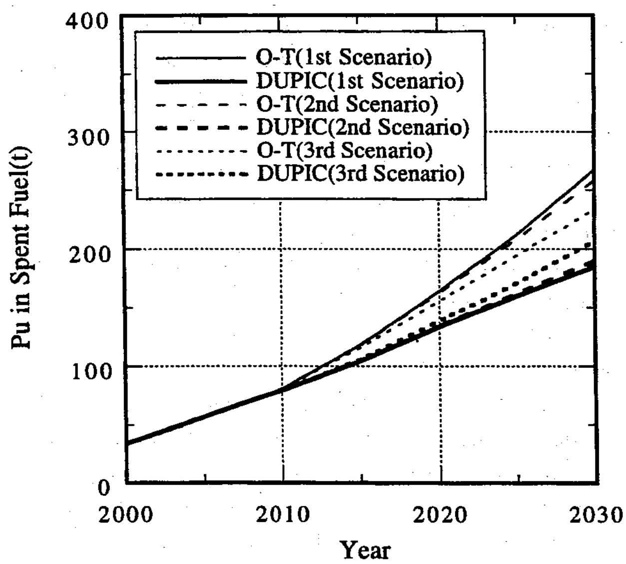

Fig. 9 Amount of Pu in Spent Fuel Accumulated in Korea Projected Between the Years 2000 and 2030

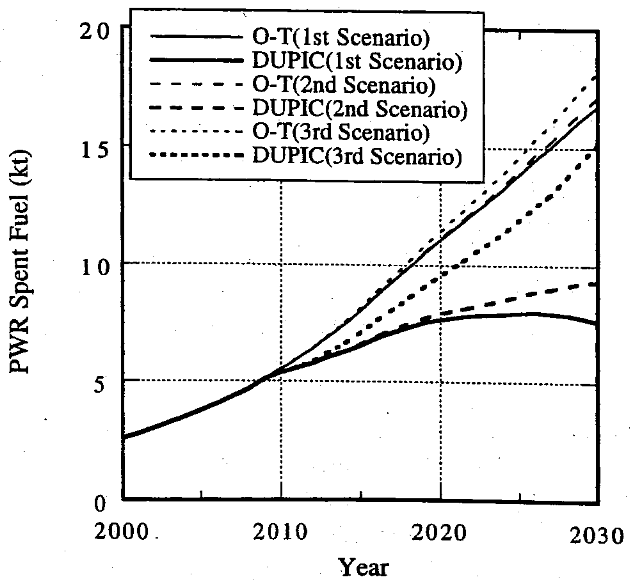

Fig. 8 Amount of PWR Spent Fuel Accumulated in Korea Projected Between the Years 2000 and 2030

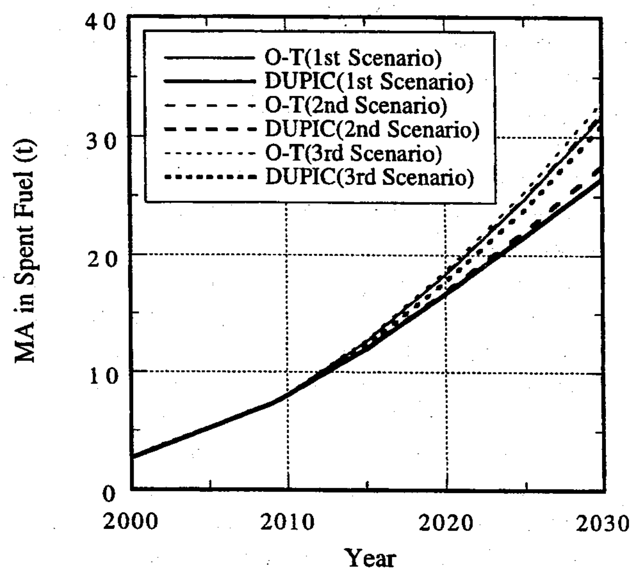

Fig. 10 Amount of MA in Spent Fuel Accumulated in Korea Projected Between the Years 2000 and 2030

io for the DUPIC fuel cycle relative to the once-through cycle is reduced by 31 %, 27 % and 12 %, respectively. The amount of accumulated MA included in spent fuel at 2030 in the first, second, and third scenario would be about 32, 32, and 33 t, respectively, for the once-through fuel cycle, but 27, 28, and 31 t with the DUPIC fuel cycle adopted from 2010. The amount of accumulated MA included in spent fuel in Korea at 2030 in the first, second, and third scenario for the DUPIC fuel cycle relative to the once-through cycle is reduced by 16 %, 13 % and 6 %, respectively.

9. Conclusions

Evaluations were made for the DUPIC fuel cycle, compared to the once-through cycle, about several issues such as a fabrication process of the DUPIC fuel, secondary radioactive wastes generated, mass flows, decay characteristics of the DUPIC spent fuel, and resource savings and environmental benefits. Impacts of three scenarios of DUPIC fuel cycle were evaluated when these are applied to Korea, compared to the once-through cycle, in reducing the amount of required natural uranium and spent fuel waste produced in Korea, based on the nuclear power capacity projected until 2030. Then, the optimized fuel cycle strategy in Korea was proposed from the view point of the optimization for the mass balance of DUPIC fuel cycle.

The DUPIC fuel cycle requires management of secondary radioactive wastes from the DUPIC fuel fabrication process unlike the once-through cycle. The DUPIC fuel cycle produces secondary radioactive wastes of solid and gaseous forms with no liquid wastes, but less than that of conventional reprocessing and MOX fuel fabrication process because there is no generation of liquid wastes in the OREOX process.

The decay characteristics of the DUPIC fuel cycle, such as TRU inventory, radioactivity, decay heat and toxicity, are favorable than those of the once-through cycle except that the increased curium, mainly Cm-244 with relatively short half-life, which could give rise to a strong radiation source in the short-term. The substantial reduction in radioactivity and decay heat of spent fuel is to some extent due to the released volatile and semi-volatile fission products in the OREOX process, which are recovered and stored for eventual disposal as secondary radioactive wastes. The DUPIC fuel cycle, compared to the once-through cycle, reduces by 30 % the amount of natural uranium consumed per year; this saving falls to about 20 % with the adoption high fuel burnup in PWR. This is the case as well in reducing the spent fuel arisings and uranium mining and milling wastes produced for the DUPIC fuel cycle, and therefore the overall risk associated with the nuclear fuel cycle.

Compared to the once-through cycle, the adoption of the DUPIC fuel cycle from 2010 onwards in Korea would reduce the amount of required natural uranium accumulation and accumulated spent fuel from PWR and CANDU reactors by 2030 by 6 % and 20 %, respectively, even in the most unfavorable scenario for the DUPIC fuel cycle, i.e., the third scenario.

The first scenario in this study would be nearly optimized fuel cycle in Korea, if DUPIC fuel cycle is adopted from 2010, from the view point of the accumulated PWR spent fuel for the mass balance of DUPIC fuel cycle.

Compared to the once-through cycle, the adoption of the DUPIC fuel cycle would reduce the amount of accumulated Pu included in the spent fuels, which makes this cycle more resistant to nuclear proliferation.

The DUPIC fuel cycle concept is attractive in terms of resource utilization and spent fuel management.

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