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여러 핵연료주기에서 방사성폐기물 관리 효율성 비교 연구

A Comparison Study on Radioactive Waste Management Effectiveness in Various Nuclear Fuel Cycles

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제 출 문

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본 보고서를 “경중수로 연계 핵연료주기 기술개발” 과제 (세부과제 "DUPIC 핵물질 안전조치 기술개발")의 기술보고서로 제출합니다.

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Abstract

This study examines whether the DUPIC (Direct Use of Spent PWR Fuel In CANDU) fuel cycle make radioactive waste management more effective, by comparing it with other fuel cycles such as the PWR (Pressurized Water Reactor) once-through cycle, the HWR (Pressurized Heavy Water Reactor) once-through cycle and the thermal recycling option to use an existing PWR with MOX (Mixed Oxide) fuel. This study first focuses on the radioactive waste volume generated in all fuel cycle steps, which could be one of the measures of effectiveness of the waste management. Then the total radioactive waste disposition cost is estimated based on two units measuring; m3/GWe-yr and US$/GWe-yr. We find from the radioactive waste volume estimation that the DUPIC fuel cycle could have lower volumes for milling tailings, low level waste and spent fuel than those of other fuel cycle options. From the results of the disposition cost analysis, we find that the DUPIC waste disposition cost is the lowest among fuel cycle options. If the total waste disposition cost is used as a proxy for quantifying the easiness or difficulty in managing wastes, then the DUPIC option actually make waste management easier.

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I. Introduction

The commercial nuclear fuel cycles in operation in the world include the once-through light water reactor (LWR) fuel cycle (e.g., U.S.A and Sweden), the once-through pressurized heavy water reactor (PHWR) fuel cycle (e.g., Canada), the LWR fuel cycle with recycled MOX (Mixed Oxide) fuel (e.g., Japan, France and Russia). The present civil use of recycled uranium and plutonium in LWR involves the development and the utilization of large scale reprocessing plants and MOX fuel fabrication facilities. Other alternative fuel cycles currently used on a limited scale or under development include the thorium fuel cycle (e.g., India) and the dry recycle DUPIC (Direct Use of Spent PWR Fuel in CANDU) fuel cycle under development in Korea.[1,2]

Many countries including France and the United Kingdom often express the view that reprocessing helps waste management (Beaumount et al. 1995 and Viala et al. 1995). They state that the recycling mode maximizes the utilization of uranium, reduces waste volumes and reduces the radio-toxicity of the waste to be disposed in a geologic repository. Ko et al.(1999, 2001) insist that the DUPIC fuel cycle must have significant waste management benefits such as a reduction of spent fuels to be disposed of and a saving in natural uranium resources. All arguments focus on only the waste volume or waste mass and on limited fuel cycle options. Not all types of waste generated through all steps in the various nuclear fuel cycles are considered.

This study examines whether the DUPIC fuel cycle can make radioactive waste management more effective compared with other fuel cycles such as the PWR (Pressurized Waster Reactor) once through cycle, the CANDU (Canadian Deuterium Uranium) once-through cycle and the thermal recycling option in use existing a PWR with MOX fuel. This study first focuses on waste volumes, which can be one of the measures of effectiveness in the waste management. Radioactive wastes are generally generated in all steps in the nuclear fuel cycle (i.e., front-end fuel cycle, reactor operation, back-end fuel cycle). For completeness, all types of waste generated in all steps from cradle to grave of the fuel cycle (i.e., low-level waste (LLW), intermediate-level waste (ILW), mill tailings generated in the mining/milling process, high-level waste (HLW) generated in reprocessing and spent fuels) are considered in this study.

In the past, a waste volume comparison was often made between directly disposed spent fuel and the HLW resulting from the reprocessing of PWR spent fuels.[3,4] A shortcoming in the previous methodology is the summation of waste volumes regardless of the radioactive level. Chow and Jones[5] has insisted that this comparison is inappropriate, because some wastes such as mill tailings are voluminous but can be taken care of cheaply. Total waste disposition cost would rather be a proxy for evaluating whether a fuel cycle "ease of waste management" – the lower the sum of the costs for conditioning and disposal of wastes generated in these steps, the easier is waste managed. His paper presented the waste disposition costs for handling wastes in different categories ranging between the PWR once-through option and MOX recycling option.

In this paper, the waste disposition costs for five fuel cycle options are also estimated and compared in order to establish which one is more cost effective for waste management. All waste volumes and waste disposition costs are expressed in unit of m^3/GWe-yr and US$/GWe-yr, respectively. First, fuel cycle scenarios are set up and reactor parameters and their fuel characteristics are assumed appropriately. Then, fuel material flows are estimated based on one GWe-yr and waste volumes in each step are assessed for different waste types. Finally, waste disposition costs are estimated. Reference fuel cycle models and approaches to estimate the waste management benefits are given in Section II. Waste volumes generated from each step and their evaluation are described in Section III and Section IV, respectively. Waste disposition costs are given in Section V.

II. Reference Fuel Cycle Model

II.A. Fuel Cycle Model

Fig. 1 shows the fuel cycle options considered in this study and the components of each fuel cycle. The first cycle is low-enriched uranium in the PWR once-through mode (hereafter called “PWR-OT”). The second fuel cycle is mixed oxide fuel in PWR (hereafter called “PWR-MOX”), in which spent PWR fuel is reprocessed and recovered plutonium is used for making MOX fuel (5% of plutonium content) and recovered uranium is recycled in a conversion plant. The spent MOX fuel is assumed to be disposed without further plutonium or uranium recovery. Some of the depleted uranium generated in the enrichment plant is assumed to be used for making MOX fuel. The third fuel cycle is natural uranium in CANDU once-through mode (hereafter called “CANDU-OT”). The fourth fuel cycle is the DUPIC cycle in which modified spent PWR fuel is used in a CANDU reactor (hereafter called “DUPIC”). The fifth fuel cycle is a proportional split of the PWR and CANDU fuel once-through modes with an electrical grid equivalent to the DUPIC fuel cycle (hereafter called “PWR-CANDU-OT”).

In the DUPIC fuel cycle, spent PWR fuel is directly refabricated into CANDU fuel to be reburnt in CANDU reactors before being disposed of permanently. On the other hand, the once-through fuel cycle (PWR-CANDU-OT) is assumed to dispose of all spent fuel generated by both PWR and CANDU reactors. As shown in Fig. 1, the front-end fuel cycle components for a PWR are established to be the same for both fuel cycles. For the DUPIC fuel cycle, however, several services such as DUPIC fuel fabrication are included but the front-end fuel cycle components for CANDU are not needed.

II.B. Waste Management in Nuclear Fuel Cycles

The fuel cycle begins when uranium is mined from the ground. During milling operation, uranium (U_3O_8) or yellow cake is removed from the ore by chemical and physical means. The ore residues containing chemical effluents and natural radioactivity (particularly radon) are called mill tailings. They are normally stabilized and disposed of at or close to the mine of origin. As these wastes contain natural long-lived radio-nuclides, they must be disposed of in a way that affords long-term protection to man and his environment.

Radioactive wastes are also generated during conversion, enrichment and fabrication. For example, there are scrap materials still containing uranium and enrichment tailings containing depleted uranium. During reactor operation, ILW/LLW are generated both as liquid and as solid. The liquid is contaminated water from different parts of the reactor system and from the plant. Purification or concentration of this water gives rise to slurries that are mixed with cement or asphalt to form a stable waste form.

During and after power reactor operations, radioactive waste remains in three sources. The first is fission products resulting from nuclear fission taken place in reactors. Typical long-life nuclide fragments with the highest radioactivity are Cesium-137, Strontium-90, and their daughters Barium-137 and Yttrium-90. The second source is actinides which are uranium and transuranic (TRU) elements mainly neptunium, plutonium, americium and curium. The third source of radioactivity is activation products such as those resulting from neutron irradiation of structural material and impurities. Thus, many radioactive elements of different intensities and half-lives are generated through the back end nuclear fuel cycles. For example, during reprocessing, spent fuel is dissolved and uranium and plutonium are separated for recycling. The main waste product is the heat-generating high level waste solutions containing the bulk amount of fission products from the spent fuel. Some of the reprocessing waste contains a substantial amount of long-lived nuclides and these will require the same degree of isolation from man’s environment as spent fuel. ILW/LLW is also generated at a reprocessing plant.

The DUPIC fabrication process involves the direct refabrication of spent PWR fuel into the CANDU fuel. The fuel material is recovered from the spent PWR fuel by disassembling and decladding using only thermal and mechanical processes. The waste products are generated at different process steps. The waste stream from the DUPIC fuel fabrication processes mainly consist of the metallic components from spent PWR fuel and the gases and semi-volatile fission products released from the bulk fuel material treatment, in addition to the measurable discards and losses.[6] There is no liquid waste arising from the DUPIC fuel fabrication processes which depend entirely on a dry oxidation/reduction method, in contrast to wet processes from which liquid waste arise as effluent.

The decommissioning and dismantling (D&D) of nuclear installations will also generate radioactive wastes. Waste types generated in D&D work will depend on the nuclear installations.

In order to evaluate all wastes generated in the various fuel cycles, radioactive wastes need to be classified appropriately according to their activity level and half-life. In fact, the classification of radioactive wastes is different country by country. For this study, the radioactive wastes are classified into five categories, which can be handled, stored and disposed of differently. The first is spent fuel itself, which is discharged directly from the reactor and may be included in high level waste class in some countries. The second is high level waste (HLW), which is a stream of waste (liquid or solidified form) after reprocessing or dirty scrap and collective volatiles and semivolatiles during DUPIC plant operation. The third is intermediate level waste (ILW) which is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and a total concentration of such radio-nuclides in excess of 0.1 Curies per metric ton of waste. The forth is low-level waste(LLW), which is generated in all steps of the fuel cycles. The last one is mill tailings, which is ore residues from milling after uranium extraction.

II.C. Reference Reactors and Fuels

For material flows of each fuel cycle, the reference PWR and CANDU reactors must be first chosen, and their fuel characteristics (e.g., initial enrichment and discharge burnup) need to be reasonably defined. For a practical purposes, a 950 MWe PWR and a 713 MWe CANDU reactor, which are now operating in Korea, are taken as reference reactor systems. The characteristic parameters of the reference reactor systems are summarized in Table 1, which are used as input data for determining the fuel material balance. In the table, the fuel load per reactor is estimated based on the reactor parameters such as

$$\text{Fuel loading per core} = \frac{P \times 100}{\varepsilon \times SH} \qquad (1)$$

where P, SH and ε are the electric power (MWe) of a CANDU reactor, the specific power (MWt/MTHM) and efficiency (%), respectively.

Table 2 shows the reference fuels of each fuel cycle. It is assumed that LEU (Low Enriched Uranium) PWR fuels and MOX fuels are burnt up to 35,000 MWD/MTU although recent PWR fuels have been mostly over 40,000 MWD/MTU fuel with higher enrichment. The reason is that 35,000 MWD/MTU with initial enrichment of 3.5% U^{235} is chosen as the reference PWR fuel in the DUPIC fuel cycle development program in Korea.[2]

In the PWR-MOX fuel cycle, the plutonium recovered from reprocessing of LEU spent PWR fuel is made into MOX fuel, which is reburned in a PWR and then the discharged spent MOX fuel is disposed of. We calculated how much plutonium is in spent PWR fuel with a burnup of 35,000 MWD/MTU with the ORIGEN 2 computer program.[7] About 0.86wt% of

U^{235} and 0.89wt% of Pu remain in the spent PWR fuel. If the MOX fuel consists of depleted uranium and 5% plutonium, an equilibrium state can be reached when the MOX burning reactor uses a core which is 14.7% MOX and 85.3% LEU. This means that all reprocessed plutonium from spent LEU-PWR fuel with a burnup of 35,000MWD/MTU can be used in the PWR core. In this situation, PWR core with MOX fuel consists of 10 MTHM MOX fuel and 59 MTU LEU fuel per reactor core.

In a CANDU reactor, the discharge burnup of natural CANDU fuel is assumed to be 7500 MWD/MTHM and the discharge burnup of DUPIC fuel is assumed to be 15,400 MWD/MTHM which is a reference fuel in DUPIC fuel development program.[2,8]

The annual requirement of nuclear fuels is calculated based on fuel burnup and other parameters such as

$$\text{Annual requirement} = \frac{P \times 365 \times C}{\varepsilon \times BU} \qquad (2)$$

where C and BU are the capacity factor (%) and burnup (MWD/MTHM), respectively. The annual requirements per unit are translated into an annual requirement based on 1 GWe-yr as shown in the last row of Table 2.

II.D. Material Flow Analysis of Fuel Cycle

For the PWR-CANDU-OT and DUPIC fuel cycles, the equilibrium core ratio between PWRs and CANDU reactors have to be known so that all spent PWR fuels can make DUPIC fuels. The equilibrium core ratio between PWRs and a CANDU reactor can be calculated as follows;

$$\text{Equilibrium core ratio } (R_C) = \frac{M_{DUPIC} \times (1 + L_{DUPIC})}{M_{PWR}} \qquad (3)$$

Where M_{DUPIC}, M_{PWR}, and L_{DUPIC} are annual mass requirement of DUPIC fuel, annual mass requirement of PWR fuel and the loss rate in the DUPIC fabrication plant, respectively. The loss rate in a DUPIC fabrication plant is assumed to be 1%. Since M_{DUPIC} and M_{PWR} are 46MTHM and 23MTU, respectively, as shown in Table 2, the equilibrium core ratio is 1.997.

The portion of electricity power generation in the PWR-CANDU-OT fuel cycle for 1 GWe-yr is as follow;

$$\text{Electricity generation portion of PWR} = \frac{P_{PWR} \times R_C}{P_{PWR} \times R_C + P_{CANDU}} \tag{4}$$

Where P_{PWR} and P_{CANDU} are the electricity power generation for PWR and CANDU, respectively. So the portion of PWR and CANDU generation will be 73% and 27%, respectively. The portions of electricity generation are applied to both the PWR-CANDU-OT and DUPIC fuel cycles.

In this study, it is assumed that the loss factors are 0.5% for conversion plant, 1% for all typed-fuel fabrication and for reprocessing plant operations. The enrichment amounts in a Separative Work Unit (SWU) is calculated as follows:

$$\text{SWU} = M_p V_p + M_t V_t - M_f V_f \tag{5}$$

Where M_p = mass of uranium to be charged in the fuel fabrication facility,

M_f = mass of uranium feed in enrichment plant (and output of conversion plant),

and

M_t = mass of uranium discharged from the enrichment plant

(i.e., depleted uranium).

$$V_x = (2e_x - 1)\ln\frac{e_x}{(1-e_x)} \tag{6}$$

where x is the subscript for f, p or t,

where e_p = fraction of ^{235}U in the uranium feed (e.g., 3.5 wt%),

e_t = fraction of ^{235}U in the tails (e.g., 0.25 wt%), and

e_f = fraction of ^{235}U of uranium to be charged in enrichment plant

(e.g., 0.711 wt%).

$$\text{Then, } M_f = M_p \frac{(e_p - e_t)}{(e_f - e_t)} \tag{7}$$

$$\text{and} \quad M_t = M_f - M_p \tag{8}$$

If M_p and three fractions of the ^{235}U in enrichment plant are known, then the SWU as well as M_f and M_t (depleted uranium) can be calculated.

The requirement of natural uranium resources are converted to that of uranium (U_3O_8) by the following formulation:

$$M_n = M_R \times \frac{e_p - e_t}{e_f - e_t} \times (1 + l_1) \times \frac{W_{U_3O_8}}{W_{U_3}} \times (1 + l_2) \qquad (9)$$

where M_n is the mass of uranium (U_3O_8) in the feed material, M_R is the mass of uranium charged to the reactor, and $W_{U_3O_8}/W_{U_3}$ is the weight fraction of uranium in the uranium resources (U_3O_8), and l_1 *and* l_2 are process loss rates for conversion and fuel fabrication, respectively.

Table 3 shows the results of the material balance analyses that are calculated by equations 1 through 9 with the reference reactors parameters (Table 1) and their corresponding fuel characteristics (Table 2). The material flows are shown in Fig. 1. All values are expressed on the basis of 1 GWe-yr for all fuel cycle options.

From the first row of Table 3, the DUPIC fuel cycle with PWR and CANDU reactors requires only 153 Mg of U_3O_8 for PWR fuel with enrichment to 3.5 wt% ^{235}U. On the other hand, 153 Mg of U_3O_8 for PWR fuel and 43 Mg of U_3O_8 for CANDU fuel are required for the PWR-CANDU once-through cycle. The DUPIC option has ~22wt% uranium resources saving, compared with the PWR-CANDU-OT fuel cycle. We also find that the uranium resource of the DUPIC fuel cycle saves 11% relative to that of the PWR-MOX cycle. From the last row of the Table 3, the amount of spent fuel annually discharged from the DUPIC fuel cycle is ~18 MTHM while the PWR-CANDU-OT is ~54 MTHM. The DUPIC fuel cycle generates ~67% less spent fuel than that of the PWR-CANDU-OT cycle. The PWR-OT requires the largest natural uranium resources (~211 Mg U_3O_8) and CANDU-OT generates the most spent fuels (133 MTHM) on the basis of 1Gwe-yr.

Relative amount of natural resources saving and spent fuel arisings reduction to maximum values are summarized in Table 4. Compared between PWR-OT and CANDU-OT, it is indicated that the PWR-OT requires the largest natural uranium resources (211 Mg U_3O_8/GWe-yr) and CANDU-OT generates the largest spent fuels (133 MTHM/GWe-yr).

Table 1 Characteristics of Reference Reactors

Reactor parameters	PWR	CANDU
- Electric power (MWe)	950	713
- Thermal efficiency (%)	34	33
- Thermal power (MWt)	2,794	2,161
- Specific power (MWt/ton U)	40.2	25.5
- Load factor	0.8	0.9
- Cycle length (Full Power Day)	290	-
- No. of fuel assemblies or bundles per core	157	4,560
- No. of batches for PWR	3	-
- Loading per core (MTU)	69.5	84.7

Table 2 Characteristics of Reference Reactors and Fuels

Item	Characteristic Parameters			
	PWR with LEU fuel	PWR with LEU and MOX fuel*	CANDU with NU fuel	CANDU with DUPIC fuel
Reactor				
- Loading per core (MTU)	69.5	69.5 (10.22 MOX) (59.28 LEU)	84.7	84.7
- Annual fuel requirement (MTU)	23.31	23.31 (3.43 MOX) (19.88 LEU)	94.63	46.09
Fuel				
- Initial enrichment	3.5%	5% Pu_f MOX 3.5% LEU	Nat. U	PWR S/F
- No. of fuel rods per assembly	264	264	37	43
- Discharge burnup (MWd/kgHM)	35	35	7.5	15.4
Normalization of Fuel				
- Required fuel amount for 1 GWe-yr (MTU or MTHM)	24.54	24.54 (3.61 MOX) (20.93 LEU)	132.73	64.64

*14.7% of the fuel in MOX and 85.3% of the fuel in LEU(Low Enriched Uranium) – an equilibrium state is reached when all spent PWR fuels are reprocessed to make needed MOX fuels.

Table 3 Material Flows for Five Fuel Cycle Options*
(Based on 1 GWe-yr)

Components		Nuclear Fuel Cycles				
		PWR-OT	PWR-MOX	CANDU-OT	PWR-CANDU-OT	DUPIC
Uranium purchase (Mg U_3O_8)	PWR	211	172	-	153	153
	CANDU	-	-	159	43.4	-
Conversion (MTU)	PWR	176	143 20.7(REU)		128	128
	CANDU	-	-	135	36.8	-
Enrichment (TSWU)		119	82.8[2] 15.6(REU)[3]	-	86.7	86.7
Fabrication (MTU or MTHM)	PWR	24.78	21.14	-	18	18
	CANDU	-	-	134	36.6	-
	MOX	-	3.64	-	-	-
	DUPIC	-	-	-	-	17.8
Interim Storage (MTHM)	PWR	24.5	20.9		17.8	-
	CANDU	-	-	133	36.3	-
	MOX	-	3.61	-	-	-
	DUPIC	-	-	-	-	17.7
Reprocessing/ vitrification (MTU)		-	20.9	-	-	-
Pu, HLW Storage (MTHM)		-	0.19	-	-	-
Conditioning /Final Disposal (MTHM)	PWR	24.5	-	-	17.8	-
	CANDU	-	-	133	36.3	-
	MOX	-	3.61	-	-	-
	DUPIC	-	-	-	-	17.7
	HLW[1]	-	20.9	-	-	-

*MTU: Metric Ton Uranium
TSWU: Ton Separative Work Unit
MTHM: Metric Ton Heavy Metal
REU: Recovered Uranium
Equilibrium Ratio of PWR and CANDU = 1.997 : 1
Portion of electricity generation of 1 Gwe-yr : 72.68% of PWR, 27.32% of CANDU

[1] Mass of the HLW is expressed as the heavy metal weight before reprocessing.

[2] In producing the 3.5 wt% ^{235}U at the uranium feed of 0.711 wt% and tails of 0.25 wt%

[3] In producing 3.5 wt% ^{235}U at the recovered uranium feed of 0.86 wt% and tails of 0.25 wt%

Table 4 Summary of the Natural Uranium Resources and Spent Fuel Arisings

	Nuclear Fuel Cycles				
	PWR-OT	PWR-MOX	CANDU-OT	DUPIC	PWR-CANDU
Natural Uranium Saving Rate*	0.00%	18.68%	24.8%	26.73%	6.18%
Disposal Waste (SF/HLW) Reduction Rate*	81.51%	81.51%	0.00%	86.69%	59.04%

* compared with maximum value.

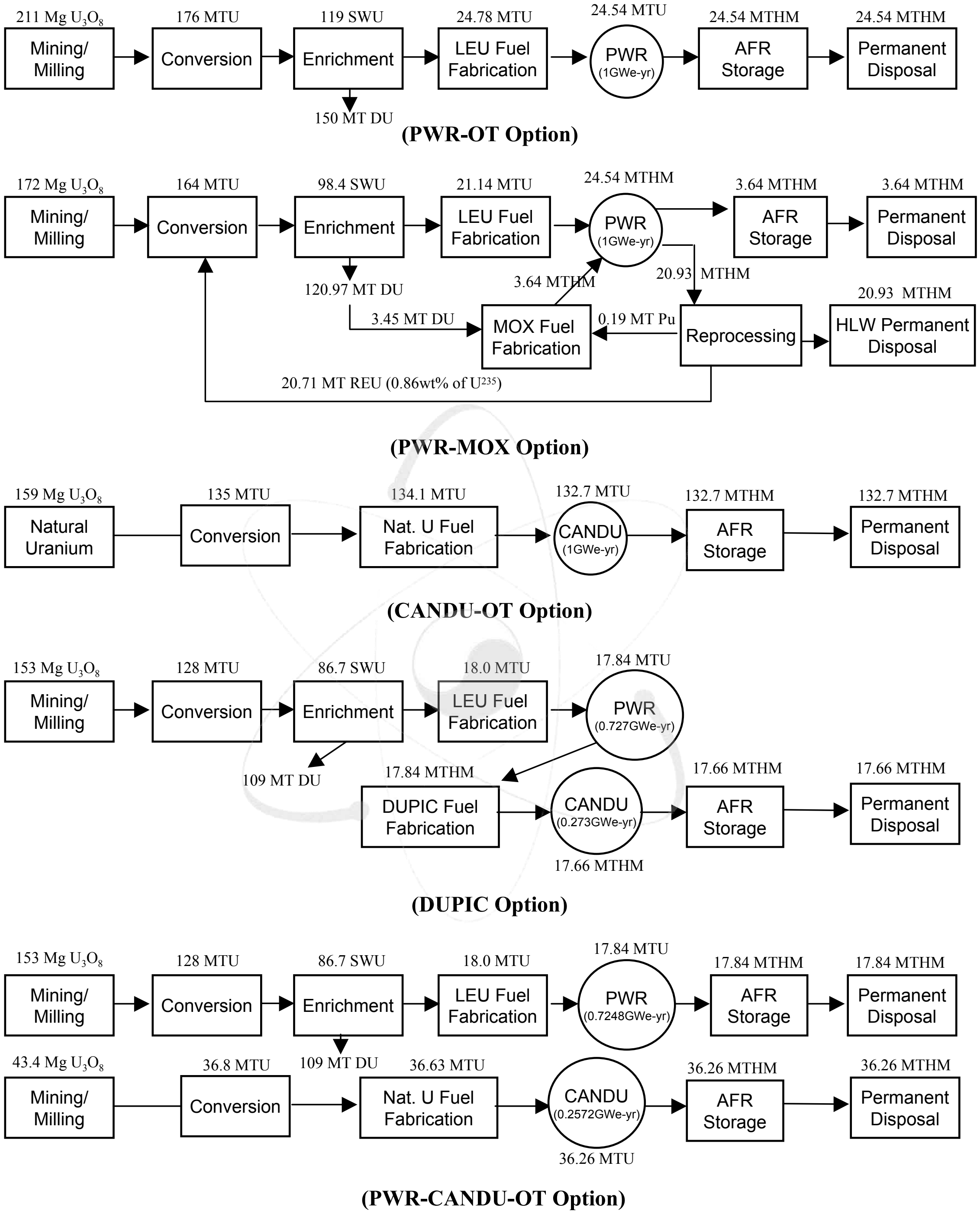

Fig. 1 Five Fuel Cycle Options and Their Material Flows (Based on 1 GWe-yr)

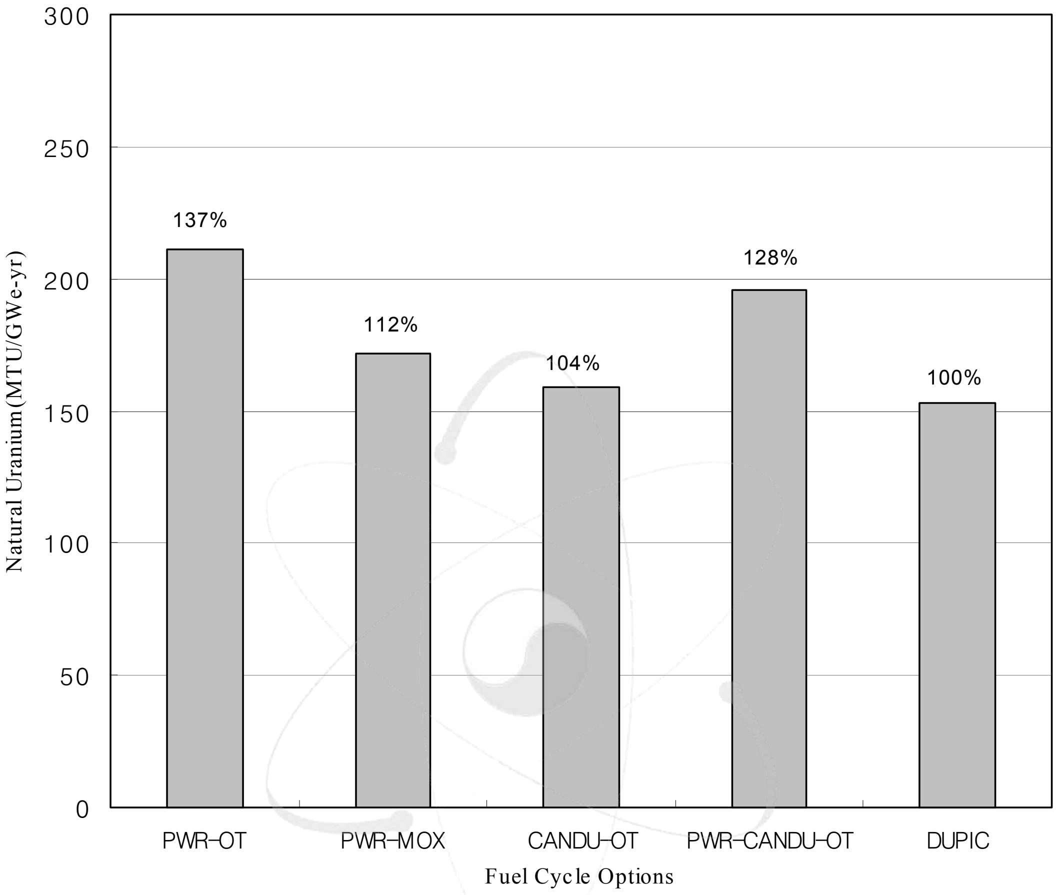

Fig. 2 Natural Uranium Needed for Electricity Generation of 1 GWe-yr

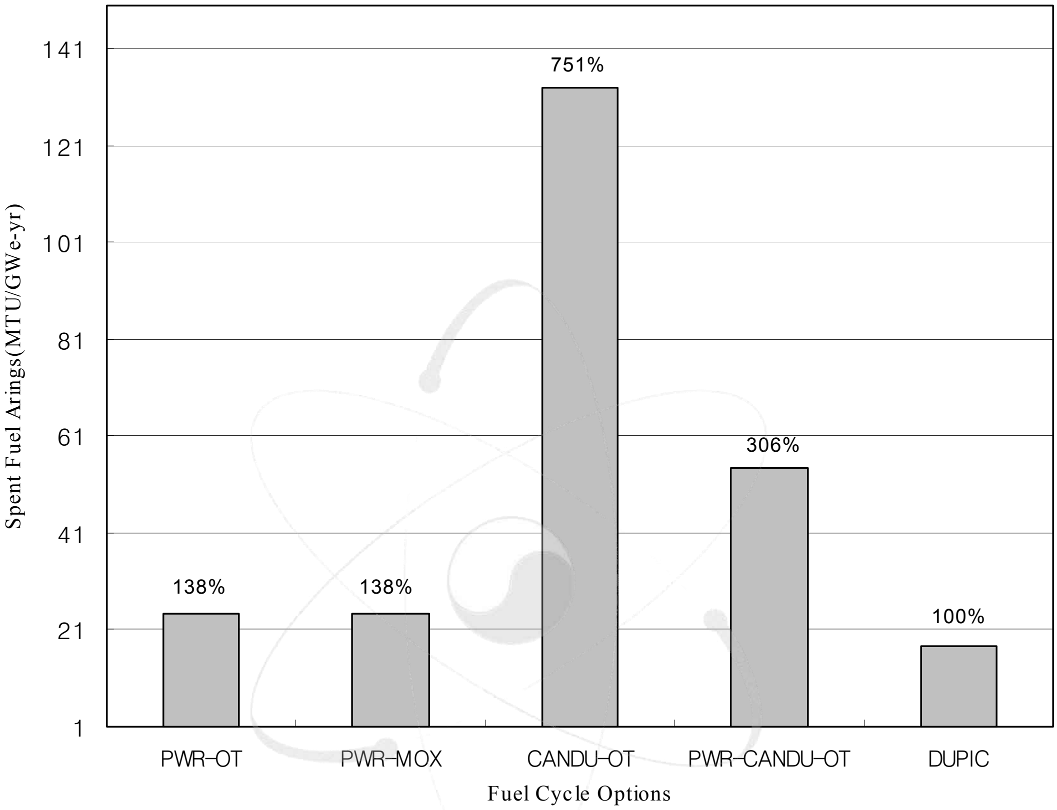

Fig. 3 Spent Fuel Arisings Comparison (Based on 1 GWe-yr)

III. Radioactive Waste Generation

In this chapter, we evaluate all wastes generated from mining to disposal in the five alternative fuel cycles. The volumes are assessed on a metric ton basis and then these values are translated into the 1 GWe-yr basis. The volumetric unit waste (m^3/MTU or m^3/MTHM) estimated in this study are summarized in Table 5. Waste volumes generated in the front–end fuel cycle and reactor operations are described in Section III.A and Section III.B, respectively. The Waste volumes generated in the back–end fuel cycle and decommissioning waste are given in Section III.C.

III.A. Front –end and Reactor Operation Wastes

Mining and mill wastes

In mining operations, rocks are moved in order to access the uranium ore. These rocks contain little uranium and are not milled. They are often returned to the pits and not considered as waste materials. On the other hand, milling operations do generate large volumes of tailings which depends most on the ore grade. Chow and Jones[5] have estimated the tailing volume from Canadian and western mill operation data, of which ~80% use conventional method generating large volumes of tailings and the remaining are unconventional methods such as in-situ leach (ISL), generating little tailings. They calculated a weighted average of 300 m^3/MTHM of mill tails. We convert this to 254 m^3/Mg U_3O_8.

Conversion wastes

The conversion to uranium hexafluoride (UF_6) for enrichment process starts with the dissolution of the yellow cake in nitric acid, and the filtering and treating the solution with chemical solvents. If enrichment is not required, for example for pressurized heavy-water reactor (PHWR) fuel, then uranium dioxide (UO_2) is produced from the uranyl nitrate and shipped directly to a fuel fabrication plant. If enrichment is required, it is converted to UF_6 for the enrichment process. During these processes, wastes are generated in the forms of dry active waste, crushed drums and scrap metal, calcium fluoride sludge, mixed waste etc. The amount of conversion waste depends on what processing procedures are used and how the wastes are treated and compacted. Chow and Jones[5] have estimated the conversion wastes to range from 32 to 112 m^3/GWe-yr from data of two conversion plants in Metropolis, Illinois and in Gore, Oklahoma. We convert 1 GWe-yr to 26 MTHM based on a reference fuel in

Chow and Jones (1999) with 3.7% U^{235}, burnup of 42500 MWD/MTU and a tails assay of 0.3% U^{235} by using equations 5 through 9. Thus, a conversion facility for PWR fuel produces 0.15 ~ 0.51 m^3/MTHM of waste. For CANDU fuel, half the value for PWR fuel (0.08 ~ 0.26 m^3/MTHM) is used in our study because of the conversion directly to uranium oxide without the hexafluride conversion process.

Enrichment wastes

During enrichment, two types of wastes are generated, mainly depleted uranium hexafluoride, and filters and sludges. The UF_6 can be chemically converted to the stable U_3O_8 for disposal or reuse. Chow and Jones[5] have used 39 m^3/GWe-yr including the 7 m^3/GWe-yr for filters and sludges. However, the volume of depleted uranium depends on the degree of the enrichment of the product, feed and tails as derived in equation 5. Instead of the unit of m^3/GWe-yr, we use a different unit, m^3 /TSWU because of the different bases including re-enrichment of recovered uranium (~0.86wt% of U^{235}) in this study.

By using equation 7, we calculate the mass of reprocessing tails for each case. In producing the 3.5 wt% ^{235}U at the uranium feed of 0.711 wt% and tails of 0.25 wt%, about 1.26 MTU per TSWU of tails is generated. In producing 3.5 wt% ^{235}U at the recovered uranium feed of 0.86 wt% and tails of 0.25 wt%, about 1.08 MTU per TSWU of tails is generated. In order to estimate the volume of depleted uranium, the density of the U_3O_8 powder is assumed to be 3 g/cm^3. In this case, 1.26 MTU and 1.08 MTU per TSWU of tails yields 0.42 m^3 and 0.36 m^3 per TSWU, respectively. The estimated filters and sludges (about 18% of total wastes) are 0.50 m^3/ TSWU for LEU fuel enrichment and 0.42 m^3/TSWU for recovered uranium enrichment.

Fabrication Wastes

Fuel fabrication includes the sintered pelletization of LEU UO_2, mixed oxide fuel, and treated spent PWR fuel for DUPIC fuel. The wastes are the discarded processing equipment and materials contaminated with uranium and other actinides. Chow and Jones analyzed five commercial UO_2 fuel fabrication plants operated in the U.S. and estimated the waste to be 3~9 m^3/GWe-yr, equivalent to 0.12 ~ 0.35 m^3/MTHM in our study. As to MOX fabrication waste, values of 87 m^3/GWe-yr of ILW and 33 m^3/GWe-yr of LLW were derived, equivalent to 3.35 m^3/MTHM and 1.27 m^3/MTHM, respectively in our study.

For DUPIC fuel fabrication, the conceptual design report of commercial DUPIC fuel fabrication[6] is used. The projected waste generation for a 400 MTHM/yr facility is summarized in Table 6. The term GTCC in the table means the greater level of wastes than the class C criteria used in the U.S. The GTCC wastes are supposed to be disposed in a deep geological repository with other high level wastes. For the GTCC wastes, dirty scrap and Cs/Ru wastes, which need to be vitrified, are classified as HLW and the remaining are classified as ILW. Thus, 2.11 m^3/MTHM is classified as LLW, 0.20 m^3/MTHM as ILW and 0.13 m^3/MTHM as HLW.

III.B. Reactor Operation Wastes

In reactor operation, wastes result from neutron activation of structural materials, corrosion products and chemical additives. Fuel cladding failure results in minute quantities of oxide fuel leaks in the primary coolant or in spent fuel storage pool coolant. These dissolved and suspended solids are removed by filters and ion exchange resins. Chow and Jones used a range of 86 ~ 130 m^3/GW-yr of LLW and a range of 22 ~ 33 m^3/GW-yr of ILW for PWR operation. In Korea, ILW and LLW are not classified separately, only as LILW (Low-Intermediate Level Waste). We assume that spent resin used for treating liquid waste is classified as ILW and all others are LLW. By KAIF(Korea Atomic Industrial Forum) report[9], from 1978 to 1998, Korean PWRs generated 78.9 GWe-yr of electricity and 433 drums with 200 liters of ILW and 48,331 drums of LLW, or alternately 1.1 m^3/GW-yr of ILW and 122 m^3/GWe-yr of LLW. We use a range of 86 ~ 130 m^3/GW-yr of LLW and a range of 1.1 ~ 33 m^3/GW-yr of ILW for PWR operation.

From 1983 to 1998, Korean CANDU reactors generated 10.37 GWe-yr of electricity and 85 drums of ILW and 3,551 drums of LLW or 1.6 m^3/GW-yr of ILW and 69 m^3/GWe-yr of LLW. We use 69 m^3/GW-yr of LLW and a range of 1.6 ~ 33 m^3/GW-yr of ILW for CANDU reactor operation.

For MOX and DUPIC fuel cycles, the waste volumes during reactor operations should be similar to PWR and CANDU cycles, respectively.

III.C. Back –end and Decommissioning Waste

Reprocessing and storage wastes

During reprocessing, the main waste product is the high level waste solution containing most of fission products from the spent fuel. These wastes are vitrificated for final disposal.

ILW/LLW is also generated at the reprocessing plant and these wastes are treated as solidified slurries in cement or asphalt, compacted waste, incinerated ash or packaged solid waste. Chow and Jones assessed the wastes volume generated from reprocessing, storage, conditioning (including vitrification in the case of HLW) and disposal using five different references as shown in Table 7. We use the range of Table, which are equivalent to 2.7 ~ 3.7 m^3/MTHM for LLW, 0.77 ~ 1.73 m^3/MTHM for ILW, and 0.08 ~ 0.15 m^3/MTHM for HLW, respectively.

Interim Storage

When spent fuel is in pool storage or packaged in casks or canisters for dry storage, ILW and LLW are generated. Chow and Jones used 2 m^3/GWe-yr for LLW and 0.2 m^3/GWe-yr for ILW from spent PWR and MOX fuel storage and from their packaging process. We convert this to 0.077 m^3/MTHM for ILW and 0.007 m^3/MTHM for LLW, from spent PWR and MOX fuels. No data is available for spent CANDU and DUPIC fuels. We assume that wastes for spent CANDU and DUPIC fuels are the same values as those of spent PWR and MOX fuel.

Disposal wastes

Before deep geological disposal of spent fuel, they must be packaged in corrosion resistant containers in a conditioning. For LLW and ILW, we use the OECD/NEA[12] value of 0.2 m^3/MTHM for ILW. Since there is no value for LLW, 0.007 m^3/MTHM is assumed because the encapsulation plants for interim storage and for disposal should be similar.

The volumes of spent fuel and HLW to be disposed of are assumed be 1.5 m^3/MTHM and 0.115 m^3/MTHM, respectively (OECF/NEA report[12]). In a geological repository, the heat generated by the disposed spent fuel and HLW will determine the actual space that the waste occupies[13] and is not considered here.

Decommissioning Wastes

For the decommissioning of a conversion plant, Chow and Jones estimated the production of 92 m^3/GWe-yr of waste from the ongoing decommissioning of the Gore, Oklahoma UF_6 conversion plant. We convert this to 0.43 m^3/MTHM. For CANDU fuel, we assume half this value, 0.22 m^3/MTHM because there is no UF_6 production as described in section III.A.

For the decommissioning of an enrichment plant, Chow and Jones estimated 5 m^3/GWe-yr from Louisiana Energy Service, Capenhurst of UK and Almelo of Netherlands. On the basis of GWe-yr requiring 26 MTHM of reference fuel (i.e., 3.7% U^{235} and burnup of

42500 MWD/MTU), 121.5 SWU is calculated from equations 5 through 9. We derive a value, 0.04 m^3/SWU of LLW.

For the decommissioning of a UO_2 fabrication plant, Chow and Jones estimated 6 m^3/GWe-yr of LLW, based on an average value of four plants located in Columbia, SC, Wilmington, NC, Richland, WA and Hematite, MO, which have a range of 3.5 ~ 10 m^3/GWe-yr. In our study, we use this range for both PWR and CANDU fuel fabrication facilities, which is converted to 0.13 ~ 0.38 m^3 /MTU of LLW. For a MOX fabrication facility, Bartlett[14] estimated that the decommissioning would generate 3 m^3/GWe-yr of ILW and 1.6 m^3/GWe-yr of LLW. We convert this to 0.12 m^3 /MTU of ILW and 0.06 m^3 /MTU of LLW for both MOX and DUPIC fuel fabrication facilities.

For PWR decommissioning, we use Chow and Jones values of 175 ~ 230 m^3/GWe-yr for LLW and 9 m^3/GWe-yr for ILW, derived from DOE data[15]. For CANDU reactor decommissioning, Unsworth[16] estimated the total decommissioning wastes for a 600 MWe CANDU reactor to be 7,250 m^3. We convert this to 403 m^3/GWe-yr assuming 30 years operation. We assume that ILW portion (3.8% of total wastes) for a PWR is 15.3 m^3/GWe-yr and 387.7 m^3/GWe-yr for LLW. For the MOX and DUPIC fuel cycles, the waste volumes from reactor decommissioning are assumed to be the same as those for PWR and CANDU cycles, respectively.

For decommissioning of a reprocessing plant, Bartlett[14] estimated 0.8 m^3/GWe-yr for ILW and 5 m^3/GWe-yr for LLW, which we convert to 0.03 m^3/MTHM and 0.19 m^3/MTHM, respectively.

Table 5 Unit Radioactive Wastes Generation from Fuel Cycle Facilities

Components		PWR Fuel	MOX Fuel	CANDU Fuel	DUPIC Fuel
Mining and milling (milling tailings, m^3/Mg U_3O_8)		254	-	254	-
Conversion (LLW, m^3/MTU)		0.15~0.51	-	0.08~0.26	-
Enrichment (LLW, m^3/TSWU)		0.50	0.42(REU)	-	-
Fabrication (m^3/MTU or MTHM)	LLW	0.12~0.35	1.27	0.12~0.35	2.11
	ILW	-	3.35	-	0.20
	HLW	-	-	-	0.13
Reactor operation (m^3/GWe-yr)	LLW	86~130	86~130	68.5	68.5
	ILW	1.1~33	1.1~33	1.6~33	1.6~33
Interim Storage /encapsulation (m^3/MTHM)	LLW	0.008	0.008	0.008	0.008
	ILW	0.077	0.077	0.077	0.077
Reprocessing /vitrification /disposal (m^3/MTHM)	LLW	-	2.7~3.7	-	-
	ILW	-	0.77~1.73	-	-
	HLW	-	0.08~0.15	-	
Coditioning/ Disposal of spent fuel/ Disposal of HLW (m^3/MTHM)	LLW	0.008	0.008	0.008	0.008
	ILW	0.2	0.2	0.2	0.2
	HLW	-	0.115	-	-
	S/F*	1.5	1.5	1.5	1.5
Decon. of conversion (LLW, m^3/MTU)		0.43	-	0.22	
Decon. of Enrichment (LLW, m^3/TSWU)		0.04	-	-	-
Decon of fabrication (m^3/MTU or MTHM)	LLW	0.13~0.38	0.06	0.13~0.38	0.06
	ILW	-	0.12	-	0.12
Decon of Reactor (m^3/GWe-yr)	LLW	175~230	175~230	387.7	387.7
	ILW	9	9	15.3	15.3
Decon. of reprocessing /vitrification (m^3/MTHM)	LLW	-	0.19	-	-
	ILW	-	0.03	-	-

*S/F : Spent Fuel

Table 6 Projected Annual Waste Generation in DUPIC Facility (400 MTHM/yr)

Waste constituent	Waste form	Storage criteria	Volume for disposal package
H^3, C^{14}	200L Cemented drums	LLW	80 m^3
Kr, Xe	Compressed 50L cylinders	GTCC	13.2 m^3
Iodines	Silver zeolites	GTCC	0.5 m^3
Dirty Scrap	Vitrified glass	GTCC	9.98 m^3
Cs, Ru	Vitrified glass	GTCC	40.44 m^3
Spent fuel H/W	Compacted	GTCC	35.12 m^3
Zircaloy hulls	Cemented drum	GTCC	30.34 m^3
Secondary wastes	Cemented drum	LLW	764.1 m^3
Total LLW			~844 m^3
Total GTCC			~130 m^3

Table 7 Wastes from Reprocessing

Source Data	Reference	Waste Volume in m^3/GWe-yr		
		LLW	ILW	HLW
BNF	Smith and Mote[10]	78	29.6	2.2
COGEMA	"	70	20	4
WAK	"			2.5
PNNL	McKee et al.[11]	13	45	2
BNFL	Beaumont et al.[3]	95	32	3
Range used		70~95	20~45	2~4

IV. Evaluation of Waste Volume Generation

Waste volumes for all steps in each fuel cycle are estimated from the unit volumes described in Table 5 and material flows in each fuel cycle given in Table 3. There are large uncertainties in the waste volumes. For example, the decommissioning volumes hinge on the stringency of the prevailing environmental regulations. The less soil and materials are as successfully decontaminated, the more waste results. More stringent regulations may also result in larger waste volumes during routine operations. Also, if one is willing to spend more money, one can further reduce or compact the waste volumes. In spite of all these uncertainties, our comparison should still be meaningful, because it is quite probable that factors would affect all waste volumes in similar ways. When regulations are tight, all waste volumes are likely to take the higher values, regardless of fuel cycles and of fuel cycle steps.

Table 8 shows the waste volumes for all steps, and the total wastes for each fuel cycle are summarized in Table 9 and 10. Considering that there are no some facilities in front-end fuel cycle such as enrichment and uranium mining in Korea, we also calculate the total wastes except for wastes from those facilities as described in Table 11 and 12.

Mill Tailings

The waste volume for mill tailings in the PWR-OT fuel cycle is higher than that for the CANDU-OT fuel cycle as expected. It means that natural uranium CANDU fuel has better natural uranium utilization than PWR fuel with low enriched uranium. The DUPIC fuel cycle has the smallest mill tailings which is 27% lower than that for the PWR-OT fuel cycle, and ~22% and 3% less than for the PWR-CANDU-OT and CANDU-OT options, respectively.

LLW

As described in Table 8, the highest volume in reactor operation and reactor decommissioning is LLW regardless of fuel cycle. From Table 10, the CANDU-OT case is a little higher than that of the PWR-OT case. The CANDU has less LLW in reactor operation but more from decommissioning. On the whole, the LLW volume from DUPIC, PWR-OT and PWR-CANDU-OT options are similar.

ILW

As shown in Table 10, the PWR-MOX option has the highest ILW volume among the options, mainly due to the wastes generated in the reprocessing plant. The ILW of CANDU-OT option is much higher than those of DUPIC option and PWR-OT options because the

CANDU-OT option has more waste volume to be treated in storage and disposal. The ILW volume levels from PWR-OT, DUPIC and PWR-CANDU-OT options are within uncertainty range each other.

HLW and Spent Fuel

HLW is generated in the reprocessing plant for the PWR-MOX option and in the DUPIC plant for the DUPIC option. The HLW volume of the DUPIC option is lower than that of the PWR-MOX (Table 9 and 10). The decay heat generated in HLW from reprocessing will be much higher than that from DUPIC fabrication, in which consists of only a small part of the fission product inventory[6]. The spent fuel volume in the CANDU-OT option is the greatest whereas the spent fuel volume in the PWR-MOX option is the least, about 8% of the volume in the CANDU-OT option. The DUPIC option has a 27%, 87% and 67% volume reduction compared to the PWR-OT, CANDU-OT and PWR-CANDU-OT options, respectively. It is important to note that volumes of HLW and spent fuel are not major factor for safety and environmental effect in geological disposal. For the HLW and spent fuel disposals, other factors such as radio-toxicity and decay heat is more important. In this respect, the CANDU fuels have lower decay heat and radio-toxicity compared to other fuels.

Table 8 Comparison of Waste Volumes for Five Fuel Cycle Options (unit : m3/GWe-yr)

Components	PWR-OT			
	tailings	LLW	ILW	SF
Interim Storage(DUPIC)	-	-	-	-
Reproc./vitrification	-	-	-	-
Disposal(PWR or MOX)	-	0.2	4.9	37
Disposal(CANDU)	-	-	-	-
Disposal(DUPIC)	-	-	-	-
Decom. of Conversion(PWR)	-	76	-	-
Decom. of Conversion(CANDU)	-		-	-
Decom. of Enrichment	-	5	-	-
Decom. of Fabrication(PWR LEU)	-	3~9	-	-
Decom. of Fabrication(CANDU)	-	-	-	-
Decom. of Fabrication(MOX)	-	-	-	-
Decom. of Fabrication(DUPIC)	-	-	-	-
Decom. of Reactor	-	175~230	9	-
Decom. of Repro.	-	-	-	-
total	53594	434~608	17~49	37

Table 8 Comparison of Waste Volumes for Five Fuel Cycle Options
(unit : m3/GWe-yr)(continued)

Components	PWR-MOX				
	taillings	LLW	ILW	HLW	SF
Interim Storage(DUPIC)	-	-	-	-	-
Reproc./vitrification	-	56~77	16~36	1.7~3.1	
Disposal(PWR or MOX)		0.03	0.7		5.4
Disposal(CANDU)	-	-	-	-	-
Disposal(DUPIC)	-	-	-	-	-
Decom. of Conversion(PWR)	-	70	-	-	-
Decom. of Conversion(CANDU)	-	-	-	-	-
Decom. of Enrichment	-	4	-	-	-
Decom. of Fabrication(PWR LEU)	-	3~8	-	-	-
Decom. of Fabrication(CANDU)	-	-	-	-	-
Decom. of Fabrication(MOX)	-	0.22	0.44	-	-
Decom. of Fabrication(DUPIC)	-	-	-	-	-
Decom. of Reactor	-	175~230	9	-	-
Decom. of Repro.	-	4	0.6	-	-
total	43688	471~660	42~94	2~3	5

Table 8 Comparison of Waste Volumes for Five Fuel Cycle Options

(unit : m3/GWe-yr)(continued)

Components	CANDU-OT			
	taillings	LLW	ILW	SF
Interim Storage(DUPIC)	-	-	-	-
Reproc./vitrification	-	-	-	-
Disposal(PWR or MOX)	-	-	-	-
Disposal(CANDU)	-	1.1	27	199.5
Disposal(DUPIC)	-	-	-	-
Decom. of Conversion(PWR)	-	-	-	-
Decom. of Conversion(CANDU)	-	30		
Decom. of Enrichment	-	-	-	-
Decom. of Fabrication(PWR LEU)	-	-	-	-
Decom. of Fabrication(CANDU)	-	17	-	-
Decom. of Fabrication(MOX)	-	-	-	-
Decom. of Fabrication(DUPIC)	-	-	-	-
Decom. of Reactor	-	388	15	-
Decom. of Repro.	-	-	-	-
total	40386	534~594	54~85	200

Table 8 Comparison of Waste Volumes for Five Fuel Cycle Options
(unit : m3/GWe-yr)(continued)

Components	DUPIC				
	taillings	LLW	ILW	HLW	SF
Interim Storage(DUPIC)	-	0.14	1.4	-	-
Reproc./vitrification	-	-	-	-	-
Disposal(PWR or MOX)	-	-	-	-	-
Disposal(CANDU)		-	-	-	-
Disposal(DUPIC)	-	0.14	3.5		26.5
Decom. of Conversion(PWR)	-	55	-	-	-
Decom. of Conversion(CANDU)		-	-	-	-
Decom. of Enrichment	-	3.5	-	-	-
Decom. of Fabrication(PWR LEU)	-	2~7	-	-	-
Decom. of Fabrication(CANDU)	-	-	-	-	-
Decom. of Fabrication(MOX)	-	-	-	-	-
Decom. of Fabrication(DUPIC)	-	1.1	2.1	-	-
Decom. of Reactor	-	227~266	10	-	-
Decom. of Repro.	-	-	-	-	-
total	38862	471~597	22~53	2	27

Table 8 Comparison of Waste Volumes for Five Fuel Cycle Options

(unit : m3/GWe-yr)(continued)

Components	PWR-CANDU-OT			
	taillings	LLW	ILW	SF
Interim Storage(DUPIC)	-	-	-	-
Reproc./vitrification	-	-	-	-
Disposal(PWR or MOX)	-	0.14	3.6	27
Disposal(CANDU)	-	0.29	7.3	55
Disposal(DUPIC)	-	-	-	-
Decom. of Conversion(PWR)	-	55	-	-
Decom. of Conversion(CANDU)	-	8.1	-	-
Decom. of Enrichment	-	3.5	-	-
Decom. of Fabrication (PWR LEU)	-	2~7	-	-
Decom. of Fabrication(CANDU)	-	5	-	-
Decom. of Fabrication(MOX)	-	-	-	-
Decom. of Fabrication(DUPIC)	-	-	-	-
Decom. of Reactor	-	227~266	10	-
Decom. of Repro.	-	-	-	-
total	49885	453~595	27~58	81

Table 9 Ranges of Waste Volume for Each Option in m^3/GWe-yr

Fuel Cycle Options	Waste Types				
	tailings	LLW	ILW	HLW	SF
PWR-OT	53,594	434~608	17~49		37
PWR-MOX	43,688	471~660	42~94	2~3	5
CANDU-OT	40,386	534~594	54~85		200
DUPIC	38,862	471~597	22~53	2	27
PWR-CANDU-OT	49,885	453~595	27~58		81

Table 10 Average Waste Volume for Each Option in m^3/GWe-yr

Fuel Cycle Options		Waste Types				
		tailings	LLW	ILW	HLW	SF
PWR-OT	volume	53,594	521	33		37
	(%)*	138	101	126		138
PWR-MOX	volume	43,688	566	68	2.5	5
	(%)	112	110	251	125	20
CANDU-OT	volume	40,386	564	70		200
	(%)	104	108	242		751
DUPIC	volume	38,862	534	38	2	27
	(%)	100	100	100	100	100
PWR-CANDU-OT	volume	49,885	524	43		81
	(%)	128	101	155		307

* Relative Value to DUPIC case

Table 11 Ranges of Waste Volume for Each Option in m^3/GWe-yr
(wastes from mining, conversion and enrichment facility excepted)

Fuel Cycle Options	Waste Types			
	LLW	ILW	HLW	SF
PWR-OT	268~378	17~49		37
PWR-MOX	332~462	42~94	2~3	5
CANDU-OT	492~523	54~85		200
DUPIC	350~430	22~53	2	27
PWR-CANDU-OT	321~419	27~58		81

Table 12 Average Waste Volume for Each Option in m^3/GWe-yr
(wastes from mining, conversion and enrichment facility excepted)

Fuel Cycle Options		Waste Types			
		LLW	ILW	HLW	SF
PWR-OT	volume	323	33		37
	(%)*	83	87		137
PWR-MOX	volume	397	6	2.5	5
	(%)	102	179	125	19
CANDU-OT	volume	508	70		200
	(%)	130	184		741
DUPIC	volume	390	38	2	27
	(%)	100	100	100	100
PWR-CANDU-OT	volume	366	43		81
	(%)	94	113		300

* Relative values to DUPIC case

V. Waste Disposition Cost

One way to quantify the relative ease or difficulty of the waste management is to estimate the disposition cost of all wastes in a given nuclear fuel cycle. The higher the waste disposition cost, the more “difficult” it is to management the fuel cycle’s wastes. In this chapter, the cost of disposing of wastes of different categories are discussed. For LLW, ILW and milling tailings, the key cost driver is the waste volume but that of HLW and spent fuel is the decay heat.

Table 13 shows the unit cost of waste disposition used in this study. We have chosen the median of the value from Chow and Jones[5] for LLW, depleted uranium, ILW and HLW disposition costs. For depleted uranium, the unit \$/GWe-yr is converted to \$/m^3, in which 1 GWe-yr can translate into 32 m^3 of depleted uranium as described in Section III.A. For disposal costs of spent fuels, DUPIC and PWR fuels are assumed to be \$320 /kgHM because the decay heat of the two spent fuels are similar. For CANDU spent fuel with low decay heat, the OECD/NEA’s value supplied by AECL, \$73 /kgHM, is used in this study.

In order to forecast the cost of the HLW generated in DUPIC process, decay heat was analyzed. It is because the decay heat is a key driver of disposal cost. For this, we have made some ORIGEN2 code[7] run in order to explore the waste heat implication of our cases (with 35,000 MWD/MTU of burnup). Table 14 shows the results of the decay heat analysis of the two HLWs to be disposed of. For reprocessing, it is assumed that they include all fission products, actinide except for U/ Pu and 1% of U and Pu to be reprocessed. For DUPIC, dirty scrap is assumed to be 1% of spent fuel to be treated.

It is seen from the table that decay heat of the DUPIC HLW is only 16% ~ 1% of the decay heat of reprocessing HLW for 10~500 years of cooling time. This decay heat generally affects disposal waste spacing. This spacing is important, because they affect the number HLW canisters that can be placed in the repository of a given size and thus the disposal cost. It means that DUPIC HLW disposition cost could be much lower than that of the reprocessing HLW. In this study, DUPIC HLW disposition cost is assumed to be one fifth of reprocessing HLW value, \$51.6/kgHM.

Table 15 summarized our estimates of waste disposition costs in \$millions/GWe-yr. As shown in the table, disposition costs range from 13 \$millions/GWe-yr ~ 16 \$millions/GWe-yr. It is indicated that the DUPIC waste disposition cost is the lowest, 12.6 ~ 14.2 \$millions/GWe-yr. When we choose the average value of the ranges, the DUPIC waste disposition cost is 12%, 5%, 14% and 12% lower relative to the PWR-OT, PWR-MOX, CANDU-OT and PWR-CANDU, respectively. It is due mainly to waste volume reduction, especially spent fuel to be disposed of as seen in Table 10. Figure 4 shows the comparisons of the range for the fuel cycle options. Table 16 summarized waste disposition costs considering the total wastes except for wastes from conversion, enrichment and uranium mining shown in Table 11 and 12. Even though waste disposition costs of Table 16 are a little smaller than those of Table 15, the trends and priorities are very similar.

On the whole, HLW and spent fuel disposal costs are main parts of the total disposition cost showing 55% ~ 46% of the total disposal costs. It is indicated that waste disposition cost for PWR-MOX option is a little higher than that of DUPIC option because it is mainly due to the ILW generated from reprocessing plant. Waste disposition cost of PWR once-through is a little lower than that of the CANDU once-through cycle.

If the total waste disposition cost is used as a proxy for quantifying the easiness or difficulty in managing waste, this study found that the DUPIC option actually make waste management more easier.

Table 13 Unit Costs for Waste Disposition

Components	Chow and Jones' Values	Values in this study	Others
Milling tailings	\$3.63 /m^3	\$3.63 /m^3	
LLW	\$2,800~13,500 /m^3	\$8,150 /m^3	
Depleted U	\$1.4~2.2 millions/GWe-yr	\$56,250 /m^3	=1.8M\$/32 m^3
ILW	\$5,600~27,000 /m^3	\$16,300 /m^3	
HLW	\$196~\$319 /kgHM(initial)	\$258 /kgHM(initial) \$51.6/kgHM(initial)	For reprocessing HLW For DUPIC HLW
SF	\$320 /kgHM	\$320 /kgHM \$73 /kgHM	for DUPIC and PWR fuel for CANDU fuel

Table 14 Decay Heat of DUPIC and Reprocessing HLW (Unit : Watt/MTHM)

HLW Type		Cooling Time (year)					
		10	20	50	100	300	500
Reprocessing HLW	Fission Products	956.3	684.9	329.0	101.3	1.0	0.0
	Actinide	112.0	126.7	136.9	128.1	92.4	67.2
	Total	1,068.3	811.6	465.9	229.4	93.4	67.2
DUPIC HLW	Dirty scrap	11.8	9.2	5.6	3.0	1.3	0.9
	Cs+Ru	155.9	78.4	38.2	12.0	0.1	0.0
	total	167.8	87.6	43.7	15.0	1.4	0.9
Decay heat ratio(%) of DUPIC HLW to reprocessing HLW		15.70	10.80	9.39	6.54	1.49	1.40

Table 15 Waste Disposition Costs in $Millions/GWe-yr

Fuel Cycle Options	Waste Types						Total
	tailings	LLW	DEU	ILW	HLW	SF	
PWR-OT	0.19	3.14~4.56 (3.85)*	2.75	0.28~0.8 (0.54)		7.85	14.19~16.13 (15.16)
PWR-MOX	0.16	3.57~5.10 (4.34)	1.91	0.69~1.53 (1.11)	5.39	1.16	12.86~15.24 (14.05)
CANDU-OT	0.15	4.35~4.84 (4.60)	-	0.88~1.39 (1.14)		9.69	15.09~16.08 (15.59)
DUPIC	0.14	3.55~4.58 (4.07)	2.00	0.36~2.00 (1.18)	0.92	5.65	12.63~14.17 (13.40)
PWR-CANDU-OT	0.18	3.40~4.56 (3.98)	2.00	0.44~0.94 (0.69)		8.38	14.38~16.04 (15.21)

* Average value of the range

Table 16 Waste Disposition Costs in $Millions/GWe-yr
(wastes from mining, conversion and enrichment facility excepted)

Fuel Cycle Options	Waste Types				Total
	LLW	ILW	HLW	SF	
PWR-OT	2.18~3.08 (2.63)*	0.28~0.8 (0.54)		7.85	10.31~11.73 (11.02)
PWR-MOX	2.70~3.76 (3.23)	0.69~1.53 (1.11)	5.39	1.16	9.94~11.83 (10.89)
CANDU-OT	4.01~4.26 (4.14)	0.88~1.39 (1.14)		9.69	14.58~15.34 (14.96)
DUPIC	2.85~3.51 (3.18)	0.36~2.00 (1.18)	0.92	5.65	9.78~11.16 (10.47)
PWR-CANDU-OT	2.62~3.34 (2.98)	0.44~0.94 (0.69)		8.38	11.44~12.66 (12.05)

* Average value of the range

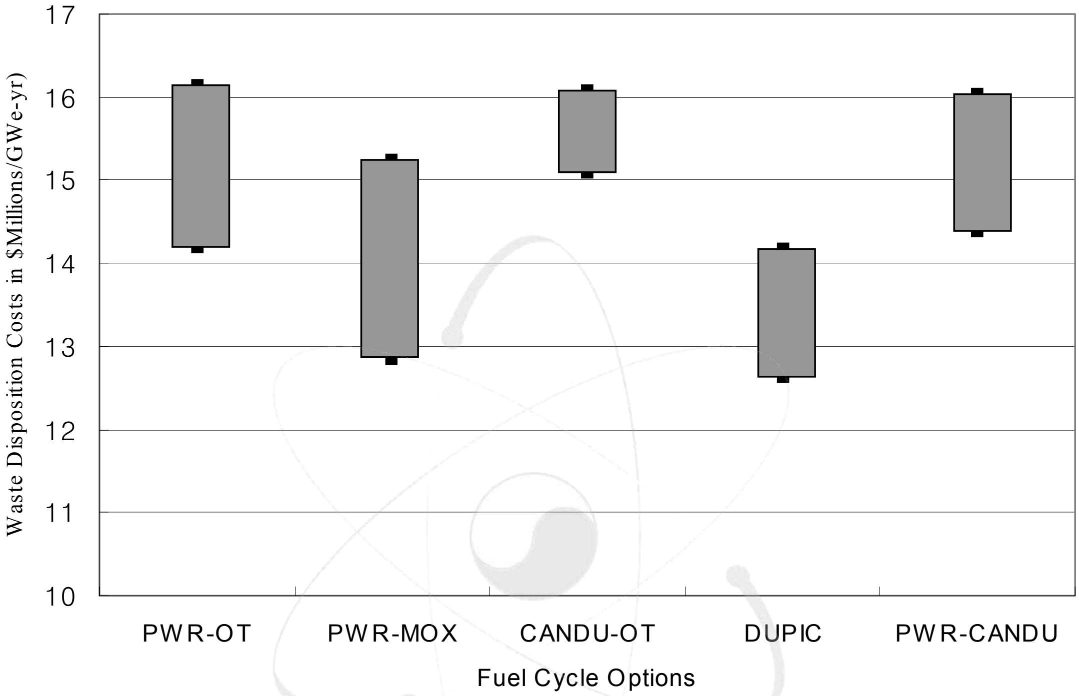

Fig. 4 Range of the Waste Management Cost for Five Fuel Cycle Options

VI. Conclusion

This study compared waste volumes and waste disposition costs from alternative fuel cycles (DUPIC, CANDU-OT, PWR-OT, PWR-MOX and PWR-CANDU-OT) that generated the same amount of electricity. Different types of waste volume and waste disposition costs are expressed in unit of m^3/GWe-yr and US$/GWe-yr, respectively. It was found from the radioactive waste volume estimation that the DUPIC fuel cycle could have lower volumes for milling tailings and spent fuel than those of other fuel cycle options. However, for intermediate level waste, the DUPIUC fuel cycle option has a little higher waste volume than that of the PWR once-through but lower than that of thermal recycling (PWR-MOX) option. It is indicated from the results of the disposition cost analysis that the DUPIC waste disposition cost is the lowest among fuel cycle options. It means that if the total waste disposition cost is used as a proxy for quantifying the easiness or difficulty in managing wastes, the DUPIC option actually make waste management easier.

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Abstract (15-20 Lines)

This study examines whether the DUPIC (Direct Use of Spent PWR Fuel In CANDU) fuel cycle make radioactive waste management more effective, by comparing it with other fuel cycles such as the PWR (Pressurized Water Reactor) once-through cycle, the HWR (Pressurized Heavy Water Reactor) once-through cycle and the thermal recycling option to use an existing PWR with MOX (Mixed Oxide) fuel. This study first focuses on the radioactive waste volume generated in all fuel cycle steps, which could be one of the measures of effectiveness of the waste management. Then the total radioactive waste disposition cost is estimated based on two units measuring; m3/GWe-yr and US$/GWe-yr. We find from the radioactive waste volume estimation that the DUPIC fuel cycle could have lower volumes for milling tailings, low level waste and spent fuel than those of other fuel cycle options. From the results of the disposition cost analysis, we find that the DUPIC waste disposition cost is the lowest among fuel cycle options. If the total waste disposition cost is used as a proxy for quantifying the easiness or difficulty in managing wastes, then the DUPIC option actually make waste management easier.

Subject Keywords (About 10 words)	DUPIC Fuel Cycle, Waste Volume, Waste Disposition Cost, Nuclear Fuel Cycles

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연구위탁기관		계약 번호	

초록 (15-20줄내외)

여러 핵연료주기에서 발생하는 방사성폐기물의 양 및 폐기물 처분 비용을 추정하여 핵연료 주기별 폐기물 관리의 효율성 정도를 비교.평가하였다. 발생 폐기물량 및 처분 비용은 단위 무게당(MTHM) 및 단위 전력 생산량당(1 GWe-yr)의 값으로 표현하였다. 본 연구에서 고려된 핵연료 주기는 DUPIC 핵연료주기, PWR 직접처분 주기, CANDU 직접처분 주기, PWR에 MOX 핵연료를 이용하는 열중성자 순환주기와 PWR와 CANDU가 혼합된 직접처분 주기이다. 폐기물 발생량 측면에서 DUPIC 핵연료 주기는 우라늄 채광.정련과정에서 발생하는 정련찌거기(milling tailings), 저준위폐기물, 사용후핵연료 발생량에서 가장 작게 나타났다. 또한 방사성폐기물 처분 비용을 단위전력 생산량당으로 평가한 결과 DUPIC 핵연료 주기가 가장 작게 평가되므로서, DUPIC 핵연료 주기는 방사성폐기물 관리 효율성 측면에서 매우 우수한 핵연료 주기로 평가되었다.

주제명키워드 (10단어내외): 듀픽핵연료주기, 방사성폐기물 발생량, 방사성폐기물 처분비용, 핵연료주기