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Comparison of Radioactive Waste Generation in Various Nuclear Fuel Cycles

Won Il Ko, Ho Dong Kim and Myung Seung Yang

Korea Atomic Energy Research Institute
P.O. Box 105, Yusong, Taejon, Korea

ABSTRACT

This study was focused on radioactive waste volume generated in various fuel cycles, which could be one of measures of effectiveness of the waste management, and then their radioactive waste disposition costs were estimated. A total of five fuel cycle options including DUPIC fuel cycle, PWR once-through cycle and HWR(Heavy Water Reactor) once-through cycle were considered in this study. It found 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. 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. From the results of the disposition cost analysis, this study found that the DUPIC waste disposition cost was 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 more easy.

I. Introduction

Many counties including France and United Kingdom often expressed the view that reprocessing helps waste management [1, 2]. They state that the recycling mode is to maximize the utilization of uranium, to reduce the waste volumes, and to reduce the radio-toxicity of the waste to be dispose of in the geologic repository. Some studies[3, 4] insisted that DUPIC fuel cycle have significant waste management benefits such as reduction of spent fuels to be disposed of and saving of natural uranium resources. All of them were focused on only the waste volume or waste weight, and on limited fuel cycle options. Besides, they have not considered all type wastes generated in all steps consisting of nuclear fuel cycles.

This study examines whether the DUPIC fuel cycle will make radioactive waste management more effective, compared with other fuel cycles such as PWR(Pressurized Waster Reactor) once through cycle, CANDU(Canadian Deuterium Uranium) once-through cycle and thermal recycling option to use existing PWR with MOX fuel.

In the past, a waste volume comparison was often made between the directly disposed spent fuel and HLW which resulted from the reprocessing of PWR spent fuels[1, 2]. A shortcoming in the previous methodology is to add up waste volumes regardless of radioactive level. Chow[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 cheaper are sum of the costs of conditioning and disposal of wastes generated in these steps, the easier is waste managed. Therefore, in our study, the waste disposition costs for five options are also estimated and compared in order to see which one is more 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. For this, fuel cycle scenarios first are set up and reactor parameters and their fuel characteristics are assumed appropriately. And then fuel material flows are estimated based on 1 GWe-yr, and waste volumes in each step are assessed for different waste types. Finally, waste disposition costs are estimated.

II. Reference Fuel Cycle Model

II.A. Fuel Cycle Model

A total of five fuel cycle option are considered in this studys. The first cycle is low-enriched uranium in PWR of once-through mode (hereafter called "PWR-OT"). The second cycle is mixed oxide fuel in PWR of reprocessing mode (hereafter called "PWR-MOX"), in which spent PWR fuel is reprocessed and recovered plutonium are used for making MOX fuel (5% of plutonium content) and recovered uranium are inputted into a conversion plant. The MOX spent fuel will be disposed of without further plutonium or uranium recovery. Some depleted uranium generated in enrichment plant will be used for making MOX fuel. The third cycle is natural uranium in CANDU with once-through mode (hereafter called "CANDU-OT"). The forth cycle is the DUPIC fuel cycle in which PWRs are linked to a CANDU (hereafter called "DUPIC"). The fifth cycle is PWR fuel and CANDU fuel in once-through mode with reactor grid equivalent to DUPIC fuel cycle (hereafter called "PWR-CANDU-OT").

In the DUPIC fuel cycle, spent PWR fuel is directly refabricated into CANDU fuel to be burnt again in CANDU reactors before being disposed of permanently. On the other hand, the once-through fuel cycle (PWR-CANDU-OT) is to dispose all spent fuel generated from both PWR and CANDU reactors. The front-end fuel cycle components for a PWR were established to be the same for both fuel cycles. For the DUPIC fuel cycle, however, several services such as DUPIC fuel fabrication included but the front-end fuel cycle components for CANDU is 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 consisting of plutonium and uranium, and enrichment tailings containing depleted uranium. During reactor operation, ILW/LLW are generated both as a liquid and as a solid. The liquid is contaminated water from different part 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. 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, the 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 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 reprocessing plant.

The DUPIC fabrication process involve the direct refabrication of PWR spent fuel in the CANDU fuel. The spent fuel materials is recovered from the PWR spent 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 would mainly consist of the metallic components from spent LWR 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].

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 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, those 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 reactor and may included in high level waste class in some country. The second is high level waste(HLW), which is stream of waste (liquid or solidified form) after reprocessing or dirty scrap during DUPIC plant operation. The third is intermediate level waste(ILW) which is contaminated with alpha-emitting transuranic radio-nuclides 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 step of fuel cycles. The last one is mill tailings, which is ore residues from milling after uranium extracted.

II.C. Reference Reactors and Fuels

For material flow of each fuel cycle, reference PWR and CANDU reactors have to be chosen first, and their fuel characteristics (e.g., initial enrichment and discharge burnup) need to be defined reasonably. For a practical analysis, a 950 MWe PWR and a 713 MWe CANDU reactor, which are now operating in Korea, were taken as reference reactor systems. Table 1 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. The reason is that 35,000 MWD/MTU with initial enrichment of 3.5% U^{235} was chosen as a reference PWR fuel in DUPIC fuel cycle development in Korea[4].

In PWR-MOX fuel cycle, the plutonium recovered from reprocessing of LEU PWR fuel is made into MOX fuel, which is burned in PWR, and then discharged MOX spent fuel is disposed of. In order to calculate how much plutonium is in PWR spent fuel burnt with 35,000 MWD/MTU, we have used ORIGEN 2 computer code [7]. It found that content 0.82wt% of U^{235} and 0.89wt% of Pu were still included in the spent fuels. If the MOX fuel is made from depleted uranium and 5% plutonium content, an equilibrium state could be reached when the MOX burning reactor uses a core which is 14.7% of the fuel in MOX and 85.3% of the fuel in LEU. It means that all reprocessed plutonium from LEU PWR spent fuel with 35,000MWD/MTU can be used in the PWR core. In this situation, PWR core with MOX fuel consists of 10.22 MTHM MOX fuel and 59.28 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 [4].

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

$$\text{Annual requirement} = \frac{P \times 365 \times C}{e \times BU} \tag{2}$$

where C and BU are the capacity factor (%) and burnup (MWD/MTHM), respectively. The annual requirements per unit are translated into annual requirement based on 1 GWe-yr.

II.D. Material Flow Analysis of Fuel Cycle

For PWR-CANDU-OT and DUPIC fuel cycle, the equilibrium core ratio between PWRs and CANDU reactors have to be known so that all PWR spent fuels can make DUPIC fuels. It is possible to calculate with the annual requirement of PWR and CANDU with DUPIC fuel. The equilibrium core ratio between PWRs and a CANDU reactor can be calculated as follows;

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

Where M_{DUPIC}, M_{PWR}, and L_{DUPIC} are annual requirement of DUPIC, annual requirement of PWR and loss rate in DUPIC fabrication plant, respectively. In this study, loss rate in DUPIC fabrication plant is assumed to be 1%. Since M_{DUPIC}, and M_{PWR} are 46.09MTHM and 23.31MTU, respectively, as shown in Table 1, the equilibrium core ratio becomes 1.997.

In the mean while, portion of electricity generation between PWR and CANDU for 1 GWe-yr can be calculated as followings;

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

Where P_{PWR} and P_{CANDU} are electricity powers of PWR and CANDU, respectively. So the portion of PWR and CANDU generation will be 72.68% and 27.32%, respectively. The portions of electricity generation will be applied to both PWR-CANDU-OT and DUPIC fuel cycle.

In this study, it is assumed that the loss factors are 0.5% for conversion and for CANDU fuel fabrication, 1% for PWR, DUPIC and MOX fuel fabrication and for reprocessing plant. Enrichment amount in unit of 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.

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

and x is subscript for *f, p* or *t*,

where e_p = fraction of ^{235}U in the uranium product (3.5 wt% in this study),
e_t = fraction of ^{235}U in the tails (0.25 wt% in this study), and
e_f = fraction of ^{235}U in uranium feed (0.711 wt% in this study).

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

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

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

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

$$M_n = M_R \times \frac{e_p - e_t}{e_f - e_t} \times (1 + l1) \times \frac{W_{U_3O_8}}{W_{U_3}} \times (1 + l2) \tag{9}$$

where M_n is the mass of uranium (U_3O_8) to feed, 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 uranium (U_3O_8), and l_1, *and* l_2 are process loss rate of conversion and fuel fabrication, respectively.

Fig. 1 shows the results of the material balance analyses which were calculated by equation 1 through equation 9 with reference reactors parameters and their fuel characteristics(shown in Table 1). All values were expressed on basis of 1 GWe-yr for all fuel cycle options.

III. Waste Generation Analysis

III.A Waste Generation

In this chapter, we will evaluate all wastes generated from mining to disposal in the five alternative fuel cycles. The volumes are assessed with metric ton basis and then those values are translated into 1 GWe-yr basis. Unit waste (m^3/MTU or m^3/MTHM) estimated in this study are summarized in Table 2. For this, most of the data were quoted form Chow's paper[5]. For components not described in the Chow's paper, some rationales are described below.

During enrichment, two types of wastes are generated. Most of them are the depleted uranium hexafluoride, left in the enrichment process. It can be chemically converted to the stable U_3O_8 for disposal or reused. Chow[5] has used 39 m^3/GWe-yr including other waste such as filters and sludge of 7 m^3/GWe-yr. In fact, the volume of depleted uranium will depend on the degree of the enrichment of the product, feed and tails described in equation 5. In our study, we used with different unit, m^3/SWU. That is because reference fuels are different each other and moreover recovered uranium(~0.82wt% of U^{235}) is re-enriched for LEU PWR fuels.

Using the equation 7, we have calculated the mass of reprocessing tails for each case. In order to obtain the 3.5 wt% ^{235}U at the uranium feed of 0.711 wt% and tails of 0.25 wt%, about 1.26 MTU-tails per TSWU is generated. In order to obtain the 3.5 wt% ^{235}U at the recovered uranium feed of 0.82 wt% and tails of 0.25 wt%, about 1.08 MTU-tails per TSWU 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-tails and 1.08 MTU-tails per TSWU will be 0.42 m^3 and 0.36 m^3 per TSWU, respectively. In this study, considering the other waste portion such as filter and sludge(about 18% of total wastes[5]), 0.50 m^3/ TSWU for LEU fuel enrichment and 0.42 m^3/TSWU for recovered uranium enrichment were used.

For DUPIC fuel fabrication, the conceptual design report of commercial DUPIC fuel fabrication carried out by jointly KAERI and Scientech Co.[6] was referred for this study. In this study, 2.11 m^3/MTHM for LLW, 0.20 m^3/MTHM for ILW and 0.13 m^3/MTHM for HLW were used for DUPIC fuel fabrication plant.

For wastes generated in reactor operation of PWR and CANDU, we will use real data generated in plants being operated in Korea which have both PWR and CANDU type reactors. In this study, we assumed that spent reign used for treating liquid waste is classified as ILW and others are LLW. From 1978 to 1998, electricity generation of PWRs in Korea is 78.9 GWe-yr [8] and 433 drums with 200 liters of ILW and 48,331 drums of LLW are generated[9]. They translate into 1.1 m^3/GW-yr for ILW and 122 m^3/GWe-yr for LLW. In the mean while, From 1983 and 1998, electricity generation of CANDUs in Korea is 10.37 GWe-yr [8] and 85 drums of ILW and 3,551 drums of LLW are generated[9]. They also translate into 1.6 m3/GW-yr for ILW and 69 m3/GWe-yr for LLW.

As to PWR decommissioning, we will use Chow's values of 230 m^3/GWe-yr of LLW and 9 m^3/GWe-yr of ILW, which were referred from DOE data[10]. For CANDU reactor decommissioning, the AECL report[11] which was a generic report to assess decommissioning of a typical 600MWe CANDU reactor will be referred in this study. The total decommissioning wastes of 600 MWe CANDU reactor was 7,250 m^3/GWe-yr. We have recalculated the value to be 403 m^3/GWe-yr with assumption of 30 year operation. Unfortunately, they did not give classified value as ILW or LLW. ILW portion (3.8% of total wastes) in PWR is used in this study. So we will use 387.7 m^3/GWe-yr for LLW and 15.3 m^3/GWe-yr for ILW. For MOX and

DUPIC fuel cycle, the waste volumes of reactor decommissioning are assumed to be the same as those of LEU PWR and natural uranium CANDU cycle, respectively.

III.B Evaluation of Waste Volume Generation

In this section, waste volumes for all steps in each fuel cycle are estimated from the unit volume described in Table 2 and material flow of each fuel cycle given in Fig. 1. Generally, 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 material can be considered as successfully decontaminated, and the more waste results. Stringent regulations will 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 this 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. Waste volumes for each step and total wastes of each fuel cycle are summarized in Table 3 and 4.

It is indicated that waste volume for milling tailings in PWR-OT is higher than that of CANDU-OT as expected. This means that CANDU with natural uranium fuels has better natural uranium utilization than PWR with low enriched uranium. On the whole, we found that the DUPIC fuel cycle has the smallest milling tailing wastes. Waste volume for milling tailings in DUPIC fuel cycle is ~27% lower than that of PWR-OT, and ~22% and 3% lower that those of PWR-CANDU option and CANDU-OT option.

The highest volume in reactor operation and reactor decommissioning is LLW wastes regardless fuel cycle options. Compared between PWR-OT and CANDU-OT, it indicated that CANDU-OT case is a little higher than that of PWR-OT case. We found that CANDU has lower LLW waste in reactor operation but higher volume in decommissioning of the reactor. On the whole, PWR-OT has the lowest LLW waste volume but the differences are very small. It is also found that LLW volume of DUPIC, PWR-OT and PWR-CANDU options are very similar.

As shown in Table 4, PWR-MOX option has the highest ILW volume among options. It is mainly due to wastes generated in reprocessing plant. Compared relatively to PWR-MOX option, ILW volume levels of PWR-OT, CANDU-OT, DUPIC and PWR-CANDU-OT options are ~32%, ~68%, ~43% and ~42%, respectively.

IV. Waste Disposition Cost

Table 5 shows the unit cost of waste disposition used in this study. We choose the medium of the Chow' s value for LLW, depleted uranium, ILW, and HLW disposition costs. For disposal costs of spent fuels, DUPIC and PWR fuels are assumed to be $320 /kgHM because decay heat of the two spent fuels are very similar. For CANDU spent fuel with low decay heat, OECD/NEA value[12] which was proposed by AECL, $73 /kgHM, was used in this study.

Table 6 summarized our estimates of waste disposition costs in $millions/GWe-yr. As shown in the table, disposition costs range from 13.39 $millions/GWe-yr ~ 15.59 $millions/GWe-yr. It indicated that the DUPIC waste disposition cost is the lowest, 13.39 $millions/GWe-yr. The DUPIC waste disposition cost is 12%, 5.3%, 13% 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 3.

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 easy.

V. Conclusion

This study compares wastes volumes and waste disposition costs from alternatives fuel cycles(DUPIC, CANDU-OT, PWR-OT, PWR-MOX and PWR-CANDU-OT) that generated the same amount of electricity. It found 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. 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. From the results of the disposition cost analysis, It indicated from the results of the disposition cost analysis that the DUPIC waste disposition cost is the lowest among fuel cycle options, showing 12%, 5.3%, 13% and 12% lower relative to the PWR-OT, PWR-MOX, CANDU-OT and PWR-CANDU, respectively. 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 more easy.

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Table 1 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) - Annual fuel requirement (MTU)	 69.5 23.31	 69.5 (10.22 MOX) (59.28 LEU) 23.31 (3.43 MOX) (19.88 LEU)	 84.7 94.63	 84.7 46.09
Fuel - Initial enrichment - No. of fuel rods per assembly - Discharge burnup (MWd/kgHM)	 3.5% 264 35	 5% Pu_f MOX 3.5% LEU 264 35	 Nat. U 37 7.5	 PWR S/F 43 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

Table 4. Waste Volumes for Each Option in m^3/GWe-yr

Fuel Cycle Options		Waste Types				
		tailings	LLW	ILW	HLW	SF
PWR-OT	Volume	53,711	562	17		37
	(%)	100.0	92.3	32.4		18.5
PWR-MOX	Volume	43,675	607	52	2	8
	(%)	81.3	99.7	100.0		3.9
CANDU-OT	Volume	40,413	609	35		199
	(%)	75.2	100.0	67.7		100.0
DUPIC	Volume	39,353	565	22	2	26
	(%)	73.3	92.8	42.7		13.3
PWR-CANDU	Volume	50,393	557	22		82
	(%)	93.8	91.6	41.5		41.0

Table 2. Unit Radioactive Wastes Generation from Fuel Cycle Facilities

Components		PWR Fuel	MOX Fuel	CANDU Fuel	DUPIC Fuel
Mining and milling (milling tailings, m^3/lb U_3O_8)		115.38	-	115.38	-
Conversion (LLW, m^3/MTU)		0.33	-	0.17	-
Enrichment (LLW, m^3/TSWU)		0.50	0.42(REU)	-	-
Fabrication (m^3/MTU or MTHM)	LLW	0.23	1.27	0.23	2.11
Fabrication (m^3/MTU or MTHM)	ILW	-	3.35	-	0.20
Fabrication (m^3/MTU or MTHM)	HLW	-	-	-	0.13
Reactor operation (m^3/GWe-yr)	LLW	122	122	68.5	68.5
Reactor operation (m^3/GWe-yr)	ILW	1.1	1.1	1.6	1.6
Interim Storage /encapsulation (m^3/MTHM)	LLW	0.0077	0.0077	0.0039	0.0077
Interim Storage /encapsulation (m^3/MTHM)	ILW	0.077	0.077	0.039	0.077
Reprocessing /vitrification /disposal (m^3/MTHM)	LLW	-	3.17	-	-
Reprocessing /vitrification /disposal (m^3/MTHM)	ILW	-	1.25	-	-
Reprocessing /vitrification /disposal (m^3/MTHM)	HLW	-	0.115	-	
Coditioning/ Disposal of spent fuel/ Disposal of HLW (m^3/MTHM)	LLW	0.0077	0.0077	0.0039	0.0077
Coditioning/ Disposal of spent fuel/ Disposal of HLW (m^3/MTHM)	ILW	0.2	0.2	0.1	0.2
Coditioning/ Disposal of spent fuel/ Disposal of HLW (m^3/MTHM)	HLW	-	0.115	-	-
Coditioning/ Disposal of spent fuel/ Disposal of HLW (m^3/MTHM)	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	0.23	0.06	0.23	0.06
Decon of fabrication (m^3/MTU or MTHM)	ILW	-	0.12	-	0.12
Decon of Reactor (m^3/GWe-yr)	LLW	230	230	387.7	387.7
Decon of Reactor (m^3/GWe-yr)	ILW	9	9	15.3	15.3
Decon. of reprocessing /vitrification (m^3/MTHM)	LLW	-	0.19	-	-
Decon. of reprocessing /vitrification (m^3/MTHM)	ILW	-	0.03	-	-

*S/F : Spent Fuel

Table 5. Unit Costs for Waste Disposition

Components	Chow' s Values[5]	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[12]	for DUPIC and PWR fuel for CANDU fuel

Table 6. Waste Disposition Costs in $Millions/GWe-yr

Fuel Cycle Options	Waste Types						Total
	tailings	LLW	DEU	ILW	HLW	SF	
PWR-OT	0.19	4.18	2.75	0.28		7.85	15.25
PWR-MOX	0.16	4.67	1.91	0.85	5.40	1.16	14.14
CANDU-OT	0.15	4.96	-	0.58		9.69	15.37
DUPIC	0.14	4.31	2.00	0.36	0.92	5.65	13.39
PWR-CANDU	0.18	4.25	2.00	0.35		8.38	15.16

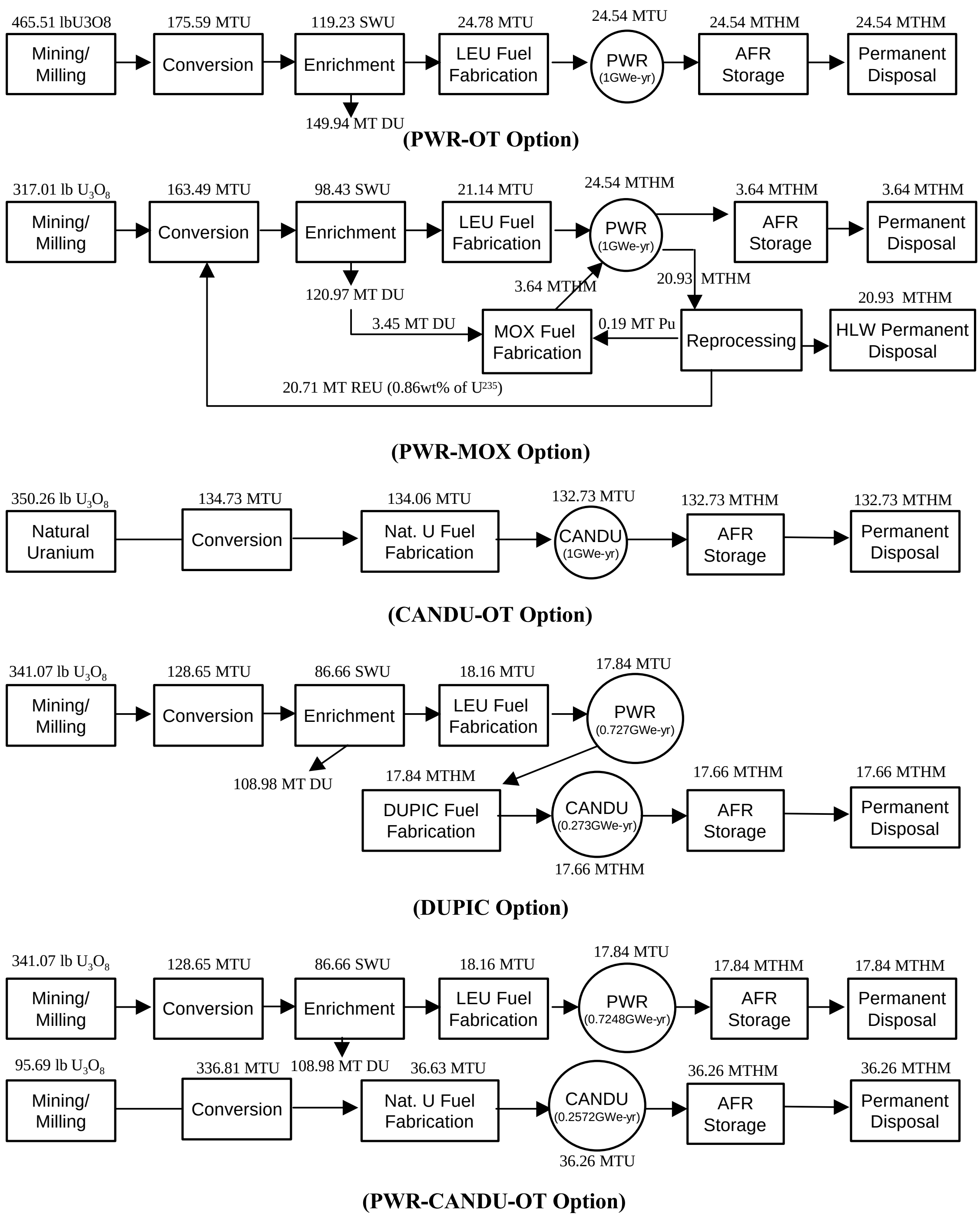

Fig. 1 Material Flows for Five Fuel Cycle Options (Based on the 1 GWe-yr)