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Multiple Recycling Characteristics and Cost of MOX Fuel Using Weapons-Grade Plutonium in Commercial PWR

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After the ratification of START-I the question of how to dispose safely and effectively of excess weapons plutonium, of which there is estimated to be about 50 t in the USA and 50 t in Russia, has become an important international issue. One of the most likely options is the proposal to use the excess weapons plutonium as MOX fuel in commercial LWRs. This paper evaluates fuel material flow and fuel cycle costs when weapons-grade plutonium is mixed with reactor-grade plutonium to fabricate the MOX fuel and to be recycled in Japanese commercial LWRs.

The results show the MOX fuel using weapons- and reactor-grade mixed plutonium facilitates multiple recycling, because the weapons-grade plutonium improves the isotopic composition of the MOX fuel working like a "purifier" of the degraded recycled plutonium. And they also indicate that it might be an economically realistic method in Japan to use the excess weapons plutonium in the commercial LWRs as MOX fuel if the fabrication cost and the reprocessing cost of MOX fuel are moderate compared to those of UO_2 fuel, assuming the MOX powder using weapons-grade plutonium would be provided free of charge.

***KEYWORDS:** excess weapons plutonium, MOX fuel, multiple recycling, commercial PWRs, fuel material flow, fuel cycle cost*

I. Introduction

After the ratification of START-I the question of how to dispose safely and effectively of excess weapons plutonium, of which there is estimated to be about 50 t in the USA and 50 t in Russia, has become an important international issue. One of the most likely options is the proposal to use the weapons-grade plutonium as MOX fuel in commercial LWRs(1)-(6).

This paper evaluates fuel material flow and fuel cycle costs when weapons-grade plutonium, which is assumed to be provided free of charge, is mixed with reactor-grade plutonium to fabricate the MOX (hereafter WMOX) fuel and to be recycled in Japanese commercial LWRs.

II. Fuel Material Flow of MOX Recycling

In this chapter, all the fuel material flows of the MOX recycling described below are calculated with reference to evaluation results by Hanayama *et al.*(7).

1. Reactor and Fuel Cycle

As shown in **Table 1**, the reactor used in this study is an existing Japanese 900 MWe class commercial PWR with 157 fuel assemblies (F/As) which comprise 117 uranium fuel assemblies with 4.1 wt% enrichment and 40 MOX fuel assemblies with 9.7 wt% total plutonium content. At refueling, 60 out of the 157 fuel assemblies are discharged and 16 of the discharged fuel assemblies are MOX fuel. The numbers of the refueling batch are 2.6 and the average burn-up of the discharged fuel is 40 GWd/t.

Spent fuel assemblies discharged from the core are stored at the cooling pool in the site for 5 years, and then transported to Europe (France or the U.K.) for reprocessing and MOX fuel fabrication, because the plants for these fuel cycle processes are not at present commercially available in Japan.

Table 1 Plant and core/fuel characteristics

Reactor type	PWR with 3 loops
Thermal output	2,660 MW
Electrical output	870 MW
Nos. of total fuel assemblies	157
(MOX fuel assemblies)	(40)
Weight of fuel assembly	460 kg HM
Uranium enrichment	4.1 wt%
Plutonium content of MOX fuel	9.7 wt% (Total)
Nos. of total reloading fuels	60
(Nos. of MOX reloading fuels)	(16)
Discharged fuel burn-up	40 GWd/t (Average)
Fuel cycle length/batch	13.5 EFPM† (15.2 GWd/t)

† Equivalent Full Power Month

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2. Multiple Recycling of Reactor-grade MOX Fuel

Figure 1 shows the isotopic composition change in plutonium and ^{241}Am when reactor-grade plutonium is recycled by MOX (hereafter RMOX) fuel on multiple occasions. Stepwise changes in the plutonium isotopic composition in the figure indicate the removal of ^{241}Am in the reprocessing process, which is produced by the decay of ^{241}Pu. It shows that the content of fissile ^{239}Pu decreases rapidly and that non-fissile even-number plutonium isotopes, especially ^{240}Pu, increase as the number of recycles increases. This results in a rapid rise in total plutonium content in MOX fuels to be loaded into reactors as shown by the dotted line in Fig. 1, for example 16, 22 and 27 wt% for the 1st, 2nd and 3rd recycle respectively. Therefore multiple MOX recycling of the reactor-grade plutonium will be difficult from the viewpoint of reactor core control. "Multiple recycling" means the repetition of recycling of spent MOX fuel discharged from reactors as shown in Fig. 1.

3. Multiple Recycling of WMOX Fuel

WMOX fuel contains 9.7 wt% of the total plutonium in which 30 wt% of the weapons-grade plutonium is mixed. It is assumed that the weapons-grade plutonium comprises 93 wt% of ^{239}Pu, 6 wt% of ^{240}Pu and 1 wt% of ^{241}Pu. **Figure 2** shows the isotopic composition change in plutonium and ^{241}Am when WMOX fuel is recycled on multiple occasions. To a good approximation the isotopic composition of plutonium is unchanged and non-fissile plutonium isotopes do not increase, so that the total plutonium content of WMOX fuel is maintained at the constant value of 9.7 wt%, even after multiple recycling is completed.

These results show that the high fissile content of the weapons-grade plutonium improves the isotopic composition of the MOX fuel working like a "purifier" of the degraded recycled plutonium, and that it enables multiple recycling.

4. Disposition of Excess Weapons Plutonium

As shown in **Fig. 3**, a 900 MWe class PWR with a 1/4 WMOX fuel core which is defined by Table 1 can burn 16 MOX fuel assemblies which contain 0.5 t of the reactor-grade and 0.21 t of the weapons-grade plutonium in one batch of the fuel cycle. Therefore 0.14 t of the weapons-grade plutonium can be disposed per year, assuming that one batch of the fuel cycle is 13.5 EFPM (effective full power months) and 18 months of reactor operation. The result indicates that this type of PWR can dispose of 50 t of Russian excess weapons plutonium over 350 reactor-years.

It has been announced that the weight of the excess weapons plutonium to be converted to MOX fuel in the USA and Russia from 2005 is 1 and 1.3 t/year respectively[(8)], so that approximately 16 PWR units can dispose of this plutonium in this way. Thus it is a realistic method to dispose of the excess weapons plutonium in commercial LWRs as MOX fuel.

III. Fuel Cycle Cost Evaluation

1. Fuel Cycle Processes

(1) WMOX Recycling

To evaluate the fuel cycle cost of disposing of the Russian excess weapons plutonium in Japanese commercial PWRs, each fuel cycle process is assumed to be as described below. The material flow of one batch of the equilibrium fuel cycle is shown in **Fig. 4**.

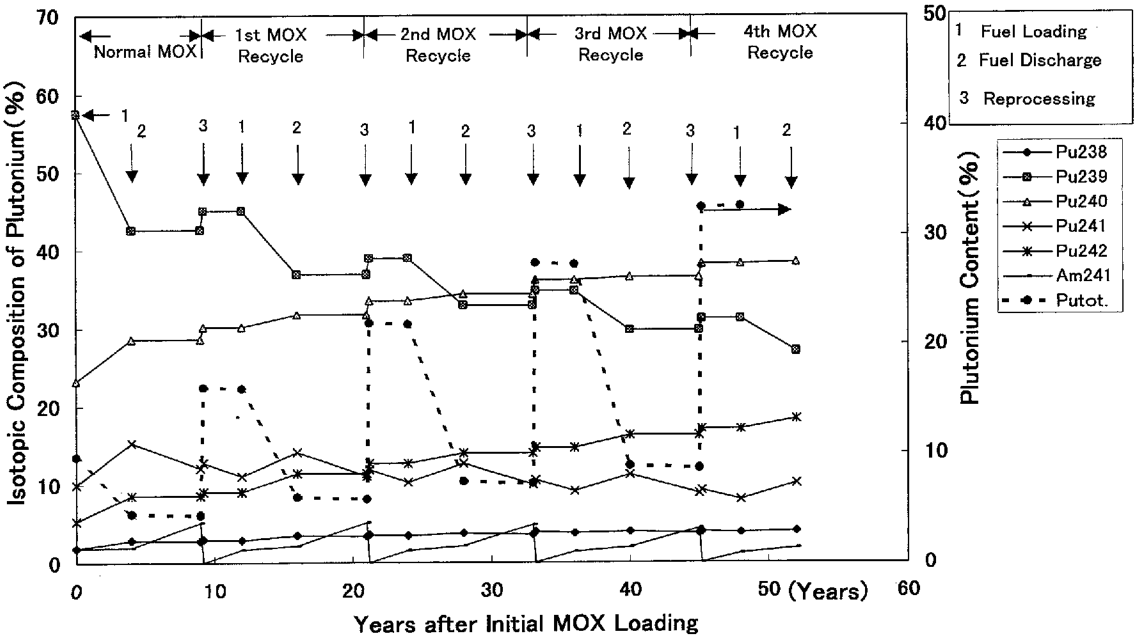

Fig. 1 Plutonium composition change after multiple RMOX recycle

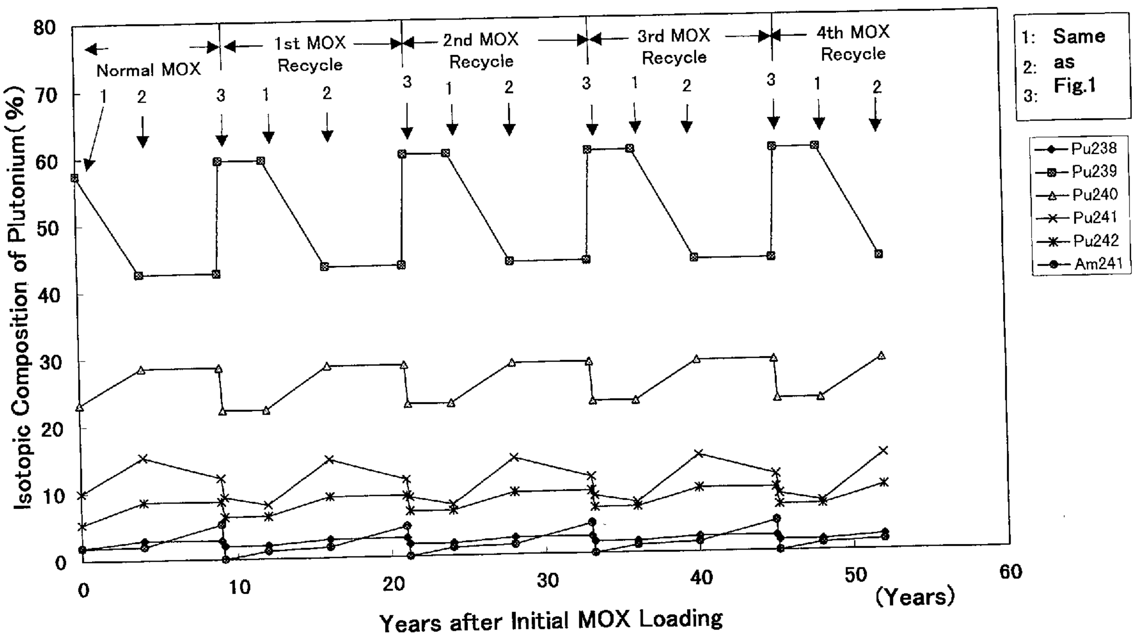

Fig. 2 Plutonium composition change after multiple WMOX recycle

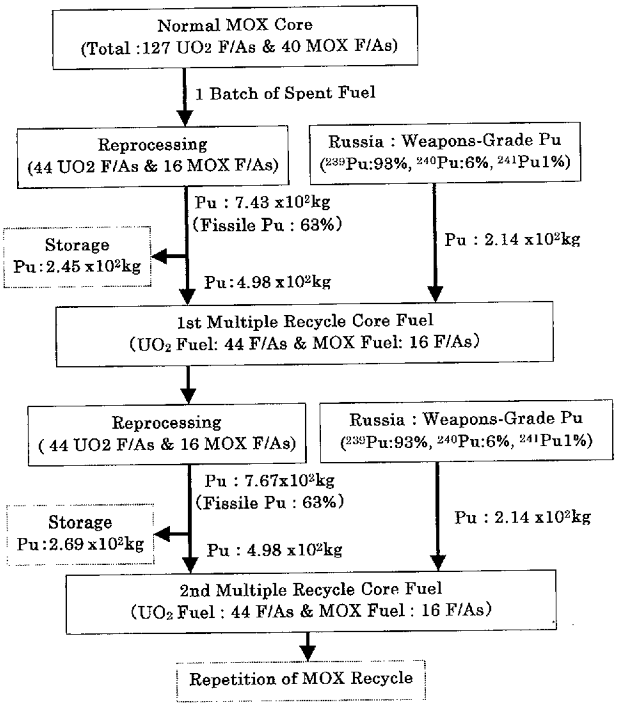

Fig. 3 Plutonium flow of the multiple WMOX recycle

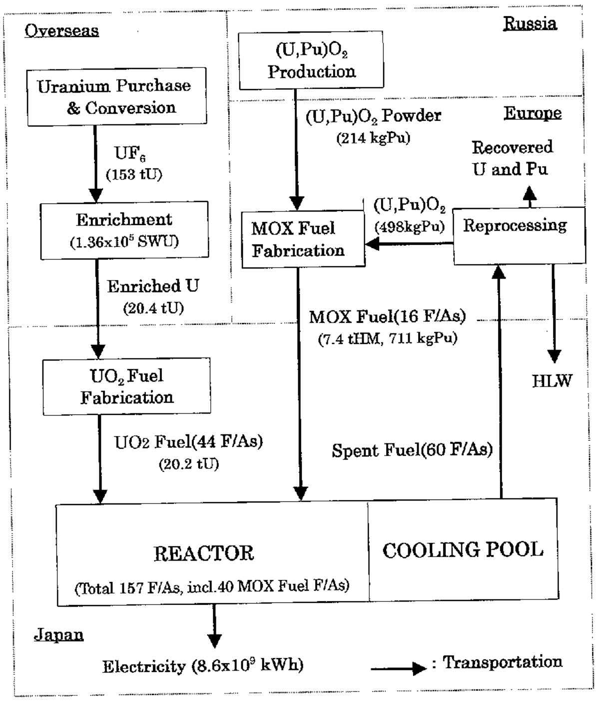

Fig. 4 Material flow of the multiple WMOX recycle

The reactor-grade plutonium used in the fabrication of MOX fuel is supplied by the reprocessing of the spent fuel assemblies cooled for 5 years. Two third of plutonium extracted from one batch of discharged fuel (60 fuel assemblies) is used for the MOX fuel fabrication. The weapons-grade plutonium is supplied from Russia in the form of uranium-plutonium mixed oxide powder, after disassembly of nuclear warheads, extraction of gallium and conversion to mixed oxide powder in Russia, in the context of nuclear non-proliferation. The mixed oxide powder is transported from Russia to Europe to blend with the reactor-grade plutonium and to fabricate 16 WMOX fuel assemblies.

After the overseas procurement of natural uranium, conversion to UF_6 and enrichment, 44 UO_2 fuel assemblies are fabricated in Japan. Sixteen WMOX fuel assemblies transported from Europe are loaded into the

Japanese 900 MWe PWR together with 44 UO_2 fuel assemblies fabricated in Japan and are burned in the reactor for 4 years on average (2.6 batches of the fuel cycle).

Sixty spent fuel assemblies discharged from the reactor are cooled at the site for 5 years, and then transported to Europe for reprocessing. High level radioactive waste (HLW) generated by reprocessing is transported to the Japanese storage site at Shimokita.

(2) UO_2 Fuel Cycling

In order to compare with the WMOX fuel recycling, the UO_2 fuel cycle process is assumed to be as described below.

After the overseas procurement of natural uranium, conversion to UF_6 and enrichment, 60 UO_2 fuel assemblies are fabricated in Japan. They are loaded into the reactor and burned for 4 years on average (2.6 batches of the fuel cycle). Sixty spent fuel assemblies discharged from the reactor are cooled at the site for 5 years and then transported to Europe for reprocessing. High level radioactive waste generated by the reprocessing is transported to the Japanese storage site at Shimokita.

2. Cost Evaluation

(1) Calculation Methods

The fuel cycle costs are calculated by multiplying unit cost, weight, material loss rate and discount rate together as shown in **Table 2**(9), assuming:

(a) The equilibrium fuel cycle,

(b) Material loss rates of conversion: 0.5%, fabrication: 1% and reprocessing: 2% are assumed and others are disregaeded,

(c) The lead and lag time of each fuel cycle process is as shown in **Table 3**,

(d) The discount rate at 5%/year,

(e) The escalation rate as zero, and

(f) One U.S. dollar is equivalent to 130 Japanese yen.

(2) Unit Cost Data of Each Fuel Cycle Process

As fully consistent unit cost data P_i which are used for the calculation shown in Table 2 for each fuel cycle process in Japan are not available at present, they are either assumed or obtained from the various papers as described below.

(a) Data Obtained from the OECD/NEA Paper(9)

-Purchase of natural uranium P_1: \$50/kg U

-Conversion to UF_6 P_2: \$8/kg U

-MOX fuel fabrication P_{4M}: \$1,100/kg HM

The unit cost of MOX fuel fabrication P_{4M} is estimated to be higher today, so that the effect of this unit cost is evaluated as varying by the factors 1.0, 1.5 and 2.0, used as a parameter in the cost evaluation results.

(b) Uranium Enrichment

Necessary separative work units (SWUs) are calculated from the product enrichment as 4.1 wt% and the depleted uranium content as 0.2 wt%, and the unit cost P_3 of \$125/SWU is adopted using the USEC uranium enrichment fee(10).

Table 2 Fuel cycle cost calculation

Fuel cycle process	Cost calculation methods
Uranium purchase	$F_1 = M_f f_1 P_1 (1+r)^{t(1)}$, where $M_f = M_p\{(e_p - e_t)/(e_f - e_t)\}$ $f_1 = (1+l_2)(1+l_4)$
Conversion	$F_2 = M_f f_2 P_2 (1+r)^{t(2)}$, where $f_2 = (1+l_2)(1+l_4)$
Enrichment	$F_3 = S f_3 P_3 (1+r)^{t(3)}$ where $f_3 = (1+l_4)$
Separative work unit	$S = M_p V_p + M_t V_t - M_f V_f$ $M_f = M_p + M_t$ $V_x = (2e_x - 1)\ln\{e_x/(1-e_x)\}$
UO_2 fuel fabrication	$F_{4U} = M_{pU} f_4 P_{4U} (1+r)^{t(4U)}$, where $f_4 = (1+l_4)$
MOX fuel fabrication	$F_{4M} = M_{pM} f_4 P_{4M} (1+r)^{t(4M)}$
S/F transportation	$F_5 = M_p P_5 (1+r)^{t(5)}$
UO_2 reprocessing	$F_{6U} = M_{pU} P_{6U} (1+r)^{t(6U)}$
MOX reprocessing	$F_{6M} = M_{pM} P_{6M} (1+r)^{t(6M)}$
HLW transportation	$F_7 = M_p P_7 (1+r)^{t(7)}$

(Symbols and subscripts)

M_x: Mass of fuel materials (kg HM)

e_x: Fraction of ^{235}U

Subscript x: $x = f$ Natural uranium ($e_f = 0.0071$)

$x = p$ New fuel ($e_p = 0.041$)

$x = t$ Depleted uranium ($e_t = 0.002$)

F_i: Total cost of each fuel cycle process (10^3 yen)

P_i: Unit cost of each process (10^3 yen/kg HM or 10^3 yen/SWU)

L_i: Material loss of each process

f_i: Total loss factor

r: Discount rate

$t(i)$: Lead or lag time of each process from the core fuel loading (year)

Subscript i: $i = 1$ Purchase of natural uranium ore

$i = 2$ Conversion

$i = 3$ Uranium enrichment

$i = 4$ Fuel fabrication

($4U$: UO_2 fuel, $4M$: MOX fuel)

$i = 5$ Spent fuel transportation

$i = 6$ Reprocessing

($6U$: UO_2 fuel, $6M$: MOX fuel)

$i = 7$ Transportation of high level radioactive waste

Table 3 Lead or lag times of fuel cycle process

Fuel cycle process	Lead/lag time (year)
MOX powder transportation (Russia-Europe)	2.0
MOX fuel fabrication (Europe)	2.0
Purchase of natural uranium (Overseas)	1.75
Conversion (Overseas)	1.5
Enrichment (Overseas)	1.0
MOX fuel transportation (Europe-Japan)	1.0
UO_2 fuel fabrication (Japan)	0.5
Fuel loading to reactor core	0
Fuel discharge	−4.0
Spent fuel transportation to Europe	−9.0
Reprocessing (Europe)	−9.0
HLW transportation to Japan	−9.0

(Note) Positive value means lead time.

(c) Plutonium-uranium Mixed Oxide Powder

The MOX powder using weapons-grade plutonium is assumed to be provided free of charge. This assumption is based on the fact that it is mainly discussed how surely and quickly the plutonium could be disposed of in the previous studies of excess weapons plutonium disposition(1)-(6), so that the monetary value of the plutonium seems not positive but negative.

The reactor-grade plutonium is also supplied free of charge in view of the fact that the value of recycled plutonium is zero.

(d) Transportation of MOX Powder from Russia to Europe

With reference to the OECD/NEA report(11), the unit cost of plutonium transportation is within the range of \$500–900/kg Pu. The highest value of \$900/kg Pu is used because of transporting the weapons-grade plutonium, even though the MOX powder is less proliferation-sensitive than pure plutonium.

(e) UO_2 Fuel Fabrication

The unit cost P_{4U} of 80.0 thousand yen/kg U (kyen /kg U) is adopted for the UO_2 fuel fabrication in Japan, using the previously announced values of 72 kyen/kg U(10) and 88 kyen/kg U(12).

(f) MOX Fuel Transportation

Japanese utilities are planning to transport MOX fuel from Europe to Japan, although the transportation fee has not yet been announced. The unit cost is assumed to be the same as that for spent fuel transportation because the same casks and ships would be used for the transportation.

(g) Spent Fuel Transportation

A unit cost P_5 of 20.0 kyen/kg U is used for spent fuel transportation to Europe in view of the previously announced unit cost of 20.0 kyen/kg U(10) and 34.9 kyen/kg U(12), because depreciation of the casks and ships will be completed in the near future.

(h) Reprocessing of UO_2 Fuel

Japanese utilities have their own independent contracts with BNFL or COGEMA for reprocessing services in Europe and the reprocessing service charges are not published. The unit cost P_{6U} of 200.0 kyen/kg HM is used in this study in view of the previously announced overseas reprocessing charge of 175.0 kyen/kg HM(12) and the domestic reprocessing service charge of 248 kyen/kg HM(10), agreed between Japanese utilities and the Power Reactor and Nuclear Development Corporation (PNC, the present Japan Nuclear Cycle Development Institute: JNC) in 1995.

(i) Reprocessing of MOX Fuel

The OECD/NEA report(11) indicates that the reprocessing cost ratio of MOX fuel to UO_2 fuel ranges from 1.0 to 1.4 depending on the design of the reprocessing plants. In this study, wider ranges from 1.0 to 6.0 for the reprocessing of MOX and UO_2 fuel cost ratio are taken as a parameter.

(j) HLW Transportation

A unit cost P_7 of 5.4 kyen/kg HM is adopted assuming that one vitrified package contains 1.8 t of HLW (equivalent to 4 fuel assemblies) and that 100 vitrified packages are transported for one shipment using the same ships and casks as those used for the spent fuel transportation.

(k) Value of Recovered Uranium

Though the recovered uranium has some value because it is slightly enriched uranium, the value of recovered uranium is reduced to some extent because it contains ^{236}U which works as a neutron poison in a reactor, and high energy γ-emitting nuclides which require additional shielding for enrichment, fuel fabrication and handling. In this study the value of recovered uranium is assumed to be zero canceling out these factors.

(l) Value of Recovered Plutonium

The plutonium value rises with increases in the price of natural uranium ore and the enrichment fee, and falls as the charges for MOX fuel fabrication and reprocessing decrease(11). In this study the plutonium value is fixed at zero in view of the present fuel cycle cost circumstances mentioned above.

3. Results of Cost Evaluation

(1) Fuel Cycle Cost

Table 4 summarizes the unit costs and the material weights used in fuel cycle cost calculations for both the UO_2 and WMOX cycles, in order to make a comparison.

The total fuel cycle cost for the UO_2 fuel cycle for one batch of the equilibrium core is 11.1 billion yen, which produces 8.8 billion kWh of actual electricity or 7.8 billion kWh of discounted electricity calculated by Eq. (1)(9):

$$Ec = E\{1 - \exp(-r'T)\}/r', \tag{1}$$

where Ec: Discounted electricity (kWh)
E: Actual generated electricity (kWh)
T: Generating period (year)
r': Continuous discount rate $\{= \ln(1 + r)\}$,

so that the unit fuel cycle cost of the UO_2 fuel cycle is 1.43 yen/kWh. This unit cost is consistent with that of 1.5 yen/kWh which Ministry of International Trade and Industry (MITI) announced as the Japanese average LWR fuel cycle cost excluding HLW disposal cost(13).

Figure 5 shows the fuel cycle cost of WMOX in relation to the unit cost ratio of MOX to UO_2 fuel reprocessing. The UO_2 fuel cycle cost is also shown in the figure. The results indicate that the fuel cycle cost of the WMOX cycle is equivalent to that of the UO_2 cycle when the reprocessing cost of MOX is 1.5 times greater than that of UO_2, where fuel fabrication costs of MOX and UO_2 are equivalent. The cost of the WMOX fuel cycle would not be 40% higher than that of UO_2 fuel even if the reprocessing cost of MOX were six times higher than that of UO_2 fuel.

(2) Effect of MOX Fuel Fabrication Cost

Figure 6 shows the cost ratio of the WMOX to the UO_2 fuel cycle in relation to that of fuel reprocessing when the unit cost of MOX fuel fabrication is varied

Table 4 Fuel cycle cost of WMOX and uranium cycle

(1$ = 130 yen)

Item	Unit cost (10^3 yen/kg HM)	Weight (10^3 kg HM)	Discount	Cost (10^9 yen)
Uranium cycle				
Uranium ore	6.5	208	1.09	1.47
Conversion	1.00	208	1.08	0.22
Enrichment	16.3 (10^3 yen/SWU)	182 (10^3 SWU)	1.05	3.12
UO_2 fuel fabrication	80.0	27.5	1.03	2.27
Spent fuel transportation	20.5	27.5	0.65	0.37
UO_2 fuel reprocessing	200	27.5	0.65	3.58
Recovered Pu/U credit	0	—		0
HLW transportation	5.4	27.5	0.65	0.10
Total				**11.13**
WMOX recycle				
Uranium ore	6.50	154	1.09	1.09
Conversion	1.00	154	1.08	0.17
Enrichment	16.3 (10^3 yen/SWU)	1.36×10^5 (10^3 SWU)	1.05	2.33
UO_2 fuel fabrication	80.0	20.2	1.03	1.66
Weapons-grade plutonium	0	0.214		0
Reactor-grade plutonium	0	0.498		0
Weapons-grade MOX transportation	117	0.214	1.10	0.03
MOX fuel fabrication	$f \times 143$	7.36	1.10	$f \times 1.16$
MOX fuel transportation	20.5	7.36	1.05	0.16
Spent fuel transportation	20.5	27.5	0.65	0.37
UO_2 fuel reprocessing	200	20.2	0.65	2.63
MOX fuel reprocessing	$F \times 200$	7.36	0.65	$F \times 0.96$
Recovered Pu/U credit	0	—		0
HLW transportation	5.4	27.5	0.65	0.10
Total				**See Fig. 5**

(Note) f: Factor of MOX fuel fabrication cost (1.0,1.5 and 2.0)
F: Cost ratio of MOX to UO_2 fuel reprocessing (1.0–6.0)

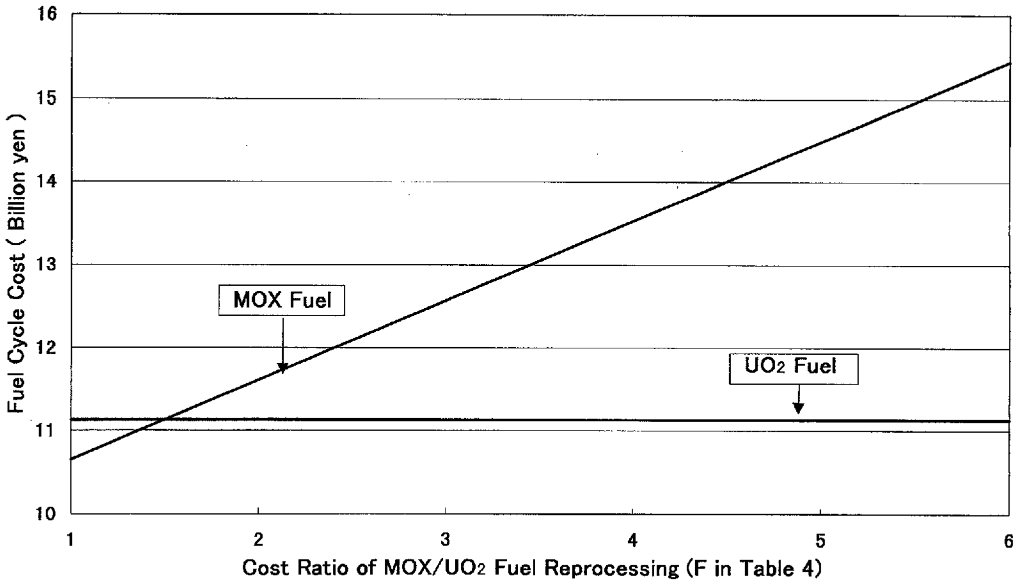

Fig. 5 Fuel cycle cost of WMOX

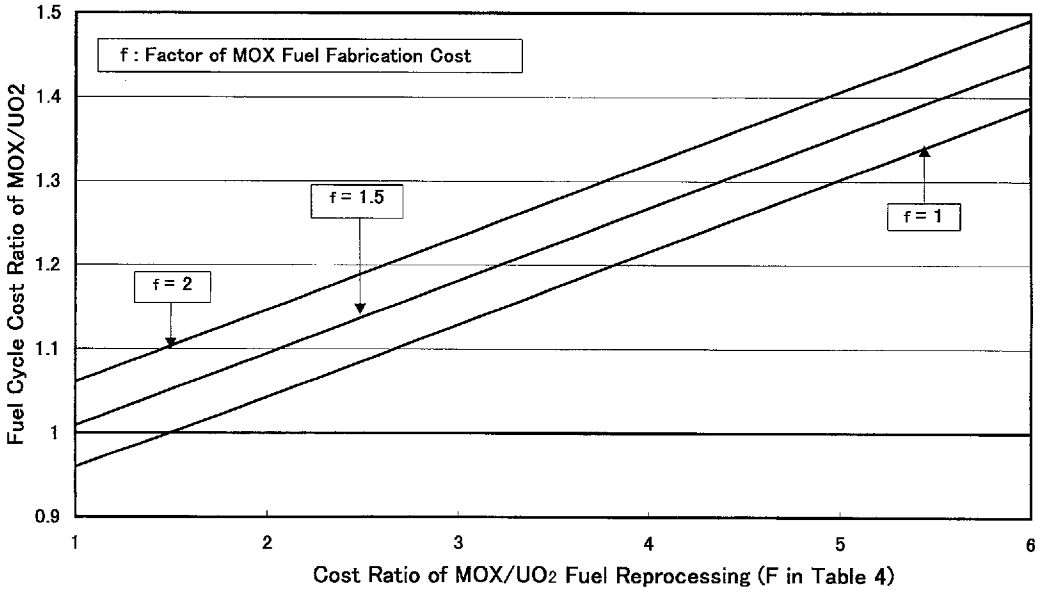

Fig. 6 Fuel cycle cost ratio of WMOX to UO_2 cycle

by factors of 1.0, 1.5 and 2.0 in relation to that given in the OECD/NEA paper(9), *i.e.* 1,100 $/kg HM. The results indicate that the fuel cycle cost of the WMOX cycle is equivalent to that of the UO_2 cycle when the fuel fabrication cost of MOX fuel is 1.5 times that of UO_2 fuel where MOX and UO_2 fuel reprocessing costs are equivalent.

It is shown that the fuel cycle cost of WMOX would not be more than 50% higher than that of UO_2 fuel, assuming that the fuel fabrication cost of MOX is double that of UO_2 fuel and the reprocessing cost of MOX six times higher. Therefore, considering that the fuel cycle costs account for only 20% of total generating costs, disposing of the excess weapons plutonium in commercial LWRs as MOX fuel would be economically realistic if the fabrication cost and the reprocessing cost of MOX fuel are moderate.

(3) Effects of the Reprocessing Cost

Japanese utilities have continued the fixed price contracts with COGEMA and BNFL to reprocess 7,000 t of the spent UO_2 fuel. However, the present contracts will end in the early years of the next century. After the end of the present contracts, the reprocessing service charge is expected to decrease because of the depreciation of the reprocessing plants and the predicted slow-down in the plutonium utilization program in LWR and LMFBR(14).

If the reprocessing unit cost of UO_2 fuel decreased by half, *i.e.* 100 thousand yen/kg HM in this study, the fuel cycle cost for UO_2 fuel would be reduced by 16% (9.3 billion yen), and that for WMOX recycling would also be reduced accordingly.

(4) Effect of the Interim Storage of Spent Fuel

In this cost evaluation it is assumed, by means of comparison with WMOX recycling, that the spent fuel assemblies of the UO_2 fuel cycle were reprocessed after 5 years cooling at the site. If however the spent fuel assemblies were to be reprocessed after 40 years interim storage, the UO_2 fuel cycle would become less expensive because of the large discount in the reprocessing cost.

IV. Conclusion

The evaluation of the fuel material flow and the fuel cycle costs when the Russian weapons-grade plutonium is mixed with the reactor-grade plutonium to fabricate MOX fuel and to be recycled in the Japanese commercial LWRs, indicated that:

(1) The MOX fuel using weapons- and reactor-grade mixed plutonium (WMOX) facilitates multiple recycling, because the weapons-grade plutonium improves the isotopic composition of the MOX fuel working like a "purifier" of the degraded recycled plutonium.

(2) It is realistic to dispose of the excess weapons plutonium in commercial LWRs as MOX fuel, because approximately 16 PWR units can burn the excess weapons plutonium to be disposed of in the USA and in Russia in the early years of the next century.

(3) It is also an economically realistic method in Japan if the fabrication cost and the reprocessing cost of MOX fuel are moderate compared to those of UO_2 fuel, assuming the MOX powder using weapons-grade plutonium would be provided free of charge.

In this study, WMOX recycling is evaluated for the 1/4 core as MOX fuel, however, the excess weapons plutonium will be more effectively disposed of by optimizing the content of weapons-grade plutonium in WMOX fuels.

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