Annex 8

PLUTONIUM AND RECOVERED URANIUM CREDITS

1. Introduction

Plutonium and uranium, recovered by reprocessing LWR spent fuel, can be used as fresh fuel. But in using recovered plutonium and uranium, it is necessary to consider the effect of their isotopic composition.

The main isotopes of plutonium recovered by reprocessing are ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu. Of these isotopes, only ^{239}Pu and ^{241}Pu are fissionable and ^{241}Pu decays to ^{241}Am with a half-life of 14.4 years. Thus, in utilising plutonium, it is necessary to consider the fraction of plutonium fissile materials. This fraction depends on the fuel burn-up and the period after the discharge from the reactor core.

In utilising of recovered uranium, it should be noted that the isotopic fraction of ^{236}U in the recovered uranium depends on the burn-up of spent fuel. As ^{236}U is a thermal neutron absorber, more separative work is needed than that for fresh natural uranium in order to compensate for this absorption effect.

2. The plutonium value estimation

In the Annex 15 of the 1985 NEA study on *The Economics of the Nuclear Fuel Cycle*[7], the plutonium value was estimated by the indifference method. By using that method, the plutonium value is settled as the economic break-even point of the MOX fuels to the fresh enriched uranium fuels.

On the other hand, the concept of "free plutonium" was proposed in the 1989 NEA study *Plutonium Fuel - An Assessment*[5]. This concept is useful to estimate the economic advantage of using plutonium for the substitution of enriched uranium.

In the present study the indifference method has been adopted as in the 1985 study for calculating the plutonium credit.

The plutonium enrichment for MOX fuel fabrication depends on the isotopic composition and burn-up required in the core. Figure 8.1 shows the Puf weight required for 1 kg HM of PWR MOX fuel, using plutonium obtained from the spent fuel with burn-up of 33 GWd/t and 43 GWd/t, respectively. This figure was obtained from the data given in Table 12 (a) & (b) in the NEA *Plutonium Fuel - An Assessment* study[5].

In this study, the fuel burn-up specification for an N4 plant of 42.5 GWd/t has been adopted. From Figure 8.1, it is estimated that the Puf weight required for 1 kg HM of MOX fuel is about 44 g. Assuming the same back-end costs for UO_2 fuel and MOX fuel, the plutonium value is obtained from the difference of front-ends costs. Table 8.1 shows the results obtained by using reference values for

Table 8.1. **Plutonium value (reference case)**

	UO_2 fuel (1kg)	**MOX fuel (1kg)**
Uranium purchase	\$509 (\$70.1 x 7.267 kg)	\$65 (\$70.1 x 0.933 kg)
Conversion	\$58 (\$8 x 7.267 kg)	\$7 (\$8 x 0.933 kg)
Enrichment	\$552 (\$110 x 5.014 SWU)	—
Fabrication	\$275 (\$275 x 1 kg)	\$1 100 (\$1 100 x 1 kg)
Total	**\$1 394**	**\$1 172**
Saving	—	**\$222**
Plutonium value	—	**\$5.0/g Puf (\$222 ÷ 44 g Puf)**

fuel cycle unit prices. The value of \$70.1 per kg U for uranium purchase price was adopted in this plutonium credit calculation. This value is the levelised price over 29 years plutonium recovered period (i.e. for the reference PWR, the first plutonium will not be separated until 2007 and will last until 2035). Based on these reference unit prices, the cost of an enriched uranium fuel element for PWR (3.6 per cent enrichment) is \$1 394 per kg. On the other hand, the cost of an equivalent mixed oxide made from 933 g of natural uranium and 44 g of fissile plutonium will be \$1 172 per kg made up of \$65 for uranium purchase, \$7 for conversion and \$1 100 for fabrication. The value of \$1 100 per kg HM for MOX fuel fabrication is consistent with the *Plutonium Fuel - An Assessment* study, where the MOX/UO_2 fabrication cost ratio used was four.

The 44 g of fissile plutonium thus save a net sum of \$222 per kg of PWR fuel and the plutonium credit is therefore \$5.0 per g plutonium fissile.

Figures 8.2 and 8.3 show how this plutonium value varies with uranium price, enrichment cost and mixed oxide fuel fabrication cost. These back-up data are shown in Tables 8.2 and 8.3, respectively.

Figure 8.2 shows the plutonium indifference value for three MOX fuel fabrications costs which are 3, 4 and 5 times the reference UO_2 fuel fabrication cost of \$275 per kg U. The ratios of 3 and 5 are settled as a lower and upper bound for the sensitivity analysis. This corresponds to the case where the MOX fuel fabrication technology will not be matured at the level of four times of UO_2 fuel fabrication cost in future.

Figure 8.3 shows the plutonium indifference value for three MOX fuel fabrication costs which are all four times the UO_2 fuel fabrication cost, but using different UO_2 fuel fabrication cost (i.e. \$200, \$275 and \$350 per kg U). This sensitivity analysis was performed in order to estimate the influence of changes of the UO_2 fuel fabrication cost on the plutonium indifference value, assuming a fixed MOX/UO_2 fabrication cost ratio of 4 to reflect the maturity of the MOX fuel fabrication technology.

As a result, both cases give a nearly identical range and the variation of the plutonium indifference values shows the same tendency in either case.

Table 8.2. Sensitivity of plutonium indifference value (\$/g Puf) to enrichment and MOX fuel fabrication prices

MOX fuel fabrication price: \$825/kg HM (UO_2 \$275x3)			
Uranium price (\$/kg U)	Enrichment price (\$/SWU)		
	80	110	130
40 70.1 90	3.53 7.87 10.73	6.95 11.29 14.15	9.23 13.56 16.43
MOX fuel fabrication price: \$1 100/kg HM (UO_2 \$275x4)			
Uranium price (\$/kg U)	Enrichment price (\$/SWU)		
	80	110	130
40 70.1 90	-2.72 1.62 4.48	0.70 5.04(reference) 7.90	2.98 7.31 10.18
MOX fuel fabrication price: \$1 375/kg HM (UO_2 \$275x5)			
Uranium price (\$/kg U)	Enrichment price (\$/SWU)		
	80	110	130
40 70.1 90	-8.97 -4.63 -1.77	-5.55 -1.22 1.65	-3.27 1.06 3.93

Table 8.3. Sensitivity of plutonium indifference value ($/g Puf) to enrichment and MOX fuel fabrication prices

MOX fuel fabrication price: $800/kg HM ($UO_2$ $200x4)			
Uranium price ($/kg U)	Enrichment price ($/SWU)		
	80	110	130
40	4.10	7.52	9.80
70.1	8.43	11.85	14.13
90	11.30	14.72	17.00

MOX fuel fabrication price: $1 100/kg HM ($UO_2$ $275x4)			
Uranium price ($/kg U)	Enrichment price ($/SWU)		
	80	110	130
40	-2.72	0.70	2.98
70.1	1.62	5.04(reference)	7.31
90	4.48	7.90	10.18

MOX fuel fabrication price: $1 400/kg HM ($UO_2$ $350x4)			
Uranium price ($/kg U)	Enrichment price ($/SWU)		
	80	110	130
40	-9.54	-6.12	-3.84
70.1	-5.20	-1.78	0.50
90	-2.34	1.08	3.36

3. The estimation of the recovered uranium value

As described in the introduction, the recovered uranium value must be estimated taking the presence of the strong neutron absorber ^{236}U into consideration. In addition, there are ^{232}U and ^{234}U in the recovered uranium; the daughter products of these isotopes are strong gamma emitters. Therefore, shielding to protect from gamma rays during the fuel fabrication process should also be considered.

The recovered uranium value is calculated with reference to the relevant annex of the NEA *Plutonium Fuel - An Assessment* study[5].

The value of the recovered uranium in the form of UF_6 is obtained by the following formula:

$$C_{REC} = C_{U_3O_8} . F_{NU}/F_{RU} + C_{UF_6} . F_{NU}/F_{RU} + C_{SWU}(S_{NU} - S_{RU})/F_{RU}$$

$$- \Delta C_{UF_6}/F_{RU} - \Delta C_{SWU} S_{RU}/F_{RU} - \Delta C_{UO_2}/F_{RU}$$

where:

$C_{U_3O_8}$	levelised natural uranium price for reference case (\$70.1/kg U);
C_{UF_6}	price of UF_6 conversion (\$8/kg);
C_{SWU}	price of enrichment (\$110/SWU);
ΔC_{SWU}	premium for enrichment of recovered uranium (\$10/SWU);
C_{UO_2}	price of UO_2 fuel fabrication (\$275/kg);
ΔC_{UF_6}	premium for conversion of recovered uranium;
ΔC_{UO_2}	premium for UO_2 fuel fabrication (\$30/kg);
F_{NU}	natural uranium requirement for 1 kg of enriched uranium (7.267 kg);
F_{RU}	recovered uranium requirement for 1 kg of enriched uranium;
S_{NU}	separative work for 1 kg of enriched uranium from natural uranium;
S_{RU}	separative work for 1 kg of enriched uranium from recovered uranium.

The natural uranium requirement is calculated using the data for the N4 plant material balance, 3.6 per cent ^{235}U enrichment for the equilibrium cycle charge. In this calculation the tail ^{235}U concentration of the enrichment process is 0.25 per cent. The ^{235}U concentration of recovered uranium is 0.81 per cent as shown in the data for the N4 plant material balance.

In this study, the uranium credit has been calculated on the basis that the recovered uranium comes from a THORP type plant in the form UO_3 and only a relatively small premium is involved in converting it to UF_6 when it is recycled. If the uranium was recovered in another chemical form, such as UHN, higher conversion costs would be incurred with a potentially higher premium. This would have the effect of reducing the credit worth of the recovered uranium.

The premium for enrichment and UO_2 fuel fabrication of recovered uranium is assumed to have the same value as in the NEA *Plutonium Fuel - An Assessment* study[5]. The premium for enrichment is expressed per SWU, but may encompass costs associated with the processing of feed and/or tail materials.

The recovered uranium requirement for 1 kg of enriched uranium is calculated to be 5.982 kg in the case of no allowance for ^{236}U. Because of the ^{236}U negative reactivity effect, additional ^{235}U enrichment required is obtained by the following equations and the data given in the 1987 NEA/IAEA "Yellow Book"[(10)].

$$X_e \ / \ X_{RU} = 0.75(a_e + e_a) \ / \ a'$$

$$e_a = 0.28 \ X_e$$

where:

X_e	^{236}U concentration in re-enriched fuel;
X_{RU}	^{236}U concentration in recovered uranium;
a_e	^{235}U concentration in fresh fuel without ^{236}U;
e_a	additional concentration of ^{235}U required to allow for ^{236}U;
a'	^{235}U concentration in recovered uranium.

From Figure 10.1 in the annex of the 1987 NEA/IAEA "Yellow Book", the ^{236}U concentration in the recovered uranium corresponding to fuel burn-up of 42 500 MWd/t, is about 0.45 per cent. The calculation results show that X_e and e_a are 1.70 per cent and 0.48 per cent, respectively. Uranium and separative work requirements are shown in Table 8.4.

When the effects of the ^{236}U content and of fabrication and enrichment premiums are neglected, the formula giving the recovered uranium value is:

$$C_{REC} = F_{(e_d)} \cdot C_{U_3O_8} + F_{(e_d)} \cdot C_{UF_6} + S_{(e_d)} \cdot C_{SWU}$$

where:

$F(e_d) = F_{NU}/F_{RU}$ and $S(e_d) = (S_{NU} - S_{RU})/F_{RU}$ are, respectively, the natural uranium and separative work required to produce 1 kg of uranium with an enrichment equal to the discharged ^{235}U content (e_d).

The resulting recovered uranium value for the reference natural uranium, conversion and enrichment prices (see Table 8.1) is shown in Table 8.5, together with the effects of ^{236}U and processing premiums, both in absolute and in relative terms.

When only the deleterious effect of ^{236}U is taken into account, the value of the recovered uranium drops to 74 per cent of the base value. It is further reduced to 70 per cent when a fabrication premium of $30 per kg is considered and to 62 per cent when an enrichment premium of $10 per SWU is, in addition, taken into account.

For the fuel cycle cost calculations, a simple mean value of 70 per cent of the value of new uranium at the same enrichment has been used.

Sensitivity analyses for uranium credit were performed in order to examine how the uranium credit value changes under the influence of the variation of each front-end fuel cycle price. In these sensitivity analyses, calculations for two extreme cases were performed, namely all the "lower" values for front-end fuel cycle prices were taken in the low case and all the "higher" values were taken in the high case. The results of low and high cases are shown in Table 8.6. The low case for uranium credit gives a value range of 52 to 71 per cent of equivalent new uranium and enrichment and the high case gives a value range of 66 to 75 per cent.

Table 8.4. Uranium and separative work requirements

	Enriched uranium from natural uranium	Enriched uranium from recovered uranium	
		No allowance for ^{236}U	Allowance for ^{236}U
Feed enrichment	0.71%	0.81%	0.81%
Tails	0.25%	0.25%	0.25%
Product enrichment	3.60%	3.60%	4.08%
Uranium requirement (kg) for 1 kg enriched uranium	7.267	5.982	6.839
SWU requirement for 1 kg enriched uranium	5.014	4.445	5.347

Table 8.5. Recovered uranium value (reference case)

	Value of recovered uranium	Ratio
No allowance for ^{236}U and no premium for fabrication	\$105/kg U	100%
With allowance for ^{236}U and no premium for fabrication	\$78/kg U	74%
With allowance for ^{236}U and premium for fabrication	\$73/kg U	70%
With allowance for ^{236}U and premium for fabrication and enrichment	\$65/kg U	62%

Table 8.6. Recovered uranium value (parametric cases)

	Low case		High case	
	Value of recovered uranium	Ratio	Value of recovered uranium	Ratio
No allowance for ^{236}U and no premium for fabrication and enrichment	$63/kg U	100%	$135/kg U	100%
With allowance for ^{236}U and no premium for fabrication and enrichment	$45/kg U	71%	$101/kg U	75%
With allowance for ^{236}U and premium for fabrication	$41/kg U	65%	$97/kg U	72%
With allowance for ^{236}U and premium for fabrication and enrichment	$33/kg U	52%	$89/kg U	66%

Note: Calculated by using the lower and higher data, i.e. $40 and $90 per kg U for natural uranium price, $6 and $11 per kg U for conversion price, $80 and $130 per SWU for enrichment price, and $200 and $350 per kg U for fabrication price.

Figure 8.1 **Masse de plutonium fissile requise pour obtenir 1 kg de ML destiné au combustible MOX des REP**

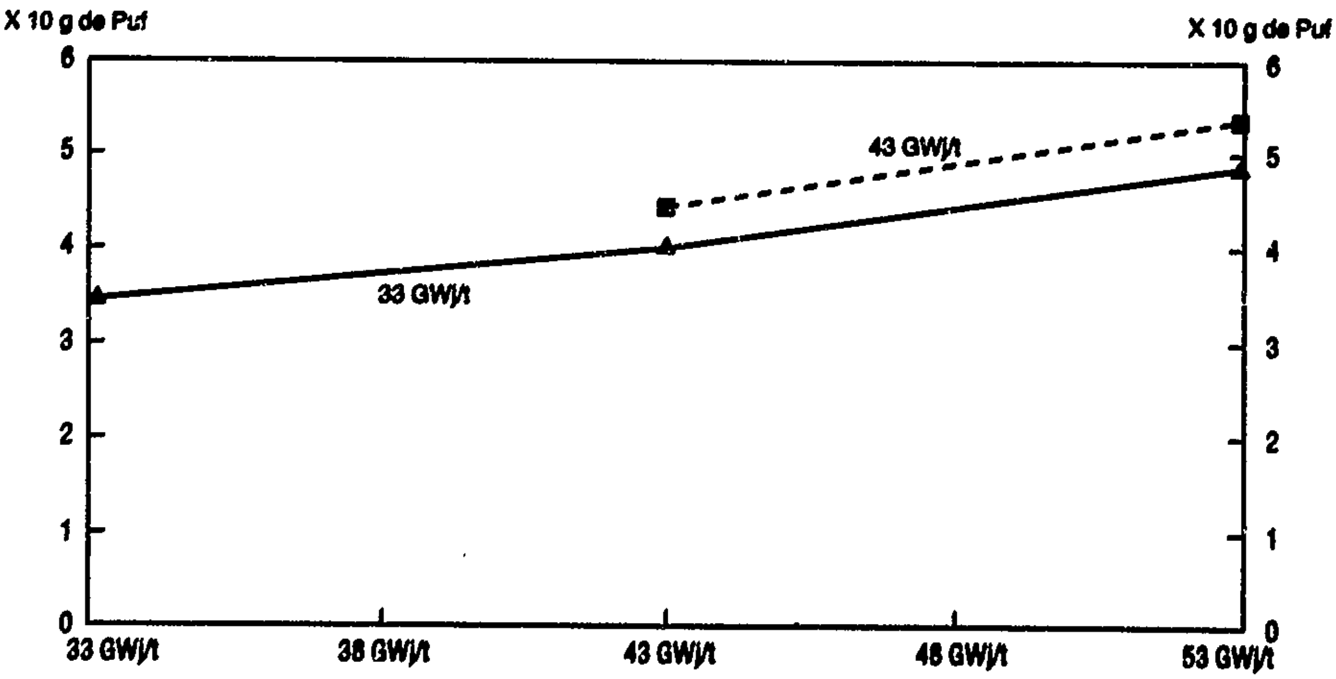

Figure 8.2 Sensitivity of plutonium indifference value to enrichment price and MOX fuel fabrication price

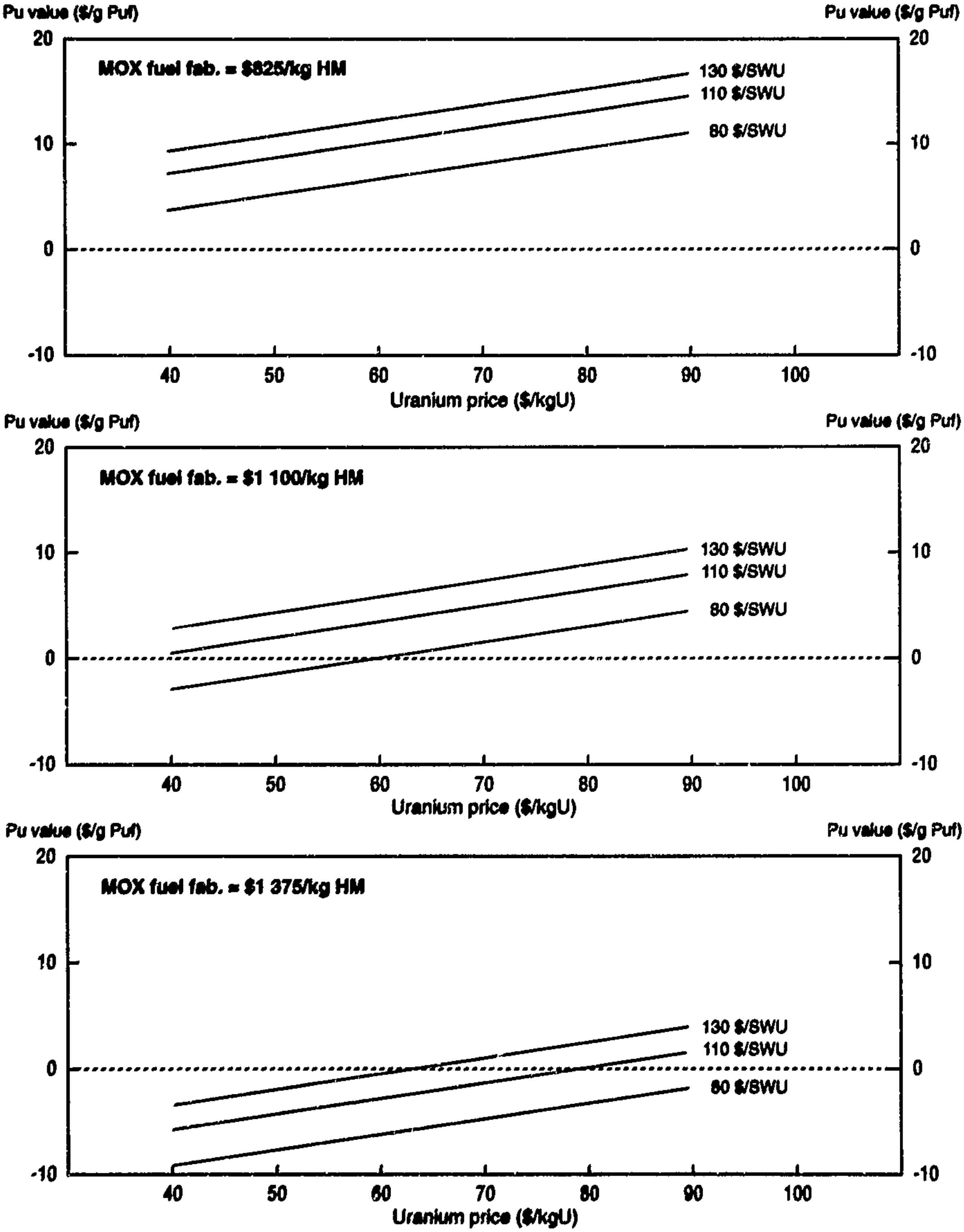

Figure 8.3 Sensitivity of plutonium indifference value to enrichment price and MOX fuel fabrication price