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GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

ECONOMICS OF BLENDING
A CASE STUDY

by

M. R. Balakrishnan
Reactor Engineering Division

BHABHA ATOMIC RESEARCH CENTRE
BOMBAY, INDIA
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INTRODUCTION

The uranium discharged from thermal reactors fuelled with enriched uranium, often contains more uranium 235 than natural uranium does. Even in those situations in which the uranium 235 content of the discharged uranium is less than that of natural uranium, but is higher than that of the tail from the diffusion plant, the uranium 235 in the discharged uranium has a certain value; and the decision to recover it or discard it essentially depends on the cost of recovering. When the uranium 235 contained in the discharged uranium is more than that in the diffusion plant tail, it can be utilized in two possible ways - the recovered uranium can be converted to uranium hexafluoride and can be sent to a diffusion plant to get enriched uranium; or the recovered uranium can be blended with appropriate amount of highly enriched uranium to get the desired enrichment in the mixture.(1) The relative merits of these two ways of utilizing the recovered uranium depend on the economics of the two methods.

Blending has many detrimental as well as many beneficial aspects. The relative economics of blending compared to re-enrichment, depend on many factors. Generally, mixing the appropriate amounts of uranium with a low content of uranium 235 and of a higher enrichment, gives a product uranium which is more expensive than what one gets by enriching natural uranium in a diffusion plant to the same enrichment. This blending loss, as it is called, arises due to the higher amount of separative work that has to be done in the former case.

Secondly, atleast until the uranium discharged from nuclear power plants becomes a significant fraction of the total feed material to diffusion plants, the uranium 236 content of the enriched uranium can be neglected in case the discharged uranium is sent back to the diffusion plant. However, in the event of blending, the uranium 236 in the discharged fuel remains with the blended uranium, and this entails a higher concentration of uranium 235 than otherwise required so that the poisoning due to uranium 236 gets nullified.

Nonetheless, blending offers some attractive features as well. The uranium recovered in the reprocessing plant need not be converted to the hexafluoride for re-enrichment. Eventhough transportation cost of fresh fuel is not a very significant part of the total fuelling cost, in those cases when the enriched uranium is to be imported from overseas for domestic fabrication, the smaller amount of uranium to be imported for blending reduces the overall transportation charges. Another potentially significant economic incentive for blending is that the uranium 236 produced in the nuclear power plant will remain with the plant operator, and this will be of considerable revenue when recovery of neptunium 237 as a valuable precursor of plutonium 238 becomes operative. Further, the additional units of separative work required if the uranium 236 is to be separated in re-enrichment, also can be saved. Finally, if the economics of plutonium utilization favour recycling the plutonium generated in the same reactor, then separation of the plutonium and uranium can be eliminated in the reprocessing step.

VARIOUS CASES STUDIED

The relative economics of blending with particular reference to procurement of the re-load fuel for the boiling water reactors at Tarapur, were analyzed to see whether blending offers any significant economic benefits. The comparative economics of seven different ways of fuelling the Tarapur reactor after the first core loading is discharged, were studied. The different cases considered are given below.

1. No blending - import the required amount of uranium with exactly the required enrichment. The discharged uranium and plutonium are assumed to be sold at the prevailing market prices.

2. Import 5% enriched uranium and blend it with part of the discharged uranium. The uranium 235 content of the imported uranium and of the discharged uranium are known and the total amount of blended uranium is also known. So, the amount of uranium to be imported and the amount of discharged uranium to be blended, can be estimated.

The part of discharged uranium not needed for blending and the recovered plutonium are sold as in the previous case.

3. Exactly the same as the previous case except for the fact that the imported uranium is of 10% enrichment, instead of 5%.

4. Same as the previous two cases, except that the required amount of 15% enriched uranium is imported.

5. Same as the previous three cases, but for the difference that the imported uranium is of 20% enrichment.

6. Utilize all the uranium discharged at the end of life of the first core, blending it with imported uranium of appropriately high enrichment.

The quantity of uranium to be imported for make up, and the uranium 235 content of the blended mixture are known, and hence, the enrichment level required in the imported uranium can be estimated.

These five cases with different enrichments of the imported uranium were studied to see whether there is any improvement in the blending loss on changing the enrichment of the imported component.

7. The last case considered was to recycle all the discharged uranium and plutonium without separating the plutonium, by mixing the discharged fuel with the required amount of imported make up uranium of appropriate enrichment. To account for the benefit due to the absence of the need to separate plutonium and uranium during the fuel processing, the reprocessing charge was reduced by a certain percentage. However, the presence of plutonium makes the fabrication process more involved and to take this into account the fabrication charge is increased by a specified percentage.

In all these cases, the fuel discharged at the end of the first batch and the fresh fuel needed at the beginning of the second batch are taken to constitute a complete financial cycle, with all the expenses and revenues associated therein. Though this approach is not quite the conventional one and is inadequate to estimate the fuelling cost in the total unit energy cost, it is felt that it is the real representation of the situation that has to be analysed.

In none of the cases considered here, any revenue is ascribed to the uranium 236 or neptunium 237. Neither is the additional amount of separative work needed to separate the uranium 236 taken into account.

However, to compensate for the uranium 236 present in the cases of blending, additional uranium 235 enrichment has been provided. So it may be said that the economic benefit of retaining the uranium 236 has been completely ignored whereas the penalty has not been overlooked. One reason for this peculiarity is that the price of neptunium 237 and the cost of recovering it are not known to any satisfactory level of accuracy - especially when the reprocessing load is quite small.

In all the cases, the net cost per kilogram of reload fuel was estimated and compared. All the expense and revenue components are normalized to one kilogram of reload fuel.

No allowance has been made for transportation of discharged fuel, as on-site reprocessing is assumed.

ECONOMICS AND OPERATIONAL PARAMETERS

Percentage by weight of the initial uranium that is discharged	= 97.63
Percentage by weight of U 235 in the discharged uranium	= 0.966
Amount of total plutonium discharged as percentage by weight of initial uranium	= 0.615
Percentage by weight of U 235 in the reload fuel if there is no U 236	= 2.24
Price of discharged uranium as UF_6*, \$/Kg U	= 43.75
Price of plutonium, \$/gm	= 9.00
Reprocessing the discharged fuel, \$/Kg U	= 16.54
Conversion of uranyl nitrate to UF_6, \$/Kg U	= 5.60

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*Price of uranium in the form of UF_6 is estimated as given in Ref. 2, and briefly indicated in Appendix.

Conversion of Pu nitrate to metal, \$/gm	=	1.50
Transportation of imported fuel, \$/kg U	=	2.50
Increase in fabrication cost if Pu is present, %	=	20
Reduction in reprocessing cost if separation of Pu and U is not needed, %	=	50
Loss of uranium during recovery, %	=	1.0
Loss of uranium during conversion to UF_6, %	=	0.3
Loss of Pu during recovery, %	=	1.0
Loss of Pu during conversion to metal, %	=	1.0

CALCULATIONS AND RESULTS

In all the cases considered here, the cost components are given in US dollars per kilogram of uranium in the re-load fuel. The amount of additional U 235 needed to compensate for the presence of U 236 in the blended fuel has been estimated from Ref. 3, by proper interpolation and extrapolation.

It was assumed that the amount of discharged uranium used for blending need not be converted to UF_6. Further, the transportation charges per kg of the imported uranium was taken to be the same irrespective of the enrichment of the shipment. This hardly is true. However, the transportation charge is comparatively small; moreover, this has been underestimated and consequently the net fuelling cost in the cases of blending will go up thereby making the general conclusions still valid.

The parameters used in the final fuelling cost calculation and all the components of the net fuelling cost, for all the seven cases considered, are given in Tables I and II.

CONCLUSION

From the net fuelling costs given in Table 2, it can be seen that unless the prospective revenue from sale of Np 237 is also taken into account and it is significant, blending does not offer any economic benefits. Besides, the loss in revenue in the cases of blending is more pronounced than the net difference in fuelling cost and this shows that in the case of blending, the net expenditure in foreign currency is higher than the difference in the net fuelling cost involved.

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REFERENCES

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2. M. R. Balakrishnan; Toll enrichment of uranium, BARC-485 (1970)

3. K. R. Srinivasan; Private Communication (1969)

TABLE I

Summary of material import and sale

Sl. No.	Material Utilization Parameters	Sell All Discharged Uranium and Pu	U_{235} Enrichment in Imported Fuel %				Recycle All Discharged Uranium	Recycle All Discharged Uranium and Pu
			5	10	15	20		
1	Amount of uranium recovered as uranyl nitrate, kg u	0.9665	0.9665	0.9665	0.9665	0.9665	0.9665	0.9665
2	Amount of plutonium recovered as plutonium nitrate, gm Pu	6.027	6.027	6.027	6.027	6.027	6.027	6.027
3	Enrichment required in reload fuel, %	2.24	2.26	2.28	2.29	2.29	2.29	2.29
4	Effective enrichment of recycled uranium, %	-	0.966	0.966	0.966	0.966	0.966	1.333
5	Amount of uranium to be imported, kg U	1.00	0.3208	0.01455	0.0943	0.0696	0.0355 (40.5% U235)	0.0275 (36.1% U235)
6	Amount of uranyl nitrate converted to UF_6 for sale kg U	0.9665	0.2873	0.1120	0.0608	0.0361	0.00	0.00
7	Amount of Pu nitrate converted to metal for sale, gm Pu	6.027	6.027	6.027	6.027	6.027	6.027	0.00

TABLE II

Summary of Results

(All numbers in US $ per Kg U in reload fuel)

Sl. No.	Cost Components	Import 2.24% Enriched Uranium	Import 5% Enriched Uranium	Import 10% Enriched Uranium	Import 15% Enriched Uranium	Import 20% Enriched Uranium	Recycle all dis-charged Uranium	Recycle all discharged uranium and plutonium
1	Price of imported UF_6	163.45	144.52	144.39	145.54	146.06	147.25	107.36
2	Transportation of imported fuel	2.50	0.80	0.36	0.24	0.17	0.08	0.08
3	Fabrication of re-load	126.00	126.00	126.00	126.00	126.00	126.00	151.20
4	Processing of dis-charged fuel	16.15	16.15	16.15	16.15	16.15	16.15	8.08
5	Conversion of nitrate to $U.F_6$	5.41	1.61	0.63	0.34	0.20	0.00	0.00
6	Conversion of Pu nitrate to metal	9.13	9.13	9.13	9.13	9.13	9.13	0.00
	TOTAL EXPENSE	322.64	298.21	296.66	297.40	297.71	298.61	266.72
7	Revenue from uranium sale	42.16	12.53	4.89	2.65	1.57	0.00	0.00
8	Revenue from plutonium sale	54.24	54.24	54.24	54.24	54.24	54.24	0.00
	TOTAL REVENUE	96.40	66.77	59.13	56.89	55.81	54.24	0.00
	FUELLING COST	226.24	231.44	237.53	240.51	241.90	244.37	266.72

APPENDIX

Price of uranium as UF_6 is calculated based on the expression[1]

$$C = A \frac{p - w}{f - w} + B \left[V(p) + \frac{p - f}{f - w} V(w) - \frac{p - w}{f - w} V(f) \right]$$

where

C = price of UF_6 with p weight fraction U 235, \$/Kg U

A = price of feed UF_6 with f weight fraction U 235, \$/Kg U

B = charge for separative work, \$/Kg U

and w = weight fraction of U 235 in the diffusion plant tail.

The value function V(x) is defined as

$$V(x) = (2x-1) \ell n \frac{x}{1-x}$$

In these calculations it was assumed that natural uranium is available at \$8/lb U_3O_8 and coversion to UF_6 costs \$5.60 per Kg. U. Separative work was assumed to cost \$26/kg unit with 0.2% tail enrichment, though it has been raised recently.