

K-OP-207

BWR FUEL RECOVERY ECONOMICS

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Operations Analysis and Planning

August 9, 1976

**UNION
CARBIDE**

**OAK RIDGE GASEOUS DIFFUSION PLANT
OAK RIDGE, TENNESSEE**

*prepared for the U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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BWR FUEL RECOVERY ECONOMICS

INTRODUCTION

This work was done as a companion to a previous study of PWR fuel recovery economics.* The formats of these reports are similar to facilitate comparison of the spent fuel economics for the two types of light water reactors. The overall purpose of these studies is to gain insight into the incentives for recovery of the fissile values in spent LWR fuel.

The plutonium "indifference value," associated "breakeven" reprocessing cost, and overall fuel cycle costs have been estimated as functions of the price of U_3O_8 , the price of uranium enrichment, and of the cost of fabricating mixed oxide fuel assemblies relative to UO_2 fabrication. The effects of spent fuel storage costs on fuel cycle and breakeven reprocessing costs have also been calculated.

The plutonium indifference value represents the value at which a reactor operator is indifferent either to recovery and reuse of plutonium (and uranium) or to recovery and sale of plutonium and uranium. The breakeven reprocessing costs represent the price that a reactor operator could afford to pay for reprocessing and waste management (combined), such that his total fuel cycle cost is the same with or without recovery.

CONCLUSIONS

As in the PWR study, the price an operator can afford to pay for reprocessing spent fuel (including waste treatment) is very sensitive to the prices of uranium feed and separative work. For example, for U_3O_8 at \$15/lb, separative work at \$53/SWU, and a zero spent fuel storage cost, a BWR operator could afford a reprocessing cost of about \$96/kg U. At \$25/lb U_3O_8 and \$75/SWU, the breakeven reprocessing charge increases to \$175/kg U. For comparison, the corresponding breakeven reprocessing costs for the PWR were calculated to be \$162/kg U and \$279/kg U (see K-OP-185, Rev. 1).

If perpetual storage were to cost \$10/kg U/yr rather than zero, both BWR and PWR breakeven reprocessing costs would be increased by \$83/kg U (assuming a discount rate of 1%/month). For the above two alternative sets of feed and separative work costs, the BWR breakeven reprocessing costs would correspondingly be increased to \$179/kg U and \$258/kg U, and the PWR costs would be increased to \$245/kg U and \$362/kg U.

*S. G. Ledford and E. H. Gift, *Economics of PWR Spent Fuel Recovery*, K-OP-185, Rev. 1, September 5, 1975.

As was similarly concluded for the PWR, recycle of uranium and plutonium in a BWR equilibrium fuel cycle appears economically advantageous compared to perpetual storage of spent fuel assemblies, for cost assumptions potentially appropriate for the early 1980s; see Table 1. Based on the assumed reactor characteristics, the incentive for fuel recovery and recycle appears slightly less for BWRs than for PWRs. This occurs primarily as a result of less fissile plutonium and lower U-235 assay in the discharged BWR fuel relative to the PWR.

As noted in K-OP-185, Rev. 1, the savings achieved by fuel reprocessing instead of "throwaway" is achieved only if both uranium and plutonium are recovered and reused. Savings for uranium recycle only are measured essentially by the reduction in natural uranium requirements, which is small compared to the savings in separative work and natural uranium for recycle of both uranium and plutonium.

SUMMARY

The plutonium indifference value, breakeven reprocessing cost, and fuel cycle cost were determined to be linear functions of the basic cost parameters used -- i.e., U_3O_8 , SWU, the difference between mixed oxide and UO_2 fabrication costs, etc. Based on the mass balance and cost data given in the Appendix, these linear relationships are listed below:

1. The plutonium indifference value as nitrate is:
 - a. reduced by \$3.12/g fissile for each \$50/kg increase in mixed oxide fabrication cost.
 - b. increased by \$8.45/g fissile for each \$50/SWU increase in separative work price.
 - c. increased by \$6.78/g fissile for each \$10/lb increase in U_3O_8 price.
 - d. reduced by \$1.3/g fissile for each \$1.0/g total plutonium spent in conversion of plutonium nitrate to PuO_2 .
2. The fuel cycle cost with reprocessing is:
 - a. increased by 0.052 mills/kWhr for every \$50/kg increase in mixed oxide fabrication cost.
 - b. increased by 0.73 mills/kWhr for every \$50/SWU increase in separative work price.
 - c. increased by 0.74 mills/kWhr for every \$10/lb increase in U_3O_8 price.
3. The fuel cycle cost without reprocessing is:
 - a. increased by 0.26 mills/kWhr for each \$10/kg spent in annual spent fuel storage costs.

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Table 1

ILLUSTRATIVE ECONOMIC PARAMETERS FOR AN EQUILIBRIUM BWR CYCLE

BWR Fuel Cycle Cost with Reprocessing, mills/kWhr	4.22
BWR Fuel Cycle Cost without Reprocessing, mills/kWhr	4.71
Plutonium Value, \$/g Fissile, as Nitrate	23.09
Breakeven Reprocessing Cost, \$/kg U	258.00

Assumptions:

\$25/lb U₃O₈
 \$75/SWU
 \$200/kg (U + Pu) mixed oxide fabrication cost
 \$100/kg U for UO₂ fabrication
 \$10/kg-yr spent fuel storage cost
 \$100/kg reprocessing cost (for calculating fuel cycle cost)

Other assumptions are as shown in Appendix A, Tables A-1 and A-2.

- b. increased by 0.86 mills/kWhr for each \$50/SWU increase in separative work price.
 - c. increased by 0.93 mills/kWhr for every \$10/lb increase in U_3O_8 price.
4. The breakeven reprocessing cost is:
- a. increased by \$83/kg for each \$10/kg spent in annual spent fuel storage costs.
 - b. increased by \$44.2/kg for every \$50/SWU increase in separative work price.
 - c. increased by \$59.8/kg for every \$10/lb increase in U_3O_8 price.
 - d. reduced by \$16.8/kg for every \$50/kg increase in mixed oxide fabrication cost.

DISCUSSION OF RESULTS

The plutonium indifference value, the equilibrium fuel cycle costs (with and without spent fuel reprocessing), and the breakeven reprocessing cost for a BWR have been computed as functions of the price of U_3O_8 and the price of separative work (SWU). These same calculations were previously reported for a PWR (K-OP-185, Rev. 1). Table 2 shows a comparison of the results of the calculations for the two reactor types. It must be noted that these reactors have different characteristics such as thermal efficiency, fuel exposure, fuel enrichment, etc.; and that the results compared in Table 2 are for the reactor characteristics shown in Tables A-1, A-3, and A-4 of the Appendix. The cost assumptions for the two reactors are listed in Table A-2 of the Appendix.

The BWR results given in Table 2, the penalties for not reprocessing, and the plutonium indifference values as a function of increased fabrication cost of mixed oxide fuel (relative to UO_2 fabrication cost) are graphically shown in Figures 1 through 6 as functions of the feed and separative work costs.

Figure 1 shows the plutonium indifference value as a function of U_3O_8 and separative work prices, for a zero mixed oxide fabrication increment (i.e., the fabrication cost for both mixed oxide and UO_2 is \$100/kg). In this case the plutonium indifference values range from \$13/g to \$93/g (fissile) over the range of feed and separative work prices investigated. For mixed oxide increments greater than zero, the plutonium indifference value decreases at the rate of \$3.12/g (fissile) for each \$50/g increase in mixed oxide fabrication cost. Figure 2 shows the plutonium indifference values for a fabrication price increment of \$100 [mixed oxide @ \$200/kg (U + Pu), UO_2 @ \$100/kg U].

Table 2

COMPARISON OF BWR-PWR

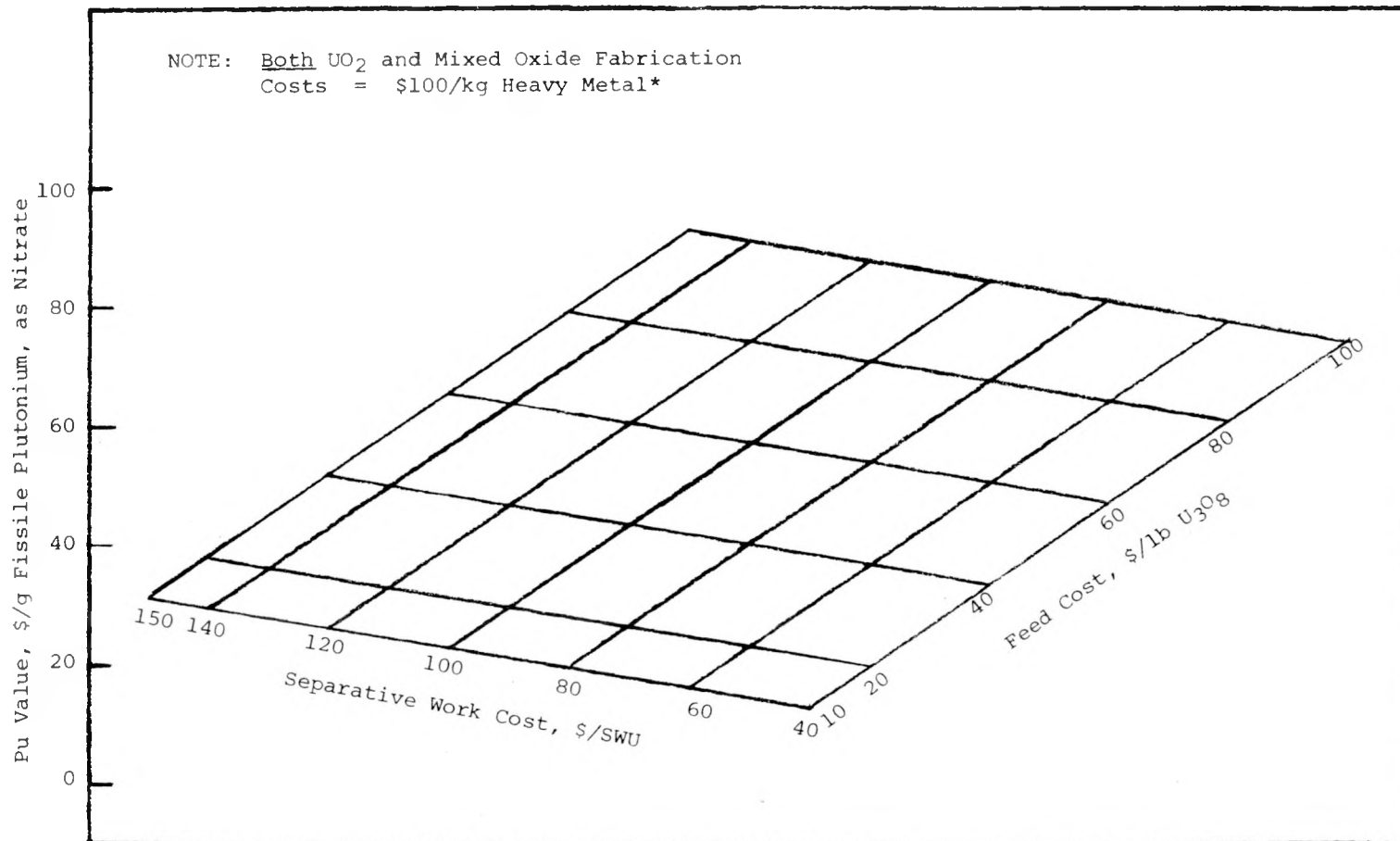
Feed Price, \$/lb U ₃ O ₈	SWU Price, \$/SWU	Fuel Cycle Cost, mills/kWhr				Breakeven Reprocessing, \$/kg U		Pu Value \$/g fissile	
		With Reprocessing		Without Reprocessing		BWR	PWR	BWR	PWR
		BWR	PWR	BWR	PWR				
10	40	2.59	2.24	2.45	2.24	54	101	7.00	8.84
10	100	3.46	3.09	3.49	3.32	107	187	17.14	19.96
10	150	4.19	3.80	4.35	4.22	151	259	25.60	29.22
25	75	4.22	3.71	4.45	4.18	175	279	23.09	25.66
50	40	5.57	4.83	6.17	5.74	293	442	34.12	36.50
50	100	6.44	5.68	7.21	6.82	346	528	44.27	47.62
50	150	7.17	6.38	8.07	7.71	391	600	52.72	56.88
100	40	9.29	8.06	10.82	10.11	592	869	68.02	71.08
100	100	10.17	8.91	11.86	11.18	645	955	78.17	82.20
100	150	10.89	9.61	12.72	12.08	689	1027	86.63	91.46

Assumptions:

Mixed oxide fabrication cost, \$200/kg U
 UO₂ fabrication cost, \$100/kg U
 Reprocessing, \$100/kg U
 Spent fuel storage cost, \$0/kg/yr

Figure 1

PLUTONIUM INDIFFERENCE VALUE AS A FUNCTION OF FEED AND SEPARATIVE WORK COSTS



*For mixed oxide fabrication costs > \$100/kg, the plutonium indifference value is decreased by \$3.12/g for each \$50/kg increment in mixed oxide fabrication cost relative to UO_2 fabrication cost.

Figure 2

PLUTONIUM INDIFFERENCE VALUE AS A FUNCTION OF
FEED AND SEPARATIVE WORK COSTS

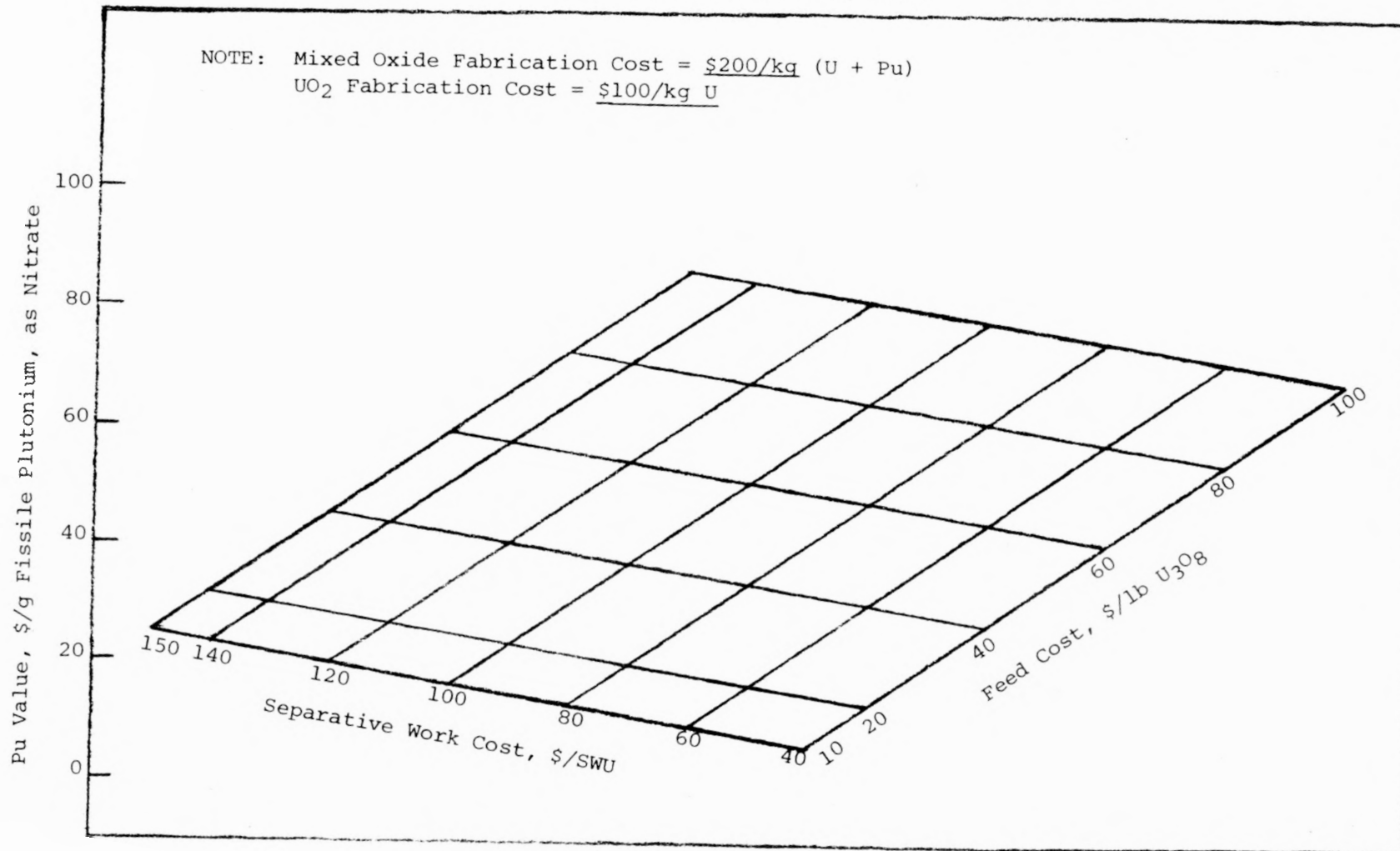


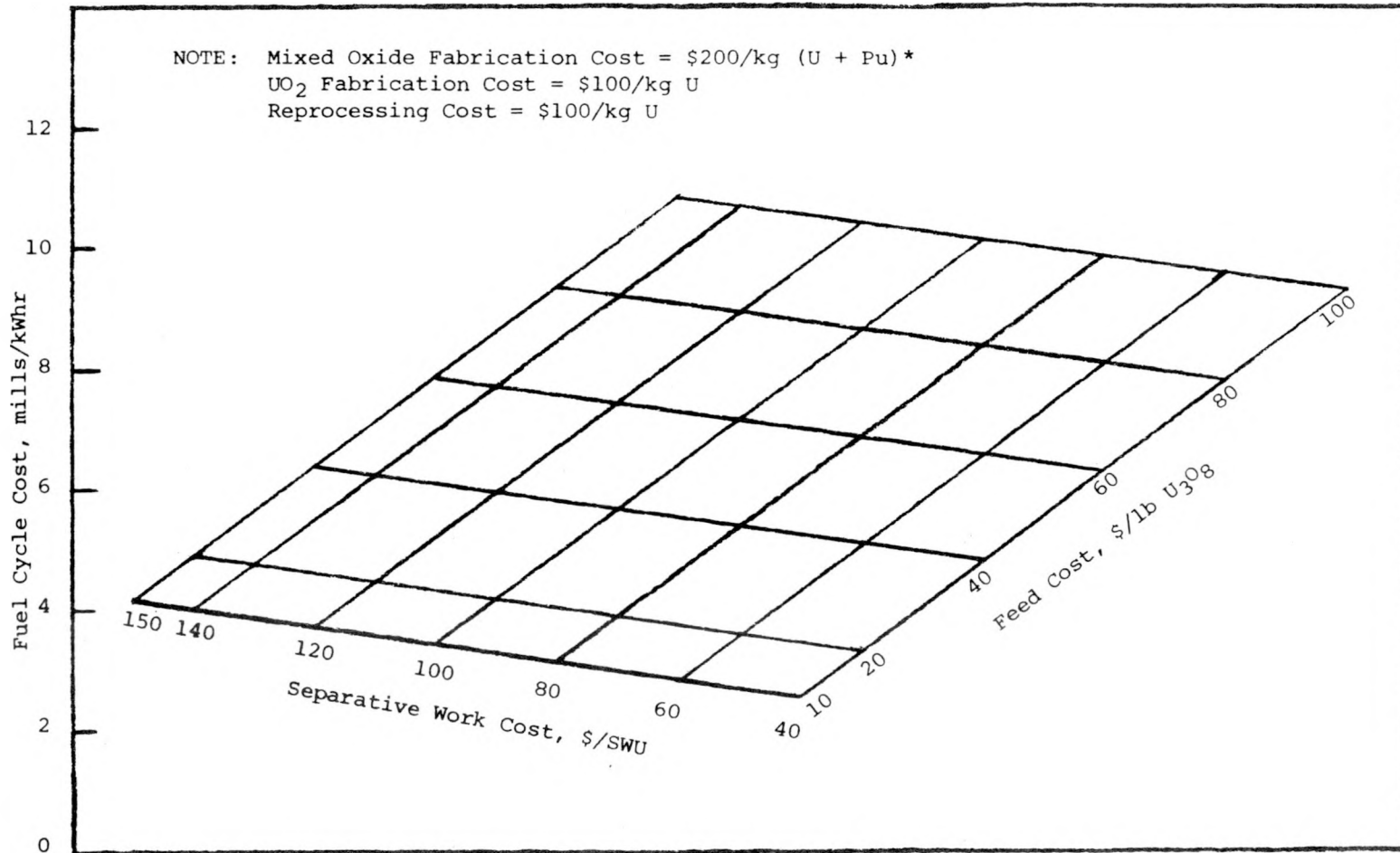
Figure 3 shows the BWR fuel cycle cost with reprocessing (@ \$100/kg) and a \$200/kg (U + Pu) mixed oxide fabrication cost (assuming UO_2 fabrication @ \$100/kg U) over the same range of U_3O_8 and separative work costs as in Figures 1 and 2. Figure 4 shows the fuel cycle cost for the alternative to reprocessing -- perpetual storage of irradiated fuel assemblies. In this figure the cost of annual storage is assumed to be \$10/kg. To calculate the fuel cycle cost for higher than \$10/kg annual perpetual storage cost, the fuel cycle values in Figure 4 should be increased at the rate of 0.26 mills/kWhr for each \$10/kg U annual fuel storage cost. This increase is based on a 12%/yr discount rate and should not be applied for other discount rates.

The fuel cycle cost penalty for not reprocessing, and assuming a perpetual storage cost of \$10/kg, is illustrated in Figure 5. Under these assumed conditions, the penalty at \$25/lb U_3O_8 cost and \$75/SWU separative work cost is 0.49 mills/kWhr. The penalty ranges from 0.12 mills/kWhr to 2.09 mills/kWhr over the range of U_3O_8 and separative work costs investigated.

The fuel cycle costs in Figure 3 were computed for an assumed \$100/kg reprocessing cost. (This cost includes waste treatment, but not the conversion of uranyl nitrate to UF_6 or plutonium nitrate to the oxide. These costs are valued explicitly.) The reprocessing cost for which the fuel cycle costs with and without reprocessing are equal (at the same feed and separative work prices) is defined here as the breakeven reprocessing cost and is shown in Figure 6 over the assumed range of feed and separative work prices. In this figure the breakeven reprocessing costs are based on zero spent fuel storage costs. For other than zero storage cost, the breakeven reprocessing costs would be increased at a rate of \$83/kg for each \$10/kg annual spent fuel storage cost (assuming a 12%/yr discount rate). The breakeven reprocessing cost is also a function of the mixed oxide fabrication cost, and would be decreased at a rate of \$16.8/kg for every \$50 increase in the mixed oxide fabrication cost relative to UO_2 fabrication. For each \$50/SWU increase in separative work price, breakeven reprocessing cost would increase \$44.2/kg; the increase would be \$59.8/kg for each \$10/lb increase in U_3O_8 price.

Figure 3

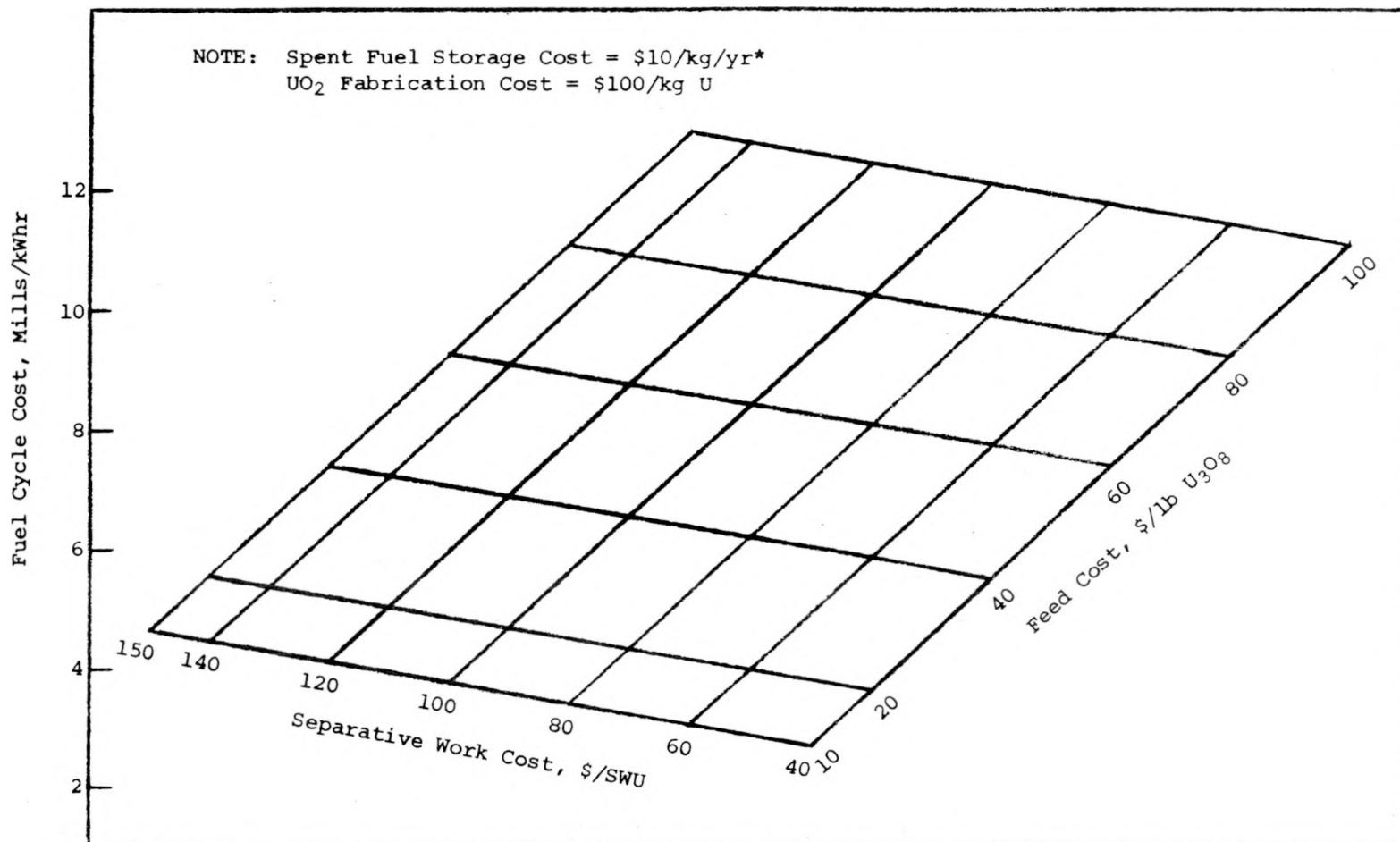
BWR FUEL CYCLE COSTS WITH REPROCESSING



*For mixed oxide fabrication costs > \$200/kg, the fuel cycle cost is increased by 0.052 mills/kWhr for each \$50/kg increase in the mixed oxide fabrication cost relative to the UO₂ fabrication cost.

Figure 4

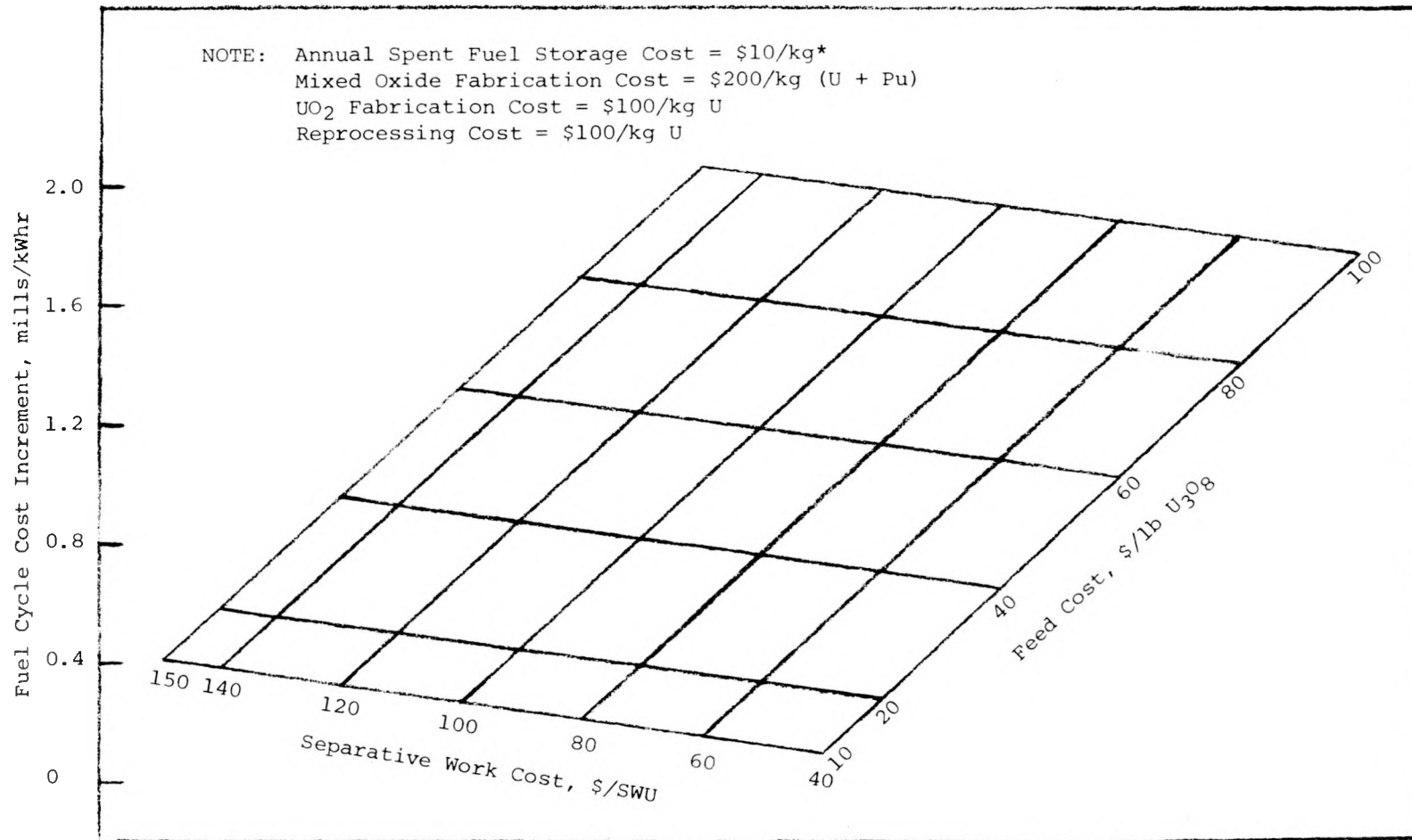
BWR FUEL CYCLE COSTS WITH NO REPROCESSING



*The fuel cycle cost is increased by 0.26 mills/kWhr for each \$10/kg increase in annual fuel storage cost.

Figure 5

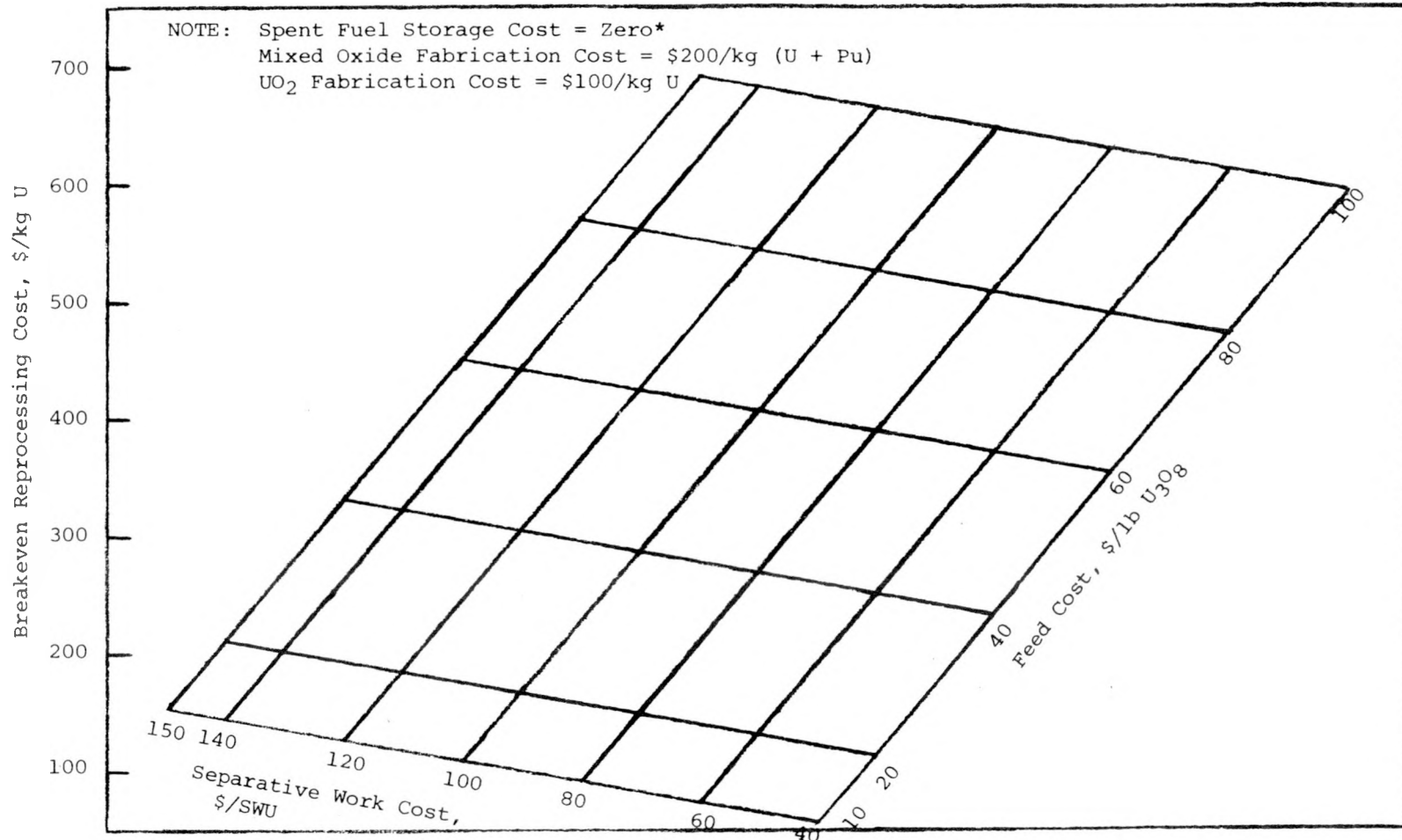
PENALTY IN FUEL CYCLE COST OF NOT REPROCESSING



*For annual fuel storage costs different from \$10/kg, the fuel cycle cost increment is increased by 0.26 mills/kWhr for each \$10/kg increase in the annual fuel storage cost.

Figure 6

BREAKEVEN REPROCESSING COST AS A FUNCTION OF URANIUM FEED
AND SEPARATIVE WORK COSTS



*For fuel storage costs > Zero, the breakeven reprocessing cost is increased by \$83/kg U for each \$10/kg increase in annual fuel storage cost.

APPENDIX

ASSUMPTIONS AND CALCULATIONS

The plutonium indifference value is calculated in this report in the same way as it was in the PWR report.* This method as well as other similarly applicable considerations are not repeated here.

The assumed BWR and PWR mass balance data are presented in Table A-1. Cost assumptions are shown in Table A-2.

A sample calculation of the fuel cycle cost method utilized in this work was also presented in the PWR report and is not repeated here. However, to facilitate comparative analysis, summary sheets for the BWR fuel cycle calculation with sale or recycle of plutonium are given in Tables A-3 and A-4, respectively. Conditions which might exist in the 1980s -- separative work price of \$75/SWU, U_3O_8 price of \$25/lb, and costs listed in Table A-2 -- are the assumptions for the calculation.

The energy value used to calculate the equilibrium fuel cycle cost is calculated as before but with appropriate BWR data [e.g., core residence time in the reactor, cycle electrical generation (MWD), etc.]. These data are also given in Table A-1.

*K-OP-185, Rev. 1, Loc. cit.

Table A-1

ASSUMED EQUILIBRIUM FUEL MASS BALANCE DATA FOR PLUTONIUM
RECYCLE AND NON-RECYCLE OPERATION OF AN LWR*

	PWR		BWR	
	No Recycle	Plutonium Recycle	No Recycle	Plutonium Recycle
<u>General Assumptions</u>				
Fuel exposure, MWd/MT	32,600	32,600	27,000	27,000
Thermal efficiency	0.3458	0.3458	0.3333	0.3333
Reload batch size, kg	31,378	31,378	37,080	37,080
Average fissile assay, wt % U-235	3.2	3.2	2.6	2.6
Residence time in reactor, months at 80% load factor	34.95	34.95	49.96	49.96
<u>Charged Fresh Fuel</u>				
Enriched uranium mass, kg	31,378	23,291	37,080	27,133
Enriched uranium assay, wt % U-235	3.2	3.2	2.6	2.6
Natural uranium mass, kg	0	7,793	0	9,678
Natural uranium assay, wt % U-235	0	0.711	0	0.711
Total plutonium mass, kg	0	294		269
Fissile plutonium (Pu-239 + Pu-241) mass, kg	0	203		190
Fraction fissile	0	0.691		0.706
<u>Discharged Spent Fuel</u>				
Enriched uranium mass, kg	30,014	22,279	35,762	26,083
Enriched uranium assay, wt % U-235	0.9	0.9	0.67	0.67
Depleted natural uranium mass, kg	0	7,565	0	9,460
Depleted natural uranium assay, wt % U-235	0	0.19	0	0.30
Total plutonium mass, kg	300	443	273.7	394.1
Fissile plutonium mass, kg	209	284	194.4	256.6
Fraction fissile	0.697	0.641	0.710	0.651

*J. D. McGaugh, *LWR Isotopic Inventories for Various Pu Recycle Techniques*, AECOP-500, April 15, 1970.

Table A-2

COST ASSUMPTIONS FOR PWR AND BWR FUEL COST CALCULATION

Natural uranium cost, \$/lb U ₃ O ₈	10 to 100
Separative work cost, \$/SWU	40 to 150
Fuel fabrication cost, \$/kg U	
For UO ₂ fuel	100
For UO ₂ -PuO ₂ fuel	100 to 200
Conversion U ₃ O ₈ to UF ₆ , \$/kg U	4.5
Conversion U ₃ O ₈ to UO ₂ , \$/kg U	4.0
Conversion Uranyl Nitrate to UF ₆ , \$/kg U	6.0
Conversion Plutonium Nitrate to PuO ₂ , \$/kg Pu	1000.0
Spent fuel shipping cost, \$/kg U	10
Reprocessing cost, including waste management, \$/kg U	100
Total irrecoverable plutonium and uranium losses in reprocessing, conversion and fabrication, wt % (each step)	0.5
Irrecoverable losses in conversion of U ₃ O ₈ to UF ₆ or to UO ₂ , wt %	0.5
Irrecoverable losses in conversion of UF ₆ to UO ₂ plus fabrication, wt %	0.5
Time for payment of U ₃ O ₈ , enrichment and fuel fabrication, months before charging to reactor	7.0
Time for payment of reprocessing and sale of recovered uranium and plutonium, months after discharge	11.0
Discount rate, %/month	1.0
Enrichment plant tails concentration, wt % U-235	0.3

Table A-3

BWR FUEL CYCLE COST WITH REPROCESSING AND SALE OF PLUTONIUM

Item	Mass Quantity x 10 ⁻³	Unit Cost	\$MM
U ₃ O ₈ Purchase	544.9	25 \$/lb	13.622
SWU Purchase	101.1	75 \$/SWU	7.583
Fabrication	37.27	100 \$/kg	3.727
Conversion (U ₃ O ₈ → UF ₆)	209.6	4.5 \$/kg	<u>0.943</u>
Subtotal Initial Costs (Undiscounted)			25.876
Shipping	37.08	10 \$/kg	0.371
Reprocessing	37.08	100 \$/kg	<u>3.708</u>
Subtotal Final Costs (Undiscounted)			4.079
U ₃ O ₈ Credit ^a	83.28	25 \$/lb	2.082
SWU Credit ^b	-0.9548	75 \$/SWU	-0.072
U ₃ O ₈ → UF ₆ Credit ^a	32.033	4.5 \$/kg	0.144
Uranyl Nitrate → UF ₆ Cost ^a	35.58	6.0 \$/kg	-0.213
Plutonium Nitrate Credit ^c	192.5	23.09 \$/g	<u>4.445</u>
Subtotal Credits			6.386
Subtotal Final Costs Minus Credits (Undiscounted)			-2.307
Discounted Initial Costs, @ 1%/month (payment made 7 months before fuel charged)			27.743
Discounted Final Costs Minus Credits, @ 1%/month (payment made 61 months after fuel charged)			-1.258
Net Present Value Cost, \$ x 10 ⁻⁶			26.48
Present Value Energy Generation, kWhr			6.2797 x 10 ⁹
Fuel Cycle Cost, mills/kWhr			4.22

^aUranium credits account for one-half percent losses each in reprocessing, conversion of uranyl nitrate to UF₆ and in conversion of U₃O₈ to UF₆. Thus, the net loss is one-half percent.

^bSeparative work credits account for one-half percent loss each in reprocessing and conversion of uranyl nitrate to UF₆. Thus the net loss is 1%. Note that since the uranium assay is less than 0.711% (feed concentration), the associated SWU is negative.

^cPlutonium assumed sold as nitrate having one-half percent loss in reprocessing and 11-month decay of discharged Pu-241.

Table A-4

BWR FUEL CYCLE COST WITH REPROCESSING AND PLUTONIUM RECYCLE

Item	Mass Quantity x 10 ⁻³	Unit Cost	\$MM
U ₃ O ₈ Purchase	424.1	25 \$/lb	10.602
SWU Purchase	74.00	75 \$/SWU	5.550
UO ₂ Fabrication	27.27	100 \$/kg	2.727
Mixed Oxide Fabrication	10.044	200 \$/kg	0.201
U ₃ O ₈ → UF ₆	153.4	4.5 \$/kg	0.690
U ₃ O ₈ → UO ₂	9.775	4.0 \$/kg	0.039
Plutonium Nitrate → PuO ₂	0.2700	1000 \$/kg	0.270
Plutonium Nitrate ^a	192.5	23.09 \$/g	<u>4.445</u>
Subtotal Initial Costs (Undiscounted)			26.332
Shipping	37.08	10 \$/kg	0.371
Reprocessing	37.08	100 \$/kg	<u>3.708</u>
Subtotal Final Costs			4.079
U ₃ O ₈ Credit ^b	60.74	25 \$/lb	1.519
SWU Credit ^c	-0.6963	75 \$/SWU	-0.052
U ₃ O ₈ → UF ₆ Credit ^b	23.36	4.5 \$/kg	0.105
Uranyl Nitrate → UF ₆ Cost ^b	25.95	6.0 \$/kg	-0.156
Plutonium Nitrate Credit ^a	254.0	23.09 \$/g	<u>5.865</u>
Subtotal Credits			7.281
Subtotal Final Costs Minus Credits (Undiscounted)			-3.202
Discounted Initial Costs, @ 1%/month (payment made 7 months before fuel charged)			28.232
Discounted Final Costs Minus Credits, @ 1%/month (payment made 61 months after fuel charged)			<u>-1.746</u>
Net Present Value Cost, \$ x 10 ⁻⁶			26.48
Present Value Energy Generation, kWhr			6.2797 x 10 ⁹
Fuel Cycle Cost, mills/kWhr			4.22

^aPlutonium assumed sold as nitrate having one-half percent loss in reprocessing and 11-month decay of discharged Pu-241.

^bUranium credits account for one-half percent losses each in reprocessing, conversion of uranyl nitrate to UF₆ and in conversion of U₃O₈ to UF₆. Thus, the net loss is one-half percent.

^cSeparative work credits account for one-half percent loss each in reprocessing and conversion of uranyl nitrate to UF₆. Thus, the net loss is 1%. Note that since the U assay is less than 0.711% (feed concentration), the associated SWU is negative.

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