FUEL CYCLE COSTS
FOR HEAVY WATER REACTORS

C. H. Bloomster

JUNE 24, 1968

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By

C. H. Bloomster

Fuel Cycle Analysis
Advanced Concepts and Analysis
Mathematics Department

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ABSTRACT

The effect of important economic and fuel design parameters on fuel cycle costs was calculated for a simulated 1000 MWe HWR based on the Pickering reactor and fuel design.

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INTRODUCTION

This report describes the effect of several important economic and fuel design parameters on the fuel cycle costs of a heavy water reactor. Heavy water reactors, which have high conversion ratios, occupy a position intermediate between present light water reactors, "burners", and fast reactors, "breeders". Under certain economic conditions heavy water reactors have the potential to become the lowest cost power producers. Fuel cycle costs were calculated for a simulated 1000 MWe heavy water reactor based on the Pickering reactor and fuel design.⁽¹⁾ Pickering is a pressure-tube reactor, D₂O cooled and moderated. The fuel element is a zirconium clad, UO₂, 28-rod bundle.

The purpose of the study was to determine the leverage of each parameter in two distinct economic environments in which (1) enriched uranium may be used, and (2) enriched uranium is prohibited. In addition, the study was to provide a measure of the benefits which would accrue from various design improvements, and thus aid in the formation of research and development programs. This study was sponsored by the Heavy Water Reactor Program Office of the USAEC.

The fuel cycle costs were calculated using the Battelle-Northwest (BNW) FULCYC code. The FULCYC Code⁽²⁾ is a system of chained computer codes for reactor fuel cycle analysis, employing burnup, economic, and optimization calculations.

SUMMARY

Fuel cycle costs were calculated for a simulated 1000 MWe heavy water reactor, and the effect of several important economic and fuel design parameters was determined. The best potential for fuel cycle cost improvement appears to be in increases in the electrical conversion efficiency obtained through higher coolant temperatures and pressures, and made possible by thicker or stronger pressure tubes. Since optimum fuel exposures in heavy water reactors are lower than in light water reactors, higher

coolant temperatures should be less deleterious from both the hydriding and cladding strain standpoint in heavy water reactors than in light water reactors.

In general, within the range of the parameters studied, minimum fuel cycle costs occurred with fuel exposures between 18,000 and 22,000 MWD/T, enrichments between 1.0 and 1.5% U^{235} , and D/U atom ratios (moderator to fuel) between 20 and 40.

DISCUSSION

The minimum fuel cycle cost is an important concept, for it provides a common basis for comparing different fuel cycles. One of the FULCYC codes, called MINIMIZER,⁽³⁾ determines the minimum fuel cycle cost under a given set of conditions. The minimum fuel cycle cost is determined from a series of independent calculations of reactivity limited fuel exposures. Under reactivity limited conditions, the initial fuel enrichment determines the maximum fuel exposure. In general, some cost components of the fuel cycle increase with exposure, e.g., inventory costs related to enrichment, and others decrease, e.g., fabrication and reprocessing costs, such that a minimum fuel cycle cost exists at a certain exposure (Figure 1) depending on the extant economic parameters.

In a heavy water moderated reactor, the moderator-to-fuel ratio (D/U) has a significant effect on the fuel cycle costs through its influence on reactivity and the D_2O loss and inventory cost. Some costs increase with the moderator-to-fuel ratio (Figure 2) and others decrease; a minimum fuel cycle cost exists at the optimum moderator-to-fuel ratio and fuel exposure. Figure 3 illustrates the three-dimensional minimization made by FULCYC to obtain the optimum moderator-to-fuel ratio, fuel exposure, and minimum fuel cycle cost.

Equilibrium fuel cycle costs were calculated for three cases: (1) the Pickering lattice using natural UO_2 , (2) the Pickering lattice optimized on enrichment, and (3) the Pickering fuel design optimized for both lattice (moderator-to-fuel ratio) and enrichment. Each parameter was varied independently from the base value (Table I), while the other parameters

remained constant. The corresponding change in the minimum fuel cycle cost for a given change in each parameter was calculated for the three cases (Table II). Inversely, the change in each parameter required to cause a 0.1 mill/kwhr change in fuel cycle cost is shown in Table III. The net effect of several simultaneous changes in parameters are additive in the Pickering natural UO_2 case since there are no changes in enrichment or lattice, but are not necessarily additive in the other cases for partially off-setting changes in enrichment or lattice may occur.

The variation in minimum fuel cycle costs with each parameter is shown graphically in Figures 4-18. The identification symbols are consistent for all figures. In general, the same vertical scale is used for each figure, and the horizontal scale extends from zero to twice the base case value. Exceptions are made in those parameters in which large variations are atypical, i.e., electrical efficiency, D_2O purity, and pressure tube thickness. The fuel cycle cost includes loss and inventory charges attributable to the D_2O coolant and moderator, but does not include costs attributable to D_2O in the reflector or heat exchange system. Some of the conclusions which may be drawn from the data are described in the following paragraphs.

Although the electrical efficiency has a relatively large effect on fuel cycle costs (Figure 4), the effect extends throughout the entire power cost calculation affecting directly both the capital and operating cost components. Thus the effect of electrical efficiency on power costs is much larger and more pervasive than is seen in Figure 4. For instance, an increase in the electrical conversion efficiency to 34%, which is projected for future light water reactors, from 29% would decrease power generation costs by 0.6 - 0.9 mills/kwhr.

The thickness of the pressure tube (Figure 5) has a much greater effect on fuel cycle cost in the natural uranium system than in the enriched uranium systems, in which the increased neutron absorption can be counteracted with slight increases in enrichment. In contrast, in the natural uranium case the fuel exposure is significantly lowered. An increase in the pressure tube thickness in the enriched uranium systems affords the opportunity to increase the coolant temperature and pressure

and thus increase the electrical conversion efficiency. Since the electrical conversion efficiency has a relatively large effect on power costs compared to pressure tube thickness, a substantial net reduction in total power cost is possible if other cost increases are not offsetting. Other costs, which would probably increase, are material costs for the pressure tube, inventory costs for added D_2O in the heat exchange system, D_2O losses, and the capital costs for the heat exchanger. The fuel problems associated with higher coolant temperatures, cladding hydriding, strain, and corrosion, should be less formidable in heavy water reactors than in light water reactors since fuel exposures in heavy water reactors are typically lower. Other than a thicker pressure tube, similar improvements in power costs might be obtained through the substitution of a stronger material for the pressure tube provided that the neutron absorption of the material was not too great. A Zr-Nb alloy has been suggested for this application.

The D_2O purity (Figure 6) has an influence on fuel cycle costs similar to pressure tube thickness. The D_2O purity is measured by the amount of H_2O impurity. The H_2O impurity causes an increase in the neutron absorption rate which increases fuel cycle costs. The increase in costs is greater in the natural uranium system than in the enriched uranium system because the fuel exposure, as with the thicker pressure tube, is lowered significantly. Increased neutron absorption, or poisoning, favors higher D/U ratios.

The effect on fuel cycle costs of plutonium prices and reprocessing cost is interdependent. The effect of plutonium price is shown for two separate reprocessing costs (Figure 7) and the effect of reprocessing cost is shown for two separate plutonium prices (Figure 8). The horizontal lines in each figure represent the range in which the throw-away fuel cycle is economic. Over this range the fissile values in the irradiated fuel are less than the cost of reprocessing. For instance, for the Pickering reactor using natural UO_2 , the throw-away cycle is economic below fissile plutonium values of \$13/g with a reprocessing cost of \$37/kg, but the throw-away cycle is economic only below fissile plutonium values of \$3/g with a reprocessing cost of \$10/kg. Similarly with varying reprocessing costs (Figure 8), with fissile plutonium at \$10/g, the throw-away

cycle is economic when reprocessing costs exceed \$30/kg (in the natural UO_2 case), but with fissile plutonium at \$20/g the throw-away cycle is economic only when reprocessing costs exceed \$50/kg. As a rule of thumb applying to these base conditions, the throw-away cycle is more economic whenever the reprocessing costs, expressed in \$/kg, exceed the fissile plutonium value, expressed in \$/g, by a factor of 3.

Increasing fabrication cost has a much greater effect on fuel cycle cost for the natural uranium case than for the enriched uranium cases (Figure 9) for the higher fabrication costs can be partially offset through increases in enrichment and fuel exposure. Conversely, as fabrication costs decrease, the optimum fuel exposure and enrichment decrease, approaching natural uranium at very low fabrication costs.

Interest rate on D_2O affects the choice of lattice pitch, as may be inferred from Figure 10 in which fuel cycle costs diverge with higher interest rates between the Pickering lattice with optimum enrichment case and the optimum lattice and enrichment case. At higher interest rates, tighter lattices, i.e., lower D/U ratios, and higher enrichments are optimum; at lower interest rates, higher D/U ratios and lower enrichments are more economic. Thus public power with lower interest rates would tend to favor higher D/U ratios than private power, other things being equal.

The effect of the D_2O cost (Figure 11) is similar to the effect of the interest rate on D_2O . Decreasing D_2O costs favor larger lattices and lower fuel enrichments.

Separative duty (Figure 12) has the opposite effect from the D_2O cost. Higher separative duty favors lower enrichment, approaching natural enrichment only at prohibitively high separative duties.

The effect of D_2O losses (Figure 13) is identical to the effect of the D_2O interest rate. A one percent loss is equivalent to a one percent increase in interest rate. At lower interest rates, the losses would make up a larger fraction of the cost of the interest plus losses than at higher interest rates.

The minimum fuel cycle cost is less sensitive to the interest rate on non-fissile working capital (Figure 14), and more sensitive to the interest

rate on the fuel inventory (Figure 15). As expected, lower enrichments are favored at higher fuel inventory interest rates. The effect of the combined interest rate on working capital and fuel inventory is shown in Figure 16.

Variations in U_3O_8 price have a significant effect on fuel cycle costs (Figure 17). The effect is nearly uniform for all three cases.

Similarly, the effect of variations in specific power is uniform for all three cases (Figure 18). Increasing specific power meets with diminishing returns. Beyond 20 kw/kg, specific power has little influence on fuel cycle costs, and the advantages of further increases may be more than offset by increases in fuel fabrication costs.

In general within the range investigated for the parameters, the optimum enrichment varies from 1.0 to 1.5% U^{235} , the optimum exposure is between 18,000 and 22,000 MWD/T, and the optimum lattice is a D/U atom ratio between 20 and 40. The Pickering D/U ratio is 48.

The conditions favoring higher D/U ratios are low fabrication costs, high separative duty, low D_2O costs, and low D_2O interest rates. Lower interest rates on other parts of the fuel cycle tend to favor higher enrichments, exposures, and lower D/U ratios.

In Table IV, the optimum lattice and enrichment and the corresponding fuel cycle cost is shown for several parametric values. As in Table I each parameter is varied independently while the others remain at the base value. The relationship between enrichment and exposure for each lattice size is shown in Figure 19.

TABLE IPARAMETRIC VALUES FOR BASE CASE

<u>Parameter</u>	<u>Value</u>
U ₃ O ₈	\$8/lb
Specific Power	14.60 kw/kg
Reprocessing Cost	\$37/kg
Fabrication Cost	\$30/kg
All interest rates	8%
Electrical Conversion Efficiency	29%
D ₂ O Cost	\$17.50/lb
D ₂ O Losses	1%
Pressure Tube Thickness	0.19"
D ₂ O Purity	99.75%
Separative Duty	\$26/kg
Pu Value	\$10/g fissile
Smear Fuel Density	10.0 g UO ₂ /cc

TABLE II

EFFECT OF VARIOUS PARAMETERS ON FUEL CYCLE COSTS

		Corresponding Change in Fuel Cycle Cost, mills/kwhr			
Parameter	Increase or Decrease in Parameter	Pickering Lattice		Optimum Lattice & Enrichment	Range
		Natural Uranium Enrichment	Optimum Enrichment		
U ₃ O ₈ Cost	\$1/lb	.04	.04	.04	\$4-\$12/lb
Pu Price	\$1/g	-.04	-.02	-.03	\$5-\$20/g
Reprocessing Cost	\$5/kg	.07	.04	.04	\$10-\$37/kg
Fabrication Cost	\$5/kg	.08	.04	.04	\$15-\$45/kg
Interest Rate on Working Capital and fuel inventory	1%	.01	.02	.02	4% - 12%
Interest Rate (Fuel inventory only)	1%	.01	.01	.01	4% - 8%
Interest Rate (Working capital only)	2%	<.01	.01	.01	8% - 12%
Electrical Conversion Efficiency	1%	-.03	-.03	-.03	29% - 34%
Separative Duty	\$10/kg of separative work	*	.04	.05	\$20-\$30/kg *No effect
D ₂ O Interest Rate	2%	.04	.04	.03	4% - 12%
D ₂ O Cost	\$1/lb	.01	.01	.01	\$13.50-\$22.80/lb
D ₂ O Losses	1%	.02	.02	.01	.5% - 2.0%
Pressure tube thickness	.1"	.11	.02	.05	.19"-.28"

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TABLE II
(Continued)

		Corresponding Change in Fuel Cycle Cost, mills/kwhr			
Parameter	Increase or Decrease in Parameter	Pickering Lattice		Optimum Lattice & Enrichment	Range
		Natural Uranium Enrichment	Optimum Enrichment		
D ₂ O Purity (% H ₂ O in D ₂ O)	1%	.22	.06	.11	100% - 99% D ₂ O
Specific Power	1 kw/kg	-.03/-.01*	-.02/-.01*	-.02/-.01*	7.3 - 21.9 kw/kg *not linear
Fuel Density					
(a) Constant Fabrication Cost per kg Fuel	10% T.D.	<.01	<.01	.01	73-91% T.D. (Smeared fuel density)
(b) Constant Fabrication Cost per unit Fuel Volume	10% T.D.	-.06	-.03	-.02	73-91% T.D.
Reactor Operating Cost	\$1,000,000/yr	.17	.17	.17	
Reactor Capital Cost (30 year plant life)					
Rate of Return on Capital					
(a) 4%	\$10/kwe	.10	.10	.10	
(b) 8%	\$10/kwe	.15	.15	.15	
(c) 12%	\$10/kwe	.21	.21	.21	

TABLE III

CHANGE IN EACH PARAMETER REQUIRED TO CAUSE
A 0.1 mill/kwhr CHANGE IN FUEL CYCLE COST

<u>Parameter</u>	<u>Natural Uranium Enrichment</u>	<u>Optimum Enrichment</u>	<u>Optimum Lattice & Enrichment</u>
U ₃ O ₈ Cost	\$2.50/lb	\$2.50/lb	\$2.50/lb
Pu Price	\$2.50/g	\$5/g	\$3.80/g
Reprocessing Cost	\$7/kg	\$12.50/kg	\$12.50/kg
Fabrication Cost	\$6/kg	\$11.50/kg	\$11.50/kg
Interest rate on Working Capital and Fuel Inventory	10%	6%	5%
Interest Rate (Fuel Inventory Only)	13%	9%	8%
Interest Rates (Working Capital Only)	40%	20%	20%
Electrical Conversion Efficiency	3.1%	3.6%	3.8%
Separative Duty	*	\$30/kg	\$30/kg
D ₂ O Interest Rate	4.4%	4.4%	6.7%
D ₂ O Cost	\$10/lb	\$10/lb	\$13/lb
Pressure Tube Thickness	.09"	.45"	.18"
D ₂ O Purity	0.45%	1.7%	0.91%

*No Effect

TABLE IV

OPTIMUM LATTICE AND ENRICHMENT CALCULATED FOR
DIFFERENT VALUES OF SEVERAL IMPORTANT FUEL CYCLE COST PARAMETERS

<u>Parameter Value</u>	<u>Minimum Fuel Cycle Cost mills/kwhr</u>	<u>Optimum Lattice D/U atom Ratio</u>	<u>Optimum Enrichment % U-235</u>
Base Case	0.88	31	1.23
Specific Power @ 7.3 kw/kg	1.12	20*	1.33
Specific Power @ 10.9 kw/kg	0.97	20*	1.40
Specific Power @ 18.2 kw/kg	0.83	32	1.27
Specific Power @ 21.9 kw/kg	0.80	32	1.30
U ₃ O ₈ @ \$4/lb	0.68	26	1.40
U ₃ O ₈ @ \$12/lb	1.05	34	1.16
Plutonium @ \$20/g fissile	0.62	20*	1.20
Plutonium @ \$15/g fissile	0.76	31	1.05
Plutonium @ \$5/g fissile	0.89	36	1.13
Reprocessing cost @ \$20/kg U	0.77	34	1.01
Reprocessing Cost @ \$10/kg U	0.69	35	0.92
Fabrication Cost @ \$45/kg U	0.99	28	1.36
Fabrication Cost @ \$15/kg U	0.75	34	1.05
Interest Rates on Working Capital and Fuel Inventory @ 4%	0.80	23	1.51
Interest Rates on Working Capital and Fuel Inventory @ 12%	1.00	40	1.02
Interest Rate @ 12% (Working Capital Only)	0.91	37	1.08
Electrical Conversion Efficiency @ 31.5	0.82	40	1.10

TABLE IV
(Continued)

<u>Parameter Value</u>	<u>Minimum Fuel Cycle Cost mills/kwhr</u>	<u>Optimum Lattice D/U atom Ratio</u>	<u>Optimum Enrichment % U-235</u>
Electrical Conversion Efficiency @ 34.0	0.76	40	1.09
Separative Duty @ \$20/kg	0.86	20	1.57
Separative Duty @ \$30/kg	0.91	40	1.06
D ₂ O Interest Rate @ 4%	0.82	40	1.10
D ₂ O Interest Rate @ 12%	0.94	20*	1.53
D ₂ O Cost @ \$13.50/lb	0.86	36	1.15
D ₂ O Cost @ \$22.80/lb	0.93	20*	1.53
D ₂ O Losses @ 1.2%	0.88	31	1.23
D ₂ O Losses @ 2.0%	0.90	29	1.30

*Lowest moderator to fuel ratio investigated. The minimum fuel cycle cost occurs below this point.

Figure 1 TYPICAL FUEL COST DATA AS A FUNCTION OF FUEL EXPOSURE

Figure 2 EFFECT OF LATTICE SIZE ON D₂O COSTS

Figure 3 OPTIMIZATION OF MODERATOR TO FUEL RATIO AND FUEL EXPOSURE

Figure 4 EFFECT OF ELECTRICAL CONVERSION EFFICIENCY
ON FUEL CYCLE COST

Figure 5 EFFECT OF PRESSURE TUBE THICKNESS ON FUEL CYCLE COST

Figure 6 EFFECT OF D₂O PURITY ON FUEL CYCLE COST

Figure 7 EFFECT OF PLUTONIUM PRICE ON FUEL CYCLE COST FOR TWO REPROCESSING COSTS

Figure 8 EFFECT OF REPROCESSING COST ON
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Figure 9 EFFECT OF FABRICATION COST ON FUEL CYCLE COST

Figure 10 EFFECT OF D₂O INTEREST RATE ON FUEL CYCLE COST

Figure 11 EFFECT OF D₂O COST ON FUEL CYCLE COST

Figure 12 EFFECT OF SEPARATIVE DUTY ON FUEL CYCLE COST

Figure 13 EFFECT OF D₂O LOSSES ON FUEL CYCLE COST

Figure 14 EFFECT OF WORKING CAPITAL INTEREST RATES ON FUEL CYCLE COST

Figure 15 EFFECT OF FUEL INVENTORY INTEREST RATE ON FUEL CYCLE COSTS

Figure 16 COMBINED EFFECT OF INTEREST RATES
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Figure 17 EFFECT OF U_3O_8 PRICE ON FUEL CYCLE COST

Figure 18 EFFECT OF SPECIFIC POWER ON FUEL CYCLE COST

Figure 19 RELATIONSHIP BETWEEN ENRICHMENT AND EXPOSURE FOR FIVE MODERATOR TO FUEL RATIOS

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