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FUEL-CYCLE COST COMPARISONS WITH OXIDE AND SILICIDE FUELS*

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INTRODUCTION

This paper addresses fuel cycle cost comparisons for a generic 10 MW reactor with HEU aluminide fuel and with LEU oxide and silicide fuels in several fuel element geometries. The intention of this study is to provide a consistent assessment of various design options from a cost point of view.

The status of the development and demonstration of the oxide and silicide fuels are presented in several papers in these proceedings. Routine utilization of these fuels with the uranium densities considered here requires that they are successfully demonstrated and licensed.

Thermal-hydraulic safety margins, shutdown margins, mixed cores, and transient analyses are not addressed here, but analyses of these safety issues are in progress for a limited number of the most promising design options.

Fuel cycle cost benefits could result if a number of reactors were to utilize fuel elements with the same number or different numbers of the same standard fuel plate. Data is presented to quantify these potential cost benefits.

REACTOR DESIGN

The reactor studied was the IAEA generic 10 MW reactor (Fig. 1) described in detail in Ref. 1. This 5 × 6 element core contained 23 MTR-type standard fuel elements and 5 control fuel elements. The core was reflected by graphite on two opposite faces and surrounded by water. One water-filled flux trap was located near the center of the core and another near an edge.

FUEL ELEMENT DESIGNS

The fuel element designs shown in Table 1 were studied using aluminide fuel with HEU and oxide and silicide fuels with LEU.

The reference HEU standard (control) element with aluminide fuel contained 23 (17) fuel plates and 280 (207) g ^{235}U. The water channel thickness was about 2.2 mm.

Fig. 1. Core and Fuel Shuffling Pattern

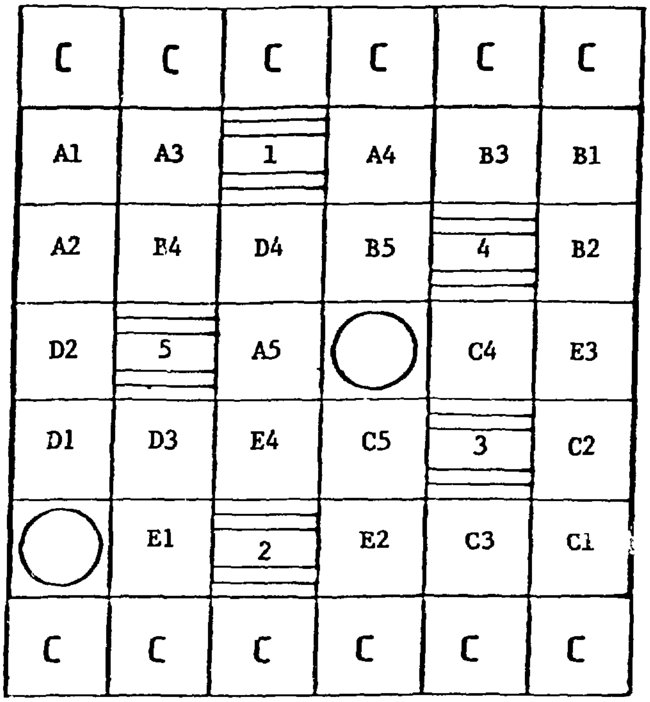

Table 1. Fuel Element Designs Studied*

Fuel Type	Enrichment, %	Plates per Element Std./Cntl.	Fuel Meat Thick., mm	Water Channel Thick., mm	Uranium Density g/cm^3	^{235}U per Std. Element, g
UAl_x	93	23/17	0.51	2.19	0.68	280
U_3O_8	19.75	16/10	0.76	3.45	3.13	284
U_3O_8	19.75	18/12	0.76	2.90	3.13	320
U_3O_8	19.75	20/14	0.76	2.46	3.13	355
U_3O_8	19.75	22/16	0.76	2.10	3.13	391
U_3O_8	19.75	20/14	0.88	2.34	3.13	411
U_3O_8	19.75	20/14	1.00	2.22	3.13	467
U_3SiAl	19.75	23/17	0.51	2.19	3.65	320
U_3SiAl	19.75	23/17	0.51	2.19	4.11	360
U_3SiAl	19.75	23/17	0.51	2.19	4.45	390

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*All cases had clad thicknesses of 0.38 mm on the inner plates and 0.495 mm on the outer plates. The fuel meat had a width of 63 mm and a length of 600 mm.

With LEU silicide fuel, the geometry of the HEU element was preserved and the ^{235}U content was varied by changing the uranium density in the fuel meat. Elements with ^{235}U loadings of 320, 360, and 390 g were selected for study. The corresponding uranium densities in the fuel meat were about 3.7, 4.1, and 4.5 g/cm^3, respectively. For convenience in determining sensitivities, additional cases were computed with 315 and 330 g ^{235}U per element.

With LEU oxide fuel, two types of design variations were made with a view to the possible standardization of fuel plate designs. These fuel plate designs and design variations were:

(1) One standard fuel plate with 0.76 mm-thick meat and a uranium density of 3.1 g/cm^3 was first defined. Fuel element designs with 16, 18, 20, and 22 of these standard plates were then studied. The corresponding ^{235}U loadings per element were 284, 320, 355, and 391 g, respectively.

(2) For the case with 20 fuel plates per element, the fuel meat thickness was increased from 0.76 mm to 0.88 mm (411 g ^{235}U per element) and to 1.0 mm (467 g ^{235}U per element) in order to determine the additional fuel cycle cost benefits that could result. The plate with 1.0 mm-thick meat and 3.1 g U/cm^3 is nearly identical with one utilized by INTERATOM in Ref. 2, and could be considered as a second standard fuel plate.

CALCULATIONAL METHODS

The methods and codes used for cross section generation (EPRI-CELL) and burnup calculations (REBUS-2) are described in detail in Appendix A of Ref. 1. However, the fuel shuffling pattern was changed from the inside-out scheme used in Ref. 1 (one standard element was replaced per cycle) to the five-batch, outside-in scheme shown in Fig. 1. This shuffling pattern is similar to that used by INTERATOM in Ref. 2 and was adopted here to enable detailed comparisons of calculated results on the same basis.

In Fig. 1, five, four, five, four, and five standard elements and one control element were replaced with fresh fuel in successive cycles in a pattern which was repetitive after every five cycles. Fresh fuel was inserted into position 1 and spent fuel was discharged from position 5 for paths A, B, C, and from position 4 for paths D, E. In paths D and E, the fuel was not shuffled during one cycle out of five so that all elements were in the core for five cycles. Control elements were inserted into position 1 and discharged from position 5.

PERFORMANCE RESULTS

In order to generalize the results to include a number of reactors with a variety of experimental loads and reactivity control requirements, the calculations were performed with the end-of-cycle (EOC) excess reactivity as a variable.

For each of the fuel element designs in Table 1, a series of burnup calculations were first performed for a number of cycle lengths. The resulting curves of EOC excess reactivity and average ^{235}U discharge burnup (in the standard elements) versus the cycle length are shown in Fig. 2 for the HEU aluminide and LEU silicide cases, in Fig. 3 for the HEU aluminide and LEU oxide cases with 0.76 mm-thick meat, 3.1 g U/cm^3, and different numbers of fuel plates per element, and in Fig. 4 for the HEU aluminide and the LEU oxide cases with 20 plates per element, 3.1 g U/cm^3, and fuel meat thicknesses of 0.76, 0.88, and 1.0 mm. The average ^{235}U discharge burnup in the control fuel elements was generally 5-6% larger than in the standard elements. These curves are not shown here.

From Figs. 2-4 and discharge burnup curves for the control elements, cycle lengths and average ^{235}U discharge burnups were obtained for EOC excess reactivities of 1 - 4% $\delta k/k$. The results are shown in Table 2 for the reference HEU design and the oxide fuel designs and in Table 3 for the reference HEU design and the silicide fuel designs. From the cycle length data, the number of standard and control elements that would be utilized per year for a 100% duty factor were derived. The mass of metal in each spent element was also tabulated for later use in computing reprocessing costs.

The data in Tables 2 and 3 show the expected result that higher ^{235}U loadings per element yield longer cycle lenghts and higher ^{235}U discharge burnups, and lead to smaller annual fuel element consumption. Relative to the HEU reference case, the peak and the average thermal (<0.625 eV) flux ratios in the central flux trap vary from 0.96 to 0.90 as the ^{235}U content per element is increased. It should be noted that these are relative values for a central flux trap filled with water only and that actual thermal flux depressions will depend on the specific design of each irradiation rig.

FUEL CYCLE COSTS

The model and assumptions used here for computing the annual costs for each fuel cycle component are described in detail in the attached Appendix. There are exceptions of course to some of the assumptions, especially those that depend on the locations of the reactor and the fuel fabricator. However, the intention here is to perform a consistent analysis for a generic reactor in order to provide a perspective on the fuel cycle cost issues. For specific reactors, the model can be used with pertinent cost input data. The cost components and assumed input data that were used are outlined below.

Enriched Uranium Costs

The price of uranium feed on the spot market for the month of September 1982 was about \$17/lb U_3O_8 and the cost for conversion to UF_6 was about \$3.1/lb U.

Using a feed assay of 0.71%, a tails assay of 0.2%, and the August 1982 DOE enrichment price of \$138.65/SWU, the prices for uranium (in UF_6) with enrichments of 93.15% and 19.75% were \$45.06 and \$41.53 per gram of ^{235}U.

Fig. 2. EOC Excess Reactivity and Average ^{235}U Discharge Burnup in Standard Elements for the Reference Design With HEU Aluminide and LEU Silicide Fuel as Functions of Cycle Length.

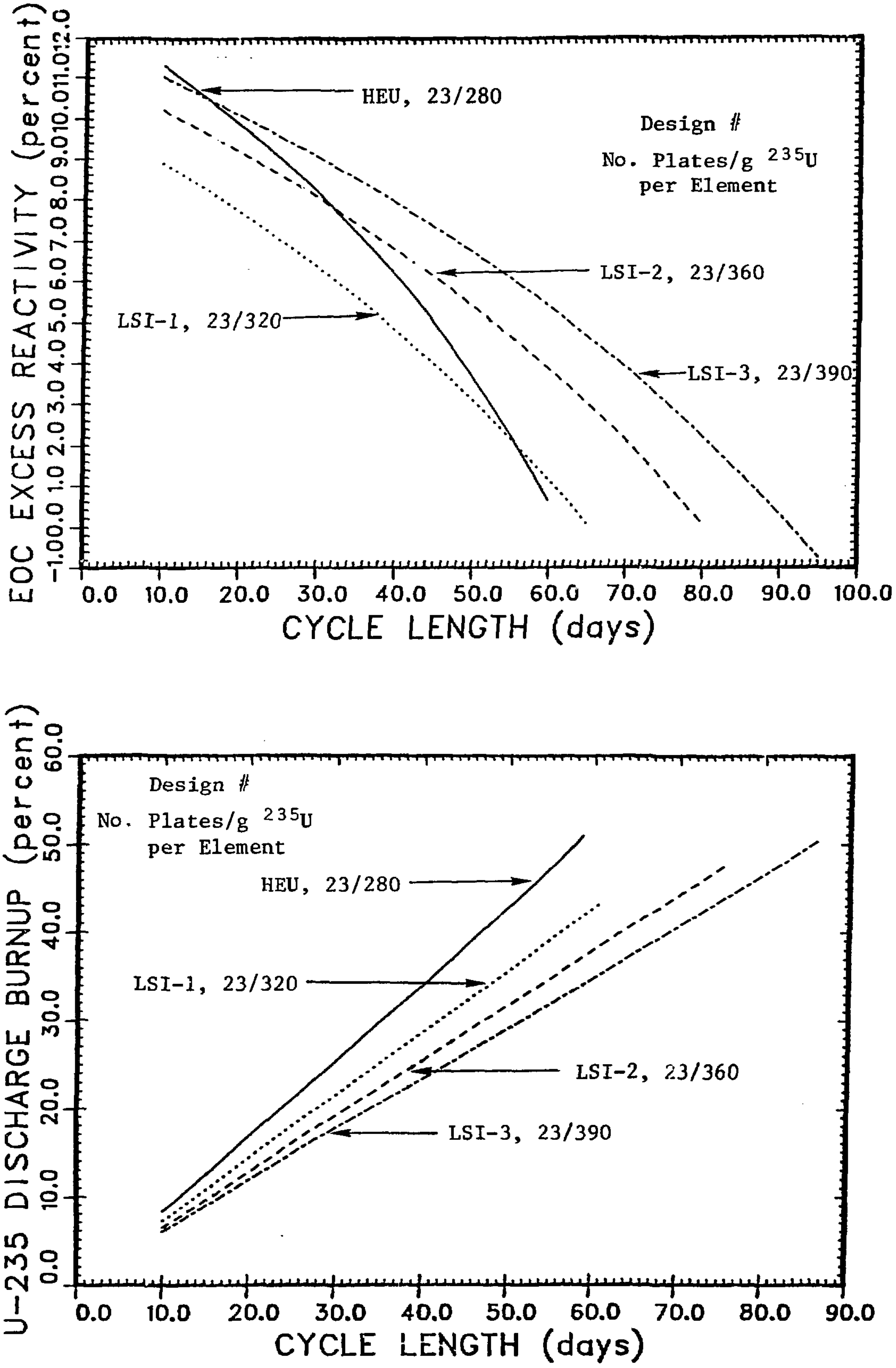

Fig. 3. EOC Excess Reactivity and Average ^{235}U Discharge Burnup in Standard Elements as Functions of Cycle Length for the HEU Reference Design and the LEU Oxide Fuel Element Designs with 16-22 Plates Containing 3.1 g U/cm^3, 0.76 mm Thick Fuel Meat.

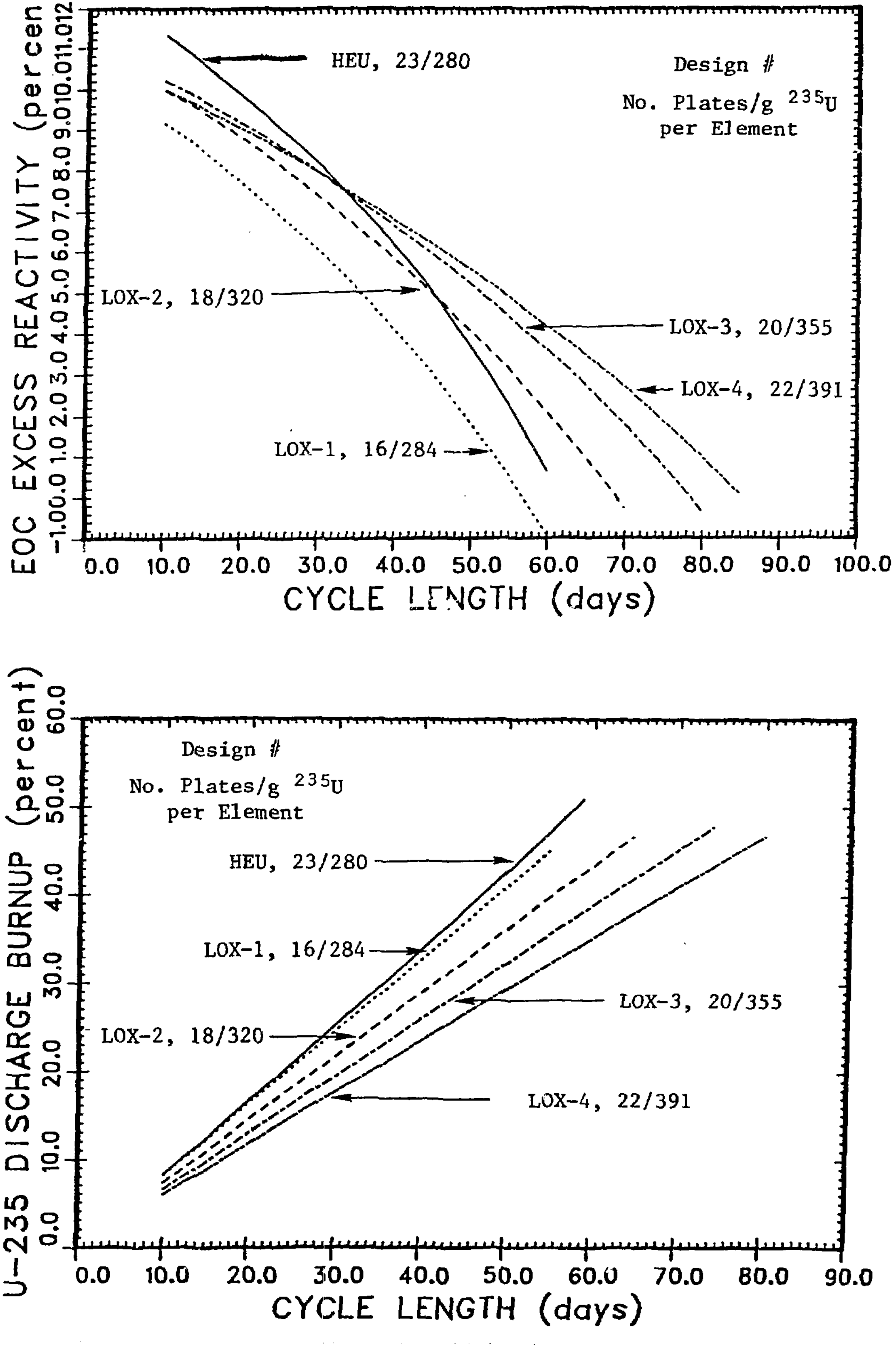

Fig. 4. EOC Excess Reactivity and Average ^{235}U Discharge Burnup in Standard Elements as Functions of Cycle Length for the HEU Reference Design and the LEU Oxide Fuel Element Designs Containing 20 Plates and 3.1 g U/cm^3 Fuel Meat with Thicknesses of 0.76, 0.88, and 1.0 mm.

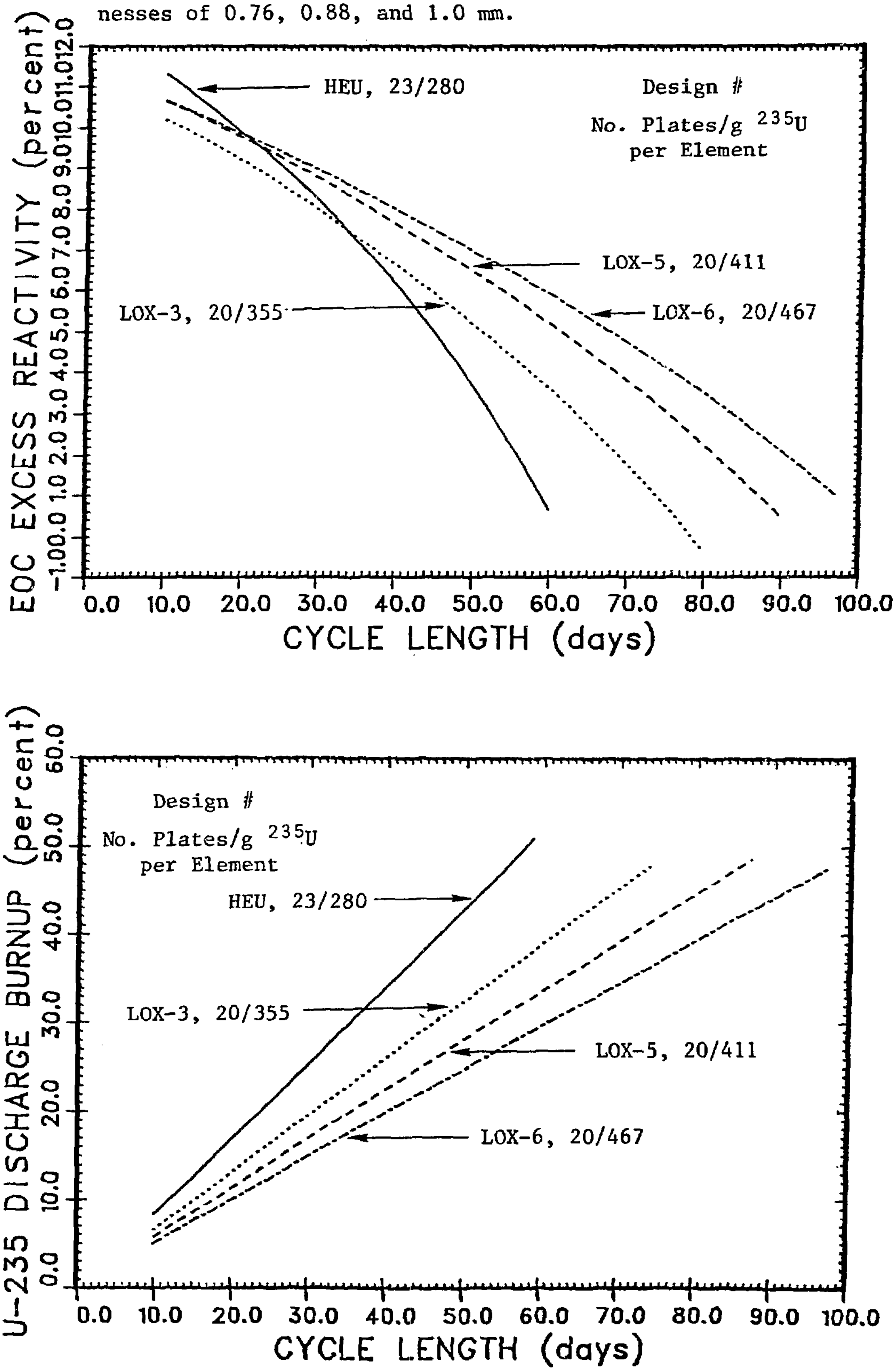

Table 2. Calculated Performance Results for Reference Design with HEU UAl_x Fuel and for Six Designs with LEU U_3O_8 Fuel as a Function of EOC Excess Reactivity.

Design No.	Fuel Type	g U/cm^3	Plates per Element Std./Cntl.	Fuel Meat Thick., mm	^{235}U per Element		EOC Excess React., % δk/k	Cycle Length, Days	^{235}U Discharge Burnup, %		No. of Elements per Year[a]		Spent Metal Mass per Element, kg		Average Thermal Flux Ratio in Central Flux Trap[b]	
					Std.	Cntl.			Std.	Cntl.	Std.	Cntl.	Std.	Cntl.	Peak	Avg.
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	1.0	58.7	51.0	56.5	28.6	6.2	5.0	4.7		
LOX-1	U_3O_8	3.13	16/10	0.76	284.1	177.6	1.0	53.0	43.6	50.6	31.7	6.9	5.3	4.6		
2	U_3O_8	3.13	18/12	0.76	319.7	213.1	1.0	64.6	46.8	53.5	26.0	5.7	5.8	5.1		
3	U_3O_8	3.13	20/14	0.76	355.2	248.6	1.0	73.9	47.9	54.0	22.7	4.9	6.2	5.6		
4	U_3O_8	3.13	22/16	0.76	390.7	284.2	1.0	80.0	46.9	52.2	21.0	4.6	6.7	6.0		
5	U_3O_8	3.13	20/14	0.88	411.3	287.9	1.0	87.1	48.7	54.6	19.3	4.2	6.7	5.9		
6	U_3O_8	3.13	20/14	1.00	467.3	327.1	1.0	96.9	47.6	53.3	17.3	3.8	7.2	6.3		
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	2.0	55.7	48.1	53.6	30.1	6.6	5.0	4.7	3.56	2.17
LOX-1	U_3O_8	3.13	16/10	0.76	284.1	177.6	2.0	49.2	40.4	47.2	34.1	7.4	5.3	4.6	0.96	0.95
2	U_3O_8	3.13	18/12	0.76	319.7	213.1	2.0	60.1	43.6	50.0	27.9	6.1	5.8	5.1	0.96	0.94
3	U_3O_8	3.13	20/14	0.76	355.2	248.6	2.0	68.7	44.6	50.4	24.4	5.3	6.2	5.6	0.96	0.94
4	U_3O_8	3.13	22/16	0.76	390.7	284.2	2.0	74.2	43.6	48.7	22.6	4.9	6.7	6.0	0.97	0.93
5	U_3O_8	3.13	20/14	0.88	411.3	287.9	2.0	81.5	45.6	51.3	20.6	4.5	6.7	5.9	0.96	0.92
6	U_3O_8	3.13	20/14	1.00	467.3	327.1	2.0	90.5	44.5	50.0	18.6	4.0	7.2	6.3	0.96	0.91
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	3.0	52.3	45.2	50.3	32.1	7.0	5.0	4.7		
LOX-1	U_3O_8	3.13	16/10	0.76	284.1	177.6	3.0	45.0	37.0	43.3	37.3	8.1	5.3	4.6		
2	U_3O_8	3.13	18/12	0.76	319.7	213.1	3.0	55.3	40.1	46.2	30.4	6.6	5.8	5.1		
3	U_3O_8	3.13	20/14	0.76	355.2	248.6	3.0	63.2	41.0	46.5	26.6	5.8	6.2	5.6		
4	U_3O_8	3.13	22/16	0.76	390.7	284.2	3.0	67.9	39.9	44.7	24.7	5.4	6.7	6.0		
5	U_3O_8	3.13	20/14	0.88	411.3	287.9	3.0	75.2	42.1	47.6	22.3	4.9	6.7	5.9		
6	U_3O_8	3.13	20/14	1.00	467.3	327.1	3.0	83.5	41.1	46.3	20.1	4.4	7.2	6.3		
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	4.0	48.6	41.9	46.8	34.6	7.5	5.0	4.7		
LOX-1	U_3O_8	3.13	16/10	0.76	284.1	177.6	4.0	40.5	33.3	39.1	41.5	9.0	5.3	4.6		
2	U_3O_8	3.13	18/12	0.76	319.7	213.1	4.0	50.2	36.4	42.1	33.5	7.3	5.8	5.1		
3	U_3O_8	3.13	20/14	0.76	355.2	248.6	4.0	57.3	37.2	42.3	29.3	6.4	6.2	5.6		
4	U_3O_8	3.13	22/16	0.76	390.7	284.2	4.0	61.1	35.9	40.4	27.5	6.0	6.7	6.0		
5	U_3O_8	3.13	20/14	0.88	411.3	287.9	4.0	68.5	38.4	43.5	24.5	5.3	6.7	5.9		
6	U_3O_8	3.13	20/14	1.00	467.3	327.1	4.0	75.9	37.4	42.3	22.1	4.8	7.2	6.3		

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[a] *For 100% duty factor.*

[b] Central flux trap filled with water only. Values for the HEU cases are the peak and the average thermal (<0.625 eV) flux in n/cm^2/s × 10^{14}. For the LEU cases, ratios of the LEU to HEU thermal fluxes are shown.

Table 3. Calculated Performance Results for Reference Design with HEU UAl_x Fuel and LEU U_3SiAl Fuel with Five Uranium Densities as a Function of EOC Excess Reactivity.

Design No.	Fuel Type	g U/cm^3	Plates per Element Std./Cntl.	Fuel Meat Thick., mm	^{235}U per Element		EOC Excess React., % δk/k	Cycle Length, Days	^{235}U Discharge Burnup, %		No. of Elements per Year[a]		Spent Metal Mass per Element, kg		Average Thermal Flux Ratio in Central Flux Trap[b]	
					Std.	Cntl.			Std.	Cntl.	Std.	Cntl.	Std.	Cntl.	Peak	Avg.
HEU	UAl_x	0.68	23/17		280.0	207.0	1.0	58.7	51.0	56.5	28.6	6.2	5.0	4.7	3.60	2.20
LSI-1	U_3SiAl	3.65	23/17	0.51	320.0	236.5	1.0	60.6	43.2	48.3	27.7	6.0	6.1	5.5	0.96	0.93
2	U_3SiAl	4.11	23/17	0.51	360.0	266.1	1.0	75.5	47.7	53.2	22.2	4.8	6.3	5.6	0.95	0.92
3	U_3SiAl	4.45	23/17	0.51	390.0	288.3	1.0	86.3	50.4	56.2	19.5	4.2	6.4	5.7	0.94	0.90
	U_3SiAl	3.60	23/17	0.51	315.0	232.8	1.0	58.6	42.4	47.5	28.7	6.2	6.1	5.5		
	U_3SiAl	3.77	23/17	0.51	330.0	243.9	1.0	64.4	44.4	49.8	26.1	5.7	6.2	5.5		
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	2.0	55.7	48.1	53.6	30.1	6.6	5.0	4.7	3.56	2.17
LSI-1	U_3SiAl	3.65	23/17	0.51	320.0	236.5	2.0	55.7	39.7	44.6	30.1	6.6	6.1	5.5	0.96	0.93
2	U_3SiAl	4.11	23/17	0.51	360.0	266.1	2.0	70.5	44.6	50.0	23.8	5.2	6.3	5.6	0.95	0.92
3	U_3SiAl	4.45	23/17	0.51	390.0	288.3	2.0	81.1	47.4	53.0	20.7	4.5	6.4	5.7	0.94	0.90
	U_3SiAl	3.60	23/17	0.51	315.0	232.8	2.0	53.8	39.0	43.8	31.2	6.8	6.1	5.5		
	U_3SiAl	3.77	23/17	0.51	330.0	243.9	2.0	59.6	41.2	46.3	28.2	6.1	6.2	5.5		
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	3.0	52.3	45.2	50.3	32.1	7.0	5.0	4.7	3.52	2.14
LSI-1	U_3SiAl	3.65	23/17	0.51	320.0	236.5	3.0	50.4	35.9	40.4	33.3	7.2	6.1	5.5	0.96	0.93
2	U_3SiAl	4.11	23/17	0.51	360.0	266.1	3.0	64.9	41.1	46.1	25.9	5.6	6.3	5.6	0.95	0.92
3	U_3SiAl	4.45	23/17	0.51	390.0	288.3	3.0	75.3	44.0	49.2	22.3	4.9	6.4	5.7	0.94	0.91
	U_3SiAl	3.60	23/17	0.51	315.0	232.8	3.0	48.6	35.2	39.6	34.6	7.5	6.1	5.5		
	U_3SiAl	3.77	23/17	0.51	330.0	243.9	3.0	54.0	37.3	41.9	31.1	6.8	6.2	5.5		
HEU	UAl_x	0.68	23/17	0.51	280.0	207.0	4.0	48.6	41.9	46.8	34.6	7.5	5.0	4.7	3.48	2.11
LSI-1	U_3SiAl	3.65	23/17	0.51	320.0	236.5	4.0	44.8	31.9	36.0	37.5	8.2	6.1	5.5	0.96	0.93
2	U_3SiAl	4.11	23/17	0.51	360.0	266.1	4.0	59.0	37.4	42.1	28.5	6.2	6.3	5.6	0.95	0.92
3	U_3SiAl	4.45	23/17	0.51	390.0	288.3	4.0	69.1	40.4	45.3	24.3	5.3	6.4	5.7	0.94	0.91
	U_3SiAl	3.60	23/17	0.51	315.0	232.8	4.0	43.0	31.1	35.2	39.1	8.5	6.1	5.5		
	U_3SiAl	3.77	23/17	0.51	330.0	243.9	4.0	48.3	33.4	37.6	34.8	7.6	6.2	5.5		

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[a] For 100% duty factor.

[b] Central flux trap filled with water only. Values for the HEU cases are the peak and the average thermal (<0.625 eV) flux in n/cm^2/s × 10^{14}. For the LEU cases, ratios of the LEU to HEU thermal fluxes are shown.

Fabrication Costs

The fabrication cost for a reference HEU standard element with 23 fuel plates was assumed to be $9,000, and that for a HEU control element with 17 fuel plates and 4 aluminum guideplates was assumed to be $8,100.

The fabrication costs for the LEU elements were obtained by using multiplicative cost factors that depend on (1) the fuel type and uranium density, and (2) the number of fuel plates per standard element. Values used for the first factor are based on data presented in Refs. 3 and 4. The second factor was incorporated since approximately 70-80% of fuel element fabrication costs are due to plate production and, in principle, an element with fewer plates should have a lower cost.

In addition, cost benefits in plate production could result if fuel fabricators were able to make production runs on a limited number of standard fuel plate designs that could then be assembled into custom elements for specific reactors. To assess the potential cost benefits of fuel plate standardization, an additional variable was introduced into the second factor. This variable was treated parametrically here since estimates of the potential reduction in plate production costs are not presently available.

Shipping Costs

The price for shipping UF_6 from the USA to the fuel fabricator was assumed to be $100-$500/kg U, and the price for shipping fresh elements from the fuel fabricator to the reactor was assumed to be $300-$500/element. The price for shipping spent fuel from the reactor to the USA was taken to be $1000-$3000/element.

These prices can vary considerably from country to country, from reactor to reactor, and from time to time depending on many variables. The high values were used in this analysis, and the low values were used to obtain a sensitivity estimate.

Reprocessing Costs and Uranium Credit

Reprocessing charges were assumed to be $1000/kg of total delivery weight for both the HEU aluminide fuel and the LEU oxide and silicide fuels. Uranium credits were computed in the same manner for all fuels.

Cost Results

The annual costs (in thousands of U.S. $) for each fuel cycle cost component are shown in Table 4 for the HEU aluminide and LEU oxide cases and in Table 5 for the HEU aluminide and LEU silicide cases. These costs are shown for a duty factor of 100%, but can be scaled directly to obtain values for any duty factor. Also shown are the costs in $/MWd and the cost ratios between the LEU and HEU cases.

Plotted in Fig. 5 are the ratios of the total fuel cycle costs with LEU oxide fuel (0.76 mm meat, 3.1 g U/cm^3) and with LEU silicide fuel to the corresponding cost with the reference HEU aluminide fuel as a function of the ^{235}U loading per standard element. (The oxide curve with 4% $\delta k/k$ dips below 1.0 at about 370 g ^{235}U per element. The dip is due to a spline function fit with four data points. The curve should be flat with a value of 1.0 in this loading range. See Table 4.) Some of the conclusions that can be drawn from Fig. 5 are:

- With oxide fuel, the costs are significantly lower than with silicide fuel for element ^{235}U loadings less than about 370 g. The main reasons for this are the higher fabrication costs anticipated with silicide fuel (Refs. 3 and 4) and the smaller number of plates per element with oxide fuel. In addition, for fewer than 19 oxide plates per element (~ 340 g ^{235}U), the element water volume fractions are higher than in the silicide design with 23 plates per element.

- With more than 20 oxide plates per element, the oxide cost ratio curves are relatively flat. The cost ratio curves with oxide and silicide fuels approached each other and cross for ^{235}U element loadings between 380 and 390 g for EOC excess reactivities between 1% and 4% $\delta k/k$.

- The element ^{235}U loading needed to match the total fuel cycle costs with HEU and LEU fuels increases with increasing EOC excess reactivity (ρ_{ex}). For 1% ρ_{ex}, the HEU costs are matched using oxide fuel elements with 320 g ^{235}U (18 plates) and using silicide fuel elements with about 360 g ^{235}U. For 4% ρ_{ex}, the corresponding ^{235}U element loadings are 360 g (20 plates) with oxide fuel and about 380 g with silicide fuel.

For the generic reactor with 23-plate HEU elements containing 280 g ^{235}U, fuel element designs using 18-20 plates with 0.76 mm-thick, 3.1 g U/cm^3, LEU oxide fuel meat would be recommended if this fuel is successfully demonstrated and if all safety criteria are satisfied. With LEU silicide fuel, the 23-plate fuel element with 360-390 g ^{235}U (4.1-4.5 g U/cm^3) would be recommended under the same conditions.

For the cases in Table 4 with 20 plates per element and 3.1 g U/cm^3 oxide fuel, increasing the fuel meat thickness from 0.76 mm to 0.88 mm and 1.0 mm leads to significant reductions in the total costs. The LEU/HEU cost ratios with 2% ρ_{ex}, for example, were 0.97, 0.87, and 0.82 with fuel meat thicknesses of 0.76 mm, 0.88 mm, and 1.0 mm, respectively. The calculations with 0.88 mm thick meat were done here only to define the trend of the costs.

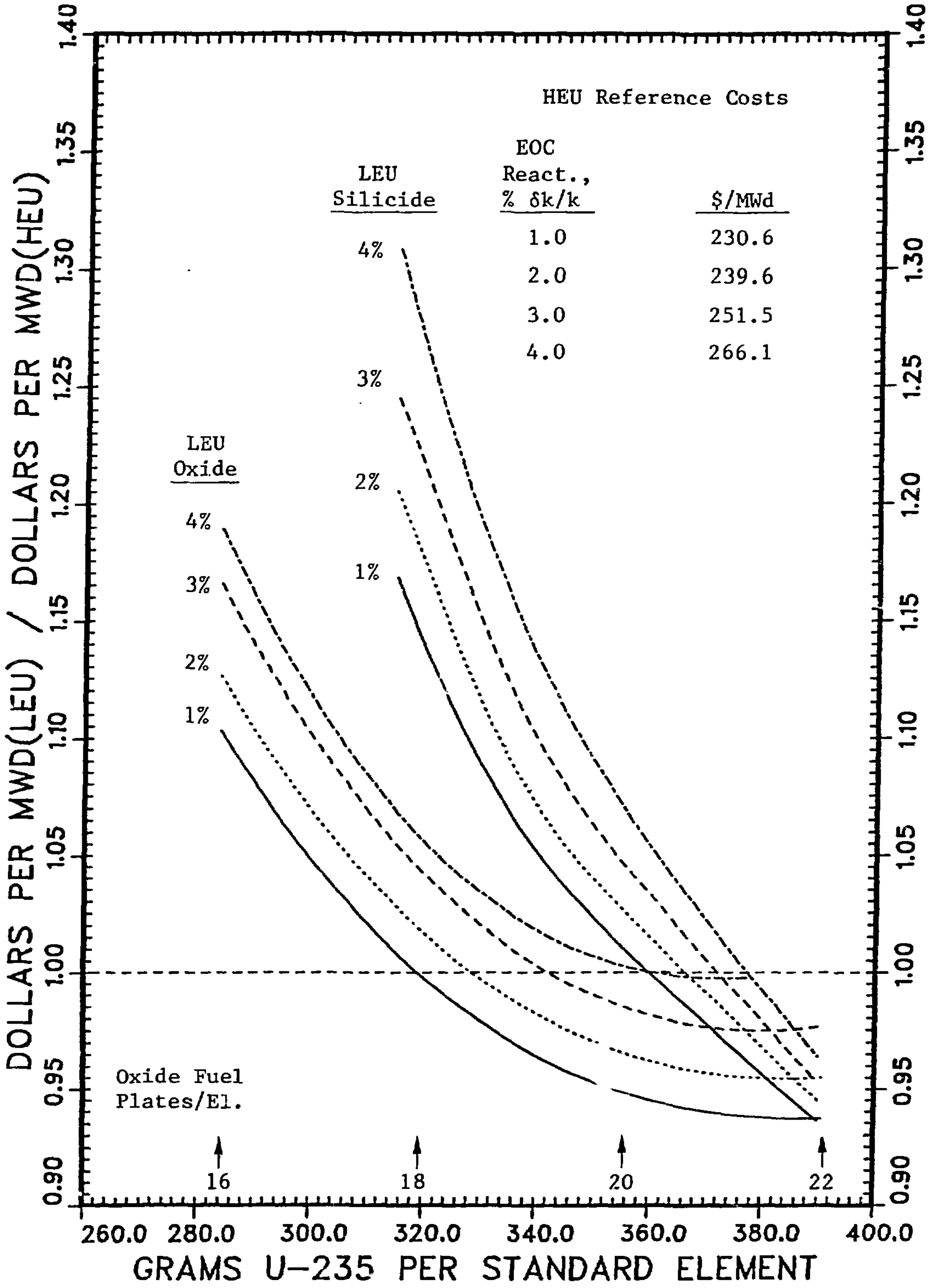
Table 4. Annual Fuel Cycle Costs (In Thousands of Dollars) for Reference Design with HEU UAl_x Fuel and for Six Designs with LEU U_3O_8 Fuel as a Function of EOC Excess Reactivity.

Design No.	Fuel Type	No. of Plates, ^{235}U per Element	g U/cm^3, Meat Thick.,mm	EOC Excess React., % δk/k	U Cost	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost	Uranium Credit	Total	MWd	$/MWd	$/MWd LEU/HEU
HEU	UAl_x	23/280	0.68/0.51	1.0	429.3	307.8	22.5	104.5	172.0	-194.3	841.8	3650	230.6	1.00
LOX-1	U_3O_8	16/284	3.13/0.76	1.0	435.3	342.0	45.8	115.7	199.7	-210.3	928.3	3650	254.3	1.10
2	U_3O_8	18/320	3.13/0.76	1.0	404.9	304.3	40.5	94.9	178.7	-182.4	841.0	3650	230.4	1.00
3	U_3O_8	20/355	3.13/0.76	1.0	395.8	286.7	38.0	83.0	169.2	-174.1	798.6	3650	218.8	0.95
4	U_3O_8	22/391	3.13/0.76	1.0	404.3	284.0	37.4	76.6	168.3	-182.2	788.5	3650	216.0	0.94
5	U_3O_8	20/411	3.13/0.88	1.0	388.9	243.3	35.4	70.4	153.4	-168.1	723.3	3650	198.2	0.86
6	U_3O_8	20/467	3.13/1.00	1.0	397.3	218.7	34.8	63.3	147.5	-176.3	685.3	3650	187.8	0.81
HEU	UAl_x	23/280	0.68/0.51	2.0	452.4	324.3	23.7	110.1	181.3	-217.2	874.5	3650	239.6	1.00
LOX-1	U_3O_8	16/284	3.13/0.76	2.0	469.0	368.5	49.4	124.6	215.2	-241.4	985.2	3650	269.9	1.13
2	U_3O_8	18/320	3.13/0.76	2.0	435.3	327.1	43.5	102.0	192.1	-210.3	889.7	3650	243.8	1.02
3	U_3O_8	20/355	3.13/0.76	2.0	425.8	308.4	40.8	89.3	182.0	-201.7	844.6	3650	231.4	0.97
4	U_3O_8	22/391	3.13/0.76	2.0	435.9	306.2	40.3	82.6	181.5	-211.2	835.5	3650	228.9	0.96
5	U_3O_8	20/411	3.13/0.88	2.0	415.6	260.0	37.9	75.2	163.9	-192.6	760.0	3650	208.2	0.87
6	U_3O_8	20/467	3.13/1.00	2.0	425.2	234.1	37.2	67.7	157.8	-201.9	720.1	3650	197.3	0.82
HEU	UAl_x	23/280	0.68/0.51	3.0	481.8	345.4	25.3	117.2	193.1	-244.8	918.1	3650	251.5	1.00
LOX-1	U_3O_8	16/284	3.13/0.76	3.0	512.6	402.8	54.0	136.3	235.2	-281.9	1058.9	3650	290.1	1.15
2	U_3O_8	18/320	3.13/0.76	3.0	473.0	355.4	47.3	110.9	208.8	-245.2	950.2	3650	260.3	1.04
3	U_3O_8	20/355	3.13/0.76	3.0	462.9	335.4	44.4	97.0	197.9	-235.9	901.8	3650	247.1	0.98
4	U_3O_8	22/391	3.13/0.76	3.0	476.4	334.7	44.1	90.3	198.4	-248.5	895.4	3650	245.3	0.98
5	U_3O_8	20/411	3.13/0.88	3.0	450.4	281.8	41.0	81.5	177.6	-224.7	807.7	3650	221.3	0.88
6	U_3O_8	20/467	3.13/1.00	3.0	461.0	253.8	40.3	73.4	171.1	-234.7	764.9	3650	209.6	0.83
HEU	UAl_x	23/280	0.68/0.51	4.0	518.6	371.8	27.2	126.2	207.8	-280.1	971.4	3650	266.1	1.00
LOX-1	U_3O_8	16/284	3.13/0.76	4.0	569.6	447.6	60.0	151.4	261.4	-334.8	1155.2	3650	316.5	1.19
2	U_3O_8	18/320	3.13/0.76	4.0	521.2	391.6	52.1	122.2	230.0	-289.8	1027.3	3650	281.4	1.06
3	U_3O_8	20/355	3.13/0.76	4.0	510.5	369.8	48.9	107.0	218.2	-279.9	974.5	3650	267.0	1.00
4	U_3O_8	22/391	3.13/0.76	4.0	529.3	371.8	49.0	100.3	220.4	-297.5	973.4	3650	266.7	1.00
5	U_3O_8	20/411	3.13/0.88	4.0	494.5	309.3	45.1	89.5	195.0	-265.3	868.1	3650	237.8	0.89
6	U_3O_8	20/467	3.13/1.00	4.0	507.1	279.2	44.4	80.8	188.2	-277.1	822.5	3650	225.3	0.85

Table 5. Annual Fuel Cycle Costs (In Thousands of Dollars) for Reference Design with HEU UAl_x Fuel and LEU U_3SiAl Fuel with Five Uranium Densities as a Function of EOC Excess Reactivity.

Design No.	Fuel Type	No. of Plates, ^{235}U per Element	g U/cm^3, Meat Thick., mm	EOC Excess React., % δk/k	U Cost	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost	Uranium Credit	Total	MWd	$/MWd	$/MWd LEU/HEU
HEU	UAl_x	23/280	0.68/0.51	1.0	429.3	307.8	22.5	104.5	172.0	-194.3	841.8	3650	230.6	1.00
LSI-1	U_3SiAl	23/320	3.65/0.51	1.0	438.1	387.6	43.6	101.2	202.3	-214.0	958.8	3650	262.7	1.14
2	U_3SiAl	23/360	4.11/0.51	1.0	395.6	335.0	37.6	81.2	166.8	-174.9	841.3	3650	230.5	1.00
3	U_3SiAl	23/390	4.45/0.51	1.0	375.0	314.1	34.7	71.1	148.9	-155.7	788.1	3650	215.9	0.94
	U_3SiAl	23/315	3.60/0.51	1.0	446.0	400.8	44.6	104.6	208.3	-221.2	983.1	3650	269.3	1.17
	U_3SiAl	23/330	3.77/0.51	1.0	425.1	364.7	41.8	95.2	191.6	-202.1	916.4	3650	251.1	1.09
HEU	UAl_x	23/280	0.68/0.51	2.0	452.4	324.3	23.7	110.1	181.3	-217.2	874.5	3650	239.6	1.00
LSI-1	U_3SiAl	23/320	3.65/0.51	2.0	476.6	421.6	47.4	110.1	220.0	-249.4	1026.3	3650	281.2	1.17
2	U_3SiAl	23/360	4.11/0.51	2.0	423.7	358.9	40.3	87.0	178.6	-200.6	888.0	3650	243.3	1.02
3	U_3SiAl	23/390	4.45/0.51	2.0	398.9	334.1	36.9	75.6	158.4	-177.7	826.2	3650	226.4	0.95
	U_3SiAl	23/315	3.60/0.51	2.0	485.7	436.6	48.6	114.0	226.8	-257.8	1053.9	3650	288.7	1.21
	U_3SiAl	23/330	3.77/0.51	2.0	459.3	394.0	45.1	102.9	207.0	-233.6	974.8	3650	267.1	1.12
HEU	UAl_x	23/280	0.68/0.51	3.0	481.8	345.4	25.3	117.2	193.1	-244.8	918.1	3650	251.5	1.00
LSI-1	U_3SiAl	23/320	3.65/0.51	3.0	526.7	466.0	52.4	121.6	243.2	-295.9	1114.0	3650	305.2	1.21
2	U_3SiAl	23/360	4.11/0.51	3.0	460.1	389.7	43.8	94.5	194.0	-234.3	947.8	3650	259.7	1.03
3	U_3SiAl	23/390	4.45/0.51	3.0	429.8	360.0	39.8	81.4	170.6	-206.2	875.4	3650	239.8	0.95
	U_3SiAl	23/315	3.60/0.51	3.0	537.8	483.3	53.8	126.2	251.1	-306.1	1146.1	3650	314.0	1.25
	U_3SiAl	23/330	3.77/0.51	3.0	507.0	434.9	49.8	113.5	228.5	-277.7	1056.1	3650	289.3	1.15
HEU	UAl_x	23/280	0.68/0.51	4.0	518.6	371.8	27.2	126.2	207.8	-280.1	971.4	3650	266.1	1.00
LSI-1	U_3SiAl	23/320	3.65/0.51	4.0	592.7	524.3	58.9	136.9	273.7	-357.0	1229.5	3650	336.9	1.27
2	U_3SiAl	23/360	4.11/0.51	4.0	506.3	428.8	48.2	103.9	213.5	-276.8	1023.9	3650	280.5	1.05
3	U_3SiAl	23/390	4.45/0.51	4.0	468.3	392.2	43.3	88.7	185.9	-241.8	936.6	3650	256.6	0.96
	U_3SiAl	23/315	3.60/0.51	4.0	607.8	546.3	60.8	142.6	283.9	-371.0	1270.4	3650	348.1	1.31
	U_3SiAl	23/330	3.77/0.51	4.0	566.8	486.3	55.7	127.0	255.5	-333.1	1158.2	3650	317.3	1.19

Fig. 5. Ratios of Total Fuel Cycle Costs (in $MWd) Between the LEU Oxide (0.76 mm Meat, 3.1 g U/cm^3) and Silicide Fuel Designs and the HEU Reference Design as a Function of Standard Element ^{235}U Loading for EOC Excess Reactivities of 1-4% δk/k. The Element Loading Was Varied by Increasing the Uranium Density in the Reference Design for the Cases with Silicide Fuel and by Increasing the Number per Element of a Fixed Standard Plate in the Cases with Oxide Fuel.



The oxide fuel element with 20 plates, 1.0 mm meat, and 3.1 g U/cm^3 has a ^{235}U loading of 467 g. For some reactors, this element may not be a viable option since the reactivity requirements for fresh and spent fuel transportation and storge may be exceeded. These issues must be examined on a case by case basis.

Cost Sensitivities

For these sensitivity studies, three fuel element designs with roughly the same total costs were compared for an EOC excess reactivity of 2% $\delta k/k$. Other choices are possible, but the conclusions would not be altered significantly. The cases chosen for this comparison are:

HEU:	Reference design with aluminide fuel, 23 plates, and 280 g ^{235}U per element.
LOX-3:	LEU design with 20 oxide plates (355 g ^{235}U) per element, 3.1 g U/cm^3, and 0.76 mm-thick fuel meat.
LSI-3:	Reference design with LEU silicide fuel, 23 plates, 4.5 g U/cm^3, and 390 g ^{235}U per element.

The reference cost data are contained in Tables 4 and 5, and any sensitivities can be readily computed.

In Table 6, the cost components for the three cases are broken down as percentages of the total fuel cycle costs in order to obtain a perspective on the various contributions. The enriched uranium costs have been combined with the uranium credit in these comparisons. For each element design, the contributions of each cost component to the total cost is approximately the same. On the average, these contributions are: 38% for fabrication costs, 27% for U costs plus U credit, 20% for reprocessing costs, and 15% for shipping costs.

The percentage increase in the total costs due to 30% increases in the individual cost components are shown in Table 7. On the average, these values are: 11.4% for fabrication costs, 8.0% for U costs plus U credit, 6.2% for reprocessing costs, and 4.4% for shipping costs.

In this analysis, the fabrication cost for a reference HEU standard element was assumed to be $9,000 and that for a reference control element was assumed to be $8,100. Table 8 shows the total costs and LEU/HEU cost ratios for three designs if these fabrication costs had been assumed to be $7,000 and $6,300, respectively, for the standard and control elements for the case with an EOC excess reactivity of 2% $\delta k/k$. The fuel cycle cost with the reference HEU design would have been lower by about 8.3%, and that for LOX-3 and LSI-3 would have been lower by 8.1% and 9.0%, respectively. Since the LEU/HEU cost ratios are very nearly the same, the cost ratio curves shown in Fig. 5 are nearly independent of a $9,000 or $7,000 assumption for the reference HEU element fabrication cost.

The costs for shipping UF$_6$, fresh elements, and spent elements were assumed to be $500/kg U, $500/element, and $3,000/element, respectively. If the corresponding costs had been assumed to be $100/kg U, $300/element, and $1,000/element, the total costs for the HEU reference case would have been lower by 9.7%. Similarly, the total costs for LOX-3 and LSI-3 would have been lower by 10.2% and 9.1%, respectively.

Table 6. Breakdown of Fuel Cycle Cost Components as Percentages of Total Costs for Three Designs With an EOC Excess Reactivity of 2% δk/k.

Element Design	No. Plates/ ^{235}U per Element	Total $/MWd	U Cost + U Credit	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost
HEU	23/280	239.6	26.9	37.1	2.7	12.6	20.7
LOX-3	20/355	231.4	26.5	36.5	4.8	10.6	21.6
LSI-3	23/390	226.4	26.8	40.4	4.5	9.1	19.2
Ave.			26.7	38.0	4.0	10.8	20.5

Table 7. Percentage Increase in Total Cost Due to 30% Increases in Individual Cost Components.

Element Design	No. Plates/ ^{235}U per Element	Total $/MWd	U Cost + U Credit	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost
HEU	23/280	30	8.1	11.1	0.8	3.8	6.2
LOX-3	20/355	30	8.0	10.9	1.4	3.2	6.5
LSI-3	23/390	30	8.0	12.1	1.3	2.8	5.8

Table 8. Fuel Cycle Costs in $/MWd and LEU/HEU Cost Ratios for Assumptions of $9,000 per Standard Element and $7,000 per Standard Element.

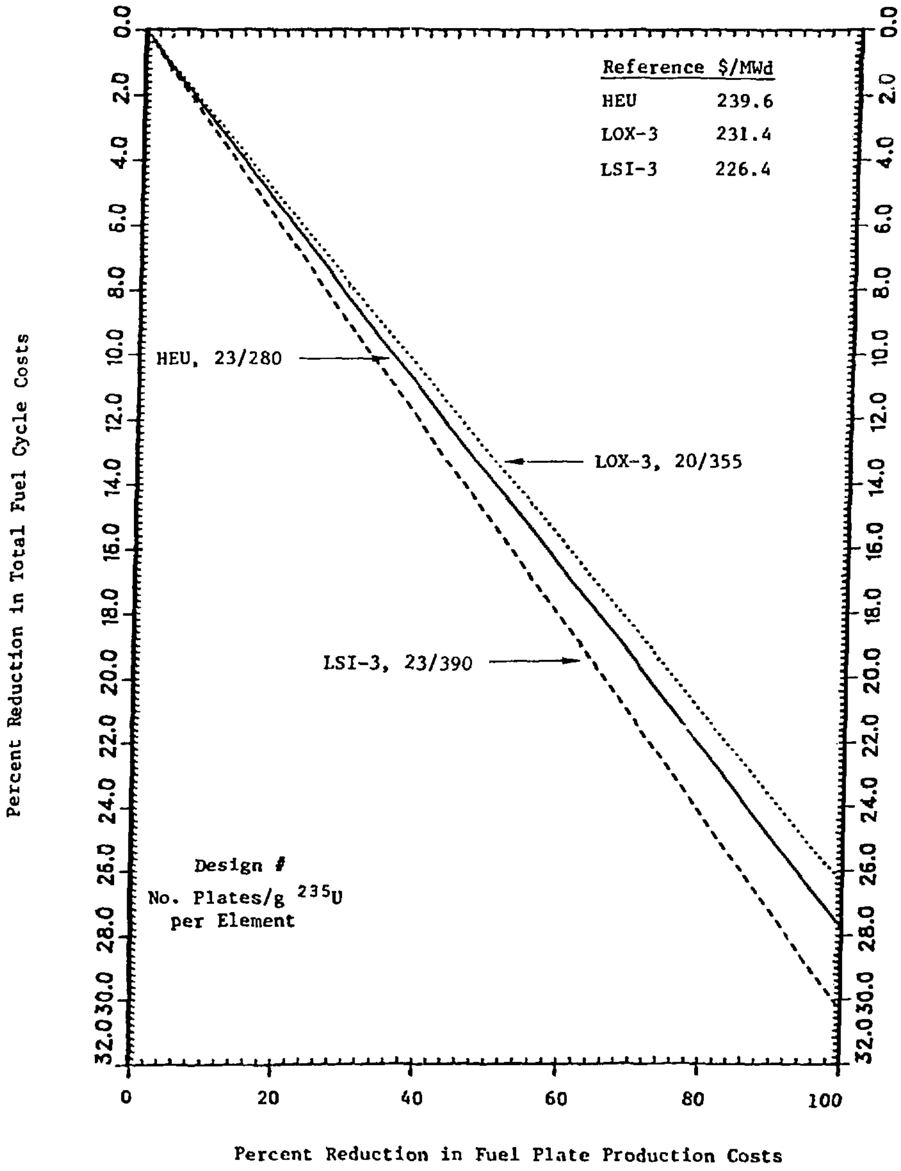
		$9,000/Std. Element		$7,000/Std. Element	
Element Design	No. Plates/ ^{235}U per Element	$/MWd	$/MWd LEU/HEU	$/MWd	$/MWd LEU/HEU
HEU	23/280	239.6	-	219.9	-
LOX-3	20/355	231.4	0.966	212.6	0.967
LSI-3	23/390	226.4	0.945	206.0	0.937

Standardization

Over the years, there has been much discussion among fuel fabricators and research reactor operators about standardization of MTR-type fuel elements designs in order to reduce fabrication costs. The probability for standardization of complete fuel elements is very small for a variety of reasons. A more realistic approach is to consider a reasonable number of standard fuel plate designs which could be utilized in manufacturing the custom elements that are in use today.

The potential cost benefits which could result from fuel plate standardization are shown in Fig. 6 for three fuel element designs. A reduction of about 35-40% in fuel plate production costs is needed to reduce the total fuel cycle costs by 10%. For a 10 MW reactor with a 70% duty factor, a 10% reduction in total fuel cycle costs implies a savings of about $60,000 per year. The maximum cost savings are in the range of 26-30%.

Fig. 6. Percent Reduction in Total Fuel Cycle Costs Versus Percent Reduction in Fuel Plate Production Costs Due To Standarization for Three Fuel Element Designs.



CONCLUSIONS

This analysis shows that there are a number of fuel element designs using LEU oxide or silicide fuels that have either the same or lower total fuel cycle costs than the HEU design. Use of these fuels with the uranium densities considered requires that they are successfully demonstrated and licensed. All safety criteria for the reactor with these fuel element designs need to be satisfied as well.

With LEU oxide fuel, 3.1 g U/cm^3, and 0.76 mm-thick fuel meat, elements with 18-22 plates (320-391 g ^{235}U) result in the same or lower total costs than with the HEU element (23 plates, 280 g ^{235}U). Higher LEU loadings (more plates per element) are needed for larger excess reactivity requirements. However, there is little cost advantage to using more than 20 of these plates per element. Increasing the fuel meat thickness from 0.76 mm to 1.0 mm with 3.1 g U/cm^3 in the design with 20 plates per element could result in significant cost reductions if the reactivity requirements for fuel transportation and storage are satisfied.

With LEU silicide fuel in the HEU element geometry, ^{235}U loadings between 360 and 390 g (4.1 - 4.5 g U/cm^3) result in the same or lower total costs than with HEU fuel.

In fuel element designs with HEU aluminide, LEU oxide, and LEU silicide fuels that have roughly the same total fuel cycle costs, the contributions of the individual cost components are approximately 38% for fabrication costs, 27% for U costs plus U credit, 20% for reprocessing costs, and 15% for shipping costs. Percentage changes in individual cost components scale the total costs according to these proportions. For example, a 30% increase in fabrication costs results in an 11.4% increase in total costs. The fabrication cost for an HEU standard element was assumed to be $9000 in this analysis. However, the LEU/HEU cost ratios are very nearly the same if a value of $7000 per element had been assumed.

A reduction of about 35 - 40% in plate production costs due to the standardization of fuel plate designs is needed in order to reduce the total fuel cycle costs by 10%. The maximum cost savings due to standardization are in the range of 26 - 30%.

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APPENDIX

FUEL CYCLE COST MODEL

1. ANNUAL ENRICHED URANIUM COSTS

- 93.15% Enriched Uranium: \$45,061.89/kg ^{235}U in UF_6^a
- 19.75% Enriched Uranium: \$41,534.05/kg ^{235}U in UF_6^a
- Uranium Losses During Conversion of UF_6 and Fuel Element Fabrication: 2.5%
- UF_6 Conversion Price is Included in the Factor, F_d, described below.

$$\text{Annual Uranium Costs} = 1.025\ C^5_{\varepsilon_o}\ (N_s\ M^5_s + N_c\ M^5_c)$$

$N_s(N_c)$ = Number of Standard (Control) Elements Used/Year

$M^5_s(M^5_c)$ = Mass of ^{235}U per Fresh Standard (Control) Element

$C^5_{\varepsilon_o}$ = Price for 1 kg ^{235}U in UF_6 (for U with enrichment ε_o)

[a] See Attachment 1 for detailed computation.

2. ANNUAL FUEL ELEMENT FABRICATION COSTS

- C_f: Fabrication Cost for Reference HEU Standard Element: \$9,000
  23 Fuel Plates, 0.51 mm Meat, 0.38 mm Clad
  UAl_x Fuel, 0.68 g U/cm^3, 280 g ^{235}U
- 0.9 x C_f: Fabrication Cost for Reference HEU Control Element: \$8,100
  17 Fuel Plates, 0.51 mm Meat, 0.38 mm Clad
  UAl_x Fuel, 0.68 g U/cm^3, 207 g ^{235}U
- F_d: Fabrication Cost Factor that Depends on Fuel Type and Uranium Density. Values Assumed Here Are 1.3 for 3.1 g U/cm^3 Oxide Fuel and 1.3, 1.4, and 1.5 for 3.7, 4.1, and 4.5 g U/cm^3 Silicide Fuel.
- F_p: Fabrication Cost Factor that Depends on the Number of Plates per Standard Fuel Element and on a Parameter, F_s, Related to Possible Standardization of Fuel Plate Designs

$$F_p = (1 - p) + p\ \ F_s\ N_p/N_{Ref}$$

p = Fraction of Fuel Element Fabrication Cost due to Plate Production. A Value of p = 0.75 Was Used in This Analysis.

F_s = Parameter Accounting for Possible Reduction in Plate Production Costs due to Standardization. A Value of $F_s = 1.0$ Was Used Here, and a Sensitivity Study Performed for Values Between 1.0 and 0.0

N_p = Number of Plates per LEU Standard Fuel Element

N_{Ref} = Number of Plates per Reference HEU Standard Fuel Element

Annual Fabrication Costs = $F_d \; F_p \; C_f \; (N_s + 0.9 \; N_c)$

3. ANNUAL FRESH FUEL SHIPPING COSTS

- Ship UF_6 from USA to Fuel Fabricator: \$100 - \$500/kg U[b]

Annual Cost = $1.025 \; \frac{\$500}{\varepsilon_o} \; (N_s \; M_s^5 + N_c \; M_c^5)$

- Ship Fresh Standard and Control Elements from Fuel Fabricator to Reactor: \$300 - \$500/Element[b]

Annual Cost = $\$500 \; (N_s + N_c)$

4. ANNUAL SPENT FUEL SHIPPING COSTS

- Ship Spent Fuel from Reactor to USA: \$1,000 - \$3,000/Element[b]

Annual Cost = $\$3,000 \; (N_s + N_c)$

5. ANNUAL REPROCESSING COSTS

- \$1000/kg Total Delivered Weight

Annual Cost = $\$1000 \; (N_s \; M_s^m + N_c \; M_c^m)$

M_s^m (M_c^m) = Total Delivered Weight of One Spent Standard (Control) Element

6. ANNUAL URANIUM CREDIT[c]

Dollar Value of the Spent Uranium (Computed for the Appropriate Enrichment) that Would be Processed for Use as Feed Material for Re-enrichment, Reduced by

- Uranium Losses During Reprocessing and Conversion to UF_6: 2.3%
- Price for Conversion of Uranyl Nitrate to UF_6: \$175/kg U
- Price for Shipment to Enrichment Plant: \$23/kg U

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[b] These prices can vary considerably from country to country, from reactor to reactor and from time to time depending on many factors. A reasonable range has been assumed here. The high value was used in this analysis.

[c] See Attachment 2 for detailed computation.

ATTACHMENT 1

COMPUTATION OF ENRICHED URANIUM PRICE

$$\text{Price/kg } U_{enr} = \left[\begin{pmatrix}\text{Quantity of} \\ U_{nat}\text{ Required}\end{pmatrix} (\text{Price of } U_{nat}) + \begin{pmatrix}\text{No. of SWU} \\ \text{Required}\end{pmatrix} (\text{Price/SWU})\right]$$

Quantity of U_{nat} Required

The mass of feed material (natural uranium concentrate) required to produce a given mass of product material (enriched uranium) can be obtained from a mass balance.

$$M_f = M_p + M_t$$

$$\varepsilon_f \, M_f = \varepsilon_p \, M_p + \varepsilon_t \, M_t$$

where

M = mass of the feed, product, or tails

ε = assay of the feed, product, or tails

Eliminating M_t from these equations,

$$M_f = \frac{\varepsilon_p - \varepsilon_t}{\varepsilon_f - \varepsilon_t} M_p$$

For example, 38.2583 kg of natural uranium feed would be required to produce 1 kg of uranium with an enrichment of 19.75% if the feed had an assay of 0.711% and the tails had an assay of 0.2%.

Price of U_{nat}

For the month of September 1982, the price of uranium concentrate on the spot market was \$16.50 - \$17.40/lb U_3O_8, and the price for conversion of U_3O_8 to UF_6 was \$2.90 - \$3.30/lb U.

Taking average values,

Uranium Price: \$16.95/lb U_3O_8 = \$44.07/kg U

Conversion Price: \$3.10/lb U = \$6.83/kg U

Total U_{nat} Price = \$50.90/kg U

Number of Separative Work Units (SWU) Required

The required SWU/kg U can be computed from the equation

$$\mathrm{SWU/kg\ U} = V(\varepsilon_p) - V(\varepsilon_t) + \frac{\varepsilon_p - \varepsilon_t}{\varepsilon_f - \varepsilon_t} [V(\varepsilon_t) - V(\varepsilon_f)]$$

where

$$V(\varepsilon) \equiv (1 - 2\ \varepsilon)\ \ln \frac{1 - \varepsilon}{\varepsilon}$$

ε = assay of feed, product, or tails.

For example, to produce 1 kg of uranium with an enrichment of 19.75% using feed with an assay of 0.711% and a tails assay of 0.2% would require 45.1182 SWU.

Price/SWU

As of August 1982, the DOE price for enrichment was $138.65/SWU.

Total Price for Enriched Uranium

Thus, the total price for 1 kg of uranium enriched to 19.75% would be

(38.2583) ($50.90) + (45.1182) ($138.65) = $8,202.99

and the price of 1 kg of ^{235}U contained in uranium with an enrichment of 19.75% would be $41,534.13. For convenience, enriched uranium prices for the month of September 1982 are tabulated in the attached table. Values in the table are different in the "cents" column from those that are computed by hand because of the number of digits carried by computers.

Enriched Uranium Prices

September 1982

Enrichment (%)	Kg Nat. U Required	Price for Nat. U	SWU	Price for Enrichment	Price for 1 kg U or ^{235}U Contained in UF6	
					ENR U	U-235
0.71	1.0000	50.90	0.0	0.0	50.90	7158.93
1.00	1.5656	79.69	0.3302	52.72	132.41	13240.59
2.00	3.5225	179.30	2.1941	304.21	483.51	24175.49
3.00	5.4794	278.90	4.3065	597.09	875.99	29199.83
4.00	7.4364	378.51	6.5437	907.28	1285.80	32144.92
5.00	9.3933	478.12	8.8509	1227.17	1705.29	34105.83
6.00	11.3503	577.73	11.2032	1553.32	2131.05	35517.48
7.00	13.3072	677.34	13.5873	1883.88	2561.22	36588.84
8.00	15.2642	776.95	15.9953	2217.75	2994.69	37433.66
9.00	17.2211	876.56	18.4219	2554.19	3430.74	38119.38
10.00	19.1781	976.16	20.8634	2892.71	3868.87	38688.74
11.00	21.1350	1075.77	23.3174	3232.95	4308.72	39170.24
12.00	23.0920	1175.38	25.7818	3574.65	4750.02	39583.52
13.00	25.0489	1274.99	28.2552	3917.59	5192.57	39942.89
14.00	27.0059	1374.60	30.7365	4261.61	5636.21	40258.64
15.00	28.9628	1474.21	33.2247	4606.60	6080.80	40538.72
16.00	30.9198	1573.82	35.7190	4952.44	6526.25	40789.06
17.00	32.8767	1673.42	38.2189	5299.04	6972.46	41014.48
18.00	34.8336	1773.03	40.7238	5646.35	7419.37	41218.75
19.00	36.7906	1872.64	43.2333	5994.29	7866.93	41404.88
19.75	38.2583	1947.35	45.1182	6255.64	8202.97	41534.05
20.00	38.7475	1972.25	45.7470	6342.82	8315.06	41575.32
25.00	48.5323	2470.29	58.3693	8092.91	10563.18	42252.76
30.00	58.3170	2968.33	71.0638	9852.99	12821.31	42737.72
35.00	68.1017	3466.38	83.8154	11621.00	15087.36	43106.76
40.00	77.8865	3964.42	96.6156	13395.74	17360.15	43400.39
45.00	87.6712	4462.46	109.4593	15176.54	19638.99	43642.21
50.00	97.4559	4960.50	122.3441	16963.00	21923.49	43847.00
55.00	107.2407	5458.55	135.2690	18755.04	24213.57	44024.68
60.00	117.0254	5956.59	148.2348	20552.75	26509.33	44182.23
65.00	126.8101	6454.63	161.2442	22356.51	28811.13	44324.83
70.00	136.5949	6952.68	174.3022	24167.00	31119.66	44456.66
75.00	146.3796	7450.72	187.4174	25985.43	33436.13	44581.52
80.00	156.1643	7948.76	200.6047	27813.84	35762.59	44703.25
85.00	165.9491	8446.80	213.8920	29656.12	38102.91	44826.95
90.00	175.7338	8944.85	227.3403	31520.73	40465.56	44961.74
93.00	181.6046	9243.67	235.5500	32659.00	41902.65	45056.61
93.15	181.8982	9258.61	235.9650	32716.54	41975.14	45061.89
93.30	182.1917	9273.55	236.3805	32774.16	42047.70	45067.21

Enriched Uranium Input Data

Assay of Uranium Feed : 0.711%
Assay of Tails : 0.2%
Price of Uranium Concentrate : \$16.95/lb U_3O_8
: \$44.07/kg U
Price of Conversion to UF_6 : \$3.10/lb U
: \$6.83/kg U
Price of Enrichment : \$138.65/SWU

ATTACHMENT 2

COMPUTATION OF URANIUM CREDIT

The uranium credit is the dollar value of the spent uranium (computed for the appropriate enrichment) that would be processed for use as feed material for re-enrichment, reduced by

- Uranium losses during reprocesssing and conversion to UF_6: 2.3%
- Price for conversion of uranyl nitrate to UF_6: \$175/kg U
- Price for shipment to enrichment plant: \$23/kg U

Credit for the contained plutonium has not been calculated here.

The enrichment (ε_B) of uranium with a ^{235}U burnup, B, is given by

$$\varepsilon_B = \frac{(1 - B)\ \varepsilon_o}{1 - \varepsilon_o B \left(1 - \frac{\alpha}{1 + \alpha}\right)} = \frac{(1 - B)\ \varepsilon_o}{1 - 0.84\ \varepsilon_o B}$$

where ε_o is the initial enrichment and α (= ~0.19) is the capture to fission ratio in ^{235}U.

Value of Contained ^{235}U, Reduced by Process Losses

The mass of ^{235}U (M_5') contained in the spent fuel elements is

$$M_5' = M_{5s}' + M_{5c}' = N_s\ (1-B_s)\ M_s^5 + N_c\ (1-B_c)\ M_c^5$$

where

$N_s (N_c)$ = Number of standard (control) elements

$M_s^5\ (M_c^5)$ = Mass of ^{235}U in one fresh standard (control) element

$M_{5s}' (M_{5c}')$ = Mass of ^{235}U in one spent standard (control) element

$B_s\ (B_c)$ = ^{235}U average burnup in standard (control) elements

Thus, the value of the contained ^{235}U, reduced by 2.3% losses during reprocessing and conversion of the uranyl nitrate to UF_6, is

$$0.977 \left[C^5_{\varepsilon_{Bs}}\ M_{5s}' + C^5_{\varepsilon_{Bc}}\ M_{5c}'\right]$$

where $C^5_{\varepsilon_B}$ is the dollar value of 1 kg ^{235}U contained in UF_6 with an enrichment ε_B, and is computed using the formulae and method described in Attachment 1, "Computation of Enriched Uranium Price."

Conversion and Shipping Charges

Assuming that the price for conversion of uranyl nitrate to UF_6 is $175/kg U and the price for shipment to the enrichment plant is $23/kg U, the conversion and shipping charges are given by

$$0.977\ (\$198) \left(\frac{M'_{5s}}{\varepsilon_{Bs}} + \frac{M'_{5c}}{\varepsilon_{Bc}} \right)$$

Uranium Credit

The uranium credit is thus

$$\text{U credit} = 0.977 \left[C^5_{\varepsilon_{Bs}} M'_{5s} + C^5_{\varepsilon_{Bc}} M'_{5c} - 198 \left(\frac{M'_{5s}}{\varepsilon_{Bs}} + \frac{M'_{5c}}{\varepsilon_{Bc}} \right) \right]$$