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A FUEL CYCLE COST STUDY WITH HEU AND LEU FUELS

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ABSTRACT

Fuel cycle costs are compared for a range of ^{235}U loadings with HEU and LEU fuels using the IAEA generic 10 MW reactor as an example. If LEU silicide fuels are successfully demonstrated and licensed, the results indicate that total fuel cycle costs can be about the same or lower than those with the HEU fuels that are currently used in most research reactors.

INTRODUCTION

Fuel cycle costs are a major concern to reactor operators who are planning to convert their cores from HEU to LEU fuel. This paper presents a consistent comparison of LEU/HEU total fuel cycle cost ratios as a function of the LEU/HEU fabrication cost ratio for several HEU and LEU fissile loadings and a range of cost input data using the IAEA generic 10 MW reactor[1] as an example.

Reactor performance data (cycle lengths and discharge burnups) for the various fuels and fissile loadings were obtained from 3D equilibrium core calculations in which an average of about two fresh elements were introduced per cycle. Analyses of the reactor safety parameters for both equilibrium and mixed cores are presented in Ref. 2 for an HEU fissile loading of 280 g and an LEU fissile loading of 390 g. A previous study (Ref. 3) of fuel cycle costs for this reactor was performed using an equilibrium core model in which 4 - 5 fresh elements were introduced per cycle.

FUEL ELEMENT DESIGNS

The fuel element designs, uranium densities, and fissile loadings that were studied with HEU aluminide fuel and LEU silicide fuels are shown in Table 1. 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.

Table 1. Fuel Element Designs Studied

Type	Plates per Element Std./Cntl.	Meat Thick., mm	Uranium Densities, g/cm^3	^{235}U per Std. El., g
HEU	23/17	0.51	0.44,0.68,0.85	180,280,350
LEU	23/17	0.51	2.86-6.05	250-530
LEU	20/14	0.76	3.0,4.5,6.0	340,511,681
LEU	20/14	1.00	3.0,4.5,6.0	448,672,896

REACTOR PERFORMANCE DATA

The calculated reactor performance data are shown in Table 2. For the lower fissile loadings, a reactor operator would normally increase the number of fresh elements charged per cycle, but all of these calculations were done with the same model so that the results would be consistent. Cycle lengths, the number of standard plus control elements that would be discharged per year with a duty factor of 100%, and the ^{235}U discharge burnup in the standard elements are plotted in Figs. 1 and 2 as a function of the ^{235}U per fresh standard element.

Table 2. Calculated Reactor Data with HEU Aluminide and and LEU Silicide Fuels. All Cases Have an EOC Excess Reactivity of 2.3% δk/k. 100% Duty Factor.

Design No.	Fuel Type	g U/cm^3	Plates per Element Std./Cntl.	Fuel Meat Thick., mm	235 per Element Std./Cntl.	Cycle Length, Days	^{235}U Discharge Burnup, % Std./Cntl.	No. of Elements per Year[a] Std./Cntl.	Spent Metal Mass per Element, kg Std./Cntl.
HEU-1	UAl_x	0.44	23/17	0.51	180/133	6.23	22.5/25.5	96.32/20.94	4.91/4.61
HEU-2	UAl_x	0.68	23/17	0.51	280/207	21.43	49.9/55.3	28.00/6.09	5.00/4.67
HEU-3	UAl_x	0.85	23/17	0.51	350/259	32.49	60.7/66.5	18.47/4.01	5.06/4.72
LSI-1	U_3Si_2	2.86	23/17	0.51	250/185	11.30	28.6/32.3	53.10/11.54	5.79/5.25
LSI-2	U_3Si_2	3.67	23/17	0.51	321/237	21.43	41.6/46.5	28.00/6.09	6.09/5.47
LSI-3	U_3Si_2	4.45	23/17	0.51	390/288	30.61	48.5/53.8	19.60/4.26	6.41/5.71
LSI-4	$U_3Si_{1.5}$	5.48	23/17	0.51	480/355	42.28	53.9/59.4	14.19/3.09	6.78/5.99
LSI-5	U_3Si	6.05	23/17	0.51	530/392	48.91	56.2/61.4	12.27/2.67	7.03/6.17
LSI-6	U_3Si_2	3.0	20/14	0.76	340/238	22.66	41.9/47.0	26.48/5.76	6.31/5.61
LSI-7*	U_3Si_2	4.5	20/14	0.76	511/358	43.57	52.5/57.5	13.77/2.99	7.03/6.11
LSI-8	U_3Si	6.0	20/14	0.76	681/477	64.48	57.7/63.6	9.31/2.02	7.75/6.61
LSI-9	U_3Si_2	3.0	20/14	1.00	448/314	30.74	43.0/48.0	19.52/4.24	7.23/6.31
LSI-10*	U_3Si_2	4.5	20/14	1.00	672/470	52.87	48.5/53.0	11.35/2.47	8.18/6.98
LSI-11	U_3Si	6.0	20/14	1.00	896/627	75.00	51.5/56.7	8.00/1.74	9.13/7.64

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*Obtained by interpolating between 3.0 and 6.0 g U/cm^3 data.

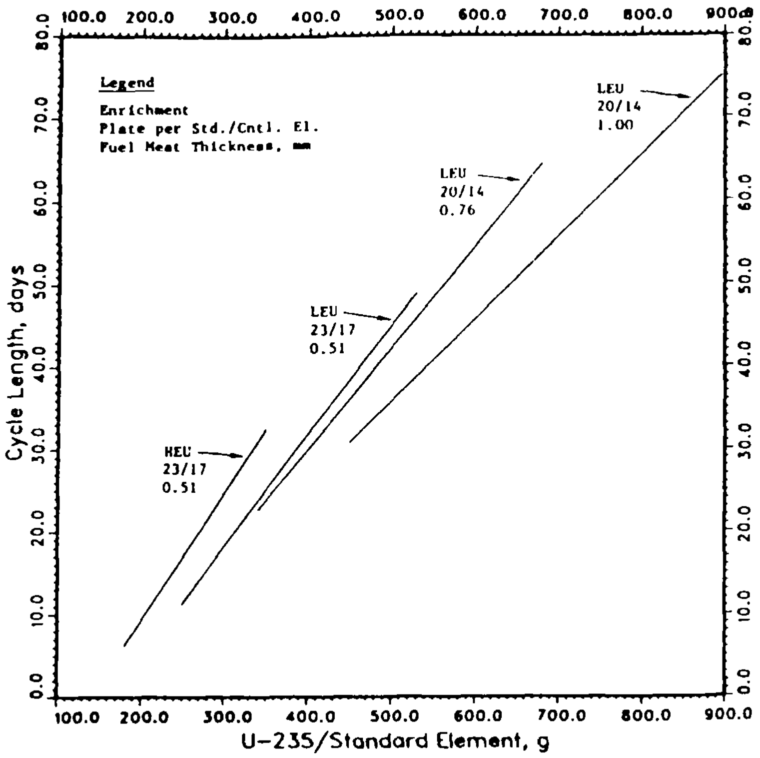

Fig. 1. Cycle Length as a Function of ^{235}U Loading per Standard Element for IAEA 10 MW Reactor with Two Elements Replaced per Cycle.

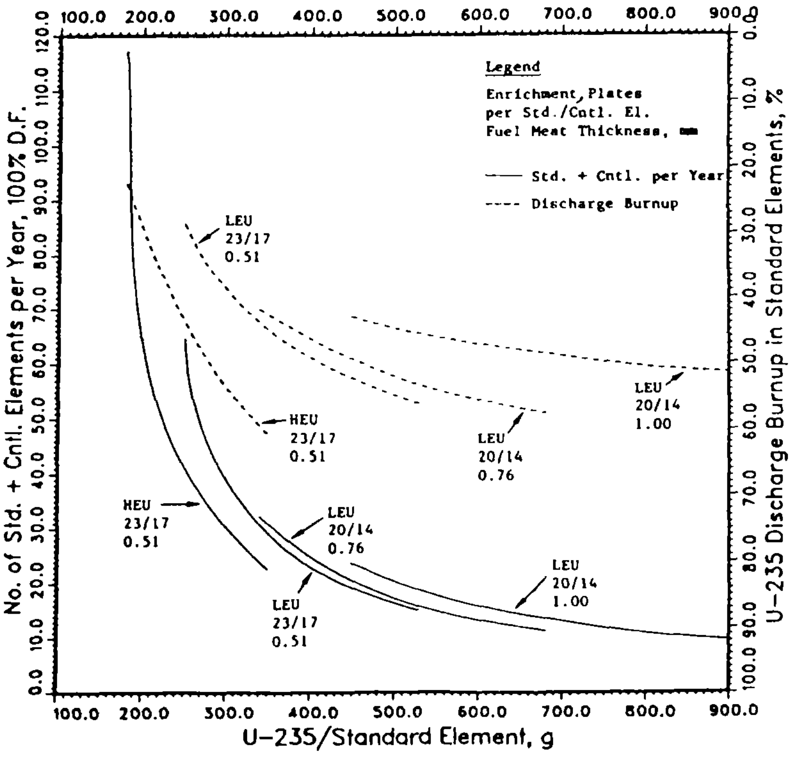

Fig. 2. Number of Standard Plus Control Elements Used per Year for a 100% Duty Factor and Discharge Burnup in the Standard Elements as a Function of the ^{235}U Loading per Fresh Standard Element.

FUEL CYCLE COST MODEL

The major cost variables in the fuel cycle are the prices for natural uranium, enrichment services, fuel fabrication, shipping, and reprocessing. Natural uranium prices are determined by the market for power reactors. The price for enrichment services is set by DOE and to some extent by the market conditions for SWUs. Reprocessing charges are set by DOE and shipping charges are about 10 - 15% of the total fuel cycle costs. The remaining major variable is the price for fuel fabrication, for which there are many nuances associated with each reactor. The range of cost input data that was assumed for this study is shown in Table 3.

In order to generalize the results, the fabrication cost component was isolated and parameterized as the LEU/HEU fabrication cost ratio. In effect, this parameterization combines all of the variables which determine fabrication costs. A few of these variables are the number of fuel elements ordered, fuel element specifications, inspection procedures, the type and volume percent of the dispersed phase, and currency exchange fluctuations.

The fuel cycle cost model is shown in detail in Ref. 3. The only differences with the model used in this study are:

(1) A cost component has been added to the annual enriched uranium costs to include charges for conversion of UF_6 to U metal and for filling and rental of the UF_6 cylinders. For some reactors, these charges are included in the fabrication price. For others, they are separate charges. The model used here assumes separate charges for these services.

(2) The fabrication cost factor in Ref. 3 that depends on fuel type and uranium density has been parameterized here. No credit is taken if the LEU element has fewer plates than the HEU element and no credit is taken for possible cost reductions due to standardization of fuel plate designs.

Table 3. Assumed Price Range for Fuel Cycle Cost Study.

Product or Service	Low - High Price	
Uranium		
Natural U_3O_8	17 - 25	\$/lb U_3O_8
Conversion of UF_6 to U Metal	6	\$/lb U
Enrichment	153	\$/SWU
Filling and Rental of UF_6 Cylinders	200	\$/kg U
Conversion of UF_6 to U Metal	400 - 1100	\$/kg U
Fabrication		
HEU Standard Element	7000 - 9000	\$/Element
HEU Control Element	6300 - 8100	\$/Element

Product or Service		Low - High Price	
Shipping			
Ship UF_6	HEU	500 - 900	\$/kg U
	LEU	300 - 500	\$/kg U
Ship Fresh Elements	HEU	300 - 600	\$/Element
	LEU	150 - 300	\$/Element
Ship Spent Elements		2000 - 4000	\$/Element
Reprocessing			
Assumed Charge for HEU and LEU Fuels		1100	\$/kg Metal
Uranium Credits			
Uranium credits for HEU fuel and assumed uranium credits for LEU fuel were computed in the same manner (See Ref. 3, p. 541).			

COST PARAMETERIZATION

Annual fuel cycle cost results for a 100% duty factor are shown in Table 4 using the low and the high price input data (Table 3) for each of the HEU and LEU fuel element designs that were studied. It is emphasized that the annual fabrication costs shown in Table 4 were computed with the assumption that all of the HEU and LEU elements have the same fabrication cost per element. This was done as a convenience in isolating and parameterizing the fabrication cost component.

The total minus fabrication cost and the fabrication cost data for the eleven LEU designs in Table 4 were parameterized with the straight line

$$R = a + b\,x$$

R = LEU/HEU Total Fuel Cycle Cost Ratio

x = LEU/HEU Fabrication Cost Ratio,

relative to the total fuel cycle cost for each of the HEU designs with fissile loadings of 180, 280, and 350 g as separate reference cases.

For example, using the low price input data and the HEU case with 280 g ^{235}U (HEU-2) as a reference, the coefficients a and b for the LEU case with 390 g ^{235}U (LSI-3) were computed as

$$R_{390} = \frac{(\text{Total Minus Fabr. Cost})_{390}}{(\text{Total})_{280}} + \frac{(\text{Fabr. Cost})_{390}}{(\text{Total})_{280}}\,x$$

$$R_{390} = \frac{493.6}{759.4} + \frac{164.0}{759.4}\,x = 0.650 + 0.216\,x$$

Using the high price input data for this example, the coefficients a and b were computed to be 0.647 and 0.225, respectively.

Since the coefficients obtained using the low price input data and the high price input data are nearly the same, this parameterization is not sensitive to the input price assumptions as long as these prices are in a reasonable range and as long as the HEU and LEU fuel cycle costs are computed in a consistent manner. The coefficients a and b are also independent of the reactor power level and duty factor.

The same conclusion with different sets of coefficients is obtained for all of the LEU designs when the HEU reference element contains 180, 280, or 350 g ^{235}U.

Table 4. Annual Fuel Cycle Costs (In Thousands of Dollars) with HEU Aluminide Fuel and LEU Silicide Fuels for a Duty Factor of 100%. IT IS EMPHASIZED THAT FABRICATION COSTS PER ELEMENT FOR THE HEU AND LEU FUELS ARE EQUAL IN THIS TABLE. FABRICATION COSTS ARE PARAMETERIZED (SEE TEXT).

Design No.	Fuel Type	No. of Plates ^{235}U per Element	g U/cm^3, Meat Thick., mm	U Cost	UF$_6$ Conv. Cost	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost	Uranium Credit	Total	Total Minus Fabr. Cost
					Low Price Input Data (Table 3)							
HEU-1	UAl_x	23/180	0.44/0.51	1030.6	13.3	806.2	46.3	234.5	626.4	-751.5	2005.8	-
2	UAl_x	23/280	0.68/0.51	466.1	6.0	234.4	15.2	68.2	185.3	-215.8	759.4	-
3	UAl_x	23/350	0.85/0.51	384.2	5.0	154.6	10.9	45.0	123.6	-138.3	584.9	-
LSI-1	U_3Si_2	23/250	2.86/0.51	727.6	48.0	444.4	33.7	129.3	404.8	-464.7	1323.1	878.7
2	U_3Si_2	23/321	3.67/0.51	492.9	32.5	234.4	21.4	68.2	224.2	-249.5	824.1	589.7
3	U_3Si_2	23/390	4.45/0.51	419.0	27.6	164.0	17.4	47.7	165.0	-183.1	657.6	493.6
4	$U_3Si_{1.5}$	23/480	5.48/0.51	373.4	24.6	118.8	14.9	34.6	126.2	-143.0	549.5	430.7
5	U_3Si	23/530	6.05/0.51	356.5	23.5	102.7	14.0	29.9	113.0	-128.6	511.0	408.3
6	U_3Si_2	20/340	3.00/0.76	490.6	32.3	221.6	21.0	64.5	219.3	-247.2	802.2	580.6
7	U_3Si_2	20/511	4.50/0.76	382.6	25.2	115.5	15.1	33.5	126.6	-152.2	546.0	430.8
8	U_3Si	20/681	6.00/0.76	344.8	22.7	77.9	13.1	22.7	94.1	-119.0	456.2	378.3
9	U_3Si_2	20/448	3.00/1.00	475.7	31.4	163.4	19.2	47.5	184.7	-234.2	687.7	524.3
10	U_3Si_2	20/672	4.50/1.00	415.0	27.4	95.0	15.8	27.6	121.1	-181.9	519.9	424.9
11	U_3Si	20/896	6.00/1.00	390.0	25.7	67.0	14.3	19.5	95.0	-159.1	452.3	385.3
					High Price Input Data (Table 3)							
HEU-1	UAl_x	23/180	0.44/0.51	1114.4	28.8	1036.5	90.3	469.0	626.4	-813.3	2552.4	-
2	UAl_x	23/280	0.68/0.51	503.9	13.0	301.3	29.5	136.4	185.3	-233.6	935.9	-
3	UAl_x	23/350	0.85/0.51	415.4	10.7	198.7	20.9	89.9	123.6	-149.8	709.6	-
LSI-1	U_3Si_2	23/250	2.86/0.51	791.3	104.0	571.4	59.4	258.6	404.8	-507.6	1681.8	1110.4
2	U_3Si_2	23/321	3.67/0.51	536.1	70.4	301.3	37.3	136.4	224.2	-273.0	1032.7	731.4
3	U_3Si_2	23/390	4.45/0.51	455.6	59.9	210.9	30.2	95.4	165.0	-200.7	816.3	605.4
4	$U_3Si_{1.5}$	23/480	5.48/0.51	406.1	53.4	152.7	25.7	69.1	126.2	-157.0	676.2	523.5
5	U_3Si	23/530	6.05/0.51	387.7	50.9	132.1	24.1	59.8	113.0	-141.2	626.3	494.2
6	U_3Si_2	20/340	3.00/0.76	533.5	70.1	285.0	36.6	129.0	219.3	-270.5	1002.9	717.9
7	U_3Si_2	20/511	4.50/0.76	416.0	54.7	148.1	26.0	67.0	126.6	-167.0	671.5	523.4
8	U_3Si	20/681	6.00/0.76	375.0	49.3	100.2	22.3	45.3	94.1	-130.8	555.3	455.1
9	U_3Si_2	20/448	3.00/1.00	517.3	68.0	210.0	33.3	95.0	184.7	-256.4	851.9	641.9
10	U_3Si_2	20/672	4.50/1.00	451.3	59.3	122.2	26.9	55.3	121.1	-199.4	636.7	514.5
11	U_3Si	20/896	6.00/1.00	424.1	55.7	86.1	24.4	39.0	95.0	-174.5	549.7	463.6

COST RESULTS

The results of this study are shown in Fig. 3 as plots of the LEU/HEU fuel cycle cost ratio (R) as a function of the LEU/HEU fabrication cost ratio (x) for cases in which the HEU reference element had a fissile loading of 180, 280, or 350 g.

HEU Reference Element with 180 g ^{235}U (Fig. 3b)

If this reactor had an HEU fissile loading of 180 g per standard element, the reactor operator would have an opportunity to make large reductions in his fuel cycle costs without any changes in the fuel element geometry if LEU silicide fuels are successfully demonstrated and licensed.

With an LEU element containing 250 g ^{235}U and a uranium density of 2.9 g/cm^3, the fuel cycle costs would be less than those with HEU fuel if the fabrication cost for an LEU element were less than 2.5 times that of an HEU element.

If the LEU fissile loading were increased to 321 g with a uranium density of 3.7 g/cm^3, the LEU fuel cycle cost would be 50% of the HEU fuel cycle cost if the fabrication cost of the LEU element were about 1.75 times that of the HEU element. If the uranium density were increased beyond 3.7 g/cm^3, the fuel cycle cost reduction could be even larger.

HEU Reference Element with 280 g ^{235}U (Fig. 3a)

With an HEU reference element containing 280 g ^{235}U, there are also opportunities for fuel cycle cost reductions both with and without changes in the fuel element geometry if LEU silicide fuels are successfully demonstrated and licensed.

Cycle lengths for the HEU and LEU cores are equal for the same element geometry with an LEU fissile loading of 321 g and a uranium density of 3.7 g/cm^3. However, even in the unlikely event that the HEU and LEU elements had the same fabrication cost, the total fuel cycle cost for the LEU core would be larger by about 10%. This is mainly due to the increased charges (see Table 4) required for converting UF_6 to U metal and reprocessing the larger mass of metal in the LEU element. Differences in enriched uranium costs, uranium credits, and fresh fuel shipping costs approximately cancel each other.

An LEU core containing 390 g ^{235}U per standard element with the HEU element geometry can have lower fuel cycle costs than the HEU core if the LEU/HEU fabrication cost ratio is less than about 1.6. If the fabrication costs of the LEU element were larger by a factor of 2.3, the total LEU fuel cycle costs would be larger by about 15%.

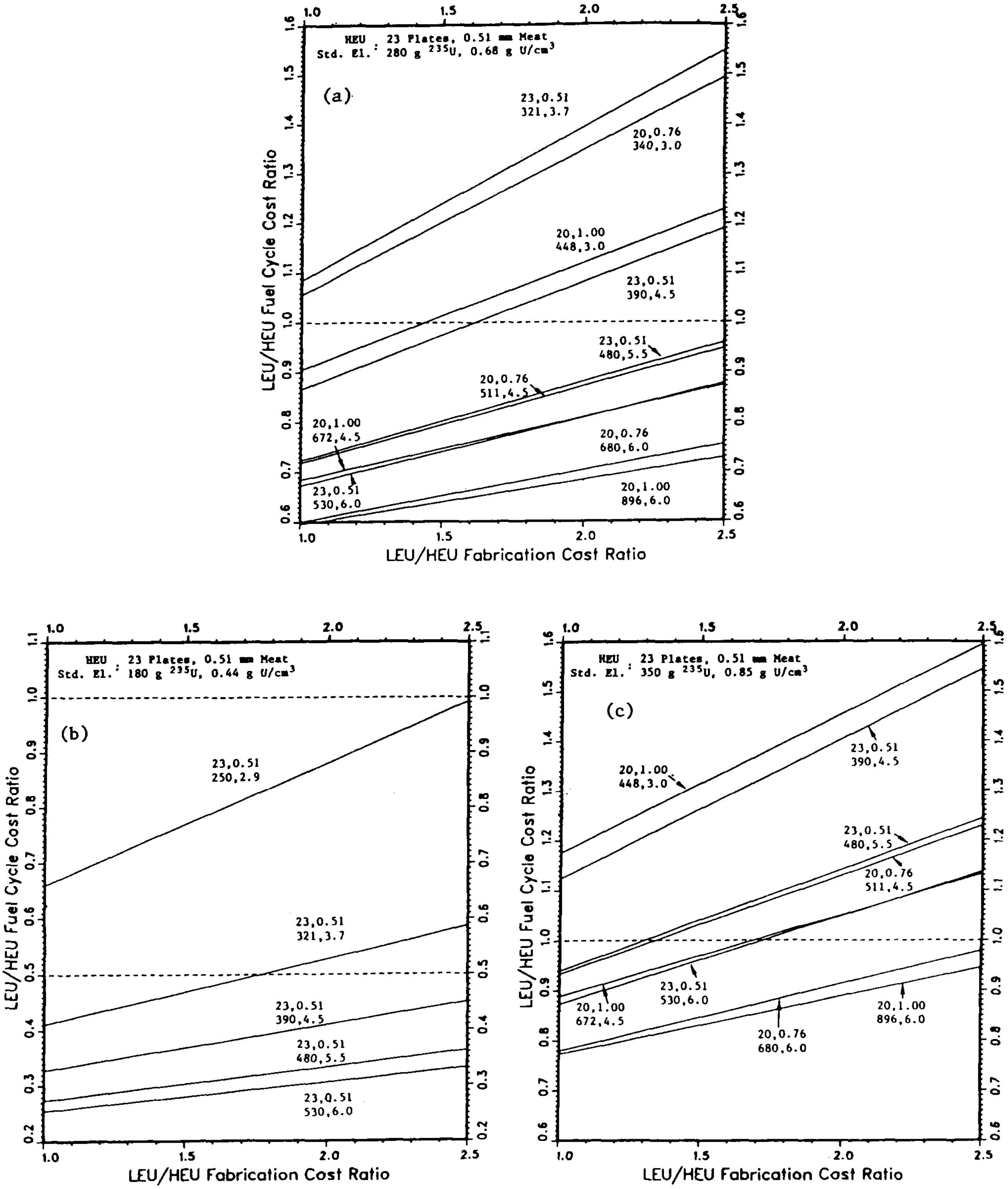

Fig. 3. LEU/HEU Total Fuel Cycle Cost Ratio as a Function of LEU/HEU Fabrication Cost Ratio for HEU Reference Elements with ^{235}U Loadings of 180, 280, and 350 g.

With LEU densities of 5.5 and 6.0 g/cm^3 in the HEU element geometry, the fuel cycle costs with LEU fuel could be significantly lower than with HEU fuel.

For reactors which are not operating at their thermal-hydraulic safety limits, it may be prudent to change the fuel element geometry during conversion to LEU fuel. The reason is that elements with fewer plates and thicker fuel meat will require lower uranium densities and hence lower volume fractions of the dispersed phase to obtain the same fissile content. For convenience, the relationship between the uranium density in the fuel meat and the volume fraction of the dispersed phase for UAl_x, U_3Si_2, $U_3Si_{1.5}$, and U_3Si fuels is shown below.

The general relationship is $\rho_U = a\,V_f^D$, where V_f^D is the volume fraction of the dispersed phase.

Fuel Type	a	ρ_U for $V_f^D = 0.4$
UAl_x	4.6	1.8
U_3Si_2	11.2	4.5
$U_3Si_{1.5}$	12.9	5.2
U_3Si	14.7	5.9

There are many variables that determine fabrication costs. Two of them are the volume fraction of the dispersed phase and the relative efficiency of producing the various powders. The commercial vendors indicate that reasonable production-scale fuel plate fabrication yields can be achieved with about 40 vol% of the dispersed phase. Since there is little experience in silicide powder production on a commercial scale at this time, the relative efficiency of producing the different powders can only be estimated.

In Fig. 3a, there are a number of cost lines for different LEU element designs that are in the same proximity. This does not necessarily mean that the two designs are cost equivalents. It is reasonable to expect that elements with fewer plates and lower uranium densities should be more economical to fabricate if they use the same type of powder.

The preceding discussion should not be interpreted as favoring designs with 1.0 mm-thick fuel meat. On the contrary, the designs with 0.76 mm-thick fuel meat are favored because there are some safety advantages with a thicker water channel.

In the design in Fig. 3a with 20 plates, 1.0 mm meat, 448 g ^{235}U and 3.0 g U/cm^3, the same fissile content would be obtained with 0.76 mm meat and 4.0 g/cm^3. For these uranium densities, there may be little difference in the plate fabrication yields with silicide fuels. For the two designs with 20 plates and 4.5 g U/cm^3, there are not significant differences in their relative costs. In the two corresponding cases with 6.0 g U/cm^3, a point of diminishing returns has been reached because the design with 1.0 mm-thick fuel meat has a very high fissile content and a hard neutron spectrum. The larger water volume fraction in the design with 0.76 mm-thick meat is equivalent to about 216 g ^{235}U from a fuel cycle cost point of view.

HEU Reference Element with 350 g ^{235}U (Fig. 3c)

For an HEU reference element containing 350 g ^{235}U, there is still an opportunity to reduce fuel cycle costs if LEU silicide fuel with high uranium densities is successfully demonstrated and licensed. However, there are fewer fuel element design choices and the potential savings are not as large.

With no changes in the 23-plate geometry and a uranium density of 6.0 g/cm^3, the LEU core would have lower total fuel cycle costs than the HEU core if the LEU/HEU fabrication cost ratio were less than about 1.7. If the reactor thermal-hydraulic conditions were to allow a change in the fuel element geometry, an LEU design with 20 plates, 0.76 mm-thick fuel meat, and 5.5-6.0 g U/cm^3 could provide fuel cycle costs that are significantly lower than those with HEU fuel. As mentioned previously, a design with 1.0 mm-thick meat, 6.0 g U/cm^3, and 20 plates offers very little cost advantage.

SUMMARY AND CONCLUSIONS

The major cost variables in the fuel cycle are the prices for natural uranium, enrichment services, fuel fabrication, shipping, and reprocessing. Natural uranium prices are determined by the market for power reactors. The price for enrichment services is set by DOE and to some extent by the market conditions for SWUs. Reprocessing charges are set by DOE and shipping charges are about 10 - 15% of the total fuel cycle costs. The remaining major variable is the price for fuel fabrication, for which there are many nuances associated with each reactor.

Reactor performance parameters that are essential for a cost analysis were computed for the IAEA generic 10 MW reactor using reference HEU fuel elements with fissle loadings of 180, 280, and 350 g and for eleven LEU fuel element design options with three geometries, silicide fuel, and a variety of fissile loadings. All of the reactor performance and cost conclusions are contingent upon the successful demonstration and licensing of LEU silicide fuels.

In order to generalize the results of this study, the fabrication cost component was isolated and parameterized as the LEU/HEU fabrication cost ratio. In effect, this parameterization combines all of the variables which determine fabrication costs. A few of these variables are the number of fuel elements ordered, fuel element specifications, inspection procedures, the type and volume percent of the dispersed phase, and currency exchange fluctuations.

The coefficients of straight lines describing the LEU/HEU total fuel cycle cost ratio as a function of the LEU/HEU fabrication cost ratio were shown to be nearly independent of the input price assumptions as long as these prices are in a reasonable range as long as the HEU and LEU fuel cycle costs are computed in a consistent manner. These coefficients are also independent of the reactor power level and duty factor.

If the reactor studied had an HEU fissile loading of 180 g per standard element, the reactor operator would have an opportunity to make large reductions in his fuel cycle costs without any changes in the fuel element geometry. For example, with an LEU fissile loading of 321 g and a uranium density of 3.7 g/cm^3, the LEU fuel cycle cost would be 50% of the HEU fuel cycle cost if the fabrication cost of the LEU element were about 1.75 times that of the HEU element. If the uranium density could be increased beyond 3.7 g/cm^3, the fuel cycle cost reduction could be even larger.

With an HEU reference element containing 280 g ^{235}U, there are also opportunities for fuel cycle cost reductions both with and without changes in the fuel element geometry. An LEU element with no geometry changes, 390 g ^{235}U, and 4.5 g U/cm^3 in the fuel meat can have lower fuel cycle costs than with this HEU element if the LEU/HEU fabrication cost ratio were less than about 1.6. If the fabrication cost of the LEU element were larger by a factor of 2.3, the total LEU fuel cycle cost would be larger by about 15%. Uranium densities larger than 4.5 g/cm^3 could lead to further cost reductions with LEU silicide fuel.

For reactors which are not operating at their thermal-hydraulic safety limits, it may be prudent to change the fuel element geometry during conversion to LEU fuel. It is reasonable to expect that elements with fewer plates, thicker fuel meat and lower uranium densities will be more economical to fabricate than elements with more plates, thinner meat, and higher uranium densities. In addition, starting out with a lower uranium density now will provide the opportunity for further fissile loading increases in the future. An LEU fuel element design with 20 plates and 0.76 mm meat appears to be a reasonable choice.

For an HEU reference element containing 350 g ^{235}U, there is still an opportunity to reduce fuel cycle costs with LEU silicide fuel. However, there are fewer fuel element design choices and the potential savings are not as large. With no changes in the 23-plate geometry and a uranium density of 6.0 g/cm^3, the LEU core would have lower total fuel cycle costs than the HEU core if the LEU/HEU fabrication cost ratio were less than about 1.7. If the reactor thermal-hydraulic conditions were to allow a change in the fuel element geometry, an LEU design with 20 plates, 0.76 mm-thick fuel meat, and about 5-6 g U/cm^3 would be a reasonable choice.

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SESSION V

October 17, 1984

MIXED CORES

Chairman: W. Krull
GKSS, FRG

APPLICATIONS

Chairman: K. Kamei
JAERI, Japan