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PERFORMANCE AND FUEL-CYCLE COST ANALYSIS OF ONE JANUS 30 CONCEPTUAL DESIGN FOR SEVERAL FUEL-ELEMENT-DESIGN OPTIONS*

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*Work performed under the auspices of the U.S. Department of Energy and the International Atomic Energy Agency.

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ABSTRACT

The performance and fuel cycle costs for a 25 MW, JANUS 30 reactor conceptual design by INTERATOM, Federal Republic of Germany, for BATAN, Republic of Indonesia have been studied using 19.75% enriched uranium in four fuel element design options. All of these fuel element designs have either been proposed by INTERATOM for various reactors or are currently in use with 93% enriched uranium in reactors in the Federal Republic of Germany.

Aluminide, oxide, and silicide fuels were studied for selected designs using the range of uranium densities that are either currently qualified or are being developed and demonstrated internationally. These uranium densities include 1.7 - 2.3 g/cm^3 in aluminide fuel, 1.7 - 3.2 g/cm^3 in oxide fuel, and 2.9 - 6.8 g/cm^3 in silicide fuel. As of November 1982, both the aluminide and the oxide fuels with about 1.7 g U/cm^3 are considered to be fully-proven for licensing purposes. Irradiation screening and proof testing of fuels with uranium densities greater than 1.7 g/cm^3 are currently in progress, and these tests need to be completed in order to obtain licensing authorization for routine reactor use.

To assess the long-term fuel adaptation strategy as well as the present fuel acceptance, reactor performance and annual fuel cycle costs were computed for seventeen cases based on a representative end-of-cycle excess reactivity and duty factor. In addition, a study was made to provide data for evaluating the trade-off between the increased safety associated with thicker cladding and the economic penalty due to increased fuel consumption.

1. INTRODUCTION

This study on the performance and fuel cycle costs of one JANUS 30 reactor conceptual design was prepared within the Reduced Enrichment Research and Test Reactor (RERTR) Program at the Argonne National Laboratory using data that was provided to BATAN and to ANL by INTERATOM. The reactor design studied was valid as of mid-1981 and does not represent the final design. The work was sponsored by the U.S. Department of Energy and the International Atomic Energy Agency.

2. JANUS 30 DESIGN DESCRIPTION STUDIED

The JANUS 30 conceptual design studied here was for a 25 MW, MTR-type, multipurpose research reactor that is cooled and moderated by light water and uses fuel containing 19.75% enriched uranium. The reactor was designed by INTERATOM, Federal Republic of Germany, for BATAN, Republic of Indonesia, and is scheduled to begin operation around 1985.

The setup for the representative working core studied here is shown in Fig. 1 (provided by INTERATOM), and a description of the salient features of the core and the reference fuel element design that were valid in mid-1981 are shown in Table 1. Briefly, the core consisted of 36 standard fuel elements and 6 control fuel elements surrounded on two sides by two rows of beryllium reflector elements and on two sides by two beryllium block reflectors. The large incore irradiation position occupied four grid locations. There were also three incore irradiation positions each occupying one grid location and ten irradiation positions among the beryllium reflector elements.

3. FUEL ELEMENT DESIGN OPTIONS STUDIED

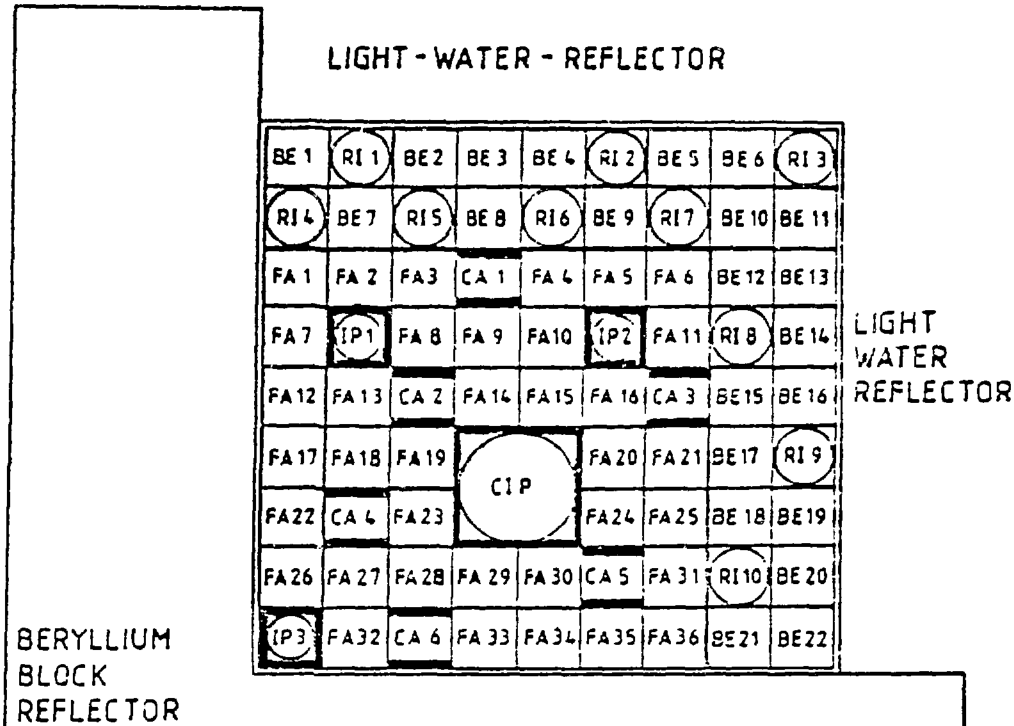
The four fuel element designs along with the fuel meat compositions and uranium densities that were studied are shown in Table 2.

Table 2. Fuel Element Designs Studied

Design No.	Fuel Type	Plates per Element Std./Contl.	Fuel Meat Thick., mm	Clad Thickness Inner/Outer, mm	Water Channel Thick., mm	Uranium Densities, g/cm^3
Ref.	U_3O_8	21/15	0.70	0.30/0.30	2.557	2.29 - 3.2
2	U_3O_8	20/14	0.735	0.38/0.495	2.5145	2.29 - 3.2
3	U_3O_8	20/14	1.0	0.38/0.495	2.217	1.7 - 3.2
	UAl_x	20/14	1.0	0.38/0.495	2.217	1.7 - 2.29
4	U_3SiAl	23/17	0.51	0.38/0.495	2.23	2.9 - 6.8

Reference Design

The reference INTERATOM standard (control) element had 21 (15) fueled plates with 0.70 mm-thick, U_3O_8-Al fuel meat and a uranium density of 2.29 g/cm^3.



(Figure provided to BATAN and to ANL by INTERATOM.)

FA	FUEL ASSEMBLY
CA	CONTROL ASSEMBLY
IP	INCORE IRRADIATION POSITION
CIP	CENTRAL INCORE IRRADIATION POSITION
RI	REFLECTOR IRRADIATION POSITION
BE	BERYLLIUM REFLECTOR ELEMENT

JANUS 30/25MW
CORE SETUP OF A
REPRESENTATIVE WORKING CORE

FIG. 1

Table 1. JANUS 30 Conceptual Design Description
Proposed by INTERATOM in mid-1981

Reactor Design Description

Reactor Type	Pool Type MTR
Steady-State Power Level, MW	25
Number of Standard Fuel Elements	36
Number of Control Fuel Elements	6
Irradiation Positions	1 Incore (4 Grid Positions) 3 Incore (1 Grid Position Each) 10 Reflector (1 Grid Position Each)
Active Core Geometry	7 × 7 Positions
Grid Plate	9 × 9 Positions
Lattice Pitch, mm^2	81.0 × 77.1
Moderator, Coolant	H_2O
Reflectors	Be, H_2O

Reference Fuel Element Design Description

Type	MTR, Straight Plates
Uranium Enrichment, w/o ^{235}U	19.75
Fuel Element Dimensions, mm^3	80.65 × 76.1 × 900
Plate Thickness, mm	1.30
Water Channel Thickness, mm	2.56
Plates/Standard Fuel Element	21
Plates/Control Fuel Element	15 + 4 Al Plates
Fuel Meat Composition	U_3O_8-Al
Fuel Meat Dimensions, mm^3	0.70 × 62.75 × 600
Clad Material	Al or AlMg1
Clad Thickness, mm	0.30
Uranium Density in Fuel Meat, g/cm^3	2.29
^{235}U/Standard Fuel Element, g	250
^{235}U/Control Fuel Element, g	179

The clad thickness on each fuel plate was 0.30 mm. Each fresh standard (control) element contained about 250 (179) g ^{235}U and was designed to achieve an average ^{235}U discharge burnup of about 50%.

Design #2

The second fuel element design was chosen to provide a design equivalent to the reference, but with a nominal clad thickness that is the international standard for MTR-type fuel elements. With 20 plates per standard element and clad thicknesses of 0.38 mm on the inner plates and 0.495 mm on the outer plates (to provide additional protection on the faces not enclosed by the side plates), a fuel meat thickness of 0.735 mm provides the same fuel meat volume as the reference design. Thus, the ^{235}U content with a uranium density of 2.29 g/cm^3 is identical with that of the reference, and the flux and fuel lifetime performance are expected to be about the same.

Design #3

The third fuel element is a design with 20 plates per standard element and 1.0 mm-thick fuel meat that has been proposed by INTERATOM (Ref. 1). Both U_3O_8 and UAl_x fuel with appropriate ranges of uranium densities were considered for this option. Although explicit calculations were not performed here, U_3Si fuels are also an option with this element geometry. Design #2 discussed in the preceding paragraph is INTERATOM Design #3 with a fuel meat thickness of 0.735 mm instead of 1.0 mm.

Design #4

The fourth fuel element design with 23 plates per standard element and 0.51 mm-thick fuel meat is identical with the fuel elements currently used with 93% enriched uranium in four reactors in the Federal Republic of Germany and in reactors in at least four other European countries. NUKEM currently fabricates fuel for most of these reactors. The design is shown explicitly in Ref. 2 (Appendix C, p. 299).

Uranium Densities

The uranium densities that were studied for the U_3O_8, UAl_x, and U_3SiAl fuel types cover the ranges that are currently qualified or are being developed and tested for each fuel type. For each geometry, the lowest uranium density considered provided a loading of about 250 g ^{235}U per standard element. Higher uranium densities were studied in order to show the potential of each design and fuel type for reducing overall fuel cycle costs if the proof-testing of each fuel type is successful. The reactor performance and economic implications for each case are discussed in subsequent sections.

4. CALCULATIONAL METHODS

The methods used in the calculations are identical with those described in detail in Appendix A of Ref. 2. A brief description of these methods is provided below.

Five-group microscopic cross sections were generated as a function of burnup for each fuel type and uranium density with the EPRI-CELL code using shielding factors from MC^2-2 in order to provide a more accurate resonance treatment in ^{238}U. Separate cross sections were also prepared for the beryllium reflector, the light water reflector, and other materials. The core was then modeled in RZ geometry in order to compute axial extrapolation lengths for later use in the burnup calculations.

The REBUS-2 fuel cycle analysis code was used for the burnup calculations in XY geometry. The 36 standard elements and 6 control elements were divided into six batches (see Fig. 2), each consisting of six standard elements and one control element. After each operating cycle, seven spent elements were discharged from batch position 6, the remaining elements were rotated sequentially, and seven fresh elements were inserted into batch position 1. Starting from a fresh core, this pattern was repeated until the equilibrium core was obtained.

This fuel shuffling pattern (Fig. 2) was chosen very early in the calculations based on the power distribution in a core with all fresh fuel, and is not necessarily the best choice since it produces a skewed flux distribution in the central irradiation position (see Fig. 3). If the calculations were to be redone, burnup calculations with several shuffling patterns would be performed to find a pattern that causes the thermal flux to peak near the center of the central irradiation position. However, the conclusions of this study will not be affected significantly by the chosen fuel management strategy.

5. CALCULATED PERFORMANCE RESULTS

In defining the scope of calculations, it was recognized that all of the experiments to be performed in the reactor had not been defined. Hence, all of the irradiation positions were filled with water only in order to obtain data on relative flux performance. In addition, the cycle length will be variable in actual operation since the excess reactivity available to accomodate fuel burnup will be affected directly by the reactivity worth of the experimental loads. In order to provide a broad overview of the possibilities, parametric studies of cycle length versus end-of-cycle (EOC) excess reactivity were performed for EOC reactivities between 0% and 6% $\delta k/k$ for the 17 cases shown in Table 3.

5.1 Fuel Lifetime Performance

In order to simplify the presentation of the performance and fuel cycle cost results, a reasonable EOC excess reactivity of 3.0% $\delta k/k$ was selected for detailed analysis. This excess reactivity was intended to account for 2.0% $\delta k/k$ for experimental loads, and 1% $\delta k/k$ for the cold-to-hot reactivity swing, xenon override, and other possible reactivity effects. The parametric data on cycle length and ^{235}U average discharge burnup versus EOC excess reactivity were interpolated to the 3.0% $\delta k/k$ value. The results are presented in Table 3 for the four element designs with various fuel types and uranium densities. From the cycle length data, the number of standard and control elements that would be utilized per year for a duty factor of 0.75 were derived. The mass of metal in each spent standard and control element was also tabulated for later use in computing reprocessing costs.

Fig. 2. The Six-Batch Fuel Management Scheme Used in These Studies. Fresh Fuel Is Inserted into Batch Position 1 and Is Discharged from Batch Position 6.

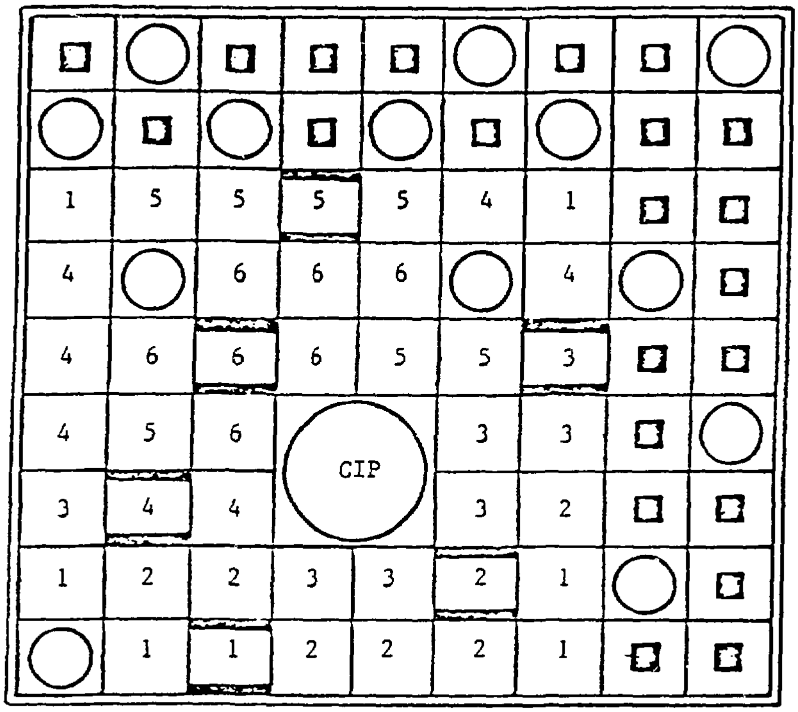


Fig. 3. Contour Plot of Thermal Flux Distribution at EOC in CIP for Reference Design with 2.29 g U/cm^3 U_3O_8 Fuel.

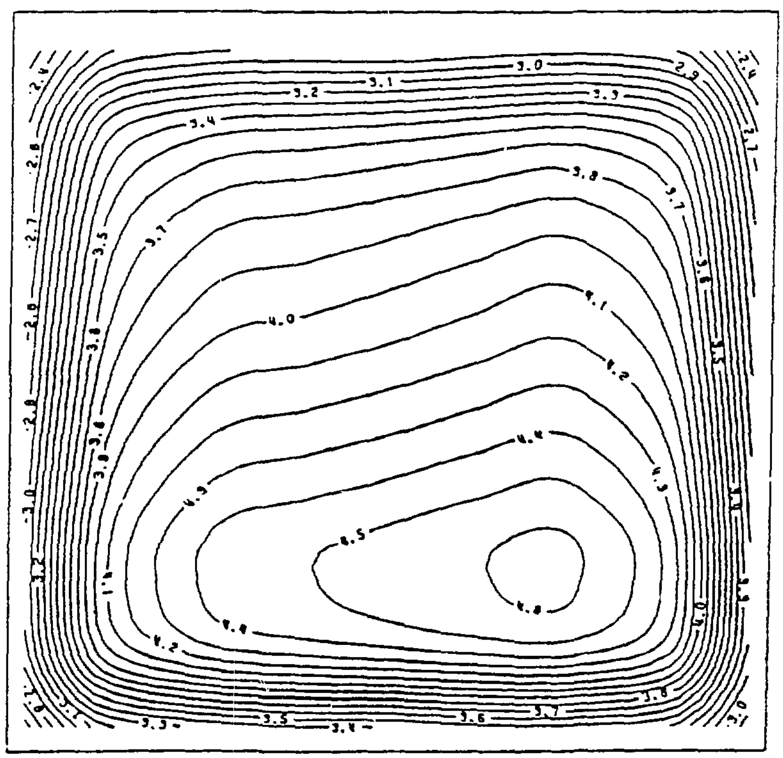


Table 3. Calculated Performance Results. All Cases Have 3.0% δk/k Excess Reactivity at End of Equilibrium Cycle.

Design No.	Fuel Type	g U/cm^3	Plates per Element Std./Cntl.	Fuel Meat Thick., mm	^{235}U per Element Std.	^{235}U per Element Cntl.	Cycle Length, Days	^{235}U Discharge Burnup, % Std.	^{235}U Discharge Burnup, % Cntl.	No. of Elements per Year Std.	No. of Elements per Year Cntl.	Spent Metal Mass per Element, kg Std.	Spent Metal Mass per Element, kg Cntl.	Average Thermal Flux Ratio in CIP[b] BOC	Average Thermal Flux Ratio in CIP[b] EOC
Ref.	U_3O_8	2.29	21/15[a]	0.70	250.3	178.8	29.2	52.0	54.2	56.3	9.4	5.0	3.9	1.00[c]	1.00[d]
		2.7			295.1	210.8	40.0	59.6	62.2	41.1	6.9	5.1	4.0	0.98	0.99
		3.2			349.8	249.9	52.5	65.5	68.2	31.3	5.2	5.3	4.1	0.95	0.96
2	U_3O_8	2.29	20/14	0.735	250.3	175.2	28.6	50.6	52.5	57.4	9.6	5.3	4.1	1.02	1.02
		2.7			295.1	206.6	38.6	57.5	60.0	42.6	7.1	5.4	4.2	1.00	1.00
		3.2			349.8	244.9	51.2	63.0	66.2	32.1	5.4	5.6	4.3	0.97	0.99
3	U_3O_8	1.7	20/14	1.00	252.8	177.0	25.8	44.9	46.5	63.7	10.6	5.9	4.6	1.07	1.06
		2.29			340.6	238.4	46.0	58.5	60.5	35.7	6.0	6.2	4.7	1.02	1.03
		2.7			401.5	281.1	59.5	63.3	65.5	27.6	4.6	6.3	4.9	1.00	1.01
		3.2			475.9	333.1	76.0	67.0	68.2	21.6	3.6	6.5	5.1	0.97	0.99
	UAl_x	1.7	20/14	1.00	252.8	177.0	25.0	43.5	45.5	65.7	11.0	5.8	4.5	1.07	1.06
		2.0			279.4	208.2	35.2	52.0	54.0	46.7	7.8	6.0	4.7	1.04	1.04
		2.29			340.6	238.4	45.0	57.3	59.5	36.5	6.1	6.2	4.7	1.02	1.03
4	U_3SiAl	2.9	23/17	0.51	252.9	186.9	29.0	50.7	53.0	56.6	9.4	5.3	4.3	1.01	1.00
		3.2			279.1	206.3	35.5	55.2	57.5	46.3	7.7	5.4	4.3	0.99	1.00
		4.8			418.7	309.5	66.8	68.0	71.0	24.6	4.1	5.9	4.7	0.93	0.95
		6.8			593.1	438.4	104.5	73.2	76.0	15.7	2.6	6.5	5.1	0.88	0.90

[a] Reference INTERATOM design had 0.30 mm clad on inner and outer plates. All other designs have 0.38 mm clad on inner plates and 0.495 mm clad on outer plates.

[b] Central Irradiation Position filled with water only.

[c] In the reference design at BOC, the average thermal (<0.625 eV) flux in the CIP was 2.71×10^{14} n/cm^2/s and the peak thermal flux was 4.53×10^{14} n/cm^2/s.

[d] In the reference design at EOC, the average thermal (<0.625 eV) flux in the CIP was 2.87×10^{14} n/cm^2/s and the peak thermal flux was 4.61×10^{14} n/cm^2/s.

The cycle length data in Table 3 are plotted versus uranium density in Fig. 4, and the average ^{235}U discharge burnup in the standard and control elements are plotted versus uranium density in Fig. 5. Only a portion of the curves for silicide fuel are shown.

Design #2 with U_3O_8 fuel, 20 plates, 0.735 mm meat, and 0.38 mm clad is approximately equivalent to the reference design with U_3O_8 fuel, 21 plates, 0.70 mm meat, and 0.30 mm clad. Design #2 offers the advantage of the additional safety provided by a thicker clad.

Design #3 with 20 plates, 1.0 mm meat, and 0.38 mm clad has about the same cycle lengths with U_3O_8 and UAl_x fuel for uranium densities between 1.7 and 2.3 g/cm^3. For the same uranium density, U_3O_8 fuel has a slightly longer cycle length since oxygen is less absorptive than aluminum. U_3O_8 fuel offers the potential of higher uranium densities than UAl_x fuel and, hence, lower fuel cycle costs if currently planned fuel demonstration efforts are successful. Design #3 with U_3O_8 or UAl_x fuel and a uranium density of 1.7 g/cm^3 has a cycle length of about 25 days, while the reference design and Design #2 with 2.29 g U/cm^3 U_3O_8 fuel have cycle lengths of about 29 days.

Design #4 with 2.9 g U/cm^3 U_3SiAl fuel, 23 plates, 0.51 mm meat, and 0.38 mm clad has nearly the same cycle length (29 days) as the reference design since the ^{235}U loadings and metal-to-water ratios are nearly the same. U_3SiAl fuel offers the potential of very high uranium densities, long cycle lengths, and very high discharge burnups if current irradiation screening and demonstration efforts are successful.

5.2 Thermal Flux Performance

Table 3 also shows the ratios at BOC and at EOC of the thermal (<0.625 eV) flux, averaged over the midplane cross section of the central irradiation position (CIP), for each of the cases relative to the reference design with 2.29 g U/cm^3 U_3O_8 fuel. In Fig. 6, fast, epithermal, and thermal fluxes for a midplane traverse through the CIP (from FA 17 through RI 9 in Fig. 1) are shown for the reference design with 2.29, 2.7, and 3.2 g U/cm^3 U_3O_8 fuel. For simplicity, the flux profiles shown in Fig. 6 do not pass through the peak flux position in the CIP since the ordering of the fluxes by uranium density at the peak is influenced by the fuel management strategy that was chosen (see Section 4).

For each geometry and fuel type, increasing the uranium density in the fuel decreases the average thermal flux in the CIP. However, as shown in Table 3, the thermal flux degradation in the CIP is small in comparison with the increased cycle length and decreased fuel consumption. Since the largest absorber in the core is ^{235}U, the thermal fluxes in the fuel will in general be decreased in approximate inverse proportion to the increase in ^{235}U content. As mentioned above, though, relative fluxes in specific locations are influenced by the fuel management strategy.

The various cases in Table 3 with about 250 g ^{235}U per fresh standard element show an increase of 0 - 7% in the average thermal flux in the CIP relative to the reference design.

Fig. 4. Cycle Length versus Uranium Density in the Fuel Meat for 3.0% δk/k Excess Reactivity at EOC

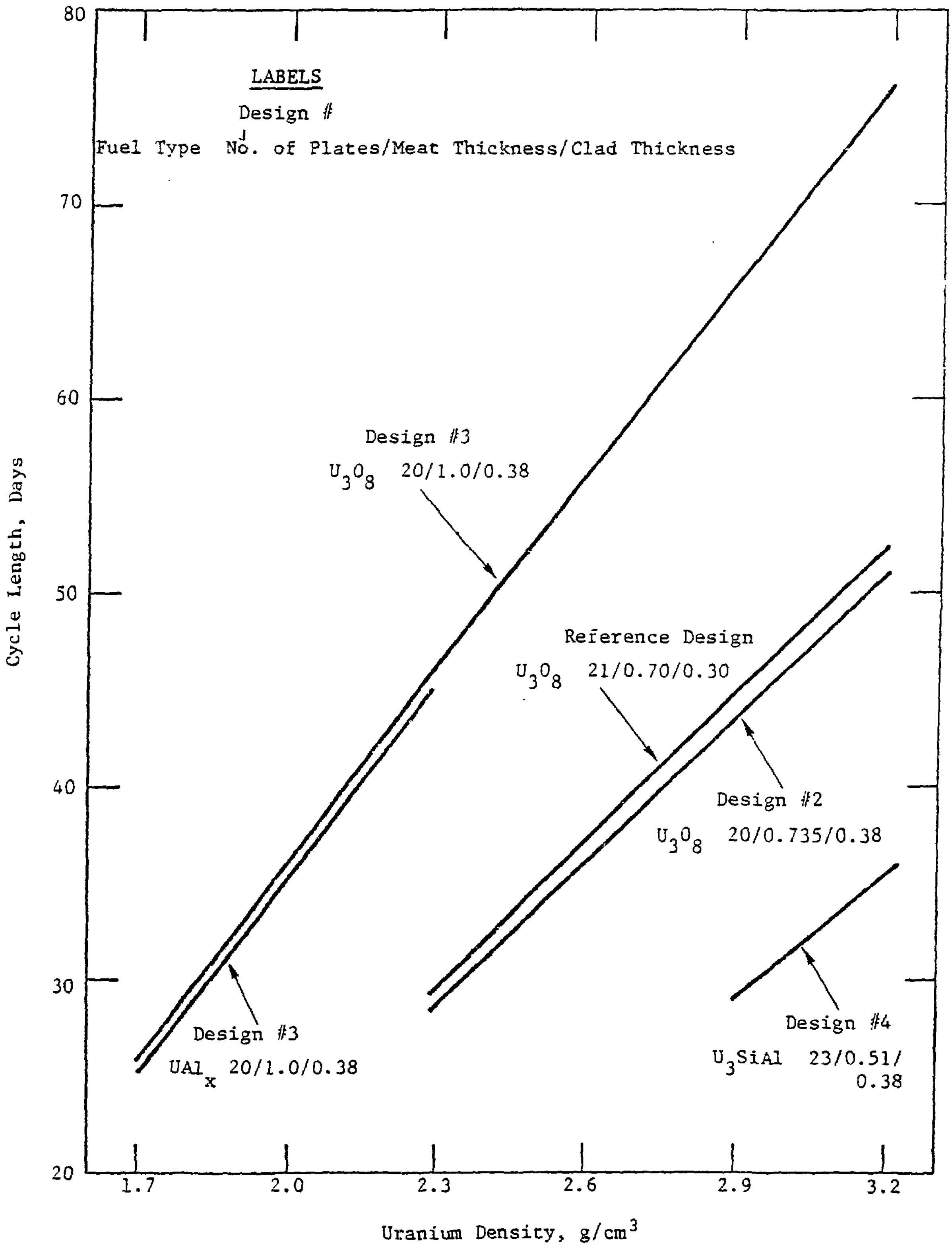


Fig. 5. Average ^{235}U Discharge Burnups in Standard and Control Fuel Elements as Functions of Uranium Density for an EOC Excess Reactivity of 3.0% δk/k.

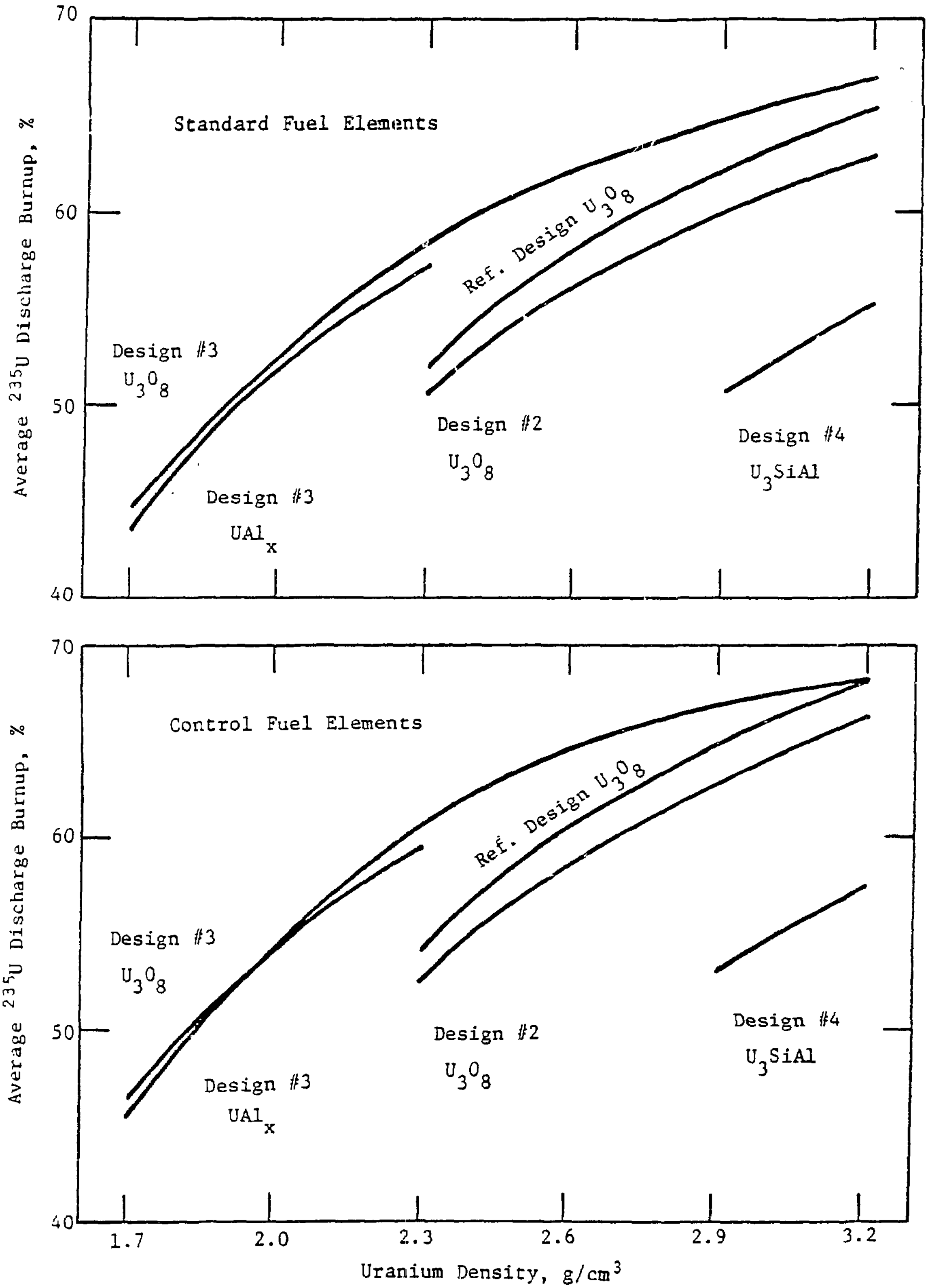
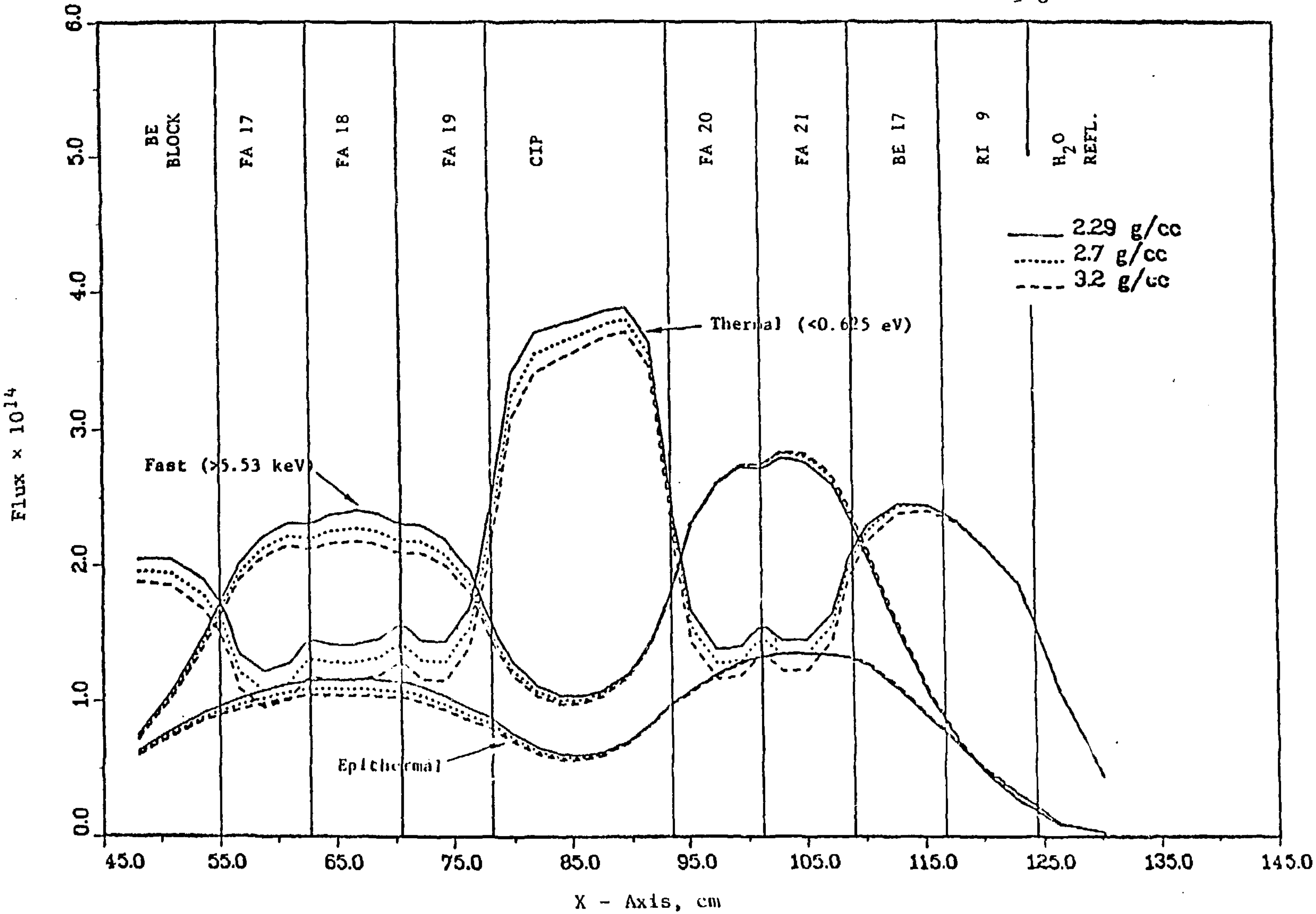


Fig. 6. *Midplane Flux Traverse Through CIP from FA 17 Through RI 9* for Reference Design with 2.29, 2.7, and 3.2 g U/cm^3 U_3O_8 Fuel



5.3 Effect of Increasing Clad Thickness

In order to provide a perspective on the reactor performance penalties associated with clad thicknesses greater than 0.38 mm, a parametric study was performed on Design #2 with 20 plates per standard element, 2.29 g U/cm^3 U_3O_8 fuel, and 0.735 mm-thick fuel meat. For this case, EOC excess reactivity changes were computed for clad thicknesses ranging from 0.38 - 0.45 mm on the inner plates of the standard and control elements and from 0.495 - 0.55 mm on the outer plates of the standard elements. Cycle lengths corresponding to the decreased EOC excess reactivities were determined from parametric curves of cycle length versus EOC excess reactivity. For an EOC excess reactivity of about 3.0% $\delta k/k$, a 1% $\delta k/k$ decrease in the EOC excess reactivity reduces the cycle length by about 1.9 days. The results are shown in Table 4, and are plotted in Fig. 7.

One of the trade-offs to be considered is the increased safety resulting from thicker cladding versus the economic penalty of increased fuel consumption. However, the fuel consumption penalty can be neutralized by increasing the uranium density in the fuel meat. The data for Design #2 in Table 3 with 2.29 and 2.7 g U/cm^3 indicate that the uranium density needs to be increased by about 0.04 g/cm^3 in order to increase the cycle length by one day. For the 0.45/0.55 mm case, for example, the uranium density would need to be increased from 2.29 g/cm^3 to about 2.36 g/cm^3 to achieve the same fuel consumption as the 0.38/ 0.495 mm case.

5.4 Burnable Poisons

Burnable poisons have not been addressed in this study. However, for a number of the cases studied here with very high uranium densities in U_3O_8 and U_3SiAl fuels, burnable poisons are likely to be required to maintain a safe shutdown margin.

6. FUEL CYCLE COST ANALYSIS

This analysis provides a consistent comparison of the estimated annual fuel cycle costs for each of the options listed in Table 3. The model used here for computing annual costs for each fuel cycle component is described in detail in Ref. 3. Since accurate data for a number of the fuel cycle cost components were not available, assumed data were utilized. Actual costs may be significantly different from those that were assumed. However, the model described in Ref. 3 will enable updated analyses to be performed as accurate cost data become available. The fuel cycle cost components assumed here are outlined below.

6.1 Assumed Fuel Cycle Cost Components

Enriched Uranium Costs (September 1982)

- 19.75% Enriched Uranium: \$41,534.05/kg ^{235}U in UF_6
- Uranium Losses During Conversion of UF_6 and Fuel Element Fabrication: 2.5%

Fuel Element Fabrication Costs

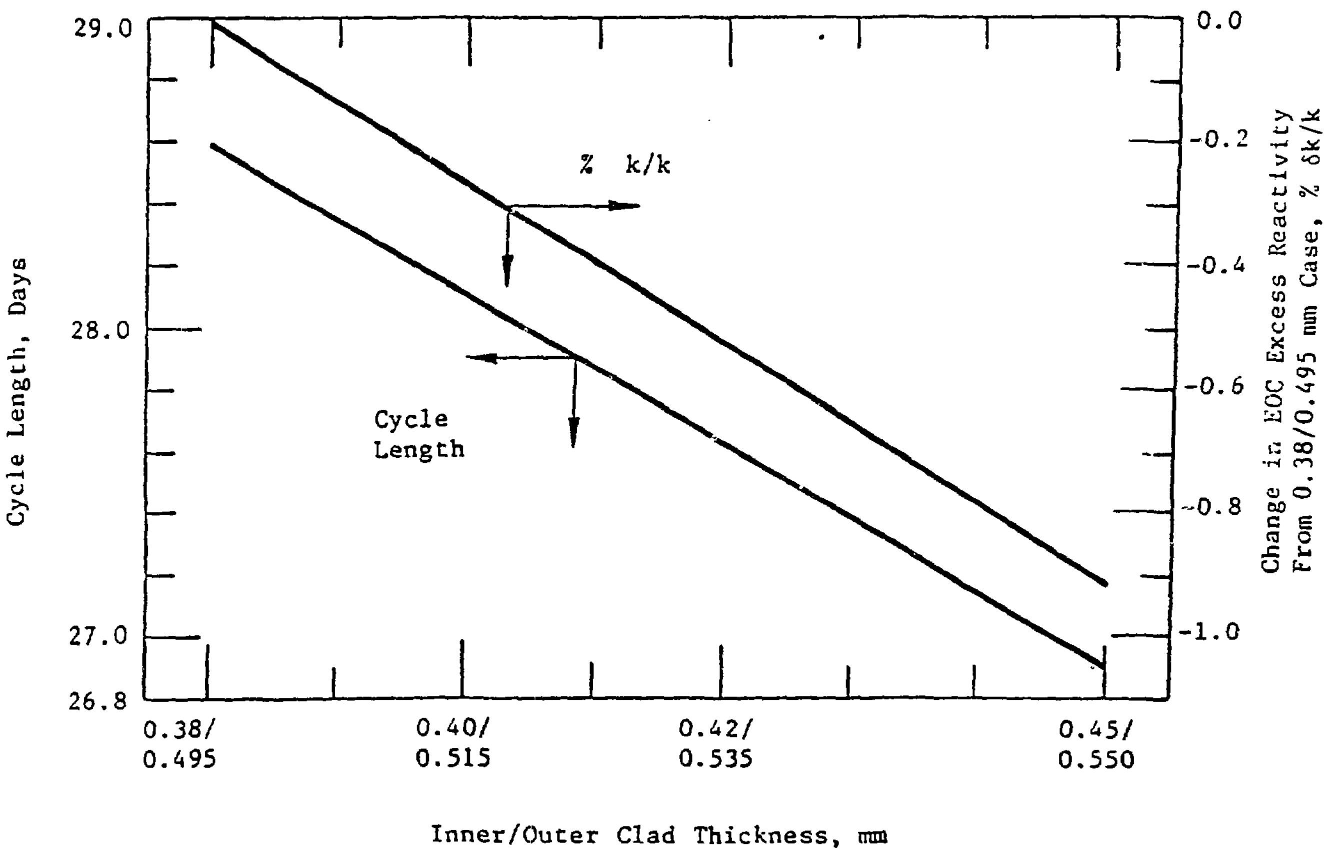
- Reference Standard Element: \$9,000
  21 Fuel Plates, 0.70 mm Meat, 0.30 mm Clad
  U_3O_8 Fuel, 2.29 g U/cm^3, 250 g ^{235}U

Table 4. Effect of Increasing Clad Thickness for Design #2 with U_3O_8 Fuel, 2.29 g U/cm^3.

Clad Thickness Inner/Outer mm	Change in EOC Excess React. % δk/k	Approx. Cycle Length, Days	Cycles* per Year	Elements per Year Std.	Elements per Year Cntl.
0.38/0.495	0.0	28.6	9.57	57.6	9.6
0.40/0.515	-0.26	28.1	9.74	58.2	9.7
0.42/0.535	-0.52	27.6	9.92	59.4	9.9
0.45/0.550	-0.92	26.9	10.2	61.2	10.2

*Duty Factor = 0.75

Fig. 7 Cycle Length and Change in EOC Excess Reactivity as a Function of Clad Thickness for Design #2



- Reference Control Element: 0.9 × Ref. Std. El. = $8,100
  15 Fuel Plates, 0.70 mm Meat, 0.30 mm Clad
  U_3O_8 Fuel, 2.29 g U/cm^3, 179 g ^{235}U

- Fabrication Cost Factors That Depend on Fuel Type and Uranium Density. These factors are based on data presented in Ref. 4 and are shown below.

Fuel Type	Uranium Density g/cm^3	Fab Cost Factor	Fuel Type	Uranium Density g/cm^3	Fab. Cost Factor
U_3O_8	1.7	0.9	U_3SiAl	2.9	1.3
	2.3	1.0		3.2	1.3
	2.7	1.1		4.8	1.5
	3.2	1.3		6.8	1.7
UAl_x	1.7	1.1			
	2.0	1.2			
	2.3	1.3			

- Fabrication Cost Factor That Depends on the Number of Plates per Standard Element. It is assumed here that 75% of element fabrication costs are due to plate production. The cost factors used are 1.0 for the reference 21 plate design, 0.96 for the designs with 20 plates, and 1.07 for the 23 plate design.

Fresh Fuel Shipping Costs

- Ship UF_6 from USA to FRG: $500/kg U

- Ship Fresh Standard and Control Elements from FRG to Indonesia: $500/Element

Spent Fuel Shipping Costs

- Ship Spent Fuel from Indonesia to USA: $3,000/Element

Reprocessing Costs

- $1,000/kg Total Delivered Weight

Uranium Credit

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

6.2 Fuel Cycle Cost Results

The annual fuel cycle costs (in thousands of U.S. $) for the four designs with various uranium densities are shown in Table 5. Since the reactor power was 25 MW and the duty factor was assumed to be 0.75, all cases have the same number of MWd. The $/MWd of operation are plotted in Fig. 8 as a function of the uranium density in the fuel meat for the reference design and each of the design options. Only a portion of the cost curve for the silicide fuel is shown in this figure. The annual costs are 156.8 $/MWd at 4.8 g U/cm^3 and 125.7 $/MWd at 6.8 g U/cm^3.

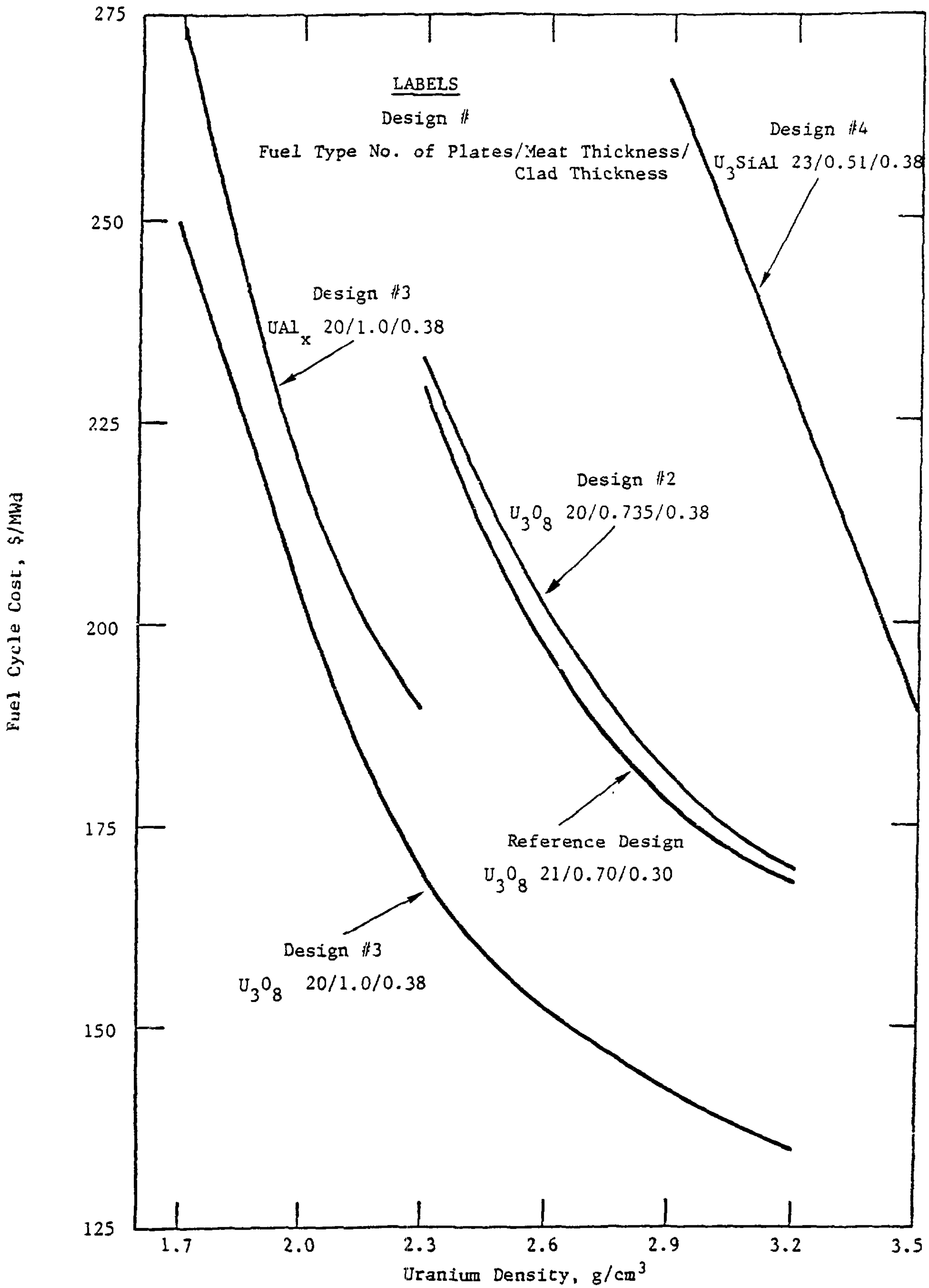
The reference design and Design #2 (both with U_3O_8 fuel) have nearly the same fuel cycle costs. Design #3 with UAl_x fuel has higher fuel cycle costs than with U_3O_8 fuel over the uranium density range of 1.7 - 2.3 g/cm^3 mainly because the fabrication cost factors by fuel type and uranium density are considerably higher for UAl_x fuel. These fabrication cost factors are larger for UAl_x fuel than for U_3O_8 fuel at the same uranium density because the cost of manufacturing the U_3O_8 powder is lower with NUKEM's production methods (Ref. 4) and because the volume fraction of the dispersed phase is larger with UAl_x fuel.

The fabrication cost factors for silicide fuel are not as well defined as those for the conventional UAl_x and U_3O_8 fuels. More experience with production of silicide powder is required before the factors for silicide fuels can attain credibility comparable with the factors assigned to UAl_x and U_3O_8 fuels. With the fabrication cost factors assumed in this anlaysis, however, both Design #3 with U_3O_8 fuel and Design #4 with silicide fuel have about the same potential for minimizing overall fuel cycle costs with the high uranium densities if the irradiation testing of these fuels is successful.

Table 5. Fuel Cycle Costs Per Year (In Thousands of Dollars)

Design No.	Fuel Type	g U/cm^3, No. Plates/ Meat Thick., mm	U Cost	Fabr. Cost	Ship Fresh Fuel	Ship Spent Fuel	Repr. Cost	Uranium Credit	Total	MWd	$/MWd
Ref.	U_3O_8	2.3,21/0.7	670.8	582.2	73.7	196.9	317.8	-271.6	1569.7	6843.7	229.4
		2.7	577.3	467.5	59.1	143.7	236.8	-190.0	1294.5	6843.7	189.2
		3.2	521.3	420.9	50.0	109.5	187.2	-141.2	1147.7	6843.7	167.7
2	U_3O_8	2.3,20/0.735	683.3	574.6	75.1	201.0	343.6	-286.5	1591.2	6843.7	232.5
		2.7	597.0	468.4	61.2	148.9	259.6	-209.0	1326.2	6843.7	193.8
		3.2	533.4	417.2	51.2	112.3	202.6	-157.4	1159.5	6843.7	169.4
3	U_3O_8	1.7,20/1.0	765.1	573.2	83.8	222.8	424.4	-364.5	1704.9	6843.7	249.1
		2.3	578.1	357.2	56.1	125.0	249.3	-196.9	1168.8	6843.7	170.8
		2.7	526.9	303.8	48.2	96.6	196.5	-154.4	1017.6	6843.7	148.7
		3.2	489.0	281.1	42.4	75.6	158.9	-126.0	921.0	6843.7	134.6
	UAl_x	1.7,20/1.0	789.6	723.1	86.5	229.9	430.3	-386.9	1872.5	6843.7	273.6
		2.0	659.6	560.1	67.4	163.3	316.6	-267.2	1499.6	6843.7	219.1
		2.3	591.0	474.8	57.3	127.8	254.9	-209.2	1297.5	6843.7	189.6
4	U_3Si	2.9,23/0.51	684.9	812.9	74.8	198.2	340.8	-286.1	1825.6	6843.7	266.8
		3.2	617.5	664.0	64.6	161.9	283.0	-230.3	1560.8	6843.7	228.1
		4.8	492.2	407.1	44.3	86.0	164.3	-121.0	1072.9	6843.7	156.8
		6.8	445.8	295.0	36.3	55.0	115.5	-87.1	860.5	6843.7	125.7

Fig. 8. Estimated Annual Fuel Cycle Costs ($/MWd) versus Uranium Density in the Fuel Meat for 3.0% δk/k Excess Reactivity at EOC.



7. CONCLUSIONS

All of the fuel element designs studied here are viable options provided that the development and demonstration of the fuels with the uranium densities considered are successful.

As of November 1982, both the aluminide and oxide fuels with a uranium density of about 1.7 g/cm^3 are considered to be fully-proven from a licensing point of view. INTERATOM Design #3 with 20 plates per standard element, 1.0 mm thick fuel meat, and a nominal clad thickness of 0.38 mm that uses either aluminide or oxide fuel with a uranium density of 1.7 g/cm^3 is considered to qualify for licensing authorization now. Irradiation screening and proof-testing of fuels with uranium densities greater than 1.7 g/cm^3 are currently in progress (see pertinent papers in these proceedings), and these tests need to be completed in order to obtain licensing authorization for routine reactor use.

Aluminide fuel with uranium densities up to about 2.3 g/cm^3 and oxide fuel with uranium densities up to about 3.2 g/cm^3 are also viable options if the irradiation tests and post-irradiation examinations are successful. Utilization of fuels with uranium densities greater than 1.7 g/cm^3 can result in significant fuel cycle cost savings. For example, with the relatively low risk oxide fuel with a uranium density of 2.29 g/cm^3 in Design #3, the overall fuel cycle cost savings were computed to be about U.S. $700,000 per year in comparison with aluminide fuel at 1.7 g U/cm^3, and about U.S. $540,000 per year in comparison with oxide fuel at 1.7 g U/cm^3.

Except for the reference design, all cases studied here utilized a nominal clad thickness of 0.38 mm. A safer design could be achieved with clad thicknesses greater than 0.38 mm. For Design #2, it was shown that the cycle length and fuel consumption penalties associated with nominal clad thicknesses even up to 0.45 mm may not be unreasonable. It was also shown that relatively minor increases in the uranium density would allow the fuel cycle cost penalty caused by the thicker clad to be neutralized.

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