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Performance and Fuel-Cycle Cost Comparisons with HEU and LEU Fuels

J. E. Matos and T. A. Daly

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Introduction

The objective of this study is a consistent analysis of the performance and fuel cycle costs with HEU (93%) fuel and the various LEU (<20%) fuels that are under development, undergoing irradiation testing of small samples, or in the demonstration phase. All calculations were performed using the generic 10 MW reactor that has been studied extensively by a number of laboratories in the IAEA Guidebook (Ref. 1).

The fuels to be compared are shown in Table 1, and the fuel element and core designs considered are shown in Figs. 1 and 2, respectively. The detailed fuel element designs are described in Ref. 1.

Table 1. Fuels Considered

		Enr.,%	g U/cm^3	No. of Plates	Fuel Meat Thicknesses, mm
HEU:	UAl_x-Al (Ref.)	93	0.7	23	0.51
LEU:	UAl_x-Al	20	2.3	19	1.24
	U_3O_8-Al	20	3.0	19	1.24
	U_3Si-Al	20	6.0	23	0.51
	CARAMEL	6.5	8.4	16	1.45
	UZrH	20	3.7	16*	12.95**

*Pins

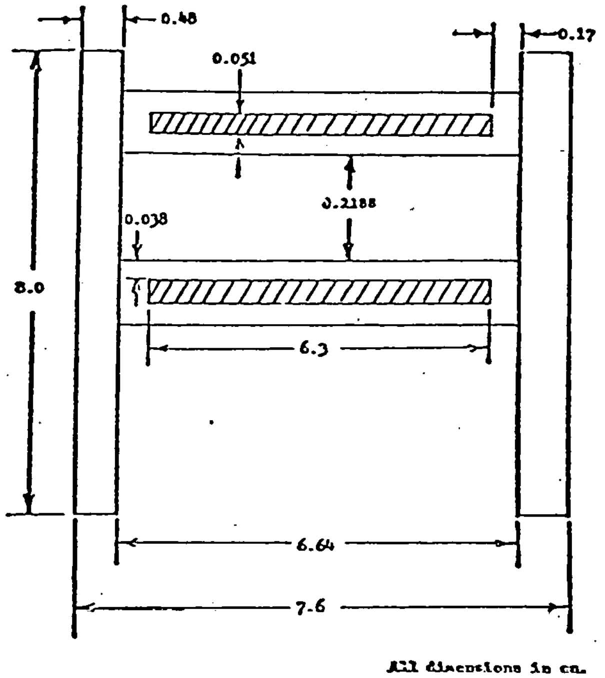
**Fuel Outer Diameter

The 5 x 6 element reference core using HEU contained 23 standard MTR elements (280 g ^{235}U per element) and 5 control elements (207 g ^{235}U per element). 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. The burnup studies of the equilibrium cores for all plate-type fuels utilized one fuel shuffling pattern in which a single fresh standard element was inserted near the center of the core and the remaining standard elements rotated sequentially after each operational cycle. The control elements were fixed. The model for the burnup studies using UZrH rodded-type fuel was based on a 6 x 6 element core (Ref. 1) designed by General Atomic for operation at 10 MW. This core had 30 fuel clusters, 4 control rods (containing no fuel), and 2 water-filled flux traps. The fuel shuffling pattern was chosen to be similar to that of the HEU reference core in order to compare performances on as nearly an equal basis as possible.

Fig. 1. FUEL ELEMENT DESIGNS

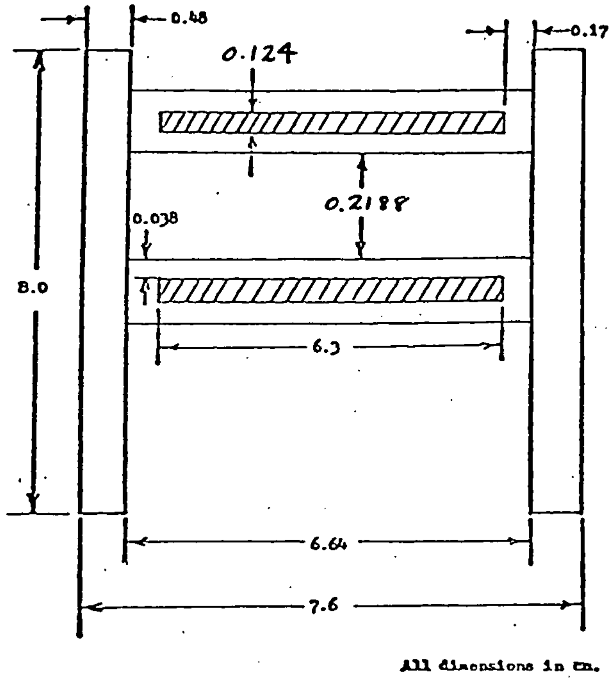
93% UAl_x-Al (0.7 g U/cc)
20% U_3Si-Al (6.0 g U/cc)

23 Plates/Element



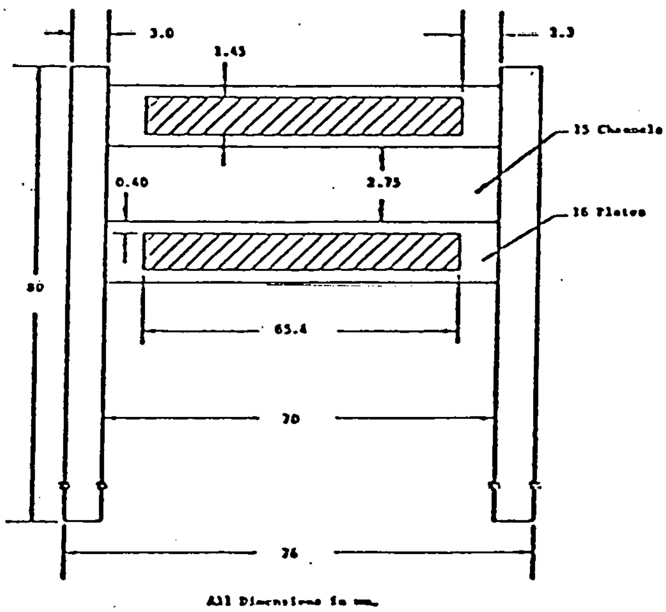
20% UAl_x-Al (2.3 g U/cc)
20% U_3O_8-Al (3.0 g U/cc)

19 Plates/Element



6.5% CARAMEL (8.4 g U/cc)

16 Plates/Element



20% UZrH (3.7 g U/cc)

16 Rods/Element

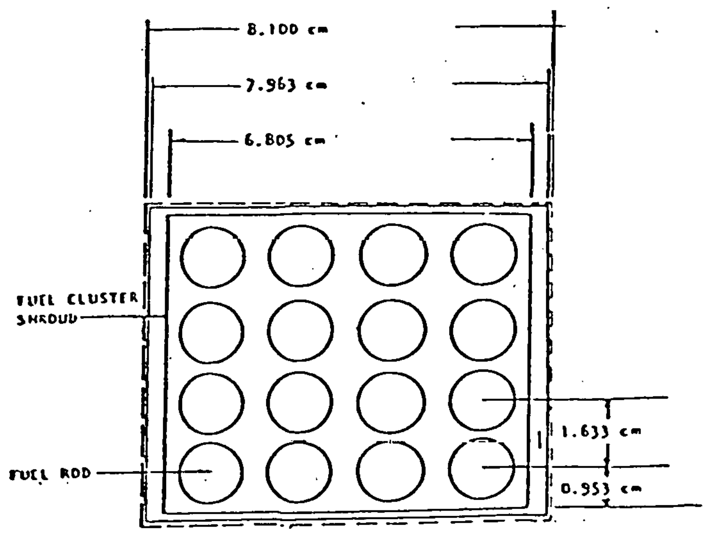
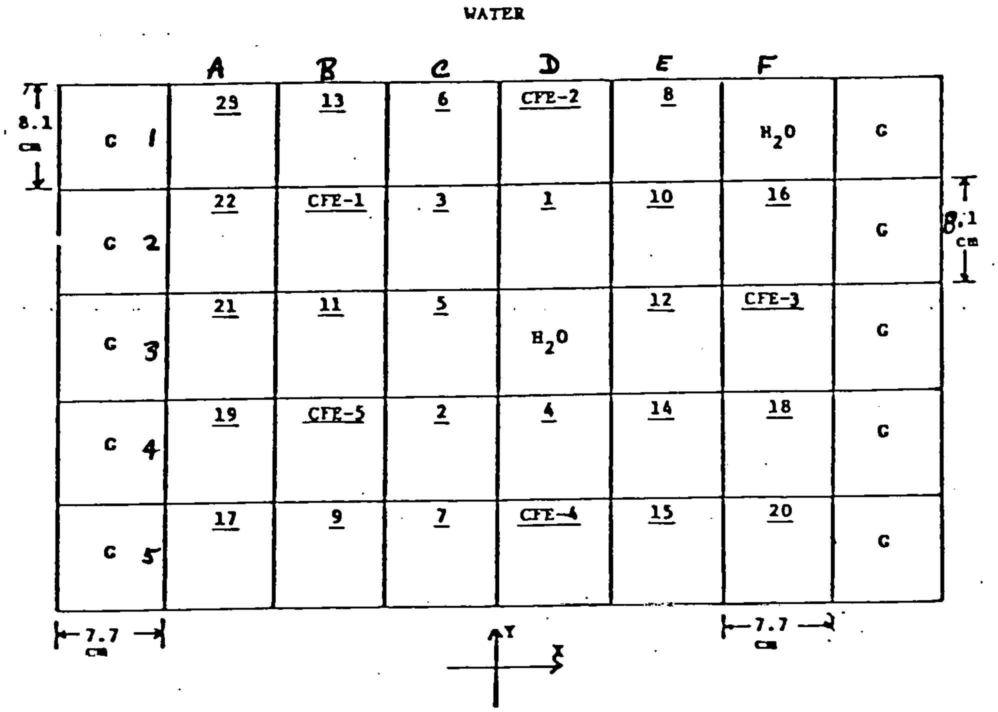
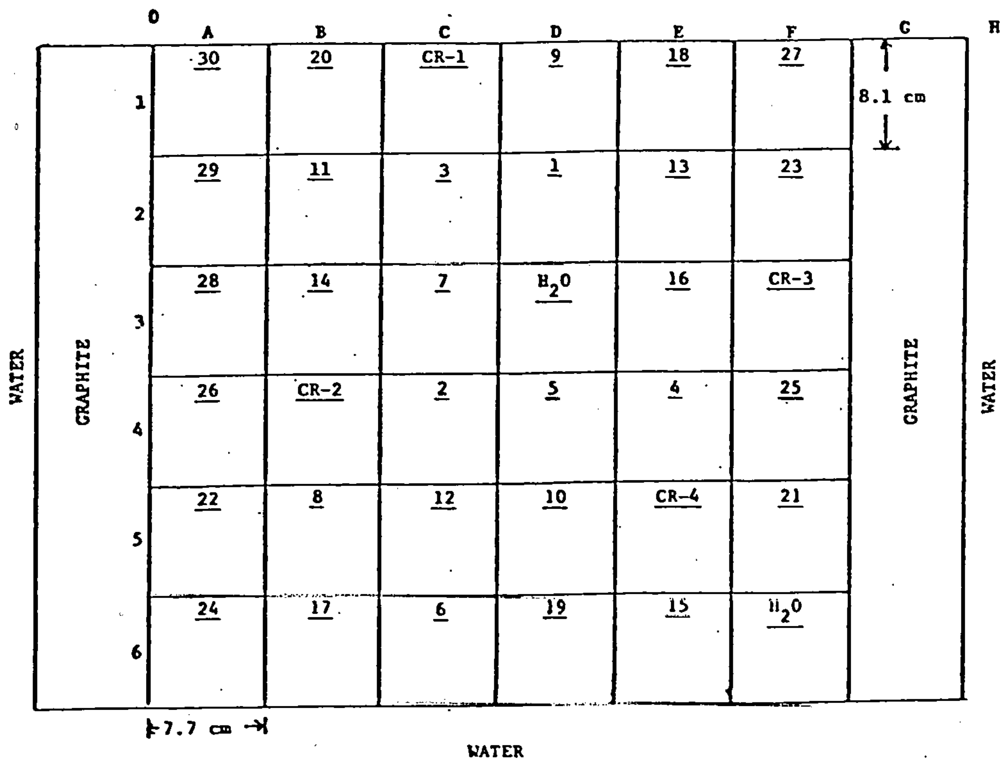


FIG. 2. CORE DESIGNS

UAl_x-Al, U_3O_8-Al, U_3Si-Al, CARAMEL



UZrH



Performance

Table 2 compares the geometry, ^{235}U loading, and burnup data for the HEU reference case and the cases with LEU fuels. The average cycle length is a function of the ^{235}U loading of a fresh standard element, the water volume fraction, the geometric buckling, and the uranium enrichment. From Table 2, some simple and predictable conclusions inter-relating these variables can be drawn:

- For the same water volume fraction, a higher ^{235}U loading yields a longer cycle length.
- For the same ^{235}U loading, a larger water volume fraction yields a longer cycle length.
- For a larger core size (i.e., smaller geometric buckling) or for a higher enrichment, a smaller ^{235}U loading per element is required to maintain the same cycle length.

Thermal fluxes at end of equilibrium cycle are shown in Fig. 3 (except for the oxide case) for a midplane traverse through the central flux trap and the water-reflected faces. One of the thermal flux peaks for the UZrH case is displaced by about one fuel element since the size of the UZrH core is larger than the reference core by one row. Although the thermal fluxes in the central flux trap and at the reflector peaks depend on several variables (such as burnup and fast leakage from the core), these peaks are ordered in approximate inverse relation to the ^{235}U loading of a fresh standard element. Thermal fluxes in the core are ordered in inverse relation to the average ^{235}U loading of the core at EOC.

Fuel Cycle Costs

The methods and assumptions used for computing fuel cycle costs are based on a model developed by A. Burtscher for the ASTRA reactor in Seibersdorf, Austria. The details of this model are described in Appendix I of Ref. 1, and are repeated here with minor modifications for clarity and completeness.

The assumed fuel cycle cost components are shown in Table 3. Several points are worth mentioning:

- The enriched uranium prices that were used were valid as of October 1979 ($47.8/g ^{235}U for 93.15% enrichment and $45.2/g ^{235}U for 20% enrichment).

- The reference HEU aluminide fuel element had a cost of $6600 per element, and the cost for an LEU aluminide, oxide, or silicide element was assumed to be higher by a factor of 1.35 - 1.5. Since little information is available at this time on the cost of caramel fuel, its fabrication cost factor (1.35 - 5.4) was treated as a parameter in this exercise. The published General Atomic catalogue price of $22,100 per element was used for UZrH fuel.

- Reprocessing charges for aluminide, oxide, and zirconium hydride fuels are based on Federal Register Notices valid through December 1982. For simplicity, the same prices were assumed for both HEU and LEU fuels. Since there is no information available on reprocessing charges for either the silicide or caramel fuels, the price was assumed to be the same as that for HEU aluminide fuel for purposes of this comparison. Actual prices may be quite different.

Table 2. Comparison of Geometry, ^{235}U Loading, and Burnup Data for the HEU Reference Case and Cases with LEU Fuels

Fuel Type and Enrichment	Plates or Rods per Std. Element	Uranium Density in Fuel Meat g/cm^3	Fuel Meat/ Water Channel Thickness mm	Water Volume Fraction Std. El.	^{235}U in Fresh Std. Element, g	Average Cycle Length, Days	Grams Fissile Burned in Discharge Element ^{235}U	Grams Fissile Burned in Discharge Element $^{239}Pu+^{241}Pu$	Average Discharge Burnup % ^{235}U	Average Discharge Burnup MWd[a]	Grams per Discharged Element $^{239}Pu/^{240}Pu$/Total Pu
Aluminide, 93%	23	0.68	0.51/2.188	0.561	280.0	16.7	178.4	0	63.7	142.7	0.39/0.12/0.58
Aluminide, 20%	19	2.27	1.238/2.188	0.468	403.0	16.7	170.5	10.7	42.3	143.3	11.0/2.1/14.2
Oxide, 20%	19	3.0	1.238/2.188	0.468	533.5	28.0	253.9	25.6	47.6	219.6	16.3/4.0/22.8
Silicide, 20%	23	6.0	0.51/2.188	0.561	532.1	37.8	367.7	44.0	69.1	322.5	15.6/5.4/24.4
Caramel, 6.5%	16	8.41	1.45/2.75	0.519	497.5	23.7	216.7	35.6	43.6	196.3	35.2/6.8/45.7
UZrH,[b] 20%	16	3.72	12.95[c]/-	0.395	876.8	40.8	477.5	56.0	54.5	418.1	33.0/7.1/45.8

[a]Energy production based on burnup of 1.25 g ^{235}U/MWd and 1.55 g (^{239}Pu + ^{241}Pu)/MWd

[b]0.81 wt% Erbium

[c]Fuel outer diameter

Fig. 3. Comparison of Thermal Fluxes at EOC for 10 MW Reactor Between HEU Reference Case and Cases with Different LEU Fuels for a Midplane Traverse Through the Central Flux-Trap and Water-Reflected Faces (ns = not shown).

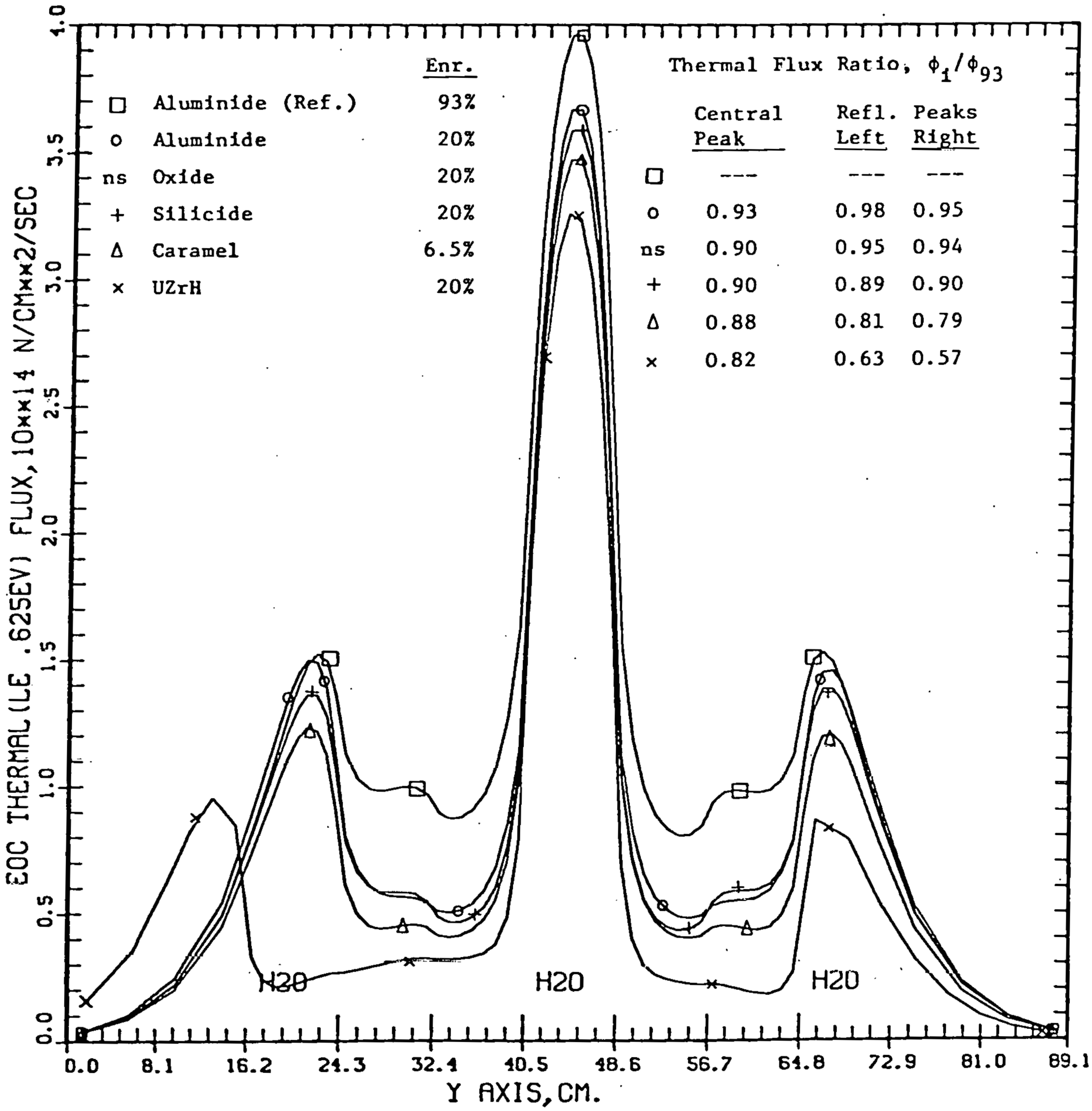


Table 3. FUEL CYCLE COST COMPONENTS

- URANIUM COSTS

  - Enriched Uranium
  - Uranium Losses During Conversion and FE Fabrication: 2.5%
  - Conversion of UF_6 to U-Metal: \$330/kg U

- FUEL ELEMENT FABRICATION COSTS

  HEU Reference Element (Approx. NUKEM Price for ASTRA Element): \$6600

  LEU Fuel Elements:

  - UAl_x-Al, U_3O_8-Al (NUKEM Estimate)
    (1.35-1.5) × HEU Ref. FE: ~\$8910-\$9900
  - U_3Si-Al (Estimate for this Comparison)
    (1.35-1.5) × HEU Ref. FE: ~\$8910-\$9900
  - CARAMEL (Estimate for this Comparison)
    (1.35-5.4) × HEU Ref. FE: ~\$8910-35,640
  - UZrH (General Atomic Catalogue Price): \$22,100

- FRESH FUEL SHIPPING COSTS

  - Ship UF_6 from USA to Europe (Based on Shipment of ~200 kg Enrichment Uranium): \$3000 + \$550/kg U
  - Ship Fresh Fuel from NUKEM to ASTRA: \$400/Element

- SPENT FUEL SHIPPING COSTS

  - Ship Spent Fuel from ASTRA to Savannah River Plant: \$3140/Element

- REPROCESSING COSTS

  - \$400/kg Metal (UAl_x-Al, U_3O_8-Al)
  - \$145/kg Metal (UZrH)

  } Based on Federal Register Notices Valid Through December 1982.

  - \$400/kg Metal (U_3Si-Al, CARAMEL) — Estimate for this Comparison Only.

- URANIUM CREDIT

  Price for Contained ^{235}U (Interpolated for Different Enrichments), Reduced by:

  - Uranium Losses During Reprocessing and Conversion: 2.5%
  - Conversion Costs: \$260/kg U
  - Shipping Charges to Enrichment Plant: 2% of Uranium Credit

- Uranium credits were computed in the same manner for all fuels and enrichments.

Additional assumptions for these cost comparisons are shown in Tables 4 and 5. All calculations were performed for a batch size of 26 fuel elements. The annual capital interest rate (P) was treated as a variable and the annual escalation rate (E) was fixed at 10%. All costs were referred to the beginning of the fuel cycle for various values of (P - E).

The results of this study are shown in Fig. 4, where the fuel cycle costs in $/MWd are plotted against (P-E) for the reference HEU fuel and the various LEU fuels (except for the caramel). Since the curves in Fig. 4 are all relatively parallel, it can be concluded that, within a reasonable range, differences between interest rates and escalation rates are not important since they influence all of the fuels in about the same manner. Thus, interpretation of the results can be simplified by considering only the case where these rates are equal (P - E = 0).

The fuel cycle cost components (in thousands of U.S. $) for this case are shown in Table 6 along with the cost in $/MWd for each of the fuels. Some of the conclusions that can be drawn from Table 6 are:

- Aluminide fuel with a uranium density of 2.3 g/cm^3 and 19 thick plates would not be a good choice for conversion of this reactor since the overall fuel cycle costs would be increased by about 20%.

- A better choice would be oxide fuel with 3.0 g U/cm^3 in this element with 19 thick plates since the fuel cycle costs would be reduced by about 7%. The larger ^{235}U loading that can be achieved in the oxide fuel leads to a considerably longer operating cycle and reduced costs.

- If the irradiation testing of silicide fuel is successful, the high uranium densities offer the advantage of a simple substitution of a new fuel meat without any changes in the 23-plate HEU fuel element geometry. With 6.0 g U/cm^3 LEU silicide fuel meat, the fuel cycle costs would be about 73% of the costs with HEU fuel.

- Referring to Table 2, it is interesting to note the advantage of the thin fuel meat case with 23 plates and LEU silicide fuel over the thick fuel meat case with 19 plates and LEU oxide fuel. Both designs contain about 530 g ^{235}U per element, but, because of the larger water volume fraction with 23 thin plates, the cycle length would be about 38 days instead of 28 days and the average ^{235}U discharge burnup would be about 69% instead of 48%. This translates into fuel cycle costs of $114/MWd with the silicide element and $145/MWd with the oxide element.

- The 16-pin UZrH fuel element with erbium burnable poison has a high ^{235}U content, a long cycle length, and a high ^{235}U discharge burnup. The resulting fuel cycle costs would be about 87% of those with the reference HEU aluminide fuel.

Table 4. Additional Assumptions for Cost Comparisons

- Equilibrium Core
- Methods Based on Fuel Cycle of the ASTRA Reactor
- Batch Size of New Elements Ordered: 26 Elements
- Reactor Operated until 26 Elements Have Achieved Discharge Burnup (Spent Fuel Shipments are Usually 26 Elements)
- Costs Referred to Beginning of Fuel Cycle Using Assumptions for the ASTRA Reactor for Various Values of (P-E).

  P = Capital Interest Rate/Yr. Duty Factor = 40%

  E = Escalation Rate/Yr. (10%) (Ref.1; Appendix I)

Table 5. Cost Flow Assumptions for Fuel Cycle Cost Components

	Cost Component	Time in Months at Which Different Costs are Incurred: Shipment Cycle 1	Shipment Cycle 2
1.	Uranium Cost	0	X
2.	Ship UF_6 to Europe	0	X
3.	Convert UF_6 to U Metal	9	X + 9
4.	Fabricate Fuel Elements	9	X + 9
5.	Ship Fresh Fuel to Reactor	12	X + 12
6.	Ship Spent Fuel to U.S.	X + 18	2X + 18
7.	Reprocessing Cost	X + 24	2X + 24
8.	Uranium Credit	X + 30	2X + 30

X = Resident Time for Burnup of 26 Fuel Elements

Fig. 4. Fuel Cycle Costs vs. P-E for Ref. HEU Fuel and LEU Fuels

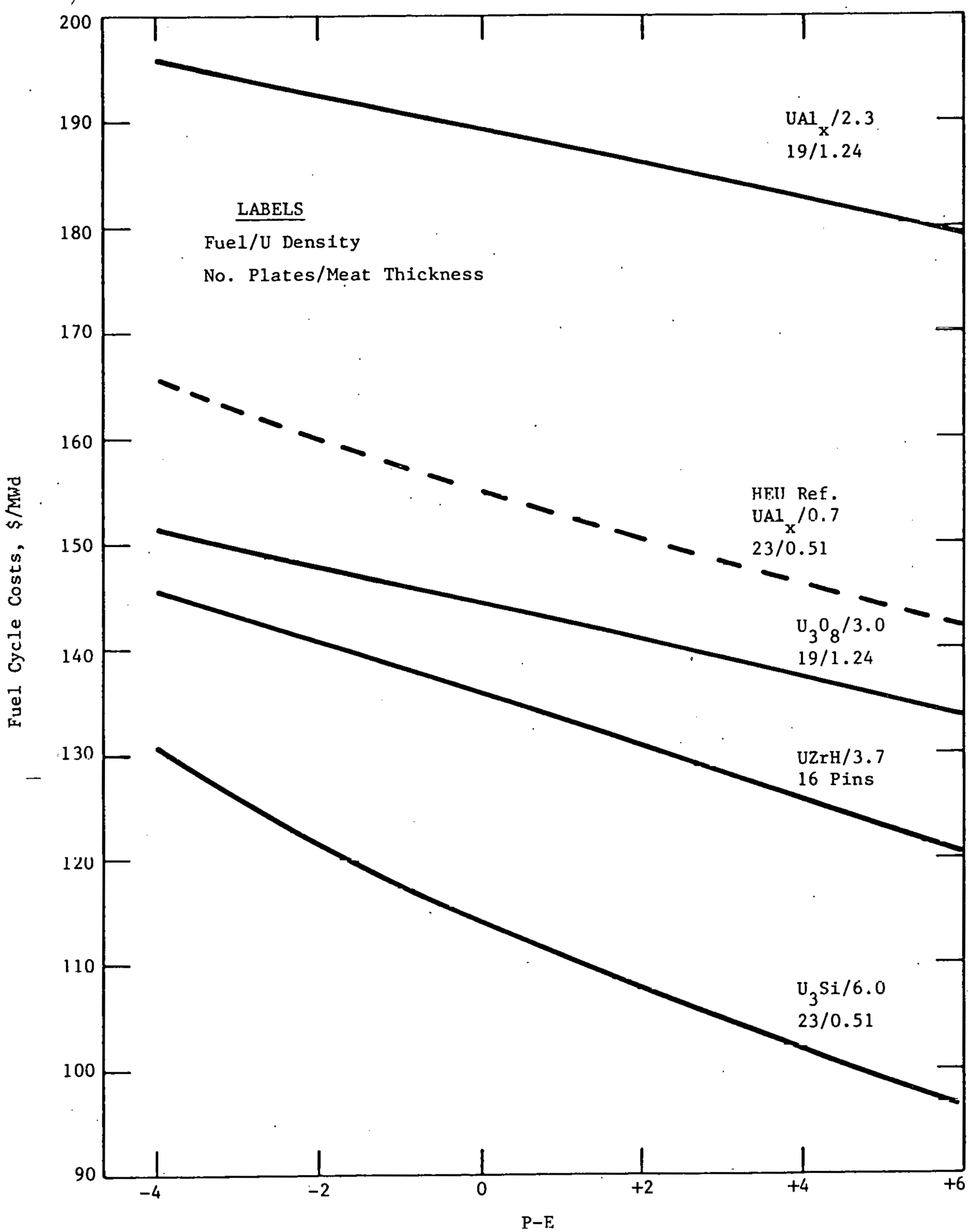


Table 6. COST COMPARISON (P-E = 0)
($000)

FUEL	U COST	FABR.[a] COST	SHIP FRESH FUEL	SHIP SPENT FUEL	REPR. COST	URANIUM CREDIT	TOTAL	MWD	$/MWD
UAl_x-Al (HEU Ref.)	341	172	18	82	48	-113	548	3524	156
UAl_x-Al	482	232	41	82	71	-232	676	3575	189
U_3O_8-Al	639	232	50	82	65	-275	793	5478	145
U_3Si-Al	631	232	50	82	62	-146	911	7964	114
UZRH	1094	575	76	82	50	-397	1480	10871	136
CARAMEL	567	232[b]	116	82	154	-213	938	4797	195
		464					1170		244
		928					1634		341

[a]Fabr. costs for LEU UAl_x-Al, U_3O_8-Al, and U_3Si-Al assumed to be 1.35 x HEU Ref. ($6600/element).

[b]Fabr. costs for CARAMEL parameterized as (1.35, 2.7, and 5.4) x HEU Ref.

Table 7. COST COMPONENT COMPARISON (P-E = 0)

(Percent of Total)

FUEL	U COST + U CREDIT	FABR.[a] COST	SHIP FRESH FUEL	SHIP SPENT FUEL	REPR. COST
UAl_x-Al (HEU Ref.)	41.6	31.4	3.3	15.0	8.8
UAl_x-Al	37.0	34.3	6.1	12.1	10.5
U_3O_8-Al	45.9	29.3	6.3	10.3	8.2
U_3Si-Al	53.2	25.5	5.5	9.0	6.8
UZRH	47.1	38.9	5.1	5.5	3.4
CARAMEL	37.7	24.7[b]	12.4	8.7	16.4
	30.3	39.7	9.9	7.0	13.2
	21.7	56.8	7.1	5.0	9.4

[a]Fabr. costs for UAl_x-Al, U_3O_8-Al, and U_3Si-Al assumed to be 1.35 x HEU Ref. ($6600/element)

[b]Fabr. costs for CARAMEL parameterized as (1.35, 2.7, and 5.4) x HEU Ref.

- As mentioned above, the fabrication cost for the caramel fuel was treated as a parameter in this study since information on this fuel cycle component was not available. Using a fabrication cost factor of 1.35 in comparison with the reference HEU fuel, the fuel cycle cost was computed to be $195/MWd, about 25% higher than the HEU case. Overall costs rise sharply if higher fabrication costs are assumed.

In Table 7, the cost components are broken down as a percentage of the total for each of the fuels. As expected, enriched uranium costs and fabrication costs are the major components, and these constitute 65 - 85% of the totals.

Conclusion

The conclusion of this study is that there are excellent opportunities for reducing fuel cycle costs in conversions from HEU to LEU if the LEU fuels that are being developed and tested are successful and if all safety considerations allow. The cost reductions described here are the direct result of the longer cycle lengths that can be obtained with increased ^{235}U loadings. Each reactor is an individual case and fuel cycle economics should, along with safety considerations, be an integral part of choosing the optimal fuel and fuel element design for conversion to LEU.

Ref. 1: "IAEA Guidebook on Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels," IAEA-TECDOC-233, August 1980.