A NEUTRONIC FEASIBILITY STUDY FOR LEU CONVERSION OF THE SAFARI-1 REACTOR*

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ABSTRACT

A neutronic feasibility study to convert the SAFARI-1 reactor from HEU to LEU fuel was performed at Argonne National Laboratory in cooperation with NECSA. Comparisons were made of the reactor performance with the current 90% enriched HEU fuel type (UAl) and two 19.75% enriched LEU fuel types (U_3Si_2 and U7Mo). The thermal fluxes with the LEU fuels were 3 - 9% lower than with the current HEU fuel. For the same fuel assembly design, a uranium density of approximately 4.5 g/cm^3 was required with U_3Si_2-Al fuel and a uranium density of about 4.6 g/cm^3 was required with U7Mo-Al fuel to match the 24.6-day cycle of the UAl-alloy fuel with 0.92 gU/cm^3. The selection of a suitable LEU fuel and the decision to convert SAFARI-1 will be an economic matter that depends upon the fuel type, fuel assembly design, experiment performance and fuel cycle costs.

INTRODUCTION

Based on an agreement on conversion studies dated June 1999, the RERTR Program at Argonne National Laboratory, in cooperation with NECSA (formally, Atomic Energy Corporation of South Africa), agreed to perform reactor neutronic calculations that would provide data to help evaluate the economics of a converted reactor operation. A previous 1994 neutronics study[1,2] gave some similar results using LEU silicide fuel.

Reactor performance evaluations were made for standard MTR-type fuel assemblies with 18 - 23 plates, 300 - 354 g ^{235}U and 22 - 28 day fuel cycles. Very similar flux performances were obtained for all fuel assembly designs giving wide latitude to make economic decisions. This report, therefore, gives only reactor performance results with no preference as to which LEU fuel assembly design might be chosen by NECSA. The safety of the SAFARI-1 reactor with the chosen LEU fuel will be the subject of a future study.

SAFARI-1 AND FUEL ASSEMBLY DESCRIPTIONS

The SAFARI-1 reactor is a 20MW pool-type materials test reactor with MTR-type standard fuel and cadmium control rods with follower fuel assemblies. The reactor is an 8 by 9 matrix with 27-standard and 6-follower assemblies, several Al, Be, Pb and H_2O reflector assemblies, and several in-core and ex-core experimental locations. The reactor is reflected on all four sides and the top and bottom with water. Figure 1 is a model of the reactor with 2.5-cm thick core-box walls on three sides and a 3.5-cm wall separating it from the pool side facility.

Flux monitors located in the following positions are used to compare the calculated thermal and total fluxes for the current HEU fuel and for each LEU fuel assembly: high-flux positions D6 and F6; thimble positions C3, E3, G3 and B8, D8, F8; fast-irradiation position A3; rabbit positions E9 and G9; and several poolside positions near the core-box wall in column 5.

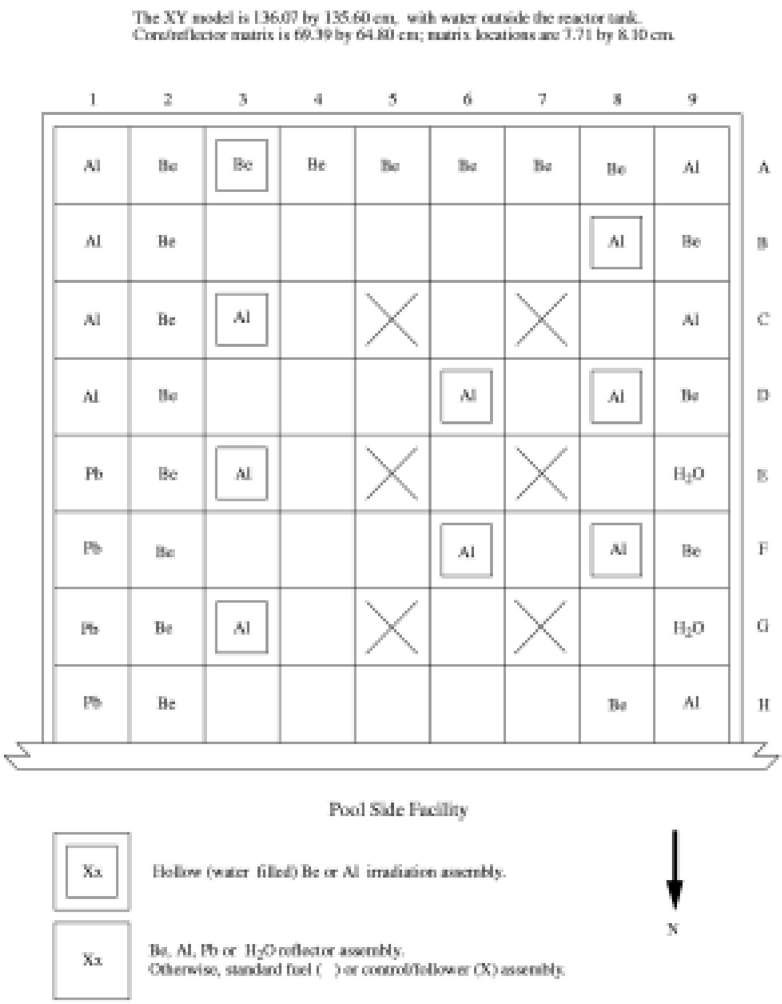

Fig. 1. SAFARI-1 Model Plan View

Table 1. MTR-Type Fuel Assembly Designs

Plates: Stnd / Foll	Meat[a,b], cm	Channel, cm: Stnd / Foll
18 / 14	0.0760	0.2914 / 0.3022
19 / 15	0.0508	0.2932 / 0.2971
20 / 16	0.0760	0.2470 / 0.2454
23 / 18	0.0508	0.2200 / 0.2263

[a] Standard fuel meat dimensions: meat thickness by 6.35 cm wide by 59.37 cm high; total meat, clad and channel thickness, 7.9933 cm.
[b] Follower fuel meat dimensions: meat thickness by 6.03 cm wide by 59.37 cm high; total meat, clad and channel thickness, 6.3690 cm.

Table 1 summarizes the MTR-type fuel assembly designs. The number of standard and follower fuel plates, the fuel meat thickness and the water channel thicknesses are shown. In all cases, the meat-clad thickness is 0.03835 cm.

The HEU fuel type is UAl-alloy fuel with 90% enrichment and 28-wt% uranium; the standard and follower fuel assemblies contain 19 and 15 fueled plates, respectively. The two 19.75% enriched LEU dispersion type fuels are U_3Si_2-Al and U7Mo-Al. The assemblies with these LEU fuels have from 18 - 23 standard plates and 14 - 18 follower plates. The water channel thicknesses in both the standard and follower fuel assemblies are nearly the same.

REACTOR MODEL CALCULATIONS

Nuclear cross sections for each fuel assembly design (Table 1) were made using ENDF/B-VI nuclear data and the WIMS-ANL cross section code[3]. These cross sections were then used with the REBUS-3 fuel cycle code[4] to determine the burnup characteristics of the standard and follower fuel assemblies in the SAFARI-1 reactor model (Fig. 1). The DIF3D diffusion theory code[5] was used to calculate neutron fluxes in the experiment locations. The calculations were made using the 7-group energy structure (maximum energy, 10 MeV) shown in Table 2.

Table 2. Neutron Energy Group Structure

Group- Lower Boundary, eV	1- 8.21+5	2- 5.53+3	3- 4.00+0	4- 6.25-1	5- 2.50-1	6- 5.80-2	7- 1.00-5

An equilibrium fuel-shuffling pattern was used to move fuel from the core perimeter towards the core center. This pattern is shown in Table 3. The standard fuel is moved every operation cycle and the follower fuel is moved every fourth operation cycle. Fresh fuel is inserted in positions H3, H7 and G8, and spent fuel is discharged from positions F5, E6 and D5. Follower fuel is inserted in G7 and C7, moved to C5 and E7, and discharged from E5 and G5.

Table 3. Standard and Follower-Fuel Shuffling Patterns

Standard Path #1	Standard Path #2	Standard Path #3	Follower Path #1	Follower Path #2
H3 H4 C8	H7 H6 B3	G8 H5 E8	G7 G7 G7 G7	C7 C7 C7 C7
B7 G4 D3	B4 F3 G6	F7 B6 D7	C5 C5 C5 C5	E7 E7 E7 E7
F4 D4 F5	B5 E4 E6	C4 C6 D5	E5 E5 E5 E5	G5 G5 G5 G5

FUEL CYCLE RESULTS

A summary of the fuel assemblies used in this investigation is shown in Table 4. This table shows the fuel type, the number of standard and follower plates in the fuel assembly, the uranium density in the fuel meat, and the ^{235}U mass per assembly. Some results of the fuel cycle calculation for each fuel assembly are also shown. These include the fuel cycle length, the beginning-of-equilibrium-cycle (BOEC) eigenvalue, and the ^{235}U discharge burnup of the standard and follower fuels.

The reference HEU fuel assemblies are 90% enriched, UAl-alloy fuel with 19-plate, 300 g^{235}U standard fuel and 15-plate, 200 g^{235}U follower fuel. These fuel assemblies have a 24.6-day operation cycle time in SAFARI-1. The fuel cycle characteristics of LEU fuel assemblies with 19.75% enriched U_3Si_2-Al and U7Mo-Al dispersion fuels were also calculated. These calculations were intended to span a range of LEU fuel assemblies. Masses were varied from 300 to 354-g^{235}U, cycle lengths from 22 to 28 days, and standard fuel assembly designs from 18 to 23 plates. Associated follower fuel assemblies with 14 to 18 plates were included with a uranium density that is 89% of the standard fuel density (same as the reference HEU fuel assemblies).

Table 4 shows separate sections for the reference HEU fuel and for each LEU fuel type in which the fuel cycle length or the fuel assembly mass was adjusted to force the EOEC eigenvalue to be same as the HEU core eigenvalue (1.0060). For a given ^{235}U mass, the fuel cycle length was determined that gave an end-of-cycle excess reactivity of 0.6% $\delta k/k^2$. For a given 24.6 day fuel cycle, the ^{235}U mass was determined so that the end-of-cycle excess reactivity was 0.6% $\delta k/k^2$. Although there are large changes in various fuel assembly parameters (plates, ^{235}U mass, cycle length, etc.), the reactor fluxes are not substantially different (see Figs. 2 and 3). These types of parameters will affect the fuel costs.

The results also show that in SAFARI-1, there is not much difference in the uranium density between U_3Si_2 and U7Mo dispersion fuels given the same fuel assembly configuration (19/15 plates) and fuel cycle length (24.6 day). This fuel assembly design requires a uranium density of 4.47 g/cm^3 in U_3Si_2-Al fuel and a uranium density of 4.58 g/cm^3 in U7Mo-Al fuel. U_3Si_2-Al fuel has been extensively qualified[6] for uranium densities up to 4.8 g/cm^3. U7Mo-Al fuel has good prospects for qualification with uranium densities of 8 - 9 g/cm^3 based on irradiation testing[7,8] of small samples in the Advanced Test Reactor in Idaho. Irradiation and post-irradiation examinations of full-size fuel assemblies need to be performed.

Table 4. Fuel Assembly Specifications and Equilibrium Fuel Cycle Characteristics

Enrichment: Fuel Type	Plates Stnd / Foll	Uranium Density[a], g/cc	^{235}U Mass, g	Cycle Length, d	BOEC k-eff[b]	Discharge Burnup[c], %
HEU: UAl-alloy	19 / 15	0.916 / 0.815	300 / 200	24.6	1.0496	59.5 / 79.3
LEU: U_3Si_2-Al	18 / 14	3.34 / 2.97	340.0 / 223.5	25.5	1.0375	51.6 / 70.9
	19 / 15	4.73 / 4.21	340.0 / 226.9	27.1	1.0396	54.6 / 73.8
	19 / 15	4.17 / 3.72	300.0 / 200.2	21.8	1.0366	50.1 / 68.9
	20 / 16	3.00 / 2.67	340.0 / 229.9	24.3	1.0347	49.1 / 66.9
	23 / 18	3.91 / 3.48	340.0 / 224.9	24.9	1.0361	50.3 / 69.1
	18 / 14	3.27 / 2.91	332.7 / 218.7	24.6	1.0368	50.9 / 70.1
	19 / 15	4.47 / 3.97	320.9 / 214.1	24.6	1.0382	52.7 / 71.8
	20 / 16	3.03 / 2.69	342.6 / 231.6	24.6	1.0350	49.3 / 67.2
	23 / 18	3.88 / 3.45	337.5 / 223.2	24.6	1.0358	50.1 / 68.9
LEU: U7Mo-Al	19 / 15	4.92 / 4.38	353.6 / 235.9	28.1	1.0392	54.4 / 73.6
	19 / 15	4.45 / 3.96	320.0 / 213.5	23.5	1.0367	50.5 / 69.6
	19 / 15	4.58 / 4.07	328.9 / 219.4	24.6	1.0375	51.3 / 70.6

[a] Follower density is 89% of the standard density. Enrichment: HEU-90% and LEU-19.75%.
[b] Average end-of-equilibrium-cycle (EOEC) eigenvalue, k-eff = 1.0060 ± 0.0001.
[c] Discharge (^{235}U): standard fuel, 3 per cycle; follower fuel, 2 per 4 cycles; reactor power, 20 MW.

NEUTRON FLUX RESULTS

Calculated neutron fluxes in the (average) experiment positions of SAFARI-1, for each fuel assembly of Table 4, are shown in Figs. 2 and 3. Figure 2 shows the thermal (< 0.625 eV) and total neutron flux for the reference 90%-enriched HEU fuel and for the seven 19.75%-enriched LEU fuel assemblies that have adjusted fuel cycle lengths. The LEU fuel thermal fluxes in the experiment locations are nearly flat and differ from the HEU fuel thermal flux by about 3 - 9% depending on location. Similar LEU fuel total fluxes in each location are flat and less than 6% different than the HEU fuel total flux. In all experiment locations there is a relatively small penalty in the thermal flux and an even smaller difference in the total flux. The pool side facility has the largest impact on the fluxes.

Similar thermal and total neutron flux data for the reference HEU fuel and the five LEU fuel assemblies that have adjusted fuel assembly masses are shown in Fig. 3. These data are also flat with similar variations in the thermal and total flux, all relative to the HEU fluxes. The flux comparison with the 19/15 plate U_3Si_2 and U7Mo fuels are clearly seen in Fig. 3.

Both Figs. 2 and 3 indicate that as the LEU fuel cycle length and loading increase, all fluxes remain about the same. There is no significant advantage to increase the ^{235}U loading and increase the cycle length from the point of view of flux performance.

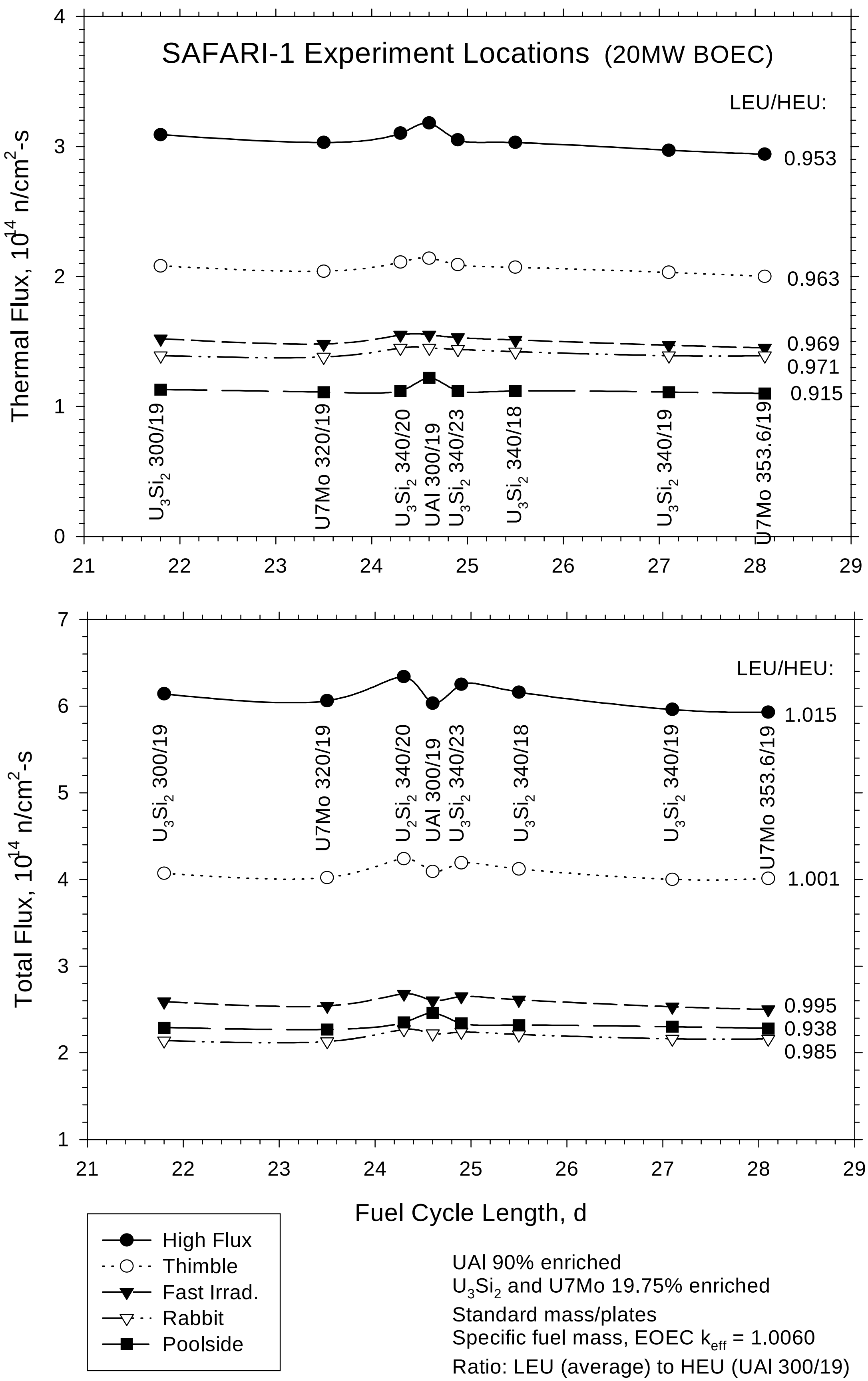

Fig. 2. Thermal and Total Flux - Adjusted Fuel Cycle Length.

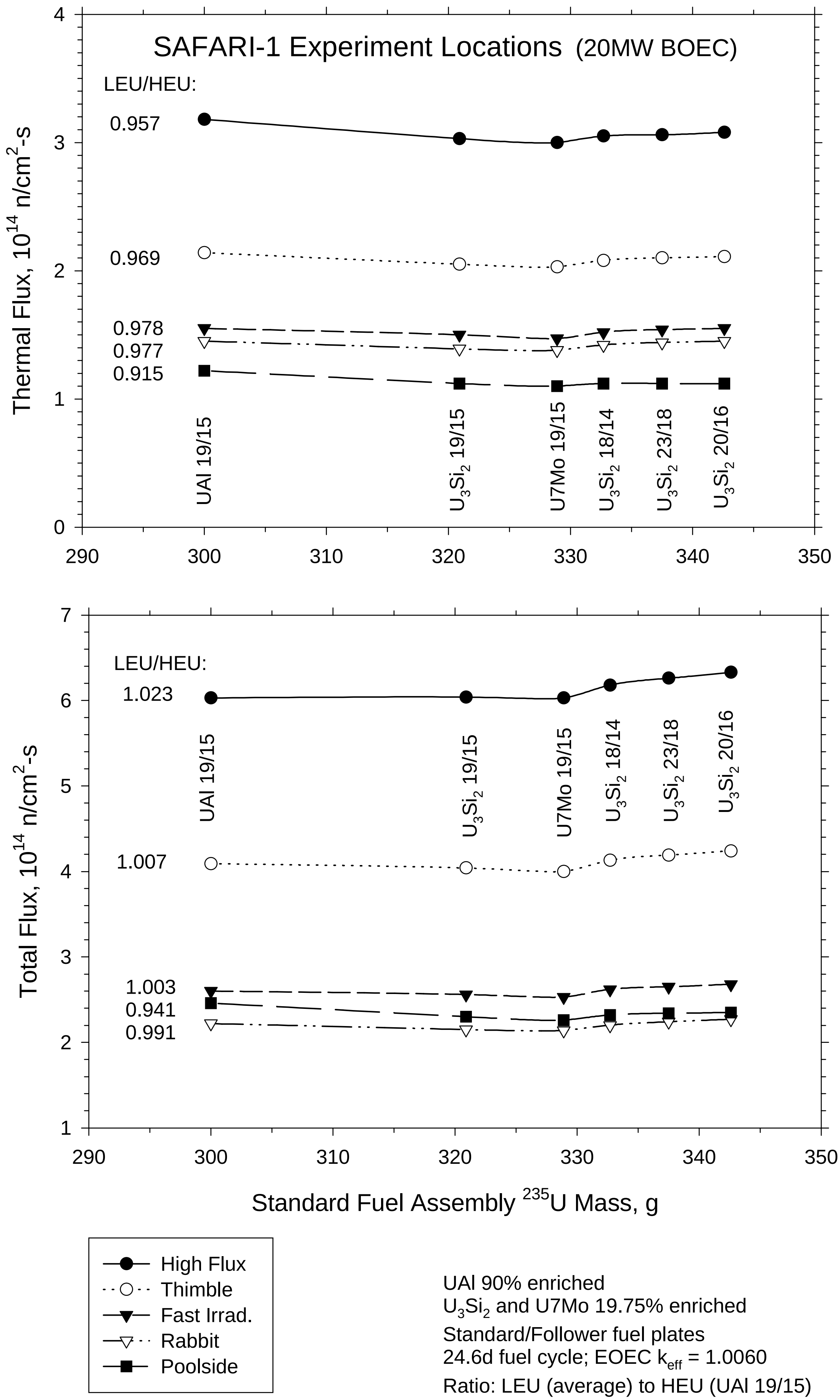

Fig. 3. Thermal and Total Flux - Adjusted Fuel Assembly Mass.

FUEL ASSEMBLY FABRICATION ESTIMATES

Table 5 shows for each HEU and LEU fuel type, the number of operating cycles per year and the number of fuel assemblies/fuel plates needed per year. These numbers assume 294 effective-full-power-days per year of reactor operation, the calculated fuel cycle length and 20 MW power. Each year, depending upon the fuel cycle length, the SAFARI-1 reactor is estimated to need 42 fuel assemblies, consisting of 700 - 900 fuel plates.

Two extreme U_3Si_2 examples are 39 assemblies/717 plates with 340 g^{235}U per standard assembly and 50 assemblies/918 plates with 300 g^{235}U per standard assembly. In these two examples the fuel cycle lengths are 27.1 and 21.8 days, respectively. A U7Mo fuel type also uses 39 assemblies/717 plates with 353.6 g^{235}U per standard assembly and has a fuel cycle length of 28.1 days.

These data are provided to help compare fabrication requirements. The fuel assembly/plate costs associated with Table 5, together with the fuel material/uranium costs associated with Table 4, will determine an important part of the overall fuel costs for the SAFARI-1 reactor operation.

Table 5. Fuel Assemblies and Fuel Plates Fabricated per Year

Enrichment: Fuel Type	Plates Stnd / Foll	Cycle Length, d	Cycles/ Year[a]	Fuel Assemblies[b]			Fuel Plates		
				Stnd	Foll	Total	Stnd	Foll	Total
HEU: UAl-alloy	19 / 15	24.6	12.0	36	6	42	684	90	774
LEU: U_3Si_2-Al	18 / 14	25.5	11.5	36	6	42	648	84	732
	19 / 15	27.1	10.8	33	6	39	627	90	717
	19 / 15	21.8	13.5	42	8	50	798	120	918
	20 / 16	24.3	12.1	39	8	47	780	128	908
	23 / 18	24.9	11.8	36	6	42	828	108	936
	18 / 14	24.6	12.0	36	6	42	648	84	732
	19 / 15	24.6	12.0	36	6	42	684	90	774
	20 / 16	24.6	12.0	36	6	42	720	96	816
	23 / 18	24.6	12.0	36	6	42	828	108	936
LEU: U7Mo-Al	19 / 15	28.1	10.5	33	6	39	627	90	717
	19 / 15	23.5	12.5	39	8	47	741	120	861
	19 / 15	24.6	12.0	36	6	42	684	90	774

[a] Reactor operation: 20 MW power and 294 efpd per year. Enrichment: HEU-90% and LEU-19.75%.
[b] Three standards and 0.5 followers replaced per cycle, rounded to the next multiple of 3 and 2, respectively.

CONCLUSIONS

Comparisons, without costs, are made for the current HEU 90%-enriched UAl-alloy fuel and a number of LEU fuel options with 19.75%-enriched U_3Si_2-Al and U7Mo-Al dispersion fuels for the possible conversion of the SAFARI-1 reactor.

The results show that there is 3 - 9% lower thermal flux (< 0.625 eV) with LEU fuel than with HEU fuel. The differences are dependent upon the flux location in the reactor. The largest difference is in the pool side facility.

On an annual basis, some LEU fuels require fewer assemblies with more ^{235}U per assembly and some fuels require more assemblies with less ^{235}U per assembly. The net fuel cost, together with the difference in the fuel cycle length, could be a factor in determining the LEU fuel assembly selection. There is no substantial flux advantage to change the ^{235}U mass loading or the fuel cycle length.

The performance difference with silicide and molybdenum dispersion fuel types is small; the U7Mo fuel density is 2.5% larger than the U_3Si_2 fuel density given the same fuel assembly parameters. Depending upon the fuel cycle length, between 39 and 50 fuel assemblies (700 and 900 fuel plates) would be required for one year of reactor operation. The estimated requirement of the current HEU fuel and some LEU fuels are 42 assemblies with 800 plates.

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