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PERFORMANCE AND FUEL CYCLE COST STUDY OF THE R2 REACTOR WITH HEU AND LEU FUELS

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ABSTRACT

A systematic study of the experiment performance and fuel cycle costs of the 50 MW R2 reactor operated by Studsvik Energiteknik AB has been performed using the current R2 HEU fuel, a variety of LEU fuel element designs, and two core-box/reflector configurations. The results include the relative performance of both in-core and ex-core experiments, control rod worths, and relative annual fuel cycle costs.

INTRODUCTION

This paper presents the results of the initial phase of a joint study between the Reduced Enrichment Research and Test Reactor (RERTR) Program at the Argonne National Laboratory and Studsvik Energiteknik AB on the options available for conversion of the 50 MW R2 reactor from HEU (93%) to LEU (<20%) fuel.

Systematic studies of experiment performance, control rod worths, and fuel cycle costs were performed with the current HEU UAl_x-Al fuel and eight cases with LEU U_3O_8-Al, U_3Si_2-Al and U_3Si-Al fuels for two reactor pressure vessel (core-box) and reflector designs. The two designs represent the core-box/reflector configuration existing prior to July 1984 and a new replacement core-box/reflector configuration that is currently being installed.

Studies addressing reactor safety issues such as thermal-hydraulic safety margins, mixed transition cores, and transient analyses are in progress.

MODELS

MASTER

Reactor Cores

Horizontal cross sections of the two R2 core-box/reflector configurations that were studied are shown in Fig. 1. In both Configurations 1 and 2, the 8 by 8 element active cores consist of 44 standard fuel elements, 6 control/fuel follower elements, 7 in-core experiment positions, and 7 empty and dummy aluminum elements.

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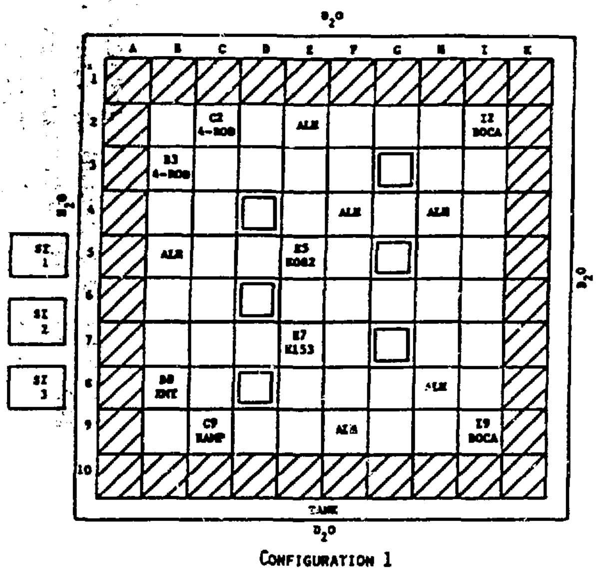


Fig. 1. Horizontal Cross Sections of the R2 Reactor with the Old Core-Box/Reflector Design (Conf. 1) and the New Core-Box/Reflector Design (Conf. 2).

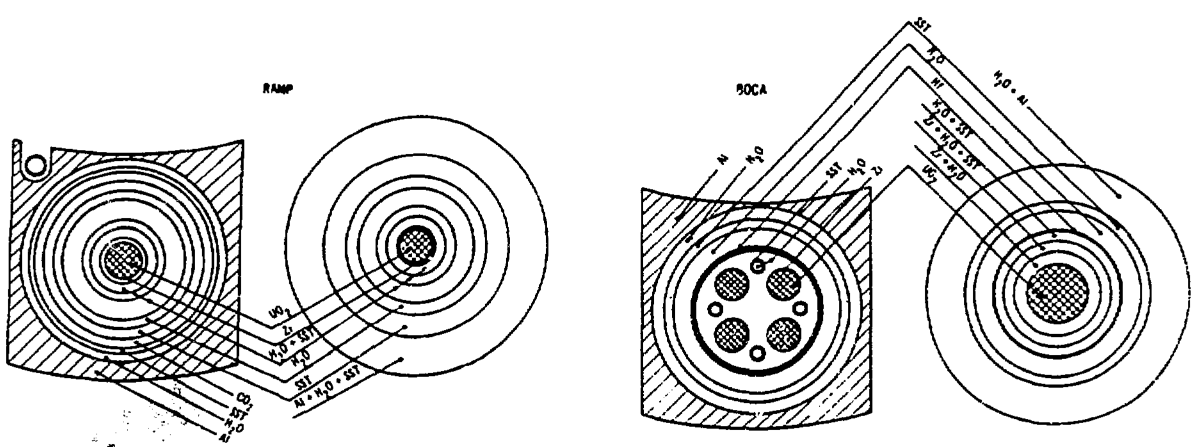


Fig. 2. Actual Geometry and Calculational Model for the RAMP and BOCA Experiments.

On three sides, the core-box is immersed in a pool of heavy water inside the reactor pressure vessel. The fourth side is a light water poolside facility located outside the reactor vessel. Beryllium reflector elements surround the core in the old core-box design (Conf. 1), but are located on only two sides in the new core box design (Conf. 2). Three silicon irradiation targets are on the light water side.

The dimensions of the grid locations represented in Fig. 1 by the lettered columns are 7.7 cm and by the numbered rows are 8.1 cm. The active core height is 60 cm with 15.5 cm top and bottom end-fittings on the in-core positions, and 7.5 cm end-fittings on the 76 cm-long beryllium reflector elements. Light water axial reflectors are represented above and below the reactor and the radial reflectors.

Experiments

Models of two of the seven in-core experiments are shown in Fig. 2. A representation of the actual geometry of the RAMP and the two BOCA experiments in the core are shown on the left and the corresponding calculational models specified by Studsvik are shown on the right. The four other experiments labeled 4-ROD, K082, and K153 in Fig. 1 were modeled in similar detail.

Fuel Element Loadings

The fuel element designs that were studied are listed in Table 1. The reference HEU element has 19 plates with 0.51 mm UAl_x meat and the eight LEU elements have 19, 18, and 17 plates with 0.51, 0.76, and 1.0 mm-thick fuel meat, respectively. All designs have a water channel thickness of about 2.95 mm.

The control/fuel follower element associated with each type of standard fuel element has four fewer fuel plates. In all cases, the ratio of standard to follower fuel fissile loading is a constant based upon the 250 g and 158 g loadings for the reference HEU elements. The LEU standard elements range between 275 and 490 g ^{235}U per element and the associated follower fuel elements range between 174 and 310 g ^{235}U per element.

The fuel types used for each design option were chosen on the basis of the following maximum uranium densities: 3.2 g U/cm^3 in U_3O_8-Al fuel, 4.8 g U/cm^3 in U_3Si_2-Al fuel and 7.0 g U/cm^3 in U_3Si-Al fuel. Since neutronics calculations are not sensitive to the dispersed phase, U_3Si_2-Al fuel could be substituted for U_3O_8-Al fuel and U_3Si-Al fuel could be substituted for either U_3Si_2-Al fuel or U_3O_8-Al fuel with very nearly the same reactor and experiment performance. However, fuel fabrication costs could be affected by changing the dispersed phase.

Burnable poisons which might be required in the heavier loaded LEU elements are being addressed as part of the continuing joint study between ANL and Studsvik.

Table 1. LEU Fuel Element Designs Studied

FUEL ELEMENT DESIGNS[a]

No. Plates per Element		Fuel Meat Thickness, mm	Water Channel Thickness, mm	Fuel Meat Volume per Element, cm^3	
Standard	Control			Standard	Control
19	15	0.51	2.953	366.28	289.17
18	14	0.76	2.938	517.10	402.19
17	13	1.00	2.960	642.60	491.40

[a]Fuel Meat: Width = 63 mm, Length = 600 mm. Clad thick.: 0.38 mm on inner plates, 0.57 mm on outer plates of standard elements and 0.38 mm on all plates of control elements. LEU = 19.75% enrichment.

FUEL ELEMENT LOADINGS

Standard			Control			
Plates/ Element	^{235}U/Element, g	ρ_U, g/cm^3	Plates/ Element	^{235}U/Element, g	ρ_U, g/cm^3	Fuel Type
19 HEU	250	0.734	15	158	0.588	UAl_x
19 LEU	330	4.562	15	209	3.660	U_3Si_2
19 LEU	490	6.774	15	310	5.428	U_3Si
18 LEU	275	2.693	14	174	2.191	$U_3O_8(U_3Si_2)$
18 LEU	326	3.192	14	206	2.593	$U_3O_8(U_3Si_2)$
18 LEU	490	4.798	14	310	3.903	U_3Si_2
17 LEU	334	2.632	13	211	2.174	$U_3O_8(U_3Si_2)$
17 LEU	405	3.191	13	256	2.638	$U_3O_8(U_3Si_2)$
17 LEU	490	3.861	13	310	3.194	U_3Si_2

Cross Sections

Microscopic cross sections in five energy groups were prepared using the EPRI-CELL code for each of the standard and control element geometries and ^{235}U loadings that are listed in Table 1. The upper energy boundaries for the five groups were 10 MeV, 0.821 MeV, 5.53 keV, 1.855 eV, and 0.625 eV. Separate cross sections were generated for the side plates of the fuel elements, the silicon irradiation targets, the dummy aluminum filler elements, the empty element, the element end-fittings and the various reflector materials.

Cross sections for each of the in-core experiments were calculated using the unit-cell models shown in Fig. 2 assuming, in addition, that each experiment was surrounded by a large core (driver) region. The cadmium cross sections for the control rods were calculated as outlined in Ref. 1.

Fuel Cycle

In actual operation, the 44 standard elements are removed from the core after each cycle and replaced with about 6 fresh elements and about 38 partially burned elements that are free of xenon. On the average, one control/follower element is replaced every two cycles. The standard elements are used for 7 or 8 cycles and each follower element has a residence time of about 12 cycles. In Conf. 1, the average ^{235}U burnup in the HEU elements at discharge is ~57% and that in the follower fuel elements is ~74%.

The REBUS3 burnup code was used to calculate the equilibrium fuel cycle with each of the HEU and LEU fuel types in both Confs. 1 and 2 using a fuel replacement pattern that was specified by Studsvik. The calculations were done in two dimensions with axial extrapolation lengths determined from three dimensional fresh core models. All cases were run such that the end-of-cycle excess reactivity was the same as that calculated for HEU fuel in Conf. 1.

EXPERIMENT PERFORMANCE RESULTS

Performance results for each experiment are stated in terms of an LEU/HEU performance index. For the RAMP, 4-ROD, and BOCA experiments, the performance index was the LEU/HEU midplane power density ratio in each experiment. For the K082 and K153 experiments, the index was the average midplane flux ratio by energy group and in the silicon targets, it was the average midplane absorption reaction rate ratio. In the heavy water reflector where the beam tubes are located, the index was the LEU/HEU peak midplane thermal flux ratio in Row 6.

Figure 3 shows the performance results for three of the in-core experiments (RAMP, I9 BOCA, and K153). For all of the experiments, the performance index is nearly a linear function of the ^{235}U content of the fuel elements. The results also show that some of the experiments tend to be sensitive to the number of plates per element, while other experiments are insensitive. In general, when the experiment performance depends on the number of plates per element, it is highest with the 17-plate design and lowest with the 19-plate design.

There is some performance loss in almost all of the R2 experiments when LEU fuel is substituted for HEU fuel. In most of the experiments the performance also decreases with increasing fissile loading. With a standard fuel element fissile loading of about 330 g the performance indices are smaller by about 4-12% in the experiments requiring thermal neutrons while the fast flux experiment (K153) shows about the same or slightly higher performance index. The experiment performance increases in the silicon irradiation targets with increasing fissile loading.

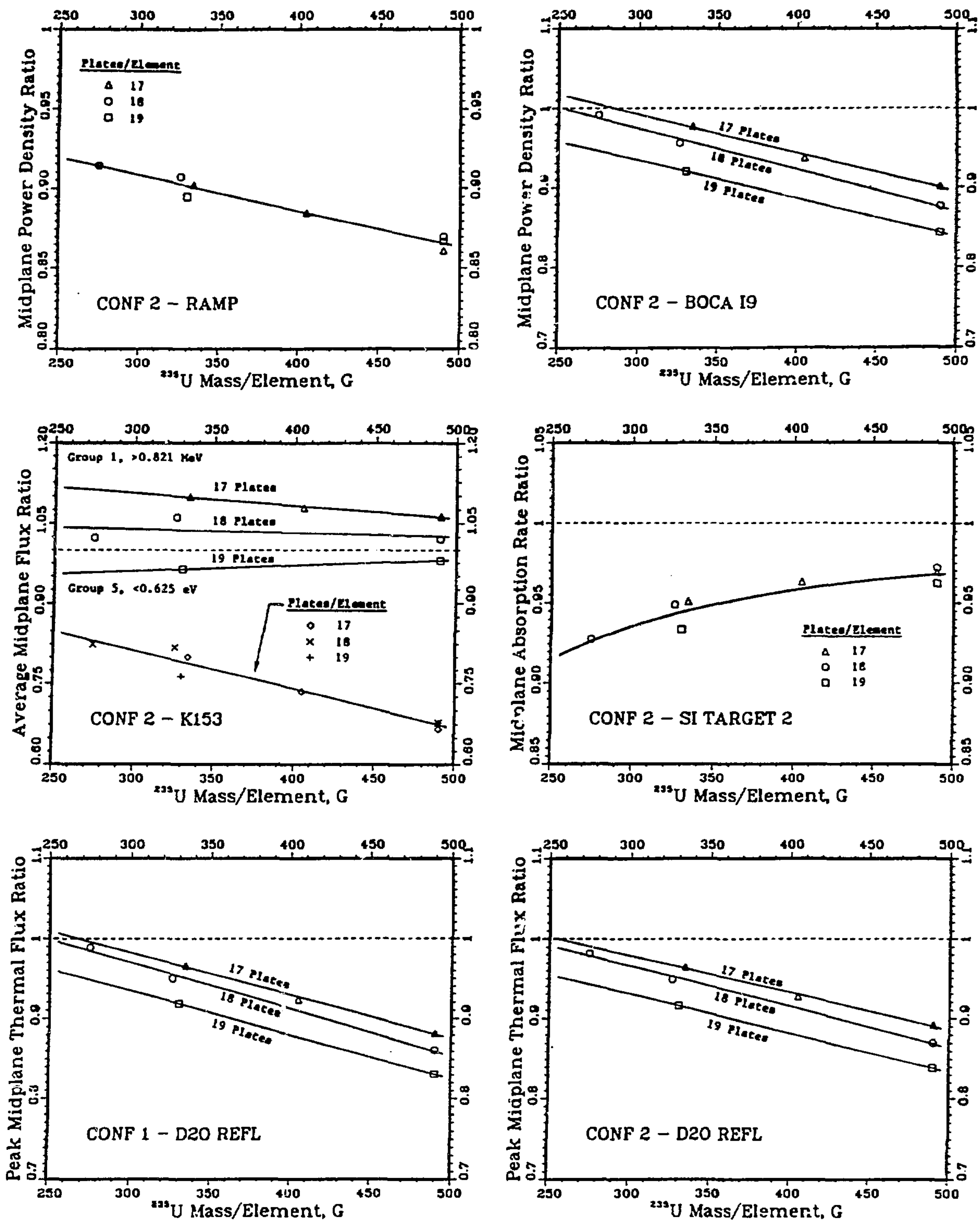


Fig. 3. Plots of the Experiment Performance Index vs. Standard LEU Fuel Element Fissile Loading for the RAMP, the I9 BOCA, K153, and the Silicon Target No. 2 in Conf. 2, and for the D_2O Radial Reflector in Confs. 1 and 2.

Ex-Core Experiments

The performance of the ex-core experiments is influenced by the different H_2O and D_2O reflector regions in Confs. 1 and 2. In addition, since the experiment performance depends upon the leakage flux, the proximity of the experiments to the core is also an important factor.

Figure 4 shows a midplane thermal flux traverse through Row 6 for both Confs. 1 and 2. Case 1 is for Conf. 1 in which the beryllium reflector is present in the A and K columns and Case 2 is for Conf. 2 in which beryllium is not present. A Case 3 is also shown in which the beryllium in the A and K columns is replaced with aluminum.

With the old core-box (Conf. 1) and beryllium reflectors on all four sides, the peak thermal flux in the radial H_2O and D_2O reflector regions occurs at the outer edge of the core-box. With the new core-box (Conf. 2), the peak thermal flux on the H_2O side is about 2 cm outside the core-box, and on the D_2O side about 7 cm outside the core-box. Overall, there is an increase of about 25% in the peak thermal flux in the H_2O and D_2O reflectors with the new core-box design. The same principles apply with LEU fuel as well as with HEU fuel.

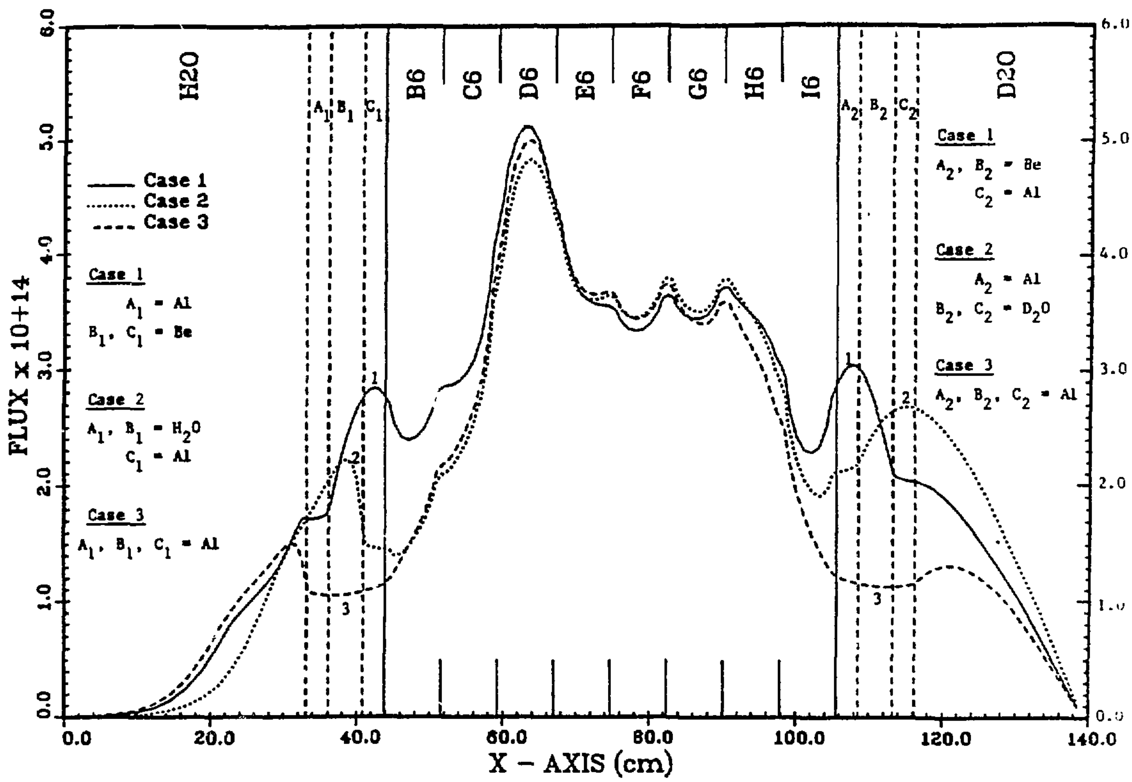


Fig. 4. Midplane Thermal Flux Traverse through Row 6 in Confs. 1 and 2.

The results in Fig. 4 also show the much different flux profile in the H_2O and D_2O reflectors when the core is reflected with beryllium (Case 1) versus aluminum (Case 3). Note also that the flux peak in control rod position D6 is not realistic because the equilibrium fuel cycle model that was used over predicts the burnup in the follower fuel.

CONTROL ROD WORTHS

The control rods in the R2 reactor (Fig. 1) are located in grid positions G3, D4, G5, D6, G7, and D8. They are cadmium box-type rods with attached fuel followers.

In a reactor model that is very similar to that of Conf. 2, rod worths were calculated using both Monte Carlo and diffusion theory in cores with the HEU elements and with two of the LEU element designs. Relative to all rods being inserted, rod worths were calculated for 100% withdrawn rods, for 50% withdrawn rods, and for the rod of maximum worth (position G3) stuck out of the core.

The results shown in Table 2 indicate that the rod worths decrease as the ^{235}U loading per element increases and that there is good agreement between the different calculational techniques for the HEU fuel and for the 326 g and 490 g LEU fuel cases.

Table 2. R2 Control Rod Reactivity Worths as a Function of Fuel Element Type and the Calculational Method.

Calculational Method[a]	HEU, 250 g ^{235}U 19 Plates/Element	LEU, 326 g ^{235}U 18 Plates/Element	LEU, 490 g ^{235}U 18 Plates/Element
	All Rods Withdrawn, % $\Delta k/k$		
Monte Carlo	17.3 ± 0.3[b]	16.9 ± 0.3	14.6 ± 0.3
Diffusion	17.4	17.1	15.2
	All Rods 50% Withdrawn, % $\Delta k/k$		
Monte Carlo	11.0 ± 0.3	10.9 ± 0.4	9.2 ± 0.4
Diffusion	11.2	11.1	9.8
	G3 Rod Withdrawn, % $\Delta k/k$		
Monte Carlo	5.7 ± 0.3	5.4 ± 0.4	4.6 ± 0.4
Diffusion	5.9	5.4	4.9

[a]The Monte Carlo code was the continuous energy VIM code and the diffusion theory code was DIF3D.

[b]This reactivity worth is 15.8 ± 0.3% $\Delta k/k$ in Conf. 1.

FUEL CYCLE COSTS

Cycle Lengths

Figure 5 shows the calculated fuel cycle lengths in Conf. 2 equilibrium cores with each of the LEU fuel types and with the reference HEU fuel element. The cycle length increases from about 14 days with the HEU fuel to about 34 days with the heaviest loaded LEU fuel elements. At 50 MW, an LEU loading of 270-285 g ^{235}U would give the same cycle length as the current HEU fuel.

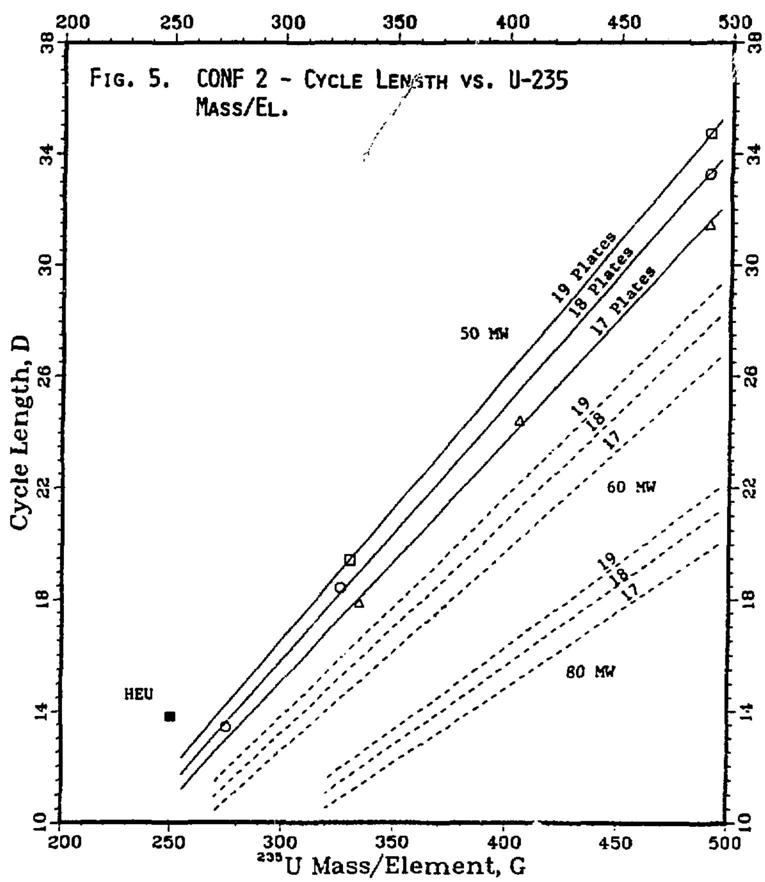
Since the cycle length is proportional to the operating power, dashed curves are also shown to indicate cycle lengths for power levels of 60 MW and 80 MW. For 100 g increments in fuel element loadings, the cycle lengths increase by about 9 days at 50 MW, by about 8 days at 60 MW, and by about 6 days at 80 MW.

Fuel Cycle Costs

The model that was used for computing the annual fuel cycle costs is described in Refs. 2 and 3. Cost input data were provided by Studsvik. Figure 6 shows the calculated LEU to HEU annual fuel cycle cost ratio as a function of the LEU to HEU fabrication cost ratio for three LEU designs with fissile loadings of about 330, 405, and 490 g. With this parameterization, the curves that are shown are nearly the same for a wide range of cost input data if the HEU and LEU fuel cycle costs are computed in a consistent manner. The curves are also independent of the reactor power level.

For an LEU fissile loading of about 330 g, the HEU and LEU cores would have the same fuel cycle costs for LEU/HEU fabrication cost ratios of 1.25, 1.4, and 1.6 in element designs with 17, 18, and 19 plates, respectively. Significant fuel cycle cost reductions should be possible if the fissile loading of the LEU elements can be increased into the 405-490 g range.

It is important to note that the designs with 17 or 18 plates per element require significantly lower uranium densities than the design with 19 plates to obtain the same ^{235}U content, and these designs should be more economical to fabricate.



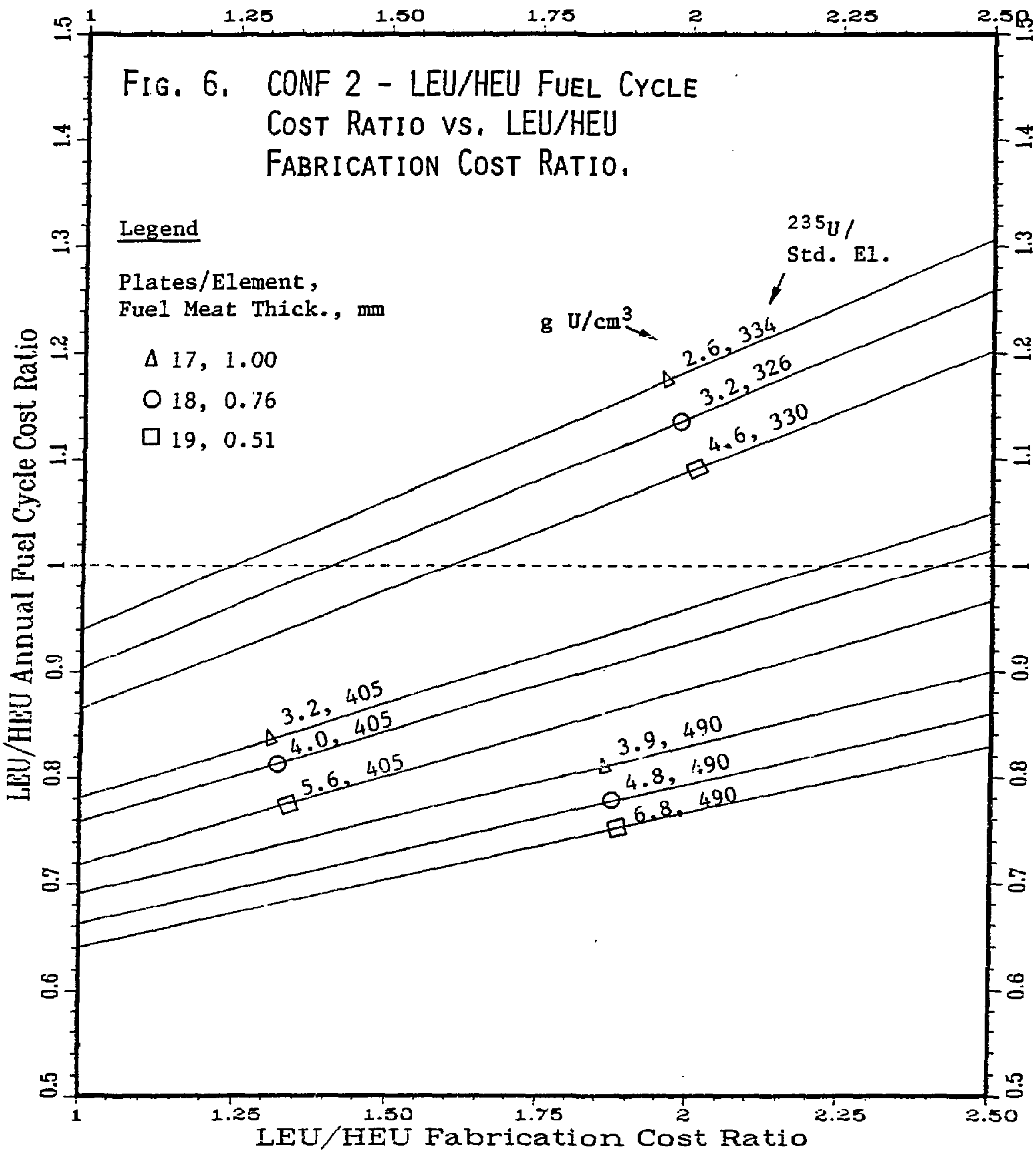


FIG. 6. CONF 2 - LEU/HEU FUEL CYCLE COST RATIO VS. LEU/HEU FABRICATION COST RATIO.

CONCLUSIONS

The experiment performance, control rod worths, and fuel cycle costs of the R2 reactor have been studied for the old and the new core-box/reflector designs with the present HEU fuel and for a variety of LEU fuel element designs. The results indicate that:

- With an fissile loading of about 330 g in the LEU standard elements, performance indices were calculated to be smaller by about 4-12% in experiments requiring thermal neutrons. Fast fluxes were computed to be about the same or slightly higher in the irradiation damage experiments.
- Performance in most of the experiments decreases with increasing fissile loading. It increases with increasing fissile loading in the silicon irradiation targets, however, and is nearly flat in the RAMP experiment. This conclusion is valid with either HEU or LEU fuel.
- Control rod worths are somewhat smaller with LEU fuel and decrease with increasing fissile loading. The latter would also be true with HEU fuel.
- Fuel cycle costs would be about the same with LEU fuel and the current HEU fuel if LEU elements with 18 plates, 0.76 mm meat, 3.2 g U/cm^3, and 326 g ^{235}U had a fabrication cost of about 1.4 times that of the HEU elements. For LEU designs with about the same fissile loading but with 17 plates and 1.0 mm meat or 19 plates and 0.51 mm meat, the LEU/HEU fabrication cost ratios that would yield the same fuel cycle costs are about 1.25 and 1.6, respectively.
- With LEU fissile loadings in the 400-500 g range, it should be possible to achieve significant reductions in fuel cycle costs.

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