Comparison of the FRM-II HEU Design With an Alternative LEU Design

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ABSTRACT

The FRM-II reactor design of the Technical University of Munich has a compact core that utilizes fuel plates containing highly-enriched uranium (HEU, 93%). This paper presents an alternative core design utilizing low-enriched uranium (LEU, <20%) silicide fuel with 4.8 g/cm^3 that provides nearly the same neutron flux for experiments as the HEU design, but has a less favorable fuel cycle economy. If an LEU fuel with a uranium density of 6.0 - 6.5 g/cm^3 were developed, the alternative design would provide the same neutron flux and use the same number of cores per year as the HEU design.

The results of this study show that there are attractive possibilities for using LEU fuel instead of HEU fuel in the FRM-II. Further optimization of the LEU design and near-term availability of LEU fuel with a uranium density greater than 4.8 g/cm^3 would enhance the performance of the LEU core. The RERTR Program is ready to exchange information with the Technical University of Munich to resolve any differences that may exist and to identify design modifications that would optimize reactor performance utilizing LEU fuel.

INTRODUCTION

The FRM-II reactor design of the Technical University of Munich is designed for the production of high intensity thermal neutrons for use in a wide variety of applications in structural research and spectroscopy. The HEU design is characterized by a compact core and a moderate power level of 20 MW, which results in a high flux to power ratio. The general concepts of compact reactor design can be found in References 1 and 2. In a previous study, a successive linear programing technique was used to optimize a core design[3] using LEU silicide fuel.

In this study, the design objectives for the LEU core were to match both the peak thermal flux (8×10^{14} n/cm^2/s) and the cycle length (50 days) of the FRM-II HEU design using a two-stage approach. In the first stage, LEU silicide fuel with a uranium density of 4.8 g/cm^3 was used to obtain the same technical performance and an acceptable economic performance in a core with a higher power level than the HEU design. In the second stage, LEU fuel with a higher uranium density was substituted into the same core geometry and the reactor power level was increased slightly so that both the peak neutron flux and the cycle length matched those of the HEU design. This approach assumes that LEU fuel with a uranium density greater than 4.8 g/cm^3 will be successfully developed.

REACTOR DESIGNS AND MODELS

Schematic diagrams of the FRM-II HEU core design and of the alternative LEU core design are shown in Figures 1 and 2. Key design and performance parameters are listed in Table 2. The FRM-II HEU core design consists of 113 involute fuel plates containing 7.5 Kg of ^{235}U in 93% enriched uranium. The core is cooled by light water and is surrounded by a heavy water reflector. The reactor is controlled at the center of the core using a hafnium control rod with a beryllium reflector follower. Power peaking is reduced by grading the fuel meat in each plate into two regions with uranium densities of 3.0 and 1.5 g U/cm^3. Additional power flattening is achieved by placing a boron ring containing 6 grams of natural boron near the bottom of the core. This ring has a relatively small reactivity worth of about 0.5% Δk/k in the fresh core.

The LEU design follows the same concept as the HEU design, but has a larger diameter and higher core that contains 153 involute plates. Since the average and peak power densities in the larger LEU core are considerably lower than those in the FRM-II HEU core, fuel grading has not been incorporated into the LEU design. However, fuel grading could be introduced if it is needed.

Diffusion theory calculations were performed for each reactor design using the DIF3D code and 15 energy-group cross sections generated using the WIMS-D4M code and ENDF/B-V data[4]. Monte Carlo calculations were performed using the MCNP code[5] and ENDF/B-V data to validate the results of the diffusion theory calculations and to calculate the control rod worth. The MCNP core models were represented by concentric fuel rings that preserved the total uranium loading, the meat, clad and coolant channel thicknesses.

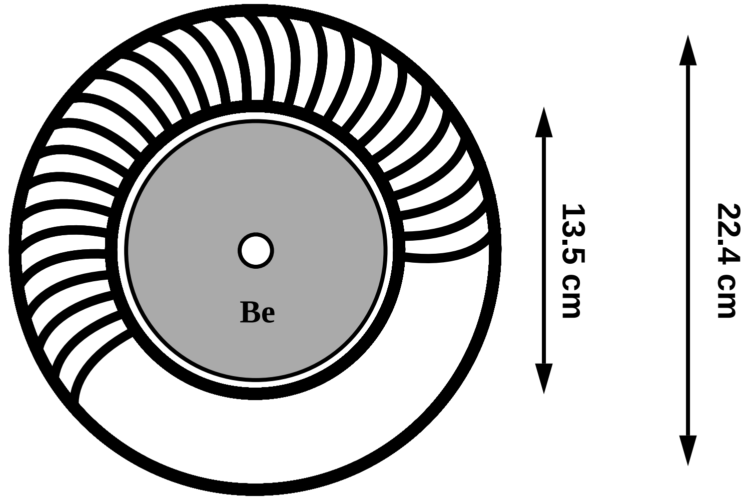
A comparison of eigenvalues and peak thermal fluxes in the reflector that were obtained from the diffusion theory and Monte Carlo calculations are shown in Table 1. Peak thermal fluxes are expressed in the form of Keff•φ to account for the movement of the control rod. The diffusion theory calculation underpredicted the reactivity of the HEU design by about 0.7% Δk/k. Much better agreement was obtained in the LEU case. The peak thermal fluxes obtained from the Monte Carlo and diffusion theory calculations are in reasonably good agreement.

Table 1: Comparison of MCNP and DIF3D Eigenvalues and Peak Thermal Fluxes in the Reflector for the FRM-II HEU Design and the Alternative LEU Design with 4.8 g/cm^3 Silicide Fuel.

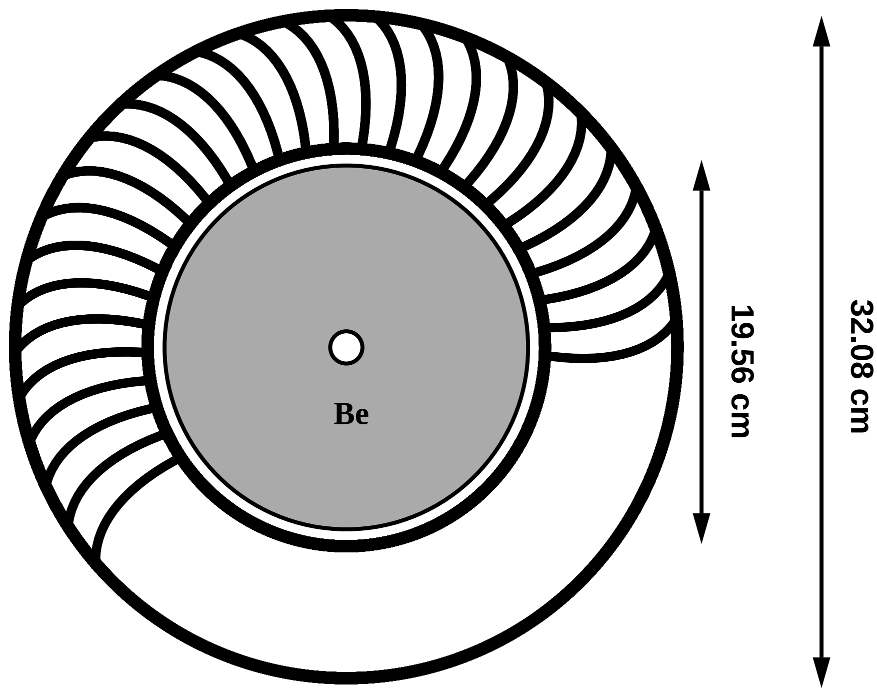
	HEU (20 MW)		LEU (30 MW) 4.8 gU/cm^3	
	DIF3D	MCNP	DIF3D	MCNP
Keff(no B^{10})	1.1899	1.2000 ± 0.0008	1.2024	1.2079 ± 0.0014
Keff(with B^{10})	1.1814	1.1937 ± 0.0006		
Keff• φth (n/cm^2/s)	8.0 x 10^{14}	7.6 x 10^{14} ± 0.3%	7.8 x 10^{14}	7.5 x 10^{14} ± 0.6%

Depletion calculations were performed for both the HEU and LEU cores using the REBUS-3 code[6] assuming an end-of-cycle reactivity of 7% Δk/k. A detailed 19 fission-product-chains

Figure 1 Horizontal Profiles of FRM-II HEU Core and Alternative LEU Core



FRM-II HEU Core



Alternative LEU Core

Figure 2 Axial Profiles of FRM-II HEU Core and Alternative LEU Core (all dimensions in cm)

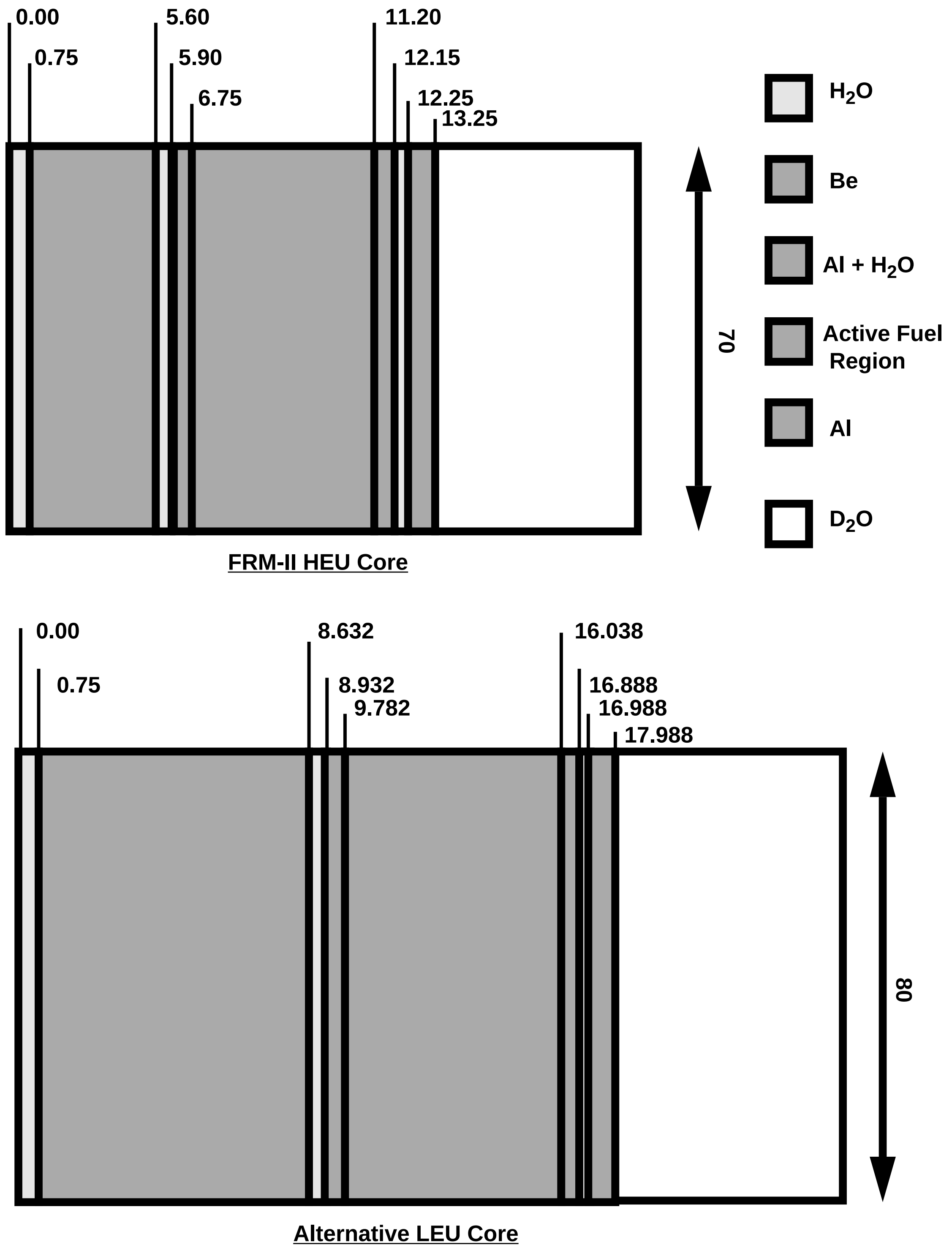


Table 2: Key Parameters in FRM-II HEU Design and Alternative LEU Design

	HEU Design	Alternative LEU Design	
Enrichment, %	93	20	
Fuel Grading	Yes	No	
Number of Fuel Plates	113	153	
Core Height (cm)	70	80	
Core Inner - Outer Radius (cm)	6.75 - 11.2	9.78 - 16.04	
Core Volume (liters)	17.6	40.6	
Length of Involute Plate (cm)	6.83	9.15	
Fuel Meat/Clad Thickness (mm)	0.60/0.38	0.51/0.38	
Coolant Channel Thickness (mm)	2.2	2.64	
Fuel Type	U_3Si_2	U_3Si_2	
Fuel Meat Uranium Density (g/cm^3)	3.0/1.5	4.8	6.4
Core Power (MW)	20	30	33
Core Loading (Kg U-235)	7.5	5.1	6.8
Keff at BOC	1.1937	1.2079	1.2459
Cycle Length (Full Power Days) (a)	50	30	48
Average Number of Cores/Year (b)	5.0	8.3	5.2
Average Burnup (% U-235 burned)	17.3	21.9	28.8
Average Fission Rate in Fuel Meat Peak Rate in Fuel Meat(fissions/cm^3/s)	2.1×10^{14} 4.7×10^{14}	1.8×10^{14} 3.7×10^{14}	2.0×10^{14} 4.6×10^{14}
Average Fission Rate: Fuel Particles Peak Rate in Fuel Particles (fissions/cm^3/s)	7.9×10^{14} (c) 17.4×10^{14} (c)	4.2×10^{14} 8.7×10^{14}	3.5×10^{14} 8.1×10^{14}
Average Fission Density in Fuel Meat (fissions/cm^3)	1.0×10^{21}	0.45×10^{21}	0.78×10^{21}
Average Power Density Peak Power Density - rod out (W/ cm^3)	1139 2537	739 1530	813 1877
Peak Thermal Flux, keff•φth,max (n/cm^2/s)	8.0×10^{14}	7.8×10^{14}	8.2×10^{14}
Reflector Volume (liters) with keff•φth > 7×10^{14} n/ cm^2/s	82	89	150

(a) EOC excess reactivity = 7% $\Delta k/k$
(b) Based on 250 days operation per year.
(c) In 3.0 g/cm^3 fuel of HEU design.

model was used in the depletion calculations to describe the buildup of fission products in the reactor[7]. The depletion calculations were performed with the control rod at its fully withdrawn position.

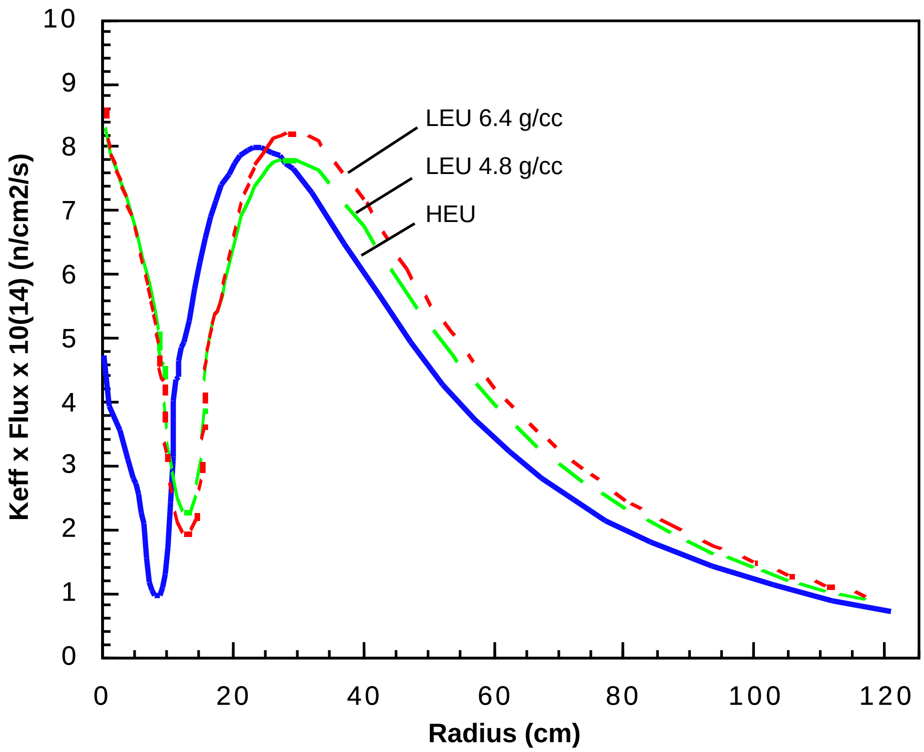
COMPARISON OF REACTOR PERFORMANCE

Key performance parameters of the FRM-II HEU and the alternative LEU design are shown in Table 2 and are summarized in Table 3. Thermal flux distributions at the core midplane are compared in Figure 3.

Table 3. Summary Comparison of Performace for the FRM-II HEU Design and the Alternative LEU Design.

Parameter	FRM-II HEU Design	Alternative LEU Design	
Uranium Density, g/cm^3	3.0/1.5	4.8	6.4
Power Level, MW	20	30	33
Peak Neutron Flux, n/cm^2-s	8.0×10^{14}	7.8×10^{14}	8.2×10^{14}
Cycle Length (Full Power Days)	50	30	48
Number of Cores per Year	5.0	8.3	5.2

Figure 3. Thermal Flux Distributions in the FRM-II HEU Design and the Alternative LEU Design.



The LEU design with both 4.8 and 6.4 g/cm^3 fuels can be further optimized to improve reactor performance. For example, the LEU fuel meat thickness can be increased from 0.51 mm to the 0.60 mm thickness of the HEU design. With 4.8 g/cm^3, this change would result in a cycle length that is estimated to be 33-35 days requiring 7 - 8 cores per year. The LEU density needed to match the neutron flux and cycle length performance of the HEU core would change from 6.4 g/cm^3 to about 6.0 g/cm^3.

The LEU design is capable of producing nearly the same intensity of thermal fluxes in the outer reflector region as the HEU design. A comparison of effective volume in the high flux region (locations with $k_{eff} \cdot \varphi_{th} > 7 \times 10^{14}$ n/cm^2-s) in the heavy water reflector shows that the LEU design with an advanced fuel offers considerably more usable volume for the installation of experimental facilities.

Although thermal-hydraulic studies have not been performed for the LEU design, the lower power densities and larger coolant channel suggest that the heat transfer requirement of the LEU core are likely to be less stringent than in the HEU design.

REACTIVITY CONTROL

The excess reactivity during the reactor operation is controlled by the movement of a central control rod with a beryllium follower. The control rod in the HEU design consists of a cylindrical column of aluminum covered with a 0.25 cm thick layer of hafnium absorber. The HEU core has a excess reactivity of 16.2% $\Delta k/k$ at the beginning of cycle. Assuming the combined reactivity worth from the experimental facilities, temperature coefficients and reactivity reserve is about -7% $\Delta k/k$, a minimum control rod worth of about -10% $\Delta k/k$ will be needed to control the reactor. The worth of the control rod at fully inserted position was calculated to be about -15 % $\Delta k/k$.

In the LEU cores, the interior surface of the core is much larger than in the HEU design. This large surface affords many possible designs for the control rod.

CONCLUSION

The results of this study show that there are attractive possibilities for using LEU fuel instead of HEU fuel in the FRM-II. A two-stage approach was used to identify a core design that would allow the use of LEU fuel and still have the same peak thermal flux available for experiments and the same cycle length as in the HEU design. In the first stage, LEU silicide fuel with a uranium density of 4.8 g/cm^3 was used to obtain the same technical performance and an acceptable economic performance in a core with a higher power level than the HEU design. In the second stage, LEU fuel with a higher uranium density was substituted into the same core geometry and the reactor power level was increased slightly so that both the peak neutron flux and the cycle length matched those of the HEU design. The LEU design can be further optimized to improve its performance.

This approach assumes that LEU fuel with a uranium density in the range of 6.0 - 6.5 g/cm^3 will be successfully developed. There are good indications[8] that LEU silicide fuel with 6.0 g/cm^3 is feasible, although the testing is not complete to our knowledge. Other fuels[9] may also be successfully developed. If the RERTR advanced fuel development effort begins as scheduled in October 1995, we are optimistic that a fuel with 6.0 - 6.5 g U/cm^3 will be successfully developed and licensed.

Only by changing the current HEU core design is it possible to use LEU fuel in the FRM-II. An LEU fuel that could be substituted for the HEU fuel in the current FRM-II HEU core geometry and have comparable flux performance and fuel cycle economics would require a uranium density greater than 16 g/cm^3, which is not feasible. However, as shown in this study, alternative FRM-II core designs can be developed in which feasible LEU fuels can be used.

The RERTR Program is ready to exchange information with the Technical University of Munich to resolve any differences that may exist and to identify design modifications that would optimize reactor performance using LEU fuel.

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