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# A NEUTRONIC FEASIBILITY STUDY FOR LEU CONVERSION OF THE HIGH FLUX ISOTOPE REACTOR (HFIR)*


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## ABSTRACT

A neutronic feasibility study was performed to determine the uranium densities that would be required to convert the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL) from HEU (93%) to LEU (<20%) fuel. The LEU core that was studied is the same as the current HEU core, except for potential changes in the design of the fuel plates. The study concludes that conversion of HFIR from HEU to LEU fuel would require an advanced fuel with a uranium density of 6-7 gU/cm$^3$ in the inner fuel element and 9-10 gU/cm$^3$ in the outer fuel element to match the cycle length of the HEU core. LEU fuel with uranium density up to 4.8 gU/cm$^3$ is currently qualified for research reactor use. Modifications in fuel grading and burnable poison distribution are needed to produce an acceptable power distribution.

## INTRODUCTION

The High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory is a 100 MW high performance compact reactor designed primarily for the production of transplutonium isotopes [1-5]. Other experimental facilities include three horizontal beam tubes and irradiation facilities in the beryllium reflector. The reactor began operation in 1965. Since 1989 the reactor has been operated at a reduced power of 85 MW [6]. The current facility is scheduled to be upgraded in 1999 to install new experimental facilities and to replace the beryllium reflector.

This paper presents the results of a feasibility study for LEU conversion of HFIR. The goal of the study is to estimate the range of uranium densities that would be required to convert HFIR from HEU to LEU fuel. Calculations were first performed for the current HEU core in order to validate the reactor model and the computational methods. The LEU model is the same as the HEU model except for the following changes in the design of the fuel plates: enrichment, fuel type, clad thickness, burnable poison and fuel meat distribution.

## REACTOR MODEL

The HFIR core consists of two concentric annuli with involute fuel plates that contain $U_3O_8$-Al fuel meat and highly enriched uranium (93%). The core is cooled by pressurized light water, and has a central flux trap and an outer beryllium reflector. A schematic diagram of HFIR is shown in Figure 1. The fuel plates are bent into involute shapes to produce a constant coolant channel thickness and to improve hydraulic stability. Key reactor design parameters are given in Table 1.

**Figure 1. Schematic Diagram of the HFIR Reactor Core**

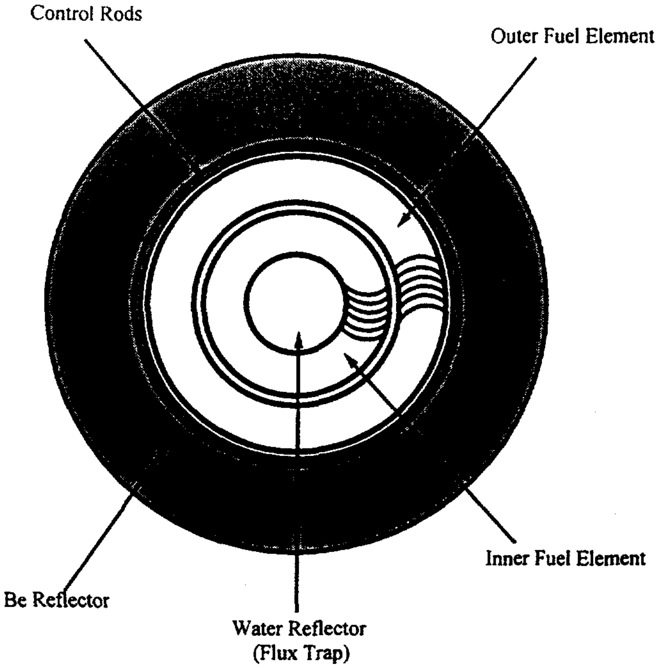



**Table 1. Key Parameters of HFIR**

| | | |
|---|---|---|
| Reactor Power (MW) | 85 | |
| Number of Fuel Elements | 2 | |
| Active Core Height (cm) | 50.8 | |
| Total $U^{235}$ Loading (Kg) | 9.43 | |
| Enrichment (%) | 93.1 | |
| Fuel Type | $U_3O_8$ - Al | |
| Coolant | $H_2O$ | |
| Fuel Element Parameters: | Inner Element | Outer Element |
| number of fuel plates | 171 | 369 |
| inner sideplate radius (cm) | 6.4 | 14.29 |
| outer sideplate radius (cm) | 13.45 | 21.76 |
| inner active core radius (cm) | 7.14 | 15.15 |
| outer active core radius (cm) | 12.6 | 21.0 |
| $U^{235}$ Loading (Kg) | 2.60 | 6.83 |
| average fuel uranium density ($gU/cm^3$) | 0.776 | 1.151 |
| $B^{10}$ in filler (g) | 2.8 | None |
| plate thickness (cm) | 0.127 | 0.127 |
| coolant channel thickness (cm) | 0.127 | 0.127 |
| minimum clad thickness (mm) | 0.25 | 0.25 |
| plate width (cm) | 8.1 | 7.3 |
| Peak $\phi_{th,max}$ in Flux Trap [a] ($10^{15}$ $n/cm^2/s$) | 3.6 | |
| Cycle Length [b] (Full Power Days) | 24 | |

[a] With control rods fully withdrawn, $\phi_{th} \leq 0.625$ eV.
[b] No experiment.

The fuel plates in the inner and outer fuel elements are graded to reduce power peaking in the reactor core (see Figure 2). The fuel distributions were obtained from Reference 1 in the form of tabulated surface densities along the involute arc. A computer code was written to compute the material compositions for two dimensional (R-Z) neutronic calculations. The radial distribution of $U^{235}$ concentration in the HFIR core is shown in Figure 3. The reactor model that was used in the analysis is shown in Figure 4. This model is similar to the VENTURE model in Reference 7, except that the sideplate and control regions are represented in more detail. The radial fuel compositions are represented by nine discrete zones in each fuel element.

**Figure 2. Graded HFIR Fuel Plate**

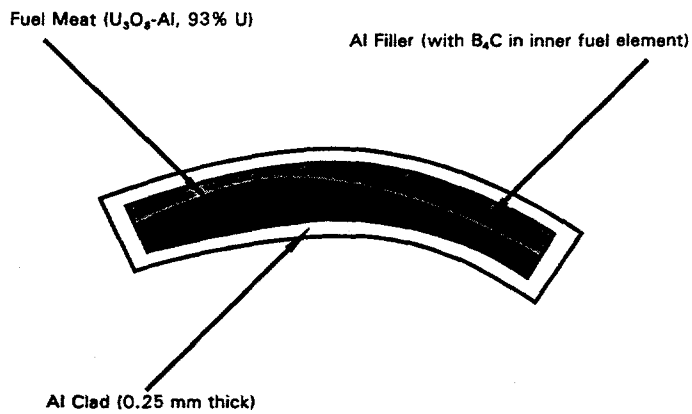



**Figure 3. $U^{235}$ Number Density Distribution in HFIR**

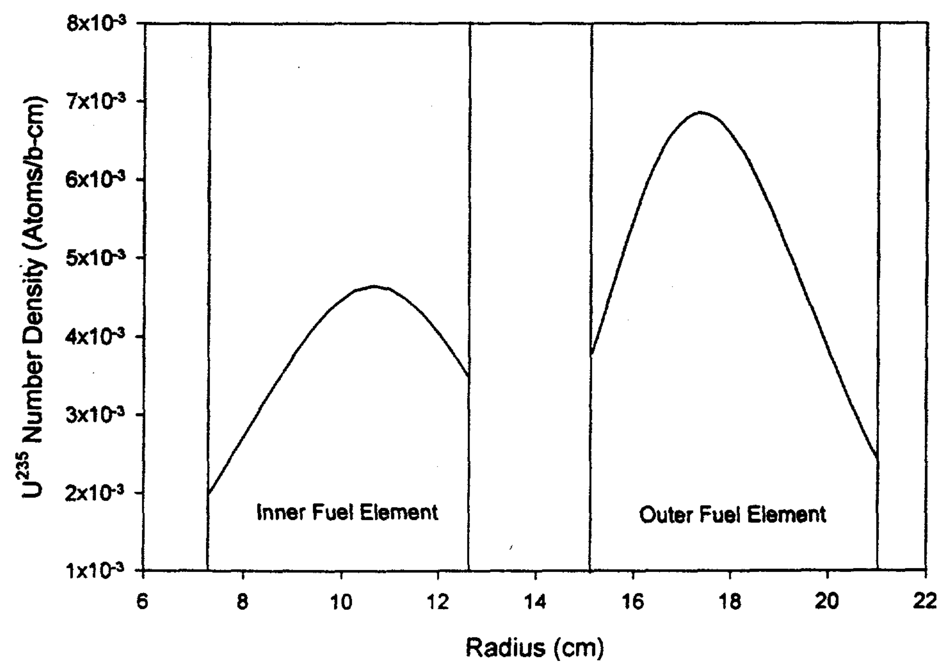
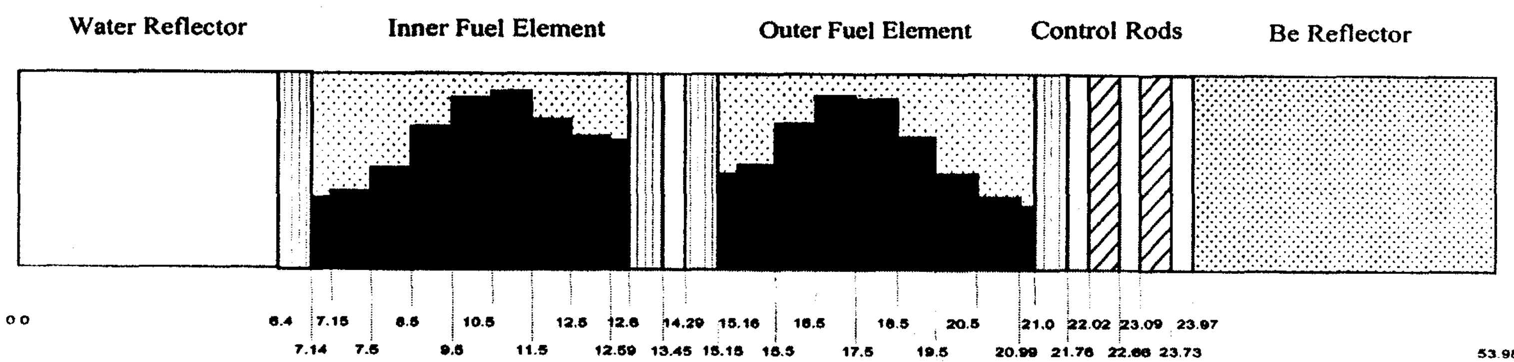


Figure 4. HFIR Model in Diffusion and Monte Carlo Calculations



## COMPUTATIONAL METHODS & RESULTS

Diffusion theory calculations were performed for HFIR using the DIF3D code [8] and 15 energy-group cross sections generated by the WIMS-D4M code [9] using ENDF/B-V data. Continuous energy Monte Carlo calculations were performed using the MCNP code [10] and ENDF/B-V data to validate the reactor model and results of the diffusion calculations. Depletion calculations were performed using the REBUS-3 code [11] with burnup dependent cross sections generated by WIMS-D4M. The cross sections were generated with a one-dimensional radial model that included the inner water reflector, inner fuel element, outer fuel element and beryllium reflector at the core midplane.

### Comparison of MCNP Results with HFIRCE-4 Experimental Data

Critical experiments were conducted during the early operation of HFIR to evaluate the reactor performance. Data obtained from the HFIRCE-4 critical experiment [1] are given in Table 2 together with MCNP calculated results. A detailed control rod model was used in the Monte Carlo calculations to represent the Europium and Tantalum absorbers. The calculated and measured peak thermal fluxes are compared in Table 3. The MCNP calculated eigenvalues and fluxes are in good agreement with experimental data.

**Table 2. Comparison of MCNP Eigenvalues with Data from HFIR-CE4 Critical Experiment**

| HFIRCE-4 Critical Experiments | MCNP $K_{eff}$ |
|---|---|
| Control rods at 44.45 cm, no soluble poison | 0.9949±0.0007 |
| Control rods at 54.09 cm, 0.91 g $B^{10}$/liter in coolant | 0.9936±0.0006 |
| Control Rods at 61.72 cm, 1.25 g $B^{10}$/liter in coolant | 0.9959±0.0006 |
| Control Rods fully withdrawn, 1.35 g $B^{10}$/liter in coolant | 0.9989±0.0006 |

**Table 3. Comparison of MCNP and Measured Peak Thermal Fluxes in Core & Reflector (critical experiment with control blades at 44.45 cm, 85 MW)**

| | MCNP Calculated $\phi_{th}$ | HFIR-CE4 Measured $\phi_{th}$ |
|---|---|---|
| Flux Trap, No Target | $4.09 \pm 0.16^{a} \times 10^{15}$ n/cm²/s | $4.0 \times 10^{15}$ n/cm²/s |
| Reflector Region | $1.24 \pm 0.015 \times 10^{15}$ n/cm²/s | $1.1 \times 10^{15}$ n/cm²/s |

[a] higher standard deviation due to small sample volume at core center

### Comparison of MCNP & DIF3D Results

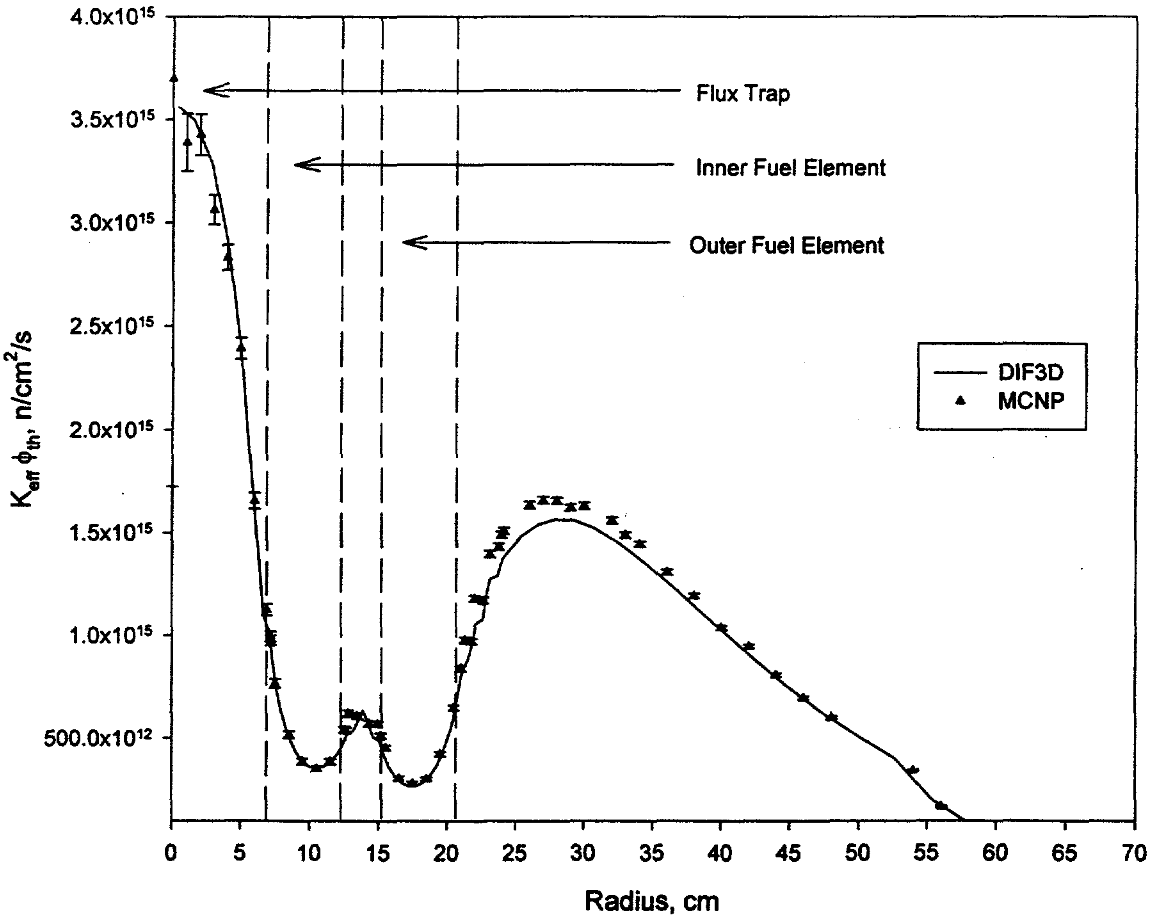
Neutronic calculations for HFIR were performed mainly with multigroup diffusion codes DIF3D and REBUS-3. Monte Carlo calculations were used to check the accuracy of the diffusion calculations. The eigenvalues and thermal fluxes obtained from MCNP and DIF3D calculations are compared in Table 4 and Figure 5. The DIF3D eigenvalues are about 0.6% $\delta k/k$ lower than the MCNP results. The fluxes are in good agreement.

**Table 4. Comparison of DIF3D & MCNP Eigenvalues**

| | DIF3D $K_{eff}$ | MCNP $K_{eff}$ |
|---|---|---|
| All control rods out, no $B^{10}$ in coolant | 1.1288 | 1.1362±0.0006 |
| All control rods out, 1.35 g $B^{10}$/liter in coolant[a] | 0.9924 | 0.9989±0.0006 |

[a] critical experiment with soluble poison in coolant

**Figure 5. Comparison of MCNP & DIF3D Fluxes at the HFIR Core Midplane (85 MW, Control Rods Fully Withdrawn)**




## Beam Tubes Reactivity Worth

The reactivity worth of the beam tubes was obtained from MCNP calculations using a reactor model that includes three horizontal tubes penetrating the beryllium reflector at radial and tangential directions. The tubes are made of Al-6061 with 4 inch inner diameters[2]. The calculated reactivity worths of the beam tubes at different control rod positions are given in Table 5. It can be seen that the worth is highest at EOC when the control rods are withdrawn from the core.

**Table 5. HFIR Beam Tubes Reactivity Worths**

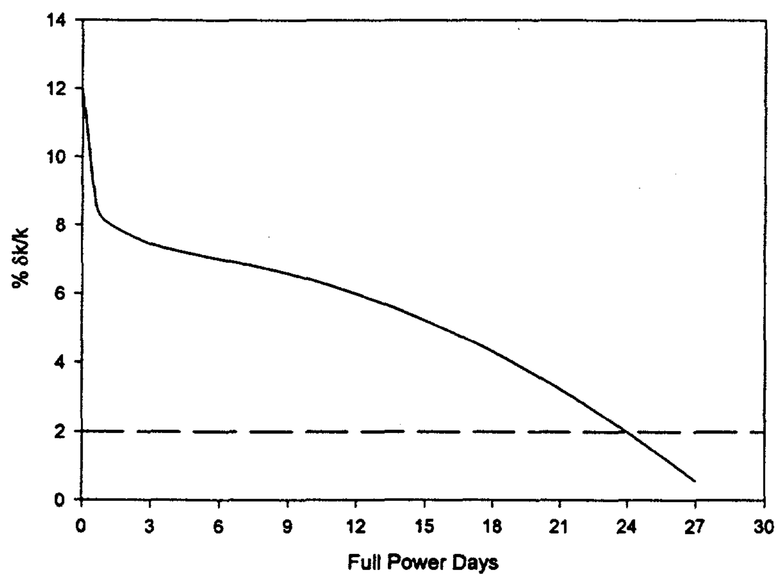
| | Beam Tubes Worth (% δk/k) |
|---|---|
| Control rods inserted at critical position | -0.25±0.10 |
| Control rods fully-withdrawn | -1.28±0.09 |

### Fuel Cycle Length Calculations

Fuel cycle length calculations were performed for HFIR using a reactor model with the control rods at their fully-withdrawn position. A separate REBUS calculation was performed for a perturbed model with control rods gradually-withdrawn from the core. The movement of control rods reduced the EOC reactivity by about 0.5 %δk/k. Accounting for reactivity components including the beam tubes, control rod perturbation, temperature and reserve, the excess reactivity requirement at EOC in this analysis was assumed to be 2 %δk/k.

A reactivity rundown at a power of 85 MW is shown in Fig. 6. The calculated cycle length with an EOC excess reactivity of 2 %δk/k is about 24 days. The result agrees well with a reported cycle length of 24 ± 2 days [7].

**Figure 6. HFIR Reactivity Run Down (85 MW, Control Rods Fully Withdrawn, No Target, No Experiments).**

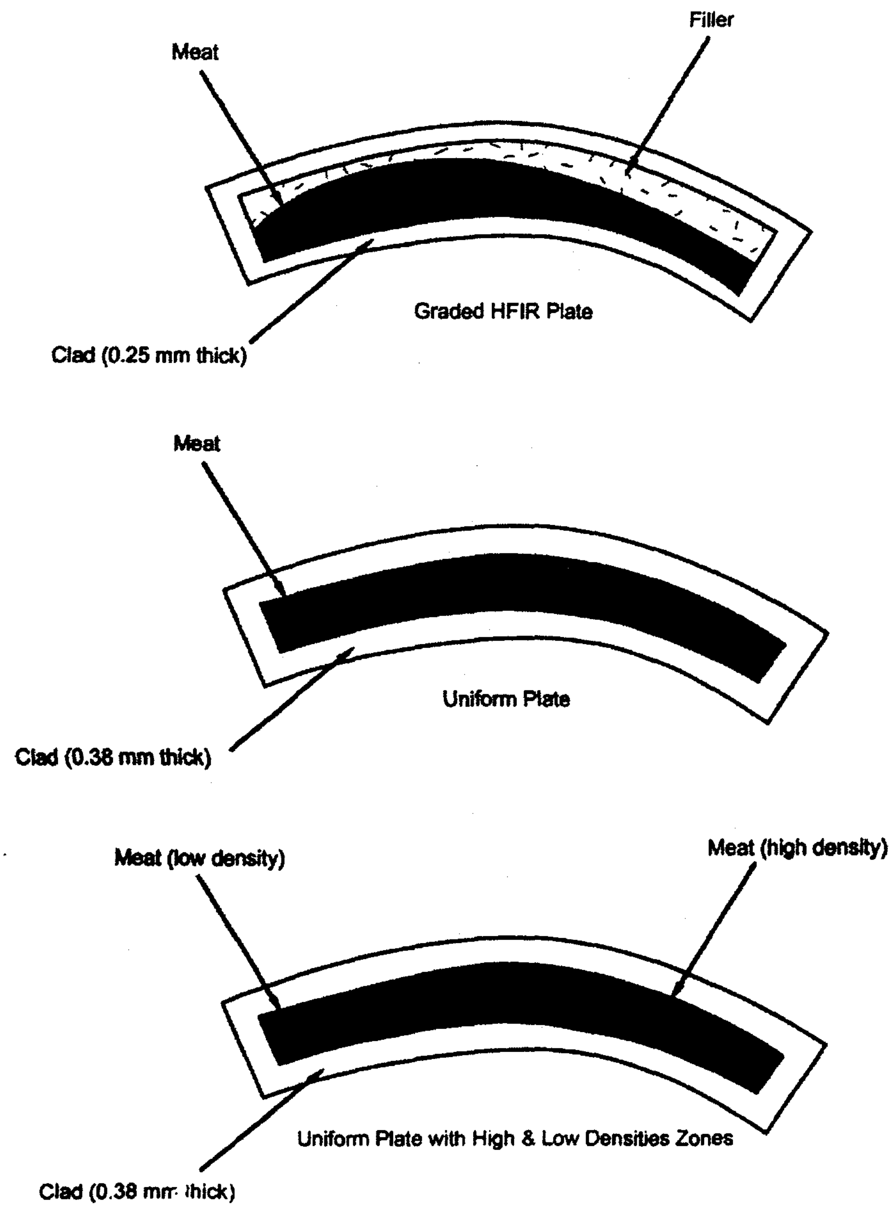



## LEU CONVERSION FEASIBILITY STUDY

The methodology and reactor model that were used in the neutronic analysis of the HEU core were also used in the LEU conversion feasibility study. The goal of the study is to estimate the uranium densities that would be needed to convert HFIR from HEU fuel to LEU fuel.

The design of the LEU core is the same as that of the HEU core, except for the fuel plates. The core geometry, overall fuel plate dimensions and coolant channel thickness are identical. The ratio of the inner fuel element to outer fuel element uranium density was preserved. High density $U_3Si_2$-Al fuel with 19.75% enrichment was used for calculational purposes only. Conversion of HFIR would require a different and still undeveloped dispersion fuel, but the neutronic behaviors of different fuel candidates should be similar [12]. Schematic drawings of the graded and uniform LEU fuel plates that were used in this study are shown in Figure 7.

**Figure 7. Schematic Drawings of LEU Fuel Plates**



## Comparison of Transport and Diffusion Theory Calculations

Monte Carlo and diffusion theory calculations were performed for HFIR using LEU fuel with uranium densities of 9.5 $gU/cm^3$ in the outer element and 6.4 $gU/cm^3$ in inner element. The calculated eigenvalues and peak thermal fluxes are compared in Table 6.

**Table 6. Comparison of MCNP, DIF3D and TWODANT RESULTS**

| | $K_{eff}$ | Peak $\phi_{th}$ ($n/cm^2/s$) |
|---|---|---|
| Continuous Energy MCNP | 1.1180±0.0006 | $3.4\pm0.2 \times 10^{15}$ |
| 15-group DIF3D | 1.0957 | $3.2 \times 10^{15}$ |
| 15-group TWODANT ($S_8$-$P_1$) | 1.1043 | $3.3 \times 10^{15}$ |

The reactivity calculated by DIF3D is 1.8% δk/k lower than the MCNP result. A transport calculation was performed for the LEU design using the TWODANT code [13] with the same DIF3D model and 15-group cross sections. The difference between the TWODANT and MCNP calculated eigenvalues is 1.1% δk/k. The source of differences in eigenvalues has not yet been fully identified but is believed to be related to the $U^{238}$ cross section generated by WIMS[14]. The results of diffusion calculations presented in this study include reactivity biases obtained from differences between DIF3D and MCNP calculations.

## Results of Conversion Calculations

Calculations were performed for several LEU fuel plate designs. The uranium densities in the fuel plates of the inner and outer elements were adjusted to match the 24 day cycle length of the HEU core. The results are summarized in Table 7.

**Table 7. Summary of HFIR HEU Core & LEU Cores Performances**

| | HEU | LEU-1 | LEU-1a | LEU-2 | LEU-3 |
|---|---|---|---|---|---|
| Fuel Plate Type | graded | graded (HFIR type) | graded (HFIR type) | Uniform (Standard plate) | Uniform (FRM-II type) |
| Uranium Density ($gU/cm^3$) | | | | | |
| inner fuel element | 0.776 | 6.4 | 6.2 | 5.3 | 3.15/6.3[a] |
| outer fuel element | 1.151 | 9.5 | 9.2 | 7.8 | 4.7/9.4 |
| BOC $K_{eff}$ [b] | 1.1362 | 1.1180 | 1.1492 | 1.1566 | 1.1517 |
| $U^{235}$ Loading (Kg) | 9.44 | 16.64 | 16.12 | 14.20 | 15.57 |
| Burnable Poison (g $B^{10}$) | 2.8 | 2.8 | 0.0 | 0.0 | 0.0 |
| Cycle Length [c,d] (FPD) | 24 | 24 | 24 | 24 | 24 |
| Peak Power Density [d] ($W/cm^3$) | | | | | |
| inner fuel element | 2800 | 3050 | 3300 | 4700 | 4000 |
| outer fuel element | 2500 | 3400 | 3250 | 4700 | 3800 |
| Peak Thermal Flux[d] ($n/cm^2/s$) | | | | | |
| at flux trap | $3.6 \times 10^{15}$ | $3.2 \times 10^{15}$ | $3.4 \times 10^{15}$ | $3.4 \times 10^{15}$ | $3.5 \times 10^{15}$ |
| at beryllium Reflector | $1.6 \times 10^{15}$ | $1.4 \times 10^{15}$ | $1.4 \times 10^{15}$ | $1.4 \times 10^{15}$ | $1.4 \times 10^{15}$ |

[a] The fuel plates in the inner and outer fuel elements contain a high density zone at center and two 0.5 cm thick low density zones near both ends to reduce power peaking.

[b] MCNP results with standard deviations of ±0.0006.

[c] The cycle length is estimated from an EOC reactivity requirement of 2% δk/k.

[d] Reactor power at 85 MW, control rods fully-withdrawn.

Case LEU-1:

The HEU fuel in HFIR was replaced by high density LEU fuel using the current graded fuel plate design. Because of its relatively hard neutron spectrum, the conversion of HFIR to LEU fuel would require a large increase in $U^{235}$ loading. The LEU uranium densities needed to achieve a 24 day cycle length are 9.5 gU/cm$^3$ in the outer element and 6.4 gU/cm$^3$ in the inner element. The peak thermal fluxes in the flux trap and beryllium reflector would be about 10% lower than in the present HEU core. A different fuel grading is needed to reduce power peaking since the peak power densities are unacceptably high.

Case LEU-1a:

As a first step, the burnable poison ($B_4C$) was removed from the inner fuel element. The reactivity worth of the burnable poison at BOC is about 2.4% δk/k. The LEU uranium densities required to produce a 24 day cycle length are reduced to 9.2 gU/cm$^3$ in the outer element and 6.2 gU/cm$^3$ in the inner element. However, peak power densities are still unacceptable. A different combination of fuel grading and burnable poison is needed to produce a more desirable power distribution. However, the required uranium densities are expected to be in the range of 6 to 7 gU/cm$^3$ in the inner fuel element and 9 to 10 gU/cm$^3$ in the outer fuel element. It should be noted that the average clad thickness of HFIR fuel plates is 0.25 mm compared with 0.38 mm for a standard MTR fuel plate.

Case LEU-2

The graded fuel plates were replaced by uniform plates with a constant fuel meat thickness of 0.51 mm and clad thickness of 0.38 mm. No burnable poison was included in the core. The LEU uranium densities needed to produce a 24 day cycle length are 7.8 gU/cm$^3$ in the outer element and 5.3 gU/cm$^3$ in the inner element. The peak power densities in the core are unacceptably high and need to be reduced.

Case LEU-3

The uniform fuel plates in case LEU-2 were divided into a high density inner zone and two low density zones near the ends of each plate. A similar plate design is being employed by the University of Munich to reduce power peaking in the FRM-II reactor design[15]. The uranium density in the low density zone was taken to be half of that of the high density zone. The uranium densities (in the high density zones) needed to produce a 24 day cycle length were computed to be 9.4 gU/cm$^3$ in the outer element and 6.3 gU/cm$^3$ in the inner element. The peak power densities are 15 to 20% lower than in the LEU-2 fuel elements, but are still high in comparison with the HEU and LEU-1 designs. Further modification of the LEU fuel plate design is needed to reduce power peaking to an acceptable level.

## CONCLUSIONS

Using a reactor model that is similar to the current HEU design, the conversion of HFIR from HEU fuel to LEU fuel would require an advanced fuel with a uranium density of 6-7 gU/cm$^3$ in the inner fuel element and 9-10 gU/cm$^3$ in the outer fuel element in order to match the 24 day cycle length of the HEU core. Peak thermal fluxes in the central flux trap and in the outer beryllium reflector would be about 10% lower in the LEU core than in the HEU core. Modifications in the fuel grading and burnable poison distribution are needed to produce an acceptable power distribution.

A uniform fuel plate design would require uranium densities in the 5-8 $gU/cm^3$ range to meet the cycle length requirement, but the power peaking is unacceptably high. A simple method of fuel grading is to divide the uniform fuel plates into regions with high uranium density at the center and low uranium density near the ends of each plate. The uranium densities that would be needed to satisfy the cycle length requirement with this grading method also fall in the range of 6-7 $gU/cm^3$ in the inner fuel element and 9-10 $gU/cm^3$ in the outer fuel element. The peak power densities are still unacceptably high. Modification of the fuel plate design is needed to reduce power peaking.

At present the highest density LEU fuel qualified for research reactor use is $U_3Si_2$-Al fuel with a uranium density of 4.8 $gU/cm^3$. The conversion of HFIR from HEU to LEU fuel would require an advanced fuel with a uranium density that is about twice the currently qualified value.

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