A NEUTRONIC FEASIBILITY STUDY FOR LEU CONVERSION OF THE HIGH FLUX BEAM REACTOR (HFBR)*

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ABSTRACT

A neutronic feasibility study for converting the High Flux Beam Reactor at Brookhaven National Laboratory from HEU to LEU fuel was performed at Argonne National Laboratory. The purpose of this study is to determine what LEU fuel density would be needed to provide fuel lifetime and neutron flux performance similar to the current HEU fuel.

The results indicate that it is not possible to convert the HFBR to LEU fuel with the current reactor core configuration. To use LEU fuel, either the core needs to be reconfigured to increase the neutron thermalization or a new LEU reactor design needs to be considered. This paper presents results of reactor calculations for a reference 28-assembly HEU-fuel core configuration and for an alternative 18-assembly LEU-fuel core configuration with increased neutron thermalization. Neutronic studies show that similar in-core and ex-core neutron fluxes, and fuel cycle length can be achieved using high-density LEU fuel with about 6.1 gU/cm^3 in an altered reactor core configuration. However, hydraulic and safety analyses of the altered HFBR core configuration needs to be performed in order to establish the feasibility of this concept.

INTRODUCTION

A neutronic feasibility study was conducted for potential conversion of the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory from the use of HEU fuel to the use of LEU (< 20% enriched) fuel. This study is focused on determining the LEU core configuration, fuel assembly, and uranium density necessary to maintain similar neutron flux and fuel cycle performance as the current HEU core configuration and fuel.

HFBR DESCRIPTION

Fuel Assembly And Reactor Core

A cross section of the HFBR is shown in Fig. 1. The reactor has 16 control rods located on the periphery; 8 main rods above the core and 8 auxiliary rods below the core can be adjusted to uncover the horizontal beam tubes located on or near the core midplane. Several vertical thimbles allow both in-core and ex-core experiment placement. The spherical-shaped aluminum reactor vessel is 208 cm in diameter and has a 122-cm diameter cylindrical vertical neck for access to the reactor core. The reactor vessel is surrounded by a 23-cm thick thermal shield of steel and lead that is cooled by light-water, and a 2.4-m thick biological shield of heavy concrete and steel.

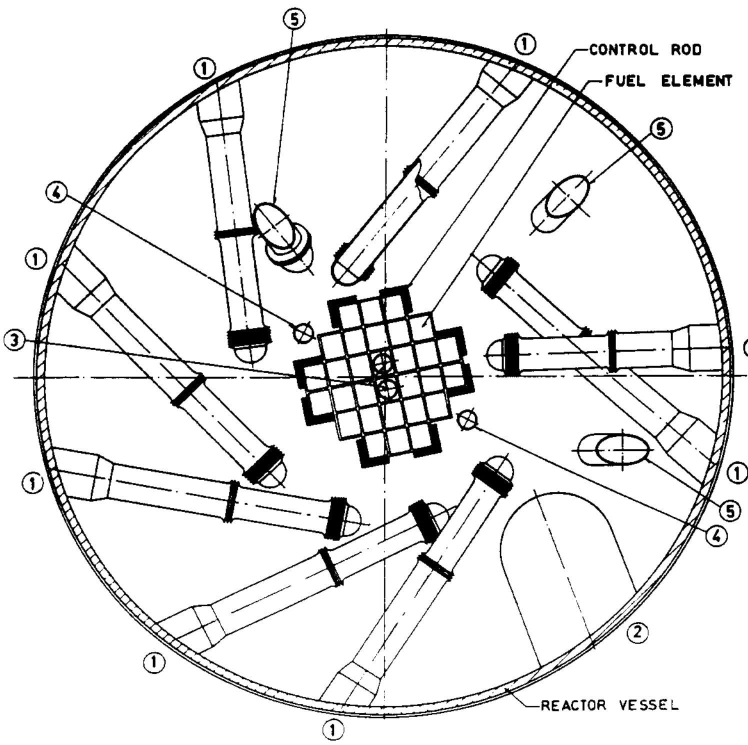

Figure 1. Plan View of the HFBR.

The HFBR is moderated and cooled with heavy-water, and consists of 28 closely packed, MTR-type fuel assemblies. Each fuel assembly contains 351g of ^{235}U using 93% enriched uranium. At a power of 40 MW, the reactor is designed to operate on a 22-day equilibrium fuel cycle. The reactor has operated at various times at different power levels and with different fuel cycles. This 22-day fuel cycle shuffles seven groups of four fuel assemblies through the 28-assembly core. Every 22 days, 7-spent fuel assemblies are removed, fuel is shuffled, and 7-fresh fuel assemblies are inserted. Not accounting for a shutdown time between cycles, the reactor would use about 116 fuel assemblies per year.

The MTR-type HEU (93% enriched) fuel assembly that is used has 20 plates: 18 plates contain U_3O_8-Al fuel and the two outside plates (2.540 mm thick) are 6061-aluminum. The fuel meat is 0.579 mm thick by 5.679 cm wide by 58.10 cm long and the uranium density is 1.10 gU/cm^3. The Al clad and D_2O coolant channel thicknesses are 0.345 mm and 2.438 mm, respectively. Somewhat thicker coolant channels, approximately 2.688 mm, are associated with each outside aluminum plate and the two adjacent fuel plates. Each aluminum side plate of the fuel assembly is 4.750 mm by 7.821 cm. (All aluminum except the aluminum in the fuel meat is Al-6061.) The fuel assembly unit-cell dimensions are 7.163 cm by 7.821 cm, spaced on a reactor lattice pitch of 7.315 cm by 8.179 cm; the average fuel assembly pitch is 7.747 cm.

The reactor core is characterized by a hard neutron spectrum that results in leakage of fast and epithermal neutrons into the surrounding D_2O reflector. These leakage neutrons are moderated, resulting in a large thermal neutron flux that peaks in the vicinity of the beam tubes. The control rods are located on the periphery of the reactor core in order to control the return of reflected thermal neutrons to the core. Because of the heavy-water coolant and the closely packed configuration of fuel assemblies, the reactor core is under-moderated and the neutron spectrum is fairly-hard. For heavy-water moderated research reactors, the HFBR core configuration is unique.

Comparison With RHF And DR3 Reactors

Figure 2 is a plot of the neutron spectra in the HEU-fuel core of three heavy-water reactors: the DR3 reactor at the Risoe National Laboratory in Denmark, the High Flux Reactor (RHF) at Grenoble France, and the HFBR. In comparison, the HFBR has the hardest spectrum, the DR3 reactor has the softest spectrum[1], and the RHF spectrum[1] is in between. The DR3 reactor has widely spaced DIDO-type fuel assemblies with a pitch of 15 cm and a well thermalized neutron spectrum; the RHF has an involute-type fuel assembly with an inside diameter of 26 cm; and the HFBR has closely packed MTR-type fuel assemblies with a pitch of 7.7 cm and a relatively hard neutron spectrum. The difference in the core configuration of these three D_2O moderated reactors leads to different HEU-core spectra.

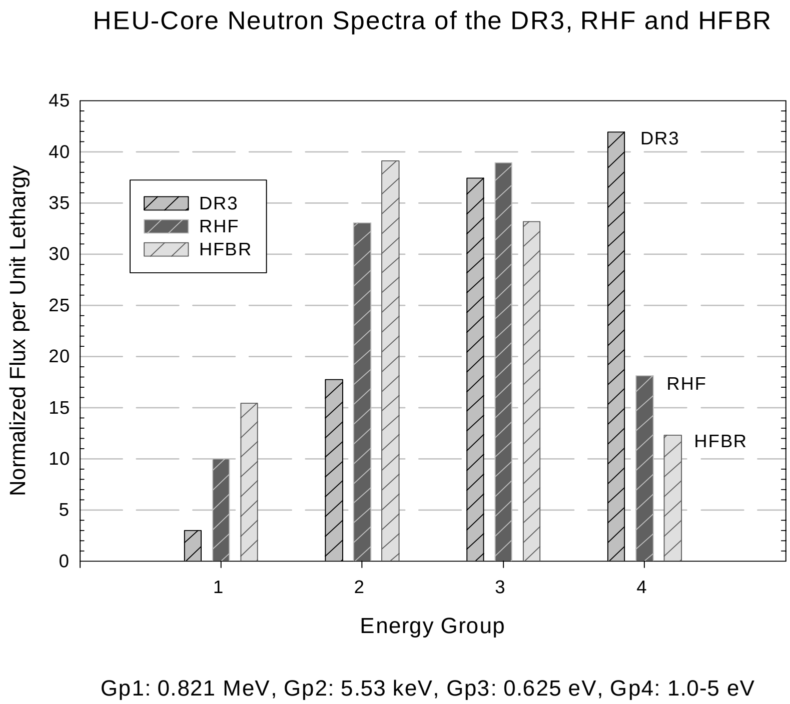

Figure 2. Comparison of DR3, RHF and HFBR Core Spectra.

LEU FUEL CONVERSION FEASIBILITY STUDY

Attempts to directly substitute LEU fuel for HEU fuel in the current 28-assembly core configuration indicate that this procedure is not possible for the HFBR because increasing the ^{235}U and ^{238}U content of the fuel assemblies hardens the neutron spectrum and reduces the core excess reactivity available for burnup. For LEU fuel densities as high as 19 gU/cm^3, fuel cycle lengths of only a few days can be achieved in comparison with the HEU fuel cycle length of 22 days. It is necessary to increase the neutron thermalization in the core in order to utilize LEU fuel in the HFBR.

Several design changes were attempted to determine which type of change was most effective in increasing the neutron thermalization. For example, the number of fuel plates in each fuel assembly was reduced and the coolant channel was increased, the D_2O coolant was replaced with H_2O, and the fuel assembly pitch was increased. Little excess reactivity was gained by increasing the coolant-to-fuel ratio within a fuel assembly. Replacing the coolant or increasing the inter-assembly pitch from 7.7 to 15.5 cm showed significant improvement, but these approaches would require a new reactor design.

Several alternative core configurations in which symmetric fuel assemblies were removed, also showed significant improvement in the excess reactivity necessary to achieve a realistic fuel cycle length. A core configuration of 18 fuel assemblies arranged in an annular-shape was shown to be optimum. Figure 3 shows both the 28- and the 18-assembly core configurations.

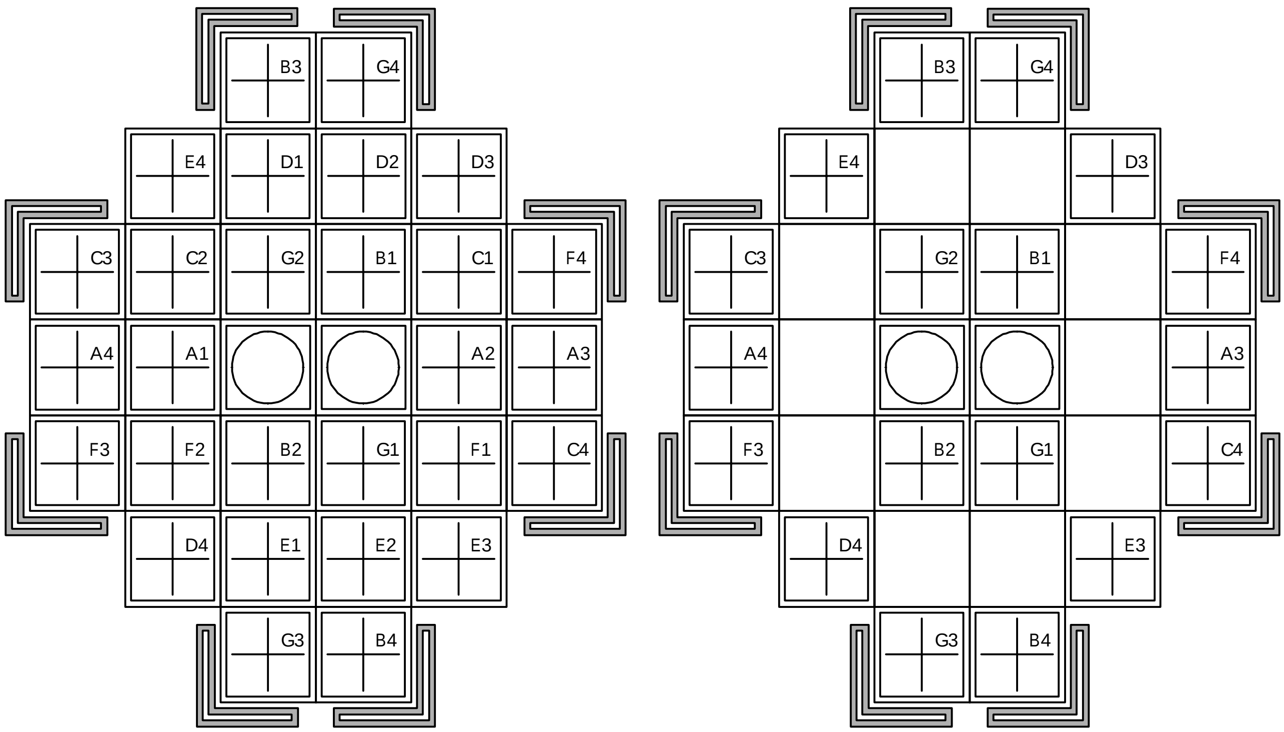

Figure 3. HFBR 28-Assembly (HEU) and 18-Assembly (LEU) Core Configurations.

REACTOR MODELS AND COMPUTATIONAL METHODS

<u>Reactor Calculations</u>

The HFBR was modeled using the three-dimensional (XYZ-geometry) DIF3D diffusion theory code[2], in eight energy groups, and with reflector and burnup dependent core cross sections generated using the WIMS-D4M code[3]. The reactor core models are shown in Fig. 3 with two central in-core experiment locations and fuel assembly locations numbered A1 - G4. Each fuel assembly was divided into quadrants in order to assess burnup and power peaking within an assembly. The models also show control rod locations, however, neither the control rods, the ex-core experiment locations, or the beam tubes were modeled. Axial and radial reflectors were modeled assuming that the reactor core was centered in a heavy-water (0.4 wt% light-water impurity) pool approximately 212 cm square by 129 cm high. The energy group structure is shown in Table 1.

Table 1. HFBR Energy Group Structure
(Group – Lower Energy)

1 – 0.821 MeV	2 – 0.183	3 – 5.53 keV	4 – 148.728 eV
5 – 4.00	6 – 0.625	7 – 0.140	8 – 1.0×10^{-5}

Calculations were also performed using the MCNP Monte Carlo code[4]. The results of these calculations for all-fresh HEU and LEU fuel assembly configurations are shown in Table 2. The reactivity difference between the DIF3D and MCNP eigenvalues is $\leq$ 0.5% $\Delta k/k^2$.

Table 2. DIF3D and MCNP Eigenvalue Comparison

Assemblies – Fuel	DIF3D	MCNP	$\Delta k/k^2$, %
28 – HEU 351 g ^{235}U 1.10 gU/cm^3, 0.579 mm meat	1.23996	1.24145 ± 0.00033	+0.097
18 – LEU 450 g ^{235}U 4.54 gU/cm^3, 0.760 mm meat	1.19794	1.20363 ± 0.00034	+0.395
18 – LEU 600 g ^{235}U 6.06 gU/cm^3, 0.760 mm meat	1.20941	1.21726 ± 0.00032	+0.533

In the reactor calculations, the MTR-type LEU fuel assemblies have 20 fuel plates and a fuel meat thickness of 0.760 mm compared to the HEU fuel assembly with 18 fuel plates and 0.579-mm thick meat. With the same Al clad thickness (0.345 mm), the D_2O coolant channel thickness in the LEU fuel assemblies is 2.459 mm compared with 2.438 mm in the HEU fuel assembly.

Fuel Cycle Calculations

The fuel cycle calculations for the HFBR were made using the REBUS code[5]. For these calculations, the end of equilibrium fuel cycle (EOEC) eigenvalue was first calculated using the HEU fuel assembly shuffling pattern and a 22-day fuel cycle length at a reactor power of 40 MW. The 28-assembly HEU fuel shuffling pattern (see Fig. 3) consists of seven series (A – G) in which four fuel assemblies (1 – 4) are shuffled. For example, the A series moves fuel assembly A1 to A2, A2 to A3, A3 to A4, discharges spent fuel from A4, and introduces fresh fuel into A1. The B, C, D, E, F and G series are similar.

For LEU fuel, the equilibrium fuel cycle length necessary to match the same HEU fuel EOEC eigenvalue (1.06031) was calculated as a function of the uranium density in the fuel meat. The 18-assembly LEU fuel shuffling pattern is shown in Table 3.

Table 3. LEU Fuel Shuffling Pattern
(Series – Moves)

1 – A3 to C3 to C4	3 – B1 to D4 to G4	5 – G1 to E4 to B4
2 – A4 to F4 to F3	4 – B2 to D3 to G3	6 – G2 to E3 to B3

This pattern (see Fig. 3) has six series in which three fuel assemblies are shuffled. Fresh fuel is introduced into locations A3, A4, B1, B2, G1 and G2, and spent fuel is discharged from C4, F3, G4, G3, B4 and B3.

FUEL CONVERSION STUDY RESULTS

Fuel Cycle Lengths

The fuel cycle results for these HEU and LEU fuel assemblies are summarized in Table 4.

Table 4. HFBR Fuel Cycles – 40 MW Reactor Power

Assemblies – Fuel	U Density, g/cm^3	Fuel Cycle Length, d	Assemblies per Year	Avg. Discharge ^{235}U Burnup, %
28 – HEU 351 g^{235}U	1.10	22.0	116	47
18 – LEU 450 g^{235}U	4.54	15.0	146	28
18 – LEU 600 g^{235}U	6.06	21.6	101	30

The two 19.75% enriched LEU fuels represent possible candidate fuels for use in the HFBR if the hydraulics of the alternative LEU core geometry are acceptable and if the core can be operated safely. The 450 g^{235}U fuel assembly (4.54 gU/cm^3) could use currently qualified U_3Si_2-Al fuel with a 15-day fuel cycle. The 600 g^{235}U fuel assembly (6.06 gU/cm^3) could match the 22-day HEU fuel cycle if a fuel with approximately 6 gU/cm^3 is successfully developed and if the conditions stated above are satisfied.

Core Power Densities

A comparison of calculated power densities at the beginning of equilibrium fuel cycle (BOEC) are shown in Table 5 for the 28- and 18-fuel assembly core configurations. The peak-to-average power density ratio (column 2) represent the axial power distribution and the average power density ratio (column 3) represent the radial power distribution. The peak power density occurs in locations symmetric to either B1 or C4 (see Fig. 3). The peak-to-core-average power density ratio for all three core configurations is about 2.2.

Table 5. HFBR Power Densities – 40 MW Reactor Power

Assemblies – Fuel	Peak-to-Avg. Power Density[a]	Average Power Density Ratio[b]	Peak Power Density, kW/cm^3
28 – HEU 351 $g^{235}U$	1.49	1.47	1.42
18 – LEU 450 $g^{235}U$	1.72	1.18	1.74
18 – LEU 600 $g^{235}U$	1.85	1.22	1.94

[a] Ratio of the peak power density (P_p) to the average power density ($\overline{P}_p$) in the peak power density assembly.

[b] Ratio of the average power density in the peak power density assembly ($\overline{P}_p$) to the average power density in the core ($\overline{P}_c$).

Reactor Fluxes

A comparison of some midplane reactor fluxes with the HEU and LEU fuels is shown in Table 6. Overall, the HEU- and LEU-fuel reactor fluxes are similar except for the central thermal flux. Because of the increased neutron moderation in the LEU-fuel cores, the thermal fluxes are larger at the center of the core compared to the HEU-fuel core. The LEU-fuel peak thermal flux in the D_2O reflector (located on an ~ 45° diagonal (see Fig. 3) and at an ~ 35 cm radius from the axial centerline) is reduced 5 - 12% relative to the HEU-fuel flux. The reflector fast flux at this same location is very similar for all three fuels. These comparisons are for all-fresh fuel core configurations calculated with DIF3D; similar fluxes were calculated with MCNP. The calculated EOEC fluxes are also in good agreement with these all-fresh fuel fluxes.

Table 6. HFBR Fluxes – 40 MW Reactor Power

Assemblies – Fuel	Fast-1[a]/Fast-2[b] Central Flux, 10^{14} n/cm^2-s	Thermal[c] Central Flux, 10^{14} n/cm^2-s	Fast-1[a]/Fast-2[b] Reflector Flux, 10^{13} n/cm^2-s	Peak Thermal[c] Reflector Flux, 10^{14} n/cm^2-s
28 – HEU 351 $g^{235}U$	1.7/3.2	2.2	1.1/2.0	9.5
18 – LEU 450 $g^{235}U$	1.6/2.9	3.4	1.1/2.0	9.0
18 – LEU 600 $g^{235}U$	1.6/2.9	2.8	1.1/2.0	8.4

[a] Normalized, group 1 (> 0.821 MeV) fast flux – $\Phi_1 \times k_{eff}$.
[b] Normalized, groups 1-2 (> 0.183 MeV) fast flux – $\Phi_{1-2} \times k_{eff}$.
[c] Normalized, groups 7-8 (< 0.625 eV) thermal flux – $\Phi_{7-8} \times k_{eff}$.

The calculated 9.5×10^{14} n/cm^2-s peak thermal reflector flux in the HEU-fuel core configuration compares to a measured[6] flux of 7.0×10^{14} n/cm^2-s for a calculated-to-experiment (C/E) ratio of 1.4. (Note: the measured datum is for a thermal flux < 0.78 eV and is normalized from 60 MW to 40 MW). The larger calculated thermal flux may be due to not modeling the beam tubes, the control rods and/or the control rod movement during reactor operation. Supplemental DIF3D and MCNP calculations with control rods, indicate a trend to reduce the calculated peak thermal reflector flux. The relative difference between the HEU- and LEU-fuel fluxes is not, however, expected to change significantly.

Recent measurements[7] (normalized from 30 MW to 40 MW) have been made of the HEU-fuel flux spectrum in the in-core experiment locations. These data are shown in Table 7, together with fluxes calculated by MCNP for an all-fresh fuel core in the indicated energy group structure and with control rods adjusted to the approximate critical-rod position for the HEU-fuel core.

Table 7. HFBR Fluxes – 40 MW Reactor Power

Assemblies – Fuel	Fast-1/Fast-2 Central Flux, 10^{14} n/cm^2-s	Epithermal Central Flux, 10^{14} n/cm^2-s	Thermal Central Flux, 10^{14} n/cm^2-s	Total Central Flux, 10^{14} n/cm^2-s
HEU Measured[a]	1.25/3.20	14.7	1.60	19.5
28 – HEU 351 g ^{235}U	1.39/3.85	15.4	2.11	21.1
18 – LEU 450 g ^{235}U	1.35/3.72	14.0	3.51	21.3
18 – LEU 600 g ^{235}U	1.38/3.66	13.3	3.08	20.1
With 2-mil Cd Filter 18 – LEU 600 g ^{235}U	1.32/3.53	13.0	1.53	18.1

[a] Fast-1: > 1.0 MeV; Fast-2: > 0.1 MeV; Epithermal: > 0.5 eV – < 0.1 MeV; Thermal: < 0.5 eV.

The agreement of the measured and calculated HEU-fuel fluxes is fairly good except at the ends of the flux spectrum where the C/E is of the order of 1.2 - 1.3. The LEU-fuel fluxes (rows 4 and 5) are similar to the HEU-fuel fluxes except in the epithermal range where they are 9 - 14% smaller and in the thermal range where they are 46 - 66% larger.

The fast (> 0.1 MeV) - to - thermal (< 0.5 eV) flux ratio in Table 7 is approximately two with HEU fuel and between 1.1 and 1.2 with LEU fuel. For the types of experiments performed in the central irradiation thimbles it is desirable to have a large fast-to-thermal (F/T) flux ratio and a small thermal flux fraction as is the case with HEU fuel. A similar flux ratio and thermal flux fraction can be achieved with LEU fuel by inserting a thin cadmium filter in the thimbles. Calculations indicate for example, that for the LEU 600 g ^{235}U fuel and a 2-mil (0.0508-mm) thick cadmium filter, the central thermal flux is reduced from 3.08×10^{14} to 1.53×10^{14}, the F/T flux ratio is increased from 1.19 to 2.31, and the thermal flux fraction is reduced from 0.153 to 0.085. There is a small (< 10%) decrease in the fast flux. With a 2-mil by 6-cm long cylindrical cadmium filter in both central irradiation thimbles, there is a total reactivity penalty equal to 0.56% $\Delta k/k^2$. This technique of using thimble filters in the LEU-fuel cores shows that the thermal flux can be made to be similar to the thermal flux in the HEU-fuel core without significantly affecting the fast flux.

CONCLUSIONS

Conversion of the HFBR from HEU fuel to LEU fuel is not possible without a reconfiguration of the current 28-assembly reactor core. Because of the closely packed fuel assemblies and the D_2O coolant, the HEU core has a relatively hard neutron spectrum which becomes much harder when LEU fuel is directly substituted for HEU fuel. This spectral hardening results in a loss of reactivity in the LEU core and an unacceptable fuel cycle length with uranium densities up to that of uranium metal (19 gU/cm^3). The core needs to be reconfigured to increase the neutron thermalization if LEU fuel is to be used. Within the constraints of the existing reactor hardware, removing fuel assemblies from the core could be an option to increase core-neutron thermalization if the hydraulics are satisfactory and if the reactor can be operated safely. An LEU core with 18 fuel assemblies arranged in an annular-shape would be an optimum configuration.

Relative to a 22-day fuel cycle at 40 MW for the current HEU fuel assembly with 351 g ^{235}U, fuel cycle lengths of 15 and 22 days are estimated for LEU fuel assemblies with 450 g ^{235}U (4.5 gU/cm^3) and 600 g ^{235}U (6.1 gU/cm^3), respectively. An LEU core with a 15-day cycle length is about the longest cycle length that can be achieved using currently qualified silicide fuel with a uranium density of about 4.8 g/cm^3. This cycle length however, is not likely to be acceptable for LEU conversion. An LEU fuel with a uranium density of about 6.1 g/cm^3 is needed in order to match the 22-day cycle length of the HEU core. If the options discussed above are not feasible, particularly in relation to the core hydraulics and safety, a new LEU reactor design may be necessary.

With high-density LEU fuels, the fast fluxes in the central irradiation and beam tube locations of the HFBR are nearly the same as with the current HEU fuel. The thermal fluxes however, are about 10% smaller in the D_2O reflector and about 50% larger in the central irradiation locations. Cadmium filters can be used in the central irradiation thimbles to reduce the thermal flux without significantly affecting the fast flux.

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