CONVERSION FEASIBILITY STUDIES FOR THE GRENOBLE HIGH FLUX REACTOR

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ABSTRACT

Feasibility studies for conversion of the High Flux Reactor (RHF) at Grenoble France have been performed at the Argonne National Laboratory in cooperation with the Institut Laue-Langevin (ILL). The uranium densities required for conversion of the RHF to reduced enrichment fuels were computed to be 7.9 g/cm^3 with 20% enrichment, 4.8 g/cm^3 with 29% enrichment, and 2.8 g/cm^3 with 45% enrichment. Thermal flux reductions at the peak in the heavy water reflector were computed to be 3% with 45% enriched fuel and 7% with 20% enriched fuel. In each case, the reactor's 44 day cycle length was preserved and no changes were made in the fuel element geometry. If the cladding thickness could be reduced from 0.38 mm to 0.30 mm, the required uranium density with 20% enrichment would be about 6.0 g/cm^3 and the thermal flux reduction at the peak in the heavy water reflector would be about 7%.

Significantly higher uranium densities are required in the RHF than in heavy water reactors with more conventional designs because the neutron spectrum is much harder in the RHF. Reduced enrichment fuels with the uranium densities required for use in the RHF are either not available or are not licensable at the present time.

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1. INTRODUCTION

The RHF was designed primarily for the production of thermal neutrons with high intensity for research experiments. The reactor operates at a power level of 57 MW and is moderated and cooled by heavy water. The core consists of a single annular fuel element with inner and outer radii of 136.9 mm and 198.8 mm, respectively. The fuel region is 800 mm long and contains 8.57 kg of ^{235}U in 280 involute fuel plates. The fuel meat is composed of UAl_x-Al fuel with a thickness of 0.51 mm and a uranium density of about 1.2 g/cm^3. The cladding and coolant channel thicknesses are 0.38 mm and 1.8 mm, respectively.

The reactor is controlled by means of a cylindrical nickel control rod with high reactivity worth located in the center of the fuel element and by five cylindrical shim and safety rods arranged almost symmetrically around the core in the heavy water reflector. Two burnable poison regions containing a total of 5.77 g ^{10}B are located at the top and bottom of the fuel element to reduce the excess reactivity at beginning-of-life (BOL) and to reduce power peaking at the top and bottom of the core.

The first part of this paper gives a brief description of the reactor model and the computational methods that were used. The results of the conversion studies are followed by a comparison of the RHF with the DR-3 reactor at the Risoe National Laboratory in Denmark. An empirical correlation is developed that relates the LEU/HEU ^{235}U loading and the moderator/fuel ratio.

2. REACTOR MODEL AND COMPUTATIONAL METHODS

The conversion feasibility studies for the RHF were performed with 15 energy groups using the diffusion theory codes DIF3D/1/ for static calculations and REBUS-3/2/ for burnup calculations. A fine group approach using 11 fast and 4 thermal groups (<0.625 eV) was used in the analyses to account for the strong spectral transition across the compact reactor core. Burnup-dependent cross sections for the diffusion theory calculations were generated with the EPRI-CELL code/3/ using a slab model. The energy boundaries in the 15-group calculations are given in Table 1.

Table 1. Energy Boundaries in the 15-Group Calculations

Group Upper Energy (eV)

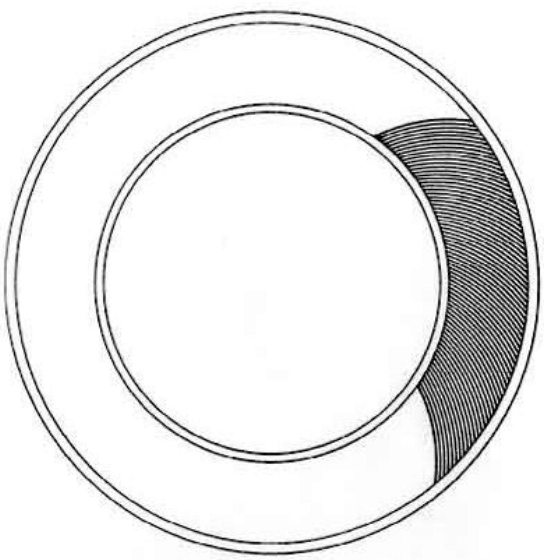
1	1.000×10^7	6	9.611×10^2	11	1.053
2	8.209×10^5	7	3.536×10^2	12	0.625
3	6.738×10^4	8	2.260×10^1	13	0.301
4	1.930×10^4	9	5.043	14	0.184
5	5.531×10^3	10	1.855	15	0.043

A horizontal cross section of the RHF core is shown in Fig. 1. The reactor calculations that were performed with the REBUS-3 and DIF3D codes were based on the two-dimensional R-Z model shown in Fig. 2. Beam tubes or other facilities were not included in the heavy water reflector. A half-core model was used in the REBUS-3 calculations to compute the burnup history and depletion of isotopes. A more detailed full core model was used in the DIF3D calculations to compute flux and power distributions. In addition to the diffusion theory calculations, selected cores were calculated with the VIM continuous-energy Monte Carlo code/4/ using a detailed 280-plate model of the RHF. The results given in Table 2 indicate a reasonable agreement between the Monte Carlo and diffusion theory results. We have not been able to determine a measured excess reactivity corresponding to this reactor condition. However, for a critical facility core/5/ with no burnable poison, the value of k_{eff} calculated by ILL was 1.277 and that calculated by ANL was 1.275.

Table 2. Comparison of Diffusion Theory and Monte Carlo Results for the RHF HEU Core (Without Beam Tubes or Other Facilities in the Reflector)

RHF Core Model	Excess Reactivity at BOL (% ?k/k)
REBUS-3 - half core	17.98
DIF3D - full core	17.90
VIM - full core	17.13 ± 0.39

Fig. 1. Horizontal Cross Section of the RHF Core



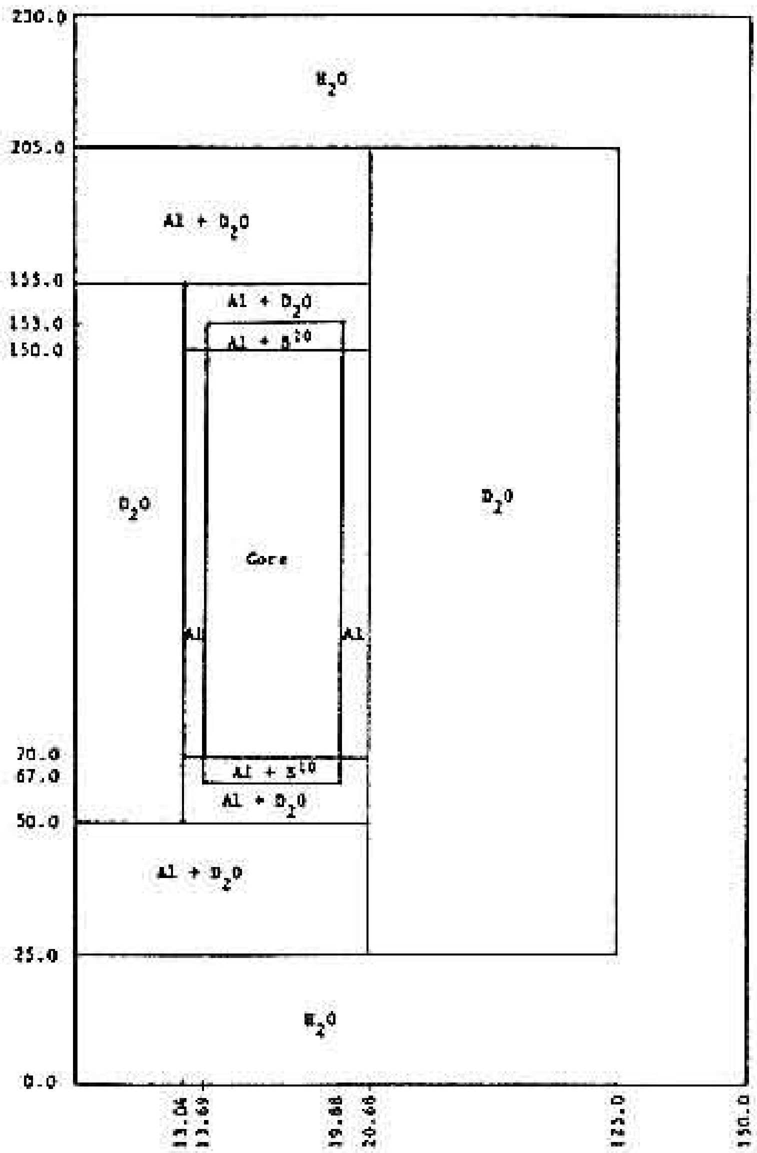
Inner Diameter = 274 mm

Outer Diameter = 398 mm

Fueled Length = 800 mm

Fuel Plate/Core = 280

Fig. 2 R-Z Diffusion Theory Model of the RHF.



3. CONVERSION FEASIBILITY STUDIES

The conversion feasibility studies performed for the RHF were based on matching the 44 day cycle length and end-of-life (EOL) excess reactivity of the HEU and reduced enrichment (REU) cores. Results of the studies are shown in Table 3. With the same fuel plate design as the HEU core, the increases in the ^{235}U loadings were found to be 17% with 45% enriched fuel, 25% with 29% enriched fuel, and 42% with LEU fuel. The latter corresponds to an LEU density of 7.9 g U/cm^3. If the cladding thickness could be reduced from 0.38 mm to 0.30 mm with the same fuel plate thickness as the current HEU plates, the required LEU density would be about 6.0 g U/cm^3.

Table 3. Results of the Conversion Feasibility Studies

	HEU(93%)	HEU(45%)	HEU(29%)	LEU(<20%)	
Enrichment (%)	93	45	29	20	20
Uranium Density (g/cm^3)	1.2	2.8	4.8	7.9	6.0
No. of Fuel Plates	280	280	280	280	280
Meat Thickness (mm)	0.51	0.51	0.51	0.51	0.67
Cladding Thickness (mm)	0.38	0.38	0.38	0.38	0.30
D_2O Channel Thickness (mm)	1.80	1.80	1.80	1.80	1.80
Cycle Length (days)	44	44	44	44	44
Burnable Poison (g ^{10}B)	5.77	5.77	5.77	5.77	5.77
^{235}U loading (Kg)	8.57	10.02	10.69	12.13	12.11
^{235}U REU/HEU Loading	1.00	1.17	1.25	1.42	1.41
BOL Excess Reactivity (% ?k/k)	17.98	17.00	16.47	15.04	15.12
EOL Excess Reactivity (% ?k/k)	5.40	5.78	5.88	5.30	5.43
Peak Thermal Flux† in Reflector x 10^{15}(n/cm^2/s)	1.28	1.25	1.22	1.19	1.19
REU/HEU Peak Thermal Flux Ratio	1.00	0.97	0.95	0.93	0.93
Maximum Power Density at Outer Core Boundary (kW/cm^3)	2.29	2.42	2.49	2.61	2.60

† With central control rod fully-withdrawn. Insertion of this rod increases the peak thermal flux in the reflector.

A profile of the thermal (<0.625 eV) flux across the HEU core with the central control rod fully-withdrawn is shown in Fig. 3, along with thermal flux ratios between cores with reduced enrichments and the HEU core. The reduction in the peak thermal flux in the reflector is ~3% with 45% enriched fuel, ~5% with 29% enriched fuel, and ~7% with 20% enriched fuel.

Fig. 3. Thermal Flux Distribution in HEU Core and REU/HEU Thermal Flux Ratios.

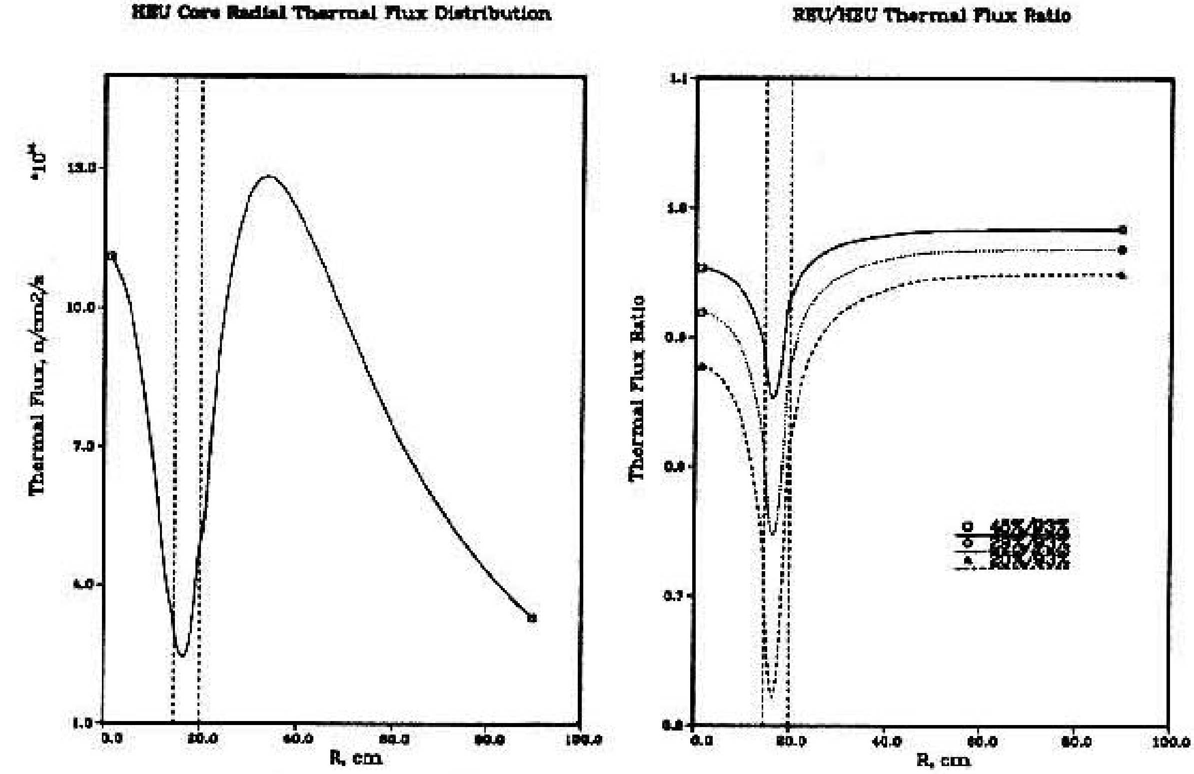
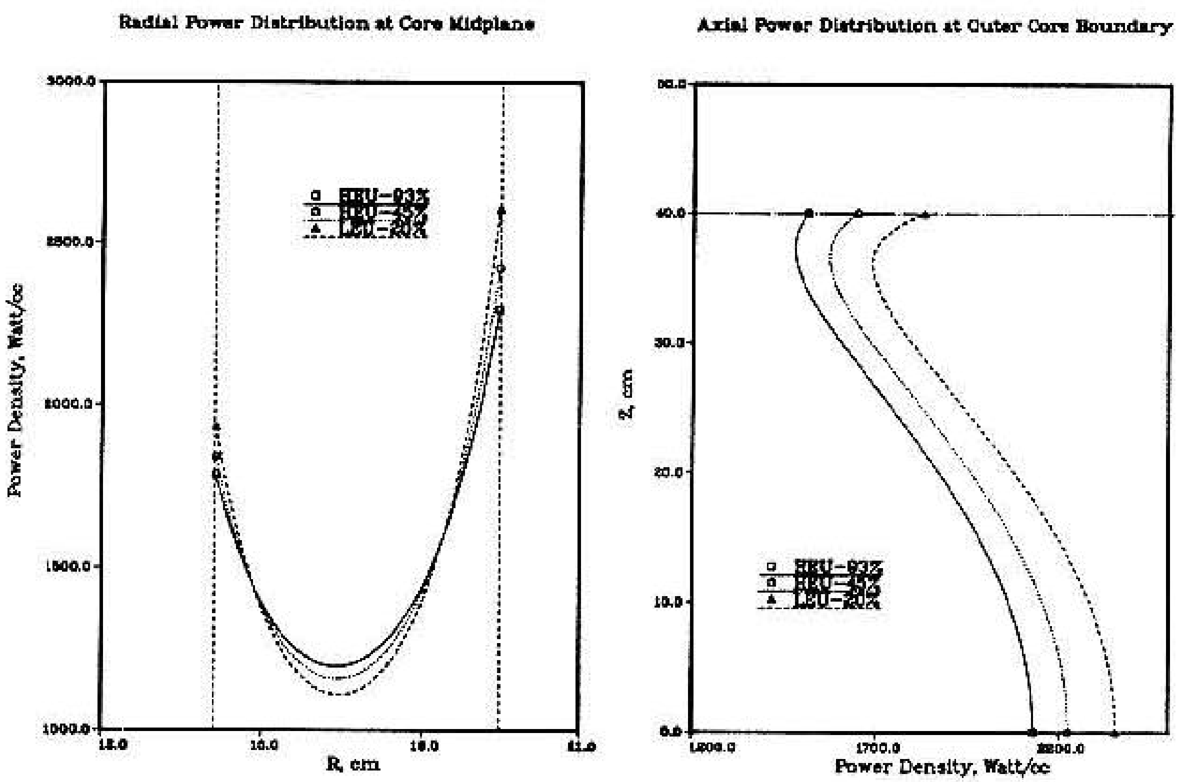


Fig. 4. Radial and Axial Power Density Distributions.



Radial and axial power density distributions are shown in Fig. 4. The power peak density at the outer edge of the core increases as the fissile loading is increased to accommodate fuels with reduced enrichments. The value of this power peak density is important because it relates to the thermal-hydraulic safety margins, which have not been addressed in this study.

4. COMPARISON OF THE RHF WITH THE DR-3 REACTOR

The results presented in Section 3 show that conversion of the RHF from HEU to LEU fuel would require an increase in the ^{235}U loading of over 40%. This result is considerably higher than the 10% increase obtained from studies/6/ of heavy water reactors with more conventional designs. In order to investigate the cause of the exceptional increase in the LEU fissile loading required in the RHF, a comparison is made with the DR-3 reactor at the Risoe National Laboratory in Denmark. Basic core parameters for the two reactors are shown in Table 4. Two important features of the RHF are its compact core and high uranium loading that are required to meet the high flux and burnup requirements. Such characteristics lead to a heavily under-moderated system that is indicated by the small moderator/fuel ratio in the RHF reactor core.

Table 4. Basic Core Parameters of the RHF and DR-3 Reactor

	RHF	DR-3
Power (MW)	57	10
Active Core Volume (l)	52.2	360.1
Enrichment(%)	93	93
^{235}U Loading (kg)	8.57	3.9
Uranium Density (g/cm^3)	1.2	0.57
Moderator and Reflector	D_2O	D_2O
Moderator/Fuel Ratio (D_2/U)	86	2089
Cycle Length (days)	44	23.5
^{235}U Worth (?k/k per kg ^{235}U)	0.0094	0.0359
^{238}U Worth/^{235}U Worth	-0.32	-0.20

Normalized core-average flux distributions in the RHF and DR-3 reactors are compared in Fig. 5. The under-moderated RHF has a much harder neutron spectrum than the DR-3 reactor. The harder neutron spectrum in the RHF, along with a harder adjoint flux distribution (not shown) result in a significantly smaller ^{235}U worth in the RHF. In cores with LEU fuel, the smaller ^{235}U worth and higher $^{238}U/^{235}U$ worth ratio in the RHF result in a higher LEU fissile loading requirement than in the DR-3.

Fig. 5. Normalized Core-Average Flux/Unit Lethargy Distributions for the RHF and DR-3 Reactors

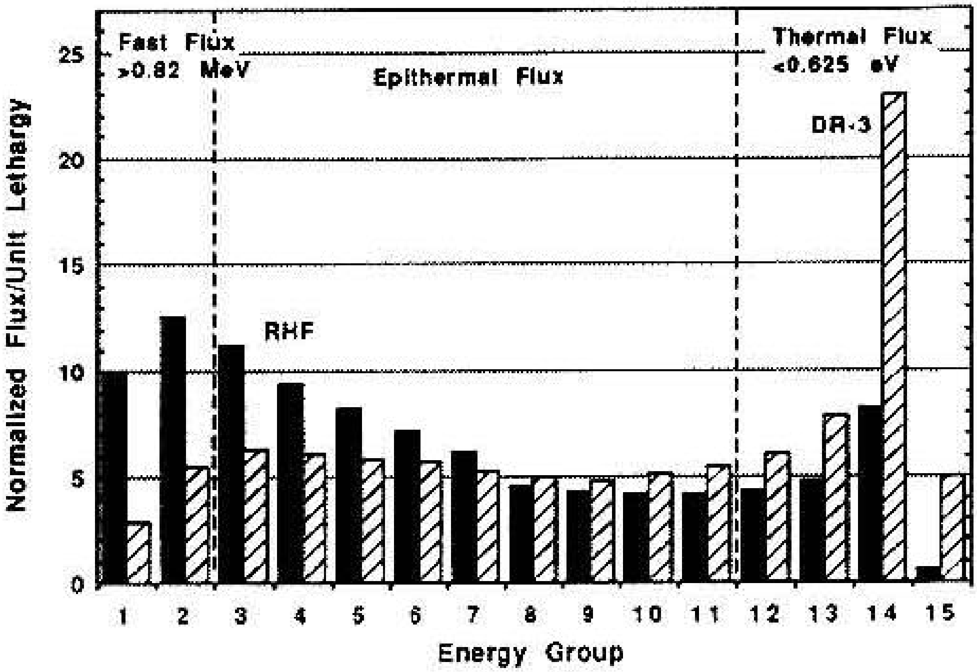
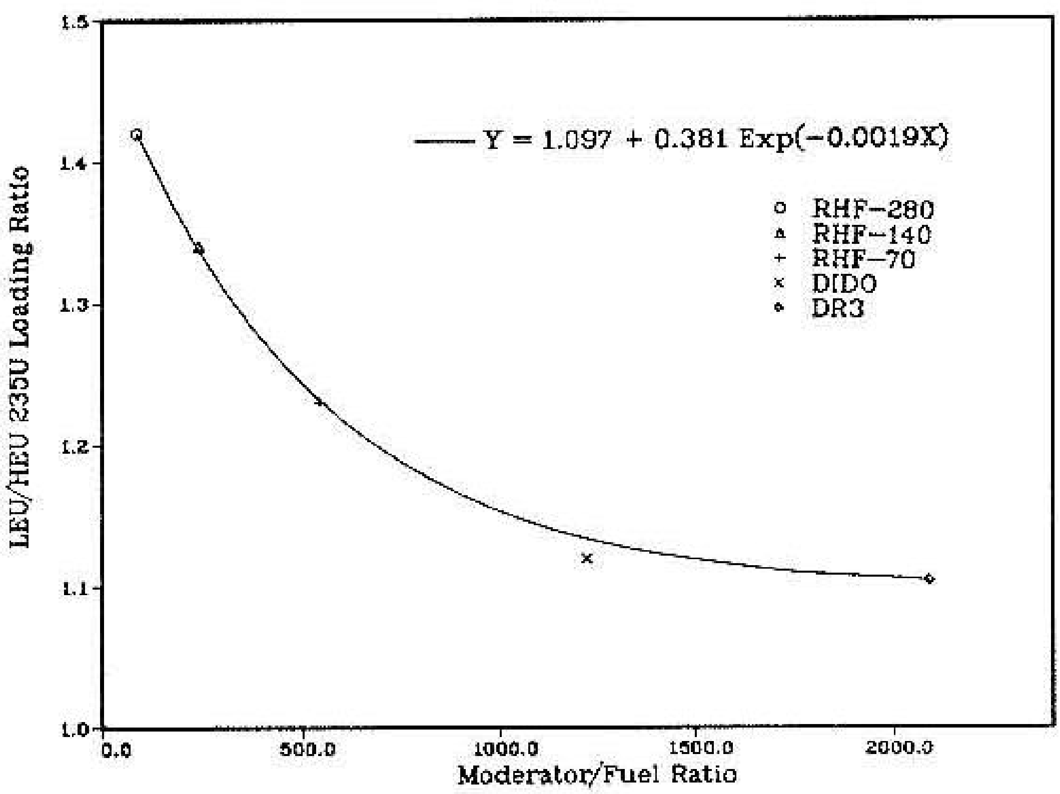


Fig. 6 235U LEU/HEU Loading Ratio vs Moderator/Fuel Ratio



5. VARIATION OF ^{235}U LEU/HEU LOADING WITH MODERATOR/FUEL RATIO

The analyses presented in Section 4 show that the conversion of the RHF from HEU to LEU fuels requires an increase in the ^{235}U loading that depends on the moderator/fuel ratio. In order to investigate the variation in the LEU/HEU ^{235}U loading for a range of moderator/fuel ratios, additional calculations were repeated with two fictitious RHF core models containing fewer fuel plates to increase the moderator/fuel ratio. The cycle length, power and burnable poison were also reduced to achieve positive EOL excess reactivities. The changes in the LEU loadings are shown in Table 5. The results indicate that the LEU loading requirement decreases with increasing moderator/fuel ratio.

Table 5. Changes in the LEU ^{235}U Loadings with Moderator/Fuel Ratio for RHF HEU Core and Two Fictitious RHF Core Models.

	RHF-280	Fictitious RHF-140	Fictitious RHF-70
Numbers of Fuel Plates	280	140	70
Power(MW)	57	57	20
HEU Density(g/cm^3)	1.2	1.2	1.2
Moderator/Fuel Ratio in the HEU Core (D_2/U)	86	241	544
Burnable Poison (g ^{10}B)	5.77	5.77	1.44
Cycle Length(days)	44	20	10
^{235}U LEU/HEU Loading	1.42	1.34	1.23

The changes in the LEU/HEU ^{235}U loadings with moderator/fuel ratio for the RHF, DR3 and DIDO reactors are shown in Fig. 6. The data for the DR-3 and DIDO reactors are taken from Ref. 6. The continuous curve in Fig. 6 was obtained from a empirical fit:

$$\text{LEU/HEU } {}^{235}\text{U Loading} = 1.097 + 0.381 \,\text{Exp}(-0.0019\, x)$$

where x is the moderator/fuel ratio of the HEU core. It should be noted that the DIDO reactor has an HEU enrichment of 75% in the computations published in /6/. It also appears from Fig. 6 that a transition between well-moderated and under-moderated reactors occurs at a moderator/fuel ratio of about 1000. For well-moderated reactors with larger moderator/fuel ratio, the increase in the required LEU/HEU ^{235}U loading is about 10%. For under-moderated reactors with smaller moderator/fuel ratio, the ^{235}U LEU/HEU loading increases exponentially with decreasing moderator/fuel ratio.

6. CONCLUSION

Conversion feasibility studies based on the cycle length and EOL excess reactivity matching criterion were performed for the RHF using 15-group burnup calculations. The results show that conversion of the RHF from HEU to LEU fuel requires a uranium density of about 7.9 g/cm^3 if no changes are made in the fuel element geometry. This uranium density corresponds to an increase of about 40% in the ^{235}U loading. With enrichments of 29% and 45%, the corresponding uranium densities are about 4.8 g/cm^3 and 2.8 g/cm^3, respectively. If cladding thickness could be decreased from 0.38 mm to 0.30 mm, the required LEU density would be about 6.0 g/cm^3. Thermal flux reductions at the peak in the heavy water reflector were computed to be ~3% with 45% enriched fuel, ~5% with 29% enriched fuel and ~7% with 20% enriched fuel.

The 40% increase in the LEU fissile loading required in the RHF is considerably higher than the 10% increase obtained from studies of heavy water reactors with more conventional designs. The difference in the ^{235}U loading requirement in the RHF is attributed to its highly under-moderated neutron spectrum. Reduced enrichment fuels with the uranium densities required for use in the RHF are either not available or are not licensable at the present time.

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