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LEU FUEL CYCLE ANALYSES FOR THE BELGIAN BR2 RESEARCH REACTOR*

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ABSTRACT

Equilibrium fuel cycle characteristics were calculated for reference HEU and two proposed LEU fuel cycles using an 11-group diffusion-theory neutron flux solution in hexagonal-Z geometry. The diffusion theory model was benchmarked with a detailed Monte Carlo core model. The two proposed LEU fuel designs increased the ^{235}U loading 20% and the fuel meat volume 51%. The first LEU design used ^{10}B as a burnable absorber and the second used Cd wires as an alternative burnable absorber. Either proposed LEU fuel element would provide equilibrium fuel cycle characteristics similar to those of the HEU fuel cycle. Irradiation rates of Co control followers and Ir disks in the center of the core were reduced 6 ± 1% in the LEU equilibrium core compared to reference HEU core.

INTRODUCTION

The Reduced Enrichment Research and Test Reactor (RERTR) Program and the Centre d'Etude de l'Energy Nucléaire (CEN/SCK) have been engaged in a joint study to determine the most suitable LEU fuel element design for the BR2 reactor in Mol, Belgium.[1-3] The previous fuel cycle analyses were performed using a five-group diffusion theory model. Comparisons of the diffusion and Monte Carlo models in hexagonal-Z geometry of fresh and equilibrium cores indicated the need for improvements to the diffusion model. Presented in this paper are the equilibrium fuel cycle characteristics calculated using the improved diffusion theory model for two proposed LEU fuel designs.

REACTOR DESCRIPTION

The BR2 core is cooled and moderated with pressurized light water with an average pressure of 12 bar. The reference steady state power level is 56 MW, but the reactor has the cooling capacity to permit operation at 125 MW. The beryllium matrix has 79 cylindrical holes in a hexagonal lattice of 9.644 cm pitch at the midplane of the core. The holes are filled with fuel elements, control rods, various experiments or Be plugs. There are 64 standard channels of 84 mm diameter, 10 small channels of 50 mm diameter, and five large channels of 200 mm diameter. All core elements are placed at a slight angle from a perfectly vertical position relative to the core midplane in order to permit easier

access to core elements. The cosine of this non-vertical placement of element varies from 0.9981 to 0.9844 and does not significantly affect smeared material densities except in the upper and lower reflectors.

Core configuration 10D, which has 31 fuel elements with six shim and two regulating control rods as shown in Figure 1, has been chosen for these anlayses. No actual experiments have been modeled in these fuel cycle analyses. All core positions have been modeled using Be central plugs.

Fuel Element Description

The standard HEU fuel element has six concentric fuel rings with an active fuel length of 762 mm placed in an 84 mm diameter channel in a Be hexagonal matrix. Each fuel ring is formed by three fuel plates secured in position by a mechanical connection along their edges to three equally spaced radial Al webs (corresponding to the side plates of box-type elements) as shown in Figure 2. The water gap between the fuel plates is 3 mm and the fuel plate thickness is 1.27 mm with a fuel meat thickness of 0.51 mm. Each HEU fuel element contains 400g ^{235}U with 3.8g B from B_4C and 1.4g Sm from Sm_2O_3 as burnable absorbers homogeneously mixed into the UAl_x fuel meat.

Control Rod Description

The six shim control rods are divided into three axial zones: a cadmium control zone; a ^{59}Co zone, 12.15 cm in length; and a Be follower zone. The annular Cd section has an outer diameter of 60 mm and an inner diameter of 50 mm as shown in Figure 3. The two regulating control rods are similar to the shim rods but have a thinner annular cadmium control zone with outer diameter of 39 mm and inner diameter of 34 mm and no cobalt annular zone.

GENERATION OF CROSS SECTIONS FOR FUEL AND CONTROL RODS

TABLE I

Broad-Group Neutron Energy Structure for Neutronic Analyses

Neutron Group	Upper Energy Boundary (ev)
1	1.0×10^{7}
2	0.821×10^{6}
3	5.531×10^{3}
4	1.855
5	6.249×10^{-1}
6	1.427×10^{-1}
7	8.197×10^{-2}
8	4.276×10^{-2}
9	3.061×10^{-2}
10	2.049×10^{-2}
11	6.325×10^{-3}

The EPRI-CELL[4] code was used to generate all neutron cross sections for use in the fuel cycle calculations. EPRI-CELL uses one-dimensional integral transport theory with 35 neutron groups below 1.8 eV (similar to THERMOS) and 68 neutron groups above 1.85 eV in a homogeneous mixture (similar to GAM). The fine group cross sections were collapsed into 11 broad groups with three groups above 1.85 eV and eight below for use in broad- group diffusion-theory fuel cycle calculations as shown in Table I. A cylindrical representation of the fuel element was developed assuming that no web material was present and that the outer Be filler block could be represented as an

Fig. 1. BR2 Core Configuration 10D

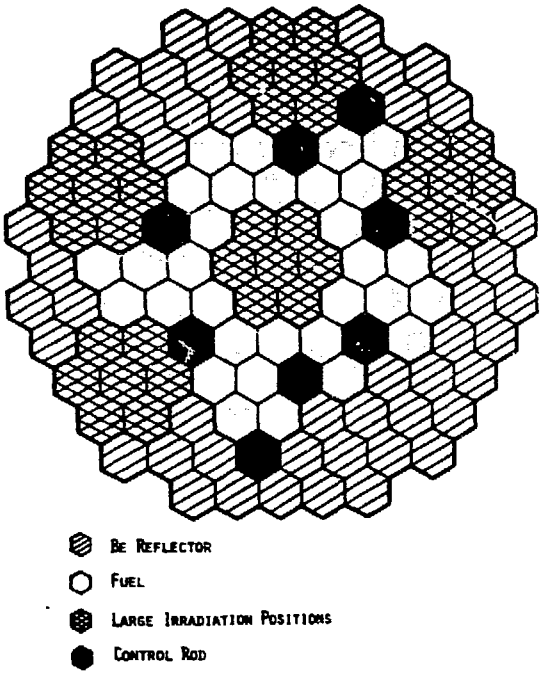


Fig. 2. BR2 HEU Fuel Element Cross Section at Core Midplane

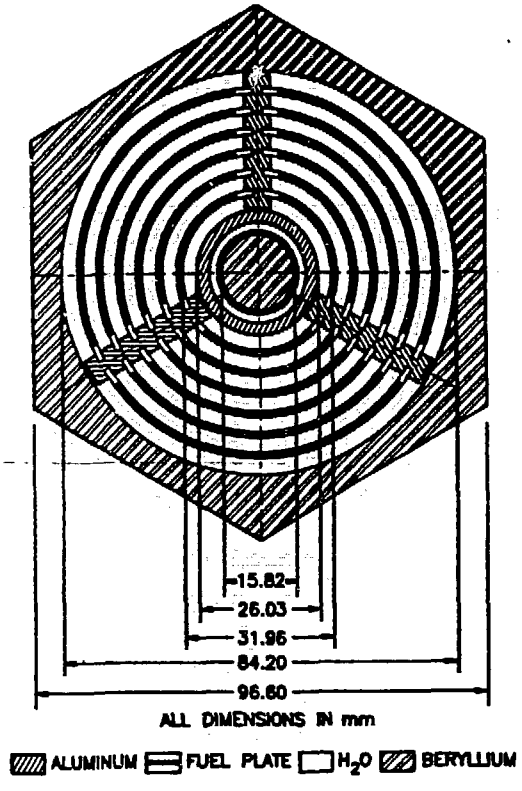


Fig. 3. BR2 Control and Follower Sections of Shim Control Rod

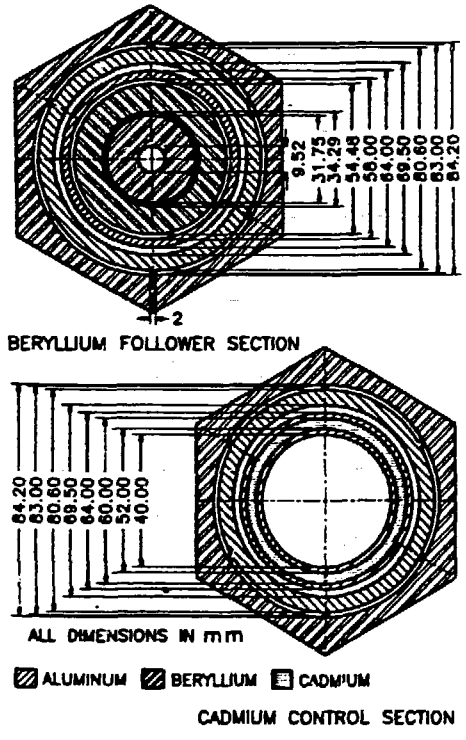
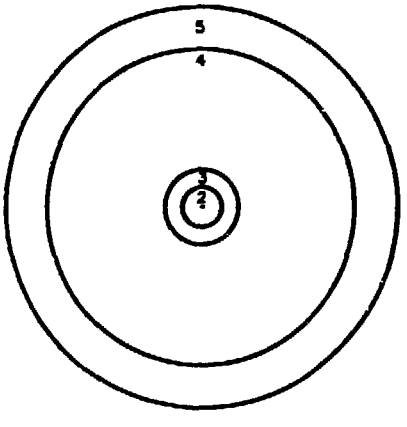


Fig. 4. EPRI-CELL Model for Cd Wire Depletion



OUTER RADII OF EACH ANNULAR ZONE

r_1 = 0.2 mm – Cd WIRE

r_2 = 2.5 mm – Al WEB

r_3 = 4.3 mm – Al/H_2O

r_4 = 19.3 mm – FUEL

r_5 = 24.6 mm – Be

annulus. Each fuel meat, clad, and moderator zone was modeled separately with one mesh point used in each zone. A total of 44 mesh points was required for this model to calculate burnup-dependent cross sections for each isotope in each fuel plate of the fuel element. Each axial zone of the control rod was represented by a cylindrical model surrounded by an outer zone of homogenized fresh fuel.

Generation of Cross Sections for Cd Wires

The EPRI-CELL model for depletion of Cd wires consisted of four different zones surrounding a single Cd wire as shown in Figure 4. The first of these zones consisted of Al, representing any wire cladding and those parts of the web and fuel plate edge cladding closest to the wire, and had a radius equal to the distance from the center of the wire to the closest moderator. The second annular zone consisted of Al and H_2O, representing a volume-averaged mixture of web, fuel plate edge cladding, and moderator within a radius equal to the distance from the center of the wire to the closest fuel meat. The third zone was a homogeneous mixture of fuel, cladding, and moderator materials. The last zone was Be to represent the presence of Be filler block and inner plug material.

The key variables in the development of this model for accurately following the changes in composition of Cd from beginning to end of life were the volumes of the outer two zones (fuel and Be). Increasing the volume of fuel would harden the neutron spectrum while Be volume increases would soften the thermal spectrum without much effect on the higher energy groups. The main criterion for achieving a good EPRI-CELL model for Cd depletion was to create a neutron spectrum over the entire volume of the wire that would be as close as possible to the spectrum calculated by an exact VIM[5] model of the fuel element with each Cd wire explicitly represented. Once this spectrum was achieved, the EPRI-CELL calculated Σ_{a_5} of the unirradiated wire was within ±1% of the VIM result averaged over all wire locations in the element.

FUEL ELEMENT BENCHMARK COMPARISONS USING VIM AND DIF3D

In order to determine the adequacy of the cross section data generated by EPRI-CELL for use in whole-core diffusion calculations, it was necessary to benchmark the data using VIM. This benchmarking activity was needed because of the unusual geometry of the standard fuel element as well as the departure from infinite lattice boundary conditions caused by numerous fuel-non-fuel interfaces in the core. Initial VIM-DIF3D comparisons were made with infinite lattice boundary conditions before whole-core comparisons were begun.

The VIM model of the fuel element was an exact geometrical representation of the location of each fuel plate, Be plug and matrix block, and water channel using the standard combinatorial geometry option. The fuel element was modeled assuming no axial leakage and perfect reflector boundary conditions for all neutron energies at all radial surfaces.

The initial comparisons of fuel cross section data were made in an infinite lattice environment with a single homogeneous-composition, 11-broad-group diffusion calculation using a nodal method[6] DIF3D[7] flux solution. The key items for comparison of the two models were k_∞ and isotopic absorption rates

normalized to unity, as shown in Table II. Also included in Table II with the HEU fuel element are the comparisons for the two proposed LEU fuel element designs. LEU design #1 was loaded with 480 g ^{235}U/element and 2.85 g B and 1.4 g Sm mixed into the fuel meat. LEU design #2 has the same ^{235}U and Sm loading but with the boron burnable absorber replaced by 36 Al-clad Cd wires (0.4 mm in diameter) placed in the Al support webs of the element. Each of the VIM cases had accumulated 100,000 neutron histories, resulting in standard deviations for the most significant isotopic absorption rates presented in Table III of less than ±2%. The standard deviation for the VIM k_∞ was ±0.003 Δk_∞.

The results of the VIM and DIF3D models were in good agreement for the case of fresh HEU or LEU fuel in an infinite array of like elements. The only adjustment that was necessary for achieving this agreement for the elements using boron as a burnable absorber was to replace the EPRI-CELL $\sigma_1(n,2n)$ for Be with the VIM $\sigma_1(n,2n)$ in the DIF3D model. With 32% of the fuel element volume occupied by the Be matrix and central plug, the n,2n scattering in Be was a significant contribution to the element reactivity with approximately four n,2n scattering events occurring for every 100 absorption events. Since the strongly absorbing Cd wires in LEU design #2 occupy a very small volume relative to the fuel element, the EPRI-CELL microscopic thermal cross sections for ^{113}Cd required adjustment until the ^{113}Cd absorption rate in DIF3D was equivalent to the VIM model prediction. Once the ^{113}Cd absorption rate was forced to be equal to the VIM rate and the VIM $\sigma_1(n,2n)$ for Be utilized, all other isotopic absorption rates in the element were brought into good agreement using unadjusted EPRI-CELL cross section data. Four additional infinite lattice VIM-DIF3D comparisons were necessary for LEU elements using Cd wires so that the thermal absorption cross sections for ^{113}Cd could be properly adjusted throughout the lifetime of the wires.

WHOLE CORE MODEL COMPARISONS USING VIM AND DIF3D

In order to benchmark the DIF3D core model, six comparisons were made with a detailed VIM core model, three each with HEU fuel and with LEU fuel. Four of the six comparisons were for all-fresh fuel with no axial leakage both with and without control rods inserted and two were hexagonal-Z core models with beginning-of-equilibrium-cycle loadings and partially inserted control rods.

The VIM BR2 core model was an exact representation of each fuel plate, water region, web, Cd wire, Be plug in planar or hexagonal-Z geometry. The only approximation to the actual core geometry was the assumption that all elements were perfectly orthogonal to the horizontal mid-plane of the core. A total of 1876 zones were required for the HEU equilibrium cycle core and 2186 zones for the LEU equilibrium cycle core. Each VIM case required 300,000 neutron histories to obtain absorption rate standard deviations <±2% for each significant isotope in each fuel element. Lumped fission products were simulated using concentrations of ^{135}Xe and ^{99}Mo. One axially averaged fuel meat concentration was used per element to reduce the volume of input that several axially dependent compositions would require. The shim rods were all positioned with the end of the 12.15 cm-long cobalt follower section at 2.5 cm above the core mid-plane. The regulating rods were pulled such that their Cd section tips were

TABLE II

Benchmark Comparisons of VIM and Single-Composition Infinite Lattice DIF3D Models of Fresh 400 g ^{235}U HEU Reference Fuel and Fresh 480 g ^{235}U LEU Fuel

Isotopic Absorption Rates Normalized to Unity

	HEU Element		LEU Element No. 1		LEU Element No. 2	
Isotope	VIM	DIF3D	VIM	DIF3D	VIM	DIF3D
^{235}U	0.6686	0.6662	0.6529	0.6551	0.6878	0.6865
^{238}U	0.0044	0.0047	0.0774	0.0780	0.0785	0.0780
^{27}Al	0.0225	0.0214	0.0180	0.0172	0.0185	0.0188
^{10}B	0.1634	0.1655	0.1344	0.1354	-	-
Si	-	-	0.0006	0.0006	0.0006	0.0005
^{149}Sm	0.0525	0.0530	0.0428	0.0419	0.0450	0.0446
^{1}H	0.0689	0.0688	0.0543	0.0537	0.0531	0.0531
^{16}O	0.0013	0.0011	0.0011	0.0010	0.0012	0.0011
^{9}Be	0.0184	0.0192	0.0185	0.0180	0.0180	0.0202
^{113}Cd	-	-	-	-	0.0974	0.0972
k_∞	1.3918	1.3914	1.3682	1.3710	1.4396	1.4411

TABLE III

Comparison of Isotopic Absorption Rates Calculated Using VIM and Several DIF3D Nodal Models for the BR2 BOL HEU Core

Isotopic Absorption Rates Normalized to Unity

Isotope	VIM	DIF3D 20 gr	DIF3D 11 gr	DIF3D 5 gr	DIF3D* 20 gr	DIF3D* 5 gr
^{235}U	0.5821	0.5826	0.5833	0.5867	0.5860	0.5893
^{238}U	0.0033	0.0034	0.0034	0.0034	0.0034	0.0034
^{9}Be	0.0570	0.0594	0.0590	0.0578	0.0583	0.0570
^{10}B	0.1451	0.1465	0.1466	0.1477	0.1474	0.1485
^{1}H	0.1313	0.1280	0.1275	0.1250	0.1251	0.1226
^{27}Al	0.0322	0.0315	0.0315	0.0312	0.0310	0.0308
^{149}Sm	0.0476	0.0476	0.0476	0.0472	0.0479	0.0475
k_{eff}	1.1581	1.1590	1.1601	1.1636	1.1663	1.1691

*Finite difference with 64 triangles per hexagon mesh.

also 2.5 cm above the core mid-plane, which corresponds to a rod position of 505 mm of withdrawal. A no-return current boundary condition was placed at axial planes 30 cm above and below the active core zone and at the outer radial boundary of seven hexagonal rings.

The DIF3D core model required 127 hexagonal unit cells for the seven hexagonal rings in each of the 21 axial mesh planes for the 31-fuel-element core. The microscopic cross sections were burnup dependent for all heavy metal and burnable absorber materials. The nodal method of flux solution to the diffusion equations using 11 broad groups was used for this model. The rationale for this selection can be deduced by a comparison of the isotopic absorption rates and k_∞ data using finite difference and nodal methods with different group structures as shown in Table III. The comparison presented in Table III was for an all-fresh HEU core with all control rods fully withdrawn. Although the finite difference and nodal methods yielded identical flux solutions in infinite lattice single fuel-element DIF3D cases, the nodal method yielded better predictions of absorption rate and k_∞ for every group structure tested in whole core calculations. Increasing the number of groups below 0.625 eV using the nodal method yielded closer agreement with VIM. A finer group structure above 0.625 eV was also compared with VIM fine group neutron spectra but found to be unnecessary to improve any reaction rates or neutron spectral comparisons.

The whole-core reactivity comparisons using the VIM and DIF3D models are presented in Table IV. In each case the k_{eff}'s agree to within $\pm 0.003\ \Delta k_{eff}$. The isotopic absorption rate comparisons for the entire core followed the same trends presented in Table III for the fresh core comparisons. The hydrogen absorption was underpredicted consistently in HEU and LEU cores but the bias is reduced upon insertion of all control rods. Most other isotopic absorption rates were predicted well except for Be, whose absorption rate is consistently larger than for VIM. The only adjustment to the microscopic cross section data was a further adjustment to the $\sigma_1(n,2n)$ of Be compared to infinite lattice comparisons. Although the k_{eff} comparisons for the equilibrium HEU and LEU cores were as good as the fresh core comparisons, the agreement in the isotopic absorption rates was not as favorable. Although all heavy metal and burnable absorber absorption rates were predicted to within $<\pm 2\%$, the hydrogen absorption was overpredicted by 3.9% in the HEU core and 6.5% in the LEU core. These differences did not affect the core reactivity because the absorption in the steel axial reflector material was underpredicted by a similar amount.

The average fission rate per element predicted by DIF3D was within $\pm 3.3\%$ of the VIM result for all elements in the HEU core. The average bias was reduced to $\pm 2.5\%$ for the DIF3D prediction of element fission rates in the LEU core relative to VIM. The peak element fission rate has been lowered in the LEU core relative to the HEU core by 5.4% because of the small shift in power out of the central ring.

FUEL CYCLE ANALYSES

The fuel management strategy used for these equilibrium fuel cycle calculations was based upon the burnup distribution and fuel cycle length of 19.8 days observed for configuration 10D. Six of the eight fresh elements loaded into the core at the beginning of each cycle were located in the fourth hexagonal ring, along with all six shim control rods. The other two fresh

elements were loaded into the fifth ring. The third ring consisted of second- and third-cycle-residence fuel in which nearly half of the total core power is produced, providing a large source of neutrons for the central irradiation position. The core power peak usually occurred in this third ring. The nominal core thermal power was 56 MW but calculations were also performed at 20% above this average power because significant portions of the BR2 operating history have been at higher-than-average power levels.

One of the primary fuel cycle objectives, in addition to minimizing LEU fuel density and power peaking, was to preserve or reduce the movement of control rods during the fuel cycle. Reduced control rod motion provides constant irradiation conditions for the in-core experiments. This was achieved through the careful selection of burnable absorber materials, concentrations and locations. The use of the rapidly depleting ^{149}Sm in the fuel meat reduced the startup control rod motion until ^{135}Xe and ^{149}Sm had reached equilibrium concentrations. The use of ^{10}B reduced the total control rod travel during a cycle by placing more absorber control material at the beginning of the cycle and depleting a significant portion of it before the end of cycle was reached. Cd wires performed much the same as ^{10}B except the difference in absorber worth from beginning to end of cycle was greater owing to the faster ^{113}Cd depletion rate.[8,9]

Equilibrium fuel cycle characteristics were obtained using the REBUS3[10] code with 11 group, burnup-dependent cross sections. The EPRI-CELL burnup-dependent cross sections were fit to different order polynomials using the least-squares method. The DIF3D model developed by benchmark comparisons with VIM was used in REBUS3 to perform all nodal diffusion theory solutions. A summary of the equilibrium fuel cycle characteristics using HEU and LEU fuels is presented in Table V. The BOEC k_{eff} was a simulated startup reactivity with saturated Sm in previously burned fuel and no ^{135}Xe. The EOEC k_{eff} assumed equilibrium concentrations of ^{135}Xe and ^{149}Sm. All control rods were fixed at their mid-cycle positions, 505 mm. By comparing the EOEC k_{eff} for the reference HEU cycle and the LEU cycle using 2.85 g B/element, the use of LEU meat with 4.9 Mg/m^3 meat density would provide ~0.7% Δk_{eff} more reactivity. Similarly when ^{10}B was replaced by Cd wires in the LEU fuel cycle, the increase in Δk_{eff} was 2.0% Δk_{eff}. This reactivity increase was caused by less burnable absorber material present at EOEC in the Cd case compared to the boron case. The required LEU fuel density was slightly higher when using the Cd wires clad with Al, but the minimum LEU density could be reduced to ~4.8 Mg/m^3 by reducing the ^{235}U loading by 6%. This would bring the reactivity performance of the LEU and HEU cycles closer together while using the ORR U_3Si_2-Al demonstrated LEU fuel density.[11] The comparison of the HEU and LEU fuel cycles operating at 67.2 MW demonstrated an increasingly favorable reactivity bonus for LEU fuel cycle operating at higher burnups. Pu fission replaces more of the reactivity lost by ^{235}U burnup in LEU fuels with higher burnups compared to the HEU fuel cycle.

The reactivity change from BOEC to EOEC increased 42% in the LEU cycle using ^{10}B absorbers and 21% using the Cd wires for operation at 56 MW relative to the reference HEU cycle. This reactivity change is an indication of the distance control rods must travel to preserve criticality during the cycle. When the power was increased to 67.2 MW, the control rod travel was reduced by ~6% in the LEU cycle relative to the HEU cycle. A further reduction in reactivity change from BOEC to EOEC could be achieved through the addition of more burnable absorber material or by operation at higher power levels.

TABLE IV

BR2 Whole Core Reactivity Comparisons for Fresh and Equilibrium HEU and LEU Cores

Enrichment	Core Burnup	All Control Rods	Whole Core k_{eff} VIM	Whole Core k_{eff} DIF3D
LEU	BOL	withdrawn	1.2160	1.2157
LEU	BOL	inserted	1.0801	1.0771
LEU	BOEC	505 mm*	1.1405	1.1390
HEU	BOL	withdrawn	1.1581	1.1601
HEU	BOL	inserted	1.0340	1.0348
HEU	BOEC	505 mm*	1.1245	1.1268

*Near core midplane position of 480 mm.

TABLE V

Summary of BR2 HEU and LEU Equilibrium Fuel Cycle Characteristics

Enrichment	HEU	HEU	LEU	LEU	LEU
Core Power (MW)	56	67.2	56	56	67.2
^{235}U/element (g)	400	400	480	480	480
Burnable Absorber	^{10}B	^{10}B	^{10}B	^{113}Cd	^{113}Cd
Meat U Density (Mg/m^3)	1.3	1.3	4.9	5.1	5.1
k_{eff} (BOEC)	1.1242	1.1108	1.1388	1.1556	1.1484
k_{eff} (EOEC)	1.1061	1.0779	1.1125	1.1331	1.1153
Discharge Burnup (%)					
Average	44	52	35	35	42
Peak	65	75	53	53	60

The peak nodal power for the LEU cores relative to the HEU cores has increased ~2 to 3% according to DIF3D predictions. Referring back to the VIM-DIF3D equilibrium core benchmark, VIM predicted an average fission rate reduction in the peak element of 5% while DIF3D predicted no change in the same peak element. Therefore the LEU peak power is probably slightly lower relative to HEU equivalent-fuel-management cores if credit is taken for the slight redistribution in the radial power from the central core to the periphery in the LEU cores.

Changes in Co and Ir Irradiation Rates

The irradiation rates of ^{59}Co and natural Ir in an LEU core were compared to an HEU equilibrium core using VIM. For the core provided by the BR2 staff, Co and Ir were the primary materials used for isotope production. Most of the Co was located in the six shim control followers and the Ir disks were located in the central large irradiation hole, H1. The capsule used for irradiation of the Ir disks was 75 mm in height located near the axial flux peak of the core. Each disk contained 35 mg of Ir and was attached to the exterior of an Al annulus 21 mm in diameter with a central water hole. There were 228 disks placed around each of three Al annuli located 106.4 mm from the center of the H1 irradiation hole. Each of these disks was modeled in exact detail in the VIM equilibrium core model. It was necessary to model Ir as a combination of ^{197}Au and ^{6}Li owing to the absence of Ir from the VIM library, assuming a resonance integral of 2000 barns and thermal absorption cross section of 426 barns for Ir.

The relative absorption rates for Co and Ir were found to be reduced by 6 ± 1% in LEU relative to an HEU core. The correction for fission source differences in adjacent power-producing elements was less than 2%. The reductions in the Ir and Co irradiation rates followed the thermal flux reduction computed for LEU relative to HEU cores without any experiments present.

CONCLUSIONS

The equilibrium HEU-LEU fuel cycle comparisons have indicated that LEU fuels with meat densities of ~4.8 Mg/m^3, comparable to the LEU density used in the LEU-ORR demonstration core, would provide fuel cycle characteristics similar to current operational characteristics. A change from the use of ^{10}B in the fuel meat to Cd wires placed in the webs would provide ~2% Δk_{eff} more excess reactivity at EOEC. Fast neutron fluxes are slightly higher in LEU cores while thermal flux reductions are less than 10% in irradiation positions adjacent to a fuel element or in the reflector. Power peaking changes would require more detailed study, but indications from these analyses were that power shifts caused by a harder neutron spectrum near the core center reduced the LEU peak power. The change in the location of the burnable absorbers from the fuel meat to the web also served to reduce local power peaking within the element. Control rod worth changes were minimal. Reductions in Ir and Co irradiation rates were less than 10%.

Detailed benchmark comparisons of the DIF3D model were required using VIM because of the unusual core and fuel element geometry and the large volume of in-core Be. The Be $\sigma_1(n,2n)$ was found to be location dependent and a neutronically important parameter for determination of core reactivity requiring

careful benchmarking with VIM. Most research reactor core analyses have been possible using one thermal group below 0.625 eV. With the presence of more Be, the BR2 core model needed a few more thermal groups to accurately determine reaction rates and reactivity. With the completion of extensive benchmark comparisons for the BR2 core diffusion model, one can have greater confidence in the fuel cycle predictions of reactivity and reaction rates.

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