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REDUCED-REACTIVITY-SWING LEU FUEL CYCLE ANALYSES FOR HFR PETTEN*

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ABSTRACT

The primary objective of these low enriched uranium (LEU) fuel cycle analyses was to effect at least a 33% reduction in the reactivity swing now experienced in the high enriched uranium (HEU) cycle while minimizing increases in ^{235}U loading and power peaking. All LEU equilibrium fuel cycle calculations were performed using either a 19- or 20-plate fuel element with 0.76-mm-thick meat and 0.5- or 0.6-mm-thick Cd wires as burnable absorbers and 16- or 17-plate control rod fuel followers with 0.76-mm-thick meat. Burnup-dependent microscopic cross sections were used for all heavy metals and fission products. A three-dimensional model was used to account for the effect of partially inserted control rods upon burnup profiles of fuel and of burnable absorbers and upon power peaking. The equilibrium cycle reactivity swing (or, equivalently control rod movement) was reduced by 50% using LEU fuel with U meat densities <4.8 Mg/m^3.

INTRODUCTION

The Reduced Enrichment Research and Test Reactor (RERTR) Program, the Joint Research Centre (Petten Establishment), and the Netherlands Energy Research Foundation have been engaged in a continuing joint study to determine the most suitable LEU fuel

element design for the High Flux Reactor at Petten. Additional fuel cycle optimization calculations were needed to investigate LEU fuel cycle performance in anticipation of future upgraded operation strategies and to reduce the reactivity swing by 1/3 compared to that of the reference HEU equilibrium fuel cycle with ^{235}U loadings of 420/290 g (standard/control). Previous LEU fuel cycle analyses explored the reactivity and power peaking trends of using various LEU fuel elements in the reference fuel cycle.[1]

A number of XY LEU equilibrium cycle calculations were performed using a 19-plate element with 0.76-mm-thick meat and Cd wires as burnable absorbers for the standard element and a 16-plate control fuel follower. The ratio of the standard to control element ^{235}U loadings was set equal to the HEU ratio of 420 ÷ 290 in order to minimize power peaking in the control elements. A description of the elements is given in Table 1. The XY fuel cycle calculations were made using "dummy" experiments for all in-core irradiation positions.

Also included in this paper are the results of XYZ calculations of fuel cycles utilizing one 19/16-plate (standard/control) fuel element, two 20/17 plate LEU fuel elements, and the reference HEU fuel element. A coarse-mesh XYZ REBUS-3 model was used to obtain equilibrium cycle burnup distributions for use in finer-mesh beginning of equilibrium cycle (BOEC) and end of equilibrium cycle (EOEC) calculations to determine power distributions and peaking, reactivity swings, and fluxes in irradiation positions. The control element fuel management was changed from the reference HEU cycle pattern of loading on the average 1.5 fresh control elements per cycle to loading one fresh control element per LEU cycle.

Table 1. Description of Standard LEU Element and Control Fuel Followers

Number of Plates, (Std/Cont)	19/16	20/17
Fuel Meat Composition	U_3Si_2-Al	U_3Si_2-Al
Fuel Meat Thickness, mm	0.76	0.76
Water Channel Thickness (Std/Cont), mm	2.656/2.656	2.45/2.35
Ratio of LEU Standard Element Moderator Volume to HEU Moderator Volume	1.007	0.977
Control Fuel Clad Thickness, mm	0.38	0.38
Standard Inner Plate Clad Thickness, mm	0.38	0.38
Standard Outer Plate Clad Thickness, mm	0.57	0.57
Fuel Meat Width, cm	6.315/5.958	6.315/5.99
Fuel Meat Length, cm	60.0	60.0
Ratio of ^{235}U Loadings (Std/Cont)	0.69	0.69

EQUILIBRIUM FUEL CYCLE MODELS

All REBUS-3[2] equilibrium fuel cycle calculations were made with burnup-dependent microscopic cross sections for all heavy metals and fission products. Mid-life cross sections were used for all other materials. Cross sections were calculated using identical models in EPRI-CELL.[3] Very-high-burnup microscopic cross sections were required for the longer-residence-time control fuel followers.

The fuel management strategy for simulating the current operating cycles has not been changed for LEU cycles. The XY diffusion-theory mesh for all fuel cycle calculations was 92 × 81. Each in-core position was modelled by a 4 × 4 mesh grid. The inner (fuel) zone of each standard fuel element was assigned a 2 × 4 mesh and each side plate zone a 1 × 4 mesh. The fuel zone of the control follower was assigned a 2 × 2 mesh. The XYZ mesh structure was 61 × 55 × 24. The reduction in the planar mesh occurred primarily in the ex-core regions by increasing the mesh intervals and by more material homogenization. Acceptable agreement was obtained between the detailed-XY-model (92 × 81) planar in-core flux solution and the coarse-mesh (61 × 55) planar flux solution from the XYZ model. Each standard and control follower fuel element was divided into eight axial burnup zones. Control rods were all banked at the estimated average position during the entire cycle. Beam tubes were not modelled owing to convergence difficulties encountered. The core consisted of 528 separate burnable absorber zones, 264 standard fuel zones, and 96 control fuel follower zones. A black boundary condition (j/ϕ = 0.4678) was imposed at the surface of the control rod absorber material for the thermal group (gp. 5).

The XY model reactivity swing is based upon REBUS-3 k_{eff} results for BOEC and EOEC. The BOEC calculation in REBUS-3 assumes equilibrium Xe and Sm only in all previously irradiated fuel. All XYZ model reactivity swing results are based upon a separate calculation of excess reactivities at BOEC and EOEC with equilibrium Xe and Sm concentration in all fuel assemblies. Therefore the reactivity swing (for XYZ calculations) is defined to be

swing = $(k_{BOEC} - k_{EOEC}) \div k_{BOEC} * k_{EOEC}$, where k_{eff}'s are for all rods fully withdrawn and equilibrium Xe and Sm in all fuel.

BENCHMARK COMPARISONS OF DIFFUSION MODEL WITH VIM-MONTE CARLO

Previous LEU standard fuel element designs using 0.4-mm-OD Cd wires and lower ^{235}U loadings have been benchmarked for an infinite lattice.[1] With higher ^{235}U loadings and larger Cd wire

diameters, it was necessary to make additional benchmark comparisons to determine the adequacy of the REBUS-3 model to predict absorption rates and reactivity for a fresh element in an infinite lattice as well as near partially inserted control rods and experiments.

The VIM[4] model used for the benchmark comparison was a detailed model of each individual fuel meat, clad, moderator, side-plate, and Cd wire. Each element was run for 100,000 neutron histories in order to obtain accurate (<±2%) power shapes and Cd absorption rates in these small volumes.

The first comparison was made for a 470-g ^{235}U 19-plate element with a Cd wire of 0.5-mm OD located at each edge of each fuel plate. The depletion rate of Cd relative to ^{235}U was 5.2% higher in the DIF3D[5] model than in the VIM model for the beginning of life (BOL) condition in an infinite lattice environment. Good agreement in the reactivity of the lattice was also achieved. The DIF3D model k_∞ was within two standard deviations of the VIM k_∞. The same conclusions were also reached for the higher-loaded 600-g ^{235}U element case with 38 Cd wires of 0.6-mm OD. The depletion of Cd relative to ^{235}U was 3.2% higher in the DIF3D model than in VIM. However, the DIF3D k_∞ was lower than the VIM k_∞ by 0.0068 Δk_∞.

In order to validate the depletion rate of ^{10}B in the top of the core adjacent to control rods in the XYZ REBUS model for the HEU core, a four-element XYZ representation of the core center was modelled in DIF3D and compared with VIM-Monte Carlo. One quadrant had a control element positioned at 51.7 cm while two other adjacent quadrants were loaded with fresh HEU elements containing 1 g ^{10}B and 420 g ^{235}U. The remaining quadrant contained a "dummy" experiment. The same mesh and homogenization of materials were used in the DIF3D model as were used in the REBUS-3 model. A black boundary condition in group 5 was used to simulate the absorption in the Cd control rod. Zero current boundary conditions were used at the X and Y boundaries of the four in-core positions, and no-return-current conditions were used at the axial reflector boundaries. The result was that the total depletion rate for ^{10}B was 3.4% higher in DIF3D than in VIM. At axial nodes near the top of the core, the depletion rate was 5 to 10% higher adjacent to the control rod and ~5% lower in the quadrant adjacent to the experiment. The k_∞ for the entire problem was 1.3027 in DIF3D and 1.3002 ± 0.0031 in VIM. Therefore, the ^{10}B depletion rate is being calculated quite well by diffusion theory, and it does not appear to be necessary in this model to generate different burnable poison cross sections for different neighboring elements or experiments.

A LEU comparison for a similar configuration was also made using the 20/17-plate fuel element loaded with 525/365 g ^{235}U/element and 20 Cd wires of 0.5 mm-OD per sideplate. The control

rod position was changed to 58.15 cm, and the experiment was loaded with a smeared concentration of ^{10}B ($N(^{10}B) = 4.0 \times 10^{-6}$ atoms/barn-cm) to simulate the presence of an "average" experiment. The results indicated an underprediction of Cd wire depletion rate by 1 to 2% in the upper 15 cm of the core controlled by the Cd rods. Conversely, a 8 to 10% overprediction in the Cd depletion rate was observed in the portion of the core opposite the control fuel followers. The total Cd wire depletion rate was 9% more than the VIM depletion rate.

RESULTS OF XY FUEL CYCLE CALCULATIONS

Several different fuel cycle options were examined with REBUS-3 using XY geometry. In these no attempt was made to change the fuel loading scheme for the reference 6/1.5 (standard element/control element) reloads per cycle or the core positions of partially depleted fuel. The first two cases presented in Table 2 are for the reference HEU fuel cycle and for a reduced control element batch size. The reference HEU cycle is Case #1. It can be compared with the proposed reduction in control element loading to one per cycle (Case #2). The reactivity penalty would be ~940 pcm without any changes to the fuel management strategy. The discharge burnup of the fuel follower would increase significantly. The burnup values for the fuel follower are probably higher in the XY REBUS-3 model than would be predicted by a full XYZ calculation with control movements modelled during the cycle. However, the predicted percentage increases in fuel follower burnup should be representative of all types of cycles having similar rod movements.

In order to achieve the same reactivity swing as with the reference HEU fuel cycle, 475/328-g ^{235}U (standard/control) elements would be needed with 46 Cd wires of 0.4-mm OD loaded into each fresh standard element (Case #3). More than 38 wires are needed to provide the additional control poison at BOEC without increasing significantly the amount at EOEC. However, more than 46 wires would be needed (perhaps eight more) to reduce the reactivity swing the additional ~500 pcm needed to achieve the design objective of a 1/3 reduction in reactivity swing from that of the reference cycle.

As an alternative to using more 0.4-mm OD wires, 38 Cd wires of 0.5-mm OD were used with a 500/345-g element loading (Case #4). This case does achieve the desired reactivity swing and EOEC k_{eff} with only a 1% higher peak power at EOEC than with the use of 0.4-mm OD wires (Case #3). The peak power density increases 10% during the cycle because the power and flux shift as the Cd depletes. This power peak increase might be minimized by alteration of the fuel shuffling scheme when using larger-diameter Cd wires. However, such changes might result in loss of reactivity and/or fast flux in the irradiation positions.

Table 2. Comparison of HEU Reference Fuel Cycle and 19-Plate LEU Fuel Cycles Calculated with the XY Model

Case	Reference #1 HEU	#2 HEU	#3 LEU	#4 LEU	#5 LEU	#6 LEU
Cycle length, days	26	26	26	26	26	26
Reloads/cycle	6/1.5	6/1	6/1.5	6/1.5	5/1.5	5/1
^{235}U load g/el.	420/290	420/290	475/328	500/345	530/366	530/366
# plates/element	23/19	23/19	19/16	19/16	19/16	19/16
Channel gap, cm	0.218	0.218	0.266	0.266	0.266	0.266
Meat ρ_u, g/cm^3	1.016/0.895	1.016/0.895	4.40/3.80	4.63/4.00	4.91/4.24	4.91/4.24
Fuel meat thk., mm	0.51	0.51	0.76	0.76	0.76	0.76
BA/element	1 g ^{10}B/element		46 Cdw (0.4-mm OD)		38 Cd wires (0.5-mm OD)	
k_{BOL}	1.0889	1.0689	1.0773	1.0797	1.0842	1.0842
k_{BOEC}	1.0518	1.0419	1.0493	1.0476	1.0524	1.0449
k_{MOEC}	–	1.0390	1.0386	1.0404	1.0383	1.0315
k_{EOEC}	1.0352	1.0252	1.0328	1.0364	1.0320	1.0249
Swing (pcm)	1525	1570	1523	1033	1880	1870
^{235}U load BOEC, kg	11.857	11.580	14.081	15.019	15.627	15.383
EOEC, kg	10.363	10.087	12.668	13.602	14.220	13.983
Burnable Absorber	^{10}B	^{10}B	^{113}Cd	^{113}Cd	^{113}Cd	^{113}Cd
BOEC, g	11.52	11.35	24.81	35.62	30.36	30.89
EOEC, g	5.60	5.42	2.94	7.37	6.82	6.67
Discharge Burnups						
STD, %	50.2	50.9	41.8	39.9	44.6	45.0
CONT, %	52.8	72.1	44.8	42.6	41.1	57.1
Peak Power Density						
BOEC, W/cm^3	904 (B4)	944 (B3)	989 (C4)	938 (C4)	1005 (B5)	1018 (B5)
EOEC, W/cm^3	943 (C4)	972 (C4)	1018 (C4)	1030 (C4)	1034 (E4)	1038 (E4)

Case	#7 LEU	#8 LEU	#9 LEU	#10 LEU	#11 LEU	#12 LEU
Cycle length, days	32	32	32	32	26	26
Reloads/cycle	6/1.5	6/1	6/1.5	6/1	5/1.5	5/1
^{235}U load g/el.	530/366	530/366	575/397	600/414	575/397	600/414
# plates/element	19/16	19/16	19/16	19/16	19/16	19/16
Channel gap, cm	0.266	0.266	0.266	0.266	0.266	0.266
Meat ρ_u, g/cm^3	4.91/4.24	4.91/4.24	5.32/4.60	5.55/4.80	5.32/4.60	5.50/4.80
Fuel meat thk., mm	0.76	0.76	0.76	0.76	0.76	0.76
BA/element	38 Cd wires					
	(0.5-mm OD)	(0.5-mm OD)	(0.6-mm OD)	(0.6-mm OD)	(0.6-mm OD)	(0.6-mm OD)
k_{BOL}	1.0842	1.0842	1.0849	1.0907	1.0849	1.0907
k_{BOEC}	1.0506	1.0420	1.0493	1.0469	1.0538	1.0528
k_{MOEC}	1.0383	1.0298	1.0416	1.0392	1.0410	1.0412
k_{EOEC}	1.0307	1.0222	1.0385	1.0368	1.0381	1.0383
Swing (pcm)	1839	1858	984	932	1438	1332
^{235}U load BOEC, kg	15.301	15.001	16.992	17.629	17.321	18.007
EOEC, kg	13.574	13.285	15.257	15.895	15.907	16.595
Burnable Absorber	^{113}Cd	^{113}Cd	^{113}Cd	^{113}Cd	^{113}Cd	^{113}Cd
BOEC, g	31.96	31.78	53.07	52.80	51.43	52.28
EOEC, g	3.71	3.53	12.04	13.07	17.53	18.38
Discharge Burnups						
STD, %	45.8	46.3	42.5	41.2	41.3	40.0
CONT, %	49.0	66.7	45.3	60.0	38.0	51.1
Peak Power Density						
BOEC, W/cm^3	1029 (C4)	1051 (C4)	940 (C4)	952 (C4)	988 (C4)	1006 (C4)
EOEC, W/cm^3	1059 (C4)	1075 (C4)	1057 (C4)	1076 (C4)	1005 (E4)	1005 (E4)

Also presented in Table 2 are the fuel cycle results using a 530/366-g element combination with 38 Cd wires of 0.5-mm OD for the desired upgraded fuel cycle performance of increased cycle length or reduced reload batch size operation. For both types of upgraded fuel cycle operation, the reactivity swing was too high and EOEC reactivity was too low. Clearly more Cd and ^{235}U are needed to achieve the desired performance. The reactivity swing was reduced slightly by loading fewer control elements per cycle. The peak power increases ~2% for the reduced control rod reload strategy for 32 day cycle operation and increases 3 to 4% for the increased cycle length from 26 to 32 days.

The same fuel cycle operation strategy shown in Cases #5-8 was used again for a 600/414-g ^{235}U element combination for the reduced control element reload batch size (Cases #10 and #12) and a 575/397-g ^{235}U element combination for the reference control element reload batch size (Cases #9 and #11). The standard fuel elements contained 38 Cd wires of 0.6-mm OD in order to reduce the reactivity swing. This goal was achieved for the 32-day cycle (Cases #9 and #10) while maintaining an adequate EOEC k_{eff}. Owing to the greater ^{113}Cd inventory reduction, during the 32 day cycle, the power peaking increased 12% from BOEC to EOEC. Comparable EOEC k_{eff}'s are noted for Cases #11 and #12 but with higher reactivity swings relative to the equivalent fuel elements used in a 32-day cycle. This is caused by more unburned Cd at EOEC in the 26-day cycle than in the 32-day cycle. Therefore, longer cycles are more advantageous when larger Cd wire diameters are needed to suppress the reactivity swing. The advantage of increased Cd at EOEC was a reduction in power peaking during the cycle by 5 to 7%.

RESULTS OF THREE-DIMENSIONAL HEU FUEL CYCLE CALCULATIONS

Comparisons of three-dimensional REBUS-3 equilibrium HEU fuel cycle results with those using previous two-dimensional (2D) models have shown only minor differences for the case with all rods fully withdrawn. The 2D model (Case #1, Table 2) gave reactivities which were 1.1%, 1.3%, and 1.2% lower than those of the 3D model at BOL, BOEC, and EOEC, respectively (Case #1, Table 3). This suggests an overestimate of the axial leakage in the 2D model. The element powers in the 2D model were overpredicted by ~3 to 4% in the fresher elements and underpredicted in the higher-burnup elements in the core peripheral column H by 5 to 10%. The peak power density in the 3D model remained nearly constant during the cycle at 860 W/cm^3. The peak power density was somewhat higher in the 2D model with a value of 904 W/cm^3 in location B4 at BOEC, increasing to 943 W/cm^3 at EOEC. The reactivity swing was 128 pcm higher in the 3D model than in the 2D model.

Another 3D REBUS-3 HEU equilibrium fuel cycle calculation was run with all control rods banked at position 51.7 cm (the average for the entire cycle) using "dummy" experiments with Al plugs in Al filler elements. Some notable differences were observed between these two cases (with and without control rods inserted). The ^{10}B burnable absorber depletion rate decreased significantly in the top of the core near the inserted rods, which resulted in more unburned ^{10}B remaining in-core at EOEC. The peak power density is higher because the flux is pushed toward the bottom of the core by the partially inserted control rods. The peaking values listed in Table 3 are for the rods at their critical position at the REBUS BOEC and EOEC conditions. Since the rods would be even lower in the core for the start-up initial condition (no Xe), the actual peak power during the cycle will be somewhat higher than indicated. The radial power distribution was only affected by 5 to 10% in most locations, however. The k_{eff} was 1.0157 at BOEC and 0.9893 at EOEC.

In order to better simulate the reactivity effect of the 17 in-core experiments, a final HEU 3D equilibrium fuel cycle calculation was made. ECN calculations[6] indicate that the actual control rod position at EOEC should be 61 cm with the 420/290 g fuel. The estimated BOEC control rod position is 55.3 cm after one day of full-power operation. Since modelling each experiment in the detail required would not be computationally feasible in a 3D REBUS-3 calculation, a small concentration of non-depleting ^{10}B was added to each of the 17 in-core dummy experiments to represent the poisoning effect of the actual experiments on total core performance. The amount of ^{10}B used was 4.0×10^{-6} atoms/bn-cm, which resulted in $k_{eff} \simeq 1.00$ at BOEC with rods at 55.3 cm and at EOEC with rods at 61 cm. The REBUS calculation was run with the control rods at the average position of 58.15 cm.

The effect of the experiments on the core performance resulted in a radial shift of power into the A and B columns. The average increase in element power in the A and B columns was 7 to 10% with respect to the case without the experiment absorption modelling. All in-core experiments are located in columns C through H, which accounts for the power shift away from that portion of the core into columns A and B. The other change from the previous case was a reduction in the peak power density from 1016 W/cm^3 to 992 W/cm^3 in the B4 fuel follower. This change was caused primarily by withdrawal of the control rods to positions higher in the core. Calculations with a more detailed mesh and with the rods at their actual critical positions are needed to determine the exact peaking for each control rod position at BOEC and EOEC.

RESULTS OF LEU FUEL CYCLE CALCULATIONS USING XYZ MODEL

The three LEU fuel cycle cases that were calculated using the XYZ model are presented in Table 3. LEU Case #1 used a 19/16 plate (standard/control) element loaded with 500/339 g ^{235}U/element with the same fuel management strategy as the reference HEU core. All LEU cases presented in Table 3 were calculated with a non-depleting ^{10}B content in the 17 in-core experiment locations of $N(^{10}B) = 4.0 \times 10^{-6}$ atoms/bn-cm and with all six control rods positioned at 58.15 cm during the entire cycle.

The effects of the control rods upon the fuel cycle characteristics can be noted by comparing Case #4 in Table 2 with LEU Case #1 in Table 3. The main differences occur in the burnable absorber depletion rates and peaking factor shifts during the cycle. The results indicate that the LEU Case #1 fuel cycle would provide essentially the same excess reactivity at BOEC and slightly more at EOEC when compared to the reference HEU core characteristics in Table 3, HEU Case #3. The overall Cd wire depletion rate has been reduced by the introduction of control rods into the top of the core. This contributed to the 44% lower reactivity swing from BOEC to EOEC. The peaking factor actually decreases instead of increasing as the XY model indicated by withdrawal of the control rods to their EOEC position.

The second LEU fuel cycle in Table 3 uses a 20/17-plate element loaded with 550/385 g ^{235}U/element. The fuel cycle was altered slightly compared to the 19/16 plate LEU Case #1 by reducing the number of control elements loaded per cycle to 1 from 1.5. From previous XY model results presented in Table 2, the reactivity penalty is about 806 pcm for 19 plate LEU fuels. The choice of 550 g ^{235}U/standard element corresponds to a uranium meat density of 4.8 Mg/m^3. The k_{eff}'s at BOEC and EOEC were slightly larger for this second LEU case compared to the reference HEU cycle even after the 33% reduction in control element loading per cycle. The average discharge burnup of the control fuel follower has increased by 21%. The ^{113}Cd burnable absorber inventory has increased slightly owing to the harder spectrum 20-plate element loaded with 50 g ^{235}U more than the 19-plate element of LEU Case #1. The increased ^{235}U loading and faster depleting Cd burnable absorbers have contributed to the 69% reduction in reactivity swing compared to the HEU reference cycle. The peaking trends are similar to those of HEU Case #1 on the same Table 3.

The third LEU case presented in Table 3 has equivalent reactivity performance to the reference HEU cycle at BOEC and slightly more at EOEC. Therefore, the control rods required withdrawal of 2.2 cm during the 26-day cycle instead of 5.7 cm for the reference HEU cycle. The reduced movement during the cycle is reflected in the 63% reduction in the reactivity swing. With

Table 3. Fuel Cycle Characteristics With Control Rods and In-Core Experiment Simulation Using 3D REBUS Model

	HEU #1	HEU #2	HEU #3	LEU #1	LEU #2	LEU #3
Number of Fuel Plates	23/19	23/19	23/19	19/16	20/17	20/17
Cycle length, days	26	26	26	26	26	26
Reloads/cycle	6/1.5	6/1.5	6/1.5	6/1.5	6/1	6/1
^{235}U load g/element	420/290	420/290	420/290	500/339	550/380	525/365
Control rod position, cm	full out	51.7	58.15	58.15	58.15	58.15
N(^{10}B) in exp, atoms/bn-cm	0	0	4.0E-06	4.0E-06	4.0E-6	4.0E-06
k_{BOL}	1.1020	1.0576	1.0586	1.0485	1.0606	1.0537
k_{BOEC}	1.0663	1.0157	1.0137	1.0128	1.0182	1.0111
k_{MOEC}				1.0002	1.0076	1.0011
k_{EOEC}	1.0478	1.9893	0.9866	0.9926	1.0026	0.9947
Swing (pcm)	1653	1107	1457	809	458	538
^{235}U load BOEC, kg	11.909	11.919	11.923	15.070	16.679	15.826
EOEC, kg	10.427	10.438	10.440	13.670	15.278	14.429
^{10}B or ^{113}Cd in SF BOEC, g	11.74	13.005	12.948	43.37	46.30	45.35
EOEC, g	5.85	7.360	7.252	15.20	16.62	15.66
^{235}U Discharge Burnups						
STD ave./peak (%)	49.9/65.9	50.1/69.3	49.7/63.5	39.4/55.9	36.7/50.7	38.2/53.8
CONT ave./peak (%)	51.5/63.5	50.1/71.0	52.5/61.7	42.6/56.0	51.4/64.0	53.2/59.0
Core Ave. Burnup						
BOEC, (%)	23.7	23.6	23.6	18.7	18.1	18.9
EOEC, (%)	33.2	33.1	33.1	26.2	25.0	26.1
^{235}U Load in Control Rods						
BOEC, g	1360	1363	1337	1659	1708	1623
EOEC, g	1136	1145	1109	1442	1514	1429
Power Peaking (W/cm^3)						
BOEC - location	858 (D3)	1012 (D3)	1067 (B4)	1102 (B4)	1102 (B4)	1097 (B4)
			975 (D3)	1059 (D3)	1063 (D5)	1051 (D3)
EOEC - location	861 (C4)	1007 (D3)	961 (D3)	966 (D3)	986 (B5)	1027 (D3)
k_{eff} (Rod Position, cm)						
BOEC*	---	0.9968	0.9946	0.9940	1.0003	0.9933
		(49.3)	(55.3)	(55.3)	(55.3)	(55.3)
EOEC*	---	0.9963	0.9930	0.9988	1.0086	0.9928
		(55.3)	(61.0)	(61.0)	(61.0)	(57.5)

*Equilibrium Xe and Sm in all fuel elements.

reduction in ^{235}U loading for this 20/17-plate fuel element of 25/15 g ^{235}U/element, the spectrum becomes softer, which increases the ^{113}Cd depletion rate and, consequently, the equilibrium cycle reactivity.

NEUTRON FLUX CHANGES IN IN-CORE EXPERIMENT POSITIONS

A summary of the average group-dependent neutron fluxes for the three LEU fuel cycles modelled in XYZ geometry relative to the reference HEU fluxes is presented in Table 4. The inner irradiation positions refer to the nine non-peripheral locations C-3, E-3, G-3, C-5, E-5, G-5, C-7, E-7 and G-7. These inner locations are modelled in an identical fashion to the eight outer (peripheral) locations D-2, F-2, H-2, H-9, H-6, H-8, D-8, and F-8, except that a stainless steel liner is placed around the central Al plug for all inner positions. All irradiation positions are primarily a mixture of Al and H_2O with a small concentration of non-depleting ^{10}B to simulate the total effect of reactivity reduction on the core performance.

Table 4. Comparison of Average Neutron Flux Ratios in Nine Inner and Eight Outer In-Core Irradiation Positions in LEU Relative to HEU Equilibrium Cycle Cores

Experiment Location	^{235}U Loading (g/el)	Number Plates/ element	Burnup	Control Rod Position (cm)	Average Group Flux Ratios (LEU ÷ HEU) ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5
Inner	500/339	19/16	BOEC	55.3	0.987	1.004	0.986	1.203	0.915
Outer					1.017	1.030	1.006	1.152	0.950
Inner			EOEC	61.0	0.985	1.002	0.978	1.187	0.880
Outer					1.014	1.027	1.001	1.143	0.924
Inner	550/380	20/17	BOEC	55.3	0.987	1.011	0.984	1.030	0.832
Outer					1.047	1.065	1.029	1.041	0.905
Inner			EOEC	61.0	0.982	1.006	0.974	0.996	0.793
Outer					1.033	1.051	1.015	1.023	0.870
Inner	525/365	20/17	BOEC	55.3	0.995	1.017	0.992	1.023	0.857
Outer					1.048	1.067	1.034	1.047	0.922
Inner			EOEC	61.0	0.990	1.013	0.983	1.008	0.821
Outer					1.036	1.054	1.021	1.031	0.889
Inner			EOEC	57.5	0.992	1.016	0.986	1.010	0.820
Outer					1.047	1.066	1.031	1.041	0.897

The neutron flux ratios (LEU ÷ HEU, Ref.) for neutrons with energies >1.85 eV range between 0.985 for the inner experiments to 1.065 for the outer experiments. The primary flux redistribution for the 19/16-plate case occurs from group 5 (E_n < 0.625 eV) into group 4. Fluxes are 5 to 12% lower in group 5 and 15 to 20% higher in group 4. This spectral hardening is caused primarily by the increased ^{235}U loading in the 19-plate LEU element relative to the 23-plate HEU reference element since the water channel flow area is nearly equivalent for these two designs. The group-5 flux ratios at EOEC are ~3% lower than at BOEC since the softening of the spectrum during the cycle is less with the LEU core relative to the HEU core.

The effect of a change in ^{235}U loading and control rod position upon the average fluxes in the irradiation positions can be observed by comparing the two 20/17-plate cases. The harder spectrum 20/17-plate cases have caused slightly larger flux ratios in groups 1-3 and reductions in groups 4 and 5 compared to the 19-plate case. The change in ^{235}U loading and control rod position have only a very minor effect upon average neutron fluxes. However, movement of control rods do cause substantial flux changes in axial zones near the bottom of the Cd control material. For the inner experiment locations group fluxes are within ±2% for E_n > 0.625 eV and are reduced by 14 to 18% E_n < 0.625 eV for the 525/365 g case. For outer or peripheral in-core positions fast flux increases of 3 to 7% and reductions in only the lowest thermal group of 8 to 10% can be expected.

CONCLUSIONS

From the neutronics point of view either the 19- or 20-plate standard element would be a suitable replacement for the current HEU design and fuel management strategy without significant increases in power peaking or losses in neutron flux in the irradiation positions. Reductions in the annual control element loading requirement by 33% and and reduction in the movement of control rods by 60% during the cycle have been achieved for all proposed LEU fuel cycles. These added features were possible using uranium meat densities of <4.8 Mg/m^3.

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