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Neutronic Feasibility Studies for LEU Conversion of the HFR Petten Reactor

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ABSTRACT

Design and safety analyses to determine an optimum LEU fuel assembly design using U_3Si_2-Al fuel with up to 4.8 g/cm^3 for conversion of the HFR Petten reactor were performed by the RERTR program in cooperation with the Joint Research Centre and NRG. Credibility of the calculational methods and models were established by comparing calculations with recent measurements by NRG for a core configuration set up for this purpose. This model and methodology were then used to study various LEU fissile loading and burnable poison options that would satisfy specific design criteria.

INTRODUCTION

The Joint Research Centre (JRC) and Nuclear Research and Consultancy Group (NRG) located in Petten, The Netherlands, and the RERTR program at Argonne National Laboratory are engaged in a joint study leading to conversion of the HFR-Petten research reactor from HEU to LEU fuel. The study has three phases[1,2] specified by JRC and NRG. Phase 1 results are described in this paper. The objective is to determine the number of fuel plates per assembly, the uranium density in the fuel meat, and the burnable poison in the sideplates that will extend the fuel cycle length from 25.7 days with the current HEU fuel to 28.3 days with LEU fuel, maximize thermal neutron fluxes in both in-core and ex-core experiment facilities, and satisfy all of the safety requirements.

Phase 2 will begin in October 2000 and consists of nine technical qualification aspects for the fuel. These include irradiation testing of two LEU prototype fuel assemblies and performing the analyses that are needed to revise the technical specifications and safety analysis report. Phase 2 is expected to be completed in the Spring of 2002. Work on Phase 3 to update the HFR license reference documentation is scheduled to be completed by the end of 2003. LEU fuel is planned to be procured in 2004, with conversion beginning in 2005 and ending before May 2006.

The first step in performing the studies for Phase 1 was to establish credibility of the calculation models and methodology by comparing measured and calculated results for a recent HEU core that was well characterized. NRG performed a special set of measurements for this purpose during a long shutdown in April 2000. A calculational model and methodology were then jointly developed by ANL and NRG to calculate key measured values. This same model and methodology were then used to study various LEU fuel assembly design options using U_3Si_2-Al fuel with up to 4.8 g U/cm^3 and different burnable poisons.

"CREDIBILITY" CORE AND MODEL DESCRIPTION

Figure 1 shows a schematic diagram of the HFR core containing 17 aluminum "license plugs" that was set up by NRG in April 2000 to make measurements that will be used to establish the credibility of the calculational methods and models for this study.

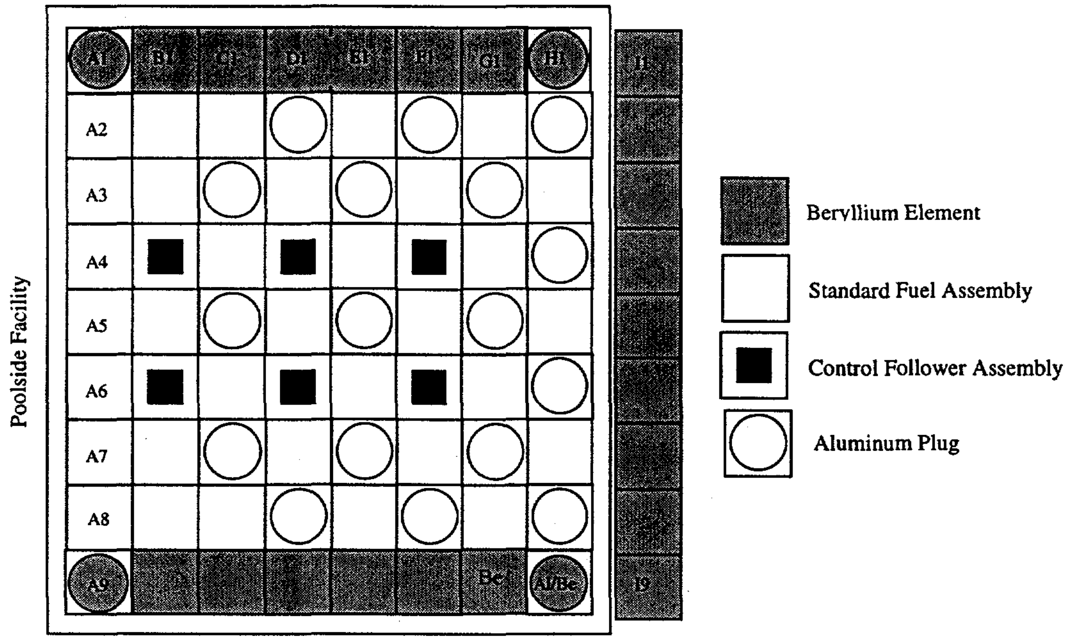

Figure 1. HFR Core Configuration for Measurements and Calculations

NRG provided measurements of the axial distribution of uranium at 15 nodes for each fuel assembly, critical control rod positions, calculated concentrations of Sm-149 in each fuel assembly, and the estimated poison content of each beryllium reflector assembly. ANL built detailed computer models of the HFR using both the DIF3D diffusion theory code[3] and the MCNP Monte Carlo code[4]. Nuclear cross sections in seven energy groups for use with diffusion theory were generated using the WIMS-ANL code[5]. ENDF/B-VI and selected JEF2.2 cross sections were used in the continuous energy MCNP code.

Burnup calculations were done by ANL using the REBUS burnup code[6] with the control rods parked at the "average" position for a typical operating cycle in order to: obtain (1) the same uranium masses by fuel assembly as the NRG measurements; (2) boron masses in the sideplates, (3) boron axial distributions, and (4) fission product concentrations other than Xe and Sm-149. Burnable poison and fission product concentrations obtained in this manner and the uranium axial distributions measured by NRG were then used in a detailed MCNP model with eight axial burnup zones per assembly and control rods set at the measured critical positions specified by NRG. Calculated eigenvalues for the critical reactor are shown in Table 1 for cases with and without the beam tubes and aluminum structural materials in the reflector.

Table 1. Calculated Eigenvalues Using the MCNP Monte Carlo Code and HFR Model

Nuclear Cross Sections*	Beam Tubes and Reflector Structure	k-eff	Excess Reactivity % dk/k
ENDF/B-VI	Not Included	0.99090 ± 0.00019	- 0.92 ± 0.02
JEF2.2 Al and ^{235}U	Not Included	1.00087 ± 0.00013	+ 0.09 ± 0.01
JEF2.2 Al and ^{235}U	Included	0.99951 ± 0.00018	- 0.05 ± 0.02

The reactivity worth of the beam tubes and aluminum structural materials in the reflector was calculated to be 0.14 ± 0.02 % dk/k using the JEF2.2 Al and ^{235}U data shown in Table 1.

Two other reactivity measurements performed by NRG were calculated by ANL:

(1) Complete withdrawal the aluminum plug in position C5, leaving this position filled with water, required that the control rods be withdrawn a distance of 0.79 cm to bring the reactor to critical. Simulation of this experiment in the ANL MCNP model with the control rods withdrawn 0.79 cm gave k-eff = 1.00059 ± 0.00020 (using the unperturbed reflector model).

(2) The differential reactivity worth of one control rod was measured by NRG and used to obtain a reactivity worth of 0.405 % dk/k/cm for all six control rods. A value of 0.496 ± 0.024 % dk/k/cm was calculated by ANL using the MCNP code.

In addition to these measurements, the license plug in position C5 was replaced by an iridium experiment. To bring the reactor to critical, the control rods had to be withdrawn a distance of 1.69 cm. The results of this experiment were used by ANL in the Monte Carlo model to determine the ^{10}B concentration that would provide the equivalent reactivity worth of a "mockup" iridium experiment. This ^{10}B equivalent concentration was then used in all of the HEU and LEU core analysis to determine the optimum LEU fuel assembly design.

All of the calculations described so far in this section used axial uranium distributions that were measured by NRG. A calculation in MCNP was also done using uranium and burnable poison distributions computed for eight axial burnup zones per fuel assembly using the REBUS code with all of the control rods parked at an "average" position for a typical operating cycle. A k-eff of 0.99669 ± 0.00017 was obtained using these axial distributions in the MCNP model – a reduction of about 0.42 % dk/k in comparison with the k-eff value of 1.00087 ± 0.00013 shown in Table 1 using measured axial uranium distributions.

Both NRG and ANL agree that the methods and models used in this section are able to predict reactivity parameters for the HFR reasonably well.

*The difference between ENDF/B-VI and JEF2.2 Al and ^{235}U results are primarily due to different thermal absorption cross sections for aluminum in the two cross section libraries. We would like to note that the "best" cross section value has not been determined, even though the JEF2.2 Al and ^{235}U data give results that are closer to measured data for the reactor system. For example, the thermal absorption cross section for aluminum in the JEF3 library is close to the ENDF/B-VI value. Cross sections for all calculations in this study were derived from ENDF/B-VI libraries, except that JEF2.2 libraries were used for Al and ^{235}U. However, the cross section differences described in this paragraph will not change the conclusions derived from this study.

LEU FUEL ASSEMBLY OPTIMIZATION STUDIES

Objectives for LEU Fuel Assembly Design

The main parameters considered for the LEU fuel assembly design are the number of fuel plates per assembly, the uranium density in the fuel meat, and the type and quantity of the burnable poison. The fuel type is U_3Si_2-Al dispersion fuel with up to 4.8 g U/cm^3. This is a well-qualified fuel[3] that has been licensed for use in many research reactors, including the 70 MW OSIRIS reactor in France, the 50 MW R2 reactor in Sweden, and the 50 MW JMTR reactor in Japan. The burnable poison is either B_4C-Al incorporated into the sideplates or cadmium wires inserted between the fuel plates and sideplates.

The first criterion for an acceptable fuel assembly design is that the LEU equilibrium core needs to operate for 28.3 full power days per cycle (instead of 25.7 days in the HEU core) and have an excess reactivity of about 1 % dk/k at end-of-cycle with the control rods fully-withdrawn. The second objective is to maximize the thermal neutron flux or a particular reaction rate in specific experiment facilities. The third objective is to minimize the motion of the control rods during an operating cycle by adjusting the type and quantity of the burnable poison. All safety margins must be satisfied to have an acceptable design. Shutdown margins for prescribed states of the reactor are addressed in this paper. Analyses of the thermal-hydraulic safety margins, mainly the margin to onset of flow instability, are not yet complete.

Computational Procedures

Figure 2 shows a schematic diagram of the HFR core with an experiment load that was specified by NRG for use in these optimizations studies. The first step was to perform a burnup calculation using the REBUS code[4] with diffusion theory flux solutions[5] to obtain isotopic compositions for the fuel and burnable poison as a function of burnup. Calculations were done in 3D with eight axial burnup zones and with all six control rods and fuel followers parked at their approximate average height during an operating cycle. The control rods were inserted in the burnup calculations in order to obtain more realistic axial distributions for the fuel and burnable poisons. Nuclear cross sections with seven energy groups were generated as a function of burnup using the WIMS-ANL code[6].

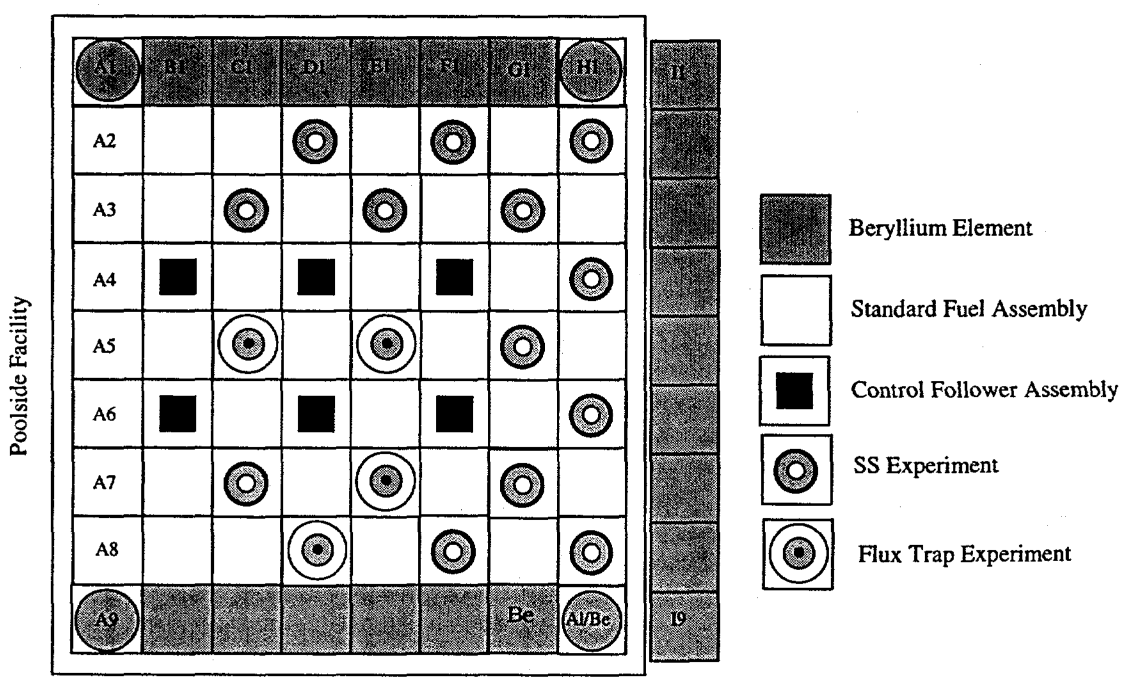

Figure 2. HFR Core with Typical Experiment Load

The material compositions at end-of-equilibrium cycle from the REBUS code were then used in the detailed Monte Carlo model to compute the excess reactivity at end of cycle with the control rods fully withdrawn. Material compositions from the middle of the equilibrium cycle were used in a second Monte Carlo calculation to compute fluxes and reaction rates in the specific experiment regions. Additional Monte Carlo calculations were also done using the so-called "License Core" at the beginning of the equilibrium cycle without xenon to check that all shutdown margin requirements are satisfied. These shutdown margin calculations will be described in a later section.

Number of Fuel Plates per Assembly

LEU standard assemblies with 20 and 21 fuel plates were considered. The control follower assemblies had 17 fueled plates in each case. All clad thicknesses were 0.38 mm. A fuel assembly with 21 plates, 0.65 mm thick fuel meat, 4.8 g U/cm^3, and 200 mg ^{10}B in each of the two sideplates gave an excess reactivity of about – 0.6 % dk/k at the end of a 28.3 day equilibrium cycle with the control followers fully-withdrawn. Since this excess reactivity is less than the goal of about + 1 % dk/k under the same conditions, the 21 plate case was not pursued further. All subsequent LEU calculations use a design with 20 fuel plates per standard assembly and 0.76 mm thick fuel meat.

Design, Reactivity, and Performance Summary

Table 2 summarizes key fuel assembly design and experiment performance parameters for the HEU core

Table 2. Summary of Design, Reactivity and Experiment Performance Parameters at 45 MW.
The HEU core has a cycle length of 25.7 days. The LEU cores have a cycle length of 28.3 days.

								LEU/HEU Performance Ratios		
Case	Enrichment, %	Burnable Poison per Sideplate	Plates Per FA	Uran. Dens., g/cm^3	g ^{235}U per FA	EOC Excess React., CR Out % dk/k	Oper. Cycle React. Swing % dk/k	Average Th. Flux Poolside Facility n/cm^2	^{10}B React. Rate, Flux Trap	Average Th. Flux SS Expt. n/cm^2
Inside-Out Fuel Shuffling Pattern										
	UAl_x-Al Fuel									
1	93	500 mg ^{10}B	23/19	1.09	450/310	0.76	1.31	-	-	-
	U_3Si_2-Al Fuel									
2*	19.75	200 mg ^{10}B	20/17	4.63	527/424	1.04	~2.15	0.92	0.94	0.89
3	19.75	0.4 mm Cd	20/17	4.5	512/412	1.04	1.98	0.91	0.96	0.90
4	19.75	300 mg ^{10}B	20/17	4.8	546/440	0.99	1.38	0.89	0.92	0.88
5*	19.75	0.5 mm Cd	20/17	4.6	523/422	0.95	~1.13	0.90	0.95	0.90
6	19.75	0.5 mm Cd	20/17	4.8	546/440	1.74	0.95	0.89	0.94	0.89
Outside-In Fuel Shuffling Pattern										
7	19.75	0.5 mm Cd	20/17	4.8	546/440	1.40	2.04	0.99	0.91	0.85
Inside-Out Fuel Shuffling Pattern, U9Mo-Al Fuel										
8	19.75	0.5 mm Cd	20/17	5.0	569/458	0.97		0.87	0.92	0.87
Outside-In Fuel Shuffling Pattern, U9Mo-Al Fuel										
9	19.75	0.5 mm Cd	20/17	5.2	592/476					

* Interpolated from data at 4.5 g U/cm^3 and 4.8 g U/cm^3.

with ^{10}B in the sideplates and LEU cores with two different types of burnable poison. One type is the same as the ^{10}B poison in the sideplates of the HEU assemblies. The second type consists of 20 cadmium wires with diameters of 0.4 mm and 0.5 mm per sideplate or 40 cadmium wires per fuel assembly. LEU calculations were done with uranium densities of 4.5 and 4.8 g/cm^3 and the results interpolated to the values shown in Table 2. The LEU optimization studies used the same inside-out fuel shuffling pattern as the HEU core. The results of using an outside-in fuel shuffling pattern are described in a later section.

End of Cycle Excess Reactvity

All of the LEU cases in Table 2 have an excess reactivity of about 1 % dk/k or greater at end-of-cycle with the control rods fully withdrawn. These reactivity data were obtained from MNCP calculations using fuel and poison compositions obtained from the REBUS diffusion theory burnup calculations.

Boron versus Cadmium Burnable Poison

Figure 3 shows the shape of the reactivity profiles for a typical operating cycle. The LEU cases with 300 mg ^{10}B per sideplate and twenty 0.5 mm diameter cadmium wires per sideplate have nearly the same shape as the reactivity profile for the HEU core. The LEU cases with 200 mg ^{10}B per sideplate and 0.4 mm cadmium wires have nearly the same shape as each other, but the curves are steeper than that for the HEU core, indicating that more control rod movement than in the HEU core would be required during each LEU fueled operating cycle. For this reason, the LEU cases with 300 mg ^{10}B and 0.5 mm diameter cadmium wires are a better choice for the burnable poison.

The cadmium wire cases require a smaller ^{235}U loading per fuel assembly to obtain the end-of cycle excess reactivity and burnup swing over an operating cycle because the cadmium is almost completely burned out after 2-3 cycles. With boron, there is always a residual, even after six residence cycles, that requires additional ^{235}U to compensate for the reactivity loss. In addition, fuel assemblies with cadmium wires inserted between the fuel plates and the sideplates may be less expensive to manufacture than fuel assemblies with B_4C-Al incorporated into the sideplates.

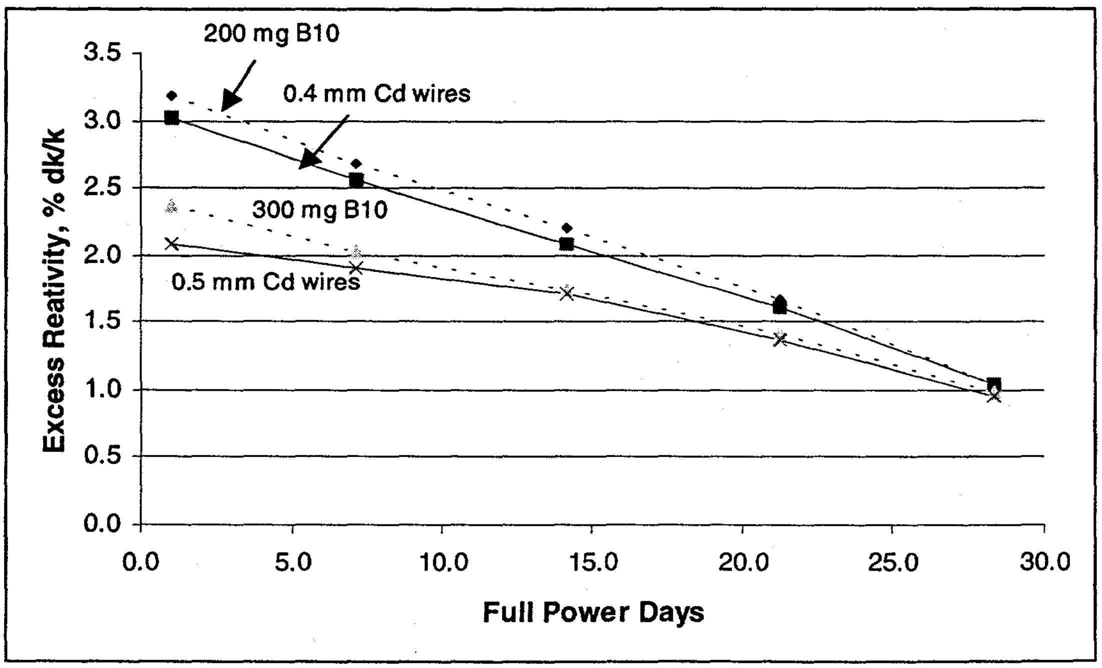

Figure 3. Reactivity Shapes for One Operating Cycle using LEU Fuel with B10 or Cd as the Burnable Poison

Experiment Performance and Core Power Distributions

Using the same inside-out fuel shuffling pattern in the LEU and the HEU cores, the LEU thermal fluxes are about 10% lower than the HEU thermal fluxes in the poolside facility at the locations where target plates are irradiated to produce Mo-99. There is essentially no difference in these fluxes between the use of boron or cadmium as burnable poisons. The reason is that fluxes in the poolside facility are dominated by the amount of power generated in the A-row of fuel assemblies adjacent to the poolside facility. Since these fuel assemblies are relatively highly burned using the current inside-out fuel shuffling pattern, most of their initial boron or cadmium content is burned out and thus the type of burnable poison has little influence on the fluxes.

However, with boron or cadmium as the burnable poison, the power distribution in the LEU cores is higher at the center and lower at the edges than in the HEU core. In fact, the power generated in the seven fuel assemblies between A2 and A8 was calculated to be 6.8 MW in the HEU core, 6.3 MW in the LEU design with 0.5 mm cadmium wires, and 6.1 MW in the LEU design with 300 mg ^{10}B per sideplate. Thus, the changes in the core power distribution in the LEU cores account for nearly all of the thermal flux losses in the poolside facility. There are other lesser factors as well.

Additional calculations showed that the power generated in fuel assemblies in the A-row (see Fig. 4) and the thermal flux in the poolside facility of LEU cores with a reactor power of 50 MW (an increase of 11%) approximately match those of the HEU core operated at a power of 45 MW.

Inside-Out versus Outside-In Fuel Shuffling Patterns

One option to restore some of the thermal flux loss in the poolside facility is to change the fuel shuffling pattern in the LEU core from the current inside-out pattern to an outside-in pattern in which several fresh fuel assemblies are inserted in the A-row. This would shift the core power distribution toward the poolside facility and increase the thermal neutron flux there. Figure 4 compares the inside-out fuel shuffling pattern used in the current HEU core and one possible outside-in fuel shuffling pattern in the LEU core. The numbers on the fuel assemblies in Fig. 4 indicate the number of residence cycles each assembly has been in the core.

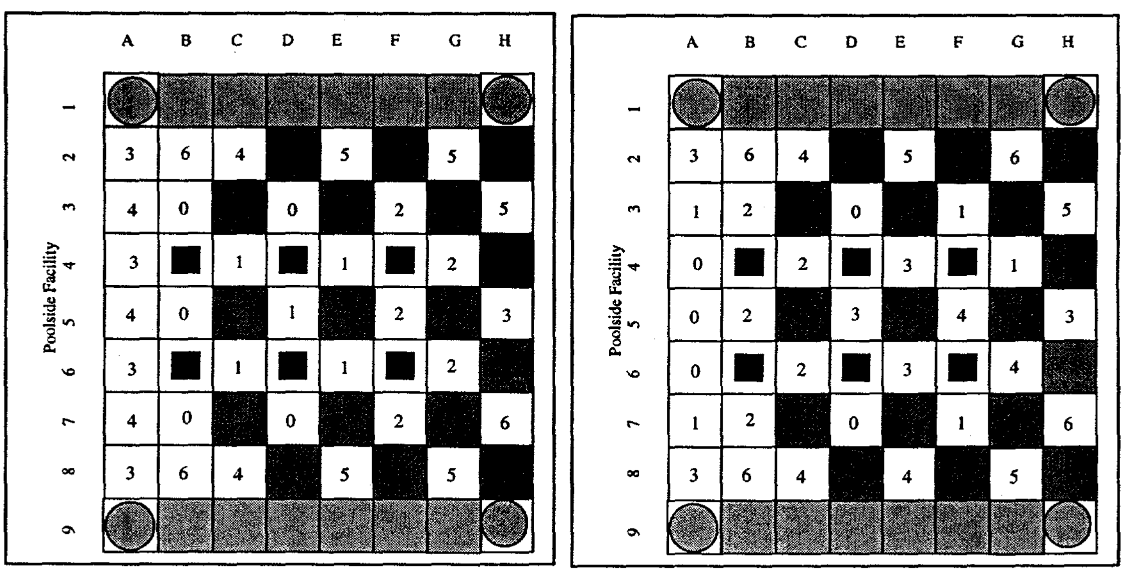

Figure 4. Comparison of Current HEU Inside-Out Fuel Shuffling Pattern (Left) and One Possible LEU Outside-In Fuel Shuffling Pattern (Right).

The results of calculations are shown in Table 2 for an LEU core using fuel assemblies containing 4.8 g U/cm^3 U_3Si_2-Al fuel, twenty 0.5 mm cadmium wires as the burnable poison, and the outside-in fuel shuffling pattern shown in Fig. 4. The excess reactivity at the end of the equilibrium cycle is 1.4 % dk/k, about 0.3 % dk/k lower than with the inside-out fuel shuffling pattern. The LEU/HEU thermal flux ratio in the poolside facility has increased to 0.99 from 0.90 since more of the reactor power has been shifted to the A-row of fuel assemblies.

We estimate that with a fuel assembly design with 4.8 g/cm^3, 300 mg ^{10}B as the burnable poison, and the outside-in shuffling pattern shown in Fig. 4 would have an end-of-cycle excess reactivity of about 0.7 % dk/k. A calculated end-of-cycle excess reactivity that is greater that 1 % dk/k would offset potential additional reactivity losses due to variations in the isotopic assay of low-enriched uranium procured from different sources. For example, a reactivity loss of ~0.35 % dk/k was calculated and included in all results shown in this paper for DOE LEU specifications with 0.22 wt-% ^{234}U and 0.01 wt-% ^{236}U. Larger isotopic contents of ^{234}U and ^{236}U would result in larger reactivity losses.

U9Mo-Al Fuel Meat versus U_3Si_2-Al Fuel Meat

In addition to using U_3Si_2-Al fuel, calculations for a fuel assembly design with 20 plates and twenty 0.5 mm cadmium wires per sideplate were also done to determine the uranium density that would be needed if the fuel meat were changed to a dispersion of U9Mo (9 wt-% Mo, 91 wt-% U) in aluminum. If U9Mo-Al fuel is qualified for reactor use, it may be viable option for replacing the U_3Si_2-Al fuel. As shown in Table 2, U9Mo-Al fuel with 5.0 g U/cm^3 would be needed to replace U_3Si_2-Al fuel with 4.6 g U/cm^3. Similarly, U9Mo-Al fuel meat with 5.2 g U/cm^3 would be needed to replace U_3Si_2-Al fuel with 4.8 g U/cm^3 in the HFR. Thermal flux performance in the poolside facility is expected to be 3-5% lower with LEU U9Mo-Al fuel than with LEU U_3Si_2-Al fuel for the same fuel shuffling pattern.

Shutdown Margins

Shutdown margins were calculated or estimated from similar calculations for each of the cases shown in Table 2, but for the "License Core" configuration in which experiments inside the core are replaced by aluminum plugs containing a central water hole. The HFR has three conditions on shutdown margin in its Technical Restrictions and Safety Regulations[7] for the "License Core". These are: (a) the maximum excess reactivity of the core may not exceed 15 % dk/k; (b) the reactor must remain subcritical for each core configuration and during the total fuel cycle, when the two most effective control rods are withdrawn completely while the remaining control rods are fully inserted; and (c) the reactor must remain subcritical when all control rods are moved out over a length corresponding to half of their total reactivity worth. To further ensure safe reactor operation, NRG operating procedures state that for condition (b), the subcriticality of the core must never be less than 1% dk/k.

Calculations were performed for each of these shutdown margin criteria for the cases in Table 2. The results shown in Table 3 indicate that all shutdown margin criteria are satisfied.

Table 3. Summary of Design and Shutdown Margin Parameters at 45 MW.
The HEU core has a cycle length of 25.7 days. The LEU cores have a cycle length of 28.3 days.

							Shutdown Margin Criteria For License Core		
Case	Enrichment, %	Burnable Poison per Sideplate	Plates Per FA	Uran. Dens., g/cm^3	g ^{235}U per FA	EOC Excess React., CR Out % dk/k	BOC Excess React. CR Out % dk/k	Core Sub-Crit. with all CR Withdrawn to Half Worth	Shutdown Margin with Two Highest Worth CR Out, % dk/k
Inside-Out Fuel Shuffling Pattern									
	UAl_x-Al Fuel								
1	93	500 mg ^{10}B	23/19	1.09	450/310	0.76	8.65	-4.93	-2.70
	U_3Si_2-Al Fuel								
2*	19.75	200 mg ^{10}B	20/17	4.63	527/424	1.04	8.89	-4.33	-2.72
3	19.75	0.4 mm Cd	20/17	4.5	512/412	1.04	9.07	-4.23	-2.89
4	19.75	300 mg ^{10}B	20/17	4.8	546/440	0.99	9.12	-3.63	-2.35
5*	19.75	0.5 mm Cd	20/17	4.6	523/422	0.95	9.17	-4.13	-2.79
6	19.75	0.5 mm Cd	20/17	4.8	546/440	1.74	8.87	-3.75	-2.67
Outside-In Fuel Shuffling Pattern									
	19.75	0.5 mm Cd	20/17	4.8	546/440	1.40	9.36	-3.09	-1.29
Inside-Out Fuel Shuffling Pattern, U-9Mo Fuel									
7	19.75	0.5 mm Cd	20/17	5.0	569/458				
Outside-In Fuel Shuffling Pattern, U-9Mo Fuel									
8	19.75	0.5 mm Cd	20/17	5.2	592/476				

* Interpolated from data at 4.5 g U/cm^3 and 4.8 g U/cm^3.

CONCLUSIONS

Detailed models of the HFR reactor for use in Monte Carlo and diffusion theory burnup calculations were set up by ANL in cooperation with NRG. The results of calculations using these models agreed reasonably well with key reactivity measurements made by NRG on a special HFR configuration set up for this purpose. These comparisons established the credibility of the models and methods for predicting HFR reactivity parameters.

JRC and NRG specified the reactor performance characteristics that were desired for an optimal LEU fuel assembly design. These included extension of the operating cycle to 28.3 days from the current 25.7 days, an excess reactivity of about 1% dk/k at end-of-cycle, minimizing motion of the control rods during a cycle, and maximizing neutron flux performance in the experiment facilities. All safety margins must be satisfied.

ANL performed analyses for LEU fuel assembly designs with U_3Si_2-Al fuel with up to 4.8 g U/cm^3 in the fuel meat and either borated sideplates or cadmium wires as the burnable poison. The specified performance criteria were used to systematically narrow the parameter choices. Two LEU design options that are approximately equivalent using the same inside-out fuel shuffling pattern in both the HEU and LEU cores are: (1) 300 mg ^{10}B per sideplate and 4.8 g U/cm^3 in the fuel meat of assemblies containing 20 fuel plates with 0.76 mm thick fuel meat and (2) twenty cadmium wires with a diameter of 0.5 mm per sideplate along with fuel meat containing 4.6 g U/cm^3 in the same 20 plate geometry. All three of the shutdown margin criteria specified in the HFR operating license were shown to be satisfied. However, the main drawback is that the thermal flux in the poolside facility is reduced by about 10% in the LEU fuel cases, mainly because the power generated in the row of fuel assemblies adjacent to the poolside facility is reduced.

One option that was studied to restore most of this performance is to change the fuel shuffling pattern to one in which several fresh fuel assemblies are inserted into the row of the core that is adjacent to the poolside facility. One calculation using an LEU fuel assembly design with 4.8 g U/cm^3 in U_3Si_2-Al fuel and twenty 0.5 mm cadmium wires per sideplate gave an LEU/HEU thermal flux ratio of 0.99 in the poolside facility. The excess reactivity at end-of-cycle was +1.4% dk/k and the shutdown margin with the two most reactive control rods stuck out of the core and the others fully inserted was -1.3% dk/k.

This study shows that it is feasible to convert the HFR to LEU silicide fuel with a uranium density that is equal to or less than 4.8 g/cm^3. A variety of other options to maximize fluxes in the experiment regions have not been explored at this time. However, the choices will clearly involve some studies with the goal of maximizing economic utilization.

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