REVISITING THE HFR-PETTEN LEU CONVERSION STUDY

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To be presented at the 2002 International Meeting
On Reduced Enrichment for Research and Test Reactors

November 3-8, 2002
San Carlos de Bariloche, Argentina

Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of International Policy and Analysis (NA-241) and National Nuclear Security Administrations under contract W-31-109-Eng-38.

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ABSTRACT

The results of a joint feasibility study between the Nuclear Research and consultancy Group (NRG) and Argonne National Laboratory for the LEU conversion of the HFR-Petten reactor in The Netherlands were presented at the 2000 RERTR meeting. Recently, improved models for cross section generation of the burnable poison (B in the side plates of the HEU core and Cd wires in the LEU core) were created at ANL, together with new diffusion theory models for burnup analyses. The purpose of this paper is to present the results of diffusion theory and Monte Carlo analyses for the HEU and the selected LEU core using these improved models, and at the same time to show that the results and conclusions reached in the previous paper are still valid.

INTRODUCTION

The results of a feasibility study for the LEU conversion of the HFR-Petten reactor were presented at the 2000 RERTR meeting[1]. The cross section generation and diffusion models used in that study produced good global results for both the HEU and LEU cores. However, the diffusion theory analyses were not as good as Monte Carlo analyses predicting the results of the "credibility core" (a core for which reactivity worth measurements and the position of the control rods for a critical configuration where available) or the power produced per fuel assembly (FA).

Improved models for cross section generation of the burnable poison (B in the side plates of the HEU core and Cd wires in the LEU core), as well as new diffusion theory models for both cores were recently created at ANL to address the problems described above. The use of these new models eliminated the small differences obtained with the previous diffusion theory and cross sections generation models.

The improved models for generation of burnable poison cross sections used in the diffusion theory models are presented first. The results of diffusion theory and Monte Carlo analyses are then compared for the "credibility core." Following that, results of Monte Carlo and diffusion theory burnup calculations for both the HEU and LEU cores are presented with discussion of results for k-effective, power produced per FA, ^{235}U burnup, and compositions for the most important fission products and other actinides.

Finally, the results of diffusion theory burnup calculations are presented for an equilibrium cycle for both the HEU and the selected LEU FA cores using the same two experiment types as in the 2000 RERTR meeting paper[1]; the new cross sections and diffusion theory models are used. The compositions from these equilibrium calculations are used in detailed Monte Carlo models to show that shutdown margins and performance indices used in the selection of the LEU fuel assembly are essentially unchanged.

MODELS FOR GENERATION OF BURNABLE POISON CROSS SECTIONS

The RERTR Program at ANL uses the WIMS-ANL[2] code for generation of multigroup cross sections to be used in the REBUS-PC[3] diffusion theory burnup code. WIMS-ANL is a one-dimensional transport cross-section generation code.

Figures 1 and 2 show the models used in the generation of cross sections for the burnable poisons, B and Cd wires respectively. The left side of these figures shows the actual geometric cross section of the FA with the side plates and the burnable poison. The right side shows the actual model used in the WIMS-ANL code. Slab geometry was selected to model the B poison in the side plates of the HEU FA and cylindrical geometry was used to model the Cd wires in the side plates of the LEU FA.

First, the MCNP[4] code was used to generate the burnable poison cross sections (in seven energy groups) for a fresh FA. The detailed FA was used in MCNP and the burnable poison cross sections were generated for the same region as that to be used in the diffusion theory models; i.e. homogeneous cross sections for a region that includes: a) water on the outside of the side plate; b) the side plate (with poison); and c) the unfueled part of the fuel plate with the corresponding coolant.

The WIMS-ANL model was then used to generate the burnable poison cross sections. It is evident that the actual geometry of the poison in relation to the FA, and the one-dimensional geometry used for the WIMS-ANL model are different. This factor will have an impact on the neutron spectrum present in the burnable poison region. Since both burnable poisons (B and Cd) are thermal absorbers, the WIMS-ANL models were modified to obtain the same spectrum as that in the MCNP calculations. The density of the water in the region close to the burnable poison was adjusted until the thermal absorption cross sections of the B-10 for the HEU FA (Figure 1) and the Cd-113 for the LEU FA (Figure 2) were essentially the same as those resulting from the MCNP calculation discussed above.

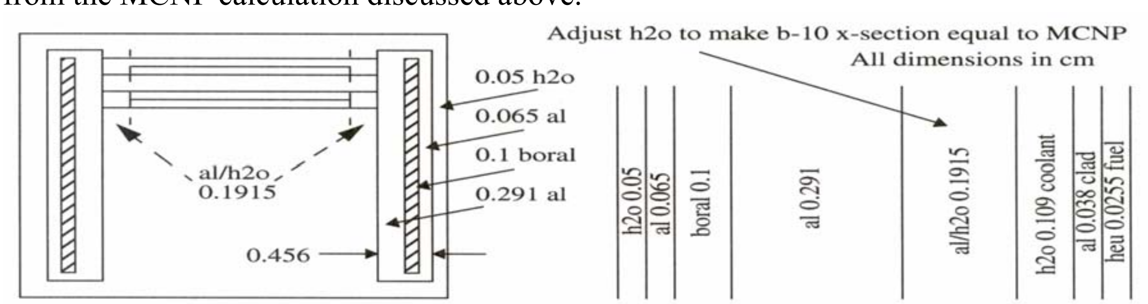

Figure 1. HEU FA: Geometry and WIMS-ANL Model for Burnable Poison XS Generation

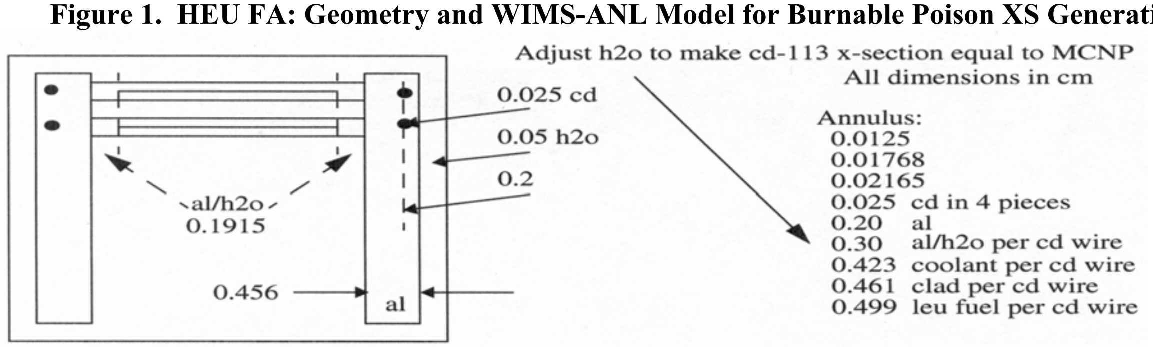

Figure 2. LEU FA: Geometry and WIMS-ANL Model for Burnable Poison XS Generation

"CREDIBILITY" CORE

Figure 3 shows a schematic diagram of the HFR core containing 17 aluminum "license plugs" that was set up by NRG in April 2000 to perform experiments that were used to establish the calculational methods and the models for the LEU conversion study presented at the 2000 RERTR meeting[1].

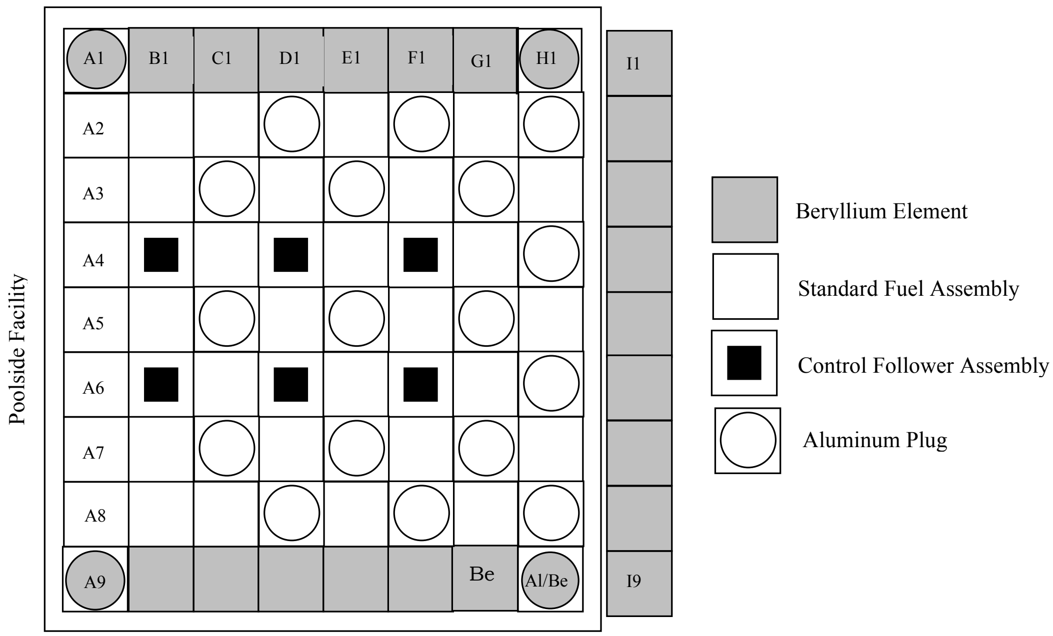

Figure 3. HFR Core Configuration for Measurements and Calculations

For this core, NRG provided measurements of the axial distributions of uranium at 15 axial nodes for each fuel assembly, critical control rod positions, calculated concentrations of Sm-149, and the estimated poison in each beryllium reflector. Using the REBUS-PC burnup code, ANL calculated the boron masses and distributions in the side plates, and the fission product concentrations other than Xe and Sm. These physical parameters were used in a detailed MCNP model and in the new diffusion theory model generated for the HEU core; the calculations with the diffusion theory model used the improved cross sections generated for the burnable poison (B) discussed above. Both the MCNP and the diffusion theory calculations used JEF2.2 cross sections for ^{235}U and for Al, and ENDF/B-VI cross-sections for all other isotopes. Calculated eigenvalues for the critical configuration and for a configuration in which the aluminum plug in position C5 was withdrawn leaving this position filled with water were performed with both the MCNP and the REBUS code; the results are shown in Table 1. A comparison of the power produced in each FA for both the MCNP and the diffusion theory models is shown in Table 2. The results in these tables show the very good agreement between the Monte Carlo results and those obtained with the new diffusion theory model combined with the improved cross sections for the boron burnable poison.

Table 1. Calculated Eigenvalues with MCNP and REBUS-PC

Configuration	Beam Tubes and Reflector Structure	Code	k-eff
Critical	Included	MCNP	0.99951 +/- 0.00018
Critical	Not Included	MCNP	1.00087 +/- 0.00013
Critical	Not Included	REBUS	0.99847
Al License Plug in C5 replaced by Water		MCNP REBUS	-0.463* -0.503*

* Reactivity worth (%) of replacement.

DIFFUSION THEORY AND MONTE CARLO BURNUP

To further enhance the credibility of the improved models to generate burnable poison cross sections for use in diffusion theory models, and to show the appropriateness of the new diffusion theory models, Monte Carlo and diffusion theory burnup analyses were performed for both the HEU and the LEU cores. The MC/REBUS[5] code was used for the Monte Carlo burnup analyses and the REBUS-PC code was used for the diffusion theory burnup analyses. The results of these analyses, which were performed for the same core configuration as in Figure 1 above, are presented in a companion paper at this meeting[5], and reproduced here for completeness.

a) HEU Core: For the HEU core, a reactivity rundown starting with fresh fuel was performed, and the reactivity trace for the burn time considered is presented in Figure 4. The agreement between Monte Carlo and diffusion theory is excellent.

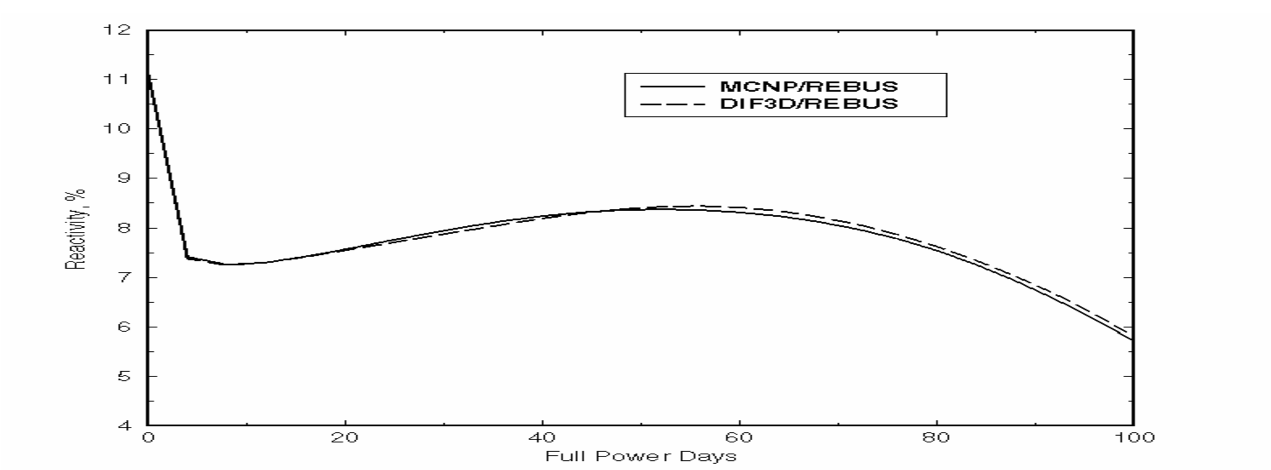

Figure 4. HFR HEU Reactivity Rundown

Very good agreement is also obtained for the power produced in each FA and the ^{235}U burnup; differences between the Monte Carlo and diffusion theory burnup analyses are smaller than 3%.

Table 2. "Credibility Core": Power Produced per FA

FA Position	MCNP	REBUS	R/M
A2	1.73	1.73	1.00
A3	2.25	2.26	1.01
A4	2.28	2.28	1.00
A5	2.69	2.72	1.01
A6	2.25	2.27	1.01
A7	2.21	2.24	1.01
A8	1.69	1.70	1.01
B2	2.12	2.13	1.00
B3	3.11	3.14	1.01
B4	3.19	3.26	1.02
B5	3.84	3.92	1.02
B6	2.82	2.89	1.02
B7	2.99	3.03	1.02
B8	2.06	2.06	1.00
C2	2.85	2.82	0.99
C4	4.01	4.09	1.02
C6	3.94	4.03	1.02
C8	2.80	2.77	0.99
D3	3.74	3.75	1.00
D4	2.50	2.56	1.02
D5	4.18	4.20	1.01
D6	2.73	2.79	1.02
D7	3.67	3.70	1.01
E2	2.04	1.99	0.98
E4	3.47	3.43	0.99
E6	3.46	3.44	0.99
E8	2.10	2.03	0.97
F3	2.85	2.81	0.99
F4	1.72	1.74	1.01
F5	2.96	2.87	0.97
F6	1.53	1.55	1.01
F7	2.90	2.85	0.98
G2	1.41	1.36	0.97
G4	2.27	2.20	0.97
G6	2.30	2.22	0.97
G8	1.42	1.37	0.97
H3	1.23	1.19	0.97
H5	1.44	1.38	0.96
H7	1.28	1.24	0.96

The same good agreement also exists for the concentration of the important fission products and other actinides. Larger differences (less than 9%) do exist for the burnable poison concentration in a few side plates, and for the concentration of higher actinides. However, these differences have almost no impact on the important results of a burnup analysis.

b) LEU Core: For the LEU core, a cycle-by-cycle burnup analysis was performed and the reactivity traces for cycles 5 and 7 are shown in Figure 5. The results in this figure show good agreement between diffusion theory and Monte Carlo methods. Small differences do exist, as expected, because of the complex nature of modeling the burnup of thin Cd wires with diffusion theory and also because the uncertainty in the Cd cross sections generated in MCNP were about 3%. The reactivity differences at the end of the cycle are less than 0.2% $\delta k/k$.

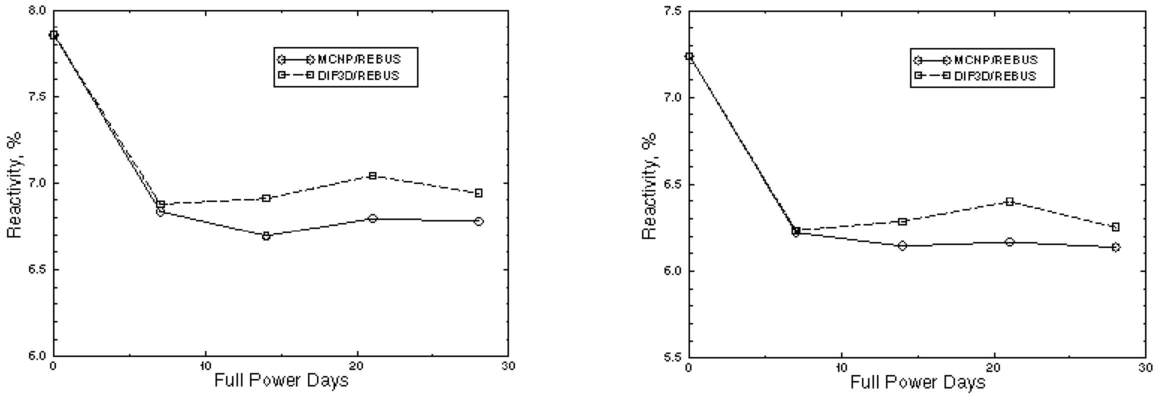

Figure 4. HFR LEU: Cycle 5 (A) and Cycle 7 (B)

Table 3 shows the results for power produced per FA and ^{235}U burnup at the beginning of cycle 5, where the very good agreement between Monte Carlo and diffusion theory can be seen.

PERFORMANCE AND SHUTDOWN MARGINS

This section presents the results for power produced per FA, experiment performance, and shutdown margins for the HEU and LEU cores. The objectives in this part of the work are: a) to show that the performance and shutdown margins calculated in Ref. 1 are essentially the same as calculated in this paper, and b) to show that the power produced per FA in the diffusion theory analyses compares well with those obtained in the Monte Carlo analyses.

One of the reasons for creating new models for burnable poison cross section generation and for the diffusion theory calculations was to improve the agreement between Monte Carlo and diffusion theory results for power produced per FA using the models used in Ref. 1. Table 4 presents a comparison of power produced per FA using Monte Carlo and diffusion theory for the LEU core at the beginning of the equilibrium cycle. The results show very good agreement.

Three types of experiments were used in the models for the LEU conversion study. The performance indices used were: a) thermal fluxes in the poolside facility at the locations where target plates are irradiated to produce Mo-99; b) B-10 reaction rate at the flux traps; and c) average thermal fluxes at the SS experiments. The performance comparisons are shown in Table 5, where the results obtained in this paper are compared with those from Ref. 1. These results show that the performance indices are essentially the same in both studies.

The shutdown margin results obtained in this study and those obtained in Ref. 1 are compared in Table 6. Again, these results show essentially no change in shutdown margins.

Table 3. MCNP Vs REBUS: Power Produced per FA and ^{235}U Burnup (BOC # 5)

	POWER PRODUCED PER FUEL ASSEMBLY (%)			^{235}U BURNUP (%)		
FA Position	**MCNP**	**REBUS**	**REBUS/ MCNP**	**MCNP**	**REBUS**	**REBUS/ MCNP**
A2	1.709	1.670	0.98	24.92	25.22	1.01
A3	1.906	1.875	0.98	29.37	29.56	1.01
A4	2.286	2.239	0.98	27.65	28.10	1.02
A5	2.244	2.192	0.98	31.59	31.91	1.01
A6	2.310	2.247	0.97	24.34	24.62	1.01
A7	1.829	1.788	0.98	33.48	33.74	1.01
A8	1.663	1.627	0.98	26.86	27.12	1.01
B2	2.273	2.232	0.98	26.40	26.19	0.99
B3	2.963	2.980	1.01	0.0*	0.0	
B5	3.588	3.601	1.00	0.0	0.0	
B7	2.917	2.923	1.00	0.0	0.0	
B8	2.245	2.229	0.99	24.06	23.74	0.99
C2	2.737	2.654	0.97	31.20	31.51	1.01
C4	3.575	3.621	1.01	8.09	8.12	1.00
C6	3.482	3.591	1.03	8.05	8.06	1.00
C8	2.688	2.633	0.98	30.33	30.55	1.01
D3	3.438	3.430	1.00	0.0	0.0	
D5	3.729	3.800	1.02	9.66	9.77	1.01
D7	3.358	3.419	1.02	0.0	0.0	
E2	2.685	2.609	0.97	27.52	27.58	1.00
E4	3.356	3.430	1.02	9.56	9.64	1.01
E6	3.329	3.440	1.03	9.62	9.63	1.00
E8	2.649	2.589	0.98	29.19	29.22	1.00
F3	2.613	2.594	0.99	17.73	18.02	1.02
F5	3.051	3.096	1.01	18.99	19.40	1.02
F7	2.584	2.600	1.01	19.18	19.56	1.02
G2	1.846	1.786	0.97	30.20	30.33	1.00
G4	2.321	2.349	1.01	20.17	20.52	1.02
G6	2.296	2.362	1.03	17.83	18.09	1.01
G8	1.817	1.784	0.98	30.74	30.78	1.00
H3	1.602	1.558	0.97	30.10	30.07	1.00
H5	1.922	1.867	0.97	26.49	26.81	1.01
H7	1.622	1.606	0.99	25.48	25.12	0.99
B4	2.902	2.924	1.01	0.0	0.0	
B6	2.633	2.655	1.01	9.63	9.75	1.01
D4	2.635	2.686	1.02	27.83	28.18	1.01
D6	2.750	2.819	1.03	18.46	18.60	1.01
F4	2.091	2.103	1.01	36.22	36.78	1.02
F6	2.058	2.099	1.02	36.45	36.89	1.01

* Fresh fuel

Table 4. LEU Core: Comparison of BOEC Power Produced per Fuel Assembly (%)

FA Position	MCNP	REBUS	R/M
A2	1.91	1.84	0.97
A3	2.16	2.11	0.98
A4	2.58	2.53	0.98
A5	2.52	2.49	0.99
A6	2.53	2.50	0.99
A7	2.00	1.99	0.99
A8	1.77	1.75	0.99
B2	2.17	2.12	0.97
B3	3.29	3.29	1.00
B4	3.33	3.35	1.01
B5	4.10	4.16	1.02
B6	2.91	2.95	1.01
B7	3.12	3.18	1.02
B8	2.01	2.02	1.00
C2	2.60	2.52	0.97
C4	3.97	4.04	1.02
C6	3.86	3.98	1.03
C8	2.59	2.62	1.01
D3	3.39	3.34	0.99
D4	2.78	2.81	1.01
D5	4.33	4.44	1.03
D6	2.93	3.02	1.03
D7	3.56	3.65	1.02
E2	2.22	2.13	0.96
E4	3.52	3.54	1.01
E6	3.73	3.83	1.03
E8	2.26	2.29	1.01
F3	2.29	2.22	0.97
F4	1.90	1.89	0.99
F5	3.01	2.99	0.99
F6	1.80	1.81	1.00
F7	2.32	2.33	1.00
G2	1.41	1.35	0.96
G4	1.95	1.89	0.97
G6	1.96	1.92	0.98
G8	1.31	1.31	1.00
H3	1.21	1.17	0.97
H5	1.55	1.52	0.98
H7	1.15	1.14	0.99

Table 5. Summary of Design, Reactivity and Experiment Performance Parameters at 45 MW
(Comparison between paper in RERTR 2000 [Ref. 1], and This Paper)
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	Burnable Poison per Sideplate	Plates per FA Std./ Control Follower	Uran. Dens., g/cm^3	g ^{235}U per FA Std./ Control Follower	EOC Excess React., CR Out %dk/k	Average Th. Flux Poolside Facility n/cm^2	^{10}B React. Rate, Flux Trap	Average Th. Flux SS Expt. n/cm^2
93% enrichment, UAl_x-Al Fuel, Inside-Out Fuel Shuffling Pattern								
Ref. 1	500 mg ^{10}B	23/19	1.09/0.96	450/310	0.76	-	-	-
This Paper					0.77	-	-	-
19.75% enrichment, U_3Si_2, Inside-Out Fuel Shuffling Pattern								
Ref. 1	0.5 mm Cd	20/17	4.8	546/440	1.74	0.89	0.94	0.89
This Paper					1.96	0.89	0.94	0.90
19.75% enrichment, U_3Si_2, Outside-In Fuel Shuffling Pattern								
Ref. 1	0.5 mm Cd	20/17	4.8	546/440	1.40	0.99	0.91	0.85
This Paper					1.64	0.99	0.94	0.86

Table 6. Summary of Design and Shutdown Margin Parameters at 45 MW
(Comparison between paper in RERTR 2000 [Ref. 1], and This Paper)
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	Burnable Poison per Sideplate	Plates per FA Std./ Control Follower	Uran. Dens., g/cm^3	g ^{235}U per FA Std./ Control Follower	EOC Excess React., CR Out % dk/k	BOC Excess React. CR Out % dk/k	Core Sub-Crit. with all CR With-drawn to Half Worth	Shutdown Margin with Two Highest Worth CR Out, % dk/k
93% enrichment, UAl_x-Al Fuel, Inside-Out Fuel Shuffling Pattern								
Ref. 1	500 m^{10}B	23/19	1.09/0.96	450/310	0.76	8.65	-4.93	-2.70
This Paper					0.77	8.61	-4.76	-2.65
19.75% enrichment, U_3Si_2, Inside-Out Fuel Shuffling Pattern								
Ref. 1	0.5 mm Cd	20/17	4.8	546/440	1.74	8.87	-3.75	-2.67
This Paper					1.96	9.15	-3.30	-2.66
19.75% enrichment, U_3Si_2, Outside-In Fuel Shuffling Pattern								
Ref. 1	0.5 mm Cd	20/17	4.8	546/440	1.40	9.39	-3.09	-1.29
This Paper					1.64	9.58	-2.71	-1.38

SUMMARY ANS CONCLUSIONS

The results of a joint feasibility study between the Nuclear Research and consultancy Group (NRG) and Argonne National Laboratory for LEU conversion of the HFR-Petten reactor were presented at the 2000 RERTR meeting[1]. Recently, improved models for cross section generation of the burnable poison (B in the side plates of the HEU core and Cd wires in the LEU core) and for the diffusion theory analyses were created at ANL. Results of analyses using these new models are shown to produce very good agreement with Monte Carlo results, demonstrating the soundness of these new models. Monte Carlo and diffusion analyses are performed to compare the results for: a) the "credibility core" (a core in which measurements were performed); b) burnup analysis; and c) performance and shutdown margins for the equilibrium cycle of both the HEU and LEU cores.

The results presented in this paper not only show the good agreement between Monte Carlo and diffusion theory, but they also show that the shutdown margins and performance indices used in the selection of the LEU fuel assembly are essentially unchanged, when compared with those presented in Ref. 1.

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