Feasibility Study for LEU Conversion of the WWR-K Reactor at the Institute of Nuclear Physics in Kazakhstan Using a 5-Tube Fuel Assembly

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ABSTRACT

A feasibility study by the RERTR program for possible LEU conversion of the 6 MW WWR-K reactor concludes that conversion is feasible using an LEU 5-tube Russian fuel assembly design. This 5-tube design is one of several LEU fuel assembly designs being studied (Ref. 1) for possible use in this reactor. The 5-tube assembly contains 200 g ^{235}U with an enrichment of 19.7% in four cylindrical inner tubes and an outer hexagonal tube with the same external dimensions as the current HEU (36%) 5-tube fuel assembly, which contains 112.5 g ^{235}U. The fuel meat material, LEU UO_2-Al dispersion fuel with ~2.5 g U/cm^3, has been extensively irradiation tested in a number of reactors with uranium enrichments of 36% and 19.7%.

Since the ^{235}U loading of the LEU assemblies is much larger than the HEU assemblies, a smaller LEU core with five rows of fuel assemblies is possible (instead of six rows of fuel assemblies in the HEU core). This smaller LEU core would consume about 60% as many fuel assemblies per year as the current HEU core and provide thermal neutron fluxes in the inner irradiation channels that are ~17% larger than with the present HEU core. The current 21 day cycle length would be maintained and the average discharge burnup would be ~42%. Neutron fluxes in the five outer irradiation channels would be smaller in the LEU core unless these channels can be moved closer to the LEU fuel assemblies.

Results show that the smaller LEU core would meet the reactor's shutdown margin requirements and would have an adequate thermal-hydraulic safety margin to onset of nucleate boiling.

1.0 INTRODUCTION

The WWR-K reactor is a water-cooled and water-moderated research reactor operated by the Institute of Nuclear Physics for the National Nuclear Center of the Republic of Kazakhstan. Criticality was first achieved in 1967. The reactor was shutdown temporarily in 1988. After major seismic proofing and other nuclear safety up-grading, the reactor was restarted in 1998 and operates at 6 MW power level using HEU (36%) fuel.

Figure 1 shows a cross section of the WWR-K reactor. A total of 85 grid positions are available for mounting fuel assemblies. The current core uses WWR-TS fuel assemblies with 5-tubes and 3-tubes containing UAl_3-Al and UO_2-Al HEU fuel with 36% enriched uranium (Figure 2). The 3-tube assembly is the same as the 5-tube assembly except that the two inner most tubes are removed so that control rods or experiments can be inserted.

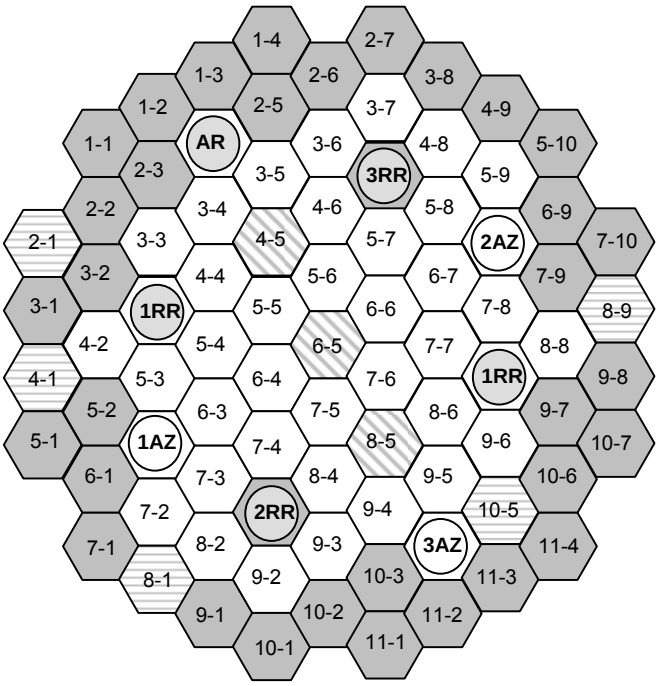


Figure 1. WWR-K Reactor Core with 85 Grid Positions and Labels Used for Fuel Assemblies, Control Rods, and Experiments

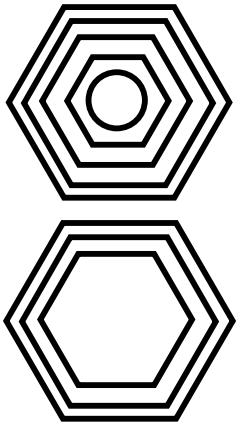


Figure 2. HEU WWR-TS 5-Tube and 3-Tube Fuel Assemblies

2.0 VALIDATION OF COMPUTATIONAL MODELS

Comparisons between calculated and measured data were done to validate the models and determine reactivity biases that need to be applied to calculated results. This section compares excess reactivity measurements for four WWR-K cores with calculated values using both uniform and heterogeneous axial distributions of the fuel meat. A comparison of measured and calculated control rod worths for a WWR-K core with 36 fresh fuel assemblies and 6 fresh control assemblies is also included.

2.1 Reactivity Comparisons between Measured and Calculated WWR-K Cores

For the excess reactivity comparisons, INP personnel related their understanding (Ref. 2) that the axial distribution of the fuel meat in the WWR-TS fuel tubes was not uniform in thickness, but could have an axial peak-to-average variation of as much as 1.3. Calculations of four WWR-K cores were done with both axially uniform and axially heterogeneous fuel meat (Table 1) to

Table 1. Impact of Axial Heterogeneity of the Fuel Meat on Reactor Excess Reactivity

Case	Configuration	Measured Excess Reactivity % Δk/k	Monte Carlo Calculation Using Uniform[1] Axial Fuel Meat, % Δk/k[3]	Monte Carlo Calculation UsingHeterogeneous[2] Axial Fuel Meat Thick., mm % Δk/k[3]
1	Critical Assembly, ρ (%)	0.00 (Critical)	- 0.64	+ 0.56
2	Fresh Core (36+6) FA All control rods out	5.09	+ 3.41	+ 4.44
3	Fresh Core (28+6) FA	1.62	+ 0.61	+ 1.61
4	Fresh Core (25+6) FA	0.00 (Critical)	- 1.99	- 0.92

[1] Fuel meat has a uniform thickness of 0.60 mm over its entire 60 cm axial height.
[2] Heterogeneous fuel meat thickness has five axial segments: Top 12 cm, 0.51 mm; 2nd 12 cm, 0.60 mm; Central 12 cm, 0.78 mm; 4th 12 cm, 0.60 cm; Bottom 12 cm, 0.51 mm The average thickness is 0.60 mm.
[3] Uncertainty in Monte Carlo calculated reactivities is less than 0.03 % Δk/k.

determine the reactivity effects that a variation of this type could have in the WWR-K reactor. The non-uniformity generally results in a reactivity increase of about 1 % Δ k/k.

2.2 Control Rod Worths versus Measurements

Measured and calculated control rod worths were compared for the fresh core with 36 fuel assemblies and 6 control fuel assemblies (Case 2 in Table 1). The results shown in Table 2 show good agreement between measured and calculated values.

Table 2. Comparison of Measured and Calculated Control Rod Worths for Core with 36 Fresh Fuel Assemblies and 6 Control Fuel Assemblies (Case 2 in Table 1).

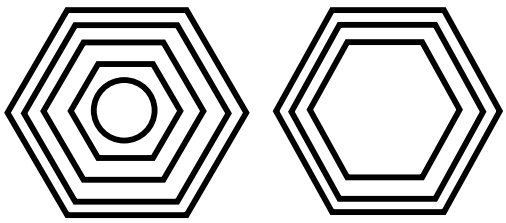
	Measured Reactivity[1] Worth, % Δk/k	Calculated Reactivity Worth, % Δk/k	Ratio of Calculated/Measured
Worth of Rods			
1 RR	2.26 ± 0.17	2.17 ± 0.02	0.96
2 RR	2.06 ± 0.15	1.83 ± 0.02	0.89
3 RR	1.96 ± 0.15	1.82 ± 0.02	0.93
AR	0.35 ± 0.03	0.34 ± 0.02	0.97
1 AZ	0.73 ± 0.05	0.81 ± 0.02	1.11
2 AZ	0.33 ± 0.02	0.36 ± 0.02	1.09
3 AZ	0.79 ± 0.06	0.82 ± 0.02	1.04
Replacement of FA with Water			
Position 5-9	0.53 ± 0.04	0.48 ± 0.02	0.91
Position 7-6	2.50 ± 0.19	2.71 ± 0.02	1.08
Position 6-6	2.11 ± 0.16	2.33 ± 0.02	1.10

[1] Measured reactivity values have an uncertainty of 5 to 10%. An uncertainty of 7.5% is shown in the table.

3.0 LEU CONVERSION FEASIBILITY STUDY

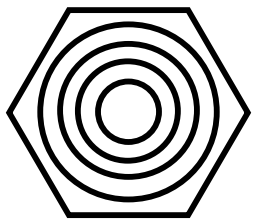
The study consists of two parts that characterize a complete evolution of HEU and LEU cores from fresh startup cores to equilibrium cores. The first part examines the initial startup of the reactor with fresh fuel loadings and then follows through the cycle-by-cycle operation of the reactor, adding fresh fuel assemblies until the desired core sizes are reached. After that, several fuel assemblies are discharged and fresh assemblies are loaded with a pre-determined shuffling pattern. This process will eventually lead to equilibrium cycles with repetitive shuffling patterns. The second part of the study investigates the performance of equilibrium cycles of HEU and LEU cores.

The LEU 5-tube FA that were studied here have the same outer hexagonal dimensions as the WWR-TS HEU FA, but all four interior tubes have a cylindrical shape (see Figure 3). Design parameters for the HEU and LEU fuel assemblies are shown in Table 3.



HEU WWR-TS 5-Tube and 3-Tube Fuel Assemblies

Figure 3.



LEU WWR-K 5-Tube Assembly

Table 3. Fuel Assembly Parameters for These WWR-K Reactor Conversion Studies

Fuel Type	HEU WWR-TS	HEU WWR-TS	LEU WWR-K
^{235}U Enrichment, wt-%	36.0	36.0	19.7
Number of Fuel Tubes in Assembly	3 / 5	5	5
^{235}U Loading per Assembly, g	85.0 / 112.5	111.8	200.3
Meat/Clad/Element Thickness, mm	0.6/0.85/2.3	0.6/0.85/2.3	1.0/0.75/2.5
Fuel Meat Length, mm	600	600	600
Fuel Meat Material	UAl_3-Al	UO_2-Al	UO_2-Al
Assembly Fuel Meat Volume, cm^3	196 / 260	260	402
Uranium Density in Meat, g/cm^3	1.12	1.20	2.53
Dispersant Fuel Density, g/cm^3	6.8	9.8	9.8
Dispersant Volume Fraction, %	22.1	13.8	29.3
Dispersant U Weight Fraction, %	74.6	88.1	88.1
Coolant Channel Thickness, mm	3	3	3
Fuel Assembly Pitch, mm	683	683	683
Number of Assemblies in Initial Core	6 / 18	19	32

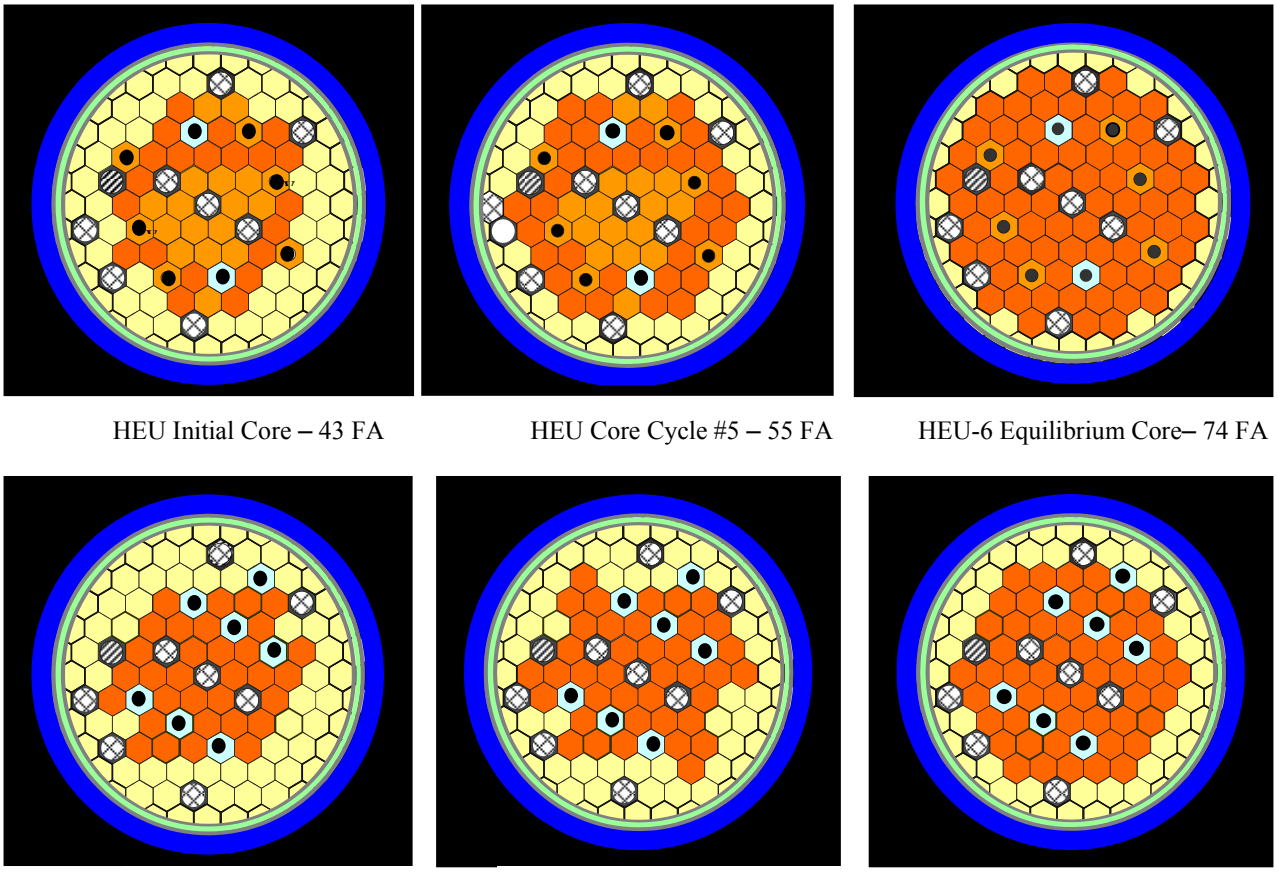
3.1 Initial Core and Subsequent Cores

The initial fresh HEU core consisted of 43 WWR-TS fuel assemblies (37 5-tube and 6 3-tube). The initial LEU core consisted of 32 WWR-K, 5-tube fuel assemblies shown in Figure 3. Horizontal cross sections of the initial fresh HEU and LEU cores, one of the subsequent cores, and the equilibrium cores are shown in Figure 4. Three inner irradiation channels are located near the center of the core and five outer irradiation channels are located on the core periphery. Neutron flux levels are compared in these locations.

To reach equilibrium cores, fuel assemblies were added in subsequent cycles to fill up Row #6 (85 core positions) for HEU-6 core and Row #5 (61 core positions) for the LEU-5 core. Equilibrium cores were reached after further fuel replacements. For consistency in the cycle-by-cycle analyses, both the HEU core and the LEU core were operated at 6 MW power for 14 days in cycle #1 and for 21 days in subsequent cycles until they reach desired core sizes, with 7 days shutdown time between cycles. Fuel assemblies were added for each cycle such that the reactivity (ρ) is within an acceptable range for operation ($\rho \sim 5\%\ \Delta k/k$ at beginning-of-cycle and $\rho \sim 1\%\ \Delta\ k/k$ at end-of-cycle).

<u>For HEU fuel</u>, the initial startup core consisted of 43 assemblies: six 3-tube control assemblies, eighteen 5-tube assemblies with HEU UAl_3-Al fuel meat, and nineteen 5-tube assemblies with HEU UO_2-Al fuel meat. Two of the 4 shim rods (1 RR in Figure 1) and the automatic regulating rod (AR) have aluminum followers and operate in water-filled guide tubes located inside assemblies with 3 fuel tubes. The other 2 shim rods (2RR and 3RR in Figure 1) also have aluminum followers, but operate inside water-filled aluminum guide tubes with the same outer dimensions as a fuel assembly. Three safety rods (AZ in Figure 1) without followers operate in

air-filled guide channels located inside fuel assemblies with 3 tubes. One air-filled channel is used for the neutron source. Cycle-by-cycle reactivity changes for the HEU core are shown in Table 4 and Figure 5. Eleven cycles are required to fill up the HEU core to row #6 with 74 FA.



HEU Initial Core – 43 FA HEU Core Cycle #5 – 55 FA HEU-6 Equilibrium Core– 74 FA

LEU Initial Core – 32 FA LEU Core Cycle #5 – 39 FA LEU-5 Equilibrium Core – 50 FA

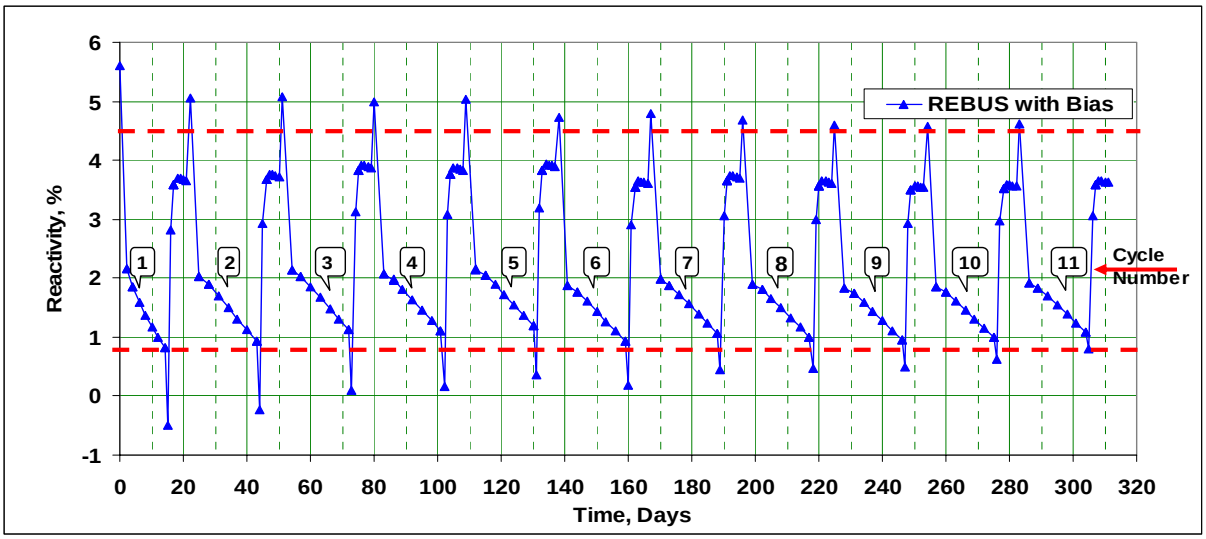
Figure 4. Initial HEU and LEU Cores, One Subsequent Core, and Equilibrium Cores

Table 4. HEU Core - Cycle by Cycle Data

Fuel Cycle	Calendar Days	Cumulative Power Output		Fuel Assembly		Reactivity, ρ % (with Bias +1.197%)[c]	
Number	Start / End	MWD	FPED	Added	Total	Start	End
1	0 / 14	84	14	Initial Core	43	5.611	0.821
2	21 / 42	210	35	9-7,2-5,3-2	46	5.061	1.121
3	49 / 70	336	56	6-9,5-2,10-3	49	5.082	1.123
4	77 / 98	462	77	10-6,2-6,6-1	52	4.991	1.099
5[a]	105 / 126	588	98	2-2,10-2,10-5	55	3.836	1.194
6	133 / 154	714	119	10-7,1-1,9-1	58	4.726	0.930
7	161 / 182	840	140	5-10,1-3,11-1,11-2	62	4.790	1.065
8	189 / 210	966	161	3-8,5-1,11-4	65	4.681	1.003
9	217 / 238	1092	182	9-8,1-4,7-1	68	4.588	0.954
10	245 / 266	1218	203	2-7,1-2,11-3	71	4.584	0.999
11[b]	273 / 294	1344	224	7-10,3-1,10-1	74	3.422	1.088

(a) Filled up Row #5; (b) Filled up Row#6; (c) Bias based on measured result for Case 2 in Table 1 and REBUS calculted result.

Figure 5. WWR-K Cycle-by-Cycle Reactivity Changes - **HEU (36%)** Core Filled up to Row #6



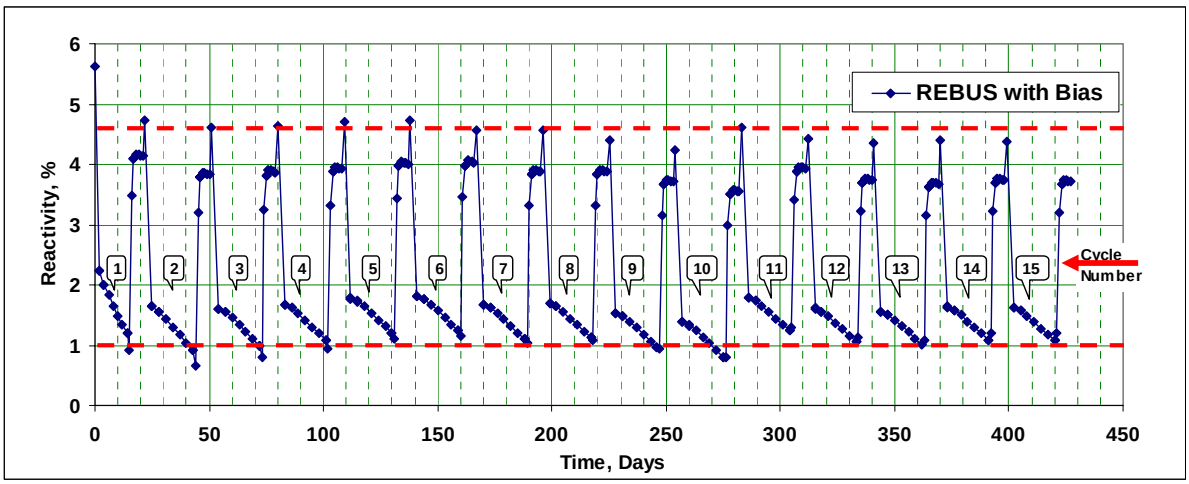
For LEU fuel, the initial startup core consists of 32 5-tube fuel assemblies with LEU UO_2-Al fuel meat. The LEU core has a total of 7 control rods (4 shim rods, 2 safety rods, and an automatic regulating rod). All of these rods have aluminum followers (Ref. 2) and operate inside water-filled aluminum guides with the same outer dimensions as a fuel assembly (similar to 2RR and 3RR rods in the HEU core). Cycle-by-cycle reactivity changes for the LEU core are shown in Table 5 and Figure 6. The same air-filled channel used for the neutron source in the HEU core is used for this purpose in the LEU core. Fifteen cycles are required to fill up the LEU core to row #5 with 50 fuel assemblies. If desired, additional fuel assemblies can be added to fill up row #6.

Table 5. LEU Core - Cycle by Cycle Data

Fuel Cycle	Calendar Days	Cumulative Power Output		Fuel Assembly		Reactivity, ρ % (with Bias -0.14%)[b]	
Number	Start / End	MWD	FPED	Added	Total	Start	End
1	0 / 14	84	14	Initial Core	32	5.619	1.210
2	21 / 42	210	35	8-8	33	4.737	0.926
3	49 / 70	336	56	10-6,2-2	35	4.602	0.998
4	77 / 98	462	77	2-5,10-2	37	4.638	1.083
5	105 / 126	588	98	2-6,10-3	39	4.712	1.203
6	133 / 154	714	119	10-5	40	4.733	1.242
7	161 / 182	840	140	2-4	41	4.572	1.103
8	189 / 210	966	161	10-4	42	4.575	1.118
9	217 / 238	1092	182	5-9	43	4.402	0.962
10	245 / 266	1218	203	4-2	44	4.237	0.810
11	273 / 294	1344	224	4-8,6-1	46	4.610	1.237
12	301 / 322	1470	245	7-2	47	4.418	1.059
13	329 / 350	1596	266	3-7	48	4.352	1.005
14	357 / 378	1722	287	8-2	49	4.410	1.086
15[a]	385 / 406	1848	308	9-2	50	4.381	1.072

(a) Filled up Row #5. (b) Bias based on calculated reactivity difference between MCNP and REBUS results for initial LEU core.

Figure 6. WWR-K Cycle-by-Cycle Reactivity Changes - **LEU (19.7%) Core** Filled up to Row #5



3.2 Fast and Thermal Neutron Flux Comparisons

Fast and thermal neutron flux levels computed with the MCNP Monte Carlo code at the 3 inner and 5 outer irradiation channels are shown in Figures 7 and 8, respectively, for the first 10 operational cycles of the HEU and the LEU cores. Fluxes are normalized to HEU core BOC #1 thermal fluxes averaged over the 3 inner channels and separately over the 5 outer channels.

Figure 7. Comparison of Flux for 3 Inner Irradiation Positions in HEU and LEU Core

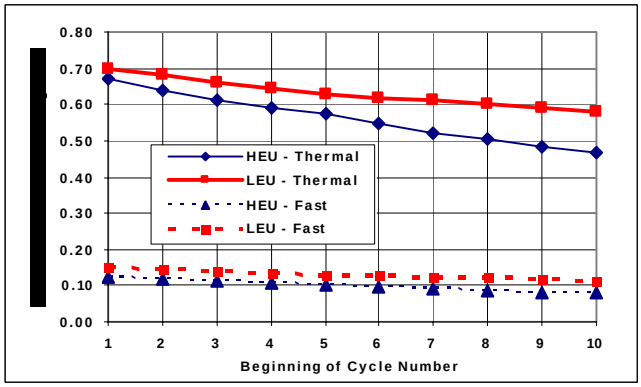


Figure 8. Comparison of Flux for 5 Outer Irradiation Positions in HEU and LEU Core

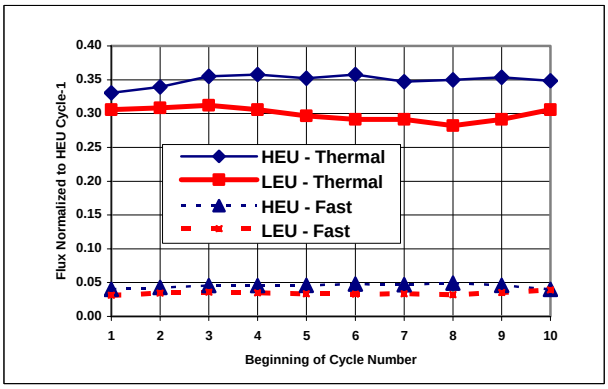
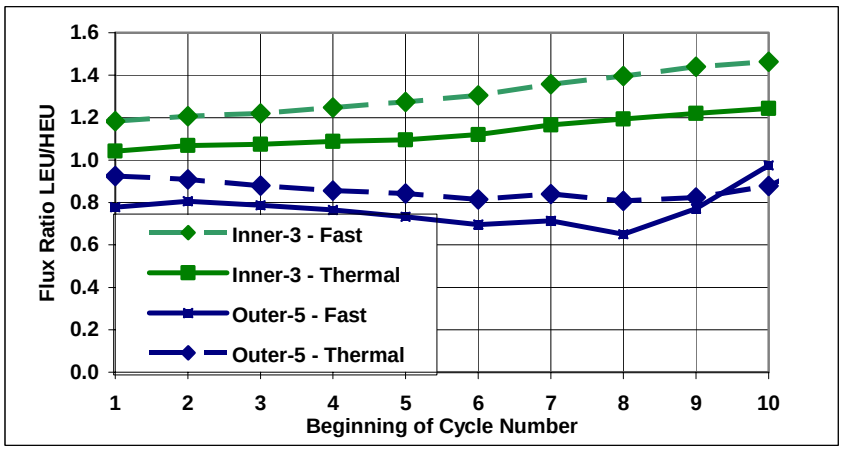


Figure 9. Relative Flux Performance in Irradiation Positions for HEU and LEU Core



The relative flux performance between HEU and LEU cores is shown in Figure 9, where the cycle-by-cycle LEU/HEU flux ratios for the 3 inner positions and 5 outer positions are shown. For the three inner positions, the LEU/HEU thermal flux ratio starts at slightly larger than 1.0 in Cycle 1 and increases steadily to more than 1.2 in Cycle 10. The LEU/HEU fast flux ratio increased from 1.2 in Cycle 1 to about 1.5 in Cycle 10. In the 5 outer positions, the LEU/HEU thermal flux ratio is about 0.9 in Cycle 1, decreases to about 0.8 in Cycle 6 and increases to about 0.9 in Cycle 10. The corresponding fast flux ratio starts at 0.8 in Cycle 1, decreases to a minimum of about 0.65 in Cycle 8, and increases to about 1.0 in Cycle 10. LEU fluxes in the outer irradiation channels are reduced because these channels are located further from the LEU fuel. LEU fluxes can be increased by moving the irradiation positions inside the core.

3.3 Shutdown Margins And Control Rod Worths

WWR-K shutdown margin criteria state that the reactor must be subcritical at all times by at least 1 % Δ k/k with all shim rods and the automatic control rod fully inserted (Ref. 2). Monte Carlo calculations using the MCNP code (Ref. 3) with fuel loading compositions determined using the REBUS diffusion theory burnup code (Ref. 4) were performed for the fresh HEU and LEU cores and also for two larger burned cores at the beginning of the operating cycle without xenon to show that this shutdown margin criteria is satisfied.

3.3.1 WWR-K HEU Core

Shutdown margins and control rod worths for the HEU cores are shown in Table 6. The bias between all results calculated with MCNP and measured results is 1.68% Δk/k. The results show that the shutdown margin criteria is satisfied for the fresh HEU core with 43 WWR-TS fuel assemblies and for the Cycle 4 and Cycle 11 cores. Shutdown margins are larger in the larger cores with burned fuel.

3.3.2 WWR-K LEU Core

Shutdown margins and control rod worths for the LEU cores are shown in Table 7. The results show that the shutdown margin criteria is satisfied for the fresh LEU core with 32 WWR-K type fuel assemblies and for the Cycle 4 and Cycle 10 cores. Shutdown margins are larger in the larger cores with burned fuel.

3.4 Equilibrium Cycles

Equilibrium fuel cycle calculations were performed for WWR-K cores with six rows of HEU fuel assemblies (HEU-6) and five rows of LEU fuel assemblies (LEU-5). All fuel management was based on an outer-core-to-inner-core fuel shuffling scheme. Cycle lengths were chosen so that the HEU and LEU cores each had an excess reactivity of ~1% Δk/k at EOEC. Configurations of the HEU-6 and LEU-5 equilibrium cores are shown in Figure 4.

For the **HEU-6** case, three fresh WWR-TS 5-tube fuel assemblies are loaded at outer core locations (row #6) at the beginning-of-equilibrium cycle (BOEC) and three spent fuel assemblies are removed from the center of the core (row #2) at the end-of-equilibrium cycle (EOEC). These three discharged fuel assemblies had been in the core for 22, 23 and 23 burn cycles, respectively.

Table 6. **WWR-K HEU Core**. Shutdown Margins and Control Rod Worths for Initial Core with 43 Fresh Fuel Assemblies, Cycle 4 Core with 52 Fuel Assemblies, and Cycle 11 Core with 74 Fuel Assemblies.

Control Rod Configuration	Calculated Reactivity No Bias % Δk/k	Calculated Reactivity With Bias[2] % Δk/k	Control Rod Reactivity Worth % Δk/k
HEU Core with 43 Fresh Fuel Assemblies			
All Rods Out	3.92	5.60	-
All Shim Rods and Auto Rod Inserted[1]	- 3.05	- 1.37	- 1.37 (Shutdown Margin)
All Safety (AZ) Rods Inserted	1.64	3.32	- 2.28
1 AZ Rod Inserted	3.19	4.87	- 0.73
2 AZ Rods Inserted	3.57	5.25	- 0.35
3 AZ Rods Inserted	2.95	4.63	- 0.97
HEU Cycle 4 Core; BOC, 52 FA			
All Rods Out	3.35	5.03	-
All Shim Rods and Auto Rod Inserted[1]	- 4.05	- 2.37	- 2.37 (Shutdown Margin)
All Safety (AZ) Rods Inserted	0.70	2.38	- 2.65
1 AZ Rod Inserted	2.43	4.11	- 0.92
2 AZ Rods Inserted	2.90	4.58	-0.45
3 AZ Rods Inserted	2.33	4.01	- 1.02
HEU Cycle 11 Core; BOC, 74 FA			
All Rods Out	2.88	4.56	-
All Shim Rods and Auto Rod Inserted[1]	- 4.46	- 2.78	- 2.78 (Shutdown Margin)
All Safety (AZ) Rods Inserted	- 0.15	1.53	- 3.03
1 AZ Rod Inserted	1.97	3.65	- 0.91
2 AZ Rods Inserted	2.01	3.69	- 0.87
3 AZ Rods Inserted	1.94	3.62	- 0.94

[1] Shim Rods are 1RR, 2RR, 3RR. Automatic Rod is AR
[2] Bias between MCNP results and measured results for HEU core with 42 fresh fuel assemblies (see Table 1, Case 2)

Table 7. **WWR-K LEU Core**. Shutdown Margins and Control Rod Worths for Initial Core with 32 Fresh Fuel Assemblies, Cycle 4 Core with 37 Fuel Assemblies, and Cycle 10 Core with 44 Fuel Assemblies.

Control Rod Configuration	Calculated Reactivity No Bias, % Δk/k	Control Rod Reactivity Worth, % Δk/k
LEU Core with 32 Fresh Fuel Assemblies		
All Rods Out	5.63	-
All Shim Rods and Auto Rod Inserted[1]	- 1.67	- 1.67 (Shutdown Margin)
All Safety (AZ) Rods Inserted	- 0.37	- 6.00
1 AZ Rod Inserted	2.98	- 2.65
2 AZ Rods Inserted	3.00	- 2.63
LEU Cycle 4 Core; BOC, 37 FA		
All Rods Out	4.78	-
All Shim Rods Inserted[1]	- 2.98	- 2.98 (Shutdown Margin)
All Safety (AZ) Rods Inserted	- 0.90	- 5.68
1 AZ Rod Inserted	2.44	- 2.34
2 AZ Rods Inserted	2.13	- 2.65
LEU Cycle 10 Core; BOC, 44 FA		
All Rods Out	4.43	-
All Shim Rods and Auto Rod Inserted[1]	- 3.52	- 3.52 (Shutdown Margin)
All Safety (AZ) Rods Inserted	- 0.73	- 5.16
1 AZ Rod Inserted	2.31	- 2.12
2 AZ Rods Inserted	1.95	- 2.48

[1] Shim Rods are 1RR, 2RR, 3RR.

Also, one fresh 3-tube fuel assembly with an air-filled guide tube and one fresh 3-tube fuel assembly with a water-filled guide tube are loaded at two control rod positions. Each remains for 8 cycles and moves to next position for 8 more cycles. After 24 cycles, each becomes a spent fuel assembly and will be discharged from the last position at EOEC. Key performance parameters are shown in Table 8.

For the **LEU-5** case, two fresh WWR-K 5-tube fuel assemblies are loaded at outer core locations (row #5) at BOEC and two spent fuel assemblies are discharged from the center of the core (row #2) at EOEC. Both discharged fuel assemblies had been in the core for 25 burn cycles.

The **LEU-5** core would have a fuel cycle length of 23 days with 2 fuel shuffling paths. The reactivity changes from 2.10% at BOEC to 1.26% at EOEC with -0.14% bias applied. The discharge ^{235}U burnup is 42% and the fuel consumption would be 20.9 assemblies per year, assuming the same 1440 MWD/year operation. Due to the smaller LEU-5 core size, quite significant improvement (~17%) over the HEU-6 core thermal flux and ~34% fast flux is observed in the inner 3 irradiation channels. The thermal flux levels in the 5 outer irradiation channels are lower by ~ 6% and the fast flux is lower by ~ 15% in LEU-5 core compared to the HEU-6 core. This is expected because the 5 outer irradiation channels in LEU-5 core are located further from the fuel assemblies than in the HEU-6 core. Again, flux performance in the outer irradiation channels of the LEU core can be improved significantly by moving them closer to the core. Key performance parameters are compared with those for the HEU core in Table 8.

Table 8. Comparison of WWR-K Reactor Equilibrium Cores With HEU (36%) Fuel and LEU (19.9%) Fuel

REBUS3 Case	Cycle, Days	Reactivity, % BOEC	Reactivity, % EOEC	Burnup, % ^{235}U	Consumption, FA/Yr[3]	Irradiation Channel	Flux Ratio to HEU-6 Case Thermal	Flux Ratio to HEU-6 Case Fast
HEU-6 WWR-TS	20	2.009[1]	0.951[1]	42	37 (36+1)	Inner-3 Outer-5	1.00 1.00	1.00 1.00
LEU-5 WWR-K	23	2.103[2]	1.263[2]	42	20.9	Inner-3 Outer-5	1.17 0.94[4]	1.34 0.85[4]

[1] The reactivity bias between REBUS results and experiment for a core with 42 FA was 1.197 % Δ k/k.
[2] With – 0.14% MCNP bias
[3] Annual fuel consumption is based on 1,440 MWD/Yr (6 MW x 20-Day/Cycle * 12 Cycles/Year) Operation
[4] The LEU/HEU fast and thermal flux ratios of 0.94 and 0.85 result from the position of the outer experiments in Row #6 of a core with only five rows of fuel. Repositioning the experiments would improve the flux performance considerably, but annual fuel consumption would also increase.

3.5 Thermal Hydraulic Safety Margins

One of the fundamental safety criteria for Russian-designed research reactors is that there can be no boiling of the cooling water at the maximum power level allowed for operation. To ensure that this criterion is met, Russian-designed research reactors are generally required to have a minimum margin to onset of nucleate boiling (ONB) of 1.4 based on the Forster-Greif ONB correlation. The PLTEMP code (Ref. 5) was used for determination of the minimum margin to ONB. Detailed power densities with radially and axially segmented fuel tubes were calculated using the MCNP code for both cores with the shim rods inserted to obtain a critical core.

3.5.1 WWR-K LEU Core with 32 Fresh Fuel Assemblies

The thermal-hydraulic safety margin to ONB was calculated for the fresh LEU core with 32 WWR-K fuel assemblies using ANL's PLTEMP code and input data provided by INP for water velocities in individual coolant channels. The basic data that were used in these calculations (inlet pressure, core pressure drop, inlet temperature, and water velocity in the six coolant channels) are shown in Table 9. The results indicate that the margin to ONB based on the Forster Greif correlation is about 1.46, which is larger than the value of 1.4 that is traditionally required for Russian-supplied research reactors. The maximum wall temperature was calculated to be 100 C and the maximum heat flux was 718 kW/m^2.

Table 9. Thermal-Hydraulic Data Used in Calculations for the LEU Core with Fresh Fuel (Data provided by the Kazakhstan Institute of Nuclear Physics)

Parameter	WWR-K
Core pressure drop, cm. w. m.	150
Water velocity, m/s -- average in 2nd. gap -- in gaps 1, 3, 4, 5, and 6	 2.46 2.09
Inlet pressure, bar	1.35
Inlet temperature, °C	45

4.0 CONCLUSIONS

The ^{235}U content of the 5-tube LEU fuel assemblies that were studied is considerably larger than in the HEU assemblies (200 g ^{235}U per 5-tube LEU FA versus 112.5 g ^{235}U per 5-tube HEU FA). This would allow the initial and subsequent LEU cores to be smaller than the corresponding HEU cores and would result in significantly larger (5% - 25%, depending on the core) thermal neutron fluxes in the three inner irradiation channels of the LEU cores. The larger ^{235}U content of the LEU fuel assemblies would also result in annual consumption of 21 LEU fuel assemblies instead of 37 HEU fuel assemblies when operated in equilibrium mode.

In these calculations, neutron fluxes in the five outer irradiation channels were smaller in the LEU cores because these channels were located further from the fuel in the LEU cores than in the HEU cores. However, if the outer irradiation positions can be moved to more advantageous locations, the thermal and fast neutron fluxes are expect to be larger in the LEU cores than in the corresponding HEU cores. Annual fuel consumption would increase if LEU fuel assemblies were displaced. Specific results are described in the paragraphs below.

Initial and Cycle-by-Cycle Cores

- The thermal neutron flux in the three inner irradiation positions starts at ~ 5% larger in the initial fresh LEU core and increases steadily to about 25% larger in the Cycle 10 LEU core (71 FA in the HEU core and 44 FA in the LEU core). The corresponding fast neutron flux is about 20% larger in the Cycle 1 LEU core and about 45% larger in Cycle 10 LEU core.
- Thermal neutron fluxes in the five outer irradiation channels of the LEU cores are 80-90% of those in the HEU cores because these outer irradiation channels are located farther from the LEU fuel than the HEU fuel. If the outer irradiation channels can be relocated closer to LEU fuel assemblies in smaller LEU cores, we expect that larger thermal and fast neutron fluxes

can be achieved in LEU cores than in HEU cores. The trade-off is that additional LEU fuel assemblies would be used per year if LEU fuel positions are replaced by experiment positions. These trade-offs need to be studied in more detail for optimization purposes.

Equilibrium Cores

- When the equilibrium cores are reached, the thermal neutron flux in the three inner irradiation positions will be larger by ~ 17% in the LEU-5 core with five rows of fuel. The corresponding fast neutron flux would by larger by ~ 34%. Annually, the LEU-5 core would consume ~21 fuel assemblies to achieve 1440 MWD of operation, while the HEU-6 core with six row of fuel would consume ~37 fuel assemblies.

- Shutdown margins: WWR-K shutdown margin criterion are satisfied for the HEU and LEU cores that were studied. This criterion states that the reactor must be subcritical at all times by at least 1 % $\Delta k/k$ with all shim rods and the automatic control rod fully inserted.

- Thermal-hydraulic safety margins: For the LEU core, the thermal-hydraulic safety margin to ONB was calculated for the fresh LEU core with 32 WWR-K fuel assemblies using ANL's PLTEMP code and input data provided by INP. The results indicate that the margin to ONB based on the Forster-Greif correlation is about 1.46, which is larger than the value of 1.4 that is traditionally required for Russian-supplied research reactors. The maximum wall temperature was calculated to be 100 C and the maximum heat flux was 718 kW/m^2.

Overall, the 5-tube LEU fuel assembly studied in this paper is a conservative, attractive candidate for conversion of the WWR-K reactor if this fuel assembly is licensed for commercial production in Russia.

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