ANALYSES OF THE IRT, SOFIA INITIAL LEU CORE PERFORMANCE

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ABSTRACT

The initial LEU (IRT-4M fuel assemblies, 19.75% ^{235}U) core of the new IRT-Sofia research reactor of the Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Science, Sofia, Bulgaria is jointly analyzed with the RERTR Program at Argonne National Laboratory (ANL) to evaluate its performance and other important characteristics for safety analyses. The initial configuration using 16 fuel assemblies (four 8-tube and twelve 6-tube fuel assemblies) detailed power distributions and beam tubes flux performance for two critical core states corresponding to different control rods positioning, and different performance characteristics are compared. Results of calculations for two configurations at the beginning of the second operation cycle using 17 fuel assemblies (sixteen burned fuel assemblies (FA) and one fresh 6-tube FA) are presented. The results provide important and useful information for safety analyses and performance of the future reactor operation.

1. Introduction

A joint study concerning IRT, Sofia research reactor (RR) between INRNE and the RERTR Program at ANL was initiated in 2002. The initial purpose was to study the possibility of using LEU fuel instead of HEU fuel in the planned new 200 kW IRT, Sofia RR [1]. The joint work was started from definition of common calculational models, and was followed with comparison of the fuel lifetime and flux performance [2]. It was concluded that the LEU core performance (both in terms of fluxes for the experiments and in fuel consumption) is similar to the HEU reference core. Thus, the IRT-4M LEU fuel assemblies were accepted as suitable for conversion of IRT, Sofia RR. After that the initial configuration for the LEU core loading was selected (in close collaboration with scientists from RRC "Kurchatov Institute", Russian Federation) and the results of calculations that are needed for modification of the Safety Analyses Report in connection with the fuel conversion were obtained [3]. Presented here are results of further analyses significant for safety assessment of the LEU core including comparison of flux performance and detailed power distribution for two critical states of the core corresponding to different RR applications. Flux performance is important for assessment of RR application capabilities and detailed power distribution is needed for thermal hydraulic safety evaluations. The results of calculations describing two different variants of the first core reloading are also presented

2. Comparison of two critical states for the initial core

The initial core configuration is presented in Figure 1. This core includes 16 IRT-4M fuel assemblies: twelve 6-tube FA, and four 8-tube FA (in positions A2 – A5). There are totally 54 cells (7.15x7.15cm) in the frames of the reactor vessel. Figure 1 shows positions and numbers

of the experimental channels (horizontal and vertical (EC)), channels for ionizing chambers (IC), and the shim (KO), safety (AZ) and auto regulating (AR) rods.

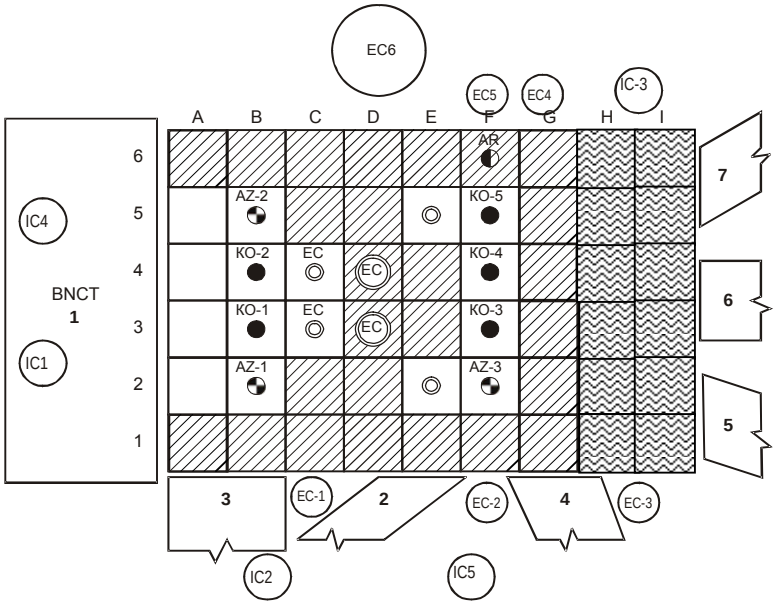

Figure 1. Initial configuration

The results of comparison of the flux performance for two critical states of the configuration are presented in Table 1.

Table 1. IRT, Sofia Beam Performance Comparison: Second critical state (CS2) to First critical state (CS1)

Channel No.	Energy range	(“CS2”/”CS1”-1)*100, %
1 in front of the filters	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+40.** **+44.** **+46.**
2	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**-10.** **-19.** **-20.**
3	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+11.** **+15.** **+15.**
4	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**-33.** **-32.** **-32.**
5	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**-40.** **-39.** **-39.**
6	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**-41.** **-41.** **-40.**
7	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**-40.** **-40.** **-39.**

The first critical state (CS1) of the core that is preferable for operation with horizontal channels No. 2, 4 -7 is realized according to previous [3] calculations (excess reactivity equal to 0.07% Δk/k) when the shim rods are inserted as follows: KO-1=KO-2=65.0cm; KO-3=KO-4=18.8cm; AR=41.5cm, and all other rods are fully-withdrawn. The second critical state (CS2) analyzed is preferable for operation with BNCT channel No.1 and is realized according to calculations (excess reactivity equal to 0.01% Δk/k) when the shim rods are inserted as follows: KO-1=KO-2=38.1cm; KO-3=KO-4=65.0cm; AR=41.5cm, and again all other rods are fully-withdrawn. The mentioned advantages for channels performance peculiar to corresponding critical states are clearly demonstrated in Table 1. The shim rods control allows to vary flux performance by 40 %.

Since analyzed critical states are achieved for the different control rods (CR) positions every critical state has its own power distributions over the core. The detailed power distributions were calculated by the MCNP code [4] for both critical states. For tallying of the power at different space locations the meat region of every tube of every fuel assembly was segmented axially by fifteen equal intervals and every axial segment was divided into eight segments corresponding to round corners and flat sides of the tubes horizontal cross section. That segmentation allows to obtain three dimensional power distribution in the core for every FA. The detailed core power distribution was calculated for the case when all control rods were withdrawn as well. For this case the power distribution was calculated by the REBUS [5] code too. In REBUS calculation tube by tube power distribution was obtained for twelve equal axial segments of every FA as well as peaking power values for every segment (for space mesh resolution). The REBUS code is applied for burn up core calculation with multi-group cross section library prepared by the WIMS [6]. There are more approximations in the REBUS calculation than in the MCNP. The REBUS results comparison with those obtained with MCNP are important for assessment if the approximations are appropriate for power density calculations. The comparison of axial power distribution for the peak FA's in positions (E2, C3, C4) is shown in Figure 2. The results for total power per FA are presented in Table 2.

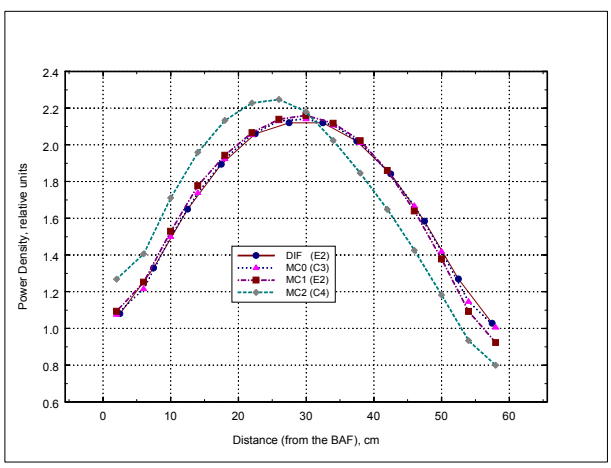

Figure 2. Comparison of axial power distribution calculated by the REBUS (DIF) and MCNP (MC0 – all CRs withdrawn, MC1 – CS1, MC2 – CS2; BAF – bottom of the active fuel)

Table 2. Comparison of the REBUS (DIF) results with the MCNP (MC) results
(DIF, MC0 – all CRs withdrawn, MC1 – CS1, MC2 – CS2)

Position	Power, %				Power Peaking Factor				Peak Power Density, W/cm^3			
	DIF	MC0	MC1	MC2	DIF	MC0	MC1	MC2	DIF	MC0	MC1	MC2
F2	5.59	5.37	6.91	4.56	1.72	1.58	1.60	1.69	37.5	33.0	43.0	29.9
F3	6.61	6.49	7.87	5.93	2.31	1.97	2.03	1.90	59.4	49.6	62.1	43.9
F4	6.58	6.50	7.78	5.95	2.32	1.98	2.04	1.91	59.4	50.1	61.8	44.3
F5	5.58	5.46	6.46	4.25	1.76	1.61	1.63	1.83	38.2	34.1	40.9	30.2
E2	**8.22**	8.08	**9.76**	7.90	**2.60**	2.36	**2.28**	2.53	**82.9**	74.1	**86.6**	77.7
E5	8.19	8.19	9.53	7.75	2.60	2.35	2.32	2.53	82.7	74.7	86.1	76.2
C3	9.20	**9.21**	8.99	10.3	2.31	**2.12**	2.29	2.11	82.7	**75.9**	80.2	84.6
C4	9.15	9.25	8.99	**10.3**	2.31	2.09	2.29	**2.16**	82.2	75.2	80.2	**86.6**
B2	6.26	6.23	5.67	7.22	2.29	2.11	2.27	2.15	55.6	51.1	49.9	60.4
B3	5.83	5.80	3.86	4.20	1.57	1.62	2.13	2.54	35.5	36.5	32.0	41.4
B4	5.83	5.83	3.87	4.14	1.57	1.63	2.13	2.55	35.6	37.0	32.0	41.1
B5	6.27	6.37	5.76	7.35	2.29	2.10	2.27	2.14	55.9	52.1	50.8	61.2
A2	4.07	4.16	3.68	4.95	2.18	1.98	2.07	2.10	30.3	28.1	25.9	35.5
A3	4.28	4.40	3.56	5.07	1.66	1.79	1.65	1.89	24.2	26.9	20.0	32.7
A4	4.28	4.42	3.57	5.09	1.66	1.76	1.65	1.87	24.2	26.6	20.1	325
A5	4.07	4.26	3.76	5.06	2.18	2.00	2.06	2.02	30.3	29.0	26.4	34.9

The comparison of axial power distribution for the FA's in positions (E2, C3, C4) where the greatest peak power density is achieved is shown in Figure 2. The results presented in Table 2 show that: 1) The REBUS and the MCNP results for power distribution by FA do not differ significantly as the greatest difference is at the core periphery (about 4.5% at A5 position); 2) The FAs with the highest power level are located in C(3,4) and E(2,5) positions for all core states analyzed; 3) The axial power distribution in the FAs with the peak power density for the cases when all CRs are withdrawn and CS1 is rather close. For the CS2 case - about 10% difference is observed in comparison with power axial distribution for other cases. These power distribution results are used for thermal hydraulics safety analysis. MCNP power distributions will generally be used; however, when not available REBUS power distributions will be used and these differences discussed above will be taken into account.

3. Comparison of alternative first reloading configurations

According to our previous evaluations [3] the time period of the first cycle for the selected initial core configuration could be about four years at 200 kW power level. This lifetime evaluation corresponds to continuous operation. The core will operate for a much longer time if a realistic duty factor would be taken into account. The maximum planed duty factor value is about 0.3. Our previous results [2] showed that to achieve an acceptable burn-up level for the discharged fuel for initial core configuration, five cycles are needed. At the beginning of these cycles (BOC) no FAs are discharged from the core but fresh FAs are added into the core replacing beryllium blocks. Here we present the results of the MCNP and REBUS calculation for the first reloading of the IRT, Sofia. Two alternative second cycle configurations (**a** and **b)** that were analyzed are presented in Figure 3.

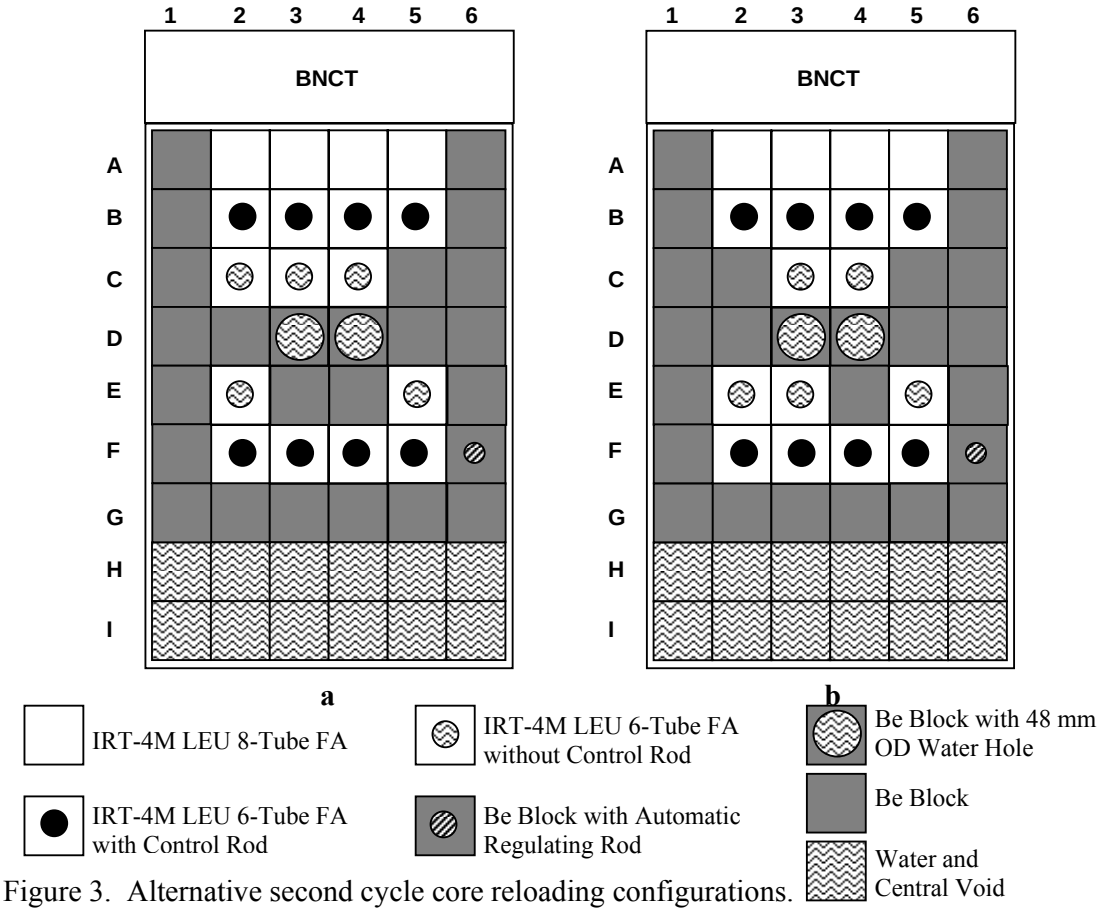

Figure 3. Alternative second cycle core reloading configurations.

The configuration **a** provides better flux performance for BNCT whereas configuration **b** provides better performance for channels No. 5 – 7. The second cycle was started with one additional 6-tube LEU IRT-4M fuel assemblies without a central control rod for both configurations. The core size was increased because sufficient burn-up had not been reached to consider discharge of any FA. The fresh fuel was loaded into locations C2 for configuration **a**, and E3 for configuration **b** without discharging or shuffling any fuel from end of cycle one (EOC-1). The REBUS fuel depletion chains accounted for during the first burn-up cycle included production of six Pu isotopes, Am-241, Np-237, and lumped fission product. Isotopic precursors of Xe-135 and Sm-149 were also included in the depletion chains so that Xe and Sm transients during periods of shutdown and startup could be modeled. Each fuel assembly was modeled using five equal volume axial depletion zones in REBUS.

The shutdown margin was calculated before startup of cycle 2 in the most reactive condition during the cycle after loading the two fresh FA and with saturated Sm-149 and no Xe-135 in the partially depleted fuel. The shutdown margin was calculated for a cold core condition, and assumes that all safety rods, the regulating rod and the most reactive shim rod (KO–1) are fully withdrawn, and all other four shim rods are fully inserted. The shutdown margin criterion is that the core should be at least 1% $\Delta k/k$ subcritical under these conditions. Shutdown margin was calculated for both second cycle cores at the beginning of the cycle using MCNP. The results are presented in Table 3, where it could be seen that the criterion is met for both second cycle core configurations.

The asymmetric core extension with only one FA (in position C2 instead C2 and C5 for **a** configuration, and in position E3 instead E3 and E4 for **b** configuration) was needed because the shutdown margin requirement would not be satisfied with the addition of two fuel assemblies to the EOC-1 in both cases.

The k-eff value before startup of the second cycle for both configurations was calculated using REBUS and MCNP (Table 3). Both codes results are in a satisfactory good agreement that demonstrates acceptability of approximations used in REBUS calculation. The excess reactivity for configuration **b** (equal to 4.47%) is higher than for **a** configuration (excess reactivity equal to 3.76%).

Table 3. IRT, Sofia: Summary of Criticality and Shutdown Margin Results

	Configuration **a**		Configuration **b**	
	CR OUT k-eff	Shutdown Margin, %	CR OUT k-eff	Shutdown Margin,%
BOL[1]				
MCNP	1.05626 ± .00014	–1.13	1.05626 ± .00014	–1.13
REBUS	1.05565		1.05565	
Δρ (M-R)	0.05%		0.05%	
BOC # 2				
MCNP	1.03903 ± .00014	–2.12	1.04674 ± .00013	–2.36
REBUS	1.03895		1.04722	
Δρ (M-R)	+0.01%		–0.04%	

[1] BOL is the same for both configurations.

The preliminary flux performance comparison between the analyzed configurations is shown in Table 4. These flux performance related differences were calculated at the BOC conditions with the control rods withdrawn, and with saturated ^{149}Sm and no ^{135}Xe, and the uncertainty in the Monte Carlo results was less than 0.5% for the thermal fluxes and less than 1.5% for the fast fluxes. As expected configuration **a** is better for the BNCT channel and channel 3, and configuration **b** is better for the other horizontal channels.

Table 4. IRT, Sofia Performance Comparison:
Configuration **b** to Configuration **a** Ratio of k_{eff} x Flux
ρ_a=3.76%, ρ_b=4.47%

Channel No.	Energy range	(**b**/**a**-1)*100, %
1 in front of the filters	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**–6.5** **–7.5** **–7.7**
2	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**–0.1** **–4.9** **+0.2**
3	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**–9.7** **–21.** **–24.**
4	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+9.7** **+10.** **+9.3**
5	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+13.** **+15.** **+15.**
6	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+13.** **+14.** **+15.**
7	E<6.25e-7 MeV 6.25e-7<E<8.21e-1 MeV E>8.21e-1 MeV	**+13.** **+14.** **+14.**

3. Conclusions

The results of this study provide important and useful information for safety analyses and planning of future reactor operation.
The comparative study for two critical core states of the initial core shows that:

- The shim rods control allows significant variation of flux performance – about 40%.
- The axial power distribution at the "hottest" fuel assembly varies within about 10% between the analyzed critical states.
- The differences for power generated in each FA as calculated by REBUS and MCNP does not exceed 5% for the core with all control rods withdrawn.

The power distribution results are used for thermal hydraulic core analysis. Separate thermal hydraulic analysis for every critical state could be needed for the safety analysis. Whenever feasible MCNP will be used, but REBUS power distributions accounting for differences with the more appropriate MCNP distributions could also be used.
A good consistency between REBUS and MCNP results substantiate credibility of the REBUS approach and gives confidence in the REBUS results.
The comparative study for two alternative initial core reloading shows that:

- Both configurations meet safety margin requirements.
- The configuration **a** has advantage for BNCT channel performance in comparison with configuration **b**.

Additional calculations of critical states for the second cycle are needed for final evaluation of the core flux performance properties.

Application of only one fuel assembly in core extension at the second cycle was needed because the shutdown margin requirement would not be satisfied with the addition of two fuel assemblies to the EOC-1 (as it was done for HEU fuel sequence at the beginning of the cycle 3 in previous analysis [2]).
Generally it could be stated that progress has been made in the study of the IRT, Sofia LEU core performance.

4. References

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