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EXPERIMENTAL AND COMPUTATIONAL STUDY OF POWER DISTRIBUTION FLATTENING IN A REACTOR OF GT-MHR TYPE AT “ASTRA” CRITICAL FACILITY

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ABSTRACT

The paper presents the results of experimental and computational study of flattening the spatial distribution of ^{235}U fission reaction rate in a critical assembly ASTRA with the annular core and poison profiling elements placed in the inner graphite reflector near the boundary with core. Presented computational analysis of experimental data was performed with the set of codes used in HTGR design calculations. It was shown, that the power distribution flattening (^{235}U fission reaction rate) in an annular core of a modular reactor such as GT-MHR could be achieved, in the certain degree, by the inserting the poison profiling elements in the inner reflector near the boundary with the core. The analysis of divergences of computational and experimental values of the ^{235}U fission reaction rate shown that the maximal deviations lay in a range of 5-7 % excepting two points in the inner reflector for the 1A configuration, where value of deviation reaches 8 %. It should be noted that the error of the experiment does not exceed 5 %, so the calculational values only slightly exceed an experimental error.

Key Words: ASTRA critical facility, HTGR, fission reaction rate, power distribution flattening, poison profiling elements

1. INTRODUCTION

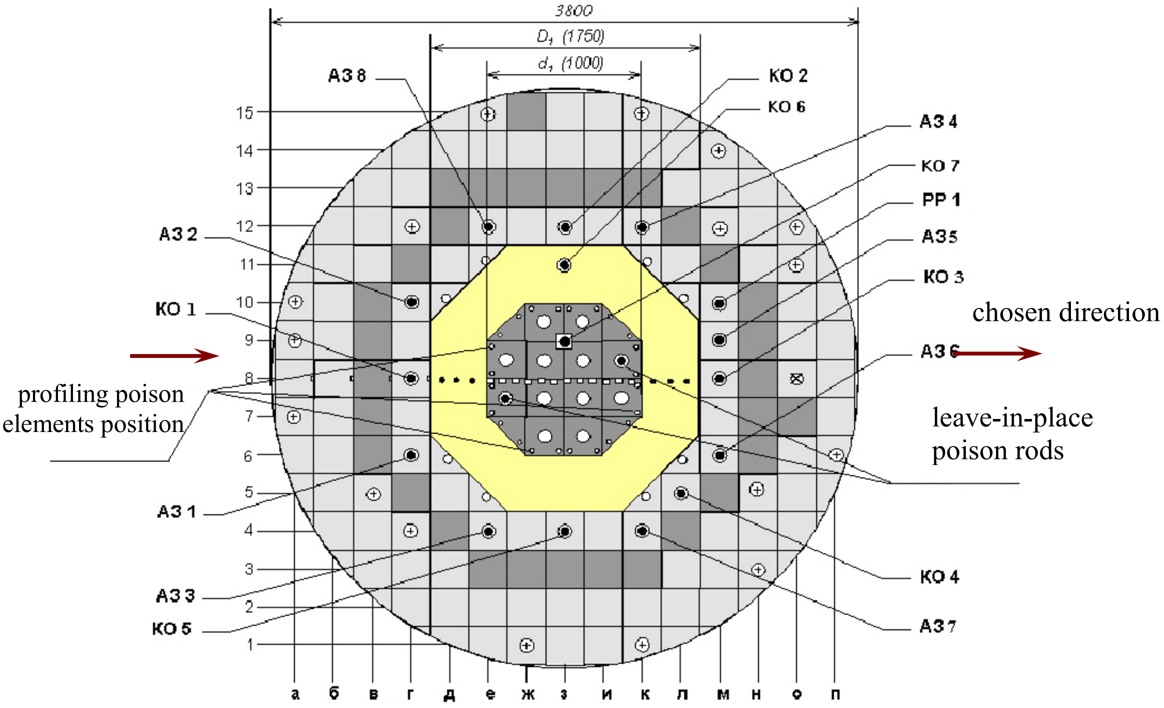
Nowadays the development of projects of High Temperature Gas Cooled Reactors (HTGRs) with gas turbines, such as GT-MHR with prismatic fuel assemblies in USA, Russia [1] or PBMR (Pebble Bed Modular Reactor) with spherical fuel elements in RSA (Republic of South Africa) [2], are widely carried out in the world. These types of reactors are expected to possess the key advantages in safety because of the absence of core melting under the accidents with loss of coolant.

The presence of an annular core in the mentioned reactor projects causes the high non-uniformity of power distribution in a core with the maximum values near the reactor core boundaries with inner and side graphite reflectors.

Following approaches to flattening the power distribution in design calculations of GT-MHR type reactor could be used:

1. Placing the “heavy” poison rods in the inner reflector [3].
2. Placing the profiling poison elements (PPEs) in the inner or side graphite reflector near the boundary with reactor core.
3. Profiling the outer layers of the fuel assemblies adjacent to reflectors by the content of burnable poison or fuel enrichment.

The computational and experimental investigation of a possibility to flatten the power distribution by placing the “heavy” poison rods (co-called “leave-in-place” poison rods similar to the compensating and safety rods) in the inner reflector has been fulfilled before on the ASTRA critical facility of Kurchatov Institute [3]. In so doing, only two “heavy” poison rods were inserted in the inner reflector (see Fig. 1) and so study was limited by the direction 8.



chosen direction

profiling poison elements position

leave-in-place poison rods

KO1 – KO7 – compensating control rods ; A31 – A38 – emergency safety rods;
PP – manual control rod;
The shaded areas in a lateral reflector are graphite blocks without holes.

Figure 1. Layout of Annular Core Assembly at the ASTRA Critical Facility.

This work is a continuation of investigations of the power distribution flattening in a reactor core such as GT-MHR with an annular core. Computational and experimental study of power distribution flattening by inserting the poison profiling elements not having the big weight in the inner reflector near the boundary with a reactor core at the "ASTRA" critical facility has been carried out. Eight PPEs were inserted in the inner reflector. Direction 8 was chosen for demonstration of power distribution flattening.

2. EXPERIMENTS ON THE POWER DISTRIBUTION FLATTENING

In the fulfilled experiments, the annular core of "ASTRA" critical assembly was loaded with spherical fuel elements with uranium dioxide fuel (Fig 1). In such configuration the graphite reflector is placed outside of the core – inner and side reflectors.

An influence of the poison profiling elements, placed in an inner reflector, on radial shape of ^{235}U fission reaction rate distribution was investigated stage by stage. At the first stage the core was loaded with a number of spherical fuel elements to achieve critical state with minimum reactivity margin. In this configuration the ^{235}U fission reaction rate distribution in radial direction (direction 8 in Fig. 1) and axial direction were measured. To ensure in the safety at subsequent final load of assembly the measurements of control rods worth and their calibration curves were also fulfilled. During the further experiments, PPEs were inserted in the inner reflector in pairs near the boundary of the inner reflector and the core (8 PPEs were inserted altogether) and a necessary number of spherical fuel elements were added to achieve new criticality. After that, measurements were repeated. The top reflector was installed in the last experimental configuration. In addition to PPEs the compensating rods KO-3 (completely) and KO-5 (in part) were inserted in the side reflector. Positions of compensating rods and PPEs are shown on Fig 1.

3. COMPUTATIONAL ANALYSIS

The computational analysis of the experimental data on spatial distributions of ^{235}U fission reaction rate was performed with the use of JAR [4, 5] and WIMS-D [6 – 8] codes, currently applied in HTGR design calculations.

13 energy groups were used when the fine-mesh full-core diffusion 3D calculations with the JAR code were carried out. WIMS-D code was applied for preparation of the macroscopic and microscopic 13-group neutron cross sections. Neutron thermalization was taken into account in the energy region below 4 eV.

The plane mesh size of a finite-difference net was equal to 2.5 cm that corresponded to 100 points per square (in plane) graphite block of reflector with 25×25 cm size. Finite-difference approximation in axial direction was non-uniform.

When preparing the 13-group macroscopic cross sections for various components of the critical assembly the key attention was given to the neutron leakage from graphite blocks with axial cylindrical holes, from channels for safety rods with inserted and withdrawn rods and some other spatial parts of calculated object.

Two sets of diffusion coefficients were used in JAR calculations. The first set of diffusion coefficients was used for taking into account: a) the neutron leakage in the radial direction for all spatial parts and b) the neutron leakage in the axial direction for spatial parts don't having essential part of void. These diffusion coefficients were prepared traditionally with WIMS-D4 code, i.g. by averaging the transport cross-sections in cell zones with weights of zone volumes and neutron fluxes. The second set of diffusion coefficients was calculated to take into account more accurately the neutron leakage in the axial direction from graphite blocks with axial cylindrical holes, from channels for safety rods with inserted and withdrawn rods and some other spatial parts of calculated object having essential part of void. This set was prepared by ARIADNE option of WIMS-D4 code.

The distinction between radial and axial diffusion coefficients was explicitly taken into account in JAR code when solving the 13-group finite-difference neutron diffusion equation was carried out.

In the present work three most typical from seven experimental configurations of a critical facility ASTRA were considered:

1. **1A configuration**. There are no profiling poison elements in the inner reflector. Space between inner and side reflectors was filled by the spherical fuel elements.
2. **5A configuration.** Eight profiling poison elements were inserted in the inner reflector. The height of pebble bed of spherical fuel elements was increased to achieve new criticality.
3. **7A configuration**. Eight profiling poison elements were inserted in the inner reflectors. Compensating rods were inserted in the side reflector: KO-3 – completely, KO-5 – half (see Fig. 1). The height of pebble bed of spherical fuel elements was once again increased. The top graphite spherical elements reflector was installed.

The tables I - III show the comparison results of computational and experimental values of the radial distribution of ^{235}U fission reaction rate in the chosen direction. The spatial distributions of fission reaction rate are shown in figures 2 – 5. When analyzing deviations, both experimental (E) and computational (C) values were normalized on the same average value. Non-symmetry of the radial distribution of ^{235}U fission reaction rate in chosen direction for 7A configuration is connected with compensating rod KO-3.

Table I. Fission reaction rates of ^{235}U in the chosen radial direction for 1A configuration (relative units)

R, cm [*]	Experiment	Computation	(C-E)/E, %
↓ Side Reflector ↓			
50	0.418	0.433	3.6
75	0.787	0.769	-2.3
100	0.734	0.733	-0.1
↓ Core ↓			
108.5	0.687	0.669	-2.6
118.5	0.708	0.678	-4.1
128.5	0.794	0.769	-3.2
↓ Inner reflector ↓			
139	0.928	1.002	8.0
147.3	1.120	1.213	8.3
155.6	1.357	1.338	-1.4
164	1.392	1.427	2.5
172.3	1.531	1.462	-4.5
180.5	1.440	1.478	2.6
197.3	1.512	1.469	-2.8
205.6	1.464	1.449	-1.0
214	1.421	1.394	-1.9
222.3	1.268	1.294	2.0
230.6	1.241	1.152	-7.2
↓ Core ↓			
246.5	0.758	0.761	0.4
256.5	0.684	0.670	-2.1
266.5	0.660	0.660	-0.1

[*] Distance from the left external surface of the side reflector (see Fig. 1).

Table II. Fission reaction rates of ^{235}U in the chosen radial direction for 5A configuration (relative units)

R, cm [*]	Experiment	Computation	(C-E)/E, %
↓ Side Reflector ↓			
50	0.522	0.507	-2.8
75	0.834	0.874	4.8
100	0.790	0.800	1.3
↓ Core ↓			
108.5	0.705	0.708	0.4
118.5	0.706	0.684	-3.1
128.5	0.761	0.733	-3.8
↓ Inner reflector ↓			
139	0.931	0.918	-1.4
147.3	1.124	1.108	-1.4
155.6	1.197	1.247	4.2
164	1.357	1.362	0.4
172.3	1.395	1.417	1.6
180.5	1.441	1.443	0.1
189	1.438	1.451	1.0
197.3	1.433	1.434	0.1
205.6	1.424	1.402	-1.5
214	1.271	1.325	4.3
222.3	1.245	1.201	-3.5
230.6	1.087	1.054	-3.0
↓ Core ↓			
246.5	0.769	0.730	-5.1
256.5	0.703	0.681	-3.3
266.5	0.740	0.703	-5.0

[*] Distance from the left external surface of the side reflector (see Fig. 1)

Table III. Fission reaction rates of 235U in the chosen radial direction for 7A configuration (relative units)

R, cm [*]	Experiment	Computation	(C-E)/E, %
↓ Side Reflector ↓			
50	0,589	0,590	0,1
75	0,943	1,008	6,9
100	0,893	0,914	2,3
↓ Core ↓			
108,5	0,790	0,804	1,8
118,5	0,755	0,770	2,0
128,5	0,825	0,817	-1,0
↓ Inner reflector ↓			
139	0,987	1,010	2,3
147,3	1,194	1,206	1,0
155,6	1,340	1,342	0,1
164	1,435	1,443	0,6
172,3	1,475	1,479	0,3
180,5	1,482	1,481	-0,1
189	1,504	1,458	-3,0
197,3	1,417	1,408	-0,6
205,6	1,393	1,345	-3,4
214	1,266	1,233	-2,6
222,3	1,150	1,084	-5,7
230,6	0,958	0,918	-4,1
↓ Core ↓			
246,5	0,543	0,569	4,7
256,5	0,497	0,470	-5,5
266,5	0,424	0,395	-6,9

[*] Distance from the left external surface of the side reflector (see Fig. 1)

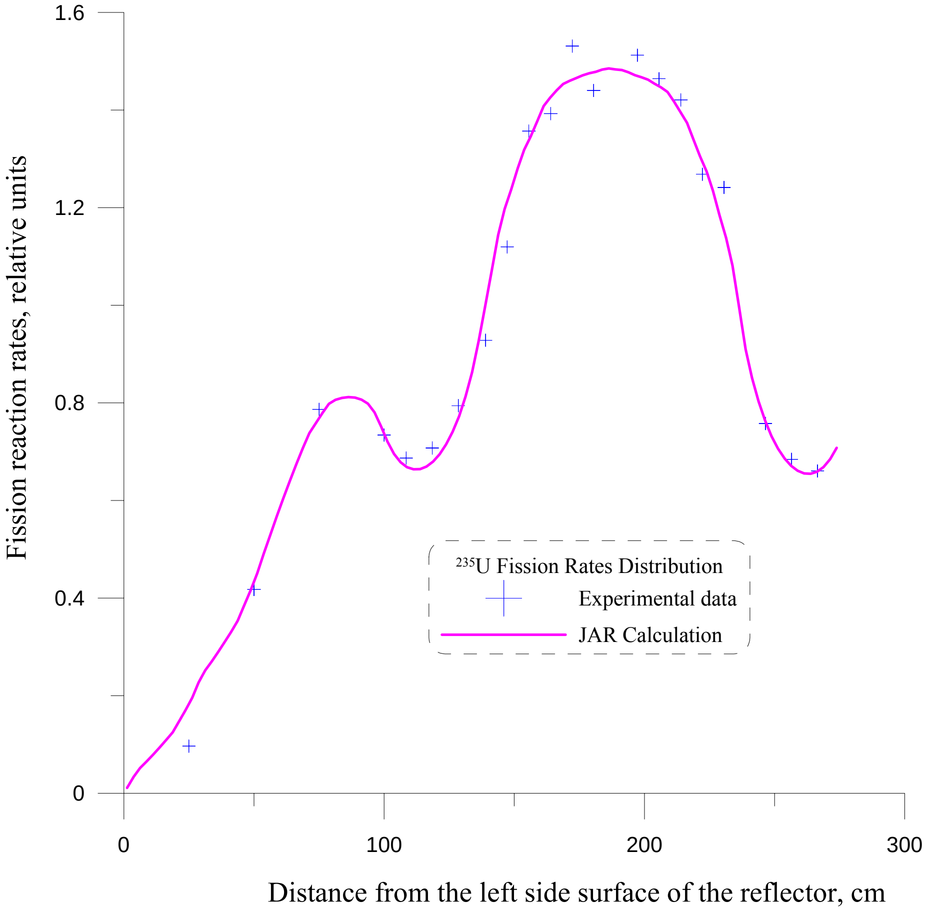


Figure 2. Radial distribution of ^{235}U fission reaction rate for 1A configuration.

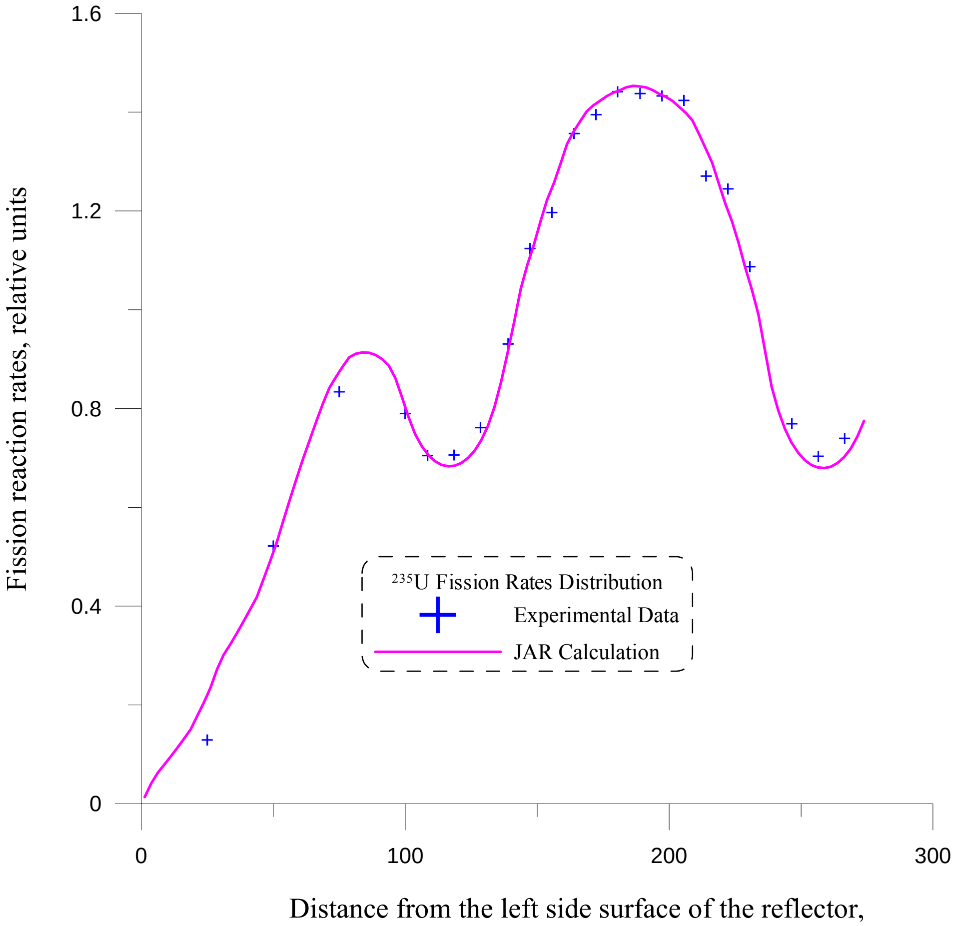


Figure 3. Radial distribution of ^{235}U fission reaction rate for 5A configuration.

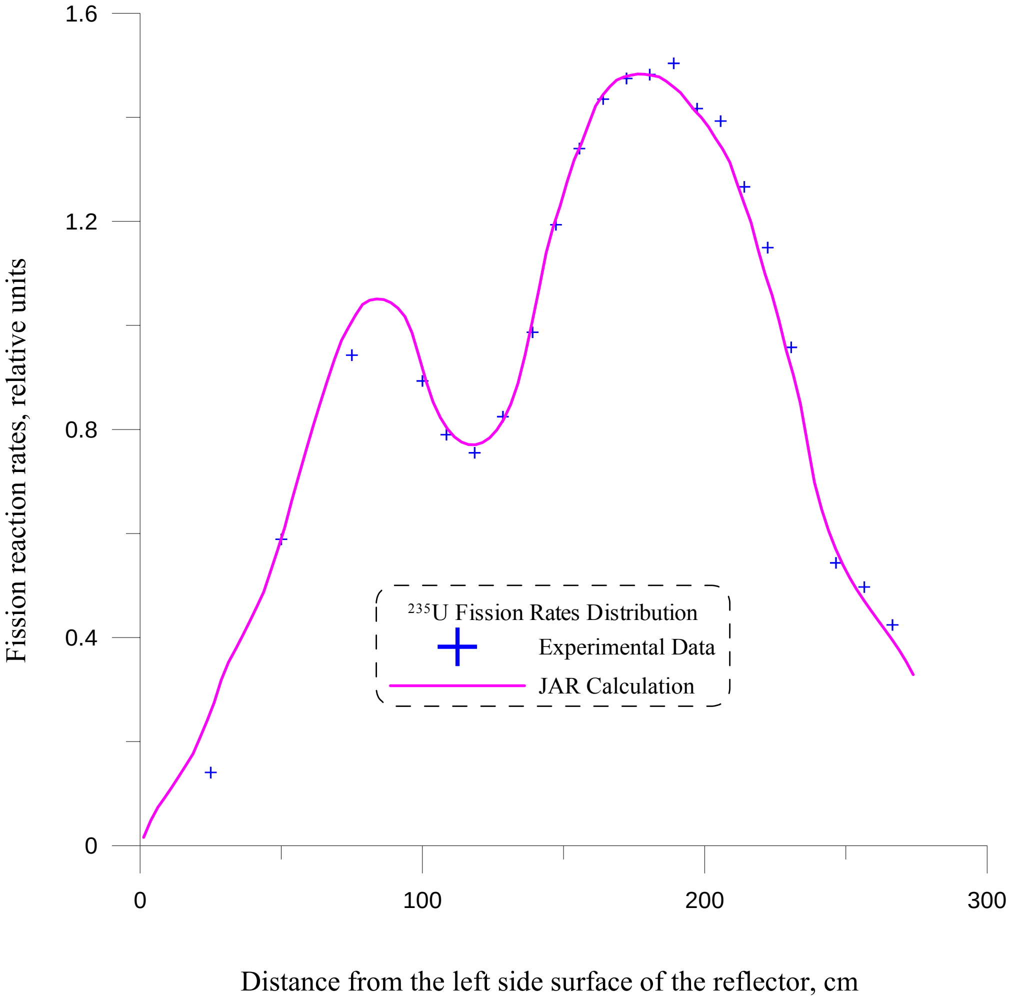


Figure 4. Radial distribution of ^{235}U fission reaction rate for 7A configuration.

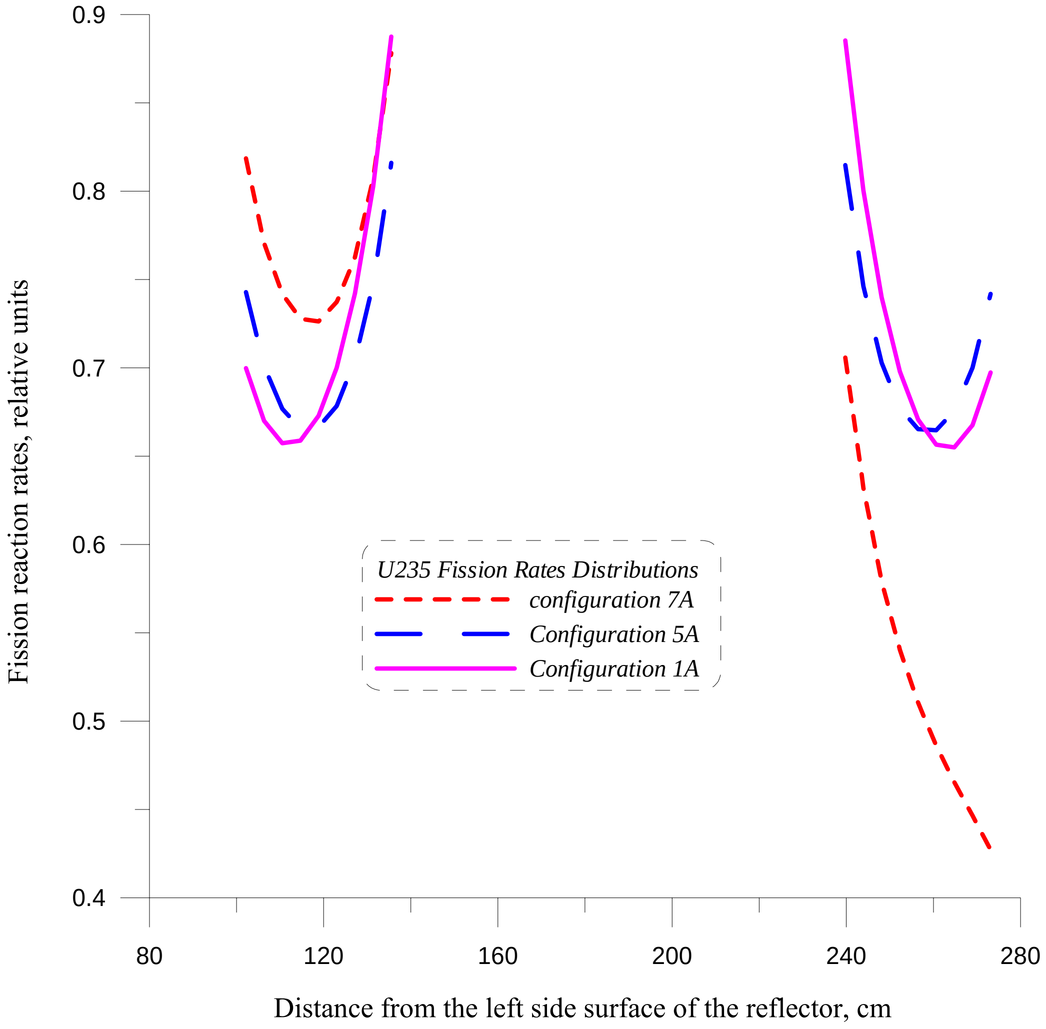


Figure 5. - Calculated radial distributions of ^{235}U fission reaction rate in the core for configurations 1A, 5A, 7A.

4. CONCLUSIONS

Computational and experimental study of power distribution flattening in annular reactor core of the "ASTRA" critical facility by inserting the poison profiling elements not having the big weight in the inner reflector near the boundary with core has been carried out. Eight PPEs were inserted in the inner reflector. Direction 8 was chosen for demonstration of power distribution flattening.

It was shown, that the power distribution flattening (^{235}U fission reaction rate) in an annular core of a modular reactor such as GT-MHR could be achieved, in the certain degree, by the inserting the poison profiling elements in the inner reflector near the boundary with the core (5A configuration, see Fig. 5).

The analysis of divergences of computational and experimental values of the ^{235}U fission reaction rate shown that the maximal deviations lay in a range of 5-7 % excepting the two points in the inner reflector for the 1A configuration, where value of deviation reaches 8 %. In so doing, the value of divergences does not exceed 7 % even in the 7A configuration when compensating rod KO-3, which have big enough weight (more than $3\beta_{eff}$), was inserted near the zone of measurements (see Fig. 1).

It should be noted that the error of the experiments does not exceed 5 %, so the calculational results only slightly exceed an experimental error.

REFERENCES

1. A.I. Kiriushin, N.N. Ponomarev-Stepnoi, E.S. Glushkov et al., “Project of the GT-MHR high-temperature helium reactor with gas turbine”, *Nuclear Engineering and Design,* **Vol. 173**, pp.119-129 (1997).
2. E.J. Mulder, “Pebble Bed Reactor with Equalized Core Power Distribution Inherently Safe and Simple”, Forschungszentrum Jülich, JÜL-3632, Jan. (1999).
3. V.F. Boyarinov, E.S. Glushkov, P.A. Fomichenko, G.V. Kompaniets, A.M. Krutov, E.V. Marova, V.A. Nevinitsa, Yu.P. Sukharev, “Computational Analysis of Experimental Results on Spatial Distributions of Fission Reaction Rates in the Annular Core of a Modular HTGR Obtained at the ASTRA Critical Facility”, *Proceeding of PHYSOR-2006, Topical Meeting on Reactor Physics*, Vancouver, BC, Canada, September 10-14, D044 (on CD-ROM) (2006).
4. L.N. Yaroslavtseva, “Program complex JARB for calculations of neutron–physical parameters of nuclear reactors”, *VANT, ser. “Physics and nuclear reactor engineering*, **v. 8** (37), pp.41-43 (1983) (in Russian).
5. L.N. Yaroslavtseva, P.A. Fomichenko, P.N. Alekseev, “Verification on stationary and time-depended algorithms in program complex JAR”, *Proceding of “Codes and algorithms for neutron-physical calculations of nuclear reactors” (Neutronics-92)*, Obninsk, Russia, pp.34-37 (1994) (in Russian).
6. J.R. Askew et al. ”A General Description of the Lattice Code WIMS”, JBWES, Oct. (1966).
7. WIMSD5, NEA Data Bank Documentation, No. 1507/02 (1996).
8. WLUP - WIMS Library Update. IAEA Final Report of a Coordinated Research Project, (2003).