MODELING OF BENCHMARK EXPERIMENTS PERFORMED AT ZR-6 CRITICAL FACILITY AND VALIDATION OF THE MCU-REA CODE

Alexeyev N.I., Gomin E.A., Gurevich M.I., Maiorov L.V., Shkarovsky D.A.
Russian Research Center "Kurchatov Institute"
Kurchatov Square, Moscow, 123182, Russia.
Fax (095) 196-9944
ani@adis.vver.kiae.ru

ABSTRACT

The report presents the results of two- and three-dimensional calculations of 154 experiments performed at ZR-6 critical facility designed to study UO_2-water lattices of VVER type reactors. The calculations have been performed to verify and validate (V&V) the new MCU-REA Monte-Carlo code (Russia) and verify the reliability of both two- and three-dimensional evaluated models of experimental configurations. The results obtained are in good agreement with the experimental data. An important conclusion that follows from the analysis of calculational results is that the two-dimensional model criticized at times due to the nonconformity with the real facility may be reliably used to validate design codes intended for VVER calculations.

1. INTRODUCTION

Reactor operation and design need reliable calculational support. To provide it, codes should be validated on the basis of reliable experiments. The experiments that have the benchmark status are considered to be such. To receive benchmark status, an adequate model of the experiment should be produced and the experiment should be analyzed using high accuracy codes (e.g. Monte-Carlo codes) with sufficient concurrence of the results. Such calculations give grounds for validation of both the experiment and the code.

The experiments performed at ZR-6 critical facility[1] are valuable for VVER type reactors. Only the two-dimensional (2D) model of the experiments was available before 1995 and the results of validations based on this model were criticized sometimes due to the non-conformity of the model and the real facility. In 1995-96 the re-evaluation of the experimental data was performed[2] within the framework of ICSBEP international program and the three-dimensional (3D) model of

the experiments was created[2]. The re-evaluated data received benchmark status. More than 150 cases were included into this evaluation.

In the 1998 the new code MCU-REA[3, 4] of the MCU code family[5] was developed. The code is intended for criticality and burnup calculations of VVER type systems using the Monte Carlo method. More than 150 configurations of ZR-6 facility were calculated using the MCU-REA code, 2D and 3D models of these configurations. The results are presented in this report and may be used to validate and verify both the code and various 2D models of the experiment.

2. THE MCU-REA CODE

The MCU-REA code allows solving the neutron transport equation using the Monte-Carlo method and evaluated nuclear data. In particular, it calculates the criticality parameters and solves burnup problems for VVER type systems.

Main application fields:

- criticality safety assessment,
- calculation of neutron physical characteristics of VVER type reactors,
- verification and validation of nuclear data libraries,
- verification of design codes intended for calculation of neutron physical characteristics of VVERs.

The code allows one to take into account the effects of continuous change of the energy at collisions, and both pointwise and step representation of cross-sections. For the unresolved resonance region the cross-sections are calculated using the temperature dependent subgroup parameters or the Bondarenko's self-shielding f-factors. For the resolved resonance region both subgroup and pointwise descriptions of cross-sections are possible. In latter case, «infinite» number of points describes the cross-sections of the most important nuclides. They are calculated in each energy point using the resonance parameters at neutron history modeling. This scheme allows one to estimate temperature effects using the analytical dependence of cross-sections on temperature. Collision modeling in the thermalization region is performed according to the user's choice: in multi-group approximation, or using the model of continuous energy change taking into account correlation between energy and angle change at scattering. The both cases use $S(\alpha,\beta)$ formalism and take into account chemical binding, crystal structure, and nucleus thermal motion.

The MCU-REA code allows the user to model practically any three-dimensional systems described by means of combinatorial geometry method. The user may describe lattices with repeated elements defining the repeated elements and translation vectors. The lattices may include heterogeneity described as applications. The combinatorial approach is strengthened by the use of the Woodcock method. Double heterogeneous systems with fuel elements containing many thousands of sphere microcells may be modeled using a special algorithm.

Different flux functionals are calculated: neutron multiplication factor, effective fraction of delayed neutrons, nuclear reaction rates for separate nuclides and their mixture in the given space-energy intervals, few-group constant set for regions, cells and assemblies (including diffusion coefficients).

3. ZR-6 CRITICAL FACILITY

In 1972-1990 Temporary International Collective (TIC) performed a wide-scale study of physics of VVER type UO_2-water lattices. One of the main goals of the program was to receive reliable experimental data for verification of VVER nuclear data libraries and codes. Specialists from 10 countries took part in the work. Experiments were performed at the ZR-6 critical facility in KFKI (Budapest, Hungary).

The experimental facilities are described in detail in the references 1, 2. The scheme of the facility is presented at Figures 1-3. Fuel rods used were of standard VVER type, but shortened to 125 cm. Borated water was used as a moderator. Criticality was achieved by varying the moderator height H_{cr}.

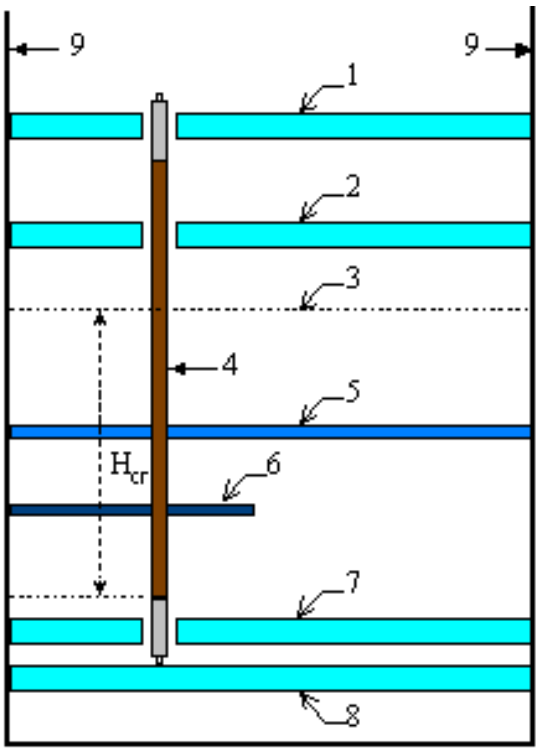

Figure 1. ZR-6. General Scheme.
1-Upper steel grid, 2-Temporary steel grid, 3-Water level, 4-Fuel, 5-Middle steel grid, 6-Sector grid, 7-Bottom steel greed, 8-Steel plate, 9-Core inner barrel.

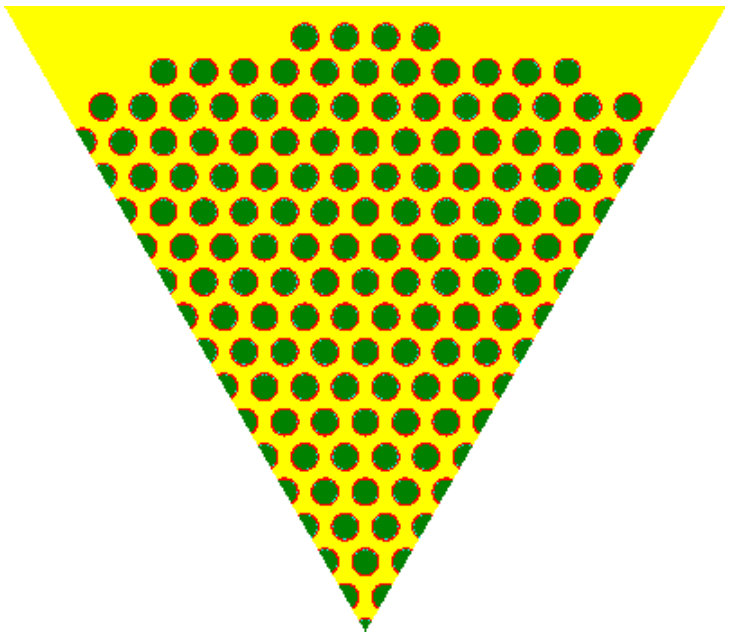

Figure 2. ZR-6. Horizontal Section. 30-degree Symmetry Angle.
Yellow - Water, Red - Cladding, Green – Fuel.

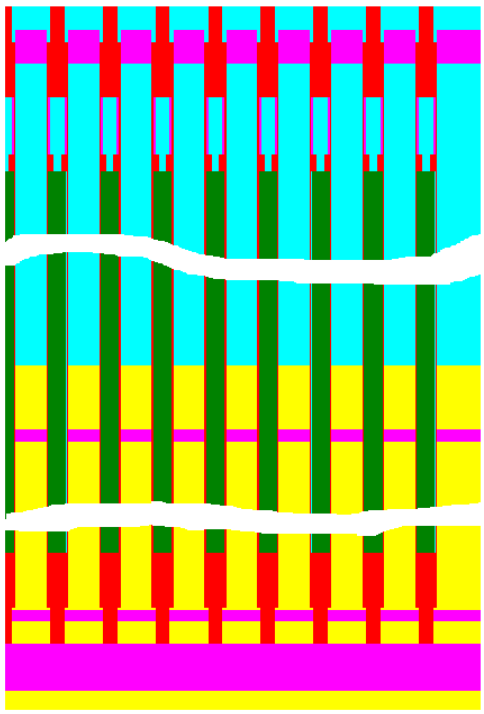

Figure 3. ZR-6. Vertical Section.
Magenta – Air, Yellow - Water, Pink – Grids, Red - Cladding, Green – Fuel.

About 300 different core configurations were studied. The configurations differed by core maps giving the layout of different kind of pins (see for example Fig. 2), by boric acid concentration, by position of movable grid plates (Fig.1, 3), and by H_{cr}.

The main features of the lattices investigated are given in Table I.

Table I. Main Characteristics of ZR-6 Lattices.

Fuel pins	UO_2
Fuel enrichment (^{235}U)	1.6%, 3.6%, 4.4% ;
Lattice pitch	11.0, 12.7, 15.0, 19.05 mm;
Boric acid	Concentration between 0 and 7.2 g/l
Absorber rods	ZrB_2, B_4C, Eu_2O_3, Gd_2O_3 rods

All the configurations were divided into two sets: regular and perturbed lattices. Regular lattices differ by core maps, lattice pitch, fuel enrichment, and boric acid concentration. Perturbed lattices were divided into two categories: point perturbations and fuel assembly imitators. The point perturbed lattices consisted of macrocells X_n containing an absorber rod X in the center surrounded by a regular fuel lattice. Macrocells X_n corresponded to lattices in which every n^{th} fuel pin was replaced by an absorber rod of the X type. Typical n values were 3,5,7.

The absorber rod types are given in Table II.

Table II. Absorber Rods.

X	Comment
A,B,C	different boron rods
D	B_4C rod
E	Water hole
F	Eu_20_3 rods
G	B_4C rods of VVER-1000
H to N	Rods containing various quantities of Gd_2O_3

Fuel assembly imitators were denoted by K_m symbols. The K_m assemblies were simulated by withdrawing rows of fuel pins from the regular lattices to imitate the assembly structure. Here, m is the total number of the lattice positions within an assembly imitator. Typical m values were 91, 271, 331.

Evaluators of ZR-6 experiments proposed two main models for every configuration[1, 2] designed to validate transport codes and nuclear data.

2D models are characterized by:

- the core map giving the layout of the fuel pins, absorbers and dummy rods (Fig. 2),
- the value of the measured axial buckling $\mathbf{B^2_z}$.

3D models are characterized by:

- the detail 3D configuration description, including the positions and materials of grid plates (Fig.1-3),
- the value of critical water height H_{cr}.

Earlier 2D models were used only to validate the design and Monte-Carlo codes. However, the accuracy of 2D models was criticized sometimes. Our aim was to clarify this problem.

4. CALCULATIONAL RESULTS

4.1 EFFECTIVE MULTIPLICATION FACTOR

The MCU-REA calculations were performed using both two- and three-dimensional models[2] of ZR-6 configurations. The regular and perturbed configurations were investigated. The K_{eff} values (see Tables III-V) and power distributions (see Tables VI-XII) were calculated for 154 of 2D models and 92 of 3D models. All K_{eff} calculations were performed with ***statistical error*** σ = ***0.001*** (one standard deviation in absolute units).

The 2D calculations were performed using the approach when the solution of transport equation is presented in the form:

$$F(x,y,z,\nu)=f(x,y,\nu)\exp(izB_z)$$

where B^2_z values are measured ones. The MCU-REA code allows solving similar problems using a special Monte-Carlo algorithm[6, 7].

The 3D calculations were performed according to the description detailed in reference 2 without any approximation.

During the work an electronic atlas[8] of the ZR-6 critical facility and auxiliary codes have been developed. The atlas contains descriptions of 154 configurations and MCU calculational results in ASCII format. The auxiliary codes allow one to create input data for MCU automatically.

In this report all the configurations investigated are marked: by absolute number changing from 1 to 154 and by the core identifier used in the reference 2 (e.g. 60/59).

The K_{eff} *-1* values calculated using 2D and 3D models are given in Figures 4 and 5.

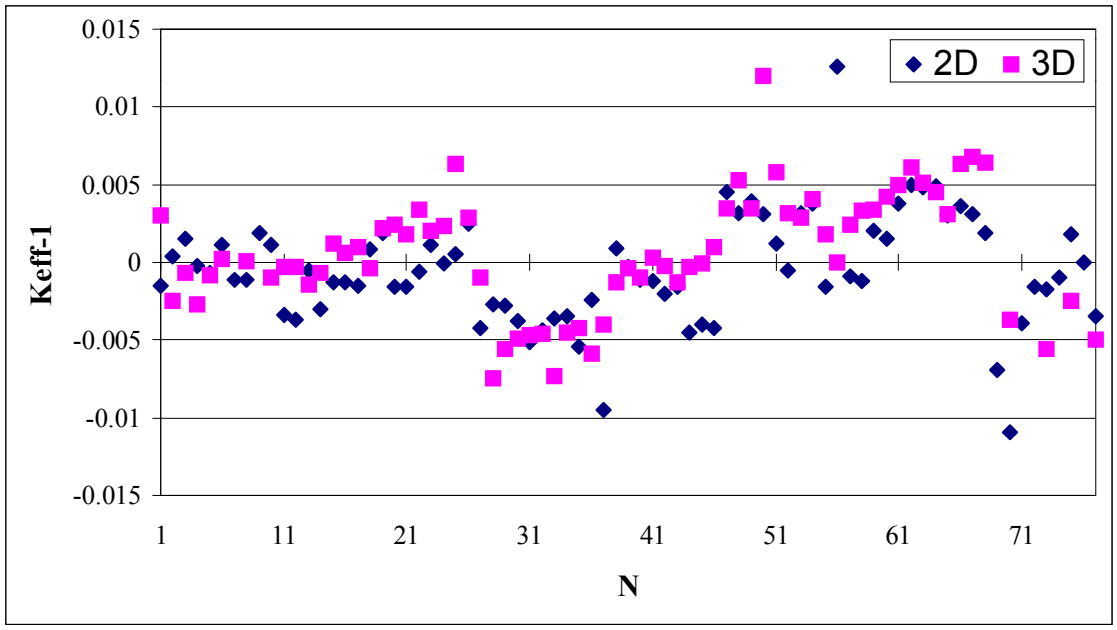

Figure 4. K_{eff}-*1*. 2D and 3D Models. Regular Lattices.

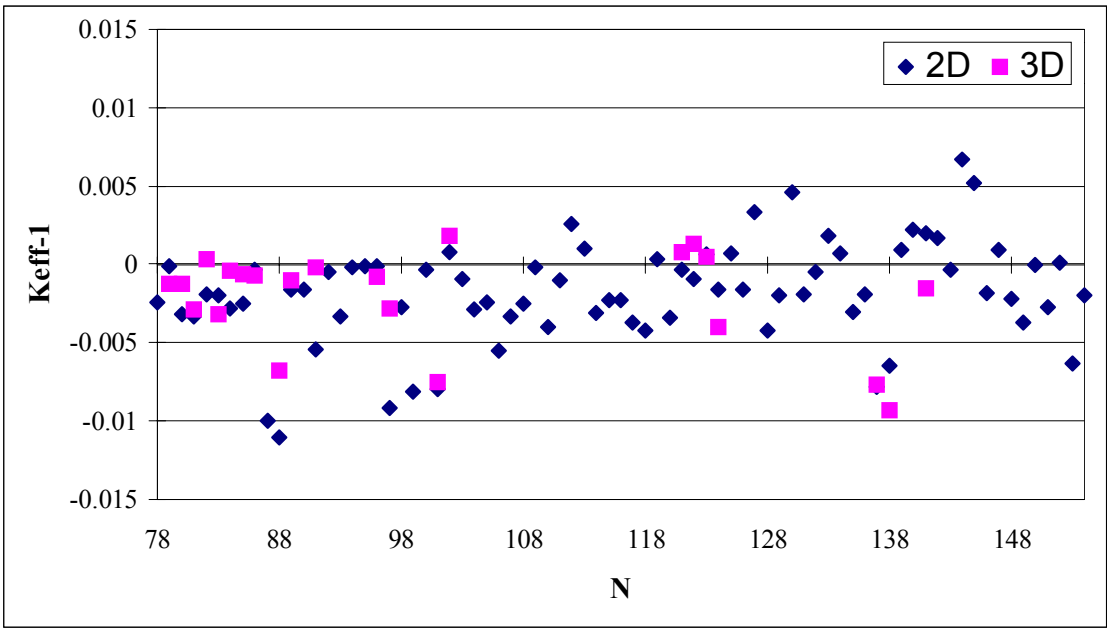

Figure 5. K_{eff}-*1*. 2D and 3D Models. Perturbed Lattices.

Table III contains the summary of K_{eff} values calculated using 2D and 3D models. The table contains three groups of results: values averaged over all 154 configurations (cores) investigated, values for regular lattices with pitches 11 mm and 19.05 mm.

Table III. Summary of K_{eff} Values Calculated Using 2D and 3D Models.

Parameters	Cores 1-154 All cores	Cores 27-37 Pitch=11mm	Cores 59-68 Pitch=19.05mm
N_{2D}	154	11	10
N_{3D}	92	11	10
$(K_{eff}\text{-}1)_{Av\text{-}2D}$	-.001	-.004	.003
$(K_{eff}\text{-}1)_{Av\text{-}3D}$	.000	-.005	.005
$(K^{3D}_{eff}\text{-}K^{2D}_{eff})_{Av}$	.001	-.001	.002
σ_{2D}	.004	.005	.004
σ_{3D}	.004	.005	.005
$\sigma_{(3D\text{-}2D)}$	.003	.003	.002

The notations used in Table III are:
N_{2D} is a number of 2D configurations,
N_{3D} is a number of 3D configurations,
$(K_{eff}\text{-}1)_{Av\text{-}2D}$ is K_{eff}-1 value averaged over N_{2D} two-dimensional configurations
$(K_{eff}\text{-}1)_{Av\text{-}3D}$ is K_{eff}-1 value averaged over N_{3D} three-dimensional configurations
$(K^{3D}_{eff}\text{-}K^{2D}_{eff})_{Av}$ is difference 2D and 3D K_{eff} value averaged over N_{3D} over configurations
σ_{2D} is an averaged root-square deviation of $(K_{eff}\text{-}1)_{2D}$.
σ_{3D} is an averaged root-square deviation of $(K_{eff}\text{-}1)_{3D}$.
$\sigma_{(3D\text{-}2D)}$ is an averaged root-square deviation of $(K_{eff})_{3D}$ - $(K_{eff})_{2D}$.

One may conclude from Table III:

- the root-square deviation of K_{eff}-1 averaged over all the cores is less than 0.004 for both 2D and 3D models
- the root-square deviation of $(K_{eff})_{3D}$ - $(K_{eff})_{2D}$ averaged over all the cores is about 0.003
- the deviations are moderately worse for lattices with pitches 11 mm and 19.05 mm.

Tables IV and V show the K_{eff} -1 values calculated by MCU-REA code using the 2D and 3D models and their differences $\Delta = K_{eff}$ (3D) - K_{eff} (2D).

The 1st column contains absolute number of the core. The 3rd column contains the core identification used in reference 2. The 2nd column describes the lattice type according to the notations used in reference 2.They are as follows.

The regular lattices:

lattice pitch[mm]/enrichment[%]/boric acid concentration [g/l]

For example 12.7/3.6/7.2 means a lattice pitch 12.7 mm, enrichment 3.6% and boric acid concentration 7.2 g/l.

The point perturbed lattices:

lattice pitch[mm]/enrichment[%]/boric acid concentration [g/l]/macrocell type

For example 12.7/3.6/7.2/F6 means a lattice with pitch 12.7 mm, enrichment 3.6%, boric acid concentration 7.2 g/l and F6 macrocell type.

The fuel assembly imitator lattices:

lattice pitch[mm]/enrichment[%]/boric acid concentration [g/l]/assembly type

For example 12.7/3.6/7.2/K91 means a lattice with pitch 12.7 mm, enrichment 3.6%, boric acid concentration 7.2 g/l and K91 assembly type.

Table IV. *Keff* Calculated with MCU-REA. Regular Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
1	12.7/3.6/0.0	020/020[a]	-.002	.003	.005
2	12.7/3.6/0.0	175/175	.000	-.002	-.003
3	12.7/3.6/0.0	174/174	.002	-.001	-.002
4	12.7/3.6/0.0	154/154	.000	-.003	-.002
5	12.7/3.6/0.0	246/246	-.001	-.001	.000
6	12.7/3.6/0.0	173/173	.001	.000	-.001
7	12.7/3.6/0.0	052/023	-.001		
8	12.7/3.6/0.0	172a/172	-.001	.000	.001
9	12.7/3.6/0.0	051/024	.002		
10	12.7/3.6/0.0	171a/171	.001	-.001	-.002
11	12.7/3.6/0.0	170/170	-.003	.000	.003
12	12.7/3.6/0.0	012a/012	-.004	.000	.003
13	12.7/3.6/0.0	169/169	-.001	-.001	-.001
14	12.7/3.6/1.1	162/161	-.003	-.001	.002
15	12.7/3.6/4.0	027/027[a]	-.001	.001	.002
16	12.7/3.6/4.0	018b/018	-.001	.001	.002
17	12.7/3.6/4.0	036/036	-.002	.001	.003
18	12.7/3.6/4.0	030/030	.001	.000	-.001
19	12.7/3.6/4.0	014b/014	.002	.002	.000
20	12.7/3.6/4.0	029/029	-.002	.002	.004
21	12.7/3.6/4.0	161/161	-.002	.002	.003
22	12.7/3.6/4.0	012b/012	-.001	.003	.004
23	12.7/3.6/5.8	163/161	.001	.002	.001
24	12.7/3.6/5.8	247/161	.000	.002	.002
25	12.7/3.6/7.2	038/038[a]	.000	.006	.006
26	12.7/3.6/7.2	037/037	.003	.003	.000
27	11.0/3.6/0.0	041/041[a]	-.004	-.001	.003
28	11.0/3.6/0.0	039/039	-.003	-.007	-.005
29	11.0/3.6/0.0	195/039	-.003	-.006	-.003

Table IV (Continued). *Keff* Calculated with MCU-REA. Regular Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
30	11.0/3.6/0.0	194/194	-.004	-.005	-.001
31	11.0/3.6/0.0	193/193	-.005	-.005	.000
32	11.0/3.6/0.0	192/192	-.004	-.005	.000
33	11.0/3.6/0.0	040/040	-.004	-.007	-.004
34	11.0/3.6/0.0	188/040	-.003	-.004	-.001
35	11.0/3.6/0.0	191/191	-.005	-.004	.001
36	11.0/3.6/0.96	209/040	-.002	-.006	-.004
37	11.0/3.6/1.41	042/040[a]	-.010	-.004	.006
38	15.0/3.6/0.0	212/212	.001	-.001	-.002
39	15.0/3.6/0.0	213/213	.000	.000	.000
40	15.0/3.6/0.0	214/214	-.001	-.001	.000
41	15.0/3.6/0.0	220/220	-.001	.000	.002
42	15.0/3.6/0.0	215/215	-.002	.000	.002
43	15.0/3.6/0.0	216/216	-.002	-.001	.000
44	15.0/3.6/0.0	217/217	-.004	.000	.004
45	15.0/3.6/0.0	218/218	-.004	.000	.004
46	15.0/3.6/0.0	219/219	-.004	.001	.005
47	15.0/3.6/4.0	233/233	.005	.003	-.001
48	15.0/3.6/4.0	232/232	.003	.005	.002
49	15.0/3.6/4.0	234/234	.004	.003	.000
50	15.0/3.6/4.0	235/235	.003	.012	.009
51	15.0/3.6/4.0	236/236	.001	.006	.005
52	15.0/3.6/4.0	237/237	-.001	.003	.004
53	15.0/4.4/0.0	230/230	.003	.003	.000
54	15.0/4.4/0.0	229/229	.004	.004	.000
55	15.0/4.4/0.0	225/225	-.002	.002	.003
56	15.0/4.4/0.0	221/221	.013	.000	-.013
57	15.0/4.4/0.0	224/224	-.001	.002	.003
58	15.0/4.4/0.0	223/223	-.001	.003	.004
59	19.05/3.6/0.0	208/208	.002	.003	.001
60	19.05/3.6/0.0	207/207	.002	.004	.003
61	19.05/3.6/ 0.0	206/206	.004	.005	.001
62	19.05/3.6/ 0.0	205/205	.005	.006	.001
63	19.05/3.6/ 0.0	204/204	.005	.005	.000
64	19.05/3.6/ 0.0	203/203	.005	.005	.000
65	19.05/3.6/ 0.0	202/202	.003	.003	.000
66	19.05/3.6/0.0	201/201	.004	.006	.003
67	19.05/3.6/ 0.0	200/200	.003	.007	.004
68	19.05/3.6/ 0.0	199/199	.002	.006	.005
69	12.7/1.6-3.6/ 0	080/080[b]	-.007		

Table IV (Continued). *Keff* Calculated with MCU-REA. Regular Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
70	12.7/1.6-3.6/ 0	160/160	-.011	-.004	.007
71	12.7/1.6-3.6/1.85	081/081[b]	-.004		
72	12.7/4.4/0.0	110/110	-.002		
73	12.7/4.4/0.0	164/110	-.002	-.006	-.004
74	12.7/4.4/0.64	111/110	-.001		
75	12.7/4.4-3.6/0.0	166/166	.002	-.002	-.004
76	12.7/4.4-3.6/7.2	112/112	.000		
77	15.0/1.6-3.6/0.0	231/231	-.003	-.005	-.002
78	12.7/3.6/0.0/E_∞	142/138	-.002		
79	12.7/3.6/0.0/reg	158/155	.000	-.001	-.001
80	12.7/3.6/0.0/E_∞	158a/155	-.003	-.001	.002
81	12.7/3.6/0.0/A_∞	158b/155	-.003	-.003	.000
82	12.7/3.6/0.0/C_∞	158c/155	-.002	.000	.002
83	12.7/3.6/0.0/B_∞	158d/155	-.002	-.003	-.001
84	12.7/3.6/0.0/F_∞	158e/155	-.003	.000	.002
85	12.7/3.6/0.0/G_∞	158f/155	-.002	-.001	.002
86	12.7/3.6/0.0/D_∞	158g/155	.000	-.001	.000
87	12.7/3.6/0.0/F7	141/138	-.010		

[a] Core with upper reflector for which not the moderator level but the supercritical K_{eff} is given in the experimental data.
[b] The lattice does not have 30° symmetry; the calculation is performed according to the description given in the reference 1.

Table V. *Keff* Calculated with MCU-REA. Perturbed Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
78	12.7/3.6/0.0/E_∞	142/138	-.002		
79	12.7/3.6/0.0/reg	158/155	.000	-.001	-.001
80	12.7/3.6/0.0/E_∞[a]	158a/155	-.003	-.001	.002
81	12.7/3.6/0.0/A_∞	158b/155	-.003	-.003	.000
82	12.7/3.6/0.0/C_∞	158c/155	-.002	.000	.002
83	12.7/3.6/0.0/B_∞	158d/155	-.002	-.003	-.001
84	12.7/3.6/0.0/F_∞	158e/155	-.003	.000	.002
85	12.7/3.6/0.0/G_∞	158f/155	-.002	-.001	.002
86	12.7/3.6/0.0/D_∞	158g/155	.000	-.001	.000
87	12.7/3.6/0.0/F7	141/138	-.010		
88	12.7/3.6/0.0/F7	155/155	-.011	-.007	.004
89	12.7/3.6/0.0/G7	156/155	-.002	-.001	.001
90	12.7/3.6/0.0/G7	244a/244	-.002		

Table V (Continued). *Keff* Calculated with MCU-REA. Perturbed Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
91	12.7/0.0/G7/130C[b]	244b/244	-.005	.000	.005
92	12.7/3.6/0.0/D7	057/057	-.001		
93	12.7/3.6/0.0/D7	140/138	-.003		
94	12.7/3.6/0.0/E7	058/057	.000		
95	12.7/3.6/0.0/E7	138/138	.000		
96	12.7/3.6/0.0/E7	157/155	.000	-.001	-.001
97	12.7/0.0/E7/130C	245b/244	-.009	-.003	.006
98	12.7/3.6/0.0/C7	068/057	-.003		
99	12.7/3.6/1.8F7	146/138	-.008		
100	12.7/3.6/1.8/E7	147/138	.000		
101	12.7/0.0/F7-E_∞	155a/155	-.008	-.007	.001
102	12.7/0.0/G7-E_∞	156a/155	.001	.002	.001
103	12.7/3.6/0.0/D7	054/054	-.001		
104	12.7/3.6/0.0/E7	055/054	-.003		
105	12.7/3.6/0.0/A6	060/059	-.002		
106	12.7/3.6/0.0/C6	061/059	-.006		
107	12.7/3.6/0.0/B6	062/059	-.003		
108	12.7/3.6/0.0/D6	063/059	-.002		
109	12.7/3.6/0.0/E6	059/059	.000		
110	12.7/3.6/0.0/C5	066/064	-.004		
111	12.7/3.6/0.0/E5	064/064	-.001		
112	12.7/3.6/0.0/A5	70/70	.003		
113	12.7/3.6/0.0/C5	71/70	.001		
114	12.7/3.6/0.0/C5	73/73	-.003		
115	12.7/3.6/0.0/C5	75/75	-.002		
116	12.7/3.6/0.0/C5	177/177	-.002		
117	12.7/3.6/0.0/C5	77/77	-.004		
118	12.7/3.6/0.0/C5	78/78	-.004		
119	12.7/3.6/0.0/C5	79/79	.000		
120	11.0/3.6/0.0/E7	189/189	-.003		
121	12.7/3.6/0.0/G7	243/243	.000	.001	.001
122	12.7/3.6/0.0/G5	242/242	-.001	.001	.002
123	12.7/3.6/0.0/E3	176/176	.001	.000	.000
124	11.0/3.6/0.0/E3	190/190	-.002	-.004	-.002
125	12.7/3.6/0.0/K331	083/083	.001		
126	12.7/3.6/0.0/K331	084/083	-.002		
127	12.7/3.6/0.0/K331	085/083	.003		
128	12.7/3.6/0.0/K331	086/083	-.004		
129	12.7/3.6/0.0/K331	087/087	-.002		
130	12.7/3.6/0.0/K331	088/087	.005		

Table V (Continued). *Keff* Calculated with MCU-REA. Perturbed Lattices.

No	Lattice Type	Core Id.	K_{eff}-1 (2D)	K_{eff}-1 (3D)	K^{3D}_{eff}- -K^{2D}_{eff}
131	12.7/3.6/0.0/K331	089/087	-.002		
132	12.7/3.6/0.0/K331	090/087	-.001		
133	12.7/3.6/0.0/K331	091/087	.002		
134	12.7/3.6/0.0/K331	092/087	.001		
135	12.7/3.6/0.0/K331	144/144	-.003		
136	12.7/3.6/0.0/K331	145/145	-.002		
137	11.0/3.6/0.0/K331/F3[c]	197/197	-.008	-.008	.000
138	11.0/3.6/0.0/K331/F3	198/198	-.007	-.009	-.003
139	12.7/3.6/4.0/K91	100/100	.001		
140	12.7/3.6/0.0/K91	101/100	.002		
141	12.7/3.6/0.0/K91	179/179	.002	-.002	-.003
142	12.7/3.6/0.0/K91	102/102	.002		
143	12.7/3.6/0.0/K91	103/103	.000		
144	12.7/3.6/0.0/K91	104/103	.007		
145	12.7/3.6/0.0/K91	105/103	.005		
146	12.7/3.6/0.0/K91	107/103	-.002		
147	12.7/3.6/0.0/K91	108/103	.001		
148	12.7/3.6/0.0/K91	109/103	-.002		
149	12.7/3.6/5.5/K91	113/113	-.004		
150	12.7/3.6/0.0/K91/D_∞	180/179	.000		
151	12.7/3.6/0.0/K271	126/126	-.003		
152	12.7/3.6/0.0/K271	127/126	.000		
153	12.7/3.6/0.0/K271	128/126	-.006		
154	12.7/3.6/0.0/K2712	129/126	-.002		

[a] Notation X_∞ means one single X type absorber rod put in the center of the core.
[b] Notation /130C means that measurements were performed at temperature 130C.
[c] Notations like K331/F3 means combinations: F type absorber rod in K331 cluster arranged according to the F3 scheme.

4.1 FISSION RATE DISTRIBUTION

This section presents calculational and experimental fission rate distributions.

Table VI presents deviations of calculated fission rate distributions (C) from the experimental data (E) for 18 different configurations.
Here
N is number of rods measured for given configuration,
σ is an averaged root-square deviation of (C-E)/E for N rods.
Relative number of rods for which $|(C-E)/E|$ is less than X% is placed in columns $\Delta < X\%$.

Table VI. Deviations of Calculated Fission Rate Distributions from the Experimental Data.

Core	Lattice Type	σ	$\Delta<2\%$	$2\%<\Delta<3\%$	$3\%<\Delta$	N
039/039	11.0/3.6/0.0	1.29	.83	.17	.00	12
041/041	11.0/3.6/0.0	1.02	.90	.10	.00	10
042/040	11.0/3.6/1.41	1.49	.85	.08	.08	13
154/154	12.7/3.6/0.0	1.50	.81	.19	.00	21
160/160	12.7/3.6/7.2	.99	.94	.03	.03	31
038/038	12.7/3.6/7.2	.93	1.00	.00	.00	14
110/110	12.7/4.4/0.0	1.05	.90	.10	.00	21
111/110	12.7/4.4/.64	1.01	1.00	.00	.00	20
155/155	12.7/1.6-3.6/0.0	1.44	.87	.06	.06	63
057/057	12.7/D7/0.0	1.70	.84	.09	.07	75
141/138	12.7/F7/0.0	1.53	.80	.15	.05	61
146/138	12.7/F7/1.8	2.45	.58	.15	**.27**	60
147/138	12.7/E7/1.8	2.02	.70	.10	**.20**	61
113/113	12.7/K91/5.5	1.21	.95	.03	.03	76
144/144	12.7/K331/0.0	2.18	.78	.08	**.14**	50
145/145	12.7/K331/0.0	1.57	.84	.10	.06	50
087/087	12.7/K331/0.0	.89	.98	.02	.00	45
088/087	12.7/K331/7.2	1.00	.98	.02	.00	45

Table VII presents the general map of the rods positions in the 30-degree symmetry angle of the core.

Tables VIII – XI show examples of deviations of calculated fission rate distributions from the experimental data printed in 1000*(C-E)/E. The deviations are given for rods investigated in the experiments and printed according to the rod's position in the 30-degree symmetry angle of the core. Deviation of calculational results on fission rate distributions from experimental data is as a rule less than 3%.

Table VII. General Map of Rod's Positions for Tables VIII-XI

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
0	*																										
1		*																									
2	*		*																								
3		*		*																							
4	*		*		*																						
5		*		*		*																					
6	*		*		*		*																				
7		*		*		*		*																			
8	*		*		*		*		*																		
9		*		*		*		*		*																	
10	*		*		*		*		*		*																
11		*		*		*		*		*		*															
12	*		*		*		*		*		*		*														
13		*		*		*		*		*		*		*													
14	*		*		*		*		*		*		*		*												
15		*		*		*		*		*		*		*		*											
16	*		*		*		*		*		*		*		*		*										
17		*		*		*		*		*		*		*		*		*									
18	*		*		*		*		*		*		*		*		*		*								
19		*		*		*		*		*		*		*		*		*		*							
20	*		*		*		*		*		*		*		*		*		*		*						
21		*		*		*		*		*		*		*		*		*		*		*					
22	*		*		*		*		*		*		*		*		*		*		*		*				
23		*		*		*		*		*		*		*		*		*		*		*		*			
24	*		*		*		*		*		*		*		*		*		*		*		*		*		
25		*		*		*		*		*		*		*		*		*		*		*		*		*	
26	*		*		*		*		*		*		*		*		*		*		*		*		*		*

Table VIII. Calculated from Experimental Deviations for Fission Rate Distribution.
Lattice N 72 (12.7/4.4/0.0). Printed in 1000*(C-E)/E.

0	-6												
1		-12											
2	-10												
3				-5									
4	2												
5						2							
6	-2						29						
7								-22					
8	7								3				
9										-14			
10	15										1		
11												4	
12	12												3
13													
14	3												
	0	1	2	3	4	5	6	7	8	9	10	11	12

Table IX. Calculated from Experimental Deviations for Fission Rate Distribution.
Lattice N 74 (12.7/4.4/0.64). Printed in 1000*(C-E)/E.

1		2												
2	-4		-1											
3				-2										
4	-10				2									
5						-16								
6	9						20							
7								-17						
8	2								7					
9										-20				
10	12										4			
11												16		
12	3													
13														1
	0	1	2	3	4	5	6	7	8	9	10	11	12	13

Table X. Calculated from Experimental Deviations for Fission Rate Distribution.
Lattice N 129 (12.7/3.6/0.0/K331). Printed in 1000*(C-E)/E.

1		-1											
2			-5										
3		-4											
4			3		-11								
5		5		-2		-18							
6			2		7								
7		3		-1		7		-2					
8	-10		-3		4		12		4				
9		-15		-8		-17		-4		-2			
10	3		3		-6			11		-1			
11													
12	9		22		15		4		8		8		
13		-16		-7		5				4		-1	
14								-12			8		-19
	0	1	2	3	4	5	6	7	8	9	10	11	12

Table XI. Calculated from Experimental Deviations for Fission Rate Distribution.
Lattice N 130 (12.7/3.6/0.0/K331). Printed in 1000*(C-E)/E.

1		-9											
2	-12		-18										
3		1											
4			2		-9								
5		-15				-13							
6			6		-1								
7		15		7		4		-6					
8	20		26		-5								
9		-5		-12		-19				4			
10	-2		-6		1		9				11		
11													
12	13		11		11		10		6		18		
13		2		-4		1		-7		-9		-3	
14											-14		-1
	0	1	2	3	4	5	6	7	8	9	10	11	12

CONCLUSIONS

Evaluators[2] consider that typical errors (standard deviations) of ZR-6 experiments are: a few cents for the criticality data and 1% for the fission rate distributions, taking into account that standard deviations of K_∞ and B^2_m due to the actual technological uncertainties are 0.16-0.39% for K_∞ and 0.7-1.98% for B^2_m (Table 11c in reference 2).

Average values of K_{eff} -1 and mean-root-square deviations calculated by the MCU-REA code are:

Parameters	$(K_{eff}-1)_{Av-2D}$	σ_{2D}	$(K_{eff}-1)_{Av-3D}$	σ_{3D}
Values	-.001	.004	.000	.004

Good agreement of 3D and 2D calculational and experimental results permits one to conclude:

- the MCU-REA code and its nuclear data libraries have the accuracy high enough to use them for VVER calculation.
- the 2D model of the ZR-6 facility is reliable enough:

$$(K^{3D}_{eff}-K^{2D}_{eff})_{Av} = 0.001;\ \sigma_{(3D-2D)} = 0.003.$$

- fission rate distributions are predicted by MCU-REA code with the uncertainty about 3%.

During the work an electronic atlas[8] of the ZR-6 critical facility has been developed.

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