KINETIC TRANSIENT EXPERIMENTS FOR THE RBMK DESIGN

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ABSTRACT

The paper presents a review of experimental data in a form of steady-state and transient neutron fields and reactivity effects obtained in the RBMK critical facility and during the physical start-up of the RBMK reactor of the Smolensk nuclear power plant Unit 3. All these experiments were performed at room temperature. The purpose of experiments was to obtain data for non-stationary neutron-code validation. The transients generated by a movement of control rods in a “cold” reactor having more non-uniform neutron fields are very important for the nuclear criticality safety. A comprehensive certification of the core components and analysis of experimental accuracy were made for experiments in the RBMK critical facility with the fragment of an initial loading of a reactor. Experiments in the RBMK reactor give a full-scale mockup.

1. INTRODUCTION

The RBMK reactor is a uranium-graphite reactor of one million kilowatts electric capacity. Now RBMK nuclear power plants (NPP) produce more than 50 % of the nuclear electricity production in Russia.

A large complex of neutron experiments was performed at the Russian Research Center “Kurchatov Institute” during the period of the RBMK design development and improvement. Different critical masses were investigated in the RBMK critical facility [1-4]. Such experiments permited to obtain comprehensive data for stationary neutron-code validation.

The RBMK reactor had become the object of intense safety studies since the Chernobyl accident. Different non-stationary neutron-codes were became to employ for analysis of kinetic transients in a core. Our paper presents a review of experimental data in a form of steady-state and transient neutron fields and reactivity effects obtained in the RBMK critical facility and during the physical start-up of the RBMK reactor of the Smolensk NPP Unit 3. The metering KENTAVR systems were used for these experiments [5]. These systems have large number measuring channels with intracore chambers and permit to conduct measurements and processing of chamber signals for a stationary critical state and during an insertion or a withdrawal of control rods. Reactivities are determined by such system too. Earlier part of presented reactivity results were discussed [5].

All experiments were performed at room temperature. The transients generated by a movement of control rods in a “cold” reactor having more non-uniform neutron fields are very important for the nuclear criticality safety. The standard power distribution monitoring system of the RBMK reactor with hafnium or silver sensors permits to conduct measurements of neutron fields at power above 5 %.

A comprehensive certification of the core components and analysis of experimental accuracy were made for experiments in the RBMK critical facility with the fragment of an initial loading of a reactor. Experiments in the RBMK reactor give the full-scale mockup. The present experimental data can be used for non-stationary neutron-code validation [6, 7].

2. EXPERIMENTS IN THE RBMK CRITICAL FACILIY

2.1 DESCRIPTION OF THE CRITICAL FACILITY

The RBMK critical facility was constructed at the Russian Research Center “Kurchatov Institute”. It is the physical mockup of a RBMK power reactor [2]. Experiments are performed at room temperature. The maximum power of the RBMK critical facility is 25 watts.

The graphite stack is close to a cube in shape. The size of the whole stack is 4.5x4.5 m in the base dimension and 4.1 m high. The stack consists of 324 (18x18) vertical graphite columns. The columns are assembled with rectangular graphite blocks having vertical cylindrical openings through the center. Aluminum channels are placed in all central openings of graphite columns. The channel lattice pitch is 0.25 m.

Fuel assemblies, additional absorbers, control rods and control rod imitators are loaded inside the channels. All elements of the core are identical to similar elements of the RBMK reactor. But the height of the core is half that of the reactor. The fuel assembly consists of 18 fuel pins (uranium dioxide of 2 % enrichment) located on two coaxial circles surrounding a central supporting tube. The height of the core is 3.46 m. Top and bottom reflectors are 0.32 m thick. The additional absorber is constructed from an internal steel tube with boron steel absorbing sleeves. The control rod consists of three standard cylindrical sections. Each section includes two concentric aluminum tubes with boron carbide sleeves. The control rod imitator is similar to the control rod.

The experiments were performed in a critical configuration with 256 channels (Figure 1). It is the fragment of the initial loading of the reactor. The periphery graphite columns are the radial reflector. The core of this configuration consisted of 192 fuel assemblies, 32 additional absorbers, 6 control rod imitators and 22 control rods. These 22 control rods included 7 emergency protection rods, 8 compensatory control rods and 7 manual control rods. Only manual control rods and compensatory control rods were moved during experiments. But emergency protection rods were maintained at the fully withdrawn positions. The fuel and additional absorber channels were both filled with water. All other channels were without water.

2.2 KENTAVR SYSTEM FOR THE CRITICAL FACILITY

The experimental data in a form of steady-state and transient neutron fields and reactivities were obtained by the KENTAVR-CF system [5]. This system permits to conduct measurements and processing of chamber signals for a stationary critical condition and during an insertion or a withdrawal of control rods at neutron flux ~$(10^5\text{-}10^7)$ n/(cm^2·s). The system consists of 68 linear measuring channels with small-size fission chambers. The chambers are placed in special channels of the stack at corners of graphite blocks. There are 56 chambers at the middle of the stack height for measurements of the radial neutron-flux distribution. In two channels there are two high strings for measurements of axial neutron-flux distributions. Each string contains seven chambers located every 0.5 m. The middle chamber of the string is placed at center of the core height and is used for the radial suite of chambers too. During each measurement it is possible to record signals of all chambers via 0.32 second for hundred states. Reactivities are determined by solving the inverse point-kinetic equation by a computer using signals of any chambers.

2.3 RESULTS OF EXPERIMENTS

The results of 10 experiments in the critical configuration with the fragment of the initial loading of the RBMK reactor are presented in Table 1. In all experiments the steady-state and transient neutron fields and reactivities were measured by the KENTAVR-CF system. The Table 1 gives: the position of control rods for just critical condition, the type of perturbation and activated control rods, the nonuniformity factors in radial (k_R) and axial (k_Z) directions for critical and subcritical (at 15 second after perturbation) states, the coordinate of chamber with maximum aspect for radial and axial distributions of neutron fields, the inserted reactivity.

The standard compensation for the just critical condition was used in experiments N1-5. For this case the axial neutron-flux distribution has practically symmetric profile with $k_Z = 1.39$. The maximum of the radial neutron-flux distribution is at the center region of the configuration and $k_R = 1.75$. In experiments N1-5 the drops of 1 (three cases with different worth of the control rod), 4 and 12 control rods were investigated. In the experiment N6 for nearly standard compensation, first, one control rod was withdrawn, then eleven control rods were dropped. In the experiment N7 the compensation permitting to displace the axial neutron field to the bottom half of the core was considered. For this purpose 13 control rods were inserted to half depth in the core. Then 15 control rods were dropped. The displacements of the radial neutron field to the right, caudal corner of the configuration were considered in experiments N8, 9 and 10. The increase of the radial nonuniformity factor to $k_R = 2.16$ was obtained in the experiment N9. For this case the displacement of the axial neutron field to the bottom half of the core was observed. In the experiment N10 the maximum radial nonuniformity factor (k_R = 2.29) was obtained. For this purpose the fuel assembly of the central channel was withdrawn and this channel was filled with water. In experiments N8, 9 and 10 five control rods were dropped. For these cases, after the drop of control rods the maximum of subcritical radial neutron field was displaced back to the center region of the core.

For each experiment the sequence of measurements was following. First, background signals of chambers were measured for the subcritical state. The configuration was made supercritical, then just critical at the necessary power. After compensation the steady-state neutron field was measured a few times. For this case the standard deviations of the relational neutron-flux distribution were equal to ~(1-2) %. Then transient measurements were performed. The recording of chamber signals was started of 1-2 seconds before a motion of control rods and was performed during 32 seconds. The time of the insertion of control rods to the bottom-end switch was nearly 2 seconds. Usually main changes of the profile of neutron field were finished during a few seconds after the end of motion of control rods. But for subcritical states the ratio of useful signal of chamber to the background was quickly decreased and uncertainties of the relational neutron-flux distribution were increased. At 15 second after the start of motion of control rods the uncertainties of the relational neutron-flux distribution are evaluated ~3 % for reactivity ≤1 β_{eff} and ~10 % for reactivity ~5 β_{eff}. The examples of the steady-state and transient neutron fields obtained in the experiment N2 are given in the Figure 2.

3. EXPERIMENTS IN THE RBMK REACTOR

3.1 DESCRIPTION OF THE RBMK REACTOR CORE

The graphite stack of the RBMK is close to a tall hat in shape. The sizes of the whole stack are 11.8 m diameter and 8 m height. The stack consists of 2488 vertical graphite columns. The core contains 1884 columns with vertical channels, which are used for loading of fuel assemblies, additional absorbers, control rods and special devices. The periphery graphite columns with graphite rods are the radial reflector. The fuel assembly consists of two sections the same construction as for the RBMK critical facility. Therefore the height of the core is 7 m, top and bottom reflectors are 0.5 m thick. There are 1661 channels containing fuel assemblies and additional absorbers, which are cooled by the main coolant circuit. Three types of control rods are used: 155 manual control rods, 24 fast scream rods, 32 short bottom absorber rods. The manual control rods and fast scream rods are inserted from the top of the reactor, but short bottom absorber rods are inserted from the bottom of the core. The manual control rod and the short bottom absorber rod have a displacer that removes water in the channel with rod withdrawn to the top-end switch. The fast scream rod does not contain a displacer. The channels with control rods are cooled by the control and protection system circuit.

3.2 KENTAVR SYSTEM FOR THE REACTOR

The KENTAVR-NPP system was made for measurements of steady-state and transient neutron fields in the "cold" zero-power reactor of the Smolensk NPP Unit 3 [5].

The system consists of 74 linear measuring channels with small-size fission chambers and 8 logarithmic channels with high-sensitive fission chambers. The linear measuring channels provide measurements of neutron flux ~ $(10^{7}\text{-}10^{9})$ n/(cm^{2}·s). Forty-two linear measuring channels were employed for six high strings located in empty dry channels of the main coolant circuit. Each high string contained 7 chambers located every 1 m. The middle chamber of the high string was placed at center of the core height. Thirty-two linear measuring channels were employed for measurements of radial neutron field. The chambers of these channels were placed in central supporting tubes of fuel assemblies and were 1 m above the middle of the core height. The logarithmic channels provide measurements of neutron flux ~ $(10\text{-}10^{9})$ n/(cm^{2}·s). These chambers were located in empty dry channels of the main coolant circuit. It is possible to record signals of all chambers via 0.4 or 0.6 second for hundred conditions. Reactivities are determined by solving the inverse point kinetics equation by computer.

3.3 RESULTS OF EXPERIMENTS

During formation of the initial loading the large volume experiments was performed in the "cold" zero-power reactor of the Smolensk NPP Unit 3 using the KENTAVR-NPP system. The results of 10 experiments are given in Table 2. For these experiments the loading of the reactor consisted of 1371 fuel assemblies, 234 additional absorbers, 46 water columns and 10 dry channels with chambers of the KENTAVR-NPP system. The main coolant circuit and the control and protection system circuit were with or without water. Twenty-four fast cream rods were maintained at fully withdrawn positions, and 32 short bottom absorber rods were inserted to 4.0 m by indicators. Number of withdrawn manual control rods for just critical conditions are given in Table 2. The measurements of steady-state neutron fields for just critical conditions and transient neutron fields for drops all withdrawn manual control rods (experiments N1, 4, 8, 10), one manual control rod in central region of the core (experiment N2, 6, 9), one manual control rod in periphery (experiment N7), one fast scream rod (experiment N5) were performed. The simultaneous insertion of 32 short bottom absorber rods of 3.5 m to 4.0 m was performed in the experiment N3.

The standard deviations of the relational neutron-flux distribution for just critical conditions were less 1 %. The time of the insertion of manual control rods to the bottom-end switch was ~16 seconds for case the control and protection system circuit with water, but ~12 seconds for dry channels with control rods. The time of the drop of fast scream rods was equal to ~5 seconds for both cases. The fast scream rods are cooled with water film. The main changes of the profile of neutron field were finished at approach of control rods to the bottom-end switch. For this moment the uncertainties of the relational neutron-flux distribution are evaluated ~(3-5) % for the insertion of one control rod or 24 short bottom absorber rods (reactivity ≤0.3

β_{eff}) and ~10 % for the drop of all withdrawn manual control rods (reactivity from ~2 β_{eff} to ~6 β_{eff}). The examples of the steady-state and transient neutron fields obtained in the experiment N1 are given in the Figure 3.

CONCLUSIONS

The study of the transient neutron fields is important task for substantiation of the nuclear criticality safety .

The multichannel KENTAVR systems allowed to measure the steady-state and transient neutron fields in the RBMK critical facility and during the physical start-up of the RBMK reactor.

The obtained experimental data can be the ground for non-stationary neutron-code validation.

REFERENCES

1. E. V. Burlakov, G.B. Davydova, V.M. Kachanov, et al., “Critical Experiments Performed for Validation and Improvement of the RBMK Design”*, Transactions of the American Nuclear Society*, **77**, pp. 380-382 (1997).

2. E.V. Burlakov, V.E. Jitarev, V.M. Kachanov, et al., “Critical Benchmark Experiments for the RBMK Design”, *Proceedings of International Conference on the Physics of Nuclear Science and Technology*, Long Island, New-York, USA, October 5-8, 1998, **2**, pp. 946-953 (1998).

3. E.V. Burlakov, V.E. Jitarev, V.M. Kachanov, et al., “ Experiments for Substantiation of RBMK Control Rods Modernization after Chernobyl Accident”, *Proceedings of the Sixth International Conference on Nuclear Criticality Safety*, Versailles, France, September 20-24, 1999, **1**, pp. 130-139 (1999).

4. E.V. Burlakov, A.V. Glembotsky, V.M. Kachanov, et al., “An Analysis of the Experiments with Erbium for the RBMK Design”, *SD ROM-proceedings of International Topical Meeting on Advanced in Reactor Physics and Mathematics and Computation into the Next Millennium*, Pittsburgh, USA, May 7-12, 2000.

5. A.N. Kuzmin, V.M. Kachanov, V.E. Jitarev, et al., “KENTAVR Complexes – Universal Equipment for the Control and Measurement of RBMK Neutron Parameters”, *SD ROM-proceedings of Fifth International Information Exchange Forum on Safety Analysis for Nuclear Power Plants of VVER and RBMK Types*, Obninsk, Russia, October 16-20, 2000.

6. A.V. Krayushkin, G.B. Davydova, A.V. Glembotsky, et al., “Re-analysis of the Transient Benchmarks Based on RRC KI Critical Facility Experiments”, *Report of RRC KI*, Moscow, 2000.

7. B.R. Sehgal, H.W. Cheng, A. Romas “Validation of the ARROTTA Code Against Experimental RBMK Critical Facility Data”, *SD ROM-proceedings of International Topical Meeting on Advances in Reactor Physics and Mathematics and Computation into the Next Millennium*, Pittsburgh, USA, May 7-12, 2000.

Table 1. Experiments in the Critical Facility

. N	Compensation at just critical condition					Activated control rods	At 15 sec. after perturbation		
	Position of control rods			k_R	k_Z		k_R	k_Z	Reactivity (β_{eff})
	Fully withdrawn	Fully inserted	Partly inserted						
1	MR3,4,5,7 CR1,2,3,4,5,6,7	MR1,6,8	CR8-1.95 m [a]	1.75 (10-10)[b]	1.39 (4)[c]	Drop of 4 rods: MR4,5,7; CR3	1.94 (10-10)	1.37 (4)	-0.63
2	MR3,4,5,7 CR1,2,3,4,5,6,7	MR1,6,8	CR8 - 1.95 m	1.75 (10-10)	1.39 (4)	Drop of CR7	1.66 (4-12)	1.37 (4)	-1.11
3	MR3,4,5,7 CR1,2,3,4,5,6,7	MR1,6,8	CR8 - 1.95 m	1.75 (10-10)	1.39 (4)	Drop of CR4	1.81 (10-10)	1.39 (4)	-0.17
4	MR3,4,5,7 CR1,2,3,4,5,6,7	MR1,6,8	CR8 - 1.95 m	1.75 (10-10)	1.39 (4)	Drop of CR8	1.88 (10-10)	1.43 (4)	-0.50
5	MR3,4,5,7 CR1,2,3,4,5,6,7	MR1,6,8	CR8 - 1.95 m	1.75 (10-10)	1.39 (4)	Drop of 12 rods: MR3,4,5,7 CR1,2,3,4,5,6,7,8	1.90 (10-10)	1.39 (4)	-4.29
6	MR3,4,5,7 CR1,2,3,5,6,7	MR1,6,8 CR4	CR8 - 1.55 m	1.75 (10-10)	1.39 (4)	Withdrawal of CR8; after 10 sec drop of 11 rods: MR3,4,5,7 CR1,2,3,5,6,7,8	1.75 (10-10) 2.15 (10-10)	1.40 (4) 1.37 (4)	+0.25 -4.04
7	MR1 CR7	—	MR4,5,6,7, 8-2 m CR1,2,3,4, 5,6,8-2 m MR3-1.75 m	1.83 (10-10)	1.40 (4,5)	Drop of 15 rods: MR1,3,4,5,6,7,8 CR1,2,3,4,5,6,7,8	2.13 (10-10)	1.36 (4)	-4.53
8	MR3 CR2,4,5,6,7,8	MR1,4, 5,7,8 CR1,3	MR6 -2.25 m	1.83 (10-10, 6-12)	1.32 (4)	Drop of 5 rods: MR3,6;CR2,4,8	2.21 (10-10)	1.36 (4)	-2.94
9	MR3,4,5,6,7,8 CR1,2,3,4,5,6	MR1 CR 8	CR7 -2.15 m	2.16 (6-14)	1.35 (5)	Drop of 5 rods: MR3,6,8;CR2,4	1.76 (10-10)	1.37 (6)	-2.72
10	MR3, 6 CR2,4,5,6,7,8	MR1,4, 5, 7 CR1,3	MR8 -1.75 m	2.29 (4-12)	1.33 (4)	Drop of 5 rods: MR6,8;CR2,4,8	2.13 (10-14)	1.35 (4)	-3.11

[a] – position of control rod by indicator.

[b] - coordinate of radial chamber with maximum aspect.

[c] - number of axial chamber with maximum aspect

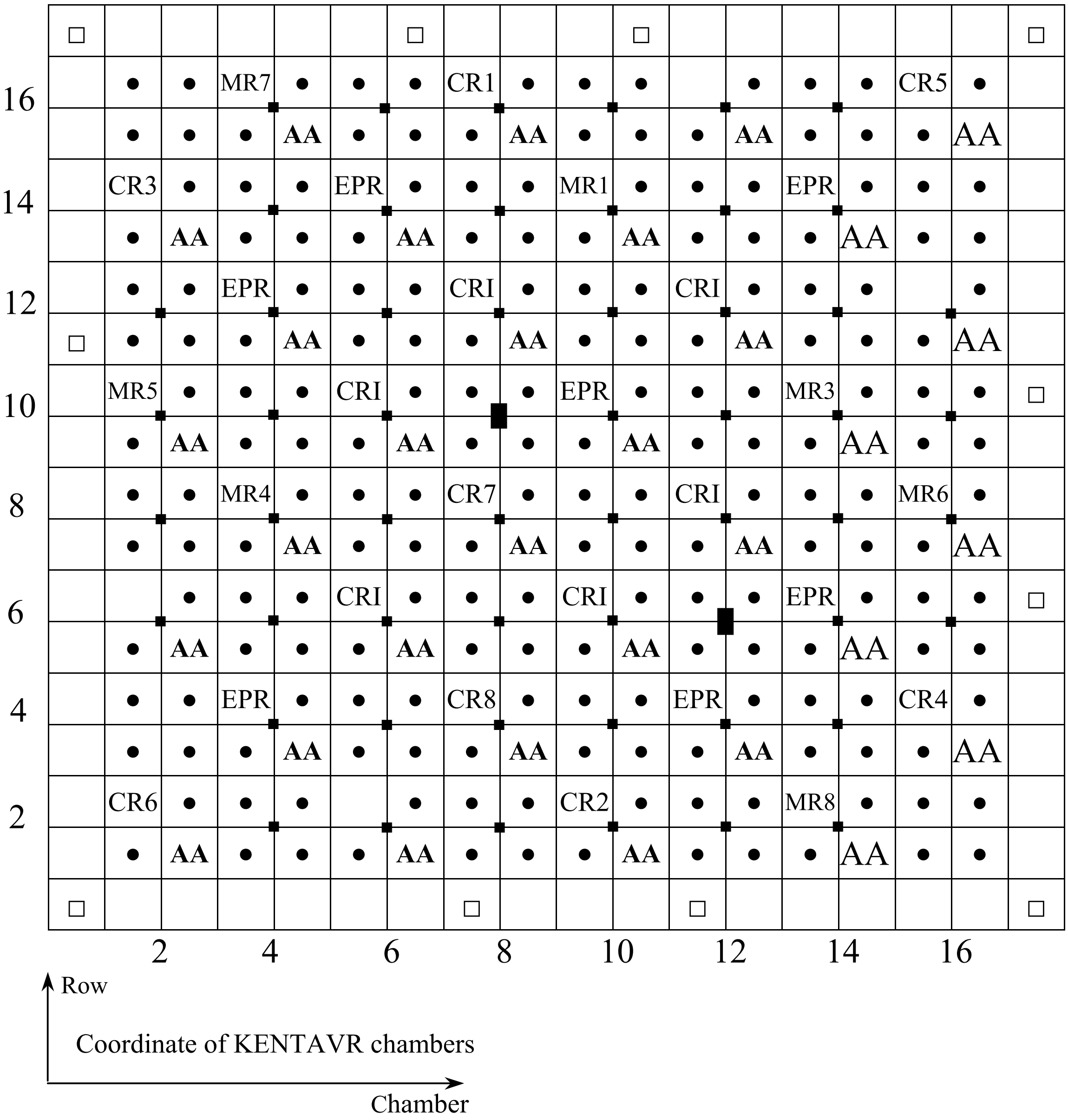
MR - manual control rod.

CR - compensatory control rod.

Table 2. Experiments in the Reactor of the Smolensk NPP Unit3

Exp. N	Presence of water in channels		Compensation at just critical condition 24 FSR – TES, 32 SBAR – 4 m			Dropped control rods	Subcritical condition		
	Main coolant circuit	Control and protection system circuit	Number of withdrawn MR	k_R	k_Z		k_R	k_Z	Reactivity (β_{eff})
1	yes	yes	32.3	1.87 (54-15)[a]	1.56 - 1.65 (3)[b]	32.3 MR	1.89 (54-15)	1.64 - 1.76 (2,3)	-2.04
2	yes	yes	32.3	1.87 (54-15)	1.56 - 1.65 (3)	MR (32-45)[c]	1.95 (54-15)	1.56 - 1.65 (3)	-0.02
3	yes	yes	25.4	2.97 (54-15)	1.63 - 1.72 (3)	32 SBAR[d]	3.15 (54-15)	1.58 - 1.67 (3)	-0.30
4	yes	no	29.3	2.46 (54-15)	1.78 - 1.88 (2, 3)	29.3 MR	2.43 (54-15, 64-35)	1.77 - 1.89 (2,3)	-2.81
5	yes	no	29.3	2.46 (54-15)	1.78 - 1.88 (2, 3)	FSR (26-25)	2.57 (54-15)	1.80 - 1.88 (2,3)	-0.05
6	yes	no	29.3	2.46 (54-15)	1.78 - 1.88 (2, 3)	MR (32-45)	2.56 (54-15)	1.83 - 1.87 (2)	-0.01
7	yes	no	29.3	2.46 (54-15)	1.78 - 1.88 (2, 3)	MR (60-17)	2.15 (64-47)	1.83 - 1.87 (2)	-0.11
8	no	yes	58.0	1.74 (34-35)	1.48 - 1.52 (3)	58 MR	1.88 (34-35, 24-35)	1.53 - 1.71 (3)	-5.49
9	no	yes	58.0	1.74 (34-35)	1.48 - 1.52 (3)	MR (32-45)	1.61 (34-35)	1.48 - 1.49 (3)	-0.08
10	no	no	50.4	2.11 (24-55)	1.70 - 1.77 (2, 3)	50.4 MR	1.97 (24-35)	1.91 (3)	-6.45

[a] - coordinate of radial chamber with maximum aspect
[b] - number of axial chamber with maximum aspect
[c] - coordinate of control rod
[d] – in the experiment N3 initial position of 32 SBAR – 3.5 m, after insertion – 4.0 m
MR – manual control rod
FSR – fast scram rod
SBAR – short bottom absorber rod
TES – top-end switch



□						□				□							□
	●	●	MR7	●	●	●	CR1	●	●	●		●	●	●	CR5	●	
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	CR3	●	●	●	EPR	●	●	●	MR1	●	●	●	EPR	●	●	●	
	●	AA	●	●	●	AA	●	●	●	AA	●	●	●	AA	●	●	
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	MR5	●	●	●	CRI	●	●	●	EPR	●	●	●	MR3	●	●	●	□
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	●	●	EPR	●	●	●	CR8	●	●	●	EPR	●	●	●	CR4	●	
	●	●	●	AA	●	●	●	AA	●	●	●	AA	●	●	●	AA	
	CR6	●	●	●		●	●	●	CR2	●	●	●	MR8	●	●	●	
	●	AA	●	●	●	AA	●	●	●	AA	●	●	●	AA	●	●	
□							□				□						□

● fuel assembly,
AA additional absorber,
CRI control rod imitator,
EPR emergency protection rod,
MR1 manual control rod,
CR1 compensatory control rod,
□ chamber of control and protection system,
empty channel,
■ radial chamber of KENTAVR system,
▮ high string of KENTAVR system.

Figure 1. Loading Diagram of Configuration in the RBMK Critical Facility.

At just critical condition

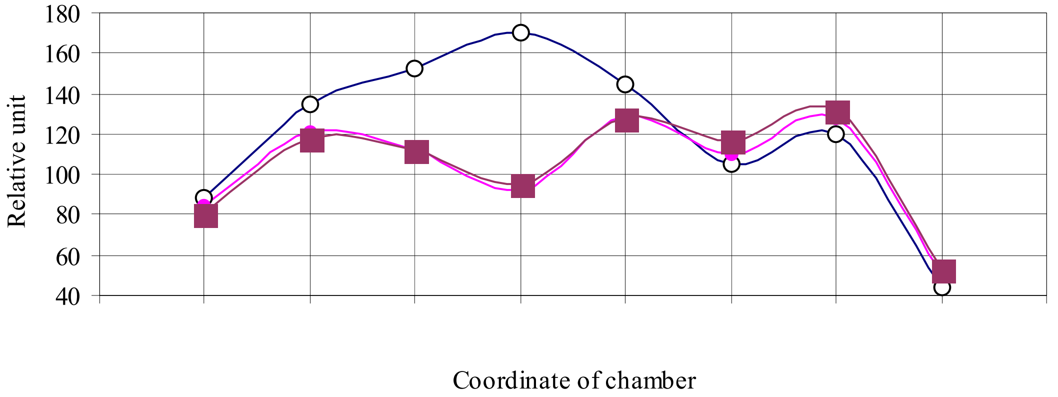
Radial

Row / Chamber	2	4	6	8	10	12	14	16
16		52	62	50	42	46	46	
14		98	104	81	62	82	83	
12	79	117	117	94	126	89	110	68
10	82	122	109	168	175	136	124	58
8	88	135	152	170	145	105	120	44
6	76	117	102	148	111	149	133	63
4		107	121	124	145	144	98	
		61	84	86	90	69	32	

Axial

Chamber / String	1	2
1	41	43
2	90	89
3	125	120
4	139	138
5	134	137
6	108	110
7	63	63

Radial transient



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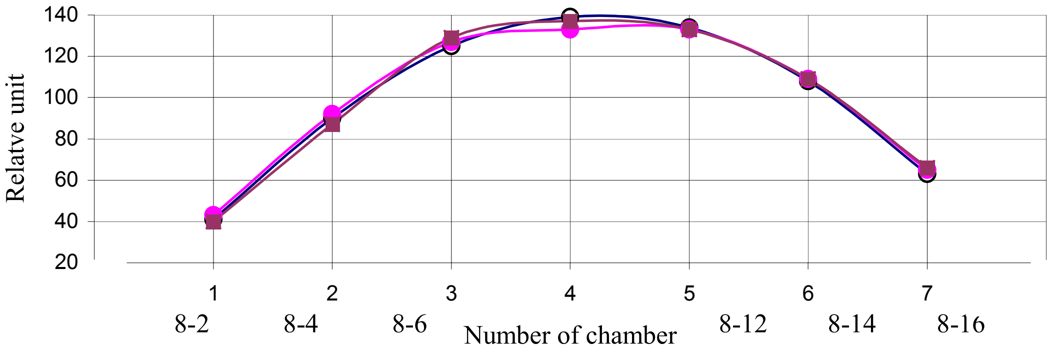


○ - 0 sec, CR7 – TES, ● - 3.18 sec, CR7 – BES, ■ - 16.60 sec, CR7 – BES
CR – compensatory control rod, TES – top-end switch, BES – bottom-end switch

Figure 2. Neutron Fields in the Reactor (Experiment 2).

At just critical condition

Radial

Channel						
64		135	160	154	71	
54	187	157	109	83	138	96
44	109	92	55	82	101	100
34	99	107	85	82	107	67
24	80	112	122	74	73	50
14		93	109	71	42	
Row	15	25	35	45	55	65

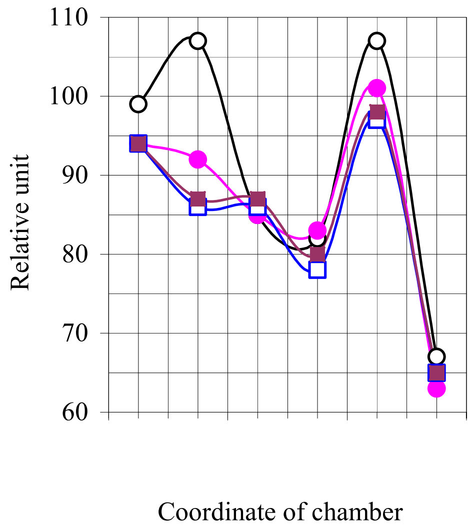
Axial

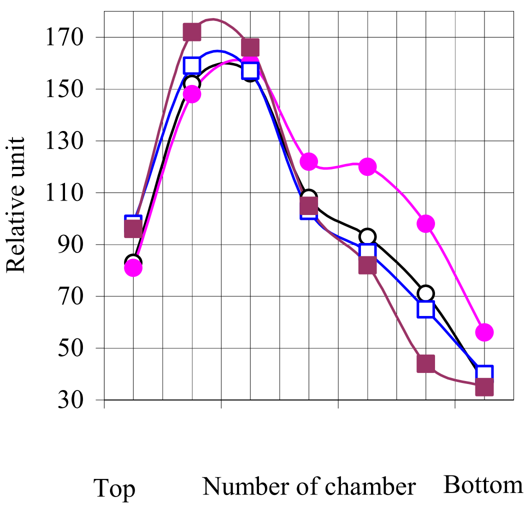
String

Chamber		2	3	4	5	6
1	74	72	72	83	77	73
2	151	147	144	150	148	142
3	161	163	165	156	160	159
4	113	109	120	108	106	107
5	92	98	93	93	96	97
6	73	74	70	73	74	77
7	36	37	37	36	39	45

Transient

Radial **Axial**





○ - 0 sec, MR – TES, ● - 5.48 sec, MR – 2.2 m, □ - 11.40 sec, MR – 4.6 m, ■ - 16.34 sec, MR – BES
MR – manual control rods, TES – top-end switch, BES - bottom-end switch

Figure 3. Neutron Fields in the Reactor (Experiment 1).