AN ANALYSIS OF THE EXPERIMENTS WITH ERBIUM FOR THE RBMK DESIGN

E. V. Burlakov
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
Fax: (007) 095 196 96 68

A.V.Glembotsky
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 72 33

G.B. Davydova
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 75 82

V. E. Jitarev
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 98 94

V. M. Kachanov
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
E-mail: galina@peerog.vver.kiae.ru

A. N. Kuzmin
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 97 31

A.V. Krayushkin
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 75 82

A.M. Fedosov
RRC «Kurchatov Institute»
Kurchatov Sq., 1
Moscow 123182, Russia
(007) 095 196 78 03

ABSTRACT

The paper presents two series of the experiments in the critical facility performed to examine a standard RBMK fuel load and a load with erbium poison. The rods filled with erbium oxide powder and installed in a fuel assembly were used for the modeling of an erbium fuel. The experiments were performed under room temperature. The goal of the experiments was to determine the influence of erbium on the void reactivity effect and to give the data for neutron codes validation. The disagreement between the results of the experiments and calculations was obtained for some experiments. To explain this disagreement the direct modeling of the experiment in space and time was performed by STEPAN code. Besides the pulsed neutron source method was used for a number dehydrated assemblies to make measurements more accurate. The MCNP4A code was chosen for final calculated analyses of the experiments. Qualitative confirmation of calculated predictions was obtained, however discrepancy in estimations of reactivity effects was not always within interval of errors.

1. INTRODUCTION

The fuel with erbium burnable poison begins to be used in the nuclear power plants with RBMK reactor [1]. Now the implementation of erbium poisoned fuel is a very important direction of RBMK safety and fuel cycle improvement. After Chernobyl accident the special safety measures for RBMK reactor were taken. The load of 80 boron additional absorbers and the increase of operative reactivity margin permit to decrease the void reactivity coefficient to +0.8 β_{eff}. This measures were effective for safety but not good from the point of view of economy.

The investigations performed last years sought for a more economical way of achievement the same level of safety [2, 3]. Many possible ways were considered and it was decided to implement a new type of fuel with erbium burnable poison. The resonance in the absorption cross-section of erbium-167 at the energy 0.47 electron volt is the main feature of erbium. Due to its resonance erbium may have strong influence on the void reactivity coefficient. In power condition the neutron spectrum moves to the higher energy under channels dehydration and such a way the absorption is increased. Besides due to erbium poison the non-uniformity of power distribution may be decreased.

Before erbium fuel implementation it was very important to have experimental confirmation of calculated predictions. This is why it was decided to make experiments in the RBMK critical facility. It was impossible at that time to fabricate fuel with erbium poison for the experiments. So erbium rods were proposed to use. These erbium rods may be installed in the fuel assembly central tube or between fuel pins. The experiments were performed under room temperature. The goal of the experiments was to determine the influence of erbium on the void reactivity effect under room temperature and to give the data for neutron codes validation.

Calculated analysis of the first experiments was performed by the MDC code. The experiments and calculations have shown the sufficient agreement almost for all cases. But for one case the opposite tendency was obtained. The calculations have predicted the increase modulus of the void reactivity effect for uniform distribution of separate fuel assemblies with erbium along the core. The experiments have given the large decrease of the void reactivity effect. The calculations by the MCNP4A code gave the same results [4]. This disagreement might be due to incorrect measurements for cases with large values of supercriticality and subcriticality or calculation inaccuracy. On the one hand to explain this contradiction it was suggested to perform the direct modeling of the experiments in space and time using the STEPAN code. On the other hand it was decided to repeat measurements of the subcriticality using a pulsed neutron source method. The MCNP4A code was decided to use too. The results of the first and second series of the experiments and their calculated analysis are described in this paper.

2. RBMK FACILITY

The critical facility reflects the typical construction of a RBMK-type reactor[5, 6]. The graphite stack of the facility has the sizes 450x450x410 cm. The stack is penetrated by 324 (18x18) vertical holes, which are located in square lattice with 25 cm pich. Channel tubes, fuel assemblies, additional absorbers, control rods are identical with similar elements in a reactor. But the height of the core is equal to a half of the reactor one. The basic full-scale load of the facility consists of 192 fuel assemblies with fresh uranium dioxide 2 % enrichment, 32 additional absorbers, 6 motionless control rod simulators and 22 control rods. These channels form the RBMK-like polycell structure facility core. The erbium rod is a chain of three stainless-steel tubes filled with erbium oxide powder. Forty erbium rods can be used in the experiments.

3. INSTRUMENTS FOR MEASUREMENT OF REACTIVITY

The special instruments were used for measurement of reactivity by a method of inverse point kinetic equations. The reactimeter which works with the sum signal of four ionisation chambers located in the channels of a radial reflector and the multichannel KENTAVR meter were used[7]. The KENTAVR meter has 68 channels with small fission chambers located uniformly in the core. The software is capable to manage signals of chambers in steady-state and transient conditions. It is possible to write signals each 0.32 sec. The reactivity may be obtained by the recalculating of the transient signals. A relative neutron distribution may be obtained from steady-state signals. The number of KENTAVR chambers is more than enough to determine reactivity practically without possible space effects.

The pulsed neutron source method was used for measurements of an assembly subcriticality in the subcritical conditions. A constant of a exponential decrease of a prompt neutrons flux during time is determined in the experiment after operation of the pulsed neutrons source according to the reading of neutron chamber[8]. The subcriticality is determined according to the formula:

$$\frac{\rho}{\beta_{eff}} = 1 + \alpha \frac{\Lambda}{\beta_{eff}} \qquad (1)$$

It is necessary to know a parameter Λ/β_{eff} for the determination of the subcriticality. Its value can be determined if to measure the significance of a dumping decrement for a assembly condition with the known subcriticality or by a calculated code. The pulsed method equipment consists of a pulsed neutron generator and a system for detection and time selection of neutrons with four fission chambers.

4. THE CODES USED

Several codes were used for the calculation analysis of the experiments. The basic code for a neutron-physical calculation of the RBMK lattice is the STEPAN code[9]. The STEPAN code is a two-group three-dimensional diffusion code capable to solve both steady-state and dynamic tasks. Two-group neutron cross-sections prepared by the WIMS-D4 code are used. Time-dependent two-group equations are solved to obtain neutron parameters in space and time. The value of reactivity during this time-dependent modeling are determined in a special routine of the code. The inverse point kinetic equations are solved in this routine in the same manner as in a reactimeter. Calculated neutron fluxes from points where chambers of a reactimeter are placed can be used as an input signal for this routine. Such an approach permits to obtain in the calculation exact analogue of a measured value. Besides an integral neutron flux around the core is used to determine the value of reactivity without possible space effects. The calculated analysis of some experiments was performed by steady-state and transient versions of the STEPAN code.

The first calculations of the premier experimental series were performed by the MDC code, which is a two-dimensional modification of the steady-state version of the STEPAN code made specially for critical facility calculations. The two-group neutron cross-sections were prepared by the WIMS-D4 in the same manner as it does for standard STEPAN library. For compare the experimental results with calculations the value of an effective delay neutron fraction is equal to 0.0071 was used [10] .

The Monte Carlo MCNP4A code is chosen for calculation analysis of the experiments too[11]. Since 1993 the MCNP4A code is in using in the Russian Research Center "Kurchatov Institute" for RBMK reactor calculations. The special efforts were undertaken to produce the RBMK-oriented cross-section library. The cross-section library used for the present calculations is based on ENDF/B-6 and has been processed by NJOY code. The applicability of the MCNP4A code to RBMK-like systems and specifically to the RBMK critical facility calculations was successfully validated [12] . It was shown that detailed modeling of the assembly geometry and material compositions allows to simulate critical experiments with sufficient reliability. The effective delay neutron fraction was calculated for different assemblies and was equal to 0.00720 for water-filled assemblies and 0.00728 for dehydrated ones.

5. THE FIRST SERIES OF THE EXPERIMENTS

The main goal of the first experiments was to determine the influence of erbium on the value of the void reactivity effect. It was possible to measure it for fresh fuel and room temperature. Several critical assemblies were investigated to realize this goal taking into account the small amount of erbium rods available. The full-scale critical assembly without erbium rods was used as the initial system N1. To simulate an erbium containing load erbium rods were placed into central tubes of some fuel assemblies within the load of the system N1. For the case of a compact placement of fuel assemblies with erbium rods the two-zone approach was used. The square fragments 5x5 and 7x7 cells were chosen in the central part of the facility. All fuel channels of these fragments were supplied by erbium rods in the central tube of fuel assemblies. The obtained critical assemblies consisted of 19 and 37 fuel assemblies with erbium (systems N2 and N3). The uniform distribution of separate fuel assemblies with erbium along the core was investigated too. Forty or thirteen erbium rods were installed in the central tubes of the fuel assemblies (systems N4 and N5). In additional case the same thirteen fuel assemblies contained three erbium rods between the fuel pins (system N6). The dehydration of various groups of fuel channels was performed in the measured systems: all 192 fuel channels, 19 fuel channels of a central fragment (5x5 cells), 37 fuel channels of a central fragment (7x7 cells), 40 or 13 fuel channels uniformly distributed along the core. Experiments were performed under two positions of control rods: all control rods were on the top end switch; four control rods were on the bottom end switch, other rods are withdrawn.

The reactivity margins, the position of control rods in critical conditions, the subcriticalities, the efficiency of control rods, neutron fields were determined in the experiments. The following methods of reactivity measurement were applied : a control rod drop method, a power rise method, an alternate compensation method, a criticality-from dewatering method. The control rod drop method was used for measurements with the KENTAVR meter. Other methods were used with the reactimeter. The calculations of the experiments were performed by the MDC code. The results of the experiments and calculations are given in Table I.

The experiments have not shown the change of the negative void reactivity effect after insertion of erbium rods within the interval of errors. The calculated results have shown the small decrease of the absolute value of the negative void reactivity effect after insertion of erbium rods, but within the interval of experimental errors. The RBMK lattices with fresh fuel 2 % enrichment have a negative sign of a void reactivity effect. The modulus of one increases under insertion heterogeneous absorbers – control rods and decreases under insertion absorbers in fuel channels[6]. Data obtained show these trends too. But the large difference between calculation and experiment is for the case of full core dehydration with 40 uniformly distributed fuel channels with and without erbium rods. After insertion of 40 erbium rods the calculation gives the displacement of the void reactivity effect equals $-0.19\ \beta_{eff}$, and the experiment gives the large positive value equals $+0.81\beta_{eff}$, This disagreement is not understandable and demands special analysis both the calculation and experimental methods. The calculation of these assemblies by the MCNP4A code gave the same results[4].

This disagreement might be because of the methods employed for the measurements of large values of supercriticality and subcriticality. The reactivity margin of the system N1-1 was determined as a sum of the efficiencies of four control rods measured separately. An alternate compensation method was used. But interference of control rods can be attend. Besides the determination of the subcriticality for the system N4-2 after dehydration was performed by using a criticality-from dewatering method. The process of dehydration is rather long (about 20 min) for such large system. The current of the reactimeter chambers is significantly decreased during this time. For the case of four control rods inserted in the system N4-2 the subcriticality was not obtained. The obtained value of the subcriticality for the system N4-2 can be inaccurate for the case of all control rods withdrawn . The decision was to repeat the measurement of large subcriticalities with a pulsed neutron source method and to make new calculations by the STEPAN code for the direct modeling of the experiments in space and time. The MCNP4A code was decided to use too.

6. CALCULATION MODELING OF THE FIRST EXPERIMENTS BY USING STEPAN AND MCNP4A CODES

For the systems with and without 40 uniformly distributed erbium rods in the case of all control rods withdrawn the STEPAN and the MCNP4A codes were used for the modeling of the experiments. The calculations were performed by steady-state and dynamic STEPAN versions. The goal of the calculations by the dynamic version was direct modeling of the reactivity margin measurement for the system N1-1 with an alternate compensation method and the dehydration process measurement for the system N4-1 with a criticality-from dewatering method in space and time. Time-depended two-group equations with spontaneous neutron source were solved. This neutron source should be taken into account because during the dehydration the significant decrease of a neutron flux takes place. The calculated neutron fluxes from points where chambers of a reactimeter are placed and the integral neutron flux around the core volume were used as an input signal of the special routine modeling the reactimeter. For the case of all control rods withdrawn the void reactivity effects obtained by steady-state and dynamic versions of STEPAN and MCNP4A are given in Table II.

One can see that direct modeling of the experiment in time also gives the positive void reactivity effect change due to inversion of erbium rods obtained in the experiment. The calculated integral signal of a neutron flux gives the positive void reactivity effect displacement due to erbium, which is less than the experimental value. On the other hand steady-state calculations performed using STEPAN and MCNP4A codes predict the negative displacement of the void reactivity effect due to erbium rods placement. Certainly the discrepancy between transient variants of the void reactivity effect is a result of space effects. The discrepancy between the transient value of the void reactivity effect obtained with the integral signal and the steady-state one can be connected with changes of the neutron field for the momentum of the transient calculation.

The calculations by the MCNP4A and the steady-state version of STEPAN were used for correction of the system N1-1 reactivity margin obtained due to an alternate compensation method. The scheme of the measurements of control rods efficiencies by step by step as in the experiment was done in the calculation. In addition, the system N1-1 reactivity margin was taken directly without all control rods from the previous calculation. Both results are given in Table III.

The average interference coefficient defined from calculation by MCNP4A and STEPAN codes was equal to 1.224 ±0.005. The experimental value of the system N1-1 reactivity margin without the effect of control rods interference is (1.52 ±0.10) β_{eff}. The experimental error of 0.10 β_{eff} taken in the first series experiments, seems to be too optimistic for the case with an interference of four control rods.

7. THE SECOND SERIES OF THE EXPERIMENTS

To make the results of some measurements of the subcriticality more precise the pulsed neutron source method was introduced at the facility for the second series of the experiments. Five half-height holes were made in the graphite stack of the facility to install a neutron generator and four fission chambers. Special experiments were performed to determine the reactivity effect because of the holes with the pulsed method equipment. The value of the reactivity effect due to holes and the placement of the pulsed method equipment was obtained equal to (0.18 … 0.21) β_{eff} for the subcriticality range of (0 … 6) $\beta_{eff.}$ Four subcritical assemblies were investigated. These assemblies were analog of systems N1-2 and N4-2 for cases: all control rods were on the top end switch or four control rods were on the bottom end switch. The special experiments were performed to estimate Λ/β_{eff} parameter as function of subcriticality [8].

The calculations of the second series of the experiments were performed by the MCNP4A code. The calculated subcriticality and Λ/β_{eff} parameter are taken from the direct MCNP4A run and the damping decrement is calculated accordingly to the formula (1). The results of the experiments and calculations are given in Table IV. Under matching similar subcriticalites of the first and second series the pulse equipment effect (~0.2 β_{eff}) must be taken into account. Tables I and IV show all subcriticalities obtained by a pulse method are larger than subcriticalities obtained by a criticality – from dewatering method, when a current of the reactimeter chambers becomes too small value under dehydration end. Almost all measured and calculated subcriticalities of the second series are the same within the interval of errors. For the case of the system N1-2* without control rods the difference between experiment and calculation is larger than the interval of errors. The difference between measured and calculated Λ/β_{eff} values is the cardinal reason for this case. All damping decrements calculated from ρ_{calc} and $(\Lambda/\beta_{eff})_{calc}$ values accoding to the formula (1) are close to the experimental data. The pulse neutron source method may be considered as a low-error technique of the damping decrement measurement. But Λ/β_{eff} parameter can produces the additional error under determination of the subcriticality.

The reactivity margins, the subcriticalities, the void reactivity effects of the second experimental series are given in Table V. The results of calculations by MCNP4A are given in Table V too.

* here and below relate to second series assemblies.

The reactiviy margin of the system N1-1* without control rods was taken from the first series with the correction on pulse method equipment effect and control rods interference effect. The reactivity margin of the system N4-1* without control rods was defined by the reactimeter using a power rise method. The subcriticalities of the systems N1-1* and N4-1* with inserted four control rods was defined by the KENTAVR meter using a control rod drop method. The results of the second experimental series have not show the change of the negative void reactivity effect after insertion of 40 erbium rods within the interval of errors. The calculations by MCNP4A code (Table V) and steady-state versions of STEPAN code (Table II) give the small increase of the absolute value of the negative void reactivity effect, but almost within the interval of errors. The discrepancy between the calculation and experiment obtained in the first series was settled.

8. ADDITIONAL CALCULATIONS BY MCNP4A

The calculations of systems N3-1 and N3-2 for the case of compact placement of fuel assemblies with 37 erbium rods from the first experimental series were performed by MCNP4A too. The results are given in Table VI. Experimental and calculated values of the reactivity margins, the subcriticalities, the void reactivity effects are almost the same within the interval of errors.

Neutron flux distributions were measured in a number of critical states for the systems with and without erbium rods in fuel assemblies from the first experimental series. Measurements were performed by radial and axial chambers of the KENTAVR meter. Two critical assemblies were chosen to calculate radial and axial neutron flux distributions by MCNP4A. Average deviation of ~7% between MCNP and the experiment with maximum deviation of 21 % is obtained for the system N1-1 without erbium rods. Disagreement between MCNP and experiments increases in the case of the system N1-6 with three erbium rods between pins of thirteen fuel assemblies. Average deviation is ~10 % with maximum deviation of 28 %.

9. CONCLUSION

Two series of the experiments in the RBMK critical facility were performed to examine a standard RBMK fuel load and a load modeling the fuel with erbium poison. The goal of the experiments was to determine the influence of erbium on the void reactivity effect and to give the data for neutron codes validation.

The results of the calculation for the first series have shown an agreement with the experimental data. But in one case experiment and calculation has given large values with the different sign of the void reactivity effect displacement under insertion of erbium rods. The direct modeling of the experiments in space and time by STEPAN code confirmed the experimental result. The calculation of reactivity effects with an integral neutron flux did not change the result qualitatively. This discrepancy was eliminated after calculated correction of the reactivity margin on the effect of the control rods interference and the additional measurements of subcriticality values in the second series of experiments.

For room temperature the void reactivity effect displacement due to insertion of rods with erbium oxide practically was not happened within interval of errors.

The detailed modeling the assembly geometry and material compositions by the MCNP4A and the STEPAN codes allows to simulate erbium fuel experiments with sufficient reliabitity.

NOMENCLATURA

BES	bottom end switch
CR	control rod
TES	top end switch
$\alpha_{exp}(\alpha_{calc})$	experimental (calculated) damping decrement of prompt neutron flux
β_{eff}	effective delay neutron fraction
$\Delta\rho_{exp}^{v,\,Er}(\Delta\rho_{calc}^{v,\,Er})$	experimental (calculated) displacement of void reactivity effect because of erbium rods
Λ	time of prompt neutron generator
$\rho_{exp}(\rho_{calc})$	experimental (calculated) reactivity margin or subcriticality
$\rho_{exp}^{V}(\rho_{calc}^{V})$	experimental (calculated) void reactivity effect

ACKNOWLEDGMENTS

This work has been partly supported by CEA (Contract B4123f). The authors would like to express gratitude for this support.

REFERENCES

1. V.N. Shevaldin, et al., “The Experience of the Uranium-Erbium Fuel Use on the Ignalina NPP”, Atomnaya Energia, 85, 2, 91 (1998).

2. G. B. Davydova, et al., “The Upgrading of RBMK Reactor Fueling”, Atomnaya Energia, 71, 1, 3 (1991).

3. G. B. Davydova, et al., “Burable Poisons Application in the RBMK ”, Atomnaya Energia, 71, 4, 344 (1991).

4. E. V. Burlakov, et.al., «Critical Experiments Performed for Validation and Improvement of the RBMK Design», Transactions of the American Nuclear Society, 77, 380 (1997).

5. G. B. Davydova, V. M. Kachanov, «The Experiments in RBMK Critical Facility. Initial Data for Calculation Simulation», RRC KI, IAE-5891/4 (1995).

6. E.V. Burlakov, et. al., «Critical Benchmark Experiments for the RBMK Design», International Conference on the Physics of Nuclear Science and Technology, October 5-8, 1998, Long Island, New-York, Proceedings, 2, 946

7. G. N. Aleksakov, et.al., «Kentavr-System for Neutronics Experiments in Uranium-Graphite Critical Facilities», Atomnaya Energia, 66, 3, 211 (1989).

8. V.E. Jitarev, V.M. Kachanov, A.N. Kuzmin, “Measurement of Subcriticality by Pulsing α-Method”, Prosidings of ninth Simposium AER, Slovakia, 1999, p.489.

9. M.N. Babaytsev, et al., “The STEPAN Code for RBMK Reactor Calculation”, RRC KI, IAE-5660/5 (1993).

10. A. A. Balygin, et.al., «About Value β_{eff} for RBMK Reactor», Atomnaya Energia, 73, 3, 247 (1992).

11. J.F. Briesmeister, “MCNP4A – Monte Carlo N-Partical Transport Code System”, LANL, Report LA-12625-M (1993).

12. D. Behrens, et al., “Validation of MCNP for RBMK Criticality Calculations”, Nuclear Technology, 11,1, April 1996.

Table I. The results of the first experimental series and calculations by MDC code

N	Presence of erbium, position	Water in fuel channels, number	ρ_{exp}, β_{eff}		ρ_{exp}^{v}(ρ_{calc}^{v}), β_{eff}		$\Delta\rho_{exp}^{v,Er}$(Δ $\rho_{calc}^{v,Er}$), β_{eff}	
			CR-TES	4CR-BES	CR-TES	4CR-BES	CR-TES	4CR-BES
1-1		yes 192	+1.86 ± 0.10	-0.080 ± 0.003				
1-2		no 192	-1.1±0.1	-3.3 ± 0.2	-2.96 ± 0.14 (-2.44)	-3.2± 0.2 (-2.97)		
1-3	no	no 19, yes 173	+1.55 ± 0.05	-0.444 ± 0.013	-0.31 ± 0.11 (-0.29)	-0.36± 0.01 (-0.41)		
1-4		no 37, yes 155	+0.98 ± 0.05	-0.923 ± 0.030	-0.88 ± 0.11 (-0.60)	-0.84±0.03 (-0.79)		
1-5		no 40, yes 152	+1.53 ± 0.05	-0.534 ± 0.020	-0.33 ± 0.11 (-0.89)	-0.45± 0.02 (-1.03)		
1-6		no 13, yes 179	+1.77 ± 0.05	-0.177 ± 0.005	-0.09 ± 0.11 (-0.24)	-0.10± 0.01 (-0.26)		
2-1	19	yes 192	+0.92 ± 0.05	-0.834 ± 0.030				
2-2	5x5 cells	no 19, yes 173	+0.66 ± 0.05	-1.12 ± 0.03	-0.26 ± 0.07 (-0.22)	-0.29 ± 0.04 (-0.30)	+0.05±0.13 (+0.07)	+0.07±0.04 (+0.11)
3-1	37	yes 192	+0.43 ± 0.03	-1.29 ± 0.04				
3-2	7x7 cells	no 37, yes 155	+0.013±0.002	-1.87 ± 0.06	-0.42 ± 0.03 (-0.46)	-0.58± 0.07 (-0.61)	+0.46±0.11 (+0.14)	+0.26±0.08 (+0.18)
4--1	40	yes 192	+0.45 ± 0.03	-1.17± 0.03				
4 -2	16x16 cells	no 192	-1.7 ± 0.1	—	-2.15± 0.10 (-2.63)	— (-3.17)	+0.81±0.17 (-0.19)	— (-0.20)
4--3		no 40, yes 152	+0.140 ± 0.003	-1.62± 0.05	-0.30± 0.03 (-0.91)	-0.45± 0.06 (-1.03)	+0.03±0.11 (-0.02)	0± 0.06 (0)
5-1	13	yes 192	+1.51 ± 0.05	-0.358± 0.011				
5-2	16x16 cells	no 13, yes 179	+1.47 ± 0.05	-0.442± 0.013	-0.04 ± 0.07 (-0.23)	-0.08±0.01 (-0.25)	+0.05±0.13 (+0.01)	+0.02±0.01 (+0.01)
6-1	3x13	yes 192	+0.61 ± 0.05	-0.938± 0.030				
6-2	16x16 cells	no 13, yes 179	+0.62 ± 0.05	-0.954 ± 0.030	+0.01± 0.07 (-0.09)	-0.02±0.04 (-0.11)	+0.10±0.13 (+0.15)	+0.08±0.04 (+0.15)

Table II. The void reactivity effects measured, calculated by steady-state and dynamic versions of STEPAN and MCNP4A codes

Parameter, System N	Experiment	STEPAN			MCNP4A
		Dynamic modeling of experiment	Dynamic modeling of integral neutron flux	Steady-state calculation	
ρ^{v}, β_{eff}, system N1	-2.96 ± 0.14	-2.41	-2.42	-2.00	-2.43 ± 0.11
ρ^{v}, β_{eff}, system N2	-2.15 ± 0.10	-1.62	-2.16	-2.34	-2.79 ± 0.11
$\Delta\rho^{v,Er}$, β_{eff}	+0.81 ± 0.17	+0.79	+0.26	-0.34	-0.36 ± 0.15

Table III. The reactivity margin of the system N1-1 (β_{eff})

Scheme	ρ_{STEPAN}	ρ_{MCNP4A}	ρ_{exp}
Experimental	1.77	1.61 ± 0.12	1.86 ± 0.10
All CR together	1.44	1.32 ± 0.08	1.52 ± 0.10

Table IV. The results of pulsed method measurements and MCNP4A calculations

System N	1-2*		4-2*	
Position of control rods	CR-TES	4CR-BES	CR-TES	4CR-BES
$\alpha_{exp}(\alpha_{calc})$, sec^{-1}	-20.5 ± 0.3 (-19.7±0.7)	-39.4 ± 0.2 (-40.1±0.9)	-30.6 ± 0.2 (-31.6±0.9)	-50.6 ± 0.7 (-50.9±0.9)
$(\Lambda/\beta_{eff})_{exp}$, $(\Lambda/\beta_{eff})_{calc}$, sec	0.128 ± 0.005 (0.116±0.001)	0.119 ± 0.004 (0.114±0.001)	0.122 ± 0.004 (0.116±0.001)	0.117 ± 0.004 (0.113±0.001)
$\rho_{exp}(\rho_{calc})$, β_{eff}	-1.63 ± 0.11 (-1.29±0.08)	-3.71 ± 0.15 (-3.57±0.10)	-2.74 ± 0.15 (-2.67±0.10)	-4.94 ± 0.22 (-4.75±0.09)

Table V. The results of the second experimental series and calculations by MCNP4A

N	Presence of erbium, position	Water in fuel channels, number	ρ_{exp}(ρ_{calc}), β_{eff}		ρ_{exp}^{v}(ρ_{calc}^{v}), β_{eff}		$\Delta\rho_{exp}^{v,Er}$(Δ $\rho_{calc}^{v,Er}$), β_{eff}	
			CR-TES	4CR-BES	CR-TES	4CR-BES	CR-TES	4CR-BES
1-1*	no	Yes 192	+1.34 ± 0.10 (+1.12 ± 0.08)	-0.261 ± 0.012 (-0.35 ± 0.08)				
1-2*	no	No 192	-1.63 ± 0.11 (-1.29±0.08)	-3.71 ± 0.15 (-3.57±0.10)	-2.97 ± 0.15 (-2.41±0.11)	-3.45 ± 0.16 (-3.22±0.13)		
4-1*	40 16x16 cells	Yes 192	+0.240 ± 0.005 (+0.194 ± 0.08)	-1.38 ± 0.07 (-1.46 ± 0.09)				
4-2*		No 192	-2.74 ± 0.15 (-2.67±0.10)	-4.94 ± 0.22 (-4.75±0.09)	-2.98 ± 0.15 (-2.86±0.13)	-3.56 ± 0.23 (-3.29±0.13)	-0.01 ± 0.21 (-0.45±0.17)	-0.11 ± 0.28 (-0.07±0.18)

Table VI. Additional calculations by MCNP4A some assemblies of the first experimental series.

N	Presence of erbium, position	Water in fuel channels, number	ρ_{exp}(ρ_{calc}), β_{eff}		ρ_{exp}^{v}(ρ_{calc}^{v}), β_{eff}	
			CR-TES	4CR-BES	CR-TES	4CR-BES
3-1	37 7x7 cells	yes 192	+0.43 ± 0.03 (+0.33 ± 0.08)	-1.29 ± 0.04 (-1.13 ± 0.08)		
3-2		no 37, yes 155	+0.013 ± 0.002 (+0.08±0.08)	-1.87 ± 0.06 (-1.82±0.08)	-0.42 ± 0.03 (-0.25±0.11)	-0.58 ± 0.07 (-0.69±0.11)