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EXPERIMENTAL RESEARCH ON SAFETY ASSURANCE OF ADVANCED VVER FUEL CYCLES

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ABSTRACT

The paper presents the results of experimental investigations on substantiation of implementation of a modernized butt joint for the VVER-440 reactor, carried out in the critical test facility "P" in the RRC "Kurchatov Institute". The comparison results of the calculation and experimental data obtained in the physical startup of Volgodonsk NPP-1 with the VVER-1000 are also given.

In the implementation of four-year fuel cycle in the VVER-440 with the average enrichment of fuel makeup 3.82% it was solved to conduct experimental research of power distribution in the vicinity of CR butt junction. Moreover, it was assumed that adequate actions should be applied to eliminate inadmissible power jumps, if necessary. It is not available to measure their values in NPP conditions. Therefore, the power distribution near the butt joint was studied in a 19-rod bank installed in the critical test facility "P" first for the normal design of the joint when surrounding FA enrichment goes up. Then a set of calculation and tests was fulfilled to optimize a butt junction design. On the base of this research the composition of a butt junction was advanced by placing Hf plates into the junction. The effectiveness of modernized butt joint design was experimentally confirmed.

In Volgodonsk NPP-1 with VVER-1000 the four-year fuel cycle is being implemented. During the physical startup of the reactor the measurements of the reactivity effects and coefficients were measured at the minimum controlled flux level, and the parameters of a number of critical states were recorded. The data obtained were compared with the calculation. The validity of the certified code package [1] for forecasting the neutronic characteristics of VVER-1000 cores in the implementation of a four year fuel cycle has been supported.

INTRODUCTION

This report presents the findings of experimental research made to justify the implementation of advanced butt joints for VVER-440 and also outcomes of comparison analysis of calculated and measured data acquired at physicist start-up of Volgodonsk NPP, Unit 1 with reactor VVER-1000. The research was executed on Kurchatov Institute critical facility.

At implementation of four-year fuel cycle to VVER-440 with average enrichment of make-up fuel as 3.82 % a suspicion has appeared, that local power increase in fuel elements of butt joint of control FA (CFA) can be inadmissible. It is not possible to test this suspicion at NPP. Therefore, there was made a decision to upgrade a butt joint by introducing hafnium (Hf) plates into it, which have high absorbing capacity. Efficiency testing of such advancement has been performed on a «P» critical facility in RRC Kurchatov Institute. A 19-assembly bundle was installed in «P» critical facility where power density distribution in butt joint was investigated first for a nominal design, and then for an advanced design. Thus, the efficiency of advanced butt joint has been proved experimentally.

At Unit 1 of Volgodonsk NPP with reactor VVER-1000 the four-year fuel cycle is being implemented now. For the purpose of test substantiation of prediction made during physicist start-up of first fuel loading at zero power of reactor, the reactivity factors and reactivity effects were measured, and the parameters of lots of critical states were registered. Measured data were compared with calculated data.

1. EXPERIMENTAL RESEARCH PERFORMED TO JUSTIFY ADVANCEMENT OF VVER-440 CFA BUTT JOINT AT FOUR-YEAR FUEL CYCLE.

1.1. Assigning a task

Calculation analysis of power distribution in the vicinity CR butt junction revealed a power jump in fuel rods neighboring with CFA, when surrounding FA enrichment goes up (in a four-year fuel cycle, for example) [2].·This fact caused a set of calculation and tests to verify calculation prediction the power jump, to optimize butt junction design and at last to justify the design changes aimed at elimination of these power jumps.

The investigation was performed in three stages.

The first investigation stage of 1995 and 1996 detected power density jumps in fuel rods arranged on the periphery of FA adjacent to CFA. Such jumps were caused by a complicated structure of butt joint [2]. Power density jump achieves maximum in fuel elements of FA periphery row at the level of upper plugs of fuel elements adjacent to CFA.

Power density due to the following CFA design elements:

• water gap between a head grid of fuel element and a set of upper plugs of CFA fuel elements;

• compensation zone between the upper bound of steel rods in CFA fuel elements and upper plugs of fuel elements.

Jump value depends on boron concentration in moderator, input fuel enrichment, depth of CFA fuel assemblies, feedbacks, etc. For example, when boric acid concentration decreases (with fuel burnup), power jump increases. That can cause a reactor power restriction.

The identified power density jump is one of the reasons for fuel element depressurization. The test findings are confirmed by operation.

The second stage investigation is the test performed in 1997. As it follows from measurement data obtained on Kurchatov critical test facility «P», a power density jump from fist investigation stage can be removed by hafnium plates. The findings of research recommend to arrange a supplementary absorbent in butt joint, and this will be the most effective way to reduce the jumps of linear load in fuel elements of FAs, which surround CFA.

On the basis of technological and neutron-physicist parameter analysis and on the basis of calculation and test research Hf was selected as material for absorbent production. The researches allowed to define the required quantity of Hf and its position in butt joint between absorbing portion and fuel of CFA in VVER-440, sufficient for complete removal of power density jump in periphery fuel elements.

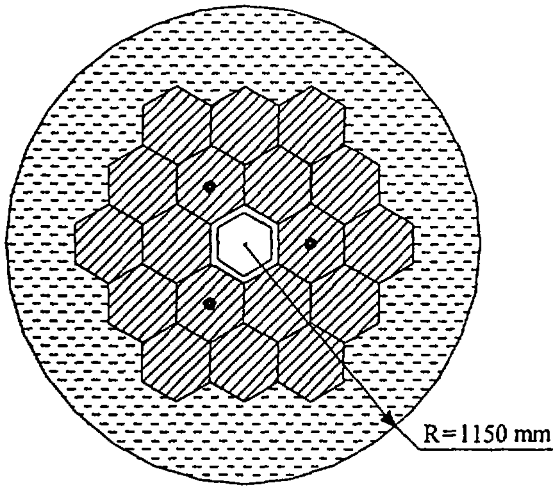
In 1998 within the framework of this problem the know-how of hafnium plates and bars production was designed, a pilot set of hafnium plates was manufactured, their behavior at flexion and welding with zirconium plates was investigated, and corrosion tests of welded joints were performed. The metallurgical researches gave a positive result for using hafnium in the structure of advanced CFA butt joint of VVER-440. Absorbent arrangement in butt joint was agreed and adopted.

When the decision about installation of 0.6 mm hafnium plates in a butt joint was made, and when in December 1999 a simulator of specified advanced butt joint was manufactured and delivered, the final third stage of research was completed.

1.2. Test fuel assembly

All three tests were completed on one and the same critical bundle arranged in Kurchatov's test facility «P».

The investigation were performed with application of boron concentration in moderator as C ~ 5 g/kg. The bundle consisted of 15 nominal assemblies (FA), 3 dismountable assemblies, completely identical with nominal assemblies, and one assembly arranged in the center, VVER-440 CFA with nominal or advanced butt joint. The map of loading is shown in Fig. 1.1, the critical level (compensation level) ranged from 80 cm to 110 cm in all the tests.



— Regular FA with fuel enrichment ^{235}U 3.6 mass % (FA)

— DismountableFA with fuel enrichment ^{235}U 3.6 mass % (FA) or graded FA

— CFA VVER-44 with fuel enrichment ^{235}U 2.4 mass %

— Moderatin

Fig. 1.1. Map of test bundle comprising 19 FAs VVER-440

Work on modernization of CFA butt joint consisted of installation of 0,6 mm Hf-plates on every brink of FA jacket in the area of transient region. Every plate had two openings of 19.1 mm by 30.4 mm caused by technological necessity. Dimensions and shape of such plates are shown in Fig. 1.2.

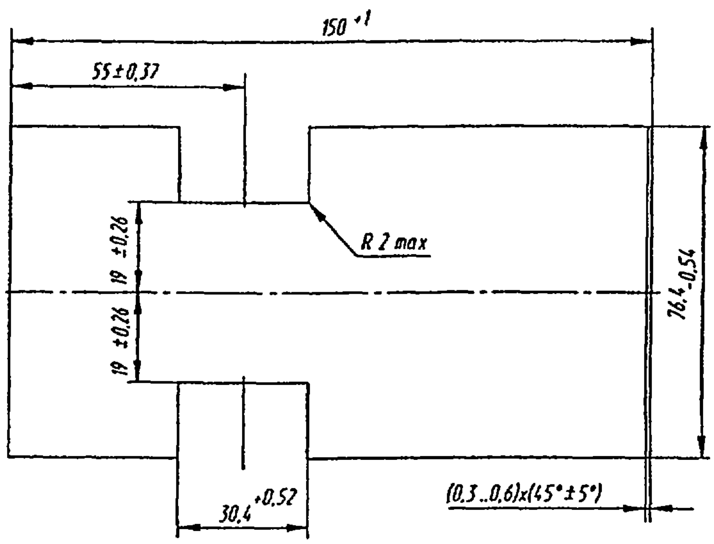


Fig. 1.2. Shape and dimensions of Hf-plates arranged in butt-joint test simulator of regular advanced CFA VVER-440

Goals of testing:

• to study the impact of advanced butt joint of nominal CFA VVER-440 to distribution of power density in fuel elements of neighboring FAs;

• to see if Hf-plate arrangement in butt joint is sufficient to make a reliable compensation of power density jump in peripheral fuel elements of surrounding FAs, caused by variety of material composition of butt joint.

The tests preparatory work was conducted pursuant to assigned goals. Before FAs were installed in a bundle, usual fuel rods were substituted by dismountable fuel rods of similar enrichment and design in the selected periphery cells. These dismountable fuel rods consisted of small blocks specially selected, measured lengthwise and weighed. Block wise measurements enable to reveal the effect without integrating the activity from adjacent parts of fuel elements by collimator. Arrangement of measured fuel elements is shown in Fig. 1.3.

Moreover, for comparison sake there were gauged axial distributions of power density in fuel elements that experience the least influence of CFA, — of the second and third rows.

As it follows from measurements performed at first stages, including measurement performed in 1999 by means of advanced butt joint, the most power stressed areas are observed in fuel elements of extreme FA row, adjacent to CFA. Therefore, the most thorough measurements were made in these very areas with block wise measurement in every small block, and pin wise measurement with a step of 1-2 cm.

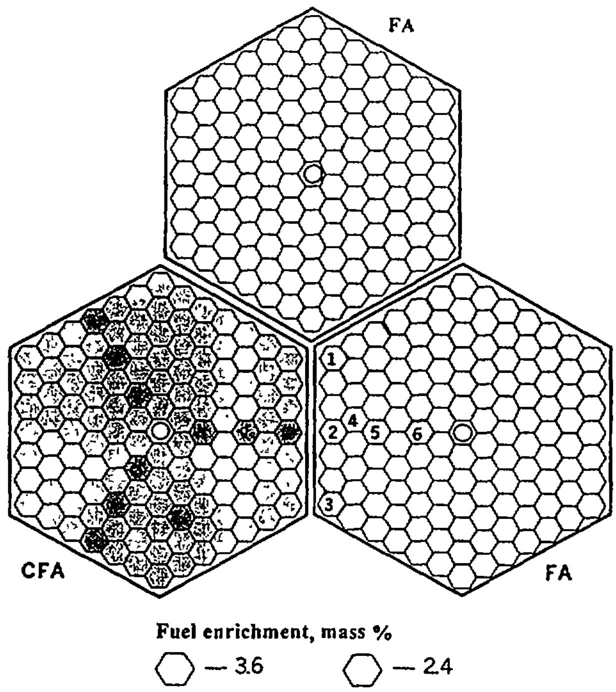


Fig. 1.3. Map of fuel elements measured in dismountable fuel assembly

Typically, the research work consisted of preparation work, irradiation, γ-scanning of fuel elements, measured data computer processing aimed at obtaining relative distributions of power density, and comparison analysis of measured data and modeling of calculation data.

Two sets of testing were conducted:
• with non-graded dismountable FA (Fig. 1.3);
• with graded dismountable FA (Fig. 1.4).

Measurement was made with similar H_3BO_3 concentrations in moderator and with difference in CFA location in the core as 1.2 cm and with difference in critical level as 6 cm for both FAs: graded, and non-graded.

In order to bind these results to earlier test outcomes, measurements of year 1997 were repeated but with CFA elevated by 54 cm and almost similar H_3BO_3 concentration in moderator.

Axial distributions of power density were measured.

Standard techniques were applied for determining relative power density. In order to make measurement in non-dismountable fuel pins a monitor was used.

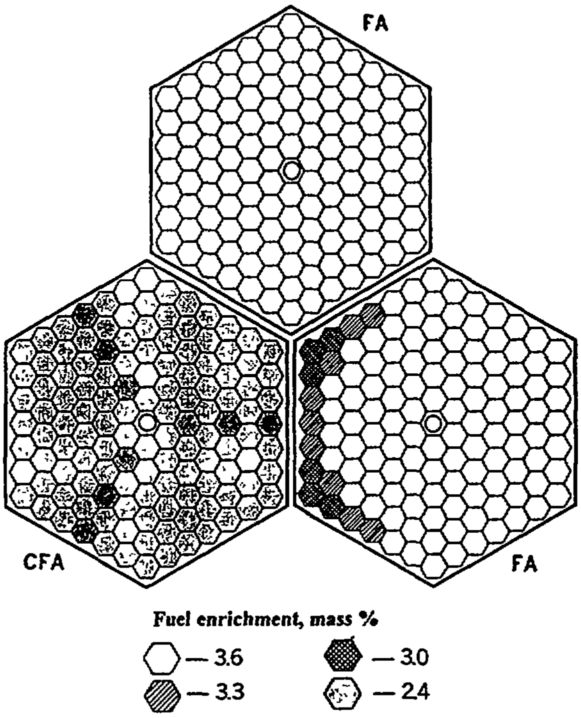


Fig. 1.4. Map of dismountable operation assembly (FA) with profiling fuel elements. Location of cells with measured power density coincides with cell locations from Fig. 1.3

Activity in each point was measured three times. In processing there were used average values and average-square deviations both for detector activity, and for the monitor.

The allowances for "dead" time and backgrounds of premises and fuel elements were taken into account.

Naturally, such high-precision measurement (30 measured points per a fuel pin and every data point measured three times) takes many hours, and; naturally, fuel element activity diminishes by several times during this period. The uranium fuel decay takes place according to the law of exponent superposition. The correction for time of measurement is entered experimentally on the basis of monitor decay, the activity measurement of which is carried out both casually and regularly. The value of exponent is determined by method of least quadrates for a small time period.

The final results are submitted in the form of average values in symmetrical points.

The following corrections were taken into account:

- for "dead" time of instrumentation;
- for residual activity of fuel elements and background of instrumentation itself;
- for decay;
- for collimator efficiency.

Measurement inaccuracies are minimized with allowance for the following:
- self-absorption of γ-quanta in fuel element material:
- fuel non-uniformity;
- registration efficiency of γ-quanta;
- instrumentation steadiness.

1.3. Measured data and comparison analysis between measured and calculated data

1.3.1. Regular butt joint

Measurement was conducted with various boron concentrations and various butt joint positions. Dependency of deviation between calculated and measured data upon the configuration of critical assembly was studied. Figs.1.5 through 1.7 present measured data and modeling calculation data, which testify to good agreement between those data. Moreover, as it follows from the picture, the deviation between calculated and measured data does not depend on assembly configuration. The maximum value of power density, naturally, depends on both: critical assembly height, and position of butt joint. However, it is important to remember that a 3D-calculation code is capable to well describe power density distribution in fuel elements surrounding a butt joint. Such code capability enables to select an optimal butt joint design. The following special measurements were made to justify the substantiality of calculation model in CFA fuel follow. Some regular fuel elements were removed by experimental fuel elements of greater height, which made it available to assess the representability of jump calculation for neutron heat flux inside a butt joint. Fig.1.6 shows calculated and measured power density distribution in fuel element of greater height in the rod of CR fuel follower sited opposite fuel rod No.2. It is visible, that a satisfactory agreement between calculated and measured data is also reached above the border of regular CFA fuel elements (see right part of Fig.1.6), that proves its compliance to a calculated model.

1.3.2. Advanced butt joint.

The work was performed in two stages: at first the work was performed on a model enabling to vary a Hf thickness and to determine the dependency of calculated prediction upon its thickness. It has been demonstrated that calculation well describe power density distributions regardless from Hf thickness (within the framework of tested configurations). On the basis of subsequent optimization calculation an advanced butt joint was designed and fabricated which was used in measurement. At that, only the fuel elements arranged in immediate proximity to butt joint (of FA adjacent to CFA) were of interest. The outcomes of this research (measurement and calculation) are presented in Fig. 1.8.

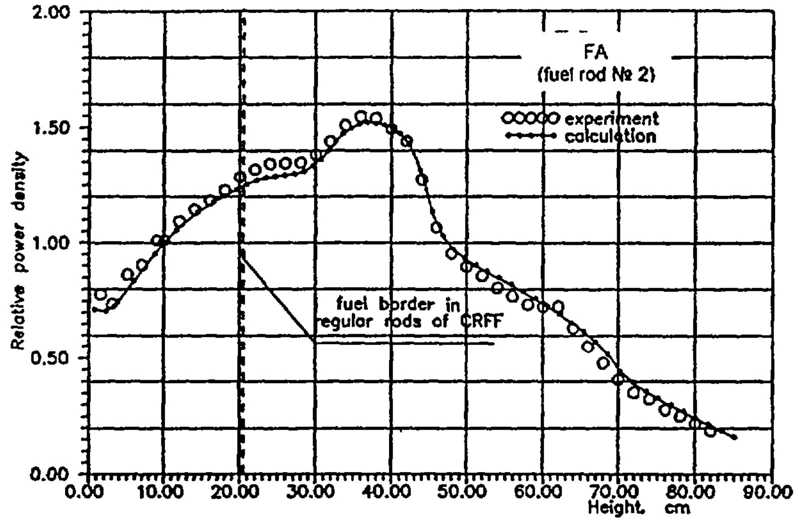


Fig. 1.5. Axial power density distribution in rod № 2 of fuel assembly. CR fuel follower withdrawal height is 20 cm. CH_3BO_3 4.1 g/kg H_2O. Critical level = 85.7 cm.

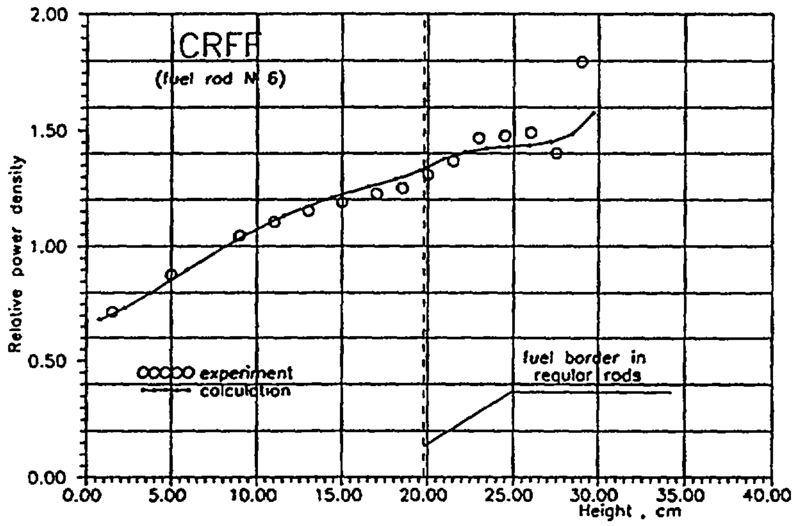


Fig. 1.6. Axial power density distribution in the rod of CR fuel follower sited opposite fuel rod № 2. CR fuel follower withdrawal height is 20 cm. CH_3BO_3 4.1 g/kg H2O. Critical level = 85.7 cm.

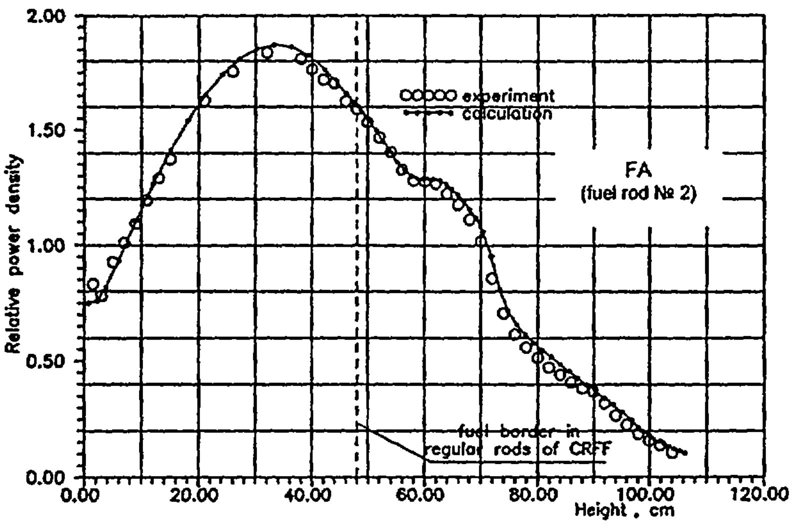


Fig. 1.7. Axial power density distribution in rods № 2 of fuel assembly.
CR fuel follower withdrawal height is 48 cm. CH_3BO_3 5.8 g/kg H2O. Critical level = 107.5 cm.

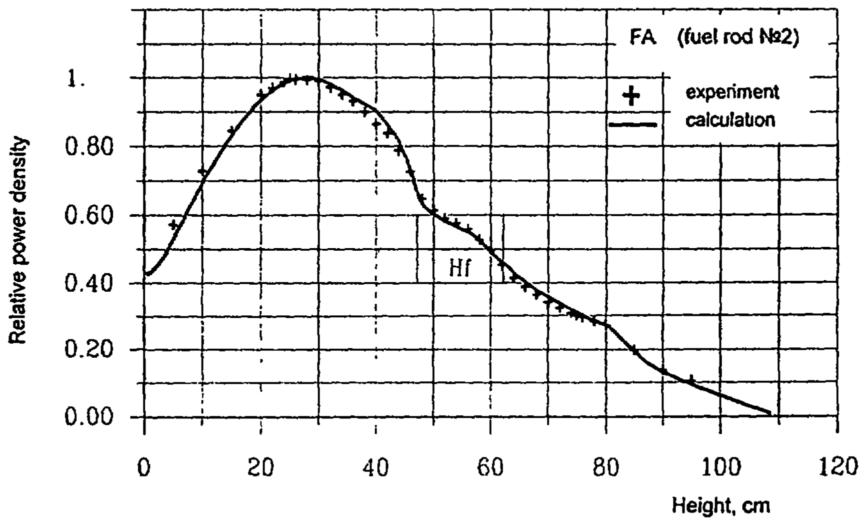


Fig.1.8. Axial power density distribution in rods № 2 of fuel assembly (Advanced junction part of CR fuel follow). CR fuel follower withdrawal height is 54 cm. CH_3BO_3 5.0 g/kg H2O. Critical level = 109.7 cm.

1.4. Conclusion to Article 1.

A large cycle of test and calculation research on impact of butt joint of CFA VVER-440 assembly to distribution of power density in fuel rods of adjacent FAs has been completed. The research resulted in modernization of butt joint and investigation of its efficiency.

To summarize the results of completed work it is possible to draw the following conclusions:

- Block wise techniques applied in activity measurement of dismountable fuel rods has made it possible to study power density distribution in the zone of high distortions;

- applicable testing allowed to work out and issue a method for compensation of power density jumps in fuel rods of outer row of FAs adjacent to CFA in the area of butt joint, which, finally, resulted in its reconstruction;

- power density jump (up to 40%) is detected in fuel rods of outer row of FAs adjacent to CFA, starting from steel insertions made in CFA fuel elements and higher, this power density jump diminishes with boron concentration increase in moderator;

- measurement performed on a simulator of advanced CFA VVER-440 allowed to promptly remove the shortcomings of initial design option with "openings" in Hf-absorbent, which caused additional 12% power density jump in a corner fuel rod arranged at the level of "opening";

- on the base of completed measurement the design of advanced butt joint CFA was verified, and a draft design of Hf-absorbent (without "openings") was issued, enabling to completely compensate the power density jump in peripheral fuel rods of FA adjacent to CFA in the zone of butt joint;
- «P» investigation proved substantiality of CFA acceptance test with hafnium plates;
- good agreement between calculated and measured values of K_{eff} is noticed: deviation from 1.0 does not exceed 0.1%;
- comparison of PERMAK-3D calculated data and measurement data reveals satisfactory agreement practically in the whole range of measurement.

2. CALCULATED AND MEASURED DATA ACQUIRED AT PHYSICIST STARTUP OF FIRST FUEL LOADING AT UNIT I OF VOLGODONSK NPP

Unit I of Volgodonsk NPP is a basic nuclear power project, where an advanced fuel cycle was first implemented, starting with first fuel loading.

Physicist study of fuel cycle project and an album of neutron-physicist parameters of first fuel loading were issued with application of certified codes used for design and operational calculation of VVER reactors, these are: TBC-M, BIPR-7A, PERMAK-A, IR.

This section of presentation gives the comparison data between calculated neutron-physicist core parameters and measured core parameters, acquired by the physicists of Kurchatov Institute. The parameter registration was made by means of regular and special instrumentation, designed in RRC Kurchatov Institute

At the stage of physicist start-up of fist fuel loading at Volgodonsk NPP, Unit 1 there was performed testing to determine the following neutron-physicist core parameters :

- parameters of critical reactor states at various positions of CPS CR in the core;
- efficiency of individual CPS CR, CPS CR banks and scram;
- efficiency of boron acid;
- reactivity temperature and pressure coefficients of the coolant and power reactivity factor.

2.1. Core Composition and core layout.

Fuel loading completely consists of FAs with zirconium thimbles and spacing grids. Fuel loading comprises FAs of three sorts of enrichment. Burnable absorber bundles of three sorts of boron concentration are used as burnable absorbers. Table 2.1 gives the description of FA types used in the first fuel loading.

Table 2.1

Description of FA types of first fuel loading at Unit I, Volgodonsk NPP

FA type	Average fuel enrichment	Number of fuel rods of various types in FA and their enrichment		Number of burnable absorber rods / boron concentration (g/cm^3)
		Type 1	Type 2	
16ZS	1.6	312 / 1.6	-	-
24ZS	2.4	312 / 2.4	-	-
24ZSA	2.4	312 / 2.4	-	18 / 0.020
24ZSB	2.4	312 / 2.4	-	18 / 0.036
24ZSC	2.4	312 / 2.4	-	18 / 0.050
362ZS	3.62	246 / 3.7	66 / 3.3	-
362ZB	3.62	246 / 3.7	66 / 3.3	18 / 0.036

Fig. 2.1. Fuel pattern in the first fuel loading.

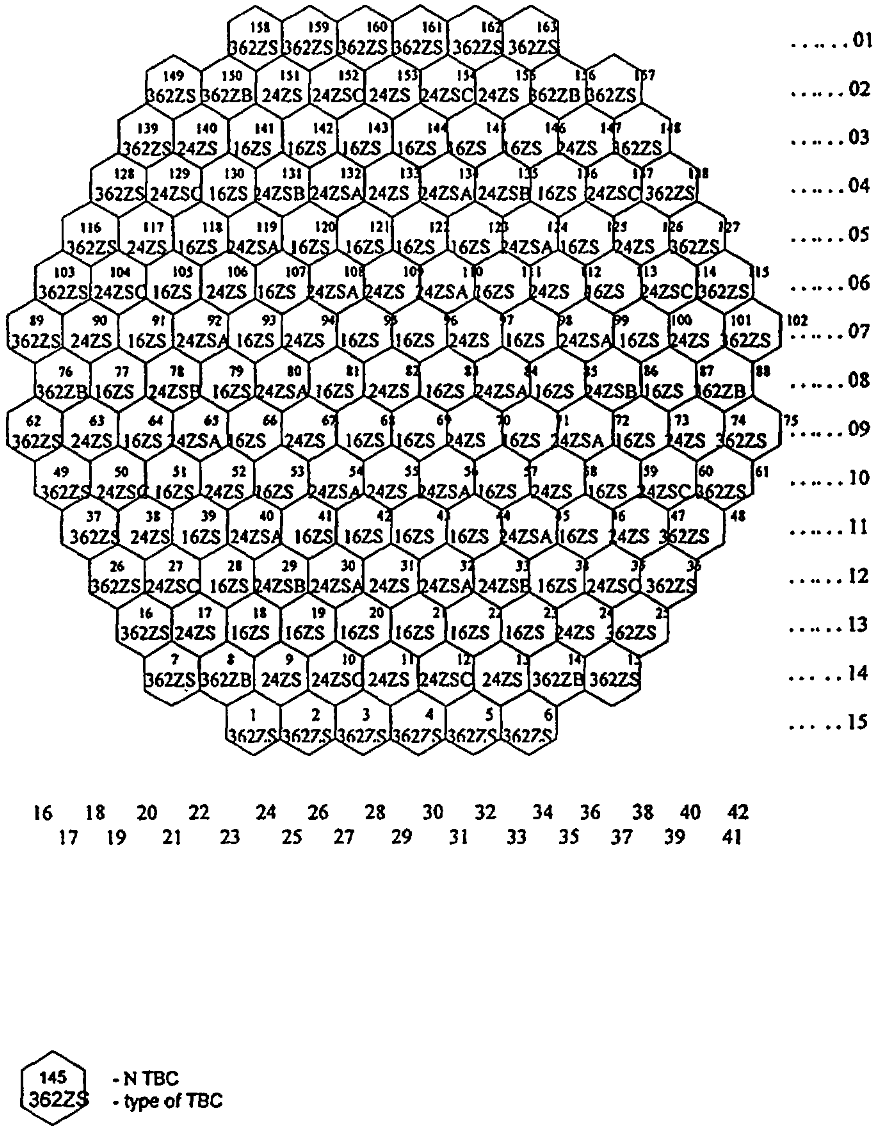


Figure 2.1 Map of first fuel loading at Unit I, Volgodonsk NPP.

Fig. 2.2 shows CPS CR bank arrangement in the core of Unit I.

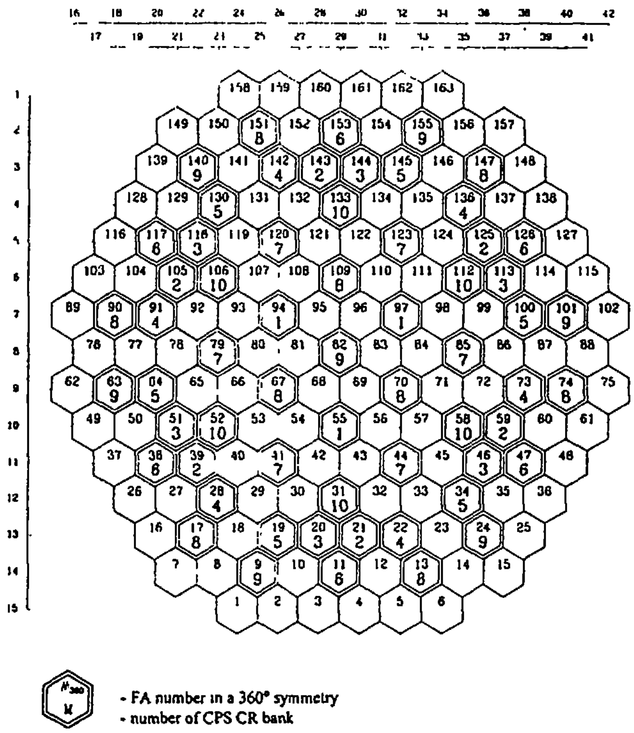


Fig. 2.2 CPS CR arrangement in the core of Unit I, Volgodonsk NPP

Unlike industrial VVER-1000, the reactor of Unit I, Volgodonsk NPP has a changed splitting of CPS CR into banks and an increased overlap between the banks (40% of the core height) at their regular movement within the core.

2.2. Comparison analysis of calculated and measured data.

2.2.1. Parameters of reactor critical states at zero power operation

Table 2.2 gives calculated and measured data of reactor critical states at zero power operation at various CPS CR positions and various coolant temperatures.

Agreement between calculated and measured data of critical boron concentration taken with allowance for calculation and measurement inaccuracies is satisfactory. The calculation slightly underestimates the critical boron concentration by 0.22 g/kg on average.

Table 2.2

Parameters of critical states of the core

No.	CPS CR sermon.	CPS CR position, %	CPS CR ser. No. in the bottom	CPS CR elevation at the top (bank ser. No.)	T_{core}, °C	CH_3BO_3, g/kg	
						Measured	Calculated
1	10	64	-	-	278.5	7.39	7.15
2	10	82	-	-	278.6	7.40	7.18
3	10	73	-	-	278.6	7.40	7.18
4	10	78	-	-	278.3	7.40	7.18
5	10	62	-	-	278.2	7.39	7.15
6	10	70	-	-	278.8	7.40	7.16
7	10	64	9	-	279.1	6.90	6.68
8	10	55	8	-	279.3	6.76	6.57
9	10	63	7	-	279.7	7.26	7.03
10	10	61	6	-	279.5	6.90	6.66
11	10	70	4	-	279.8	7.10	6.88
12	10	58	2	-	279.3	7.10	6.86
13	10	56	1	-	279.3	7.31	7.08
14	10	22	-	-	279.1	7.23	7.02
15	10	25	-	-	279.2	7.23	7.03
16	9	87	10	10-23 (10)	280.0	7.23	7.03
17	9	70	10	-	279.2	7.14	6.94
18	9	21	10	10-23 (10)	279.2	6.77	6.56
19	8	62	9, 10	09-18 (9)	279.1	6.77	6.61
20	9	26	10	-	279.2	6.77	6.56
21	8	66	9, 10	-	279.8	6.60	6.35
22	10	45	8	09-26 (8)	279.8	6.80	6.55
23	10	60	7	10-23 (10)	279.6	7.27	7.03
24	10	53	7	11-26 (7)	279.5	7.27	7.03
25	10	59	6	10-23 (10)	279.7	6.90	6.67
26	9	75	6, 10	11-20 (6)	279.7	6.90	6.68
27	9	60	8,10	02-25 (8)	279.8	6.80	6.57
28	10	58	2	11-22 (2)	279.3	7.10	6.94

2.2.2. Efficiency of individual CPS CR.

Efficiency of individual CPS CR out of banks 1 through 9 was experimentally determined by measuring the reactivity registered at drop of CPS CR into the core from the ultimate upper position.

The measurement was made with partial or full immersion of bank 10. Figs. 2.3 - 2.4 show measured and calculated CPS CR efficiency. These pictures also give serial numbers of banks to which CPS CR belong (symbol "c" behind the digit, indicates that this CPS CR belongs to central subbank), index "p" indicates that this CPS CR belongs to a peripheral subbank. As it follows from the pictures, the calculation underestimates the efficiency of individual CPS CR. It is necessary to stress, that the data measured by two independent groups of scientists, who use different instrumentation and different ionization chambers, differ from each other much less, than these data differ from calculated data.

2.2.3. CPS CR banks efficiency.

Movement of CPC CR banks was performed in steps. At each of the steps the reactivity was compensated by change of boron concentration in the primary loop.

Figs. 2.5-2.6 give typical examples of measured and calculated dependency of bank efficiency upon its position in the core.

It is possible to consider the results of comparison analysis between calculated and measured values of CPS CR integral efficiency as satisfactory.

2.2.4. Temperature coefficients of reactivity.

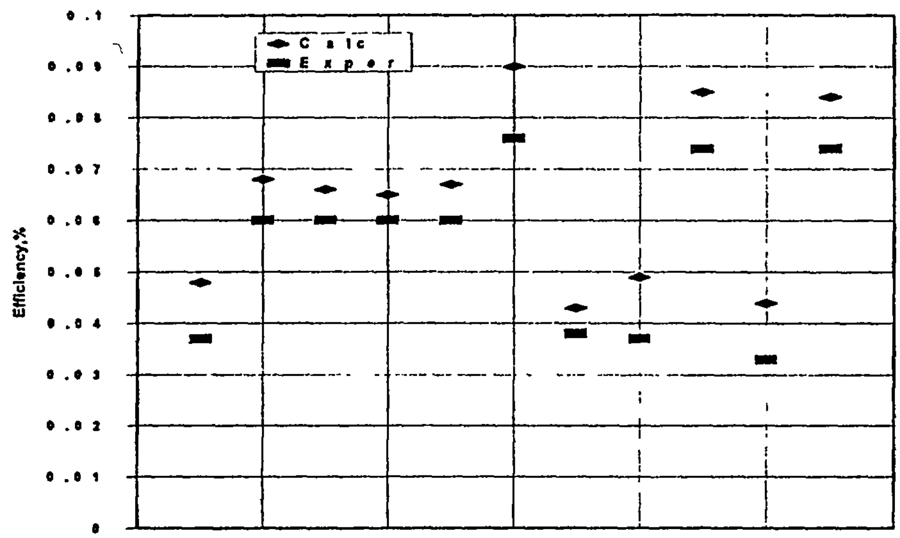
Calculated and measured temperature coefficients of reactivity are given in Table 2.3. As it follows from the Table, the deviation between calculated and measured data, as a rule, does not surpass $3\cdot10^{-5}$ 1/°C. The only exception makes a measured datum, where this difference makes $5.5\cdot10^{-5}$ 1/°C.

2.2.5. Scram efficiency.

Table 2.4 gives the data of scram efficiency for three hot tests (~279 °C), and one cold test (~120 °C)).

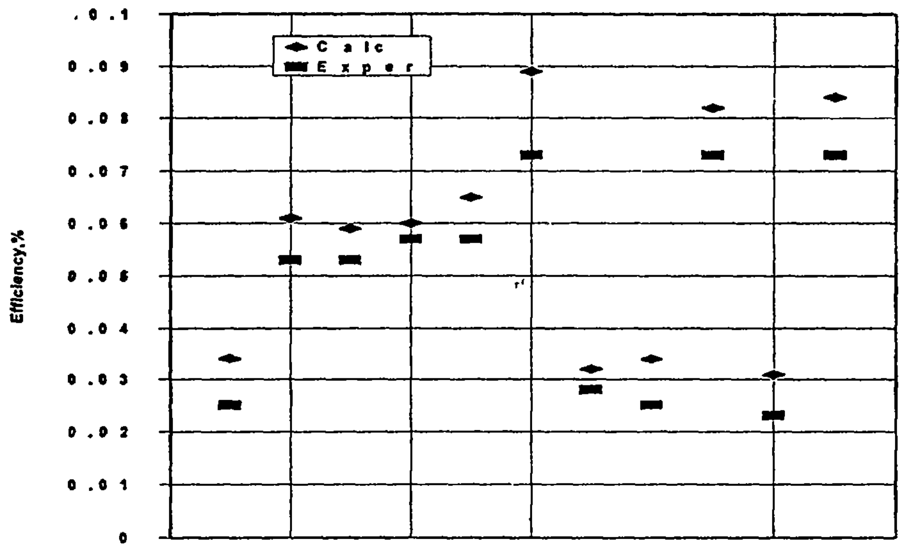
Scram efficiency was determined by measuring the reactivity which is introduced at CPS CR drop into the core. Initially all the CPS CR banks took the upper position, except bank 10, located in the position of 60-80%.

The comparison results of measured and calculated scram data may be considered as satisfactory.



Bank 1 2 3 4 5 6 7 8 8c 9 9c

Fig. 2.3. Measured and calculated efficiency of certain CPS CR at bank positions as: H10 - 71%, H1÷H9 – in top position



Bank 1 2 3 4 5 6 7 8 8c 9 9c

Fig. 2.4. Measured and calculated efficiency of certain CPS CR at bank positions as: H10 - 27%, H1÷H9 – in top position

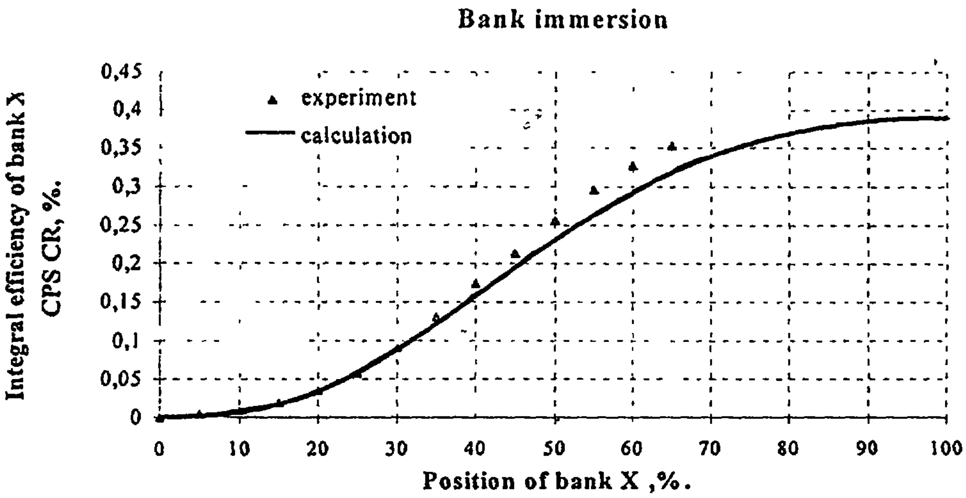


Fig. 2.5. Integral efficiency of X bank CPS CR at immersion in the core without transfer of bank motion to CPS.

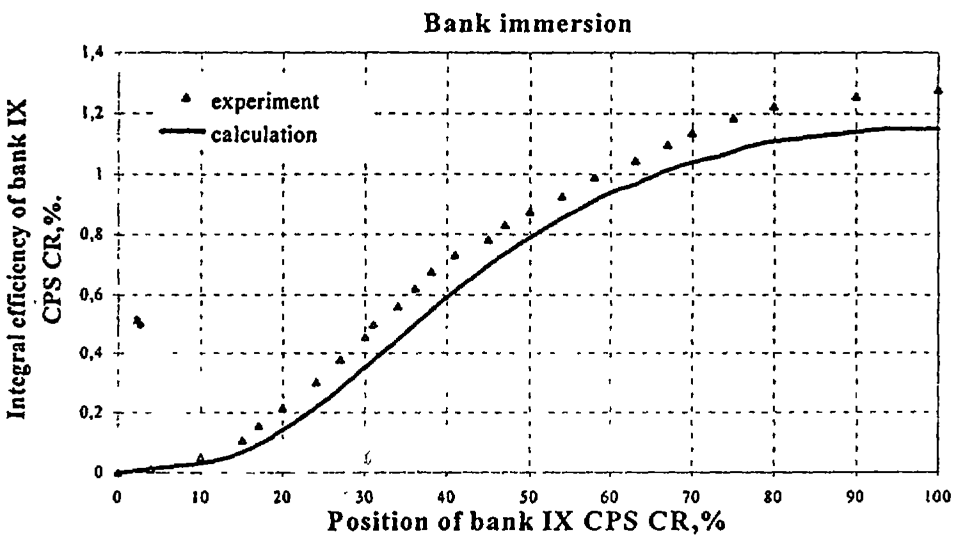


Fig. 2.6 Integral efficiency of IX bank CPS CR at immersion in the core without transfer of bank motion to CPS with X bank in bottom position.

Table 2.3

Temperature coefficients of reactivity

Bank No.	H %	Tcore °C	C_{H3BO3}, g/kg	$\partial\rho/\partial T$, 10^{-3}%/°C	C_{H3BO3}, g/kg	$\partial\rho/\partial T$, 10^{-3}%/°C
			Measured data, *)		Calculated data	
10	82	279.6	7.40	-2.52±0.02	7.18	-3.76
10	23	279.2	7.23	-6.64±0.02	7.02	-8.39
9	70	279.2	7.14	-8.40±0.19	6.94	-9.50
9	26	279.2	6.80	-10.87±0.02	6.56	-11.43
9	0	279.3	6.90	-7.822±0.02	6.66	-5.53
8	66	279.8	6.60	-17.14±0.02	6.35	-12.60
8	0	279.6	6.80	-8.82±0.01	6.56	-8.94
1	0	279.3	7.33	-6.76±0.03	7.08	-7.34
2	0	279.3	7.10	-7.87±0.04	6.86	-9.42
4	0	272.8	7.10	-6.12±0.03	6.90	-7.66
6	0	279.3	6.90	-4.56±0.02	6.67	-4.40
7	0	279.7	7.27	-9.94±0.03	7.04	-8.71

*) a statistical error component is indicated here

Table 2.4

Efficiency of reactor scram, full efficiency of cram and reactor unit parameters at which the scram drops were made.

Parameters	Scram drop			
	First	Second	Third	Fourth
H_1-H_9,%	100	100	100	100
H_{10},%	62	80	80	70
C_{H3BO3}, g/kg	7.39	7.39	7.39	7.54
T_{core},°C	279.3	278.2	279.3	120.4
Measured,% *)	6.0±0.01	6.47±0.01	6.42±0.01	4.35±0.01
Calculated,%	6.87	6.90	6.93	4.41

*) a statistical error is indicated here when reactivity increase was calculated, at that the error makes up to 5% of length

2.3. Conclusion to Article 2.

Calculation and measurement research of fuel loading implemented at Unit I, Volgodonsk NPP allows to state, that this loading completely complies to all safety requirements and can be recommended for implementation at other NPPs. Results of comparison analysis between calculated and measured data justify the certificate data of qualified codes that were used in selection of loading.

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