16th Symposium of AER on VVER Reactor Physics and Reactor Safety
22-29 September 2006, Slovac Republic.

EXPERIMENTS ON SIMULATION OF COOLANT MIXING IN FUEL ASSEMBLY HEAD AND CORE EXIT CHANNEL OF VVER-440 REACTOR

L.L. Kobzar, D.A. Oleksyuk
RRC «Kurchatov Institute», NRI, Moscow,
Russia

ABSTRACT

RRC “Kurchatov Institute” has performed coolant mixing investigation in a head of a full-size simulator of VVER-440 fuel assembly. The experiments were focused on obtaining the data important for investigating the trends in temperature difference between the value registered by a ICIS thermocouple and the value of average temperature. The completed experiments ensure representability of configuration simulation by reproducing every construction peculiar feature of flow part of fuel assembly in the domain between the lower spacing grid and thermocouple location, and also by slightly modified fuel assembly regular elements (or analogues thereof).

For the purpose of effectiveness of coolant mixing assessment within the head cross section of FA simulator, we measured coolant temperature distribution both in the place where coolant flow leaves the rod bundle simulator (in 39 data points along the cross section) and in the cross section location of regular ICIS thermocouple simulator (30 data points).

The testing was conducted with pressure of 90 – 95 Bar, mass coolant flow rates up to· 2300 kg/(m^2·s), temperature of coolant heating in “hot” parts of the bundle up to 35^{o}C and differences between coolant temperature extremes measured in rod bundle simulator outlet up to 20^{o}C. Temperature fields were registered in 63 conditions that differ in coolant flow and inlet coolant temperature, electrical heating rate of FA simulator, and radial coolant distribution. In certain registered conditions we simulated coolant leakage to the space between the fuel assemblies.

The received test data may be important both for investigation of dependencies between the coolant temperature in regular thermocouple location or average outlet temperature in assembly head, and for validation of CFD codes or subchannel codes.

INTRODUCTION

At the meeting of AER working group G that took part earlier in Tengelik (Hungary) in May 2005 we made a presentation of preparatory work for simulation of coolant mixing within the head of VVER-440 fuel assembly, which were performed by RRC “Kurchatov Institute”. The first series of experiments was completed in November 2005,the second series - in April 2006 . The subject of this paper is presentation of such testing findings.

The experiments were focused on the two main tasks, these are:

– to determine coolant mixing in the region between the end of fuel bundle and a thermocouple;

– to obtain the data sufficient for validation of computer codes that calculate coolant flow and coolant mixing in FA head and protective tube unit (PTU) of reactor VVER-440.

For the purpose of the first task, we used to advantage the elements of a regular VVER-440 fuel assembly that were fabricated at a TVEL plant. To accomplish the other task we selected a vast list of power distribution options, FA flow rates and powers.

This kind of investigation can further develop in the direction of design and experimental justification of construction elements capable to intensify coolant mixing in the head. This could result in a perfectly flat temperature profile for thermocouple locations and solve the problem of any kind of corrections to thermocouple signals.

The experiment findings solve a certain application task and, moreover, they are important for validation of computer codes that perform a 3D thermal hydraulic calculation (CFD codes), i.e. CFX, STAR-CD, FLUENT and PHOENICS, which have been recently involved in reactor calculations.

BRIEF DESCRIPTION OF KS TEST FACILITY

Test facility “KS” suggests two testing loops intended for VVER core simulation. One of the loops is a low-pressure loop (up to 98 Bar), the other is a high-pressure loop (up to 170 Bar). Our experiments need a low-pressure loop (Fig. 1).

Low-pressure loop performances

Primary circuit parameters:

- Coolant water, steam and water mixture;
- Maximal operation pressure, MPa 9,8;
- Maximal coolant temperature, °C:

at the test section inlet 260;

at the test section outlet 310;

- Maximal coolant flow in the test vessel, t/h 120;
- Available electrical power supplied to FA simulator, kW 8000.

A principal flow sheet of low-pressure loop of KS test facility is shown in Fig. 2.

DESCRIPTION OF FUEL ASSEMBLY SIMULATOR

Coolant mixing test section is intended for investigation of coolant mixing in the head of VVER-440 fuel assembly. It is constructed on the basis of a regular VVER-440 fuel assembly and consists of the following elements:

- pressure vessel;
- full-size spacing grids and a central tube (Fig.3);
- rod bundle simulator (Fig.4);
- full-size FA housing (Fig.4);
- full-size upper grid (Fig.5);
- full-size assembly head (Figs.6 and 7);
- hexagonal tube to simulate the housing walls of adjacent fuel assemblies;
- protective tube unit (PTU) simulator (Fig.8);
- regular thermocouple simulator (Fig.9);
- instrumentation.

The test section is shown in Fig. 10.

Pressure vessel consists of a vertical vessel in the middle and two downcoming side branches. The VVER-440 assembly simulator is located in two vessel housings in the bottom of a vertical vessel (hereafter referred to as a bundle vessel and PTU simulator vessel).

The diameter of bundle vessel is 195 mm, its height is 3397 mm, the diameter of PTU simulator vessel is 197 and the height is 1140 mm.

The rod bundle simulator is represented by a bundle of 126 rods with indirect electrical power supply. The heater elements are arranged in a 12,3 mm triangular lattice within the assembly-housing simulator and simulate VVER-440 fuel rods. The heater element positions are fixed by spacing grids, which are axially arranged with a step of 250 mm.

Figure 11 presents a rod bundle simulator cross-section. The heater elements have a numbering from 2 to 127; number 1 is given to the central tube. The vertical simulator rows have a Rome numbering from I to XIII (from left to right). Rows I and XIII consist of 7 heater elements, rows II and XII consist of 8 elements, rows III and XI consist of 9 elements, rows IV and X consist of 10 elements, rows V and IX consist of 11 elements, rows VI and VIII consist of 12 elements, and row VII has 13 elements.

Fuel rod simulator consists of a shell, Ni-Cr rod, upper end and a copper current lead arranged in the bottom. The shell represents a stainless steel tube with outer diameter of 9.15 mm and wall thickness 0,8 mm. The upper end is made of stainless steel; current lead is made of copper rod. Heater elements are made of Ni-Cr rod.

To simulate an axially symmetric rod-wise power distribution in the bundle we used the simulators of three types, which have electrical resistance distinctions of Ni-Cr rods. The rod resistance was selected with the aim to assure the following values of q_k - the relative power of fuel rod simulators:

- The simulators in the outer bundle row (numbers from 92 through 127 in Figure 11) should have q_k = 1,10.

- The simulators in the second outer bundle row (numbers from 62 through 91) and 6 middle simulators should have q_k = 1,00.

- All other simulators (numbers from 8 through 61) should have q_k = 0,93 (a calculated value).

To ensure one-sided (bottom) current lead, the rod simulators of identical type shall be joined in the top by conductors. The conductors shall be made of copper plates 1.5 mm thick and 10 mm wide. The electric current upstream along one simulator of the couple, and downstream along the other one.

For simulation of asymmetrical pin power distribution we use the three authentic electric power supplies available in the KS test facility. One of them supplies electricity to rod simulators of rows I to VI (fuel rod simulators of group 1), the second supplies electricity to rod simulators of rows VII to IX (fuel rod simulators of group 3), the third power supply gives electricity to rod simulators of rows X to XIII (fuel rod simulators of group 2). Since the power supply voltage may be varied, it is available to create various options of heat proportion within the three groups of fuel rod simulators. The basic power distribution option is considered to be in groups 1, 3 and 2 with relation of average rod power 1,15:1,00:0,743 (as per the balance).

When fabricated, the fuel rod simulators were arranged within the bundle section in accordance with their actual electrical resistances in such a manner, that the radial heat distribution were, firstly, qualitatively close to actual heat distribution, and, secondly, were axially symmetric. The obtained radial relative heat distribution is shown in Figure 12.

The bottom ends of fuel rod simulators are supplied with individual rubber seals at the exit from test vessel.

The central tube is represented by a regular central tube made of zirconium alloy and with outer diameter 10.3 mm and wall thickness 0.75 mm and supplied with a steel end tip.

The spacing grids are represented by regular VVER-440 grids (zirconium alloy) connected to the central tube in a regular manner. In the course of assembling a rod bundle every following spacing grid shall have a 180^o angle in relation to the previous one.

Assembly simulator geometry parameters

- Heat release length, mm	2420
- Number of fuel rod simulators, pcs	126
- Lattice pitch, mm	12,3
- Hydraulic diameter, mm	8,92
- Cross-section area, mm^2	9235

The fuel assembly simulator is located inside the housing represented by a regular housing modified and made of zirconium alloy. The housing has a hexagonal cross section with the nominal outer dimension 145 mm and wall thickness 1.4 mm.

Upper grid configuration and geometry dimension perfectly agree with those of a regular upper grid. This upper grid is supplied with guides 39 in number, which are designed for thermocouples and represent steel tubes with outer diameter 2 mm and wall thickness 0.4 mm. The holes, where these guides attach the upper grid, are located between the slots for coolant flow and they do not make an obstacle in the upper grid cross-section.

The assembly head is represented by a regular assembly head additionally supplied with six transverse orifices 6.5 mm in diameter and intended for thermocouple taps. To prevent the coolant leak these orifices shall be sealed with paronite bushes tightened by riffled sleeves.

The head penetrates into the housing a s deep as 65 mm where it attaches the housing by six screws M10. The housing and head orifices 12 mm in diameter, which are intended for partial penetration of the gap leaks into the assembly, shall coincide.

A hexagonal tube shall be put on the housing. This tube id intended for simulation of the gap between the assemblies. It consists of a hexagonal cover with the nominal inner dimension 149 mm and wall thickness 2 mm, and two flanges welded to it.

Coolant leaks in the gap between the assemblies are simulated by an independent coolant lead, whose flow rate can be controlled and may make 10 % of the flow rate in a rod bundle.

A PTU plate simulator simulates a real PTU plate cell located above a fuel assembly. Its design enables investigation of catcher effect on coolant mixing. For this purpose the catcher must be removable.

A PTU plate simulator represents a welded construction whose height (150 mm) and inner diameter of the channel (85 mm) are of similar size with a real plate.

A PTU plate simulator is mounted on the upper flange of a hexagonal tube through paronite bushes. In this case the gap between the plate bottom end and the head upper end should be 5 mm, just similar to the reactor case.

On the upper plate side there should be fixed a thermocouple simulator, whose axial position, design and geometry dimensions are identical to a regular thermocouple.

The principal testing goal is to measure the coolant temperature fields in two cross sections – at the rod bundle exit and in the regular thermocouple axial position.

To achieve this goal we arrange the thermocouples of two groups in the test vessel (see Figures 13 and 14).

The thermocouple arrangement (in the number of 39 pieces) at the rod bundle exit is shown in Figure 13. Axially the hot junctions are situated on the level of upper rims of rod simulator edges. The thermocouples are introduced through guide channels in upper grid, 10 mm of them being left outside.

In the cross section of regular thermocouple location for temperature control (50 mm beneath the upper edge of PTU plate simulator) the thermocouples, 30 in number, are arranged in the three axis similar to the case with rod bundle exit (see Figure 13). In order to supply stiffness to them these thermocouples shall be fixed to the wire 2 mm in diameter and then they are protruded through six unions with a seal in paronite bushes, and then they pass a ring channel and achieve the vessel unions.

Like a regular thermocouple, the thermocouples simulator is brazed to the bottom of a hermetic tube 4x1. Inside this hermetic tube the thermocouple leaves the detector simulator and goes outside through the vessel union.

All thermocouples that measure coolant temperature are made of a thermocouple cable type KTMC, which is 1 mm in the outer diameter.

At the upper edge of central tube we arrange a thermocouple, a Pitot tube and a static pressure measuring probe.

At the rod bundle simulator exit section we arrange a probe for measuring static pressure.

RESULTS

The objective of testing was to measure coolant temperature distribution in two cross sections: directly at rod bundle outlet and at regular thermocouple axial elevation.

The tests results may be applied for research purposes, such as:

- dependence between coolant temperature in thermocouple location and average temperature at rod bundle outlet, which will allow to determine correction functions for converting the measured temperature into averaged coolant temperature;
- verification and validation of subchannel codes ;
- verification and validation of CFD-codes.

The experiments simulated various options of coolant temperature distribution at rod bundle outlet.

A first part of testing was performed at pressure condition of 90 - 95 Bar.

For the purpose of various options of coolant temperature distribution at fuel bundle outlet we simulated various options of rod-wise power distribution.

The first experimental series paid much attention to the fields of significant asymmetry. Such fields may be of special interest for computer code validation or calculating methods verification. These fields were simulated by disabling one or two sections of fuel rod simulators. We also investigated the fields of actual rod-wise power distribution.

We selected only 3 type of asymmetric field of heat release, which is characteristic for a VVER-440 fuel assembly: option 1 is axially symmetric power distribution (when identical energy is supplied to each of the three group of rod simulators, see Fig. 12); option 2 is asymmetric power distribution (average relative power generated by rod simulators in “hot” group is k_{gr} = 1.10, Fig. 15); option 3 is asymmetric power distribution (this is a basic option of asymmetric power distribution, k_{gr} = 1.15, Fig. 16); option 4 is asymmetric power distribution (k_{gr} = 1.20, Fig. 17).

In every experimental points the heat balance correlation error does not exceed ±3 %. Meanwhile, in major experimental points the temperature measured in test vessel outlet T_{out} differs from the averaged coolant temperature derived from heat balance at least by ±0.3°C (see a foregoing Table 1). More significant deviations (up to 0.7 °C) were obtained for the cases of low coolant flow rates (~20 t/h), which may be related to a greater error in coolant flows of smaller rate.

The matrix of completed tests is shown in Table 1.

Table 1 consists of 12 columns. The columns contain the following data:

Column 1 shows the serial number of the selected state.

Column 2 shows a coolant mass flow in a rod bundle simulator, named M_B.

Column 3 shows a mass coolant flow in the model of assembly-to-assembly gap, named M_G.

Column 4 depicts electrical energy supplied to rod simulator group 1 from power supply unit W_1 (the magnitude free from heat loss).

Column 5 shows electrical energy supplied to rod simulator group 2 from power supply unit W_2 (the magnitude free from heat loss).

Column 6 shows electrical energy supplied to rod simulator group 3 from power supply unit W_3 (the magnitude free from heat loss).

Column 7 gives inlet temperature at heat generation area, which is measured by resistive thermometer T_{in}.

Column 8 gives outlet temperature in test vessel, which is measured by resistive thermometer T_{out}. Since the resistive thermometer locates at a big distance upward from the head of FA simulator (approximately 2m), it is assumed to measure an average coolant mixing temperature.

Column 9 gives the magnitude of error in correlation of heat balance Δ_{Bal}, measured in ^oC;

Column 10 depicts the values of ΔT, which denotes average coolant heating in ^oC;

Column 11 depicts the number of type rod-wise distribution.

Figures 18 and 19 depict temperature profiles for two testing conditions. Temperature profiles show both the outlet temperature in rod bundle simulator and the temperature within a regular thermocouple section. A special indication depicts the signals from a regular thermocouple. The Figures give chains of thermocouples, which are called rays. Figure 14 gives the numbers of rays 1 through 6 as the first digit in thermocouple identification No. The second digit in thermocouple identification No. (going after a dash) stands for the distance between the thermocouple and the centre of the cross section, were it is arranged.

The comparison measured temperature and temperature calculated by CFD-code Phoenics can be seen in figures 20 and 21. Present results for rays 2 and 5.

Table 1 - Experiment matrix

Ser. No.	M_B t/h	M_G t/h	W_1 кW	W_2 кW	W_3 кW	T_{in} ^oC	T_{out} ^oC	Δ_{Bal} ^oC	ΔT ^oC	Type pin-wise power distributions
Part 1										
1_1	40,19	0,0	0,0	0,0	157,3	132,2	135,4	0,1	3,2	Asymmetric profile
1_2	40,10	0,0	0,0	172,6	0,0	133,9	137,6	0	3,7	
1_3	39,80	0,0	0,0	173,5	156,9	149,8	156,8	-0,2	7,0	
1_4	39,72	0,0	295,3	0,3	0,0	152,1	158,5	-0,2	6,4	
1_5	40,03	0,0	305,0	180,2	149,5	149,9	163,1	0,1	13,2	1
1_6	39,54	3,32	305,8	181,4	150,0	150,9	163,5	-0,3	12,6	1

Table 1(Sequel)

Ser. No.	M_B t/h	M_G t/h	W_1 кW	W_2 кW	W_3 кW	T_{in} ^oC	T_{out} ^oC	Δ_{Bal} ^oC	ΔT ^oC	Type pin-wise power distributions
1_7	39,96	0,0	334,3	143,0	160,2	153,0	166,2	0,1	13,2	2
1_8	40,11	0,0	345,1	127,0	159,5	152,1	165,2	0,1	13,1	3
1_9	39,62	3,26	346,4	126,6	159,4	151,0	163,3	0,1	12,3	3
1_10	40,08	0,0	365,0	112,8	158,8	150,7	164,0	0,1	13,3	4
1_11	21,15	0,0	0,0	175,8	0,0	152,0	159,1	-0,2	7,1	Asymmetric profile
1_12	21,32	0,0	0,0	0,3	158,6	151,0	157,1	0	6,1	
1_13	58,71	0,0	0,0	346,5	317,0	185,5	194,6	0	9,1	
1_14	59,15	0,0	0,0	349,2	0,0	186,1	190,8	0,3	4,7	
1_15	59,50	0,0	0,0	0,3	315,5	184,2	188,6	0	4,4	
1_16	59,64	0,0	605,8	0,4	0,0	186,8	195,0	0,1	8,2	
1_17	40,79	0,0	0,0	0,4	334,6	189,8	196,5	-0,1	6,7	
1_18	40,88	0,0	0,0	327,9	0,0	189,3	195,9	0	6,6	
1_19	40,79	0,0	0,0	319,9	327,8	190,8	203,8	-0,5	13,0	
1_20	40,76	0,0	598,3	0,4	0,0	193,7	205,6	-0,2	11,9	
1_21	23,82	0,0	298,0	0,3	0,0	194,4	204,4	0,2	10,0	
1_22	23,80	0,0	0,0	178,4	158,2	192,5	203,9	0,2	11,4	
1_23	23,95	0,0	306,5	174,0	152,8	193,0	214,3	0,1	21,3	1
1_24	24,13	0,86	306,3	174,1	152,5	197,3	217,7	-0,6	20,4	1
1_25	24,44	0,32	354,6	128,1	159,7	200,9	221,8	-0,6	20,9	3
1_26	24,43	1,18	354,5	127,4	159,7	203,2	223,3	-0,7	20,1	3
1_27	23,94	0,0	369,7	111,5	152,2	200,8	221,9	-0,2	21,1	4
1_28	24,04	0,0	339,3	142,7	157,0	202,0	223,2	-0,1	21,2	2
Part 2										
2_5	78,53	0	92,7	53,5	43,8	100,7	102,8	0,0	2,1	
2_23	38,63	0	586,9	376,7	276,8	202,9	228,4	-0,1	25,6	1
2_24	39,38	1,88	588,0	376,9	277,1	195,6	220,0	0,1	24,3	1
2_25	39,06	0	660,5	281,9	298,6	195,0	220,7	0,2	25,5	2
2_26	39,05	0	691,4	252,5	302,0	199,5	224,9	-0,1	25,5	3
2_27	38,31	4,37	694,7	253,4	303,6	201,9	225,2	-0,2	23,5	3
2_28	38,91	0	713,6	219,8	301,1	200,3	225,7	0,0	25,4	4
2_29	58,67	0	590,3	384,9	275,2	194,9	212,3	0,2	17,2	1
2_30	56,63	6,25	589,5	385,0	273,5	203,0	218,9	0,0	15,9	1
2_31	56,97	5,94	686,5	253,2	303,0	201,1	216,9	0,0	15,8	3

Table 1(Sequel)

Ser. No.	M_B t/h	M_G t/h	W_1 кW	W_2 кW	W_3 кW	T_{in} °C	T_{out} °C	Δ_{Bal} °C	ΔT °C	Type pin-wise power distributions
2_32	58,11	0	684,3	253,7	302,5	206,3	223,5	0,2	17,0	3
2_33	58,31	0	661,7	287,4	299,9	201,6	218,9	0,2	17,1	2
2_34	58,65	0	713,2	222,0	297,5	201,9	218,7	0,0	16,8	4
2_35	57,82	0	588,2	380,5	275,9	237,4	253,8	0,1	16,3	1
2_36	57,67	0	657,4	284,2	295,8	237,8	254,2	0,2	16,2	2
2_37	57,48	0	686,6	249,5	302,2	238,3	254,6	0,0	16,3	3
2_38	57,59	0	711,0	223,2	299,4	238,5	254,8	0,1	16,2	4
2_39	57,81	5,95	588,1	383,9	275,6	240,5	255,2	-0,1	14,8	1
2_40	57,79	5,93	686,0	252,5	302,7	241,7	256,2	-0,1	14,6	3
2_41	39,16	3,84	681,3	253,1	303,7	236,4	257,9	-0,2	21,7	3
2_42	39,05	3,82	587,3	383,6	279,3	236,6	258,4	-0,2	22,0	1
2_43	38,89	0	582,8	386,9	279,6	236,8	260,7	-0,2	24,1	1
2_44	39,38	0	661,8	286,0	300,9	236,9	260,8	0,1	23,8	2
2_45	39,41	0	685,6	250,0	301,4	236,1	259,8	0,1	23,6	3
2_46	39,11	0	714,7	219,5	297,6	236,7	260,2	-0,2	23,7	4
2_47	38,83	0	861,8	571,1	428,0	235,8	271,6	0,3	35,5	1
2_48	38,66	0	1009,4	388,6	448,4	235,6	271,2	0,1	35,5	3
2_49	37,80	3,88	1016,0	402,1	444,5	235,1	268,3	-0,2	33,4	3
2_50	37,70	4,05	879,0	574,4	424,5	237,2	270,7	0,0	33,5	1
2_51	57,19	5,76	876,5	572,5	421,3	236,8	259,5	0,3	22,4	1
2_52	57,40	5,6	1014,1	402,1	445,0	234,9	257,5	0,3	22,3	3
2_53	60,02	0	1014,8	401,8	463,7	225,0	249,5	0,5	24,0	3
2_54	59,47	0	1011,1	403,5	464,2	222,2	246,8	0,3	24,3	3
2_55	59,82	0	1020,1	405,4	462,0	220,1	244,7	0,3	24,3	3
2_56	57,88	0	1018,8	406,9	463,8	219,9	245,3	0,2	25,2	3

CONCLUSIONS

RRC “Kurchatov Institute” has performed coolant mixing investigation in a head of a full-size simulator of VVER-440 fuel assembly. The experiments were focused on obtaining the data important for investigating the trends in temperature difference between the value registered by a ICIS thermocouple and the value of average temperature. The completed experiments ensure representability of configuration simulation by reproducing every construction peculiar feature of flow part of fuel assembly in the domain between the lower spacing grid and thermocouple location, and also by slightly modified fuel assembly regular elements (or analogues thereof).

For the purpose of effectiveness of coolant mixing assessment within the head cross section of FA simulator, we measured coolant temperature distribution both in the place where coolant flow leaves the rod bundle simulator (in 39 data points along the cross section) and in the cross section location of regular ICIS thermocouple simulator (30 data points).

The testing was conducted with pressure of 90 – 95 Bar, mass coolant flow rates up to· 2300 kg/(m^2·s), temperature of coolant heating in “hot” parts of the bundle up to 35°C and differences between coolant temperature extremes measured in rod bundle simulator outlet up to 20°C. Temperature fields were registered in 63 conditions that differ in coolant flow and inlet coolant temperature, electrical heating rate of FA simulator, and radial coolant distribution. In certain registered conditions we simulated coolant leakage to the space between the fuel assemblies.

On the basis of test data analysis we made the following major conclusions:

- In cross section location of regular ICIS thermocouple simulator temperature profiles become visibly flatter, as compared with outlet temperature profiles for rod bundle, however, the profiles do not become absolutely flat. The residual curvature of profiles is more intensive, the more intensive is the original curvature. With the pin-wise power distributions typical for VVER-440 fuel assembly, the deviation between the signal from ICIS thermocouple simulator and average temperature does not exceed 10 % of the average coolant heating within the bundle.
- The impact of cold coolant flushes that penetrate to assembly head from the simulator of assembly-to-assembly gap covers much of the periphery area, thought does not reach the centre of the cross section, where the regular thermocouple simulator is located.

The received test data may be important both for investigation of dependencies between the coolant temperature in regular thermocouple location or average outlet temperature in assembly head, and for validation of CFD codes or subchannel codes.

FIGURES

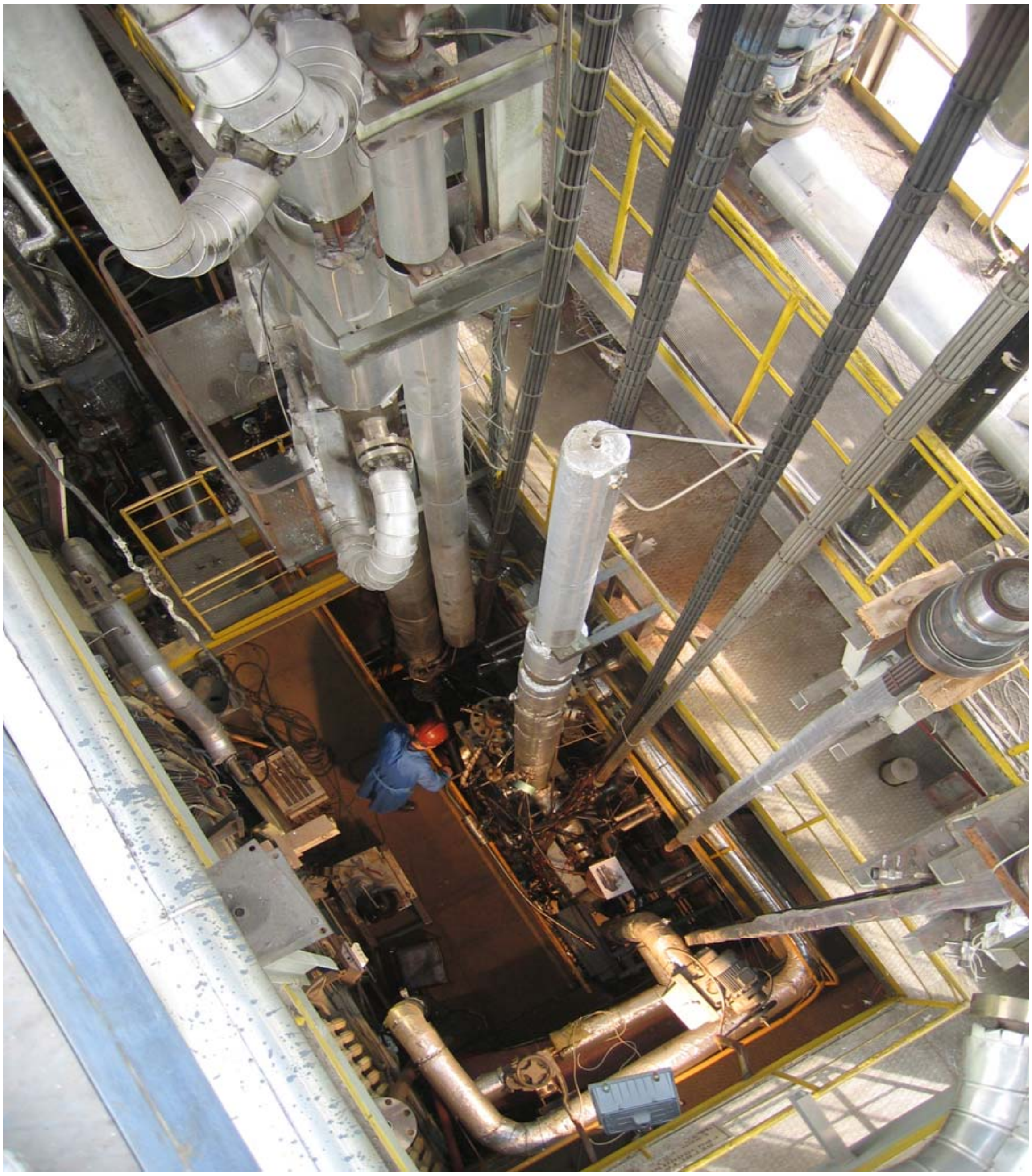
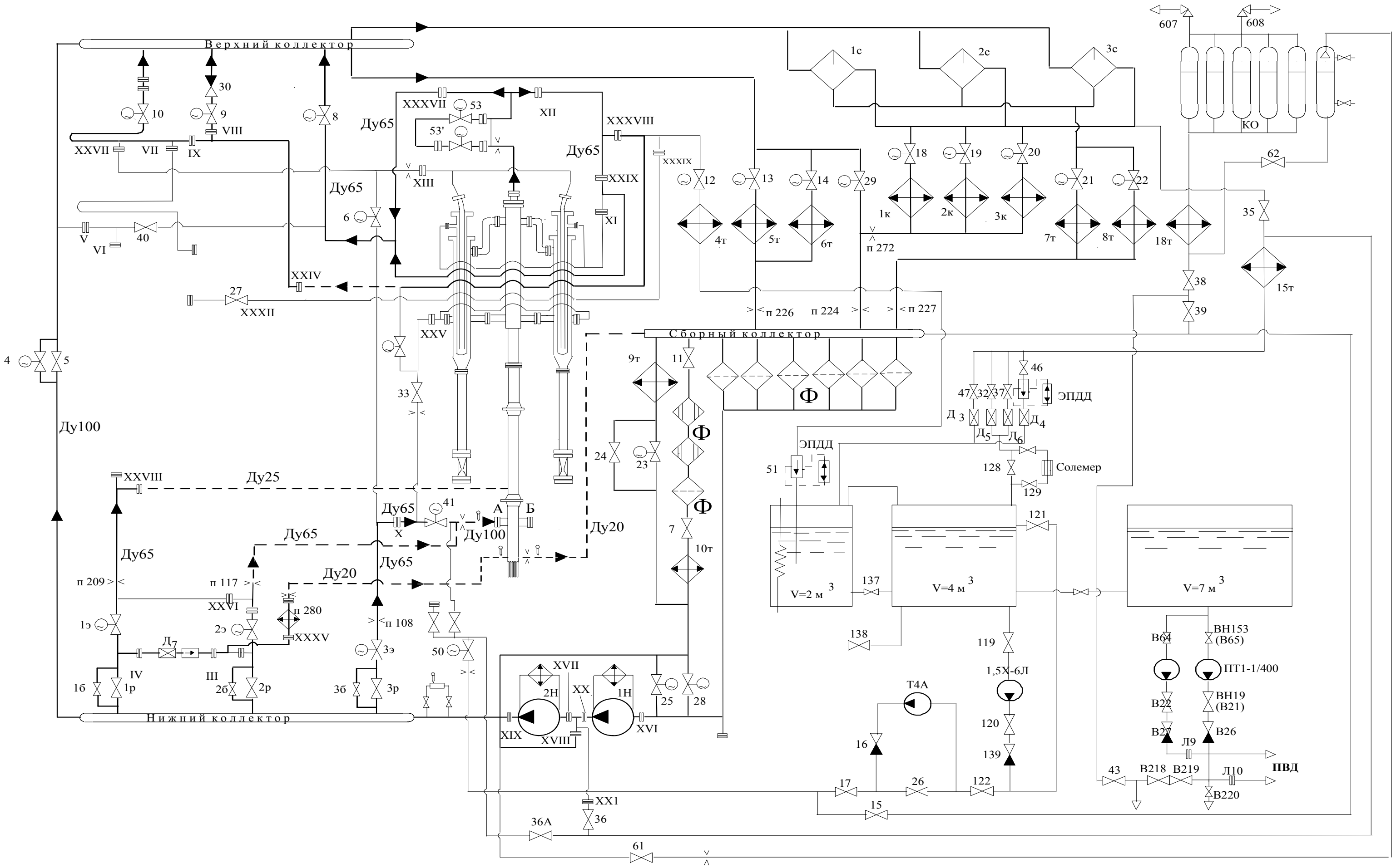


Figure 1 - Test facility “KS”



Symbols

н is a pump; с is a separator;
к is a condensator; т is a heat exchanger;
ф is a filter; ко is a pressureriser
The bold type stands for the forced circulation circuit, which will be employed in the tests;

Figure 2 – Principal flow-sheet of low-pressure loop of KS test facility

Figure 3 - Full-size spacing grids and a central tube (to the left);
Figure 4 - A full-size rod bundle simulator and a full-size FA (to the right)

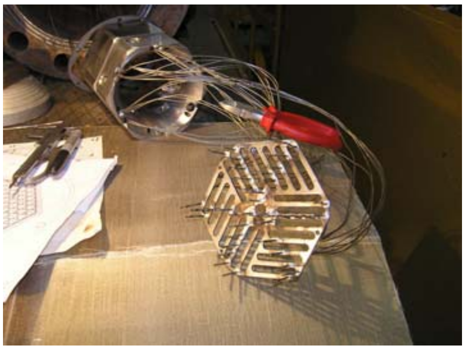
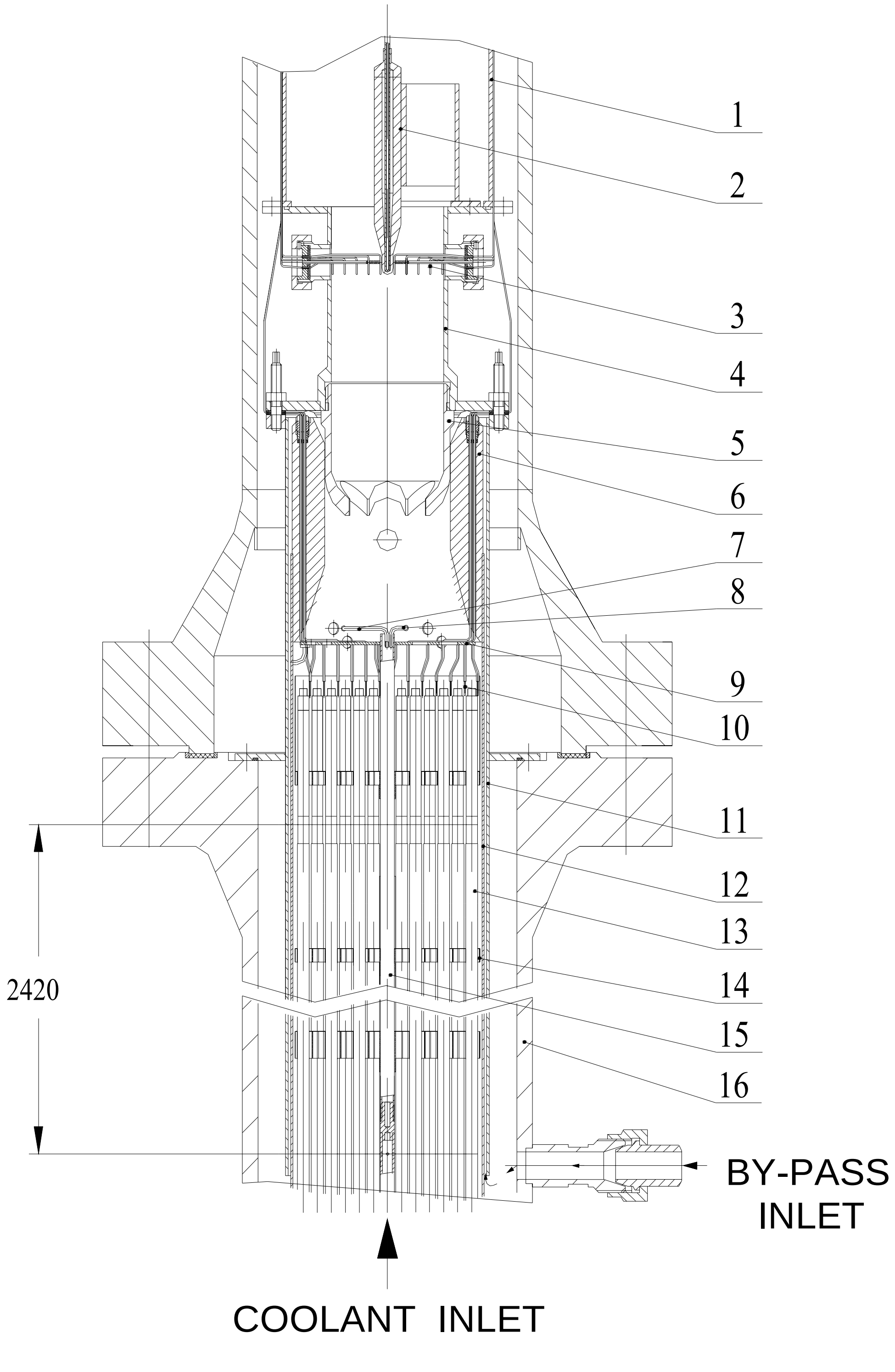
 

Figure 5 - A full-size upper grid and thermocouples (to the left)
Figure 6 - A full-size head (down view) (to the right)

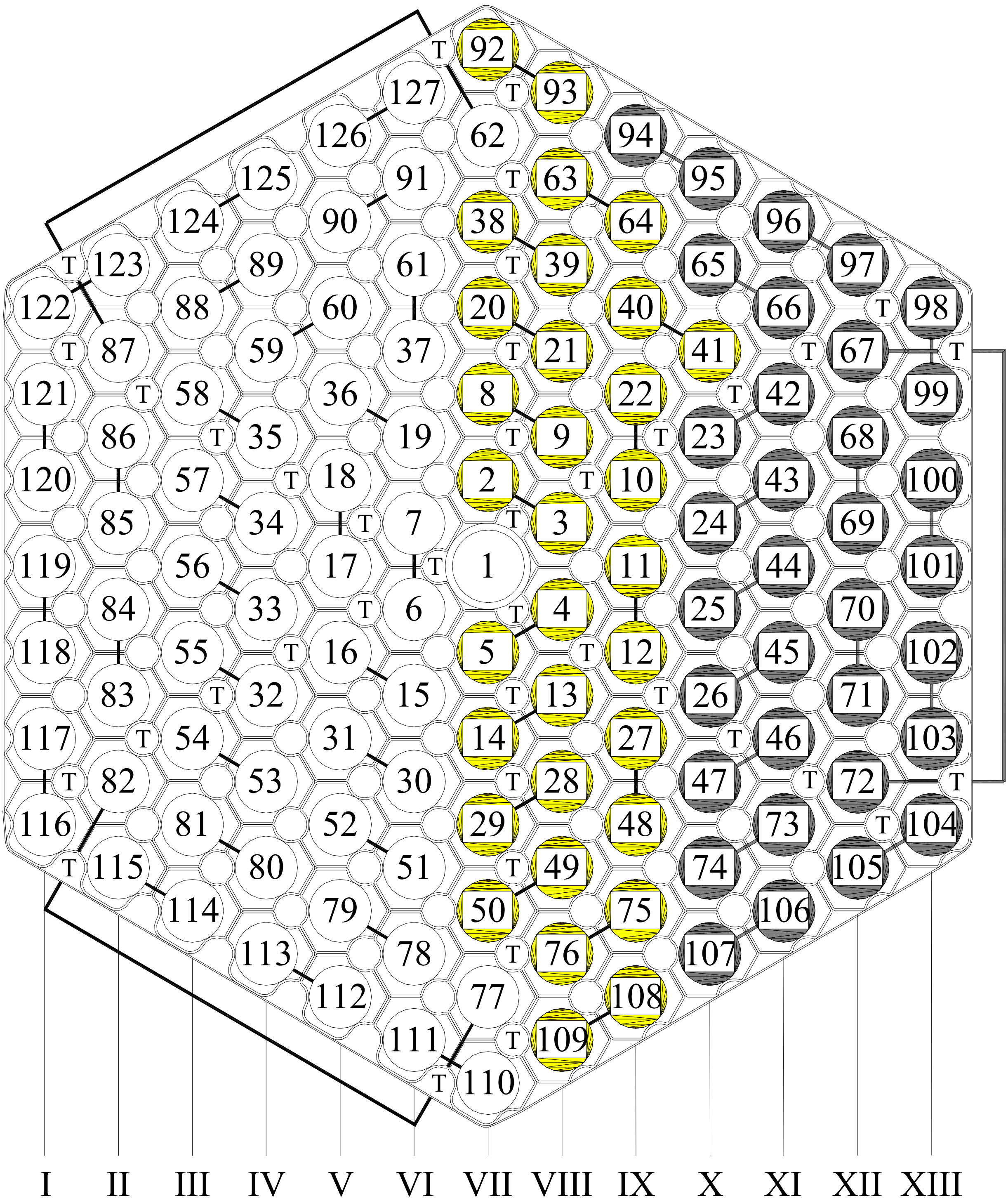
Figure 7 - A full-size head (upper view) (to the left)
Figure 8 - Protective tube unit (PTU) simulator (to the right)

Figure 9 - Regular thermocouple simulator (upper view)



1 – upper housing; 2 – regular thermocouple; 3 – thermocouples (30 pcs); 4 – PTU plate simulator; 5 – catcher; 6 – cap (head); 7 – Pito tube; 8 – static pressure measuring probe; 9 – upper grid; 10 – bundle exit thermocouples (39 pcs); 11 – hexagonal tube; 12 – assembly housing; 13 – rod simulators; 14 – spacing grid; 15 – central tube; 16 – test vessel.

Figure 10 – Test section



Symbols:

1 is a central tube,

2 through 127 are fuel rod simulators (rods 62, 67, 72, 77, 82 may also simulate Gd rods),

T are the thermocouples.

Figure 11 – Test bundle cross section

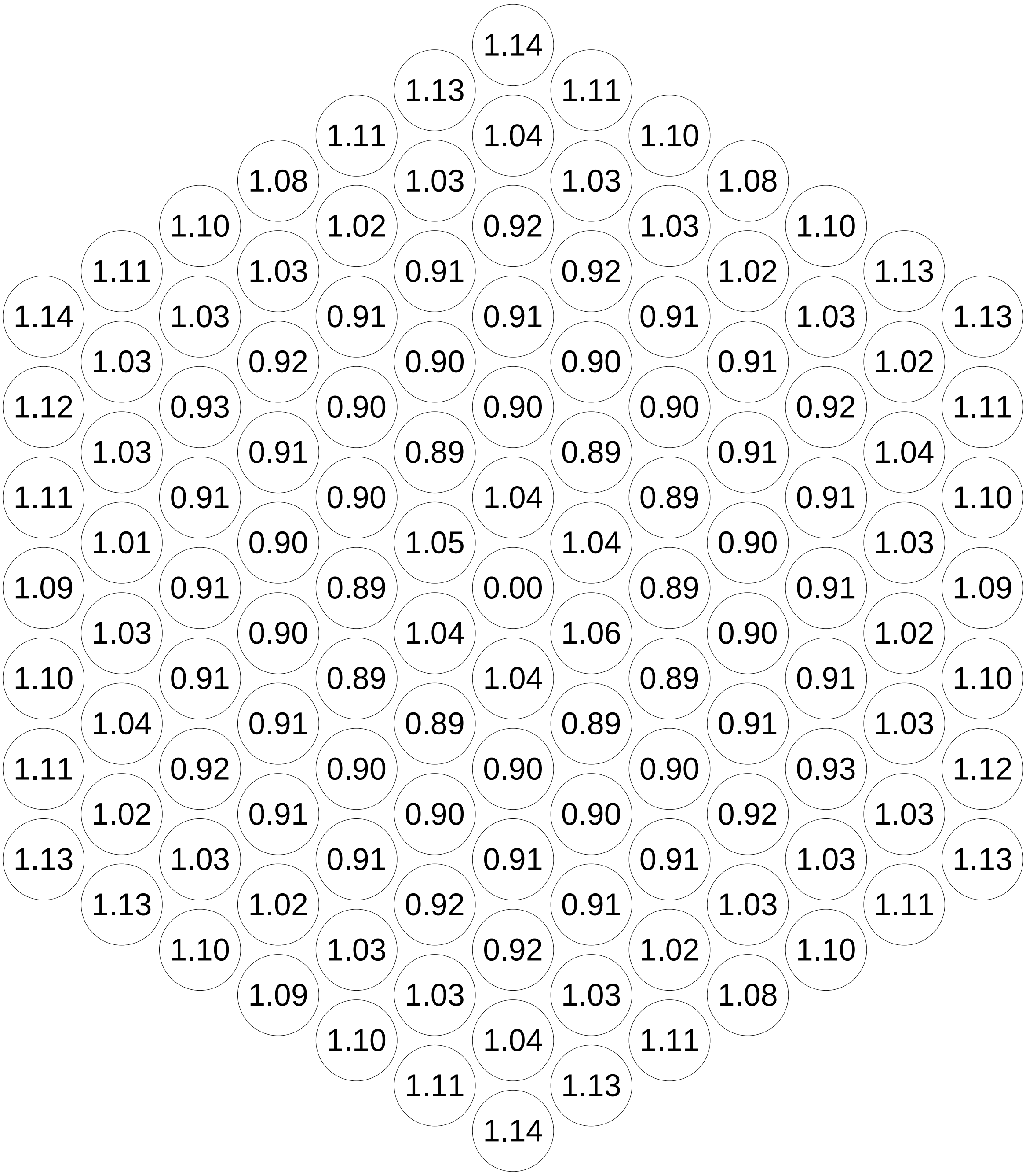
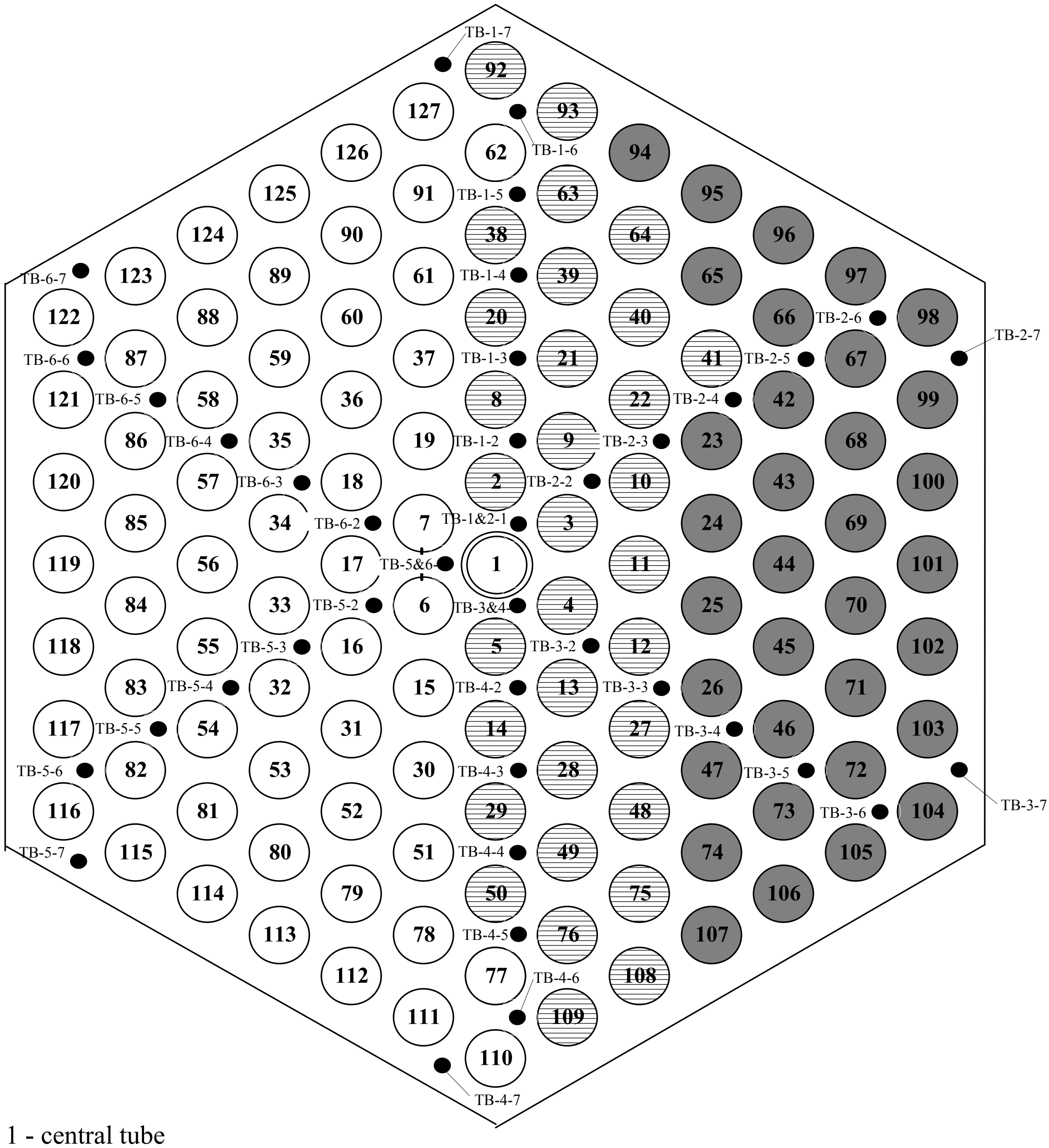


Figure 12 –Radial heat release distribution calculated using realistic rod simulator resistances with assumed equal voltage and temperature for all fuel rod simulators

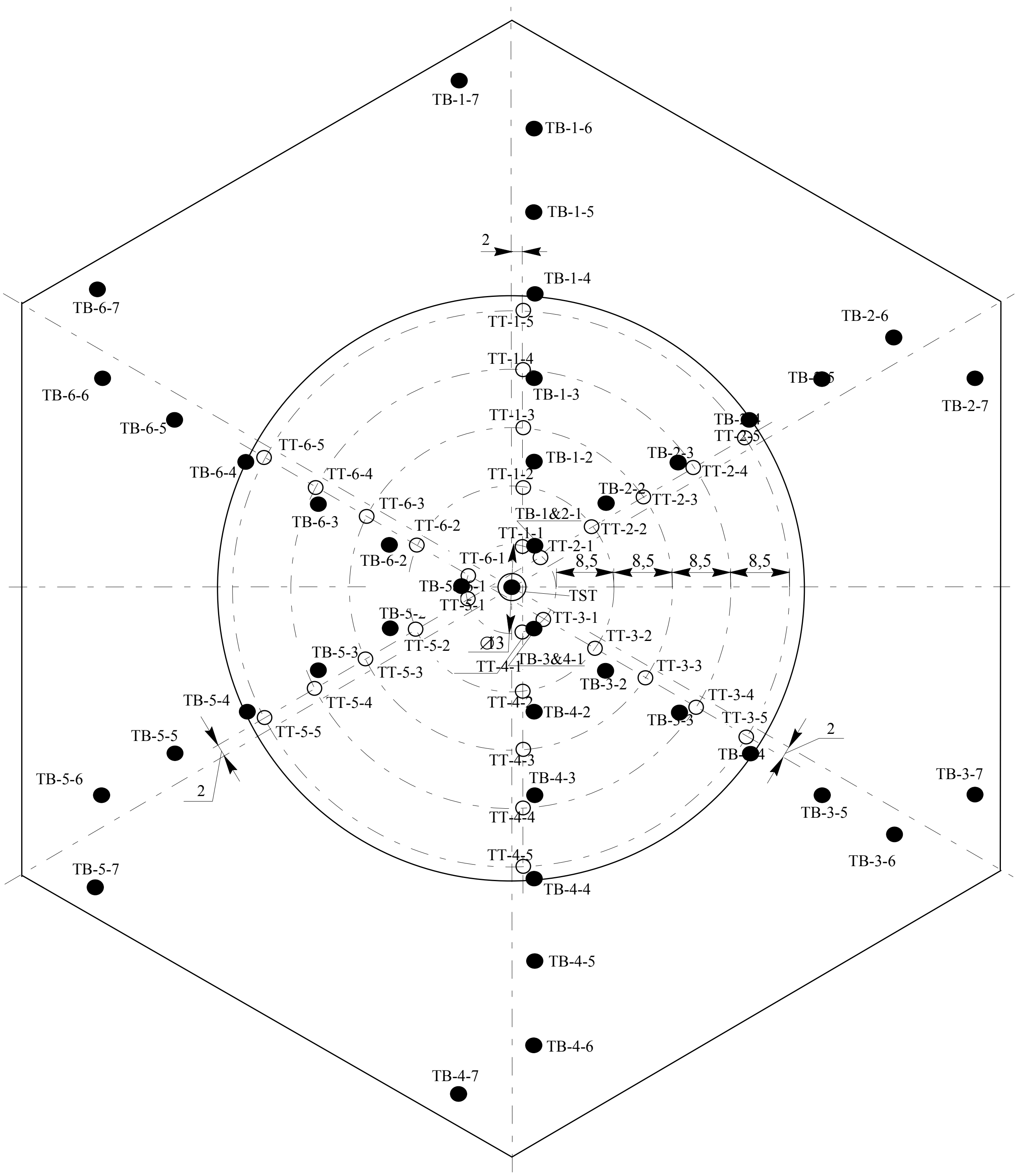


1 - central tube

2 through 127 are fuel rod simulators (rods 62, 67, 72, 77, 82 may also simulate Gd rods),

- is group 1 of fuel rod simulators
- is group 2 of fuel rod simulators
- is group 3 of fuel rod simulators
- are the hot junctions, situated at the bundle exit section

Figure 13 – Thermocouple arrangement at the bundle exit section



● - are the thermocouples, arranged at the bundle exit section

○ - are the thermocouples, arranged at the location section of a regular thermocouple

Figure 14 – Integrated maps of thermocouple at the bundle exit section (see Figure 13) and at the section of a regular thermocouple location

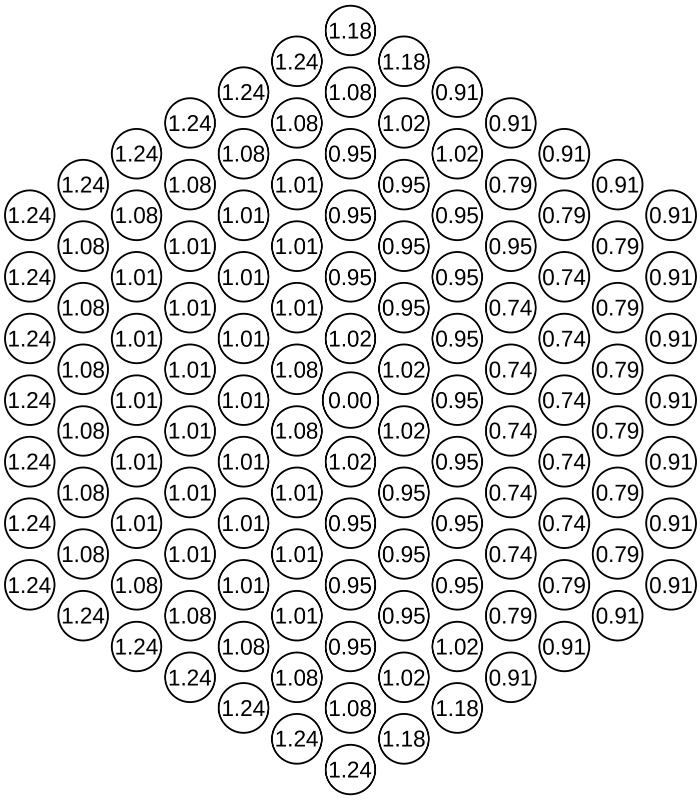


Figure 15 – Assymetric field of heat release (type 2)

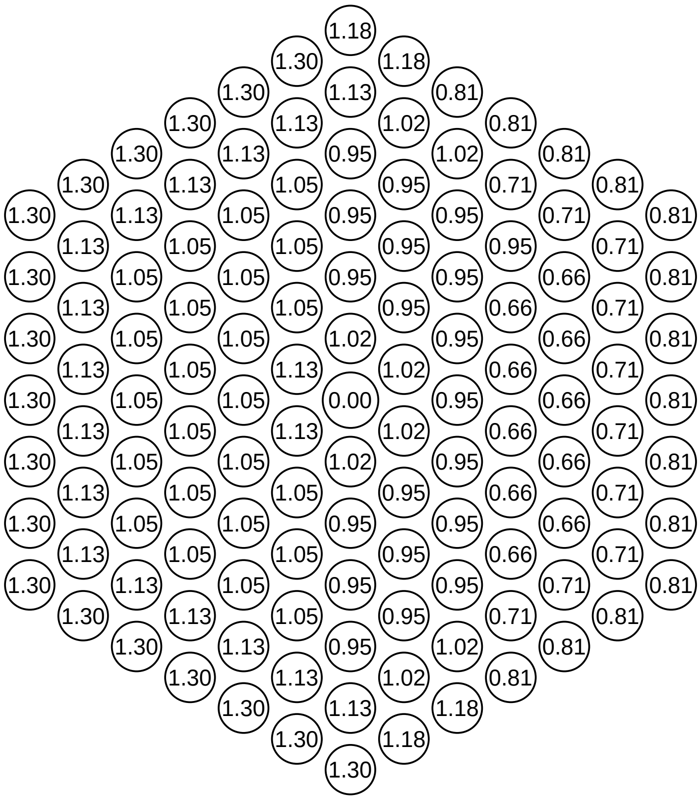


Figure 16 - Assymetric field of heat release (type 3)

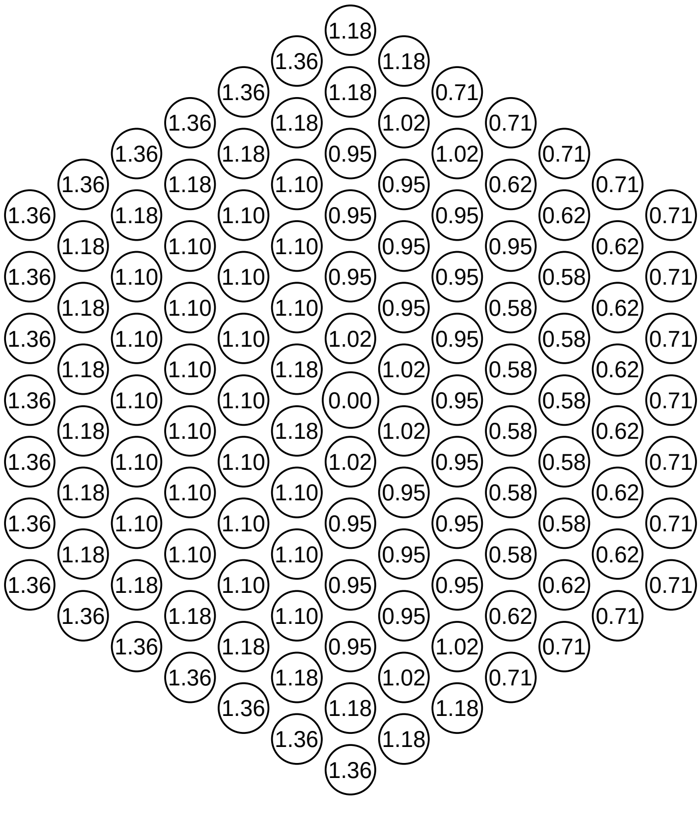
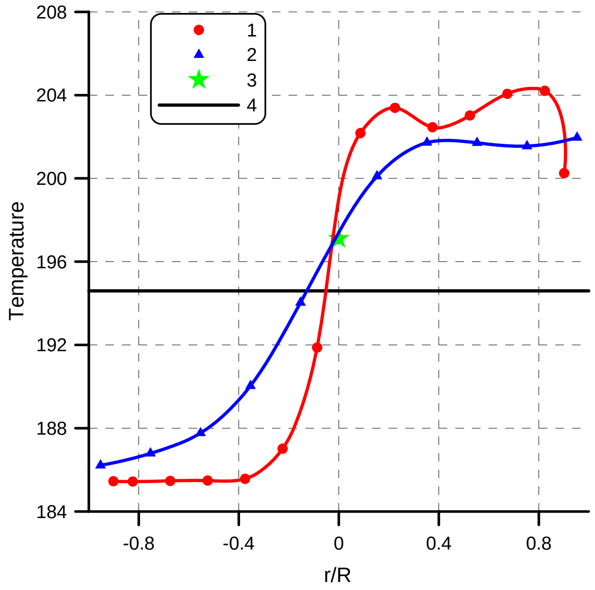
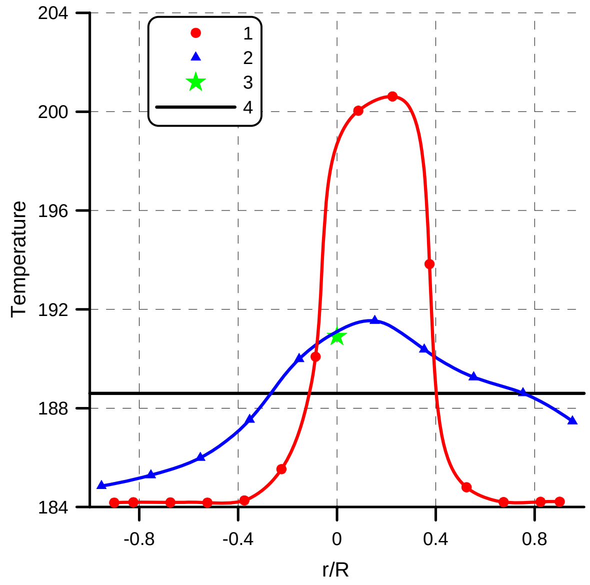


Figure 17 - Assymetric field of heat release (type 4)



1 –at outlet from rod bundle;
2 – in cross section of regular thermocouple;
3 – outcome of regular thermocouple;
4 – average temperature in cross section of regular thermocouple.

Figure 18 - Coolant temperature profiles for the head of VVER-440 fuel assembly simulator. Position 1_13 (Table 1). Thermocouple chains along rays 3 and 6



1 –at outlet from rod bundle;
2 – in cross section of regular thermocouple;
3 – outcome of regular thermocouple;
4 – average temperature in cross section of regular thermocouple.

Figure 19 - Coolant temperature profiles for the head of VVER-440 fuel assembly simulator. Position 1_15 (Table 1). Thermocouple chains along rays 3 and 6

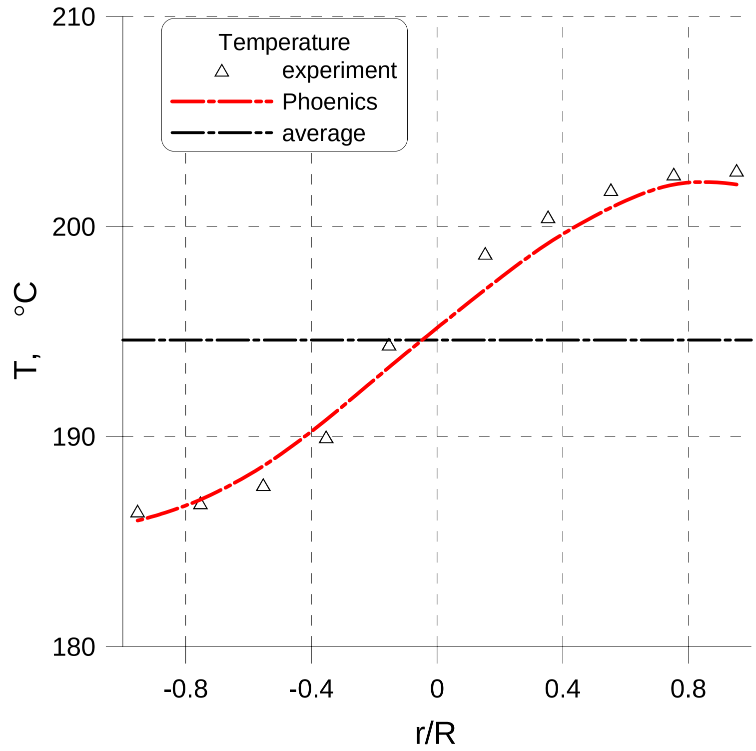


Figure 20 – Measured and calculated coolant temperature profiles along rays 2 and 5 Position 1_13 (Table 1). Thermocouple chains along rays 2 and 5

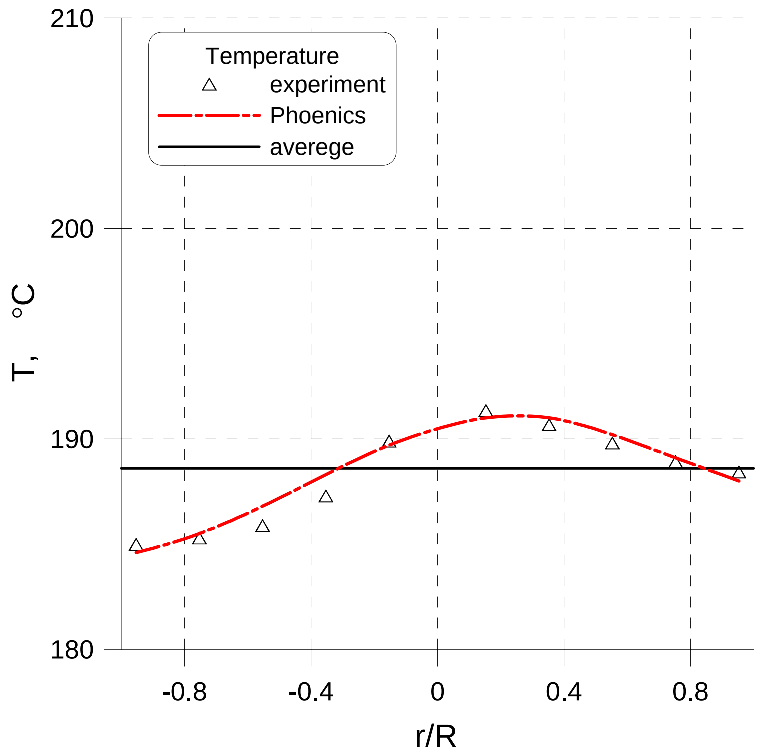


Figure 21 – Measured and calculated coolant temperature profiles along rays 2 and 5 Position 1_15 (Table 1). Thermocouple chains along rays 2 and 5