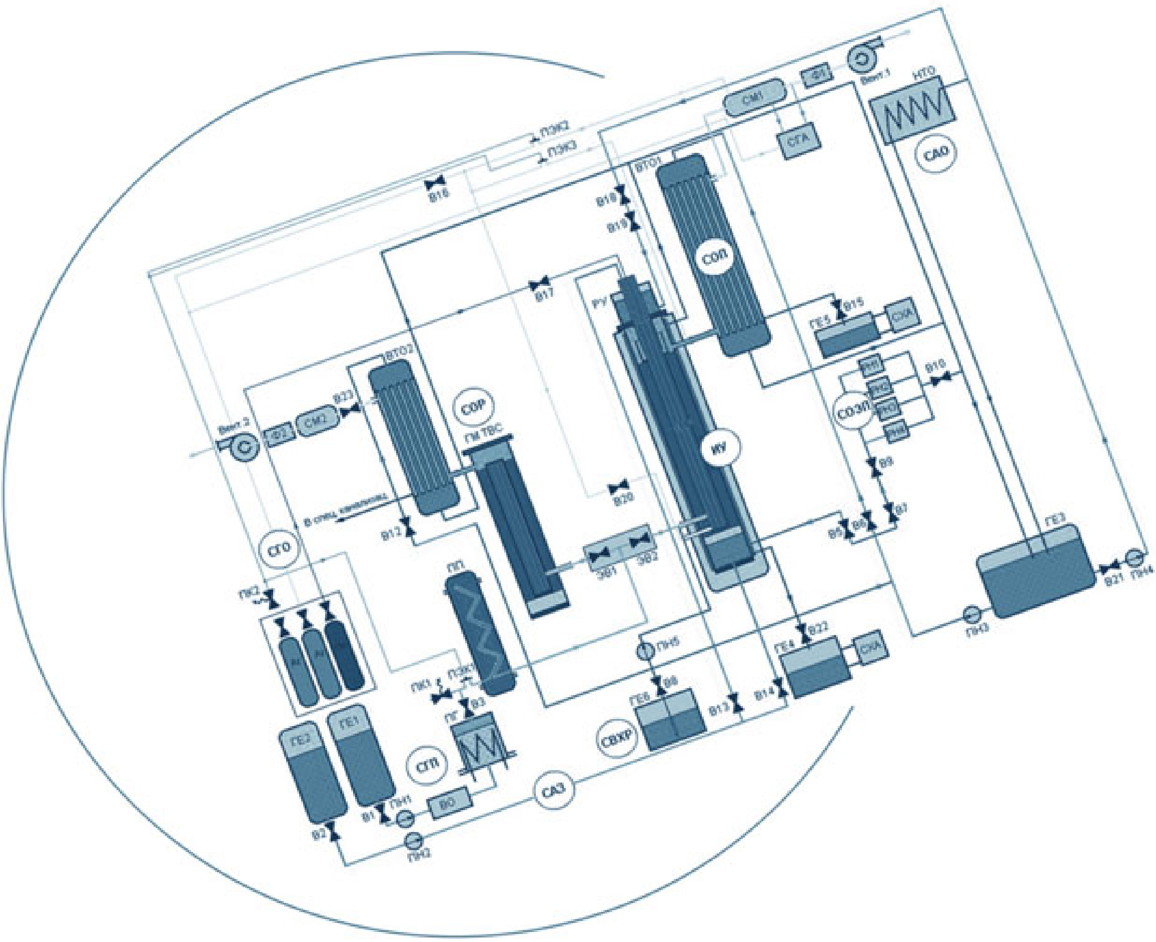
SPECIFICATION
OF THE PARAMETER-SF3 EXPERIMENT

(investigation of overheated WWER fuel rods bundle under top flood conditions)

ISTC Project 3690



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1. INTRODUCTION

In terms of consequences the most serious accident at NPP with WWER (PWR) is beyond design basis accident with loss of coolant (LOCA) – severe accident that could lead to core melting, damage of reactor vessel, release of hydrogen, fission radioactive products into the containment and the environment.

Special measures (accident management) shall be taken to mitigate the consequences of severe accident. Elaboration of adequate technical solutions and measures on accident management is based on the knowledge of the laws of accident scenario and response of the reactor to interference (actions on accident management) into the natural course of accident process. One of the urgent measures on accident management is the reflooding of the overheated core. Thereupon, experimental and computational studies of physical-chemical processes, occurring in the overheated core during quenching, are relevant. And one of the most important tasks can be considered the integral experiments aimed at checking the effectiveness of accident management measures.

WWER-1000 is the main reactor type operated in Russia and abroad. Elaboration of measures on accident management is directly connected with the reactor design and equipment capabilities. WWER-1000 is a loop reactor. The reactor coolant system includes the reactor and four circulation loops, each consisting of steam generator, reactor coolant pump set, main gate valves on the hot and cold legs, and main coolant pipelines connecting the equipment of loops to the reactor. The reactor coolant system provides heat removal from the reactor core by water circulation in the closed circuit and heat transfer to the secondary circuit. Water supply from the emergency core cooling system (ECCS) and other accumulators during accident can be done simultaneously from top and bottom that will make possible to avoid the situations when the whole amount of the supplied water is entrained into leak.

As the event that could result in the core drying and, with severe failures, could lead to severe accident, the primary circuit coolant leak is considered. The initiating event is the primary leak with superimposing of additional failures, for example, under complete failure of ECCS active part that could lead to the core uncovering. In WWER-1000 there is a possibility to restore the core cooling. One of the design features of WWER-1000 is a possibility of the core reflooding from top and bottom.

The difference between quenching from top and from bottom is that during bottom quenching the pressure chamber is filled first, and only after its filling the boiling is started and the core is cooled with steam and then with water after fuel rods wetting. During top quenching the water is supplied to the reactor collection chamber, distributed over the core cross-section, and then moves downwards cooling the core. Consequently, the core cooling under top quenching can be done a little sooner than under bottom quenching.

The efficiency of the reactor core cooling with water moving from top to bottom is a question of study in the PARAMETER-SF3 test.

Top flooding conditions come in PWR when:

- steam condensed in SG steam tubes returns to a core through a hot leg;

- water which injected in the hot leg from the emergency cooling system enters of into the core partially.

The PARAMETER-SF3 test is a continuation of the PARAMETER-SF1 one, performed in the framework of ISTC project #3194. The complex character of the cooling front motion under top flooding in the PARAMETER-SF1 experiment is caused by violation of the model assembly geometry and blocking of the assembly flow area by the formed melting regions. To avoid significant melting in PARAMETER-SF3 test the target maximal temperature of the assembly is planned to be ~1600°C.

Pre-test numerical analysis precedes the PARAMETER-SF3 test conduction. The main goals of pre-test runs are to develop test scenario and to assess possible bundle response to some deviation of design parameters (codes sensitivity analysis). Uncertainties in relation to treatment of some processes occurring during top flooding should be taken into account to be sure that time delay of cooling down due to CCF won't lead to significant bundle overheating above melting point.

2. OBJECTIVES AND TASKS OF THE INVESTIGATION

In the PARAMETER-SF3 experiment the initial stage of severe accident with large break LOCA was simulated with the core drying up, its heating-up to ~ 1600°C and top flooding.

The goal of the PARAMETER-SF3 experiment is to study the 19-rods model FA of WWER-1000 under the simulated conditions of severe accident including the stages of low rate cooling down with top flooding, and namely:

- Study of the behaviour of structural components of the 19-rods model FA of WWER-1000 (fuel pellets and claddings, shroud, spacer grids);
- Study of the WWER assembly cooling down under top flood condition;
- Study of the oxidation degree of the structural components of the 19-rods model FA of WWER-1000;

- Study of interaction and structural-phase changes in the materials of the model FA of WWER-1000;
- Study of the hydrogen release.

The set tasks will allow:

- To check an adequacy of processes modeling during flooding
- To assess the oxidation models
- To collect data for thermohydraulic models development:
  - Determination of the heat transfer coefficients in POST-CHF mode using the data on temperature evolution during quench phase;
  - Evaluation of the components deformation after test and possible limitation of surface wetting due to decrease of flow area;
  - Specification of parameters in models available in computer codes for POST-CHF heat transfer and flooding treatment. Justification of the applicability of these parameters for simulation of the processes occurring under the conditions similar to the experiment SF3 ones.

3. DESIGN CHARACTERISTICS OF PARAMETER FACILITY

PARAMETER facility includes the following technological systems:

- The test section with a model FA;
- The electric power supply system for the test bundle heating up;
- The steam supply system;
- The water supply system;
- The argon gas supply system;
- The system of hydrogen measurement;
- Temperature, pressure, mass flow measurement devices;
- The facility control system
- The data acquisition system.

A simplified flow diagram of the PARAMETER test facility is presented in Fig. 1.

During experiment superheated steam from the steam generator and superheater enters through connecting pipe 3 into a lower part of test section (Fig. 2). The heated argon as the carrier gas for hydrogen measurement system, are supplied through connecting pipe 4 (Fig. 2) into the lower part of the test section as well. Steam flow rate is set by the water flow rate of the steam generation system (Pump 1) and is controlled by the parameters of the steam generator and parameters of the steam at the flowmeter section of steam pipeline (Fig. 1).

Steam together with argon flow upwards and pass through the heated part of the test bundle (Fig.3). The steam that has not consumed, argon and hydrogen released in the zirconium-steam reaction come from the top part of the test section through a water-cooled connecting pipe 8 to a condenser 1 (Fig. 1). Here the steam is separated from the non-condensable gases argon and hydrogen. Steam flowrate at off-gas pipe is controlled using by measurement data of water mass in the condensate tanks Tank 5, Tank 5', Tank 5.1,…, Tank 5.5 (Fig. 1). Non-condensable gases come to the gas analysis system and then to the ventilation system.

Steam switching off precedes top flood start (argon steam flowrate is kept). Water comes from the Tank 7 which holds water under a pressure p7 through an electric valve V3 and an flow meter R3 (Fig. 1) to 41 tubes and then is injected into the top part of the test section. Water flowrate is controlled by a level meter M7 (Fig. 1). Some of the water is pushed by steam flowed up and is ejected from the test section through connecting pipes 8 and 10 (Fig. 4). Ejected water together with condensed steam are collected in the Tank 5 and Tank 6 (Fig. 1).

Experimental data on steam flowrate (p1 T1, p2 T2), water condensate mass in the Tank 5, Tank 5', Tank 5.1,…, Tank 5.5, water mass in the Tank 6, top flood water mass in the Tank 7 and water flowrate R3 and water mass in the lower plenum after test (Tank 6) are applied for steam-water balance control.

In the PARAMETER-SF experiments to cool down and condense steam-gas mixture three heat exchangers are used (see Figure 15): main Condenser and tow intermediate ones with internal and external cooling of the hot mixture. 5 separate lines are used for:

- outlet connecting pipe cooling (G1, Tcol1);
- external cooling of the first intermediate heat exchanger (G2, Tcol2)
- internal cooling of the first intermediate heat exchanger (G3, Tcol3);
- external cooling of the second intermediate heat exchanger (G4, Tcol4);
- main Condenser heat exchangers cooling (G5).

For assessing the efficiency of condensers one can use some experimental date of PARAMETER-SF2 experiment. The cooling system thermocouples readings for PARAMETER-SF2 experiment are plotted in Figure 16. Average cooling water flowrates were G1 $\approx$ 185 g/s, G2 $\approx$ 187 g/s, G3 $\approx$ 168 g/s, G4 $\approx$ 182 g/s, pressure was $\sim$ 0,3 MPa.

A water check located between the second intermediate heat exchanger and the Condenser doesn't allow entering of the hot steam-gas mixture into the Condenser.

The temperature drop in the Condenser is presented in Figure 17. The thermocouple T9 measured the gas mixture temperature at the Condenser inlet (see Figure 15). The thermocouple T10 measured gas mixture temperature at length of 80 mm (pipe ∅8x1 mm) downstream the Condenser (see Protocol of on the results of PARAMETER-SF2 experiment (April 3, 2007), Figure 1), the gas mixture pressure at that point was ~ 0.15 MPa (p10). Pressure of the gas mixture at the Condenser inlet didn't measure. The nearest pressure sensor upstream the Condenser (p15) was located near the rod 3.9 at the 1500 mm elevation (see Protocol of on the results of PARAMETER-SF2 experiment (April 3, 2007), Table 2).

Average cooling water flowrate in the Condenser was G5 ≈ 700 g/s, pressure was ~ 0.3 MPa.

For assessing efficiency of the cooling jacket one can use experimental date on cooling water temperature in the PARAMETER-SF2 experiment. The test section is cooled down with water which flow upwards in a gap between cylinders (inner cylinder is the test section body -SS tube ∅ 133x6 mm, outer cylinder is SS tube ∅ 139x1 mm). Cooling water thermocouples readings at inlet Tw1 and outlet Tw2 of the cooling jacket for central part of the test section (see Figure 19) are presented in Figure 20. Initial cooling water flowrate at inlet was ~ 88 g/s, water pressure at the inlet was ~ 0.3 MPa.

3.1. Test section

The test section comprises three parts joined with the flanges 11 (Fig. 4), 3 (Fig. 3), 8 (Fig. 2).

The lower part of the test section (Fig. 2) includes a body 1 – two SS tubes (∅ 156x6x690 mm, ∅ 203x3x210 mm), lower water-cooled flange 7 through which of electrodes and thermocouples are inserted. Superheated steam together with argon are injected in the test section through inlets pipe 3 and 4 (DI=8 mm).

To decrease effect of steam and argon flows on each other and to improve argon-steam mixing inlets are located opposite each other (90^o и 270^o), inlet pipes 3 and 4 are installed at an angle of sixty degrees to vertical axis and their ends are displaced to opposite direction on ~ 12 mm from the line connecting inlets (Fig. 5). Inlet pipes 3 and 4 are provided with thermocouples (TC XA) for argon and steam temperature measurement (Fig. 2).

Before experiment starting the lower part of the test section is filled with water up to the elevation of – 670 mm for the electrodes cooling down.

It can be expected steam condensation in the lower part of the test section (on a cold test section body and on the water surface). It would lead to uncontrolled steam flowrate decrease through the bundle. Upon the pre-test numerical analysis of PARAMETER-SF2 test using SOCRAT code one can conclude that water evaporation and steam condensation would be in equilibrium if water level elevation is at – 550 mm. During starting-up and adjustment of PARAMETER-SF2 test the elevation was specified (– 670 mm), this value is applied as an initial datum for pre-test runs of PARAMETER-SF3. To prevent steam condensation on a cold wall of the body in the lower part of the test section is heated up to a temperature of 150°C by electric heaters fixed to the external surface of the body (Fig. 2).

Steam-argon mixture injected into the test section flows upwards to the middle part of the test section (Fig. 3). Fuel rod simulators are heated electrically, heaters are installed in the center of the fuel pellets. The central rod is unheated. The test bundle 5 is surrounded by cylindrical shroud 6, thick ZrO_2 fiber insulation 7 to decrease radial heat losses, thermoinsulation shroud 11, then the body 1 – SS tube ∅ 133x6 mm with the water cooling jacket 2 ∅ 139x1 mm.

To avoid the possibility of steam bypassing two membranes 8 and 9 (upper Zr1%Nb membrane 8 thickness ~ 8 mm, lower SS membrane 9 thickness 14 mm) are welded to top and bottom edges of the shroud 6 and are fixed in the flange joints (Fig. 3). Free volume between the shroud 6 and the test section body 1 is filled through connecting pipe 12 with argon under a pressure slightly above the system pressure before the experiment starting (Fig. 3).

In the middle part of the test section high temperature is achieved (up to 1600°C). The shroud temperature linear expansions are compensated bellows joint 10 (Fig. 3).

Steam released in zirconium-steam reaction together with steam that is not consumed and argon flow out through off-gas pipe 8 DI=26 mm (Fig. 4) located in the upper part of the test section.

The upper part of the test section includes (Fig. 4) a body 1 – SS tube ∅ 133x6 mm, the upper water-cooled flange 3 and lower flange 11. The water cooling jacket 2 (∅ 139x1) mm is installed on the external surface of the body.

In the upper flange holes are drilled for 19 fuel rods simulators and for 41 tubes ∅ 4x1 mm (4) through which the quench water enters the test section. Tubes bottom end elevation is 1995 mm. Arrangement of rod simulators and water supply tubes is presented in Fig. 6. Coordinates of the rods simulators and water supply tubes are listed in the Table 1, 2. Point (0, 0) corresponds to the center of unheated rod simulator.

In the upper plenum of the bundle a guide tube 5 (∅ 73x2, L=300 mm) restricts water flow in radial direction. To reduce steam-water counter current flow phenomena in the injection region an additional cylinder 7 (∅ 102x1.5, L=200 mm) was designed. This cylinder, fixed to the shroud is external in relation to the guide tube. As a result the steam-argon flow path to outlet is complex (Fig. 5). One can see that hot gas flows upward between guide tube and cylinder up to the top edge of the cylinder and then flows downward to outlet.

Nevertheless some of water injected is entrained by steam flow. A portion of water remains on the membrane 8 (Fig. 3). Another way of water appearing on the membrane is superheated steam condensation on cold elements of the upper plenum of the test section (on the water-cooled body 1 and upper flange 3 - Fig. 4). Steam condensate flows downwards, then leave the test section through a nozzle 10 (DI=8mm). A screen 6 (∅ 110x1.5, L=200 mm) is designed to prevent condensate penetration into the test section. It is fixed to guide tube 5.

Table 1

Coordinates of rod simulators centers

No.	rod number	Coordinates of rod center	
		X, mm	Y, mm
1	1.1	0	0
2	2.1	12.75	0
3	2.2	6.375	11.042
4	2.3	-6.375	11.042
5	2.4	-12.75	0
6	2.5	-6.375	-11.042
7	2.6	6.375	-11.042
8	3.1	25.5	0
9	3.2	19.125	11.042
10	3.3	12.75	22.084
11	3.4	0	22.084
12	3.5	-12.75	22.084
13	3.6	-19.125	11.042
14	3.7	-25.5	0
15	3.8	-19.125	-11.042
16	3.9	-12.75	-22.084
17	3.10	0	-22.084
18	3.11	-12.75	-22.084
19	3.12	-19.125	-11.042

Table 2

Coordinates of water supply tube centers

Tube number	Coordinates of water supply tube centers		Tube number	Coordinates of water supply tube centers	
	X, mm	Y, mm		X, mm	Y, mm
1	6.375	3.68	22	12.75	-14.72
2	0	7.36	23	12.75	-7.36
3	-6.375	3.68	24	19.125	-3.68
4	-6.375	-3.68	25	25.5	7.36
5	0	-7.36	26	25.5	14.72
6	6.375	-3.68	27	19.125	18.4
7	19.125	3.68	28	6.375	25.76
8	12.75	7.36	29	0	29.446
9	12.75	14.72	30	-6.375	25.76
10	6.375	18.4	31	-19.125	18.4
11	0	14.72	32	-25.5	14.72
12	-6.375	18.4	33	-25.5	7.36
13	-12.75	14.72	34	-25.5	-7.36
14	-12.75	7.36	35	-25.5	-14.72
15	-19.125	3.68	36	-19.125	-18.4
16	-19.125	-3.68	37	-6.375	-25.76
17	-12.75	-7.36	38	0	-29.446
18	-12.75	-14.72	39	6.375	-25.76
19	-6.375	-18.4	40	19.125	-18.4
20	0	-14.72	41	25..5	-14.72
21	6.375	-18.4	42	25.5	-7.36

3.2. Test bundle

The test bundle designed for PARAMETER-SF3 test differs slightly from one for PARAMETER-SF1 test: cylindrical Zr-1%Nb shroud ∅ 70x2 мм is used instead of hexahedral one. Design characteristics of the model FA are given in Table 3. General views of the test section, the bundle cross-section are presented in Fig. 5.

The test bundle is made up of 19 fuel rod simulators. The claddings of the fuel rods are identical to those used in WWER with respect to material and dimensions, i.e. Zr1%Nb alloy is used as a cladding material, 9.13 mm is external diameter, 7.73 mm is internal diameter. The fuel rods are filled with UO_2 pellets, bore diameter is 4.2 mm for 18 heated rods and 1.6 mm for one unheated rod located in the center of the bundle. General view of fuel rod simulators is presented in Fig. 7. 18 fuel rods are heated over a length of 1275 mm.

For rods heating up tantalum heaters are installed in the center of the rods. The tantalum heaters are connected to electrodes made of molybdenum and brass at the each end of the heater. Main dimensions of heater and electrodes can be taken from Fig. 8.

Table 3

Main design characteristics of the model FA

Number of fuel rods heated	18
Number of fuel rods unheated	1
Grid pitch, mm	12.75
Outer/inner diameter of fuel rod cladding, mm	9.13/7.73
Cladding material	Zr-1%Nb
Length of fuel rods heated, mm	3120
Length of fuel rod unheated, mm	2950
Heater material	tantalum
Fuel rod heater, mm:	
diameter/length	4/1275
location	0 to 1275
Location of steam/argon inlet (radial), mm	-355 ($270^o/90^o$)
Location of steam/argon outlet (radial), mm	1425 (0^o)
Inside pressure of gas (helium) in fuel rods, MPa	0.2
Fuel pellets	
Fuel rods heated Outer diameter/of central hole/height, mm	UO_2 pellets with holes $7.6^{-0.03}/4.2^{+0.15}/11^{\pm0.1}$
Fuel rod unheated Outer diameter/of central hole/height, mm	UO_2 pellets with holes $7.6^{-0,03}/1.6/11^{\pm0,1}$
Spacer grid	
Material	Zr-1%Nb
Height, mm	20
Number, pcs.	6
Distance between grids, mm	255
Location of the upper edge of grids, mm:	
of the first (lower)	30
of the sixth (upper)	1305
FA shroud	
Material	Zr-1%Nb
Size: diameter/wall thickness, mm	70/2
Length, mm	1490
Thermoinsulation	
Material	ZrO_2 ZYFB-3
Thickness, mm	23
Length, mm	1490
Thermoinsulation shroud	
Material	Steel 2X18H10T
Thickness, mm	1
Length, mm	1490
Outer diameter/thickness, mm	118/1

3.3. Test bundle instrumentation

The structure and composition of the test section and model FA temperature measuring system are given in Table 4 and in Fig. 9.

Table 4

List of instrumentation

No.	Designa-tion	Type	Instrument, location	Output in
1	$T_{st\ in}$	Ch/Al	TC, Steam temperature at the inlet of the test section, steam inlet nozzle – 355 mm, 270°	^oC
2	$T_{Ar\ in}$	Ch/Al	TC, Argon temperature at the inlet of the test section, argon inlet nozzle – 355 mm, 90°	^oC
3	T11-6	Ch/Al	TC, Fuel rod 1.1, -600 mm	^oC
4	T11-5.5	Ch/Al	TC, Fuel rod 1.1, -550 mm	^oC
5	T11-4.5	Ch/Al	TC, Fuel rod 1.1, -450 mm	^oC
6	T24-3	Ch/Al	TC, Fuel rod 2.4, -300 mm	^oC
7	T25-1.5	Ch/Al	TC, Fuel rod 2.5, -150 mm	^oC
8	p-1.5	-	Pressure sensor near fuel rod 3.2, -150 mm	MPa
9	T32-0.5	Ch/Al	TC, Fuel rod 3.2, -50 mm	^oC
10	T260	Ch/Al	TC, Fuel rod 2.6, 0 mm	^oC
11	T230.5	Ch/Al	TC, Fuel rod 2.3, 50 mm	^oC
12	T221	Ch/Al	TC, Fuel rod 2.2, 100 mm	^oC
13	T3101	Ch/Al	TC, Fuel rod 3.10, 100 mm	^oC
14	T212	Ch/Al	TC, Fuel rod 2.1, 200 mm	^oC
15	T352	Ch/Al	TC, Fuel rod 3.5, 200 mm	^oC
16	p2	-	Pressure sensor near fuel rod 3.7, 200 mm	MPa
17	T253	Ch/Al	TC, Fuel rod 2.5, 300 mm	^oC
18	T363	Ch/Al	TC, Fuel rod 3.6, 300 mm	^oC
19	T314	Ch/Al	TC, Fuel rod 3.1, 400 mm	^oC
20	T394	Ch/Al	TC, Fuel rod 3.9, 400 mm	^oC
21	T235	Ch/Al	TC, Fuel rod 2.3, 500 mm	^oC
22	T3115	Ch/Al	TC, Fuel rod 3.11, 500 mm	^oC
23	T376	Ch/Al	TC, Fuel rod 3.7, 600 mm	^oC
24	T227	Ch/Al	TC, Fuel rod 2.2, 700 mm	^oC
25	T397	Ch/Al	TC, Fuel rod 3.9, 700 mm	^oC
26	$T_{sh}7$	WRe	TC, Shroud outer surface (opposite fuel rod 3.2), 700 mm	^oC
27	$T_{th}7$	Ch/Cop	TC, Thermal insulation shroud inner surface (opposite fuel rod 3.2), 700 mm	^oC
28	$T_{st}8$	WRe	TC, Steam temperature, 800 mm	^oC
29	T248	WRe	TC, Fuel rod 2.4, 800 mm	^oC
30	T369	WRe	TC, Fuel rod 3.6, 900 mm	^oC
31	T389	WRe	TC, Fuel rod 3.8, 900 mm	^oC
32	p9	-	Pressure sensor near fuel rod 3.11, 900 mm	MPa
33	$T_{sh}9$	WRe	TC, Shroud outer surface (opposite fuel rod 3.8), 900 mm	^oC

34	$T_{th}9$	Ch/Cop	TC, Thermal insulation shroud inner surface (opposite fuel rod 3.8), 900 mm	^oC
35	T1110	WRe	TC, Fuel rod 1.1, 1000 mm	^oC
36	T2610	WRe	TC, Fuel rod 2.6, 1000 mm	^oC
37	$T_{st}10$	WRe	TC, Steam temperature, 1000 mm	^oC
38	T1111	WRe	TC, Fuel rod 1.1, 1100 mm	^oC
39	T2111	WRe	TC, Fuel rod 2.1, 1100 mm	^oC
40	T2411	Ch/Al	TC, Fuel rod 2.4, 1100 mm	^oC
41	T3311	Ch/Al	TC, Fuel rod 3.3, 1100 mm	^oC
42	T31011	WRe	TC, Fuel rod 3.10, 1100 mm	^oC
43	T31211	WRe	TC, Fuel rod 3.12, 1100 mm	^oC
44	$T_{sh}11$	WRe	TC, Shroud outer surface (opposite fuel rod 3.1), 1100 mm	^oC
45	$T_{th}11$	Ch/Cop	TC, Thermal insulation shroud inner surface (opposite fuel rod 3.1), 1100 mm	^oC
46	T2312.5	WRe	TC, Fuel rod 2.3, 1250 mm	^oC
47	T2512.5	PtRh	TC, Fuel rod 2.5, 1250 mm	^oC
48	T2612.5	Ch/Al	TC, Fuel rod 2.6, 1250 mm	^oC
49	T3212.5	WRe	TC, Fuel rod 3.2, 1250 mm	^oC
50	T3412.5	WRe	TC, Fuel rod 3.4, 1250 mm	^oC
51	T31112.5	Ch/Al	TC, Fuel rod 3.11, 1250 mm	^oC
52	p12.5	-	Pressure sensor near fuel rod 3.6, 1250 mm	MPa
53	T1113	WRe	TC, Fuel rod 1.1 , 1300 мм	^oC
54	T2212.3	WRe	TC, Fuel rod 2.2, 1300 мм	^oC
55	$T_{st}13$	WRe	TC, Steam temperature, 1300 мм	^oC
56	T3113	Ch/Al	TC, Fuel rod 3.1, 1300 mm	^oC
57	T3513	Ch/Al	TC, Fuel rod 3.5, 1300 mm	^oC
58	T3713	Ch/Al	TC, Fuel rod 3.7, 1300 mm	^oC
59	$T_{sh}13$	WRe	Shroud outer surface (opposite fuel rod 3.6), 1300 mm	^oC
60	$T_{th}13$	Ch/Cop	TC, Thermal insulation shroud inner surface (opposite fuel rod 3.6), 1300 mm	^oC
61	T2314	Ch/Al	TC, Fuel rod 2.3, 1400 mm	^oC
62	T2114.75	Ch/Al	TC, Fuel rod 2.1, 1475 mm	^oC
63	T2514.75	Ch/Al	TC, Fuel rod 2.5, 1475 mm	^oC
64	p14.75	-	Pressure sensor near fuel rod 3.9, 1475 mm	MPa
65	$T_{st\ out}$	Ch/Al	Steam temperature at the outlet of the test section, steam outlet nozzle, 1425 mm, 0^o	^oC

The test bundle was instrumented with 46 TCs for measurements of the cladding temperature of fuel rods located at 23 different elevation: from -600 to +1500 mm (with a pitch of 100 mm along heated zone); 8 TCs for measurements of the spacer grids temperature at 3 elevation (775; 1030; 1285 mm); 8 TCs for measurements of the cladding and the thermal insulation temperature at 4 elevation (700; 900; 1100 and

1300 mm); 3 TCs for measurements of the steam temperature in FA at three elevation (800; 1000; 1300 mm) and 3 TCS for measurements of the steam and argon temperature at the inlet and outlet. Exact location and mounting of the thermocouples to measure the temperature of the shroud and the thermoinsulation are given in Figure 18.

For temperature measurement three types of TCs were used (see Fig. 9): cable Ch/Al (Ch/Cop) in the SS sheath ∅ 1.5 mm with the limit of measured temperatures of 1300°C (800°C) and high-temperature WRe thermocouples with W+5%Re/W+20%Re wire in zirconium alloy Zr+1%Nb sheath ∅ 2.8x0.7 mm with the limit of measured temperatures of 2000°C.

TCs were fastened in alignment with fuel rods on claddings surface using the zirconium clamp with width ~5 mm and thickness 0.3 mm by electric resistance welding, in addition the TCs were fixed with Ir wire of 0.3 mm diameter.

Pressure of steam-argon mixture was monitored with five pressure sensors at the elevation of Z = -150 mm (p-1,5); 200 mm (p2); 900 mm (p9); 1250 mm (p12.5) and 1475 mm (p14.75). Helium pressure in fuel rods was monitored with pressure sensor in the compensatory volume (p_{rod}).

3.4. Hydrogen measurement system

The hydrogen measurement system is located downstream the condenser 1 in additional gas path of the facility after the point of monitoring the gas mixture parameters T10, p10 (see Fig. 1). Operation of the system is based on two methods of measurement: continuous and discrete.

For continuous hydrogen measurement a SOV-3 device is used. This device has been developed by SSC RF IPPE for automatic monitoring of hydrogen content within the containment in NPP. It is a hydrogen-sensitive conductometric detector. When argon-hydrogen mixture passes through the sensor cavity hydrogen is absorbed by sensitive element made of Pd-Ag alloy increasing its electric resistance till setting the equilibrium corresponding to the volumetric hydrogen concentration in gas mixture. Change in electric resistance of the sensitive element is converted into continuous electric signal displayed on a computer.

Main design parameters of SOV-3 device:

- gas mixture:
  - carrier gas - argon;
  - monitored gas – hydrogen;
- pressure of gas mixture – 0.15 – 0.35 MPa;

- flow rate of gas mixture – $(8 – 25)\cdot10^{-5}$ m^3/min;

- measurement range - $5\cdot10^{-4}$ – 80 vol.%;

- transition time within the concentration range:

    - $5\cdot10^{-4} – 1\cdot10^{-1}$ vol.% – ~ 2 min;
    - $\geq1\cdot10^{-1}$ vol.% – 1 min.

Location of the SOV-3 hydrogen control system in a bypass to the off-gas line allows monitoring the change in hydrogen concentration throughout the entire experiment if the valve F11 is open.

With discrete method of hydrogen concentration measurement 10 sampling tanks are used (Vol.1, Vol.2,…, Vol.10) with volume of 2 L each. Before the experiment the tanks are washed with high purity argon and vacuum treated. Sampling with the assigned interval and duration of sampling is made using the electric valves (V8,…, V17) controlled remotely. The time of sampling is registered by the data acquisition system.

After the experiment the tanks are sealed and disconnected from the gas pipe. Then gas mixtures are analyzed by a gas chromatograph CHROMATEC-CRYSTAL 5000 (ХРОМАТЭК-КРИСТАЛЛ). The obtained results are synchronized in time with the indications of the continuous control system SOV-3.

4. SCENARIO OF THE PARAMETER-SF3 EXPERIMENT

The proposed PARAMETER-SF3 test experimental scenario is presented in Table 5. Duration of transient phases (heating up to 1470 K and heating up to 1870 K) can be specified as the pre-test calculations perform.

Table 5

Proposed PARAMETER-SF3 test scenario

No.	Stage	Main parameters			
		FA temperature, K	Medium	Heating rate, K/s	Time, s
1	Joule heating up of FA in argon flow	~300-670	Argon flow at temperature to 720K (argon flow rate - 2 g/s)	-	0-1500
2	Joule heating up of FA in the flow of steam-argon mixture	670→770	Steam-argon mixture (argon/steam flow rate - 2/3,5 g/s, at temperature of 720/770K)	-	1500-3500
3	FA heating up to 1470 K (transient phase I)	770→1470	Steam-argon mixture (argon/steam flow rate - 2/3,5 g/s, at temperature of 720/770K)	0.25 (at the beginning), 0.1 (towards the end)	3500-7500
4	FA pre-oxidation	~ 1470	Steam-argon mixture (argon/steam flow rate - 2/3,5 g/s, at temperature of 720/770K)	-	7500-11500
5	Assembly heating up to maximum temperature (transient phase II)	1470→1870	Steam-argon mixture (argon/steam flow rate - 2/3,5 g/s)	0.4 (initial)	11500-12400
6	Top flooding of the assembly (as soon as FA will reach Tmax=1870 K)	Up to saturation	Water (flow rate 40 g/s, water temperature ~300K)	-	As soon as design temperature will be reached

Temperature together with steam and argon flowrate are given in Fig. 10, 11 and 12. System pressure is governed by argon flowrate and is settled about 0.3 MPa during the experiment except for some short period at the end of transient phase and flood phase as shown in Fig. 13.

The phases and performing of PARAMETER-SF3 test are similar to PARAMETER-SF1 test (Fig. 10).

During the stabilization stage the following sequence of events is expected:

- filling the fuel rods with helium under pressure which slightly above the system pressure p_{bl} (F21, p_{rod});

- filling the cavity of the thermoinsulation with helium at T ≈ 20°C and under pressure slightly above the system pressure p_{bl} (V5, p14);

- argon supply with ~ 0,5 g/s flowrate (F39, G_{Ar}, V2, p10, V7, R4) at 0 s;

- electric power supply at 0 s;

- heating up of the external wall of the body in the lower part of the test section up to ~ 150°C (starts at 0 s);

- switching on the cooling jacket (F5) at 0 s; water flowrate is ~ 50 g/s, water temperature at inlet is 20°C;

- argon flowrate increasing up to ~ 2,0 g/s (F39, G_{Ar}, p_{bl}, p10, p12, R4) at 500 c;

- argon heating up to 450±50°C (T5, T6, T9, p10, T10) by 600 s;

- steam supply with ~ 3,5±0.1 g/s flowrate (G_{st}, p1, T1, p2, T2, $T_{st\ in}$, $T_{st\ out}$, T9) at 1500 s.

- steam heating up to 500±30°C (T1, T2, $T_{st\ in}$, $T_{st\ out}$, T9) by 3000 c ;

- Joule heating up of the test bundle up to temperature of 500±30°C by 3500 s;

Stabilization of the initial parameters (p1, T1, p2, T2, $T_{st\ in}$, $T_{st\ out}$, T9, G_{Ar}, p_{bl}, T6, p10, T10, R4) is expected by 3500 s.

After stabilization of the initial parameters the test bundle is heated up at initial heatup rate of 0.25 K/s to temperature of 1100°C, then at 0.1 K/s to temperature of 1200°C by 7500 s (in the hottest zone) and is held at this temperature for ~ 4000 s for the required oxide scale thickness of ~200 μm on the claddings surface to be obtained.

At the end of the pre-oxidation phase electric power is increased stepwise to start the transient phase at 0.4 К/c heat up.

The quenching phase is initiated by shutting off electric power. In 5 s steam supply is turned off, argon inlet position is switched to upper plenum of test section. The top quenching system is switched on as soon as fuel rods claddings temperature in the hottest region will be reached of 1600°C (in 5 s after steam supply is turned off). Top flood water flowrate is 40±2 g/s, water temperature at inlet is about room temperature (~25°C).

5. INITIAL DATA ON MATERIAL PROPERTIES

Materials are the same as for CORA-W2 (WWER). Thermal conductivity of insulation Zirconia Board Type ZYFB3 is contained in Table 6.

Table 6

Thermal conductivity of insulation - Zirconia Board, Type ZYFB3

T, °C	400	800	1100	1400	1650
thermal conductivity coefficient λ, W/(K · m)	0.08	0.11	0.14	0.19	0.24

Material properties of heater and electrodes can be found in [1, 2].

1. Brass ЛС59-1.

Chemical composition (%):
Cu – 57-60
Pb – 0.8-1.9
Other – Zn.

Specific resistance at 20°C [1]
$\rho = 0.065\times10^{-6}$ Ohm·m.

Temperature coefficient of resistance at 20°C
$\alpha_0 = 1.7\times10^{-3}$ 1/K [2]

Linear expansion factor at 20°C
$\alpha = 20.6\times10^{-6}$ 1/K [2]

Density
$\rho = 8.5$ g/cm^3

Melting point
T = 900°C [2].

2. Cu, Mo and Ta

Cu, Mo specific resistances are calculated by the formula [2]
$\rho = \rho_0 \cdot T/273 \cdot F(\theta/T)/ F(\theta/273)$

Table 7

Material	**ρ_0, 10^{-6} Ohm·cm**	**θ, K**
Cu	1.55	347
Mo	5.03	423

Table 8

θ/T	**F(θ/T)**
0	1.000
0.1	0.9994
0.2	0.9978
0.3	0.9950
0.4	0.9912
0.5	0.9862
0.6	0.9803
0.7	0.9733
0.8	0.9653
0.9	0.9563
1.0	0.9465
1.1	0.9357
1.2	0.9241
1.3	0.9118
1.4	0.8986

1.5	0.8848
1.6	0.8704
1.7	0.8554
1.8	0.8398
1.9	0.8238
2.0	0.8073
2.1	0.7905
2.2	0.7733
2.3	0.7559
2.4	0.7383
2.5	0.7205
2.6	0.7026
2.7	0.6846
2.8	0.6666
2.9	0.6486
3.0	0.6307

Linear expansion factor is given in Table 3 (10^{-6} 1/K) [2].

Table 9

Temperature, K	300	400	500	600	800	1000	1200	
Cu	16.7	17.3	17.9	18.6	20.1	21.8	23.8	
Mo	5.27	5.45	5.63	5.82	6.20			11.43 (at 2400 K)
Ta	6.60	6.72	6.84	6.95	7.12	7.32	7.53	

Tantalum specific resistance calculated in accordance with [2] is given in Table 10.

Table 10

T, K	ρ, Ohm·m
300	$13.9 \cdot 10^{-8}$
1000	$44.1 \cdot 10^{-8}$
1100	$47.3 \cdot 10^{-8}$
1200	$50.9 \cdot 10^{-8}$
1300	$54.7 \cdot 10^{-8}$
1400	$58.1 \cdot 10^{-8}$
1500	$62.3 \cdot 10^{-8}$
1600	$65.7 \cdot 10^{-8}$
1700	$69.2 \cdot 10^{-8}$
1800	$72.4 \cdot 10^{-8}$
1900	$75.7 \cdot 10^{-8}$
2000	$78.8 \cdot 10^{-8}$
2100	$81.9 \cdot 10^{-8}$
2200	$85.1 \cdot 10^{-8}$
2300	$88.3 \cdot 10^{-8}$
2400	$91.3 \cdot 10^{-8}$
2500	$94.3 \cdot 10^{-8}$
2600	$97.4 \cdot 10^{-8}$
2700	$100 \cdot 10^{-8}$
2800	$103 \cdot 10^{-8}$

2900	$106 \cdot 10^{-8}$
3000	$109 \cdot 10^{-8}$
3100	$112 \cdot 10^{-8}$
3200	$114 \cdot 10^{-8}$
3269	$115 \cdot 10^{-8}$

Results of rods inner resistance measurements done 15.01.2007 at room temperature are given in Table 11.

Table 11

Results of rods inner resistance measurements

Rod number	Inner resistance of rods, Ohm	L, mm
2.1	0.0140	755
2.2	0.0140	840
2.3	0.0140	755
2.4	0.0140	840
2.5	0.0140	755
2.6	0.0140	840
3.1	0.0134	585
3.2	0.0134	670
3.3	0.0134	755
3.4	0.0133	670
3.5	0.0131	585
3.6	0.0126	670
3.7	0.0134	755
3.8	0.0138	670
3.9	0.0132	585
3.10	0.0131	670
3.11	0.0131	755
3.12	0.0130	670

6. PROPOSAL FOR CALCULATIONS RESULTS COMPARISON

The preferable form of the calculation results is presented below (Table 12), which will allow comparing the results and analyzing convergence of calculations done by deferent participants.

Table 12

Format of presented data (table of results)

Column No	Name	Parameter	Elevation (Fig. 5), mm
1	Time	Experiment time, s	-
2	Gst_in	Steam Inlet flow rate, g/s	-
3	Gar_in	Argon Inlet flow rate, g/s	-
4	Gh2_out	Hydrogen Outlet flow rate, g/s	-
5	Mh2	Total Hydrogen released, g	-

6	Qtot	Total Electric Power, kW	-
7	Qaz	Core (0÷1275 mm) Joule Power, kW	-
8	Qcool	Coolant Heating Power, kW	-
9	Qloss	Heat Loss through Shroud, kW	-
10	Qchem	Chemical Power, kW	-
11	Tst_in	Coolant Inlet Temperature, K	-355
12	Tar_in	Coolant Inlet Temperature, K	-355
13	Tg_0000	Coolant Temperature, K	0
14	Tg_0600	Coolant Temperature, K	600
15	Tg_0800	Coolant Temperature, K	800
16	Tg_1000	Coolant Temperature, K	1000
17	Tg_1250	Coolant Temperature, K	1250
18	Tg_1300	Coolant Temperature, K	1300
19	Tg_1475	Coolant Temperature, K	1475
20	Tsh_0200	Shroud External Surface Temperature, K	200
21	Tsh_0500	Shroud External Surface Temperature, K	500
22	Tsh_0700	Shroud External Surface Temperature, K	700
23	Tsh_0900	Shroud External Surface Temperature, K	900
24	Tsh_1100	Shroud External Surface Temperature, K	1100
25	Tsh_1300	Shroud External Surface Temperature, K	1300
26	Tsh_1475	Shroud External Surface Temperature, K	1475
27	Tth_0700	Thermoinsilation Temperature, K	700
28	Tth_0900	Thermoinsilation Temperature, K	900
29	Tth_1100	Thermoinsilation Temperature, K	1100
30	Tth_1300	Thermoinsilation Temperature, K	1300
31	Tcl_1_-450	Central Rod Cladding Temperature, K	-450
32	Tcl_1_1000	Central Rod Cladding Temperature, K	1000
33	Tcl_1_1100	Central Rod Cladding Temperature, K	1100
34	Tcl_1_1300	Central Rod Cladding Temperature, K	1300
35	Tcl_2_-300	2^{nd} Ring Rod Cladding Temperature, K	-300
36	Tcl_2_-150	2^{nd} Ring Rod Cladding Temperature, K	-150
37	Tcl_2_0000	2^{nd} Ring Rod Cladding Temperature, K	0
38	Tcl_2_0050	2^{nd} Ring Rod Cladding Temperature, K	50
39	Tcl_2_0100	2^{nd} Ring Rod Cladding Temperature, K	100
40	Tcl_2_0200	2^{nd} Ring Rod Cladding Temperature, K	200
41	Tcl_2_0300	2^{nd} Ring Rod Cladding Temperature, K	300
42	Tcl_2_0500	2^{nd} Ring Rod Cladding Temperature, K	500
43	Tcl_2_0700	2^{nd} Ring Rod Cladding Temperature, K	700
44	Tcl_2_0800	2^{nd} Ring Rod Cladding Temperature, K	800
45	Tcl_2_1000	2^{nd} Ring Rod Cladding Temperature, K	1000
46	Tcl_2_1100	2^{nd} Ring Rod Cladding Temperature, K	1100
47	Tcl_2_1250	2^{nd} Ring Rod Cladding Temperature, K	1250
48	Tcl_2_1300	2^{nd} Ring Rod Cladding Temperature, K	1300
49	Tcl_2_1400	2^{nd} Ring Rod Cladding Temperature, K	1400
50	Tcl_2_1475	2^{nd} Ring Rod Cladding Temperature, K	1475
51	Tcl_3_-050	3^{rd} Ring Rod Cladding Temperature, K	-50
52	Tcl_3_0100	3^{rd} Ring Rod Cladding Temperature, K	100
53	Tcl_3_0200	3^{rd} Ring Rod Cladding Temperature, K	200
54	Tcl_3_0300	3^{rd} Ring Rod Cladding Temperature, K	300
55	Tcl_3_0400	3^{rd} Ring Rod Cladding Temperature, K	400
56	Tcl_3_0500	3^{rd} Ring Rod Cladding Temperature, K	500
57	Tcl_3_0600	3^{rd} Ring Rod Cladding Temperature, K	600
58	Tcl_3_0700	3^{rd} Ring Rod Cladding Temperature, K	700
59	Tcl_3_0900	3^{rd} Ring Rod Cladding Temperature, K	900
60	Tcl_3_1100	3^{rd} Ring Rod Cladding Temperature, K	1100
61	Tcl_3_1250	3^{rd} Ring Rod Cladding Temperature, K	1250
62	Tcl_3_1300	3^{rd} Ring Rod Cladding Temperature, K	1300

63	Tcl_max	Maximum Rod Cladding Temperature, K	-
64	zro2_2_0200	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	200
65	zro2_2_0400	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	400
66	zro2_2_0600	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	600
67	zro2_2_0800	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	800
68	zro2_2_0900	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	900
69	zro2_2_1000	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1000
70	zro2_2_1100	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1100
71	zro2_2_1200	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1200
72	zro2_2_1250	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1250
73	zro2_2_1300	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1300
74	zro2_2_1400	2nd Ring Fuel Rod Cladding ZrO_2Thickness, µm	1400
75	P_{bl}_-150	System Pressure, MPa	-150
76	P_{bl}_1475	System Pressure, MPa	1475

7. REFERENCES

1. В.С. Чиркин. Теплофизические свойства материалов. Москва. Физматгиз, 1959.
2. Физические величины. Справочник под ред. И.С.Григорьева и Е.З. Мейлихова. Москва. Энергоатомиздат. 1991.

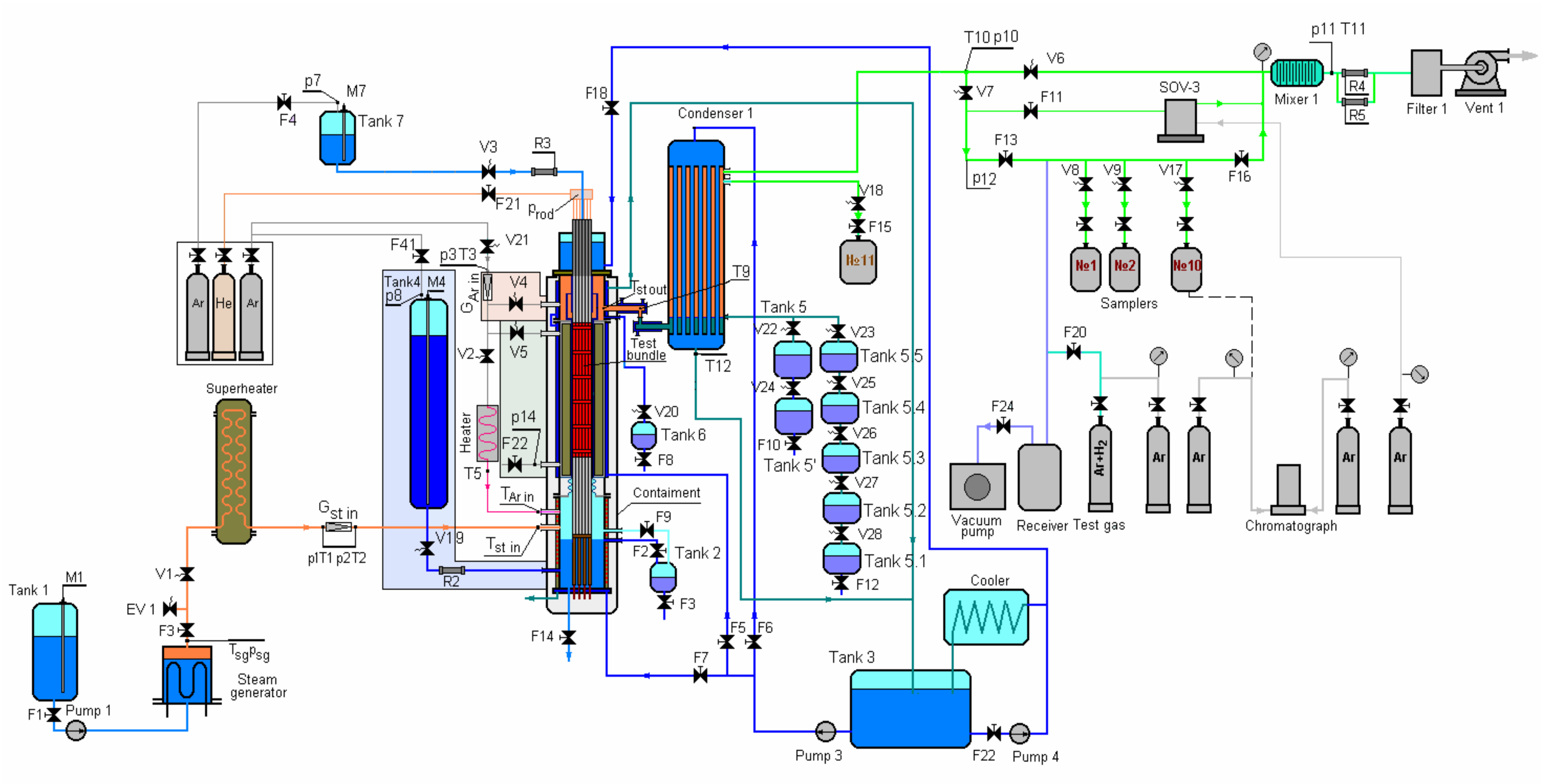


Fig. 1 - Flow diagram of the PARAMETER test facility.

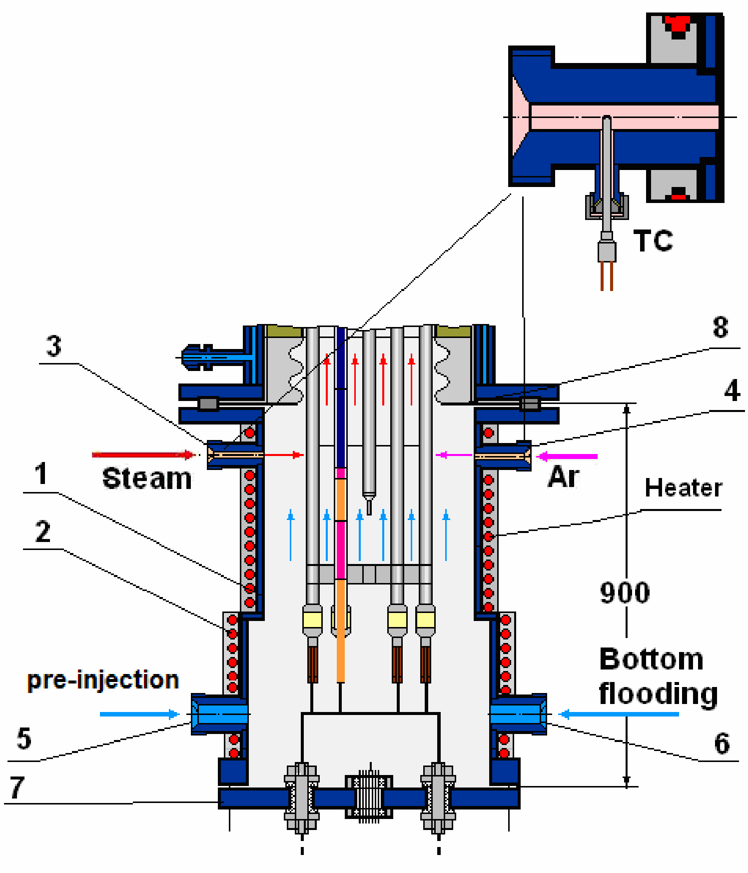


Fig. 2 - Lower part of the test section.

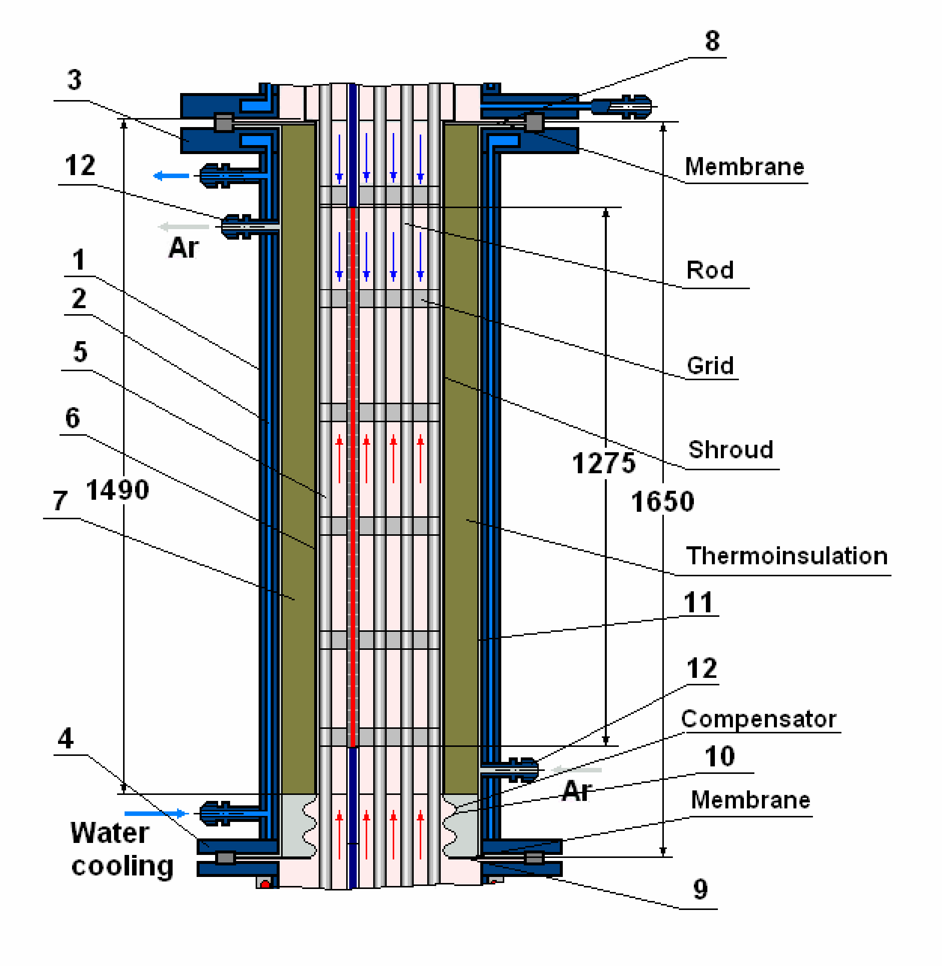


Fig. 3 - Middle part of the test section.

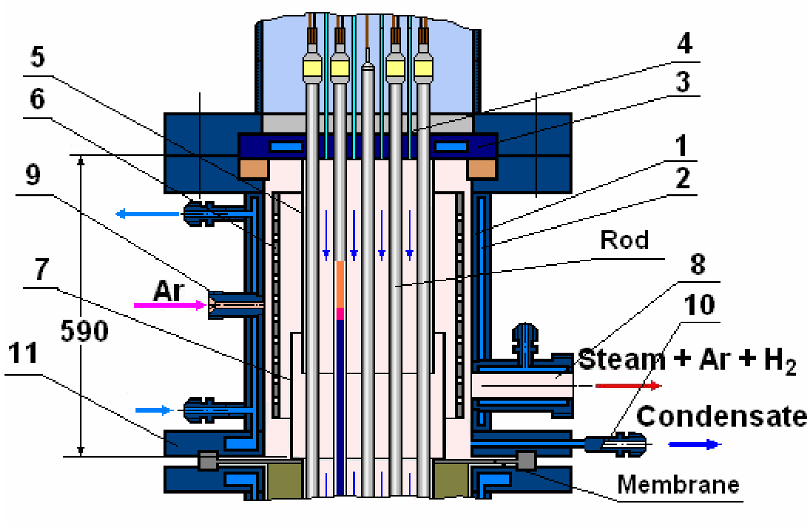


Fig. 4 - Upper part of the test section.

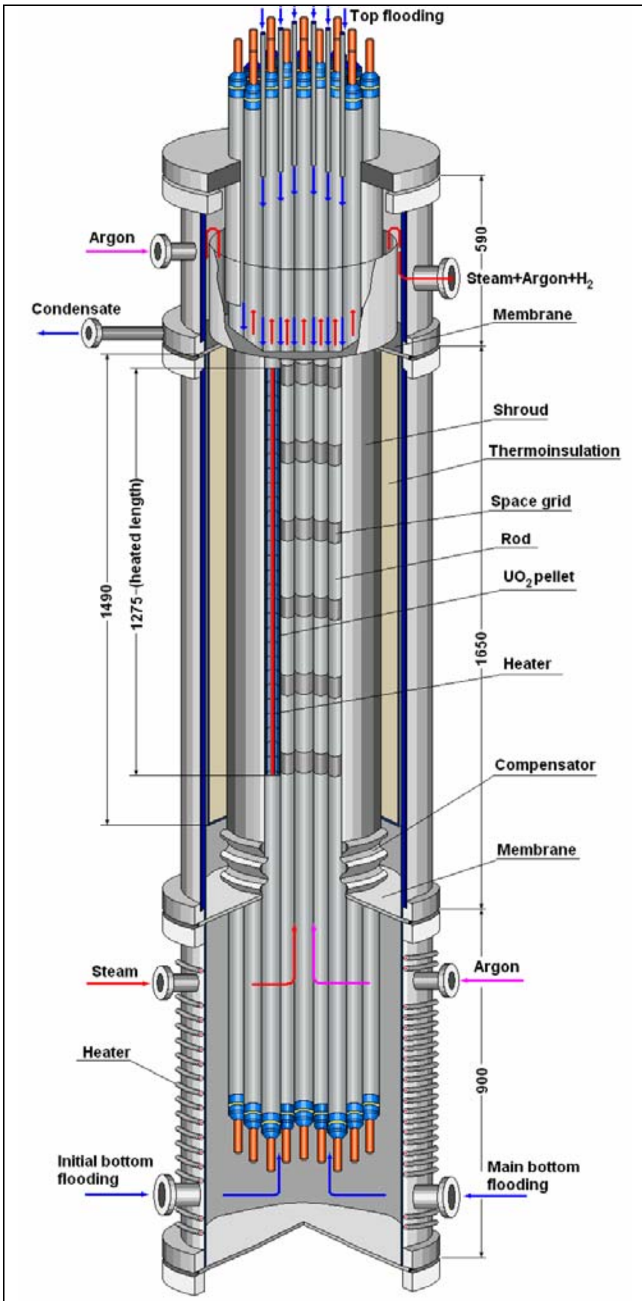
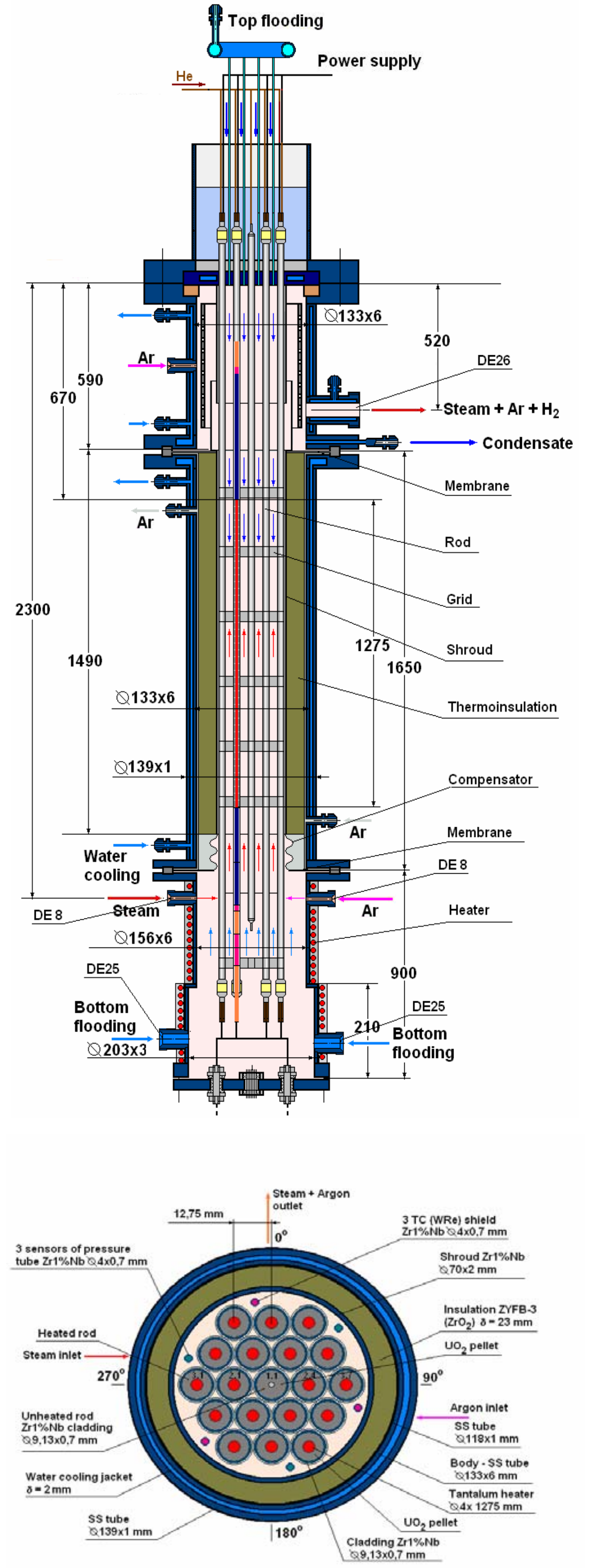
	
Overview	*Cross-section*

Fig. 5 - The test section and the fuel rods bundle.

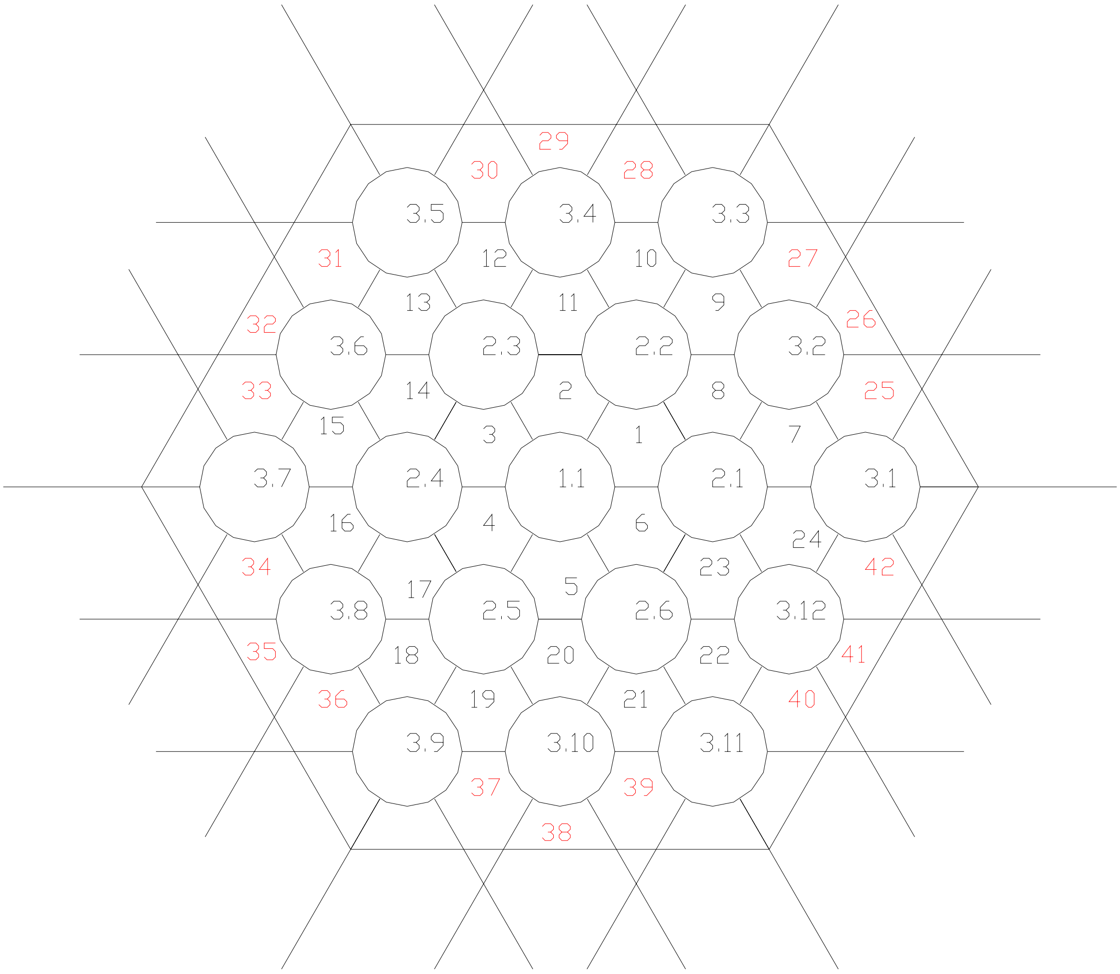
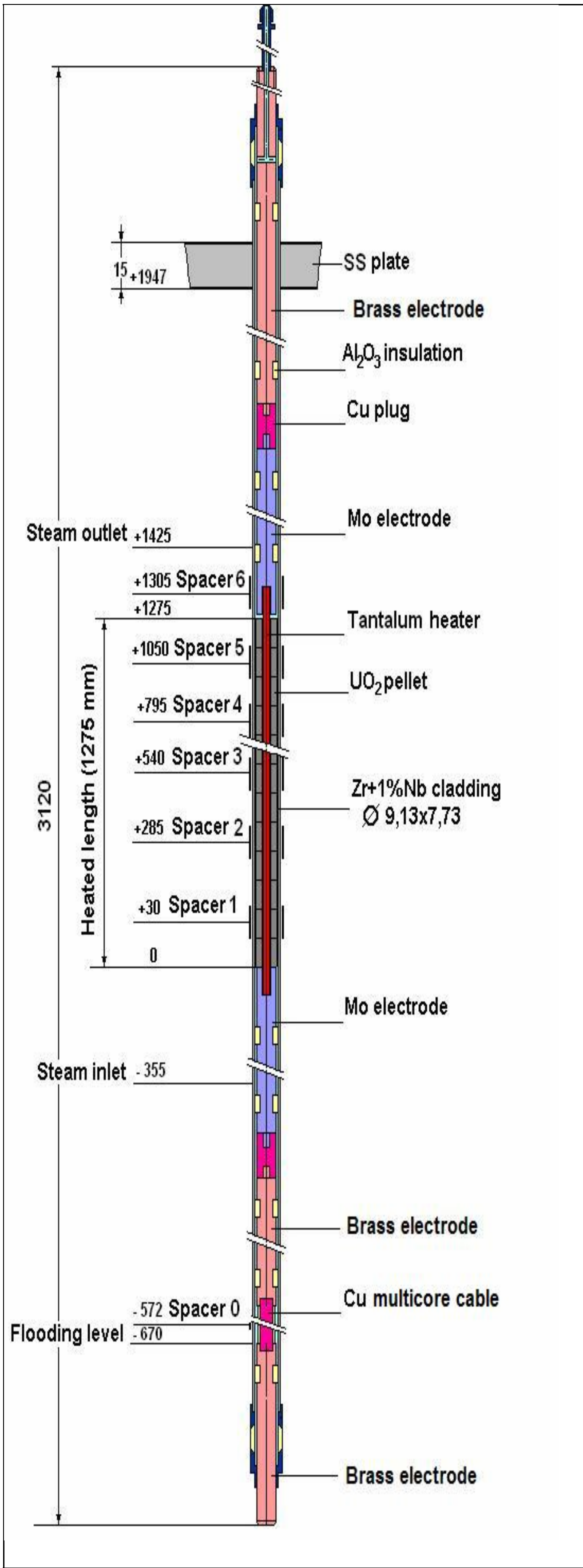
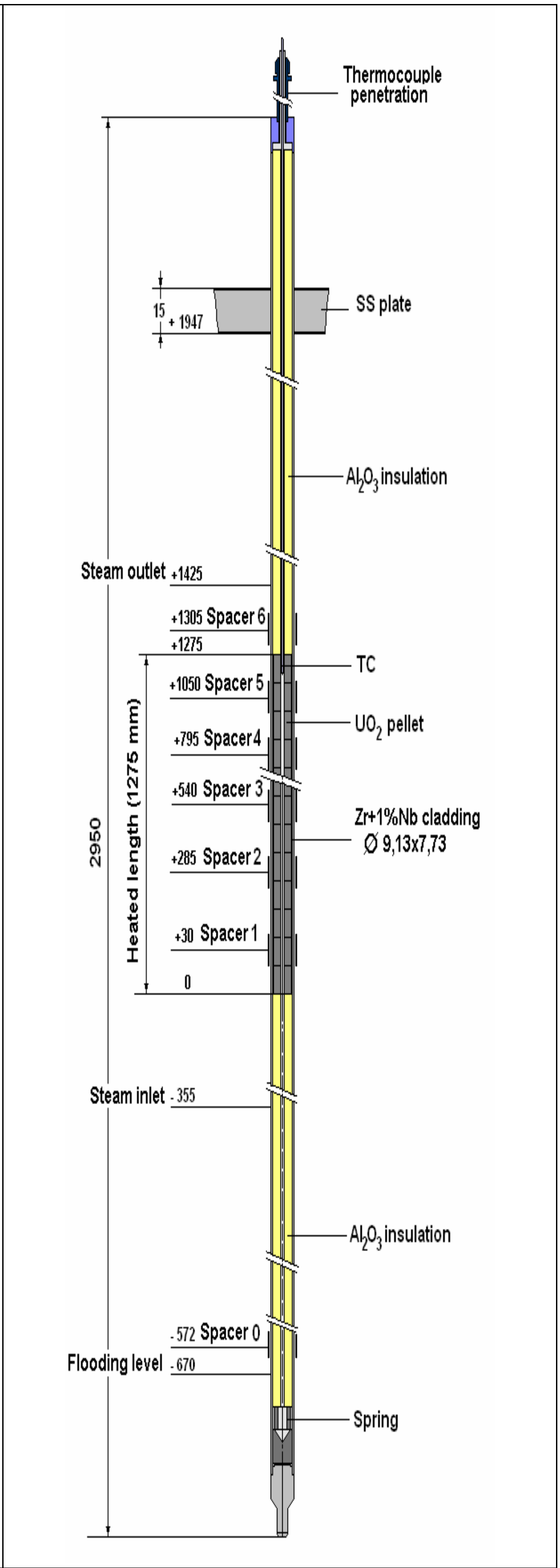


Fig. 6 - Rod simulators (1.1 – 3.12) and water supply tubes (1 – 42) arrangement.

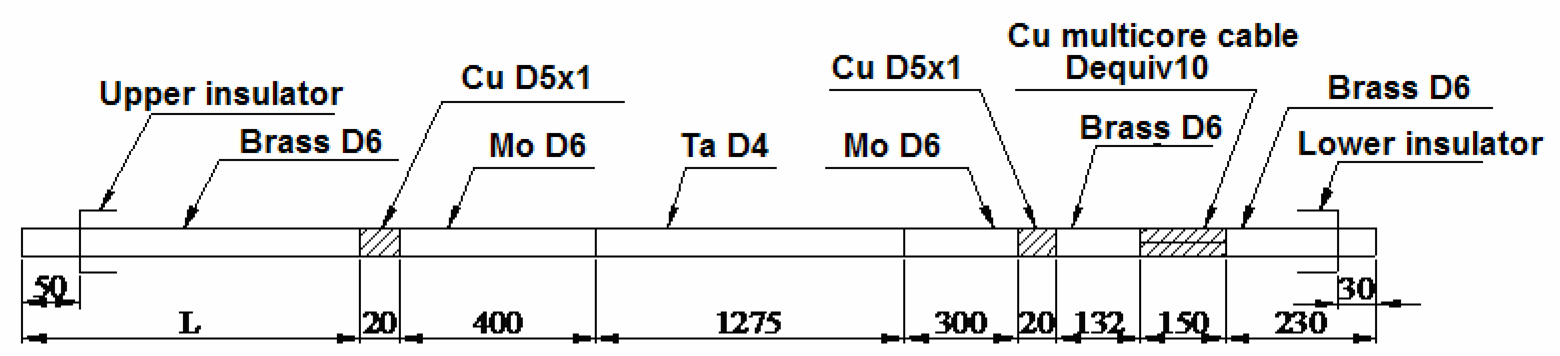


Heated rod



Unheated rod

Fig. 7 - Fuel rod simulators of the PARAMETER-SF3 bundle.



Rod number	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12
L, mm	755	840	755	840	755	840	585	670	755	670	585	670	755	670	585	670	755	670

Fig. 8 - Design characteristics of electrodes.

Z, mm	Rods																					
	1.1	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	Tsh	Tth	Tst
1475		TChA				TChA										PS						
1400				TChA																		
1300	TWRe		TWRe					TChA				TChA		TChA						TWRe	TChA	TWRe
1250				TWRe		TWRe	TChA		TWRe		TWRe		PS					TChA				
1100	TWRe	TWRe			TChA					TChA							TWRe		TWRe	TWRe	TChA	
1000	TWRe						TWRe															TWRe
900													TWRe		TWRe			PS		TWRe	TChA	
800					TWRe																	TWRe
700			TChA													TChA				TWRe	TChA	
600														TChA								
500				TChA														TChA				
400								TChA								TChA						
300						TChA							TChA									
200		TChA										TChA		PS								
100			TChA														TChA					
50				TChA																		
0							TChA															
-50									TChA													
-150						TChA			PS													
-300					TChA																	
-450	TChA																					
-550	TChA																					
-600	TChA																					

TC ChAl - 31, TC WRe – 15,
Tsh – 4, Tth – 4, Tst – 3, PS (pressure sensor) - 5

Fig. 9 - Test section instrumentation.

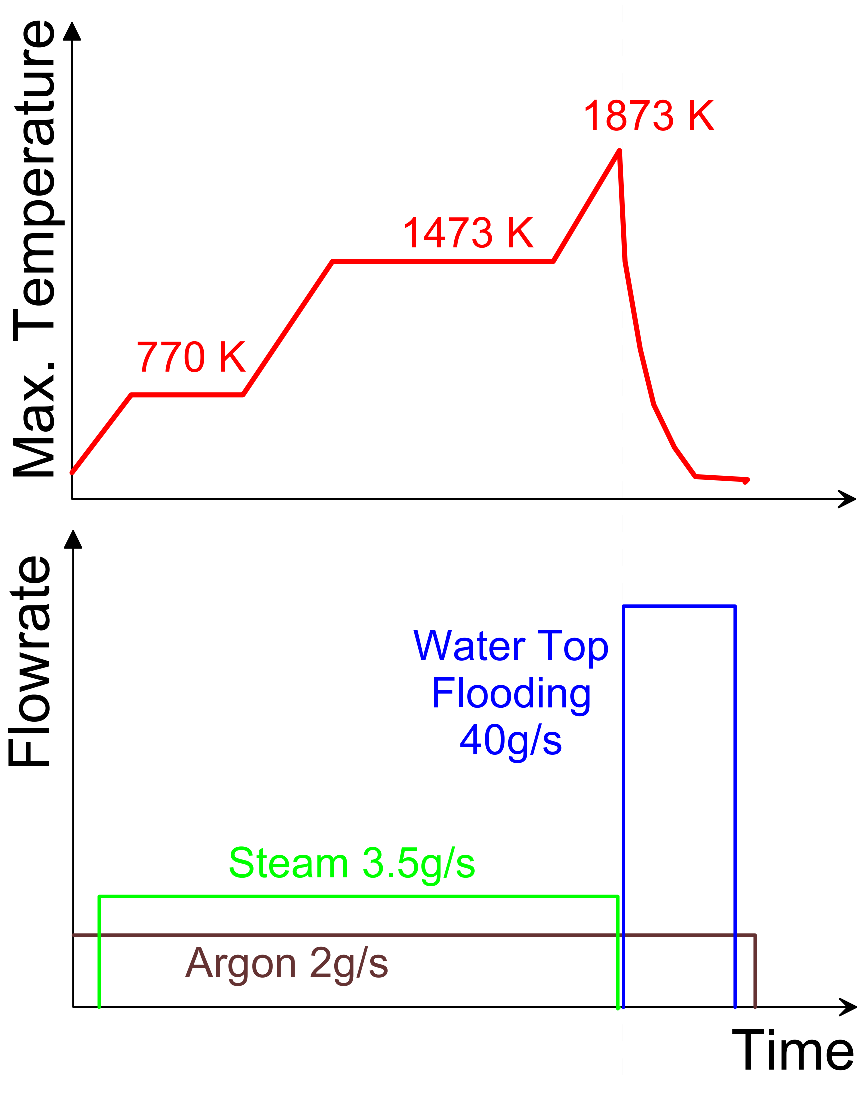


Fig. 10, 11 - Proposed test conduction.

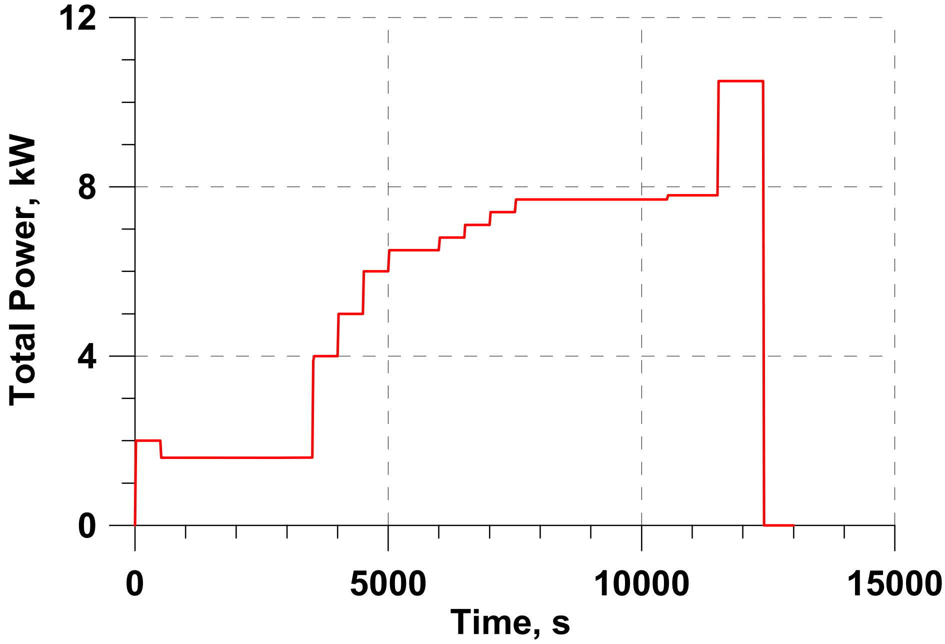


Fig. 12 – Total electric power.

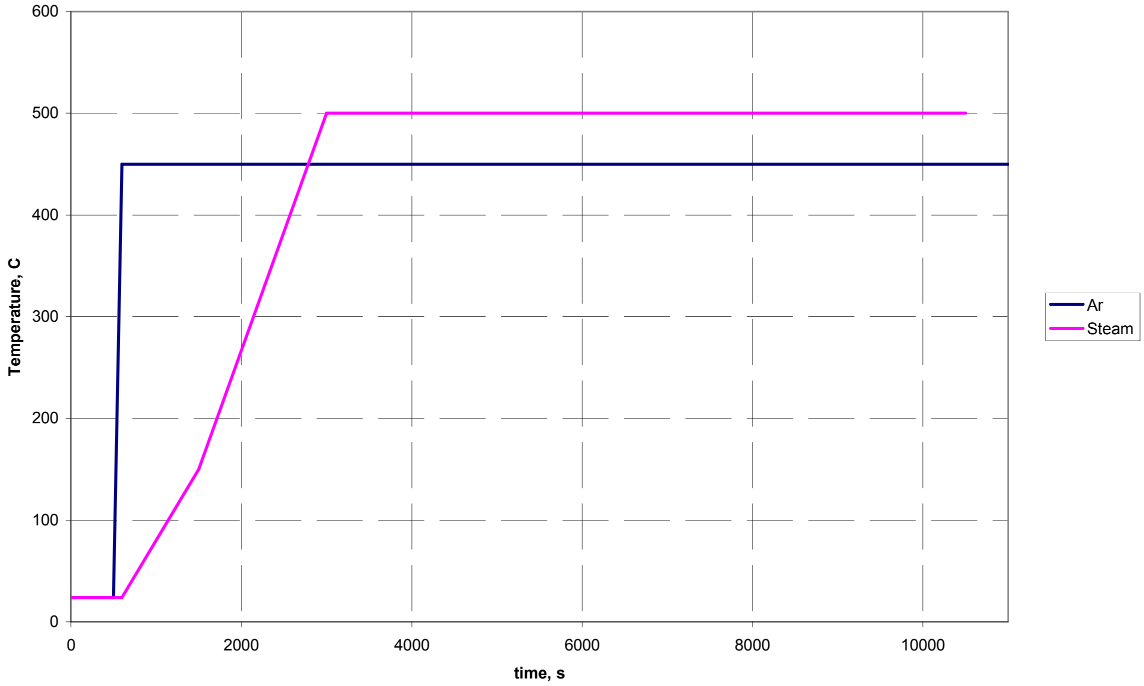


Fig. 13 - Inlet gas temperature.

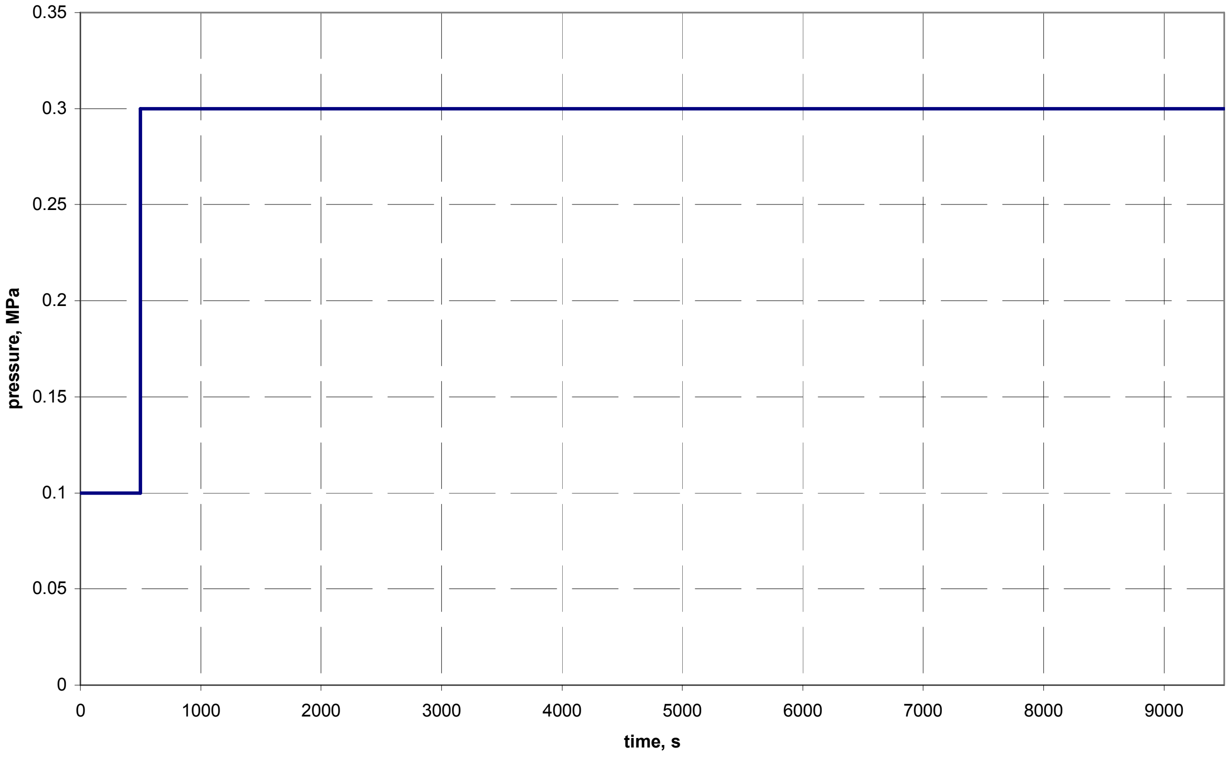


Fig. 14 - System pressure.

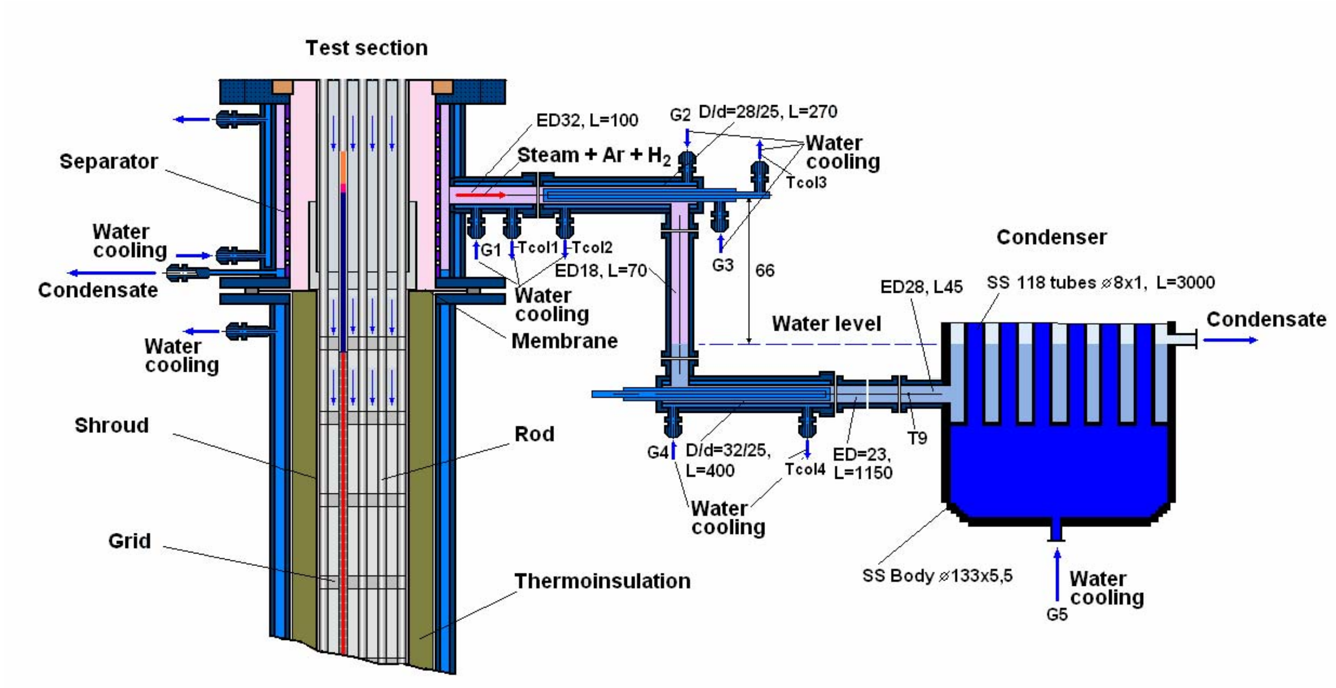


Fig. 15 – Condensation system.

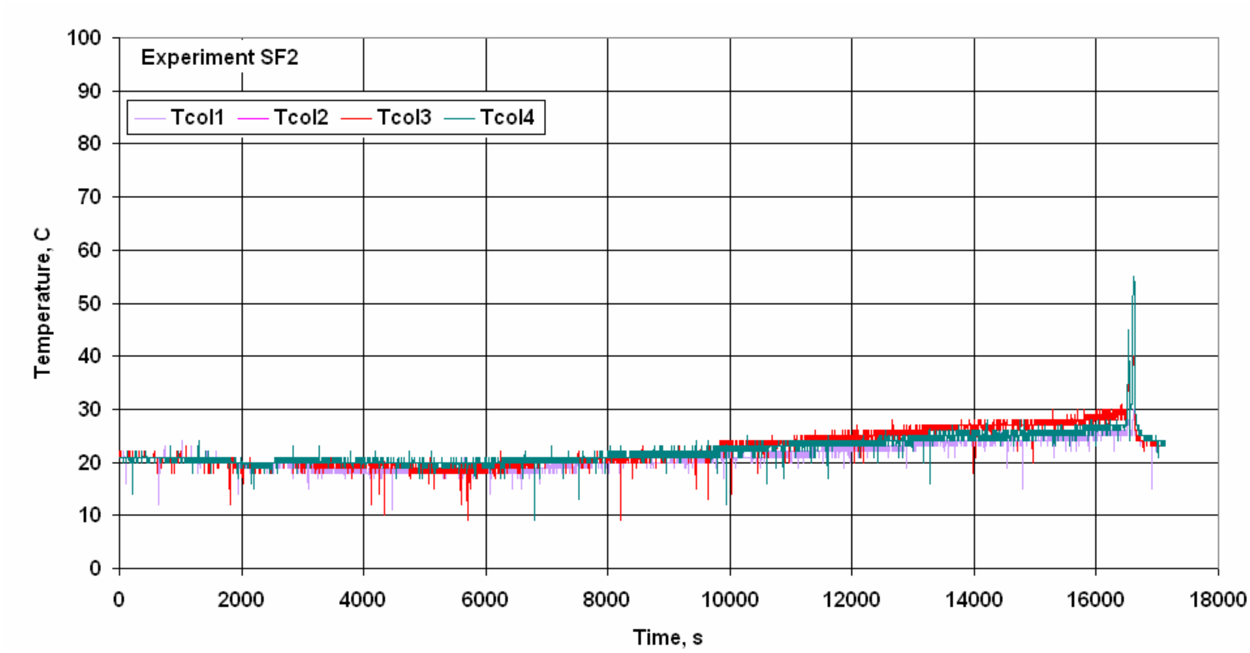


Fig.16 - The cooling system thermocouples readings. PARAMETER-SF2 experiment.

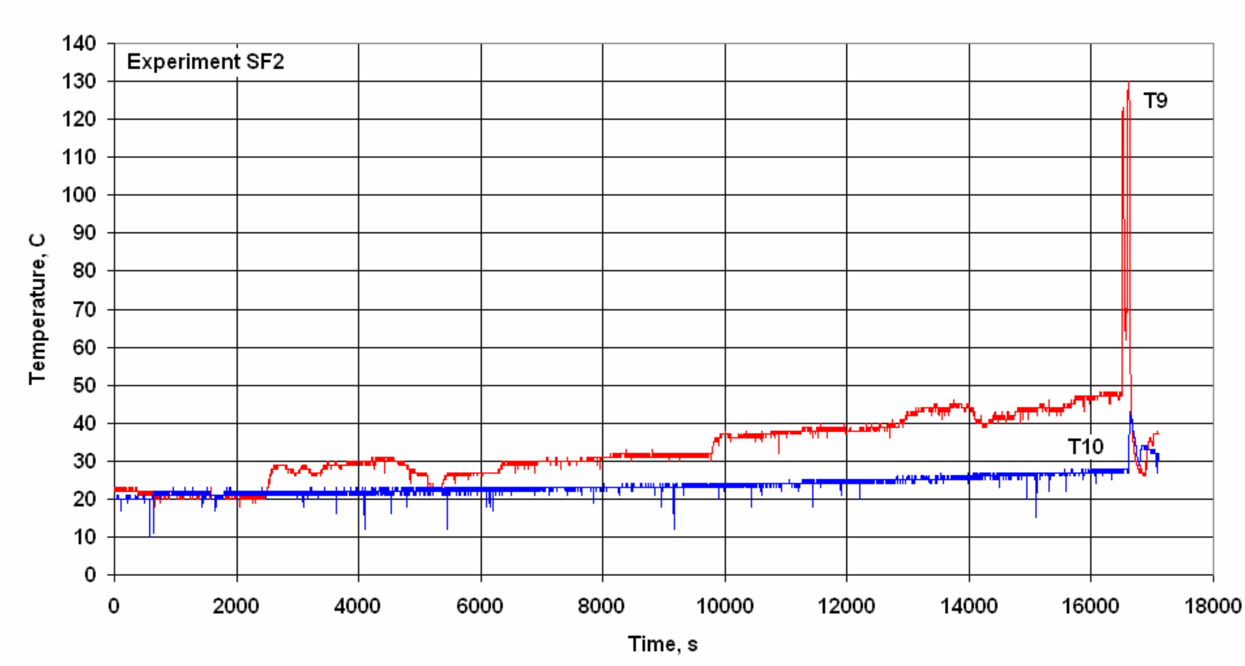


Fig. 17 - The temperature drop in the Condenser. PARAMETER-SF2 experiment.

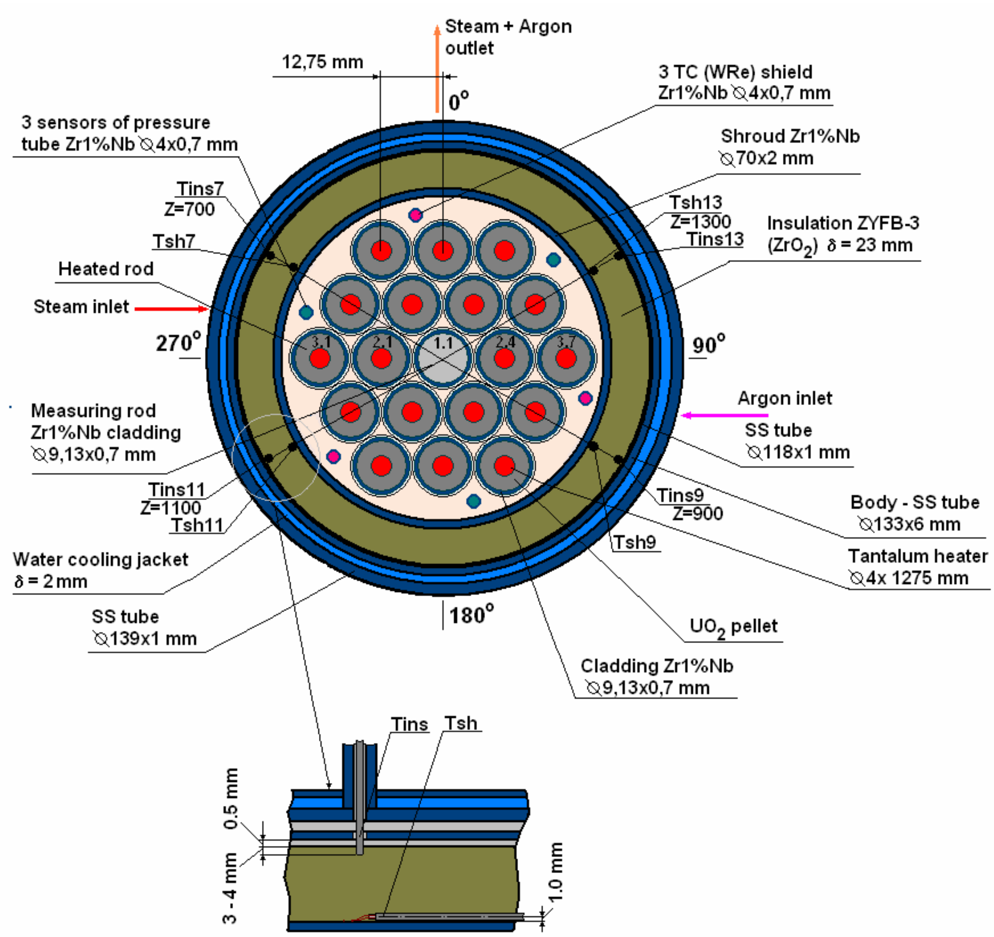


Fig. 18 - Location and mounting of the shroud and the thermoinsulation thermocouples.

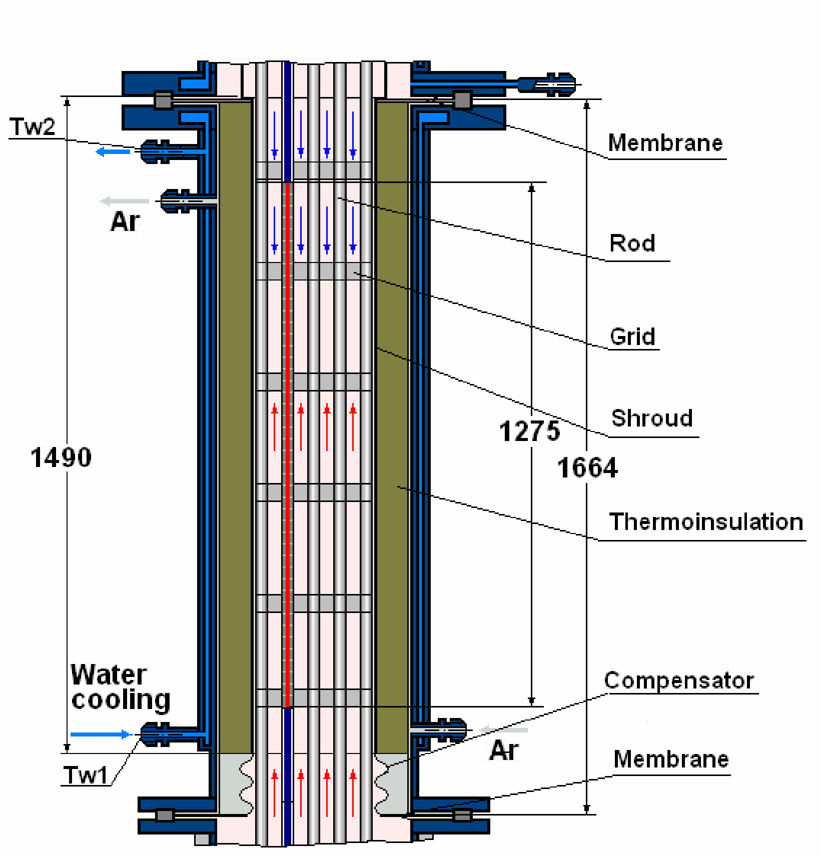


Fig. 19 - Cooling jacket for central part of the test section. PARAMETER-SF2 experiment.

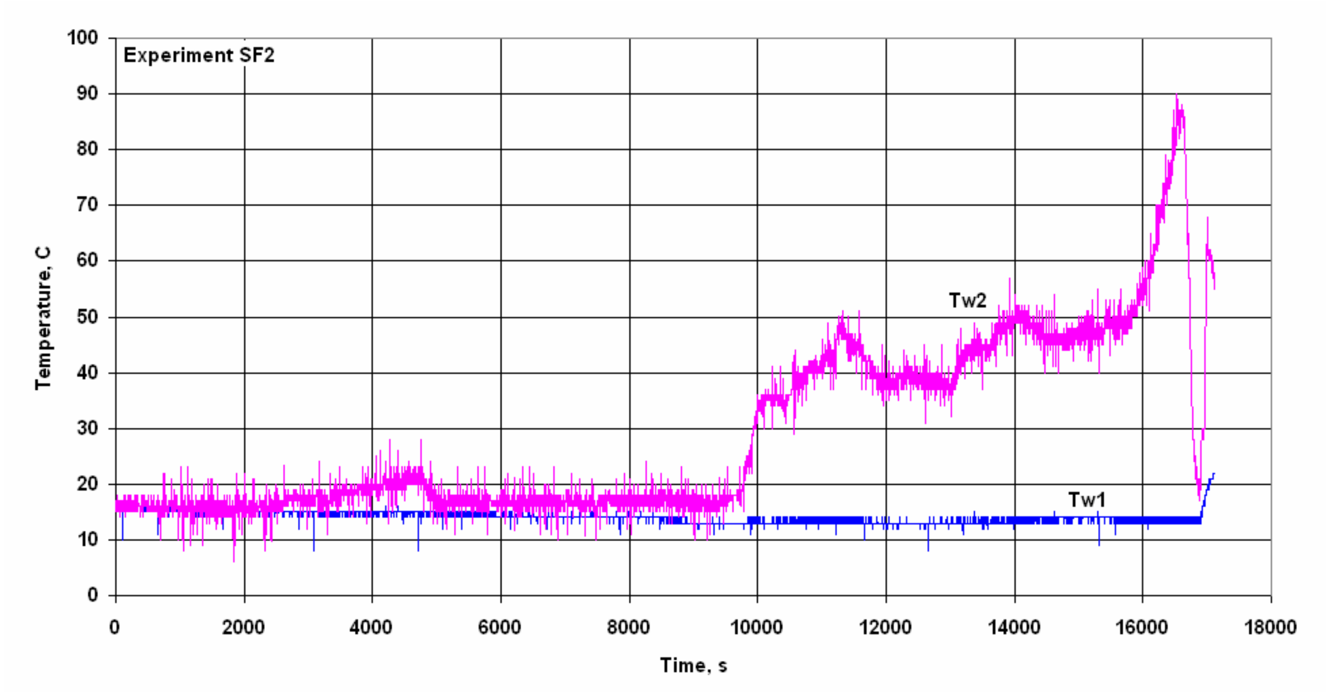


Fig. 20 - Cooling water thermocouples readings at inlet Tw1 and outlet Tw2 of the cooling jacket. PARAMETER-SF2 experiment.