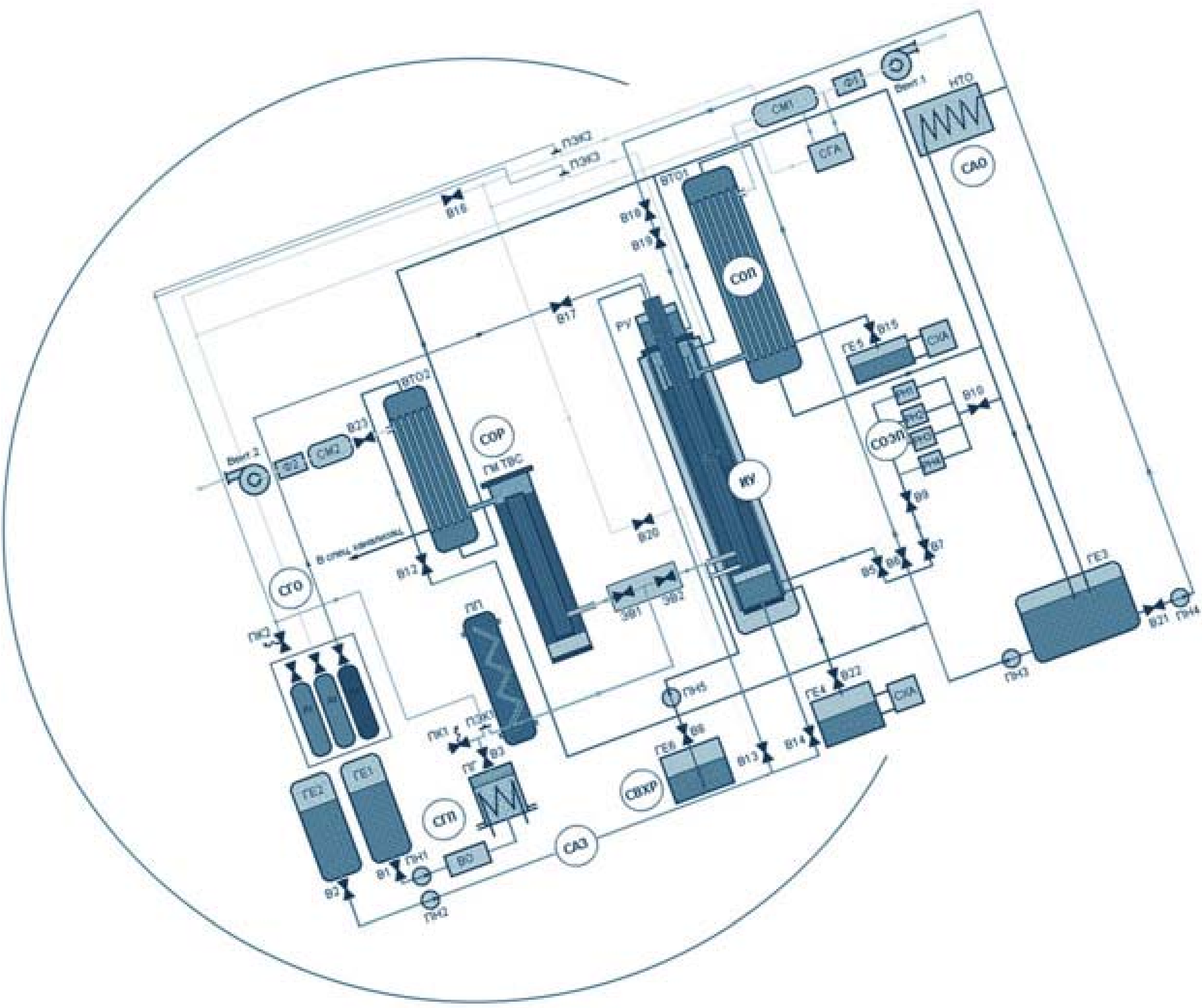
I S T C
М Н Т Ц

НИИ НПО "ЛУЧ"

PROJECT # 3194

"Fuel assembly tests under severe accident conditions"



2006

PROTOCOL
Of PARAMETER-SF1 Experiment Results (April 15, 2006)

Main Participants:
FSUE SRI SIA "LUCH"
IBRAE RAS
FSUE EDO "GIDROPRESS"

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2006

INTRODUCTION

PARAMETER-SF1 experiment was performed on April, 15, 2006 at the PARAMETER test facility of FSUE SRI SIA "LUCH" in cooperation with IBRAE RAS, FSUE EDO "GIDROPRESS", A.A. Botchvar FSUE VNIINM, A.I. Leypunskiy SRC RF IPPE, RRC "Kurchatov Institute" in framework of ISTC Project # 3194 with analytical support of foreign collaborators (FZK, GRS, EdF, IRSN).

SF1 experiment was the first out of two experiments scheduled within the framework of the ISTC Project # 3194.

The conditions of PARAMETER-SF1 experiment simulated a severe stage of accident of LOCA type, in which the core superheated to ~ 2000°C is flooded from the top in case of recovery of emergency core cooling system (ECCS) operation.

The SF1 experiment was aimed at the following:

- A study of thermo-mechanical and corrosion behaviour of a model 19-fuel rod assembly for VVER-1000 under the simulated conditions of a severe accident, including the stage of low-rate top flooding;
- A study of overheated FA components behaviour under the conditions of top flooding: fuel rod claddings, fuel pellets, guiding tube, spacing grids;
- A study of the degree of oxidation of the structural components of the model 19-fuel rod assembly for VVER-1000;
- A study of the interaction and structural-phase changes in the materials of model FA for VVER-1000 (fuel pellets and claddings);
- A study of hydrogen release rate under the conditions of severe accident simulation, including the stage of low-rate cooling at top flooding.

EXPERIMENTAL FACILITY

SF1 experiment was performed in PARAMETR facility that comprises (see Fig. 1):

- Test section with the model FA (TF);
- System for the model FA electric heatup and facility process system power supply;
- Steam generation and condensing system (SSG, SSC);
- System for the model FA top and bottom flooding (SF);
- Argon and helium gas supply system (SGF);
- System of gas analysis (SGA);
- Data retrieval and instrumentation system.

The superheated steam (out of the system of steam generation) and heated argon (carrier gas used in the system of hydrogen measurement) are supplied at the bottom of the test section with the model FA. The steam that has not consumed, argon and hydrogen released in the oxidation reaction come from the top part of the test section into water-cooled condenser 1. Argon and hydrogen come from condenser 1 into the system of gas analysis and then into the ventilation system.

Top flooding is implemented as an independent system (see Fig. 1), that contains a pressurized water tank (volume being 75 l and constant pressure p7), electric Valve 3 and flow meter R3.

In the course of the experiment the flow rates of steam G_{st} and argon G_{Ar} are monitored at the inlet to the test section and G_{Ar}(R4) at the outlet to the ventilation system, as well as the mass of condensate in condenser 1 – M5 and water level in the test section – M4.

MODEL FA

The model FA design characteristics are provided in Table 1.

The model FA diagram is presented in Fig. 2, general drawing of heated and unheated fuel rod simulators is given in Fig. 3. All the fuel rod simulators (except for the central unheated fuel rod) are joined into a heated assembly (see Fig. 4).

The model FA top is equipped with water injection system (see Fig. 2, 5), that contains 41 tubes ∅ 4x1 mm in the upper flange of the test section, a guide tube and collecting cylinder.

In its upper part each fuel rod of the assembly is equipped with a helium-supply device that comprises a capillary ∅ 1,6x0,3 mm, ~1500 mm long. A joint compensation tank, its volume being ~10 l, connects all the capillaries.

Table 1

Design parameters of model FA

Fuel rod simulators and model FA	
Number of heated fuel rods	18
Number of unheated fuel rods	1
FA spacer grid pitch, mm	12.75
Outside/inside diameter of fuel rod cladding, mm	9.13/7.73
Cladding material	Zr-1%Nb
Heated fuel rod height, mm	3120
Unheated fuel rod height, mm	2950
Heater material	tantalum
Fuel rod heater dimensions, mm:	
diameter/height	4/1275
coordinates	from 0 to 1275
Coordinate of the place of steam/argon inlet (radial), mm	-177 (300^o/120^o)
Coordinate of the place of steam/argon outlet (radial), mm	1425 (30^o)
Fuel rod internal gas pressure (helium) in fuel rods, MPa	0.2
Fuel pellets	
Heated fuel rods Diameter: external/of centerline hole/height, mm	UO_2 with holes $7.6^{-0,03}/4.2^{+0,15}/11^{\pm 0,1}$
Unheated fuel rod	No UO_2
Spacer grid	
Material	Zr-1%Nb
Height, mm	20
Quantity, pcs	6
Distance between the spacer grids, mm	255
Coordinates of spacer grid top edge, mm:	
Of the first grid (lower)	30
Of the sixth grid (upper)	1305
FA casing – hexahedral shroud	
Material	Zr-1%Nb
Width across flats/wall thickness, mm	62.5/1.5
Height, mm	1650
Thermoinsulation	
Material	Fiber-type ZrO_2 ZYFB-3
Thickness, mm	19.8
Height, mm	1500
Thermoinsulation shroud	
Material	Steel 12X18H10T
Thickness, mm	1
Height, mm	1500
Outside diameter, mm	119

MODEL FA TEMPERATURE MEASUREMENT SYSTEM

The architecture and components of the model FA temperature measuring system are provided in Table 2.

Table 2

Architecture and components of the model FA temperature and pressure measuring system

Number	Designation	Type	Purpose and location	Outlet signal
1	Tst in	Ch/Al	Steam temperature at the test section inlet, steam inlet sleeve, - 177 mm, 300°	°C
2	T6	Ch/Al	Argon temperature at the test section inlet, argon inlet sleeve, - 177 mm, 120°	°C
3	T310-1,5	Ch/Al	Cladding temperature of fuel rod 3.10, -150 mm	°C
4	T39-0,5	Ch/Al	Cladding temperature of fuel rod 3.9, -50 mm	°C
5	T320	Ch/Al	Cladding temperature of fuel rod 3.2, 0 mm	°C
6	Tst0	Ch/Al	Steam temperature, fuel rod 2.2, 0 mm	°C
7	T311	Ch/Al	Cladding temperature of fuel rod 3.1, 100 mm	°C
8	T361	Ch/Al	Cladding temperature of fuel rod 3.6, 100 mm	°C
9	T3101	Ch/Al	Cladding temperature of fuel rod 3.10, 100 mm	°C
10	T372	Ch/Al	Cladding temperature of fuel rod 3.7, 200 mm	°C
11	T3112	Ch/Al	Cladding temperature of fuel rod 3.11, 200 mm	°C
12	Tsh2	Ch/Al	Shroud temperature (opposite fuel rod 3.2), 200 mm	°C
13	Tth2	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.2), 200 mm	°C
14	T243	Ch/Al	Cladding temperature of fuel rod 2.4, 300 mm	°C
15	T353	Ch/Al	Cladding temperature of fuel rod 3.5, 300 mm	°C
16	T224	Ch/Al	Cladding temperature of fuel rod 2.2, 400 mm	°C
17	T3124	Ch/Al	Cladding temperature of fuel rod 3.12, 400 mm	°C
18	T215	Ch/Al	Cladding temperature of fuel rod 2.1, 500 mm	°C
19	T325	Ch/Al	Cladding temperature of fuel rod 3.2, 500 mm	°C
20	Tsh5	Ch/Al	Shroud temperature (opposite fuel rod 3.10), 500 mm	°C
21	Tth5	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.10), 500 mm	°C

22	P st5,4	-	Steam pressure, fuel rod 1.1, 540 mm	MPa
23	T236	Ch/Al	Cladding temperature of fuel rod 2.3, 600 mm	°C
24	T316	Ch/Al	Cladding temperature of fuel rod 3.1, 600 mm	°C
25	Tst6	Ch/Al	Steam temperature, fuel rod 1.1, 600 mm	°C
26	T267	Ch/Al	Cladding temperature of fuel rod 2.6, 700 mm	°C
27	T367	Ch/Al	Cladding temperature of fuel rod 3.6, 700 mm	°C
28	Tsh7	Ch/Al	Shroud temperature, fuel rod 3.4, 700 mm	°C
29	Tth7	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.4), 700 mm	°C
30	T258	Ch/Al	Cladding temperature of fuel rod 2.5, 800 mm	°C
31	T338	Ch/Al	Cladding temperature of fuel rod 3.3, 800 mm	°C
32	T119	WRe5%/WRe20%	Cladding temperature of fuel rod 1.1, 900 mm	°C
33	T249	Ch/Al	Cladding temperature of fuel rod 2.4, 900 mm	°C
34	T3129	Ch/Al	Cladding temperature of fuel rod 3.12, 900 mm	°C
35	Tsh9	Ch/Al	Shroud temperature (opposite fuel rod 3.2), 900 mm	°C
36	Tth9	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.2), 900 mm	°C
37	T2210	WRe5%/WRe20%	Cladding temperature of fuel rod 2.2, 1000 mm	°C
38	T2610	Ch/Al	Cladding temperature of fuel rod 2.6, 1000 mm	°C
39	T3810	Ch/Al	Cladding temperature of fuel rod 3.8, 1000 mm	°C
40	T1111	WRe5%/WRe20%	Cladding temperature of fuel rod 1.1, 1100 mm	°C
41	T2111	WRe5%/WRe20%	Cladding temperature of fuel rod 2.1, 1100 mm	°C
42	T2411	WRe5%/WRe20%	Cladding temperature of fuel rod 2.1, 1100 mm	°C
43	T3911	WRe5%/WRe20%	Cladding temperature of fuel rod 3.9, 1100 mm	°C
44	Tsh11	Ch/Al	Shroud temperature (opposite fuel rod 3.8), 1100 mm	°C
45	Tth11	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.8), 1100 mm	°C
46	T1112.5	Pt/Rh	Cladding temperature of fuel rod 1.1, 1250 mm	°C
47	T2212.5	Ch/Al	Cladding temperature of fuel rod 2.2, 1250 mm	°C

48	T2412.5	WRe5%/WRe20%	Cladding temperature of fuel rod 2.4, 1250 mm	^oC
49	T2512.5	Ch/Al	Cladding temperature of fuel rod 2.5, 1250 mm	^oC
50	T3112.5	WRe5%/WRe20%	Cladding temperature of fuel rod 3.1, 1250 mm	^oC
51	T3512.5	WRe5%/WRe20%	Cladding temperature of fuel rod 3.5, 1250 mm	^oC
52	T31212.5	Ch/Al	Cladding temperature of fuel rod 3.12, 1250 mm	^oC
53	Tsh12.5	WRe5%/WRe20%	Shroud temperature (opposite fuel rod 3.4), 1250 mm	^oC
54	Tth12.5	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.4), 1250 mm	^oC
55	Tst12.5	Ch/Al	Steam temperature, fuel rod 2.1, 1250 mm	^oC
56	T2513	WRe5%/WRe20%	Cladding temperature of fuel rod 2.5, 1300 mm	^oC
57	T2613	Ch/Al	Cladding temperature of fuel rod 2.6, 1300 mm	^oC
58	T3713	WRe5%/WRe20%	Cladding temperature of fuel rod 3.7, 1300 mm	^oC
59	T31113	Ch/Al	Cladding temperature of fuel rod 3.11, 1300 mm	^oC
60	Tsh13	Ch/Al	Shroud temperature (opposite fuel rod 3.10), 1300 mm	^oC
61	Tth13	Ch/Al	Thermoinsulation temperature (opposite fuel rod 3.10), 1300 mm	^oC
62	T1114	WRe5%/WRe20%	Cladding temperature of fuel rod 1.1, 1400 mm	^oC
63	T2514	Ch/Al	Cladding temperature of fuel rod 2.5, 1400 mm	^oC
64	T31014	Ch/Al	Cladding temperature of fuel rod 3.10, 1400 mm	^oC
65	T2215	Ch/Al	Cladding temperature of fuel rod 2.2, 1500 mm	^oC
66	T3715	Ch/Al	Cladding temperature of fuel rod 3.7, 1500 mm	^oC
67	P st15	-	Steam pressure, fuel rod 3.5, 1500 mm	MPa
68	Tst out	Ch/Al	Steam temperature at test section outlet, steam outlet sleeve, 1425 mm, 120^o	^oC

The measurement system for PARAMETER-SF1 test comprises 46 TC thermocouples for cladding temperature measurement in fuel rods located at 18 levels: from -150 to +1500 mm (with a 100 mm pitch at the heater section); 14 TC for shroud and termoinsulation temperature measurement at 7 levels (0; 200; 500; 700; 900; 1100; 1250 and 1300 mm); 3 TC for steam temperature measurement in FA at three levels (0; 600;

1250 mm) and 2 TC for steam temperature measurement at the test section inlet and outlet.

Two types of thermocouples (TC) were applied in the temperature measurement system (see Fig. 6): cable Ch/Al TCs in a stainless steel sheath ∅ 1,5 mm with the measured temperature range 1300 ^{o}C and high-temperature TCs – W+5%Re/W+20%Re in a sheath made of zirconium alloy Zr+1%Nb ∅ 3 mm with the measured temperature range 2000 ^{o}C.

The thermocouples were mounted axially to fuel rods on the surface of fuel rod cladding with a Zr clamp ~5 mm wide and 0,3 mm thick by electric contact welding, additionally the TCs were fixed with Ir wire 0,3 mm in diameter.

Steam-argon flow pressure was monitored by two pressure sensors at levels 540 (p5,4) and 1500 (p15) mm. Helium pressure in fuel rods was monitored by pressure sensor in the compensating tank (p_{rod}).

PROCESS PARAMETER MONITORING

Measured data acquisition and recording are performed by facility Data retrieval and instrumentation system based on two PENTIUM-II PCs with PARAM_19 Program, developed on the basis of GENIE 3.0 Package, its inquiry frequency being 2 s.

FA electric power is determined by instantaneous values (inquiry frequency 0,01 s) of current I(τ) and voltage U(τ) in FA, that are measured with analog-digital converter, subsequently integrated with Power5V electric power computation program.

Steam flowrate G_{st} is set by water flowrate in the system of steam generation (Pump 1) and is monitored by the steam generator parameters ($N_{el.sg}$, T_{sg}, p_{sg}) and steam parameters at the pipeline flow meter section (T_1, p_1, T_2, p_2).

Argon flowrate G_{Ar} is set by argon pressure at the outlet of the gas cylinder and is monitored on the basis of argon parameters at the flowmeter section (T_3, p_3) and with R4 electronic flowmeter.

Top flooding system flowrate is set by pressure p7 in the service Tank 7 and is monitored by R3 electronic flowmeter.

The process of steam condensation in condenser 1 and test section as well as water level at top flooding in the test section is monitored by M4 and M5 level meters of ИСУ100 type, their accuracy being to 1%.

HYDROGEN CONTENT MEASURING SYSTEM

General view of the system to measure the content of hydrogen that is generated at high temperature interaction of steam and the model FA materials, including fuel rod claddings, spacer grids, shroud and thermocouple protective sheath, is provided in Fig.7.

The hydrogen content measuring system is located downstream of condenser 1 in the additional gas duct of the facility downstream of the gas mixture parameter monitoring point (T10, p10). The system is operating on the basis of two measuring methods, continuous and discrete.

For continuous hydrogen analysis SOV-3 system for hydrogen content determination is used. The system was developed by SRC RF IPPE for automatic monitoring of hydrogen content inside NPP containment. The principle of the system operation is electric conductance metering that is selective with respect to hydrogen. As the analyzed gas mixture comes into the pickup, the hydrogen is absorbed by the sensor made of palladium-silver alloy, increasing its electric resistance until equilibrium is established that corresponds to hydrogen volumetric concentration in the gas mixture. A variation of electric resistance of the sensor is then converted into a continuous electric signal output to the computer.

SOV-3 performance:

- medium:
    - Carrier gas – argon;
    - Monitored gas – hydrogen;
- medium pressure – 0,15 – 0,35 MPa;
- medium flowrate – $(8 – 25)\cdot10^{-5}$ m^3/min;
- measurement limits - $5\cdot10^{-4}$ – 80 vol.%;
- time for signal setting within the range of concentrations:
    - $5\cdot10^{-4}$ – $1\cdot10^{-1}$ vol.% – ~ 2 min;
    - $\geq1\cdot10^{-1}$ vol.% - 1 min.

The location of SOV-3 hydrogen content measuring system in the additional gas duct permits to monitor the hydrogen content variation with F11 valve open within the entire course of the experiment.

In case of the discrete method of hydrogen concentration measurement 10 sampling tanks are used (Vol. 1, Vol. 2,…, Vol. 10), their volume being 2 l each. Before the experiment, the tanks are washed with high purity argon and are vacuumized. Sampling is performed with electric valves (Valve 8,…, Valve17), remotely controlled with automatic sampling system with sampling interval and duration designed. The sampling time is recorded by the facility data acquisition system.

Additional tank (Vol.11) with a volume of 250 liters is installed directly on condenser 1 for gas mixture sampling in the course of assembly flooding with water. A sample is taken into the tank via electric Valve 18 either manually or automatically – together with electric Valve 3 of top flooding water supply with account for the time of water flow along the flooding duct.

After the experiment the tanks are sealed and disconnected from the gas duct with a subsequent analysis of gas mixtures with gas chromatograph ХРОМАТЭК-КРИСТАЛЛ 5000. The results obtained are synchronized in time with the readings of SOV-3 continuous recording system.

PARAMETER-SF1 EXPERIMENT

Experiment scenario

PARAMETER-SF1 experiment was performed on April, 15, 2006 at PARAMETR test facility in FSUE SRI SIA "LUCH" with the support of work teams that perform calculations with RATEG/SVECHA, SCDAPSIM, MELCOR, MAAP-4, ATHLET and PARAM-TG computer Codes. Anticipated pre-test scenario of the experiment is provided in Table 3.

Table 3

Anticipated pre-test scenario of PARAMETER-SF1 experiment

Number	Stage substance	Main parameters			
		FA temperature, °C	Medium	Heating/ cooling rate	Time, s
1	Heating of the fuel bundle within argon	20 - 100	Argon with flow rate of 2 g/s and temperature up to 160 °C	-	0-500
2	Heating of the fuel bundle within the steam and argon flow	100-500	Steam/Argon with flowrates of 3/2 g/s	0.1-0.3 K/s	500-1600
3	Facility stabilization (electric power variation)	~ 500	Steam/Argon with flowrates of 3/2 g/s	-	1600-2500
4	Heating of the fuel bundle (transient phase I)	500-1200	Steam/Argon with flowrates of 3/2 g/s	~0.25 K/s	2500-5000
5	Pre-oxidation of the bundle	~ 1200	Steam/Argon with flowrates of 3/2 g/s	-	5000-9000
6	Heating of the fuel bundle (transient phase II)	1200-1850	Steam/Argon with flowrates of 3/2 g/s		Define experimentally as design temperature will be attained
7	Flooding of the fuel bundle from the top (10 s after T_{FAmax}=1850°C reached)	Till bundle cooling	Water with flowrate of 40 g/s per bundle		~300 (duration)

The main events of the experiment are provided in Table 4.

Table 4

Main events of PARAMETER-SF1 experiment

Moment of time, s	Events
0	Data retrieval and instrumentation system switched on
~8200	FA heatup to temperature 500 °C at the level of 1100 mm
~8800	FA heatup uniformly along the height (300-1300 mm) to temperature 500°C
~9300	Slow heating of assembly begins
10250	Cooling jacket switched on
~11000	Pre-oxidation stage begins
14450	Transient phase begins (in response to electric power increase)
14850	Electric power switched off
14858	Valve for steam supply to assembly closed
14892	Top flooding valve opened
15408	Top flooding valve closed
16490	Data retrieval and instrumentation system shutdown

EXPERIMENT DESCRIPTION

PARAMETER-SF1 experiment began after the correctness of valve position and sufficiency of available inventory of argon, helium and distilled water had been checked up.

The experiment consisted of four stages:

- *preparation stage* (0 – 11000 s) – stabilization of designed flowrates of argon ($G_{Ar} \approx 2$ g/s) and steam ($G_{st} \approx 3$ g/s) at FA temperature $T_{FA} \approx 500^oC$, assembly heatup to temperature ≈ 1200°C in the most heated zone;

- *pre-oxidation phase* (11000 – 14450 s) – FA annealing at temperature ≈ 1200°C in the most heated zone within ~ 3450 s. The maximum temperature deviations in the hottest cross-section (1300 mm) ~330 °C;

- *transient phase* (14450 – 14850 s) – FA temperature increase in the hottest cross-section to 1800 – 2000°C and above;

- *top flooding* (14892 – 15408 c) – assembly flooding on top at a flowrate of $G_{tf} \approx 40$ g/s.

Preparation stage

At 0 s the Data retrieval and instrumentation system was switched on, as well as the SOV-3 system for hydrogen content measurement, Valve 2 opened and preliminary flowrate of argon $G_{Ar} \approx 0,8$ g/s set for steam-gas pipeline and tank purging (see Fig. 8).

At 104 s pressure p3 was increased to augment argon supply into the assembly, however the designed flowrate settled at about 700 s after orifice meter heatup. At ~950 s the reference electronic rate-of-flow meter R4 at the outlet to special ventilation system recorded the designed argon flowrate $G_{Ar} \approx 2$ g/s. (see Fig. 8).

At 936 s Valve 7 of sampling duct was opened.

At 979 s argon heater to heatup argon to the designed temperature T6 ≈ 500 °C was switched on.

At 1835 s the heatup of the model FA in argon flow began – the supply of electric power ~ 500 W began, which at ~ 3000 s was increased. By ~3400 s power had been installed at the level of ~ 1340 W (see Fig. 9).

At 5392 s, at FA temperature ~ 400-480°C in cross-sections at levels 300-1250 mm, Valve 1 was opened and steam was supplied to the test section (see Fig. 8, 10-11, - FA temperature decrease within the time interval of 5400-6500 s was caused by FA cooling with steam flow).

By ~ 8200 s FA temperature in the cross-section at the level of 1100 mm had reached ~500 °C.

By ~ 8800 s a steady behaviour of basic parameters was observed: at the settled flowrates of argon and steam ($G_{Ar} \approx 2$ g/s, $G_{st} \approx 3,3$ g/s) FA temperature (T_{FA}) actually along the entire length of the core (300-1300 mm) was ~ 500°C (see Fig. 10-11); the pressure of steam-gas mixture in the FA was ~ 0,3 MPa, in the sampling duct: p10 - ~ 0,31 MPa, p12 - ~ 0,16 MPa, that of helium inside the fuel rods - ~ 0,32 MPa.

Since ~9302 s a slow assembly heatup began (see Fig. 9).

At 10250 s after the temperature of the test section body had reached ~ 140°C (see Fig. 13) the cooling jacket was switched on at the flowrate of cooling water ~ 110 g/s.

At 10430 s the power was increased to ~ 6400 W.

At 10762 s the pressure of steam-gas mixture in the FA increased from 0,3 MPa to ~ 0,32 MPa, in the gas duct (p10) – from ~ 0.31 MPa to ~ 0,34 MPa, in the sampling system (p12) – from ~ 0,16 MPa to ~ 0,17 MPa.

At ~11000 s the thermocouple T3713 in the cross-section at the elevation of 1300 mm (fuel rod row 3) recorded the temperature of fuel rod cladding 1200°C.

At 11172 s, as the SOV-3 system begins recording hydrogen the automated sampling system was switched on with gas sampling time of 8 s and frequency ~ 750 s (Vol.1 - Vol.5) and ~ 150 s (Vol.6 - Vol.8) (see Fig. 19).

Pre-oxidation

At ~ 11000 s thermocouple T3713 in the cross-section at the elevation lof 1300 mm (row 3) recorded the temperature of fuel rod claddings 1200°C. This is the beginning of the assembly pre-oxidation stage. By ~11200 s the hottest zone of the assembly (above 1200°C) had propagated down to the elevation of 1000 mm. Since the time the SOV-3 system had been recording a significant increase in hydrogen content in the gas that comes out of the assembly (beginning of the first peak in the hydrogen content curve).

The stage of pre-oxidation only lasted 3450 s, the maximum deviation of cladding temperature in the hottest cross-section (1250 mm) was ~330 °C.

Fast heatup stage

At 14450 s in the time interval 14450 – 14629 s a graduated power increase was performed from ~ 5600 W to ~ 9300 W (see Fig. 9). FA temperature in the hottest zone at the beginning of the gradual power increase was ~1250 °C.

~ 215 s later at 14850 s at FA temperature of ~ 1800 ^oC in the hottest zone power was switched off (see Fig. 9).

In the course of FA temperature increase pressure was increased: of steam-gas mixture in FA from ~ 0,31 MPa to ~ 0,43 MPa; in the sampling duct: p10 – from ~ 0,32 MPa to ~ 0,46 MPa, p12 – from ~ 0,16 MPa to ~ 0,19 MPa; of helium inside the fuel rods from ~ 0,31 MPa to ~ 0,41 MPa.

Following electric power switch-off a step-by-step disconnection of the steam generation system was realized: at 14852 s water supply to steam generator stopped, at 14854 s steam generator power supply and steam superheater power supply was switched off. At 14856 s argon heater was switched off. At 14858 s Valve 1 for steam supply to FA was closed.

At 14880 s Valve 7 was closed in the sampling duct (actuation of Valve 16 and Valve 17 to fill up the sampling tanks Vol. 9, Vol. 10 took place in the absence of argon-hydrogen mixture in the sampling duct).

Top flooding

At 14892 s at FA temperature ≥2000 ^oC Valve 3 was opened and top flooding water was injected out of the accumulator Tank 7 at an average rate, recorded by the electronic flow meter R3, ~ 41 g/s. The duration of top flooding was ~ 516 s.

At 14897 s Valve 18 was opened in the sampling tank Vol. 11. ~ 115 s later at pressure in the tank ~ 0,3 MPa Valve 18 was closed. At 15190 s gas mixture sampling was performed from tank Vol. 11 to two tanks with the 2 l volume each (see Fig. 15).

At 14932 s Valve 6 was opened in the gas discharge duct of special ventilation system.

At 15408 s with FA temperature decrease to ~ 80 ^oC top flooding stopped.

At 16490 s the Data retrieval and instrumentation system and SOV-3 hydrogen content measuring system were shut down.

EXPERIMENTAL RESULTS

Experimental results are provided in Figures 8 – 25.

In Figures 8 – 9 one can see the results of measurement of the main parameters of the experiment: flowrates of argon, steam and top flooding water (Fig. 8), changes of electric power of the model assembly (Fig. 9).

Figures 10-13 provide the plots of the change of fuel rod cladding temperature in the FA parts: top Z = (1400 – 1500) mm (Fig. 10a), middle Z = (900 – 1300) mm (Fig. 10b) and bottom Z = (0 – 800) mm (Fig. 10c); that of the shroud (Fig. 11), thermoinsulation (Fig. 12) and test section body (Fig. 13).

Figure 14 shows the results of fuel rod cladding temperature measurement in FA parts: top Z = (1500 – 1400) mm (Fig. 14a), middle Z = (900 – 1300) mm (Fig. 14b) and bottom Z = (0 – 800) mm (Fig. 14c) at the stage of flooding.

The plots of pressure change in the fuel rods (p_{rod}), model FA ($p_{(540)}$, $p_{(1500)}$), testing rig gas duct (p10, p11, p12) and sampling tank Vol. 11 (pv11) at the stage of top flooding are depicted in Figure 15.

Figures 16, 17, 18 present the plots of the temperature change of the shroud (Fig. 16), thermoinsulation (Fig. 17) of FA and test section body (Fig. 18) at the top flooding stage.

Figure 19 shows the results of volumetric hydrogen concentration measurement with SOV-3 hydrogen content measuring system as well as nine sampling points (Vol1, …, Vol8, Vol11), Figure 20 provides the rate of hydrogen generation and amount of generated hydrogen.

PRELIMINARY EXPERIMANTAL DATA ANALYSIS

Preparation stage

Preliminary analysis of experimental results has shown that at the stage of preparation the model FA was gradually heated up in argon medium from room temperature to ~ 500°C, initially at small flowrate of argon and then at assigned flowrate of ~ 2.0 g/s, after 5392 s in the flow of steam-argon mixture at the steam flowrate of ~ 3.3 g/s.

Till ~10376 s the PARAMETER-SF1 experiment was performed in accordance with the pre-test scenario. All the measurement and process systems operated in a satisfactory way.

Pre-oxidation stage

Beginning with ~10376 s the readings of thermocouples that measure the fuel rod cladding temperature in the FA top part were found to deviate from the expected values. In particular, the expected stabilization of fuel rod cladding temperature ~1200^{o}C was not recorded in the hottest cross-section at electric power level of 6400 W (see Fig. 9, 10-11). Since the moment the electric power supply was switched over by the operator to manual control based on thermocouple readings only.

This permitted to hold the assembly at temperature of ~1200^{o}C within 3250 s (in the hottest zone at elevations 1000-1300 mm), though the maximum temperature deviations in the hottest cross-section at the elevation of 1300 mm reached ~330^{o}C. A post-test measured data interpretation permits to suppose that the deviation of the temperature behavior of the assembly can be caused by thermal balance disturbances due to a decrease in steam flowrate through the heated part of the assembly. The cause of the decrease in steam flowrate can be in a following:

- steam condensation at the bottom after the test section cooling jacket is switched on;
- steam bypass through the assembly process slots: between test section body and SS thermal insulation shroud as well as between SS thermal insulation shroud and fiber ZrO_2 insulation.

Transient stage

Transient stage began at ~14450 s. The operable thermocouples at this stage recorded assembly heating in the hottest cross-section from the values of ~ 1250°C at the beginning of power surge to ~1850°C at the moment of power switch off. At the moment of power switch off (14850 s) the operable thermocouples displayed the following maximum readings:

In the FA top part (1400 – 1500 mm):

at the elevation of 1400 mm, row 2, T2514 ~ 1050 ^{o}C ;

at the elevation of 1400 mm, row 3, T31014 ~1000 ^{o}C;

at the elevation of 1500 mm, row 2, T2215 ~ 800 ^{o}C;

at the elevation of 1500 mm, row 3, T3715 ~ 650 ^{o}C.

In the FA middle part (900 – 1300 mm):

at the elevation of 1300 mm, row 3, T3713 ~ 1450 ^{o}C;

at the elevation of 1100 mm, row 3, T3911 ~ 1850 ^{o}C;

at the elevation of 1250 mm, row 3, T3512,5 ~ 1750 ^{o}C;

at the elevation of 1250 mm, row 3, T3112,5 ~ 950 ^{o}C;

at the elevation of 900 mm, row 3, T3129 ~ 1250 ^{o}C;

at the elevation of 900 mm, row 2, T249 ~ 1300 ^{o}C;

In the FA bottom part (0 – 800 mm):

at the elevation of 800 mm, row 2, T258 ~ 1200 ^{o}C;

the thermocouple readings below the elevation of 800 mm did not exceed 1000 ^{o}C.

Meanwhile, at this stage in the course of temperature increase, sharp jumps in the thermocouple readings occurred: the values reached 2000 ^{o}C in the hottest zone with a subsequent thermocouple damage:

at the elevation of 1300 mm, row 2, T2513 (14824 s) from ~ 1400 ^{o}C to 2000 ^{o}C and above;

at the elevation of 1400 mm central rod simulator T1114 (14806 s) from ~1100 ^{o}C to 1200 ^{o}C;

at the elevation of 1000 mm, row 2, T2210 (14804 s) from ~1450 ^{o}C to 2000 ^{o}C and above;

at the elevation of 1000 mm, row 2, T2610 (14818 s) from ~1400 ^{o}C to 2000 ^{o}C and above;

at the elevation of 1250 mm, row 3, T31212,5 (14780 s) from ~1350 ^{o}C to 2000 ^{o}C and above.

On the basis of these data a supposition can be made that the temperatures in the hottest zone (1000-1300 mm) at the moment of power switch off to all appearance exceeded 2000^{o}C.

Flooding stage

At 14892 s water injection began at a rate of ~ 41 g/s. Assembly cooldown was implemented for ~ 516 s (see Fig. 14).

Within the time interval from the moment of power switch off (14850 s) till the moment the top flooding stopped, the thermocouples displayed the following maximum readings:

In the FA top part (1400 – 1500 mm):

at the elevation of 1400 mm, row 2, T2514 (~ 14890 s) ~1050 ^{o}C;

at the elevation of 1400 mm, row 3, T31014 (~ 14890 s) ~ 950 ^{o}C;

at the elevation of 1500 mm, row 2, T2215 (~ 14890 s) ~800 ^{o}C;

at the elevation of 1500 mm, row 3, T3715 (~ 14890 s) ~700 ^{o}C.

In the FA middle part (900 – 1300 mm):

at the elevation of 1300 mm, row 2, T3713 (~ 14890 s) ~1450 ^{o}C;

The readings of all thermocouples at levels 900-1250 mm exceeded 2000 ^{o}C.

In the FA bottom part (0 – 800 mm):

at the elevation of 800 mm, row 2, the readings of thermocouple T258 reached the limiting value of 1400 ^{o}C;

at the elevation of 500 mm, row 2, T215 (~ 14912 s) ~1000 ^{o}C;

at the elevation of 500 mm, row 3, T325 (~ 1504 s) ~1000 ^{o}C;

at the elevation of 400 mm, row 2, T224 (~ 14910 s) ~900 ^{o}C;

at the elevation of 400 mm, row 3, T3124 (~ 14906 s) ~900 ^{o}C;

at the elevation of 300 mm, row 2, T243 (~ 14910 s) ~850 ^{o}C;

at the elevation of 300 mm, row 3, T353 (~ 14926 s) ~800 ^{o}C;

at the elevation of 200 mm, row 3, T3112 (~ 14910 s) ~700 ^{o}C;

In the course of flooding a sharp jump of thermocouple readings took place:

at the elevation of 700 mm, row 2, T267 (14970 s) from ~1150 ^{o}C to the limiting value – 1400 ^{o}C;

at the elevation of 600 mm, row 2, T236 (14916 s) from ~1100 ^{o}C to the limiting value – 1400 ^{o}C;

at the elevation of 600 mm, row 3, T316 (14978 s) from ~1000 ^{o}C to ~1150 ^{o}C;

In the course of top flooding the assembly top levels were cooled quite quickly (Z=1250 - 1500 mm, see Fig. 14a). At this, the part was cooled unevenly: first, the zone was cooled to ~ 130°C within 3-5 s and then, ~ 150 s later, to ~ 50°C (Fig. 14a,b). Meanwhile the bottom flooding of assembly lower part (Z=0 - 600 mm, see Fig. 14c) was performed much later (400-600 seconds later). At these elevations the cooling front slowly moved upwards from the bottom of the test section (Fig. 14c). At the elevation of 800 mm the assembly was cooled, actually, at the end of the experiment.

The dynamics of shroud cooling in the course of top flooding was somewhat different from the dynamics of FA cooling: first, at ~14900 s, the FA top part was cooled (1250 – 1300 mm), then at ~15050 s the cooling front descended to the elevation of 500 mm and at ~15150 s to the elevation of 200 mm, i.e. the external surface of the shroud was cooled from the top to the bottom (see Fig. 16).

At ~14900 s there was a jump of temperature of the thermoinsulation external surface at the elevation of 900 – 1300 mm (see Fig. 17). Almost simultaneously (beginning with ~ 14894 s) a temperature jump to ~ 450 ^{o}C (~14950 s) was recorded at the external surface of the test section body at the elevation of ~ 800 mm (see Fig. 18).

In the course of FA temperature increase there was an increase in the pressure: of FA steam-gas mixture from ~ 0,31 MPa to ~ 0,43 MPa; in the sampling duct: p10 – from ~ 0,32 MPa to ~ 0,46 MPa, p12 – from ~ 0,16 MPa to ~ 0,19 MPa; of helium inside the fuel rods from ~ 0,31 MPa to ~ 0,41 MPa.

At top flooding stage a decrease in pressure took place: of FA steam-gas mixture from ~ 0,43 MPa to ~ 0,34 MPa; in the sampling duct: p10 – from ~ 0,46 MPa to ~ 0,36 MPa; of helium inside the fuel rods from ~ 0,41 MPa to ~ 0,36 MPa (see Fig. 15).

The measurement of volumetric hydrogen concentration was implemented with SOV-3 system at all the stages of the experiment (see Fig. 19). The variation of volumetric hydrogen concentration is provided with consideration of the persistence of the SOV-3 system (to 2 min), but with no account for the measurement transport delay (time of argon-hydrogen mixture passage from the FA as far as SOV-3). The Figure also presents the results of gas sampling with account for the post-test analysis of the mixture for hydrogen content (see Table 5).

Table 5

Volumetric hydrogen concentration in sampling tanks

Tank number	1	2	3	4	5	6	7	8	11
Sampling time, s	11172	11878	12672	13422	14172	14422	14622	14772	14897-15012
Volumetric hydrogen concentration in the sample, %	6,48	1,14	3,71	1,08	1,27	2,22	3,61	17,18	81

From the comparison of the data presented in Figure 19, a conclusion can be made that the readings of SOV-3 and the results of the analysis of gas sampling agree well.

The maximum rate of hydrogen generation was ~ 0,19 g/s. Complete amount of the generated hydrogen was ~ 91 g, of which ~ 59 % produced during the flooding stage (see Fig. 20).

After the experiment the test section was disassembled and the state of the model FA inside the test section was fixed with a compound (epoxy resin) in a vertical position. After the compound had hardened the assembly was withdrawn, the test section body and thermoinsulation were removed and the assembly was cut along the height.

Visual examination of the thermoinsulation shroud at assembly withdrawal out of the test section showed that there is a burnout on the thermoinsulation shroud surface (a cylinder made of a stainless steel sheet 1 mm thick) (see Fig. 21) at the level of ~ 800 mm along assembly facet 90^o – 120^o (fuel rods 3.7 – 3.9). This explains the temperature peaks in the thermocouple readings on the test section body and in thermoinsulation.

After the thermoinsulation shroud had been opened, its internal surface (see Fig. 22) and external surface of the thermoinsulation showed traces of steam-gas mixture release (local oxidized zone with peeling oxide scale) and frozen melt. Evidently, at the moment of flooding the shroud melting occurred, which resulted in steam and melt release from the core through thermoinsulation to the test section body.

Figure 24 shows the post-test view of the model FA with the shroud at the elevations of 700 – 1000 mm along the assembly facet 90^o – 120^o (fuel rods 3.7 – 3.9).

Figure 25 provides the pictures of the cross-sections at elevations 400 – 1300 mm after templates had been cut. The pictures provide the views beginning with the top (for orientation fuel rod 3.1 was marked).

It is worth mentioning that at the elevation of 1283 mm the assembly remained undamaged, though it was the hottest zone (at least before the moment of flooding). In this cross-section the assembly could remain intact either due to complete oxidation of zirconium structures (shroud, claddings) or due to fast cooling of the zone at top flooding, so the metal zirconium in the oxidized shroud and claddings melted and then quickly froze at flooding and there was no time for external oxide scale to collapse. The results of metallographic analysis can help to get the answer to these questions.

FIGURES

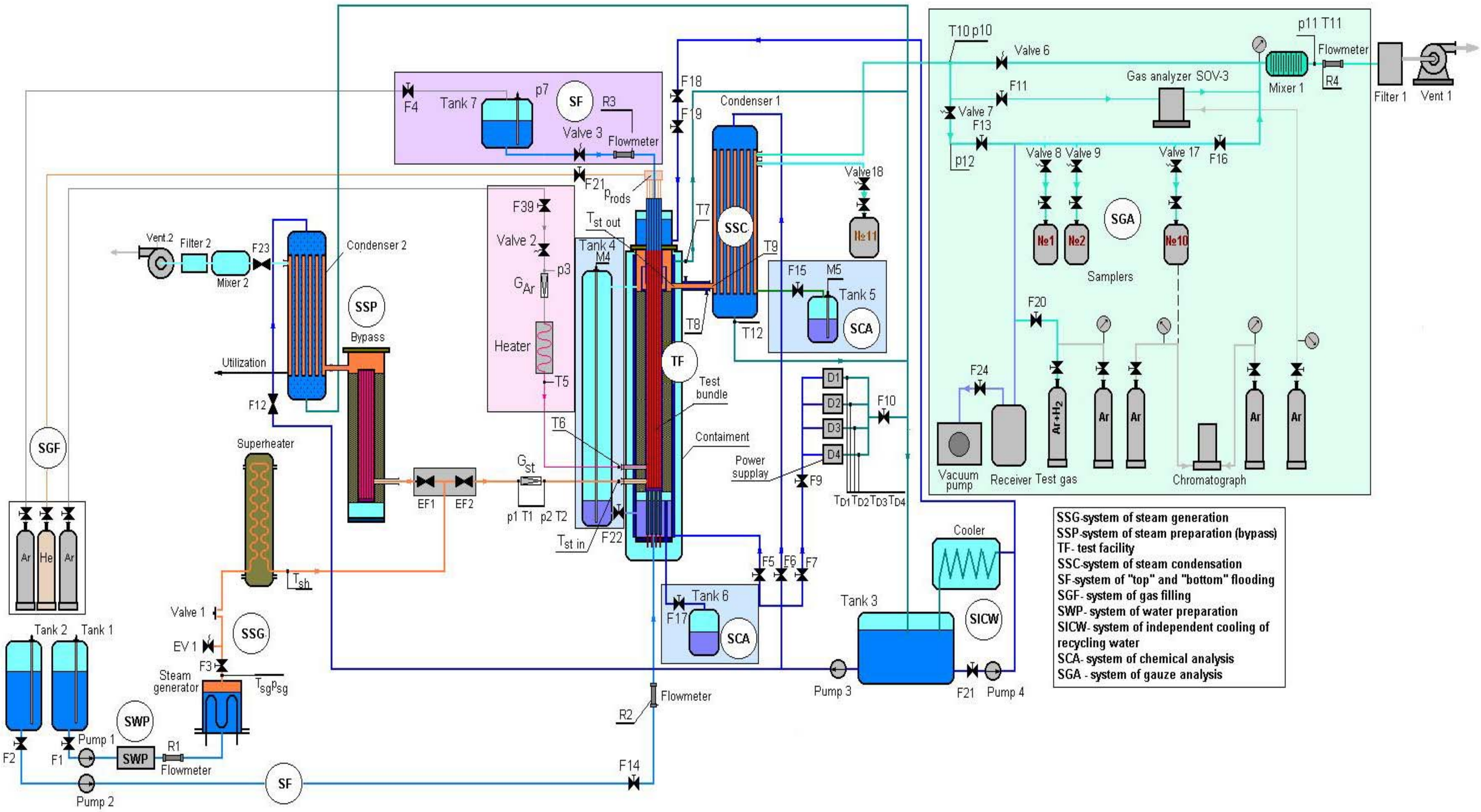


Fig. 1. Functional diagram of PARAMETER test facility.

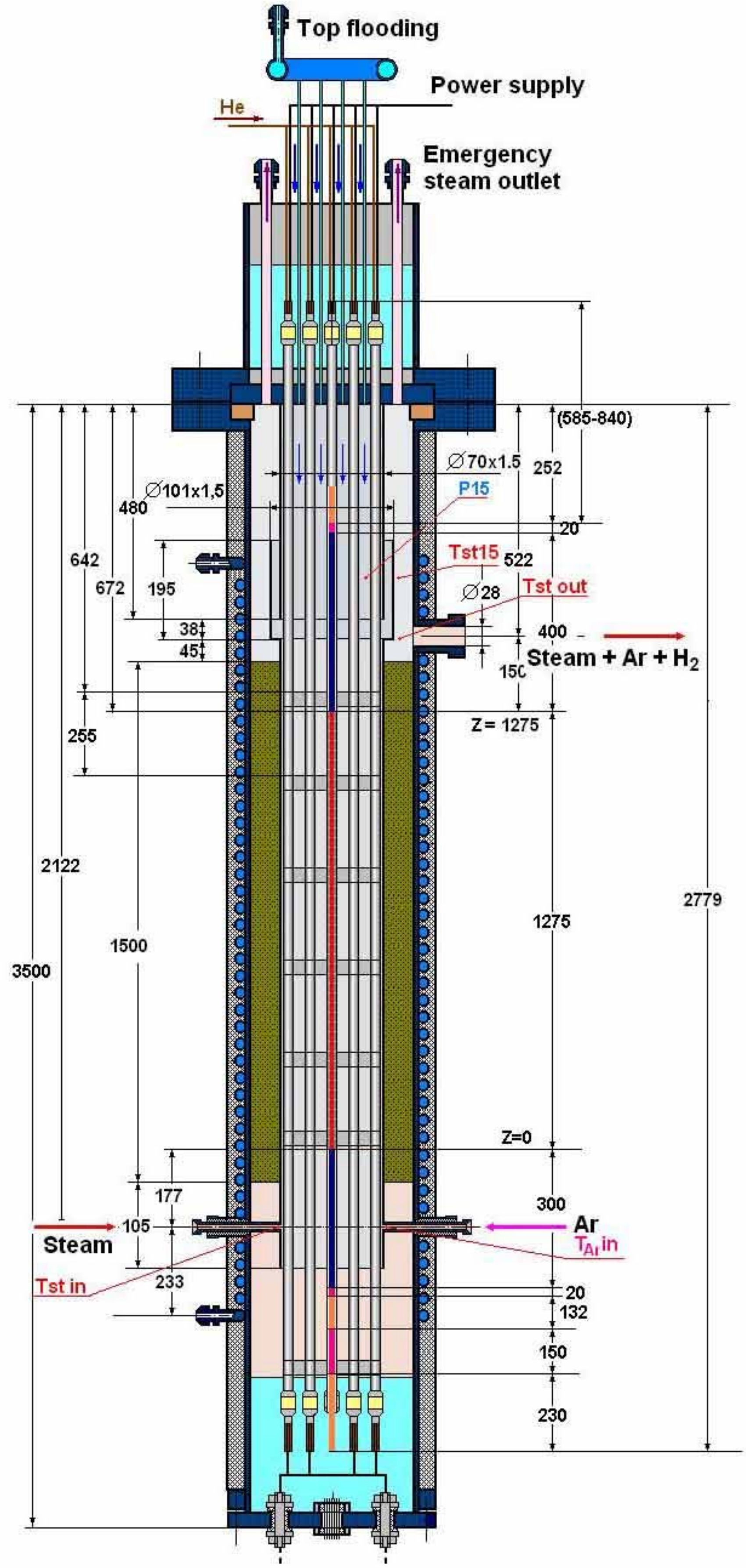
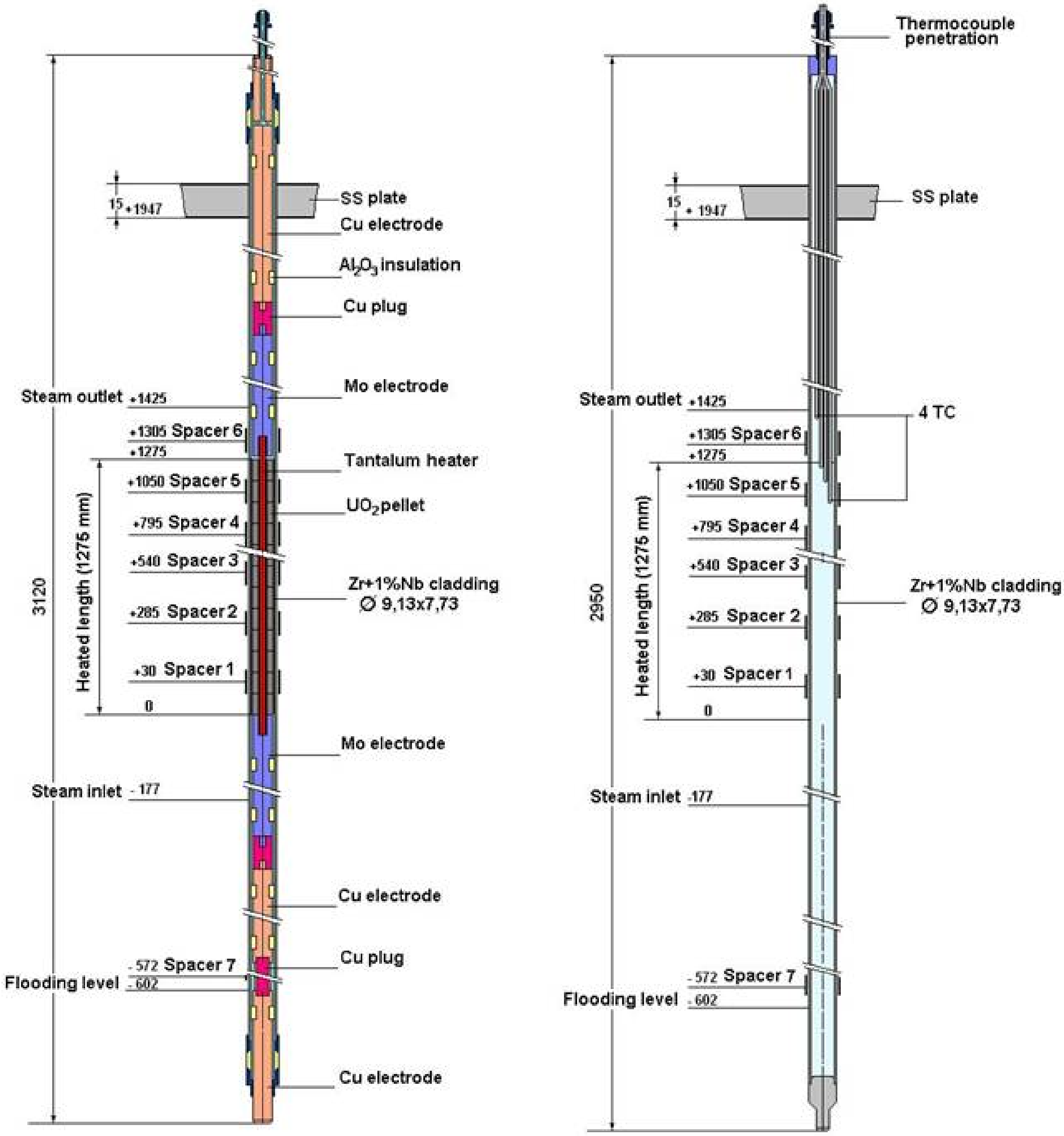


Fig. 2. Model fuel assembly diagram.



Heated fuel rod Unheated fuel rod

Fig. 3. Fuel rod simulators.

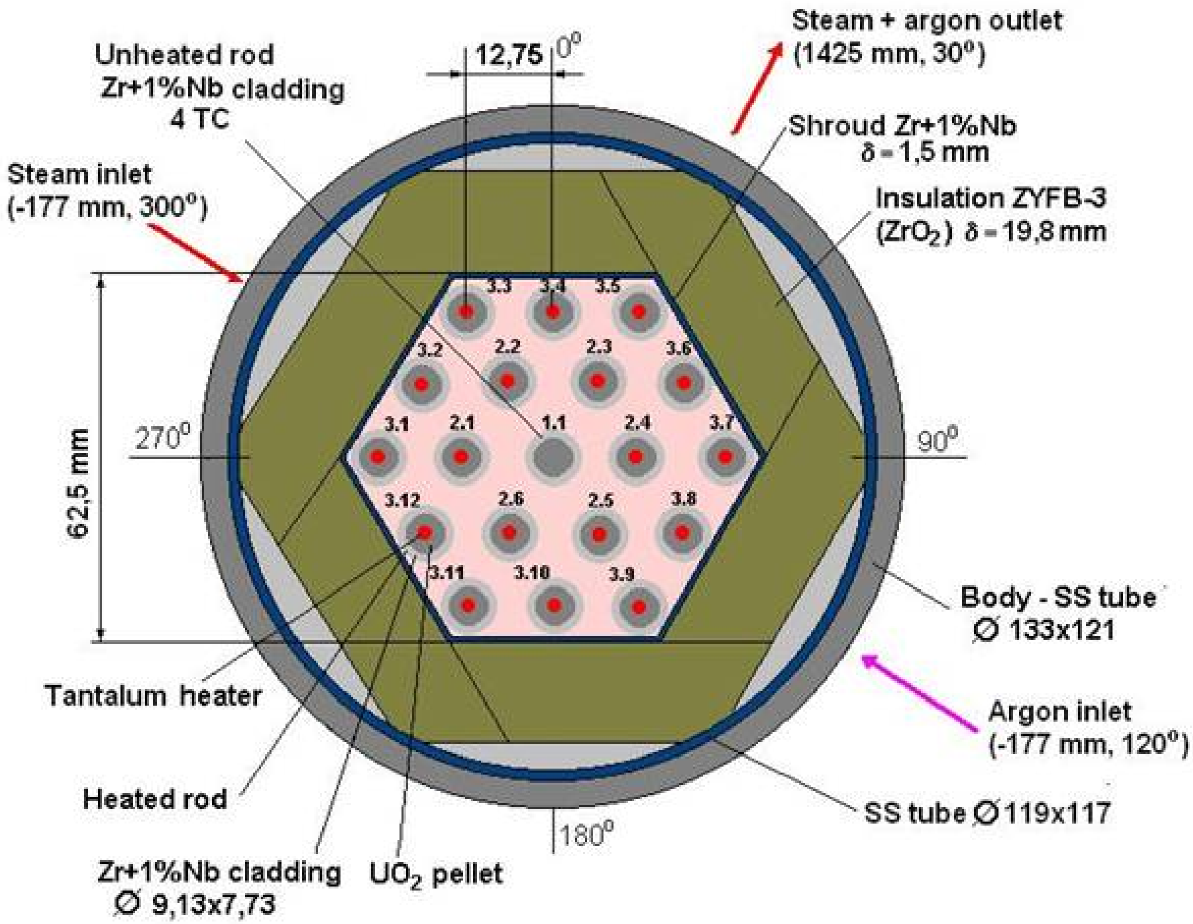


Fig. 4. Model fuel assembly cross-section.

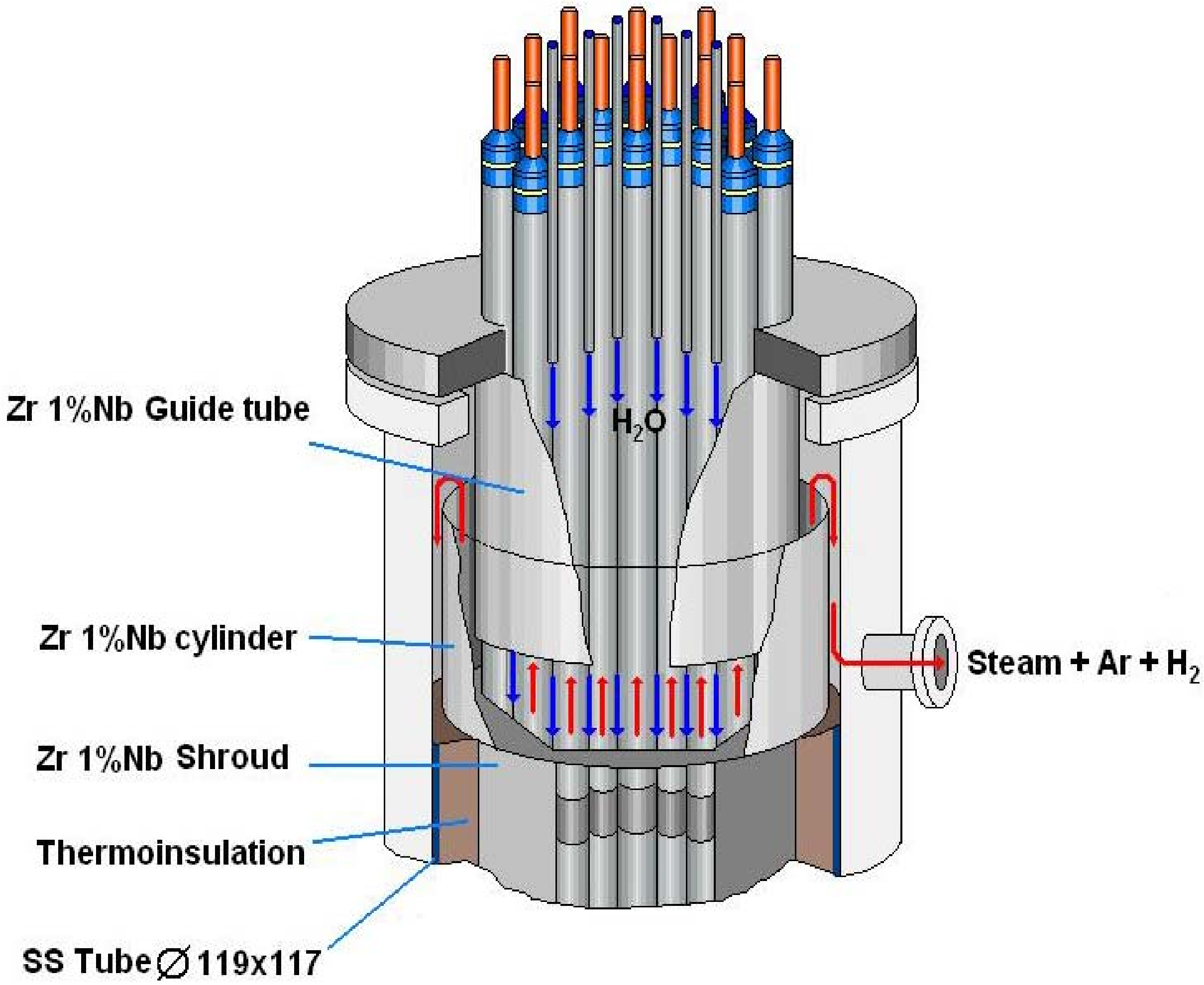


Fig. 5. Model fuel assembly top.

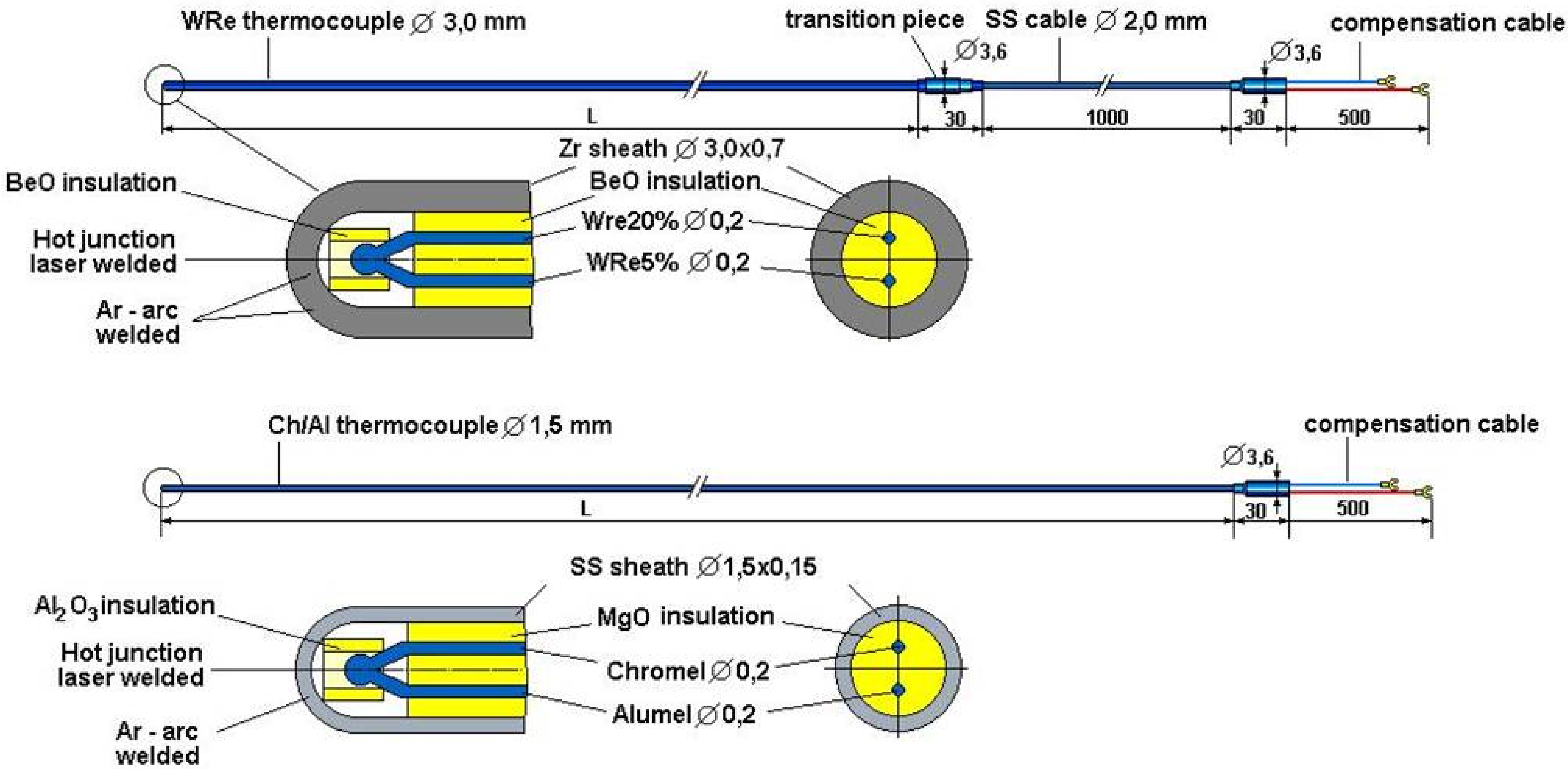


Fig. 6. FA thermocouples.

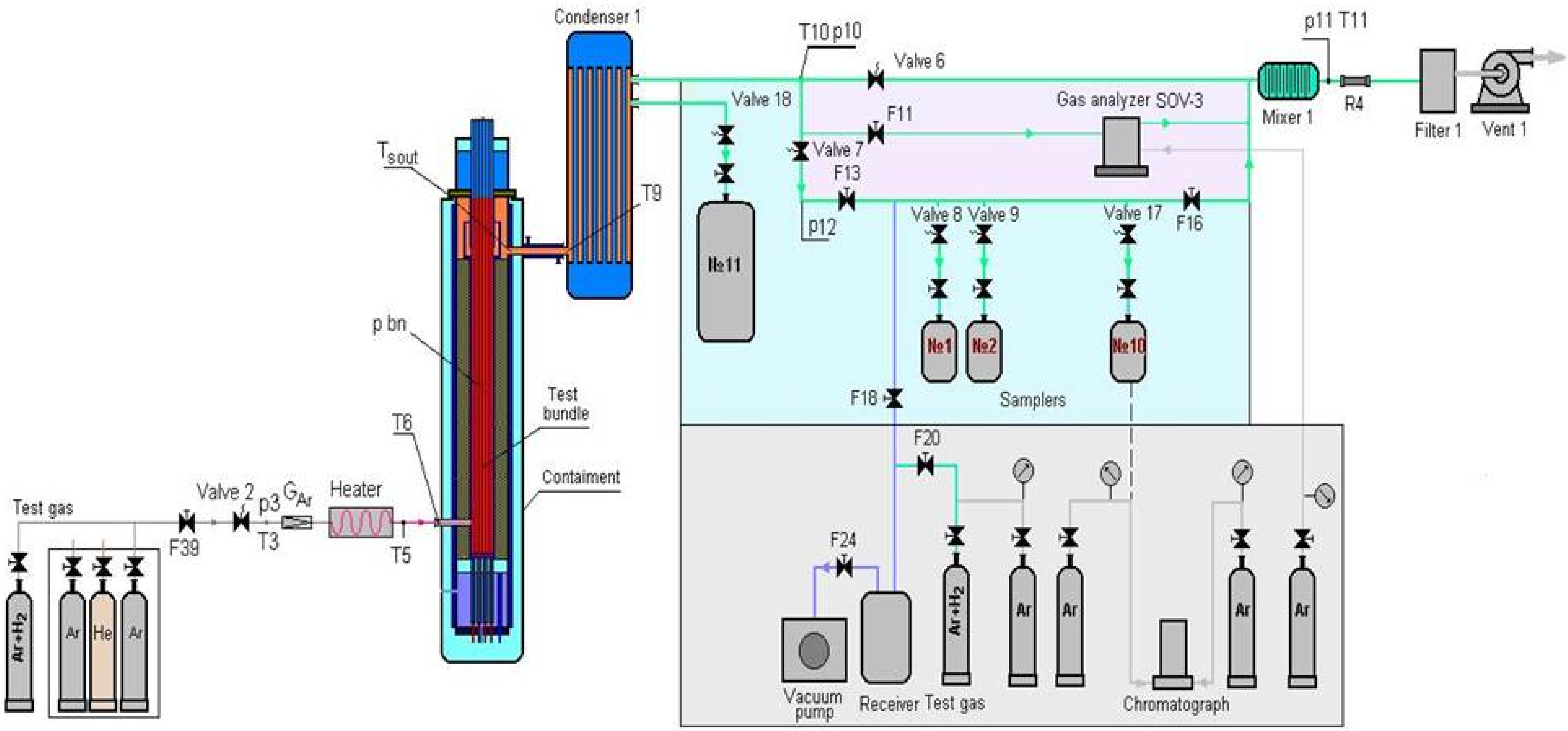


Fig. 7. General view of hydrogen content measurement system.

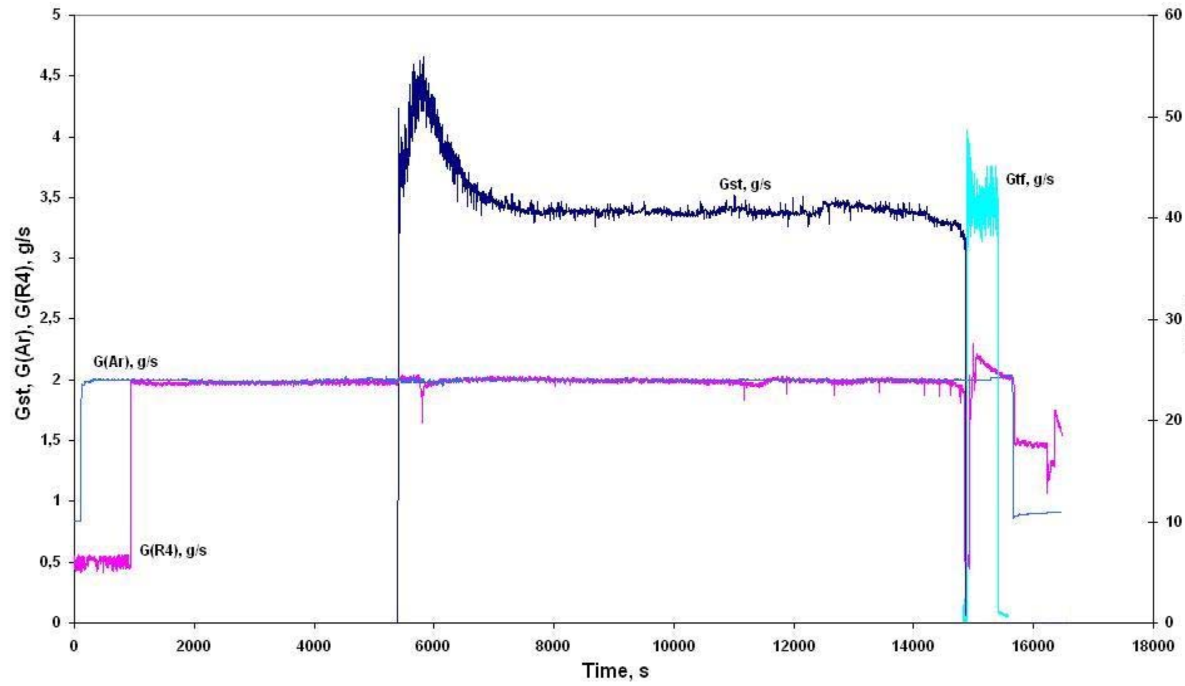


Fig. 8. Flowrates of argon (G_{Ar}, G_{Ar}(R4)), steam (G_{st}) and top flooding water (G_{tf}).

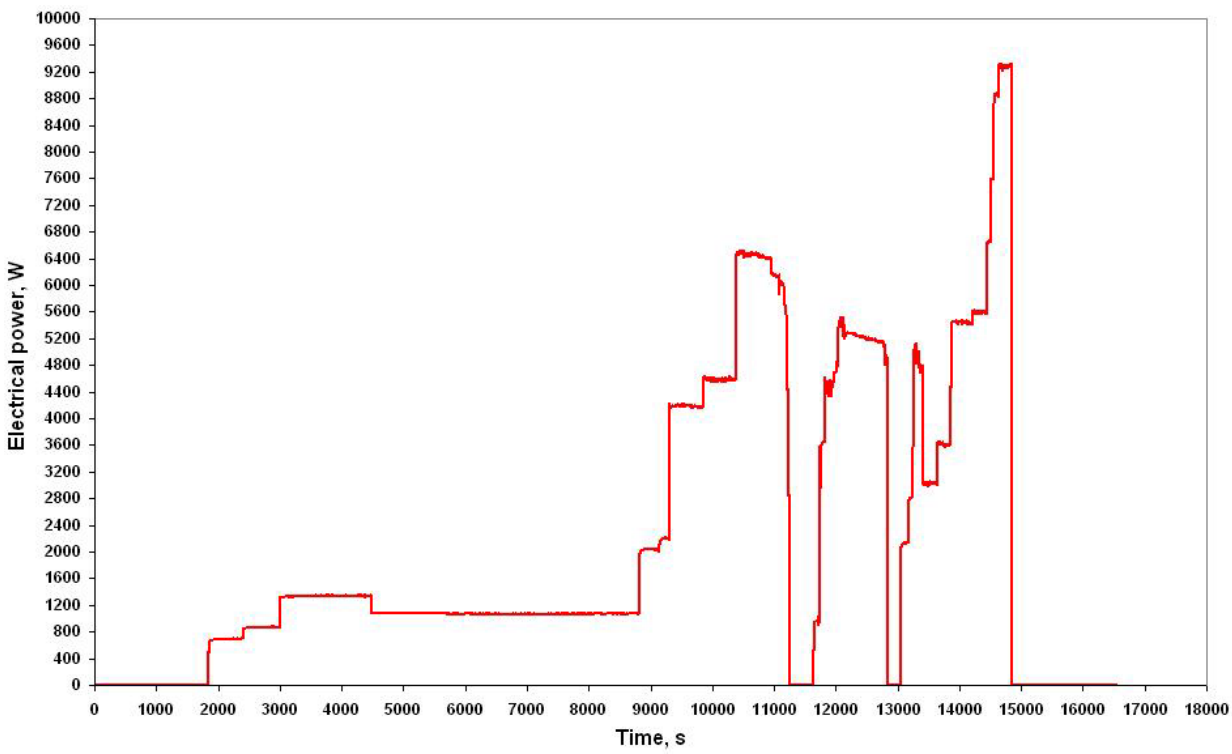
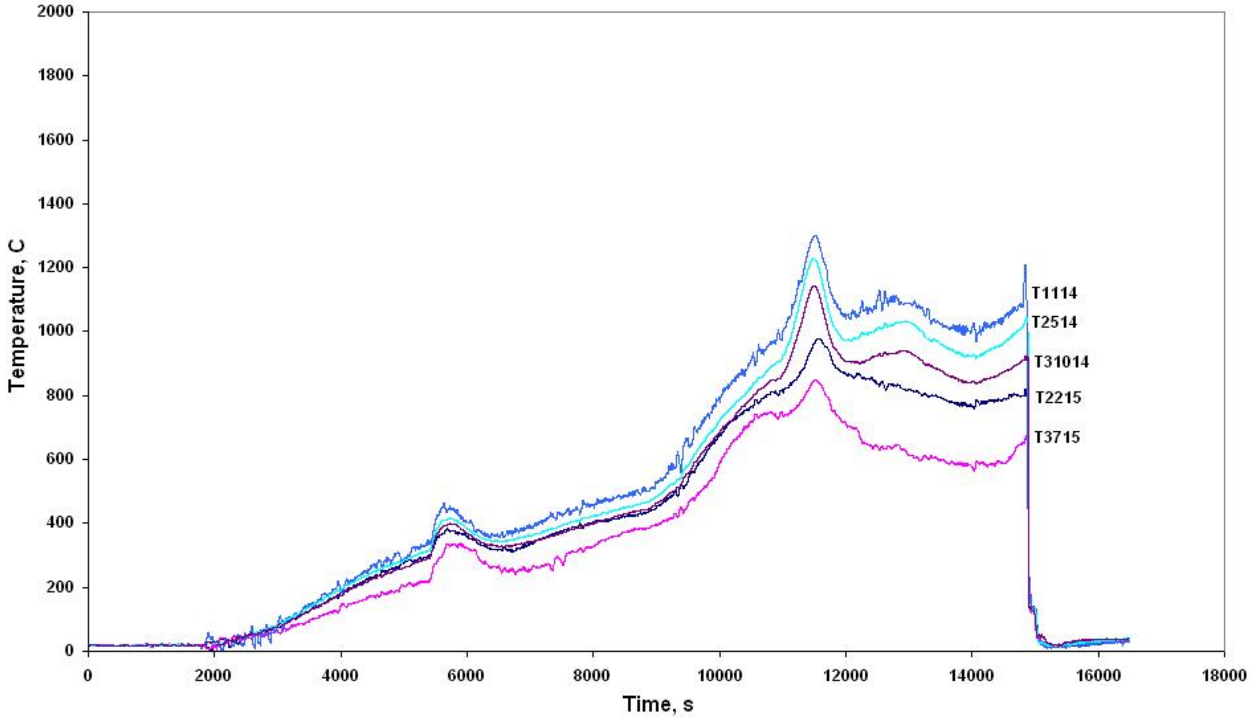
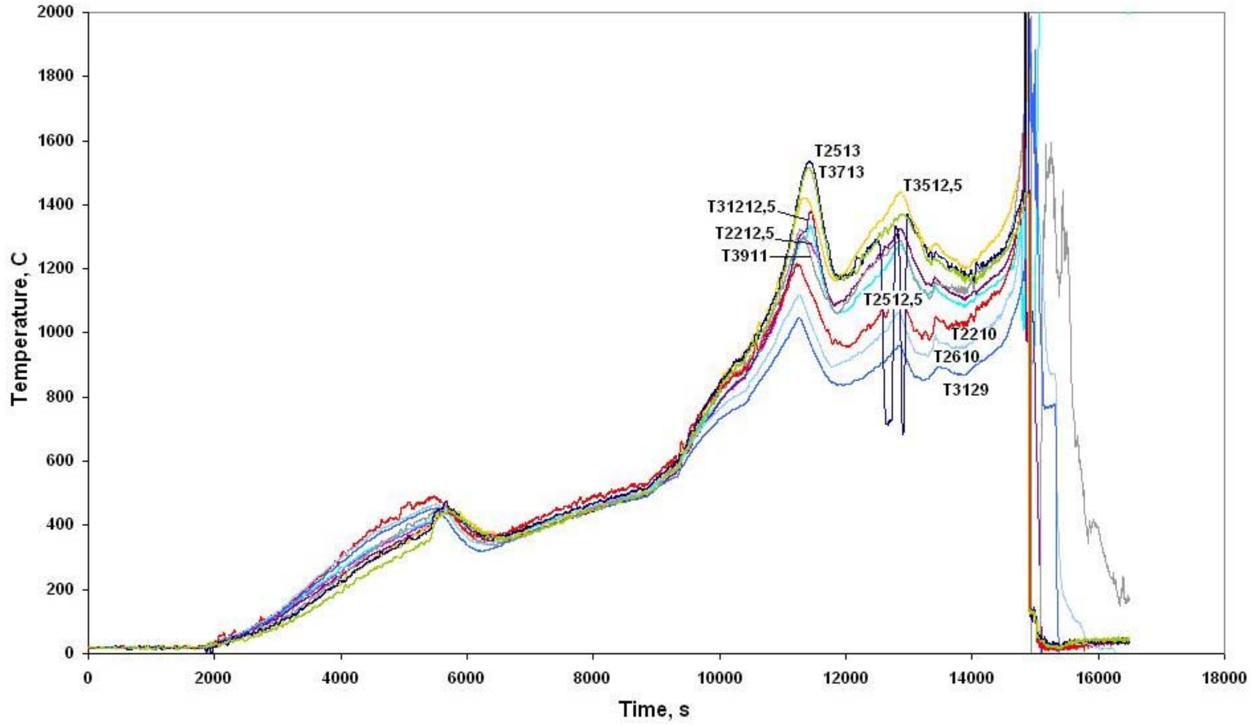


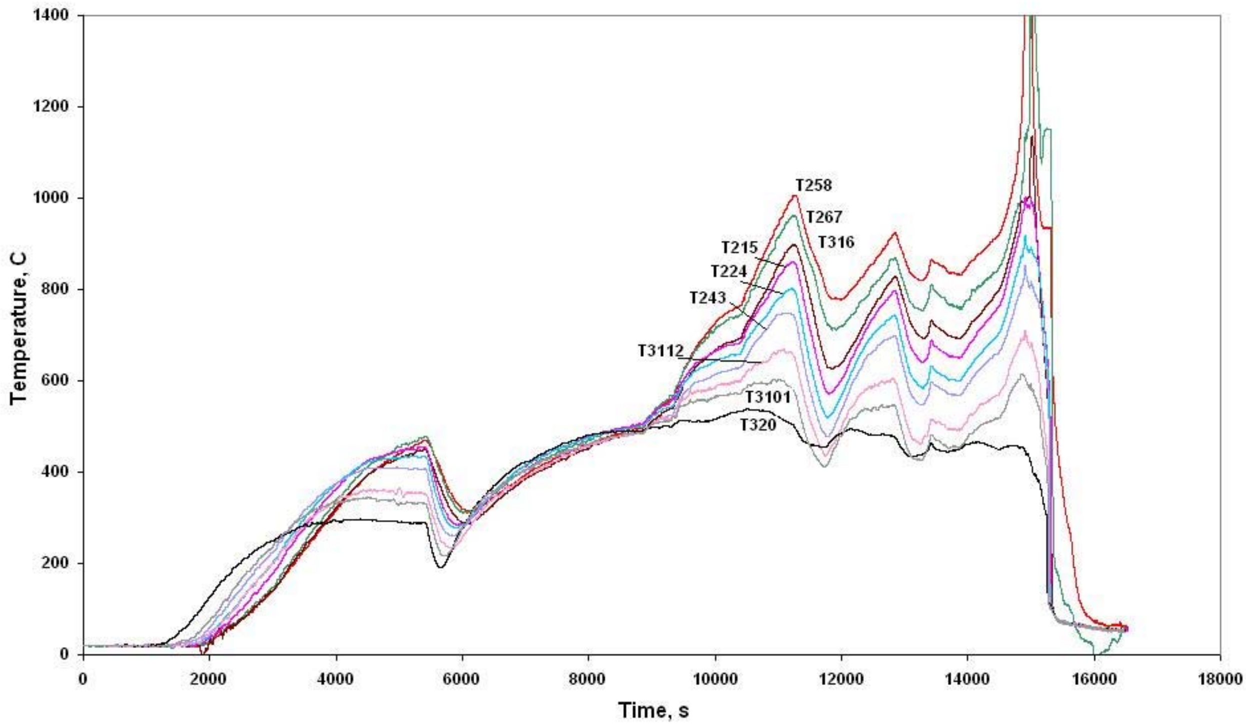
Fig. 9. FA electric power.


Temperature, C
Time, s
T1114
T2514
T31014
T2215
T3715

a)


Temperature, C
Time, s
T2513
T3713
T3512,5
T31212,5
T2212,5
T3911
T2512,5
T2210
T2610
T3129

b)



c)

Fig. 10. Fuel rod cladding temperature variations along FA axis:
a – in the top part at the level of 1400 – 1500 mm;
b – in the middle part at the level of 900 – 1300 mm;
c – in the bottom part at the level of 0 – 800 mm.

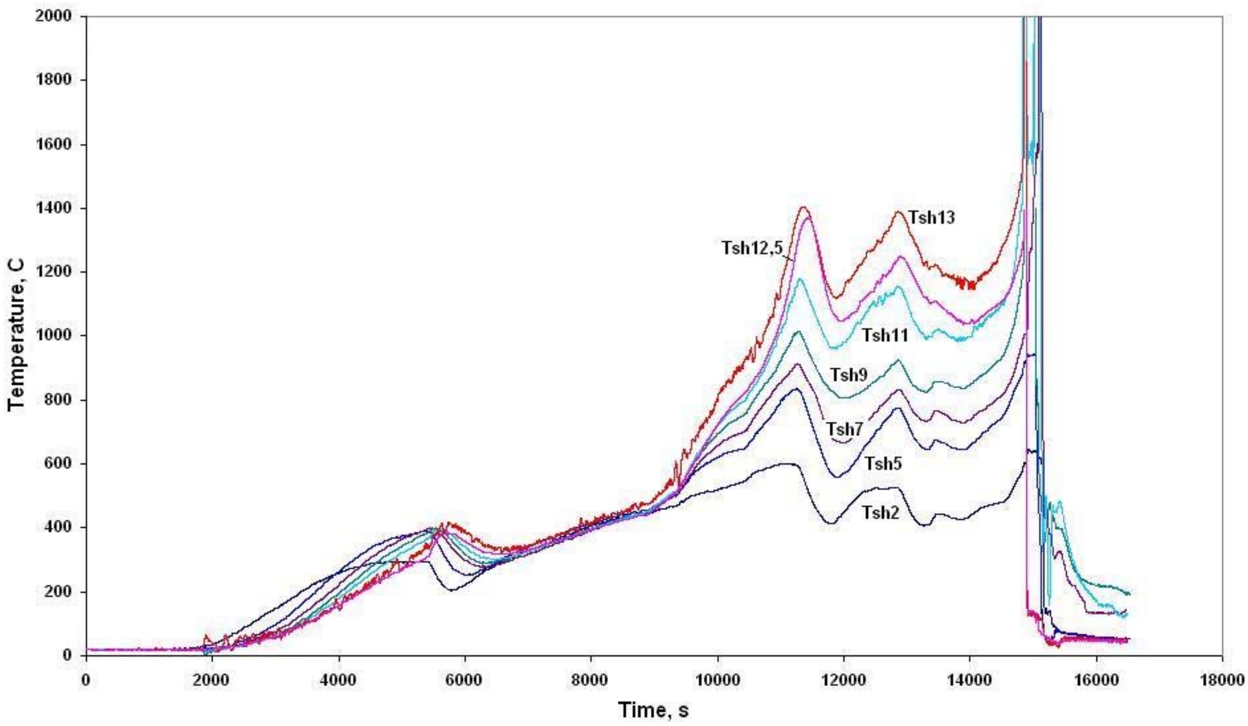


Fig. 11. Shroud temperature variations along FA axis.

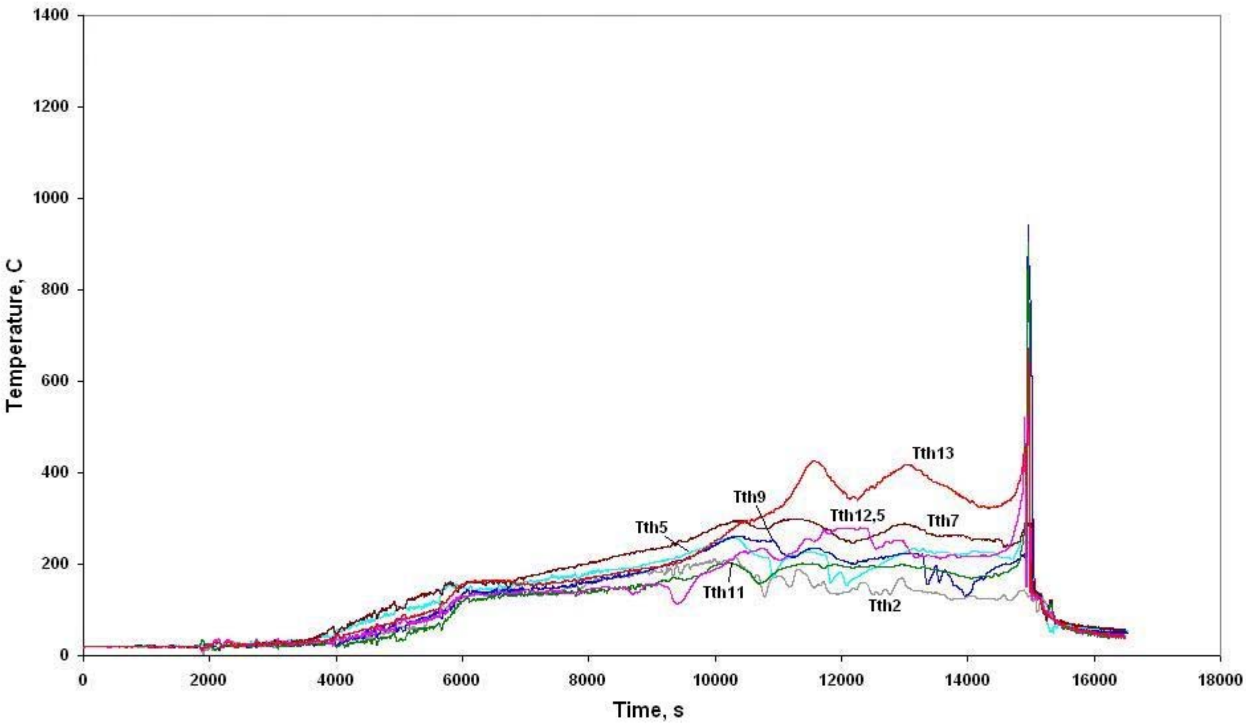


Fig. 12. Thermoinsulation temperature variation along FA axis.

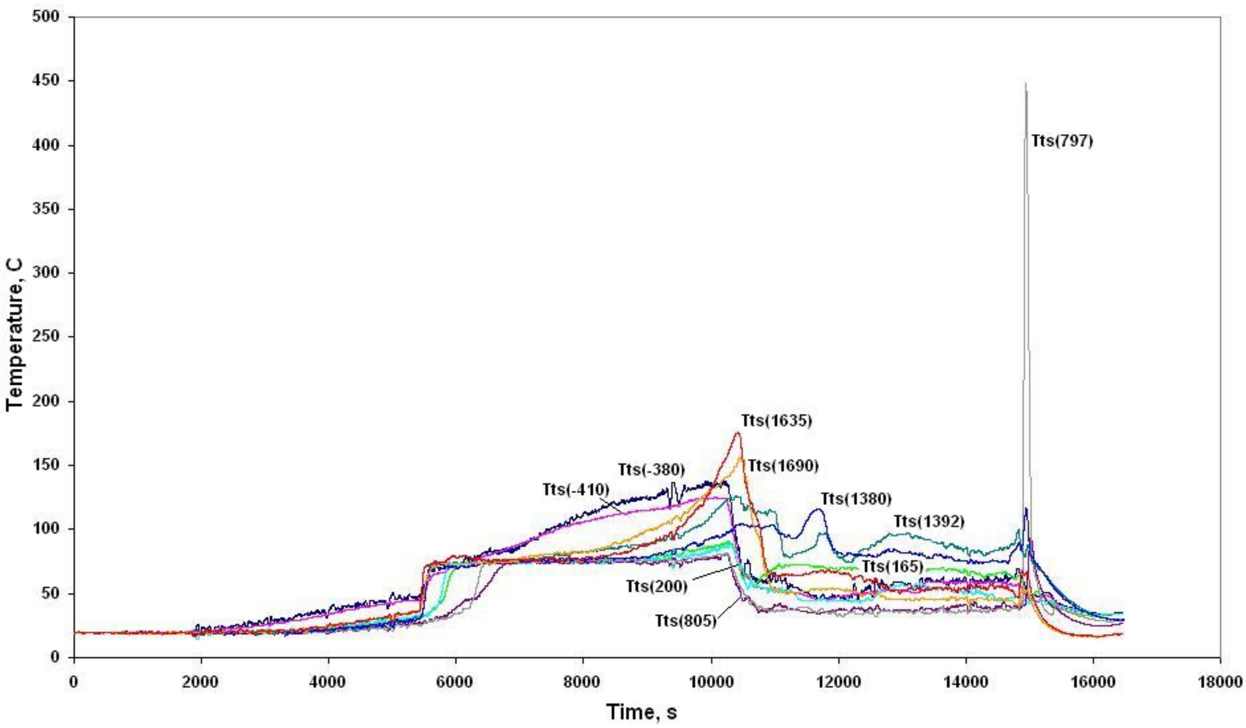
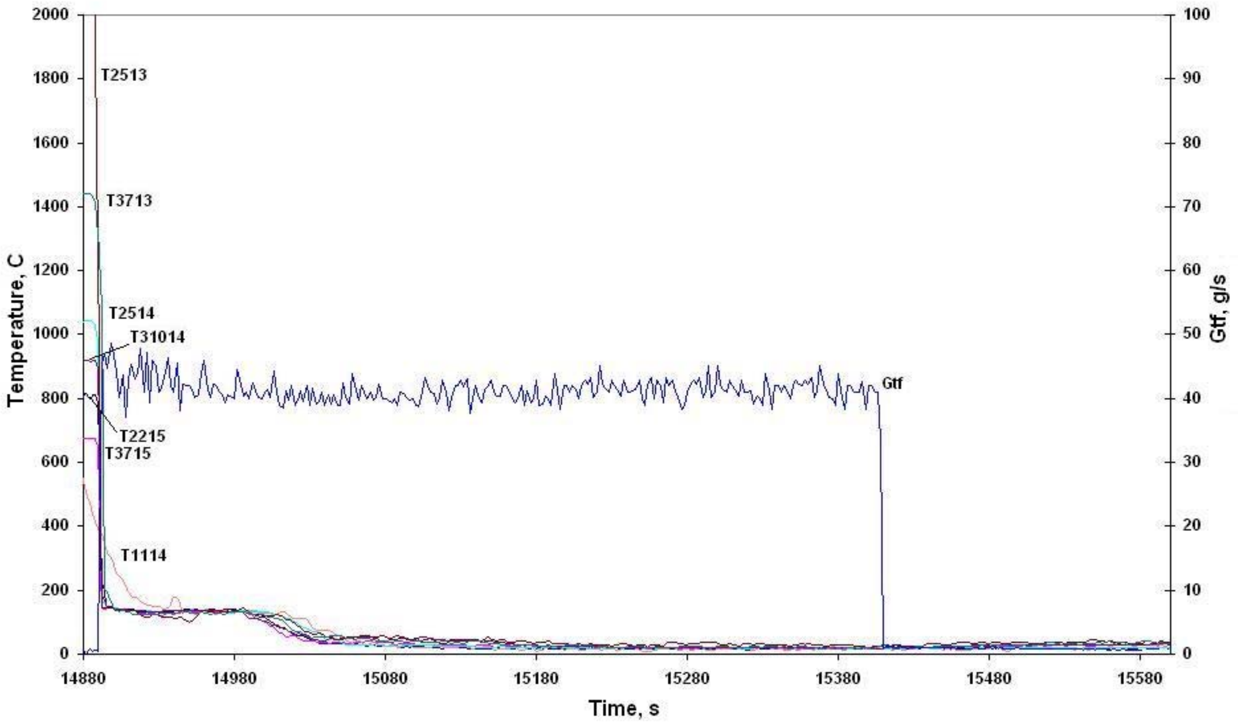
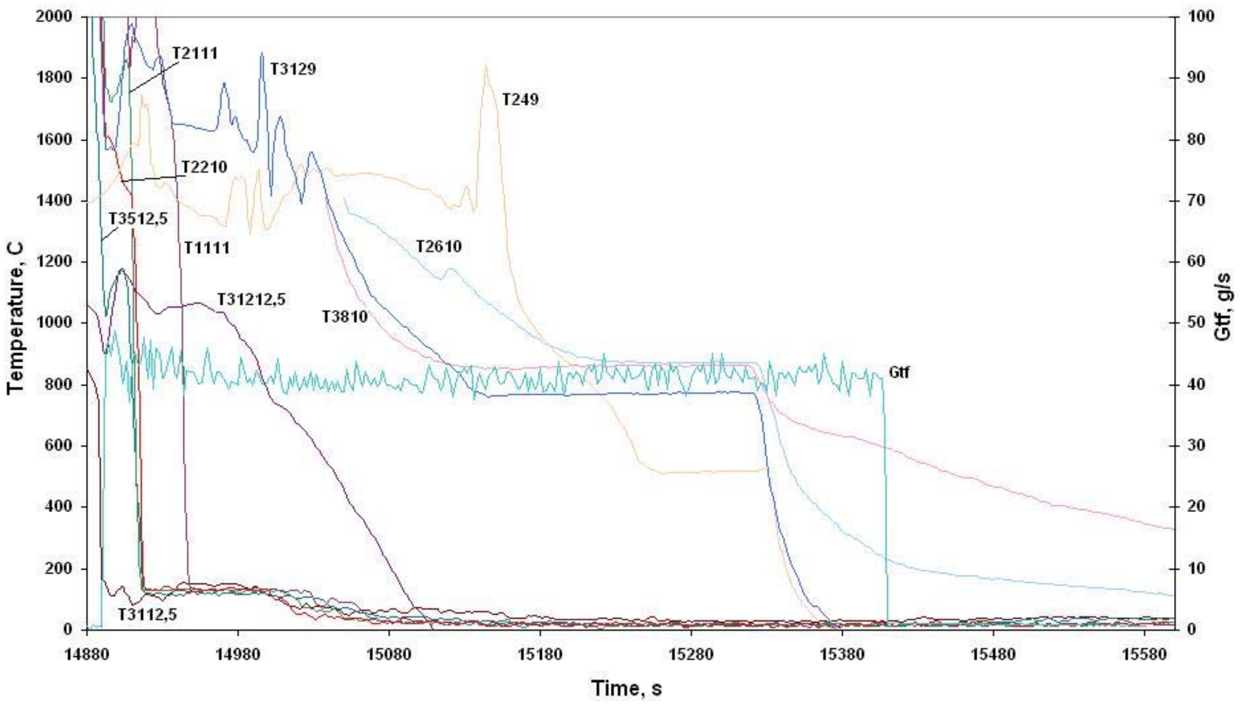


Fig. 13. Test section body temperature variation along the height (number in brackets corresponds to FA level).



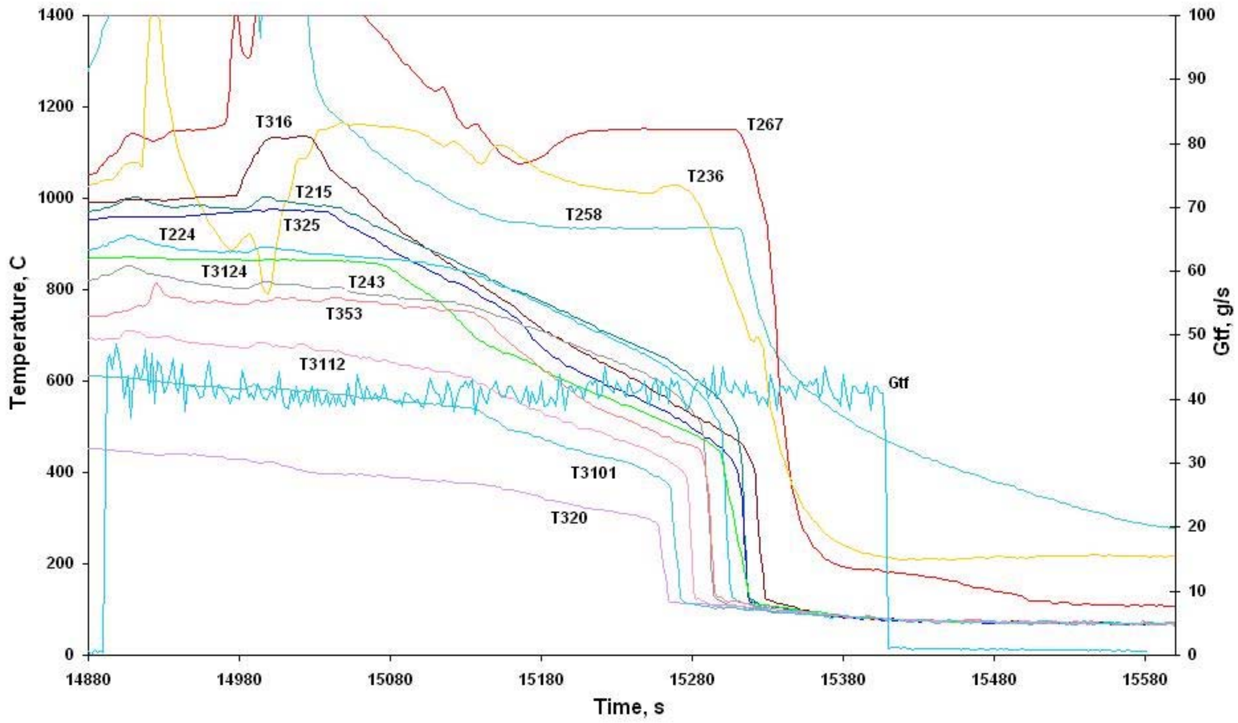
Temperature, C
Gtf, g/s
Time, s
T2513
T3713
T2514
T31014
T2215
T3715
T1114
Gtf

a)



Temperature, C
Gtf, g/s
Time, s
T2111
T3129
T249
T2210
T3512,5
T1111
T2610
T31212,5
T3810
Gtf
T3112,5

b)



c)

Fig. 14. Fuel rod cladding temperature variations along FA axis at the stage of top flooding:

a – in the top part at the level of 1300 – 1500 mm;
b – in the middle part at the level of 900 – 1250 mm;
c – in the lower part at the level of 0 – 800 mm.

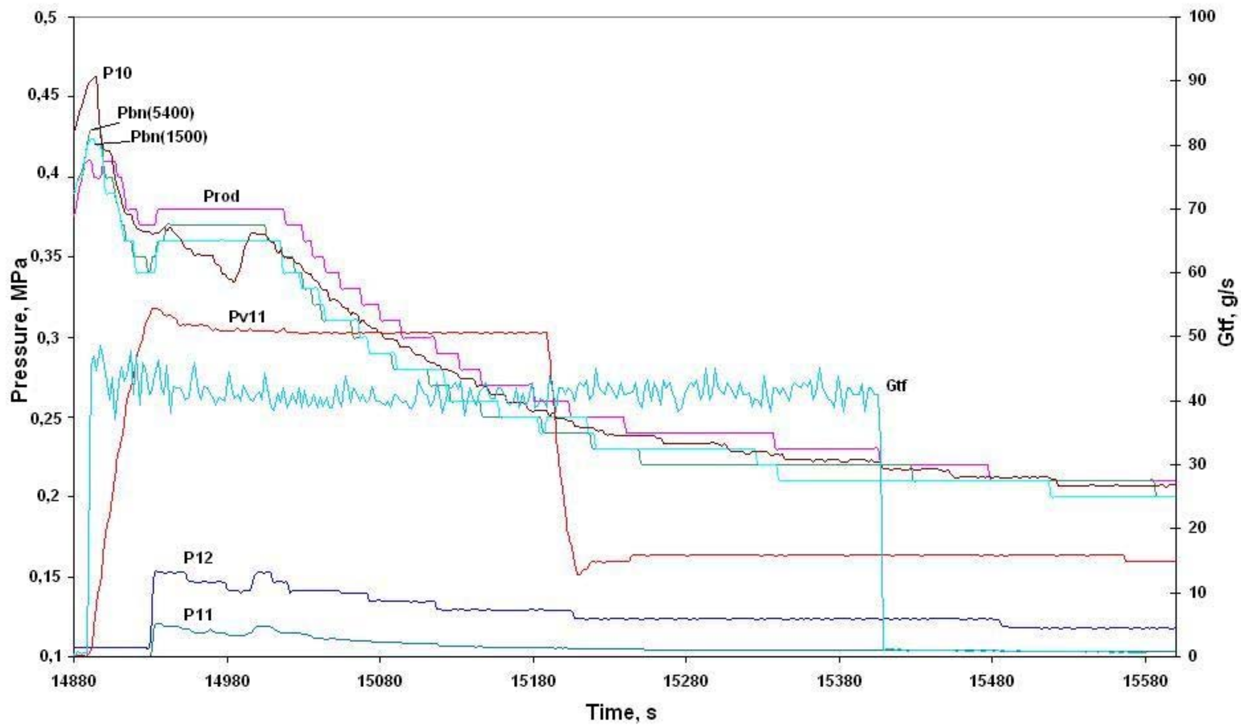


Fig. 15. Pressure variation in fuel rods (p_{rod}), model FA ($p_{(540)}$, $p_{(1500)}$), in gas duct of the rig (p10, p11, p12) and sampling tank Vol. 11 (pv11) at the stage of top flooding.

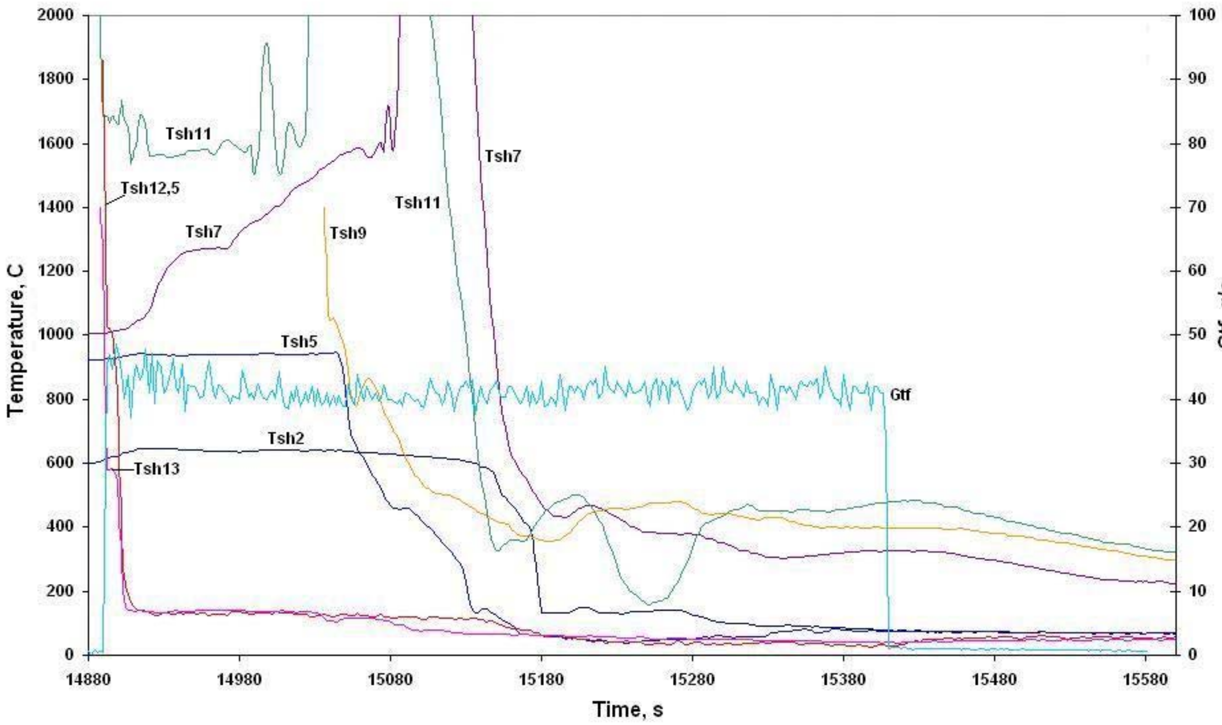


Fig. 16. Shroud temperature variation along FA axis at the stage of top flooding.

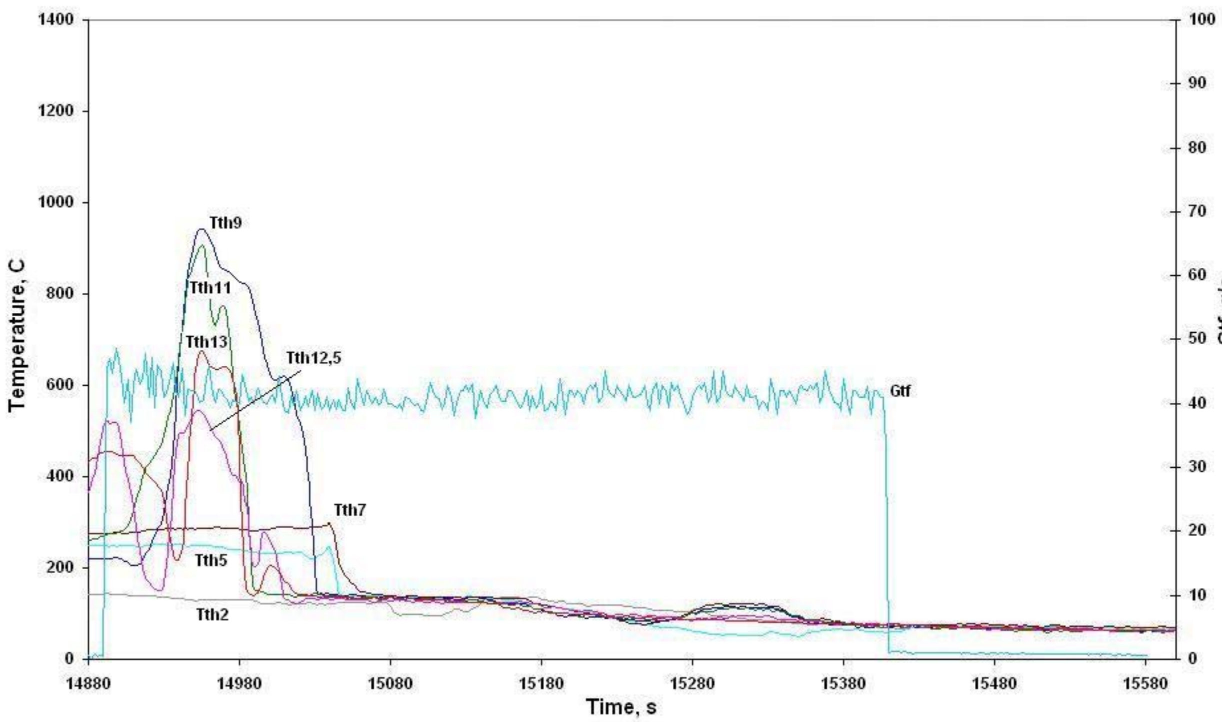


Fig. 17. Thermoinsulation temperature variation along FA axis at the stage of top flooding.

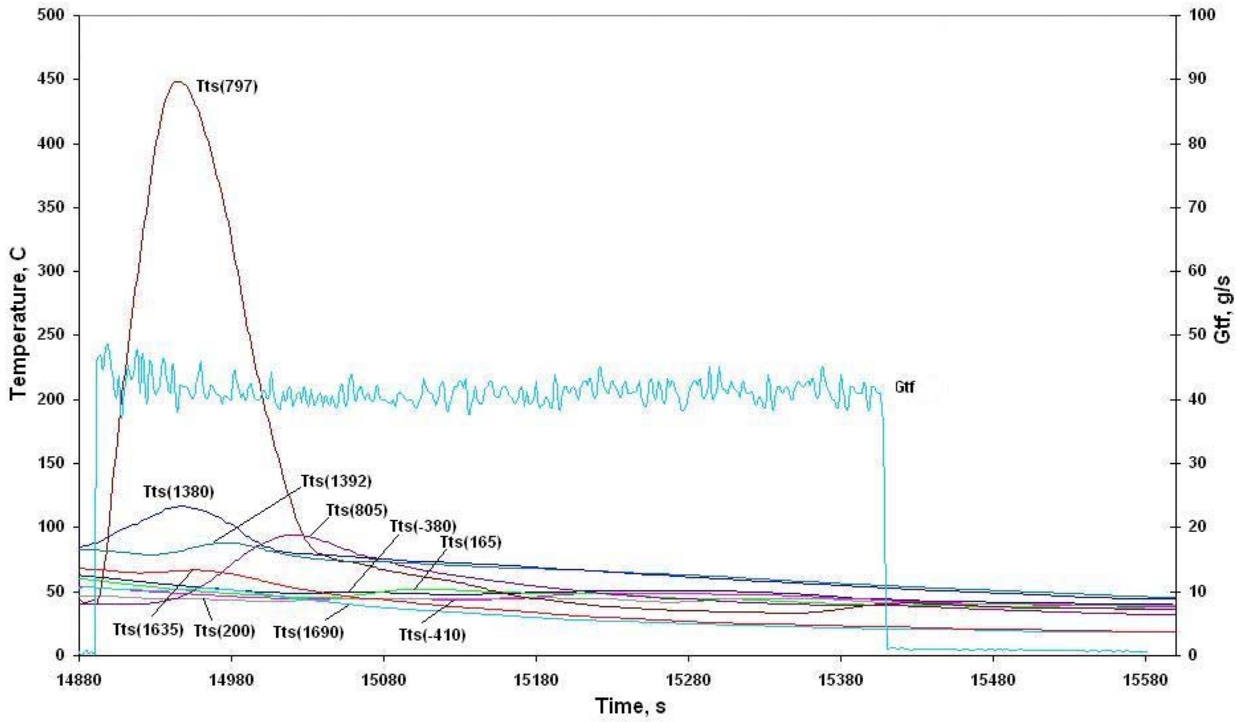


Fig. 18. Test section body temperature variations along the height at the stage of top flooding.

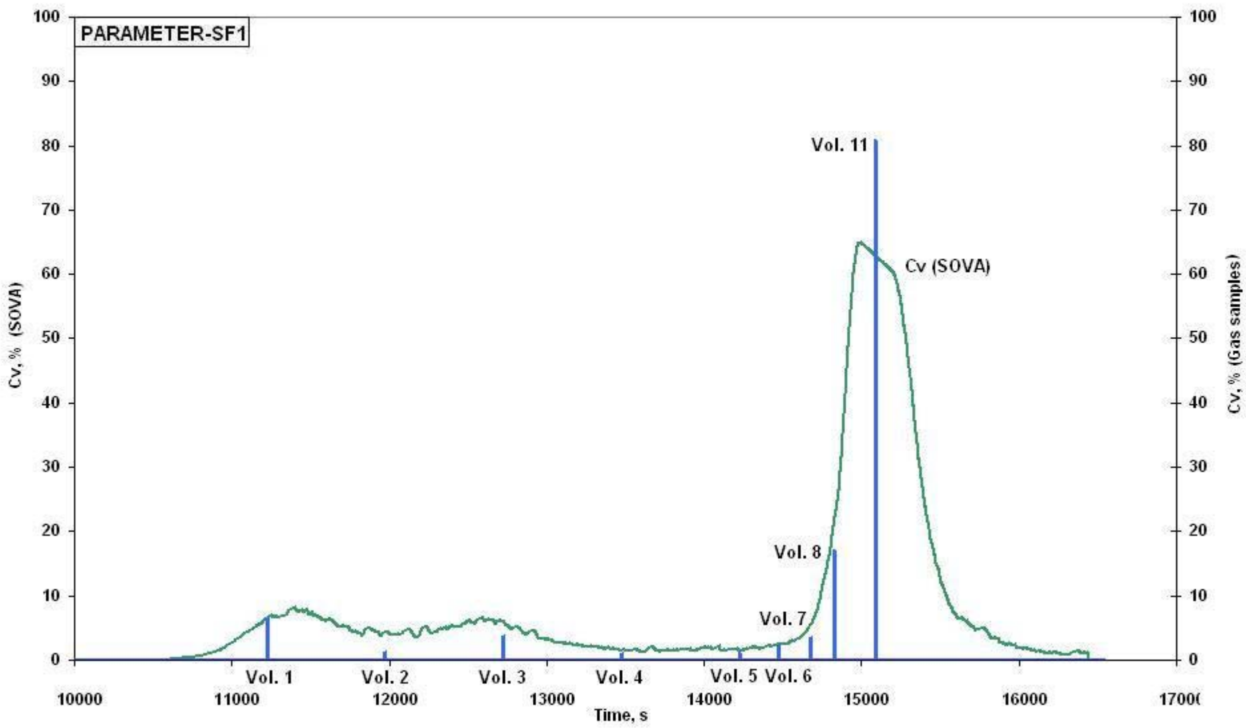


Fig. 19. Variation of volumetric hydrogen concentration versus time

(Vol1, …, Vol8 – gas sampling (duration 8 s), Vol11 - 115 s).

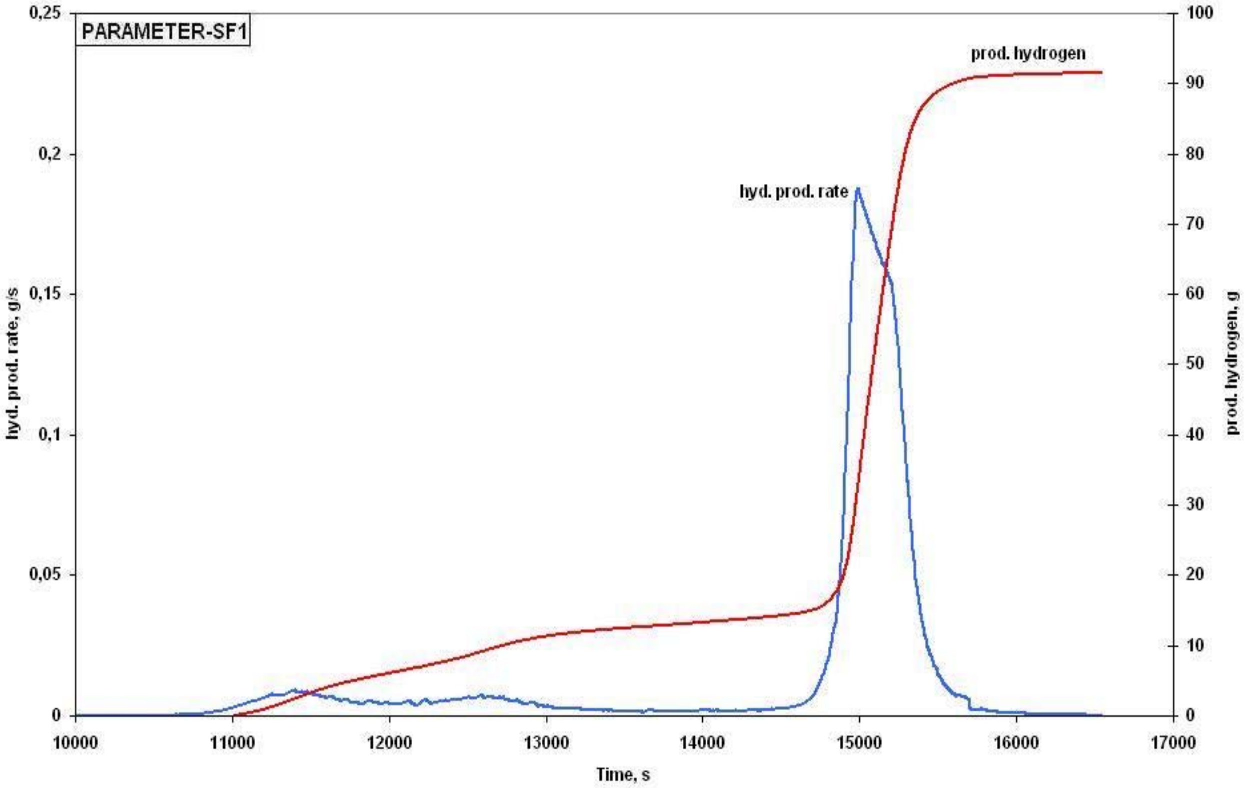


Fig. 20. Regeneration rate and mass of evolved hydrogen.

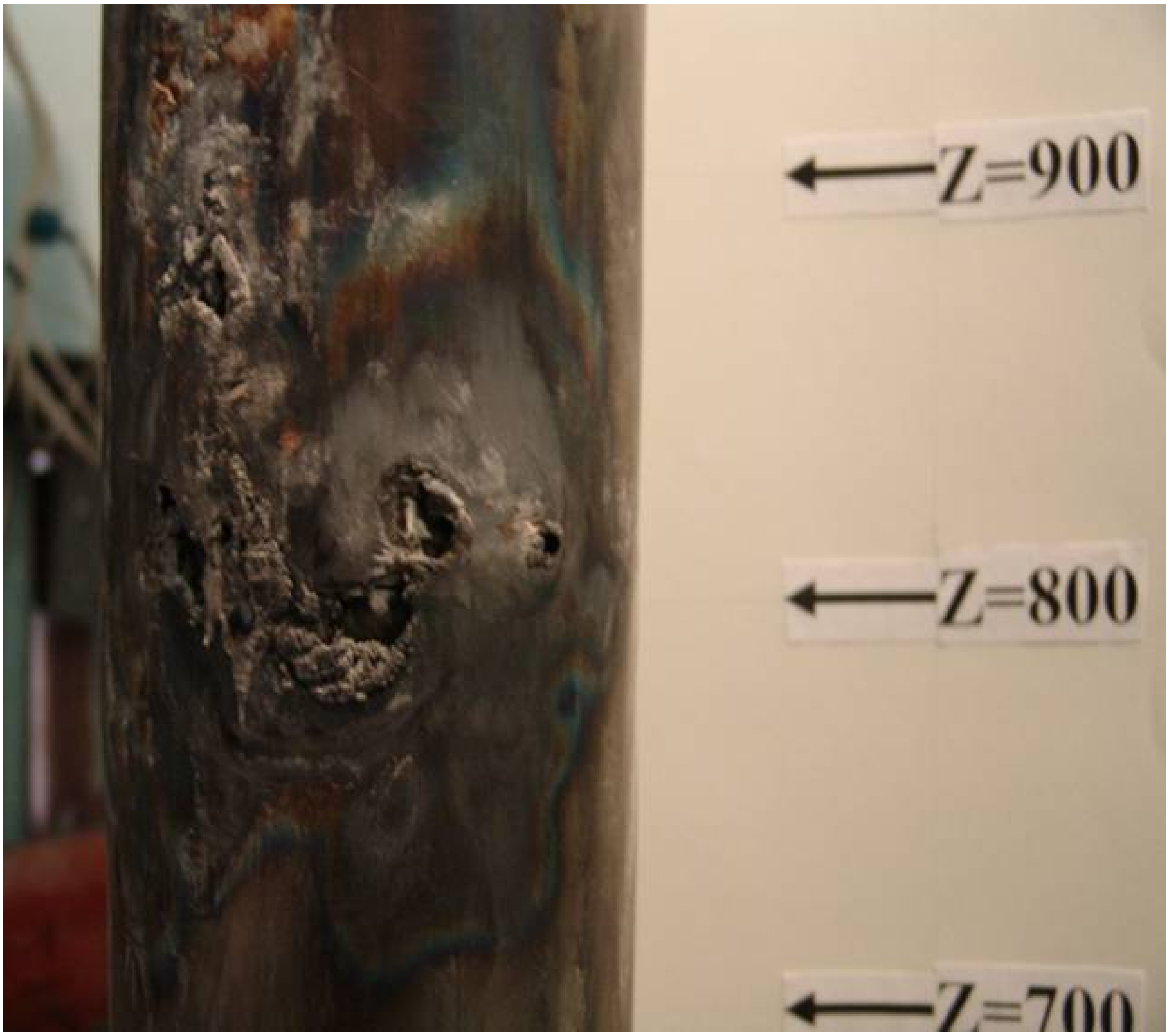


Fig. 21. View of thermoinsulation shroud on the outside at the level of 700 – 900 mm after the experiment.

Fig. 22. View of thermoinsulation shroud on the inside
at the level of 700-1300 mm.

Fig. 23. View of thermoinsulation with traces of melting
at the level of 700 – 1000 mm.

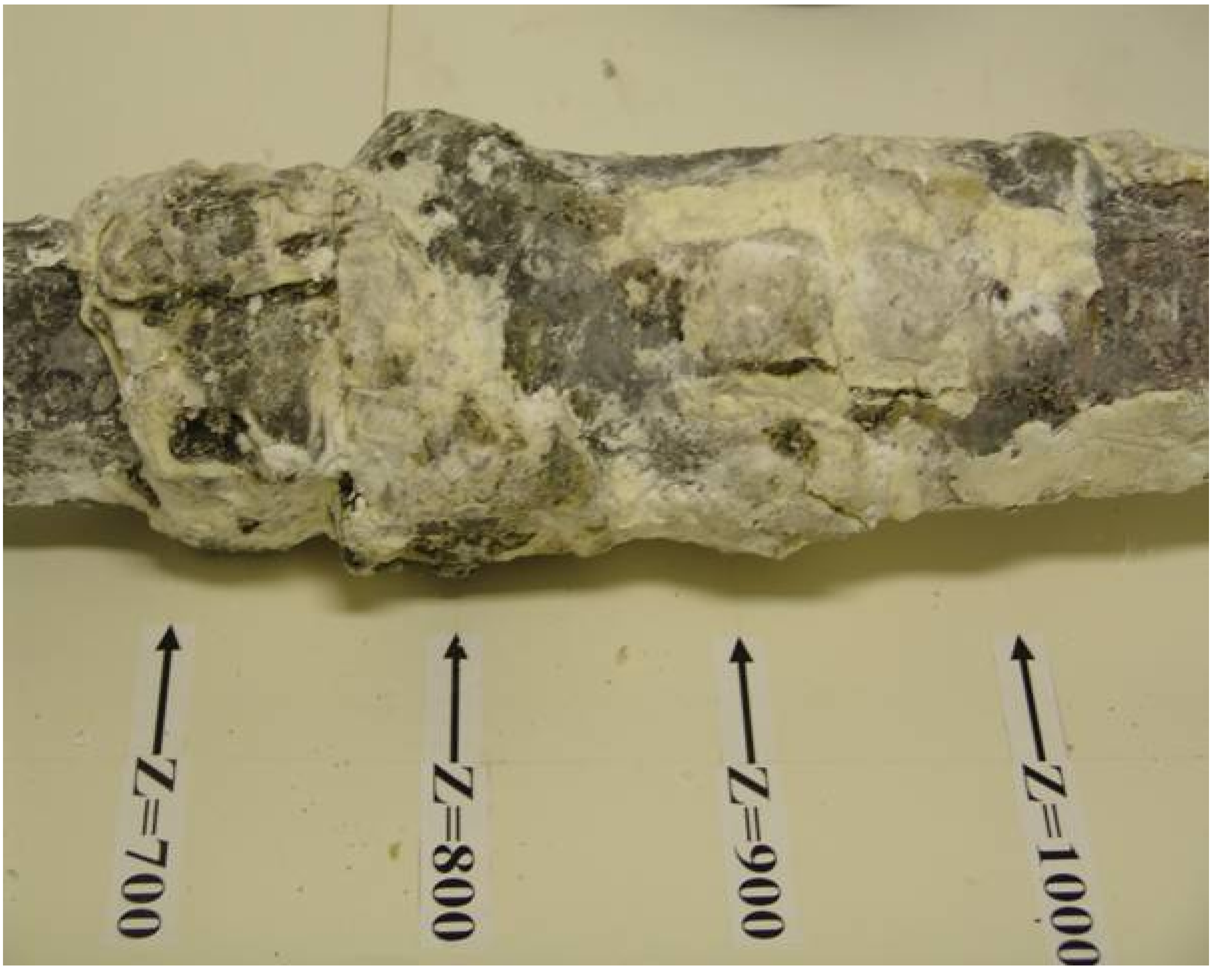
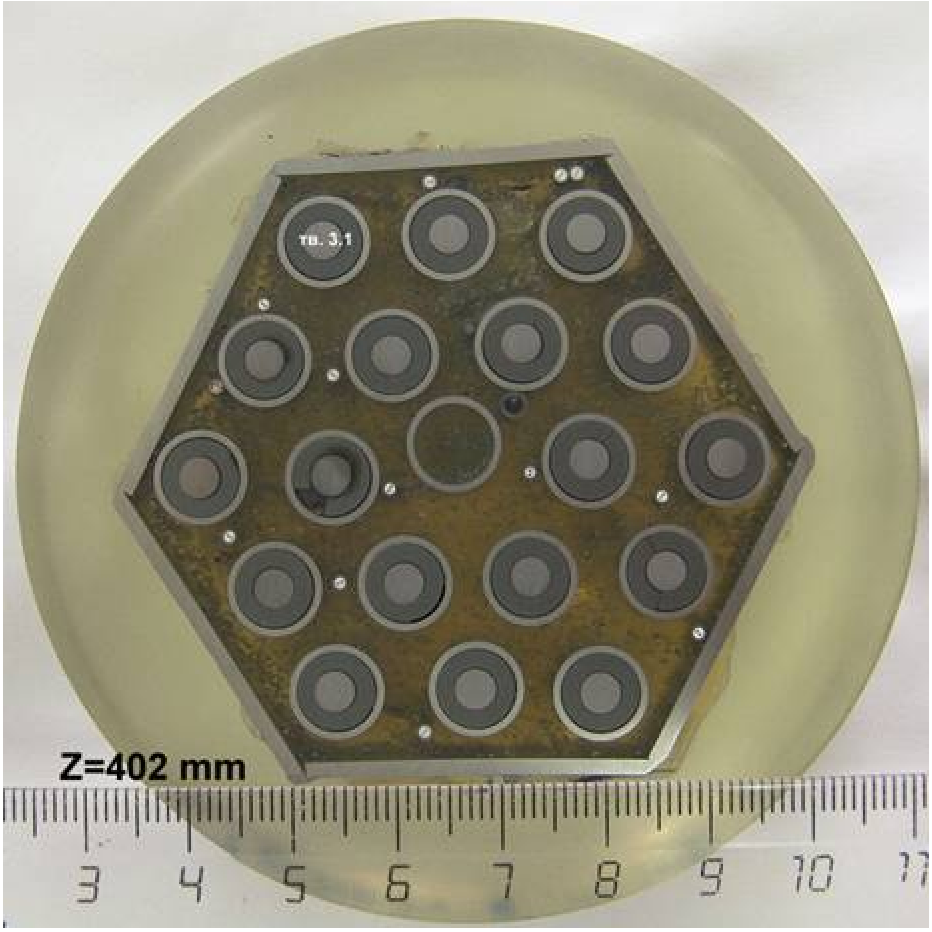
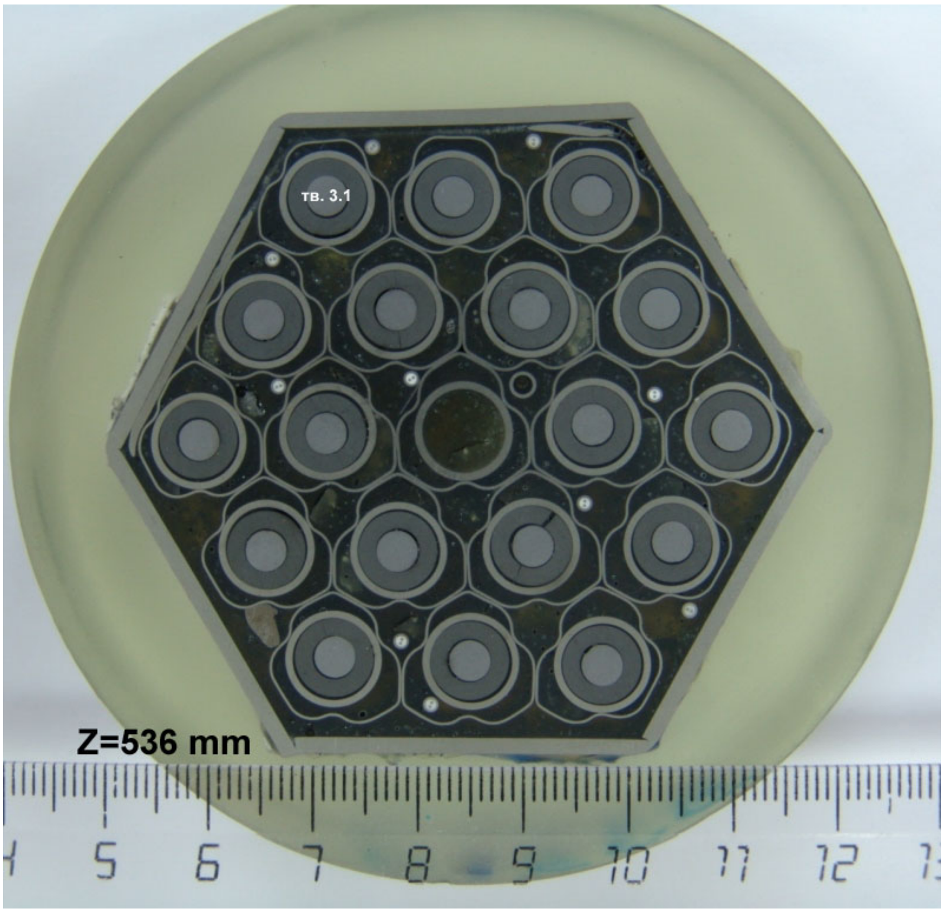
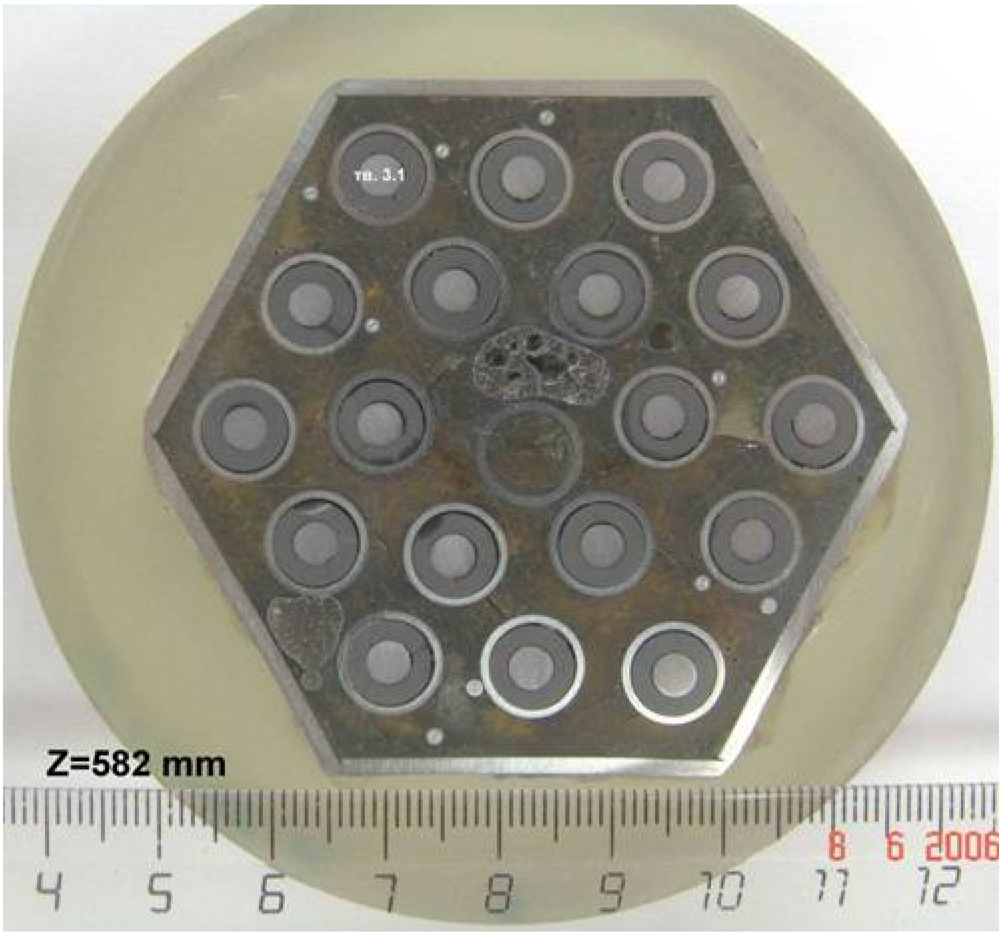
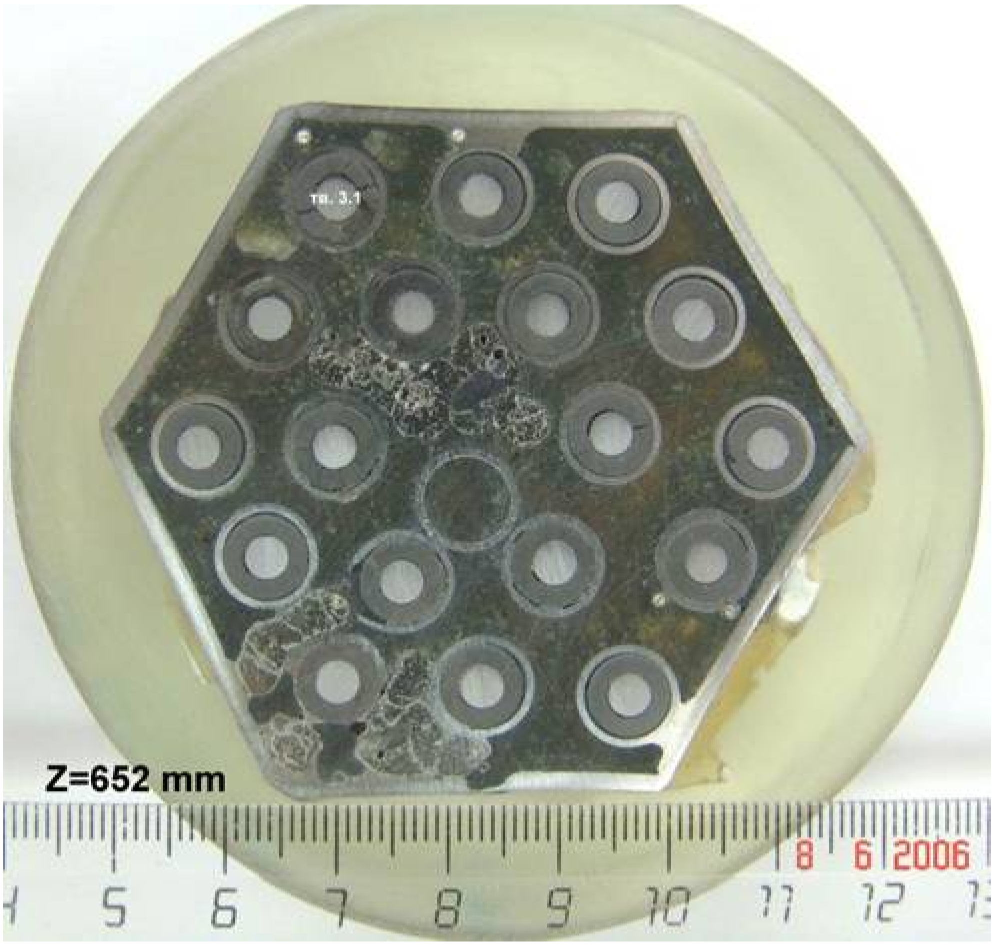


Fig. 24. Post-test view of the shroud
(level 700 – 1000 mm, 90^o – 120^o).


ТВ. 3.1
Z=402 mm
3
4
5
6
7
8
9
10


ТВ. 3.1
Z=536 mm
5
6
7
8
9
10
11
12


тв. 3.1
Z=582 mm
8 6 2006
4 5 6 7 8 9 10 11 12


тв. 3.1
Z=652 mm
8 6 2006
5 6 7 8 9 10 11 12


тв. 3.1
Z=679 mm
8 6 2006
4 5 6 7 8 9 10 11 12


тв. 3.1
Z=699 mm
4 5 6 7 8 9 10 11 12 13


тв. 3.1
Z=724 mm


тв. 3.1
Z=745 mm


тв. 3.1
Z=793 mm


тв. 3.1
Z=839 mm

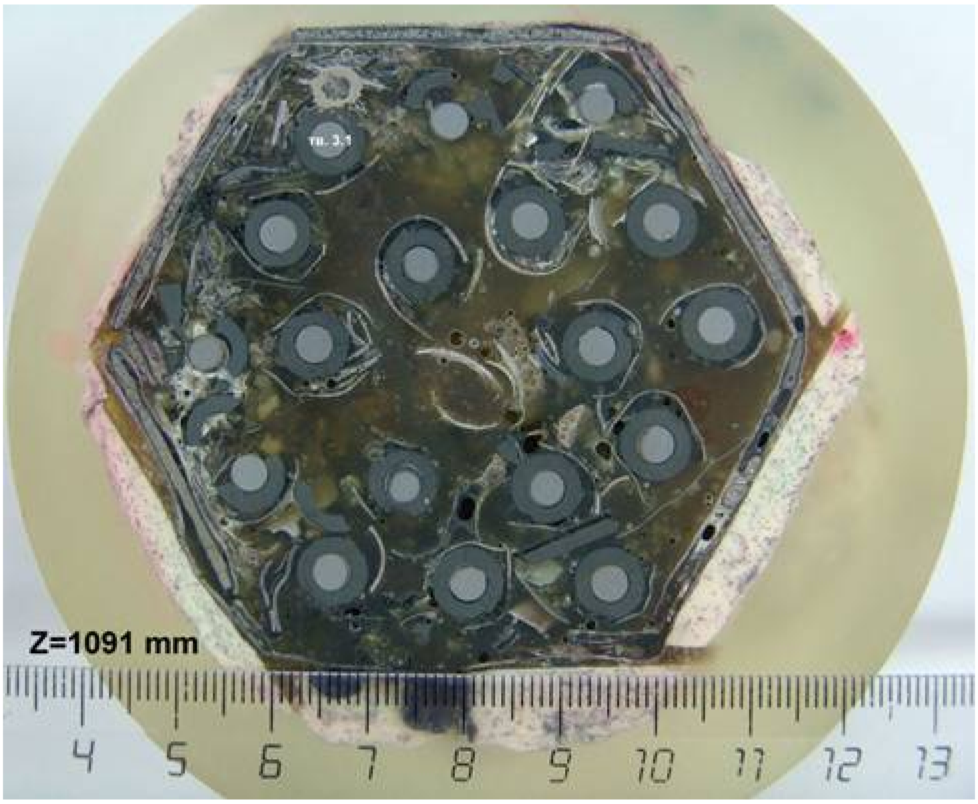

тв. 3.1
Z=886 mm
3
4
5
6
7
8
9
10
11
12
13

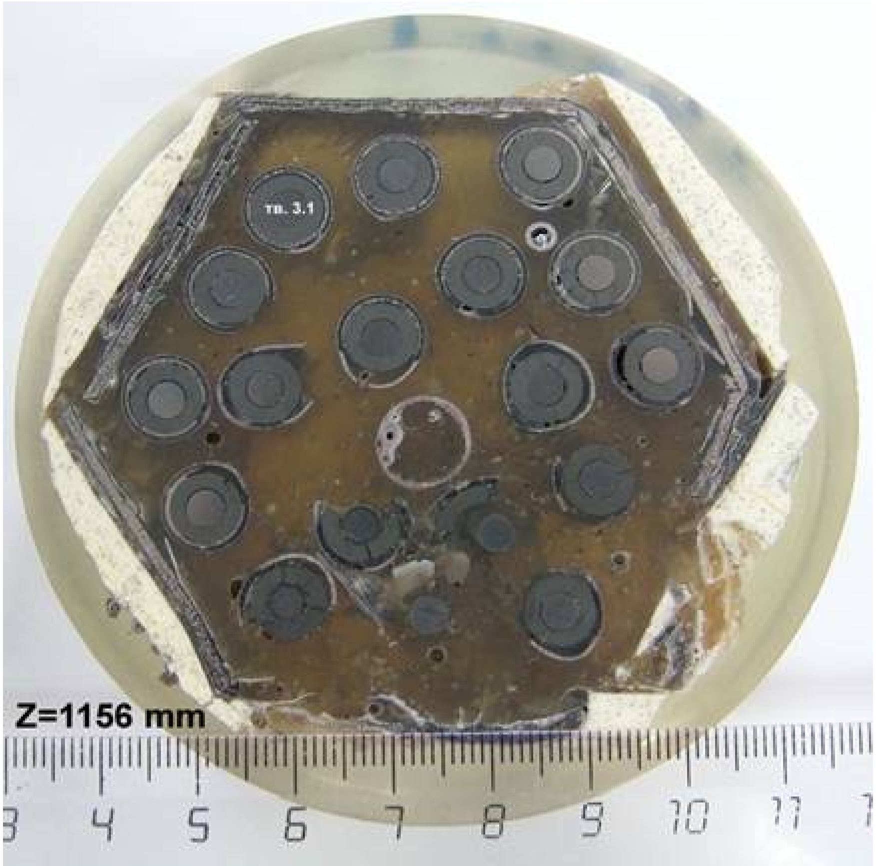

тв. 3.1
Z=930 mm
3
4
5
6
7
8
9
10
11
12
13


тв. 3.1
Z=976 mm
3 4 5 6 7 8 9 10 11 12


тв. 3.1
Z=1021 mm
3 4 5 6 7 8 9 10 11 12


тв. 3.1
Z=1066 mm
3
4
5
6
7
8
9
10
11
12


тв. 3.1
Z=1091 mm
4
5
6
7
8
9
10
11
12
13



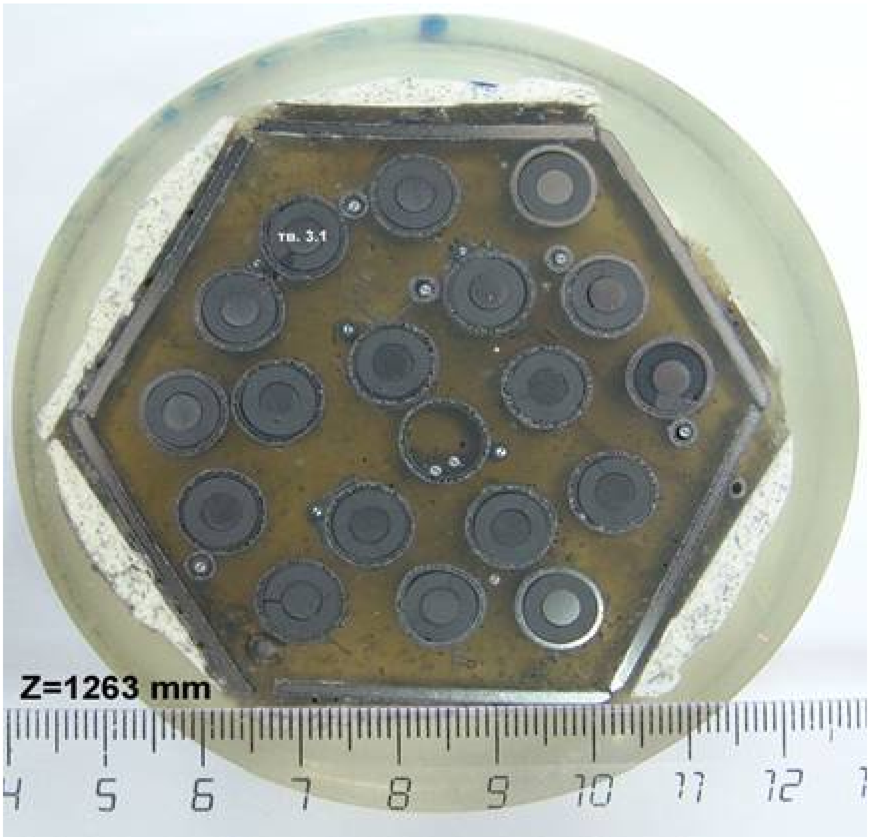


Fig. 25. Photos of cross-sections along fuel assembly axis ~ 400 – 1300 mm.