PROJECT # 3690

"Study of fuel assemblies under severe accident top quenching conditions in the PARAMETER-SF test series"

2008

НИИ НПО "ЛУЧ"

PROTOCOL

of PARAMETER-SF3 Experiment Results

INTRODUCTION

The PARAMETER-SF3 experiment was performed in the PARAMETER test facility of FSUE SRI SIA “LUCH” according to the Work Plan for ISTC Project #3690.

The PARAMETER-SF3 experiment was the first of the two experiments planned in the framework of Project #3690.

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 following top flooding.

The SF3 experiment was performed to study the behavior of a 19-rod model fuel assembly (FA) of VVER-1000 under simulated conditions of severe accident, including the phase of low-rate quenching from top, namely:

- Study of the behavior of the structural components of a 19-rods model VVER-1000 FA (fuel pellets and claddings, shroud, spacer grids);
- Study of the degree of oxidation of the structural components of a 19-rods model VVER-1000 FA;
- Study of the interaction and structural-phase changes in the materials of a model VVER-1000 FA (fuel pellets and claddings);
- Study of the hydrogen release.

EXPERIMENTAL FACILITY

The PARAMETER-SF3 experiment was carried out at the PARAMETER test facility using the following equipment (see Fig. 1):

- Test section with the model FA;
- The system of electric heating of the model FA and power supply of the test facility process systems;
- The system of steam generation and condensation;
- The system of the model FA top flooding;
- The system of argon and helium gas supply;
- The system of gas analysis;
- Information-and-measurement system.

The superheated steam from the steam generation system and heated carrier-gas (argon), used in the hydrogen measurement system, are supplied from bottom into the test section with the model FA. The steam not consumed, argon and hydrogen released in the oxidation reactions, enter the water-cooled condenser 1. Argon and hydrogen then leave the condenser 1 and enter the system of gas analysis and subsequently – ventilation.

The water supply of the steam generation is provided with Pump 1 from the Tank 1 (see Fig 1), its volume been 75 liters.

The top flooding is effected with an autonomous system which includes 27 l water Tank 7 under constant pressure p7, electric valve V3 and flow meter R3.

In the course of the experiment, the monitoring of parameters is carried out for steam ($G_{st\ in}$, $T_{st\ in}$) and argon ($G_{Ar\ in}$, $T_{Ar\ in}$) on the test section inlet, gas mixture flow rate (G_{Ar}(R4)) at the inlet to special ventilation, as well as the water mass inside the main supplying tank (M1, Tank 1) and top flooding tank (M7, Tank 7), mass of the steam condensate in the tanks (Tank 5, Tank 5', Tank 5.1, Tank 5.2, Tank 5.3, Tank 5.4, Tank 5.5), located downstream the condenser 1, and mass of the discharge water from the test section upper flange (Tank 6.1, Tank 6.2, Tank 6.3).

TEST SECTION

The test section (Fig. 2) consists of three parts: upper, middle and lower, connected with flange joints.

To carry out the PARAMETER-SF3 experiment, FSUE SRI SIA «LUCH» introduced the following alterations to the test section design: independent cooling of the upper and central parts of the test section.

1) The upper part (Fig. 3) is intended for:

- insertion and sealing of the fuel rods, thermocouples and tubes of top flooding system into the working volume;
- argon supply during bottom flooding;
- steam-gas mixture ejection from the test section into the heat exchanger-condenser;
- discharge of water ejected from the model assembly during top flooding and monitoring of its volume.

The upper part includes: the body – stainless steel tube ∅ 133x6 mm (1) with water cooling jacket ∅ 139x1 mm (2), the upper water-cooled flange (3) with the top flooding system including 42 tubes ∅ 4x1 mm (4), the guide tube (5), the screen (6), the cylinder (7), the nozzles of steam-gas mixture outlet (Dnom=26) (8), argon supply (Dnom =8) (9) during bottom flooding, water discharge (Dnom =8) (10), ejected from the model assembly during top flooding, and the lower connecting water-cooled flange (11).

2) The middle part (Fig. 4) is intended for:

- location of the test model assembly, thermoinsulation and test parameter monitoring system;
- hermetization of the cavity of thermoinsulation;
- compensation of the shroud temperature linear expansions.

The middle part includes: the body – stainless steel tube ∅ 133x6 mm (1) with the water cooling jacket ∅ 139x1 mm (2) and the upper (3) and lower (4) connecting flanges, the model assembly (5), the cylindrical zirconium shroud (6) ∅ 69.7x1.2 mm of the model FA, thermoinsulation (7), upper (8) and lower (9) sectioning membranes, compensating bellows (10), the thermoinsulation shroud (11), the nozzles (12) of argon inlet and outlet from the thermoinsulation cavity.

3) The lower part (Fig. 5) is intended for:

- separate supply of steam and argon into the working volume of the model assembly;
- water supply into the test section during bottom flooding;

- heating-up of cold walls of the body lower part to the steam saturation temperature in order to diminish condensation of the supplied steam in the lower part of the test section.

The lower part includes: the body (1) – two stainless steel tubes: ∅ 156x6x690 mm, ∅ 203x3x210 mm with the heater (2), nozzles of steam (3) and argon (4) supply (Dnom = 8 mm), water inlet nozzles for water pre-injection (5) and main (6) bottom flooding (2 nozzles Dnom = 25 mm), upper connection flange (7) and lower water-cooled flange (8) for insertion of current leads, thermocouples and for water discharge. The temperature of the environment in the lower part of the test section and the body is monitored with 9 thermocouples (TC): 5 TC – environment temperature monitoring, 4 TC – body temperature monitoring.

MODEL FA

The main design parameters of the model FA are presented in Table 1.

Table 1

Main design parameters of the model FA

Fuel rod simulators and model FA	
Number of fuel rods heated	18
Number of fuel rods unheated	1
FA 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 geometry, mm:	
diameter/length	4/1275
location	0 to 1275
Location of steam/argon inlet (radial), mm	-372 ($270^o/90^o$)
Location of steam/argon outlet (radial), mm	1425 (0^o)
Inside pressure of gas (helium) in fuel rods, MPa	0.24
Fuel pellets	
Fuel rods heated outer diameter/central hole diameter/height, mm	UO_2 pellets with holes $7.6^{-0.03}/4.2^{+0.15}/11^{\pm0.1}$
Fuel rod unheated outer diameter/central hole diameter/height, mm	UO_2 pellets with holes $7.6^{-0.03}/4.2^{+0.15}/11^{\pm0.1}$
Spacer grid	
Material	Zr-1%Nb
Height, mm	20
Number, pcs.	6
Interval 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

Dimensions: diameter/wall thickness, mm	69.7/1/2
Length, mm	1450
Thermoinsulation	
Material	ZrO_2 ZYFB-3
Thickness, mm	23
Length, mm	1450
Thermoinsulation shroud	
Material	Steel 12X18H10T
Thickness, mm	1
Length, mm	1450
Outer diameter/thickness, mm	118/1

The scheme, general view and cross section of the model bundle are presented in Fig. 6 and 2, general view of the heated and unheated fuel rod simulators – in Fig. 7.

The length of fuel column (pellets) inside unheated fuel rod simulator is 2200 mm from elevation Z = -200 mm. The lower part of the fuel rod from elevation Z = -200 mm is filled with Al_2O_3 ceramic tube ∅ 8x5 mm.

All fuel rod simulators (the central, unheated fuel rod excluded) are assembled into one heating section.

The upper part of the model bundle houses the water injection system (see Fig. 2, 3), which consists of 42 pipes ∅ 4x1 mm in the test section upper flange, the guiding channel and the collecting cylinder.

The upper part of every fuel rod in the bundle is equipped with the helium filling device including a ∅ 1.6x0.3 mm capillary ~1500 mm long. All the capillaries are connected to the common compensation tank, its volume been ~ 1.5 L.

TEMPERATURE MEASUREMENT SYSTEM

List of instrumentation is presented in Table 2.

Table 2

List of instrumentation

No.	Designation	Type	Measured data and instrument location	Output signal
1	**$T_{st\ in}$**	Ch/Al	Steam temperature at the inlet, steam inlet nozzle, - 372 mm, 270°	°C
2	**$T_{Ar\ in}$**	Ch/Al	Argon temperature at the inlet, argon inlet nozzle, - 372 mm, 90°	°C
3	**T11-6**	Ch/Al	Fuel rod 1.1 cladding temperature, -600 mm	°C
4	**T11-5.5**	Ch/Al	Fuel rod 1.1 cladding temperature, -550 mm	°C
5	**T11-4.5**	Ch/Al	Fuel rod 1.1 cladding temperature, -450 mm	°C
6	**T24-3**	Ch/Al	Fuel rod 2.4 cladding temperature, -300 mm	°C
7	**T25-1.5**	Ch/Al	Fuel rod 2.5 cladding temperature, -150 mm	°C

8	**T32-0.5**	Ch/Al	Fuel rod 3.2 cladding temperature, -50 mm	°C
9	**T260**	Ch/Al	Fuel rod 2.6 cladding temperature, 0 mm	°C
10	**T221**	Ch/Al	Fuel rod 2.2 cladding temperature, 100 mm	°C
11	**T3101**	Ch/Al	Fuel rod 3.10 cladding temperature, 100 mm	°C
12	**T212**	Ch/Al	Fuel rod 2.1 cladding temperature, 200 mm	°C
13	**T352**	Ch/Al	Fuel rod 3.5 cladding temperature, 200 mm	°C
14	**T253**	Ch/Al	Fuel rod 2.5 cladding temperature, 300 mm	°C
15	**T363**	Ch/Al	Fuel rod 3.6 cladding temperature, 300 mm	°C
16	**T314**	Ch/Al	Fuel rod 3.1 cladding temperature, 400 mm	°C
17	**T394**	Ch/Al	Fuel rod 3.9 cladding temperature, 400 mm	°C
18	**T235**	Ch/Al	Fuel rod 2.3 cladding temperature, 500 mm	°C
19	**T311'5**	Ch/Al	Fuel rod 3.11 cladding temperature, 500 mm	°C
20	**T376**	Ch/Al	Fuel rod 3.7 cladding temperature, 600 mm	°C
21	**T227**	Ch/Al	Fuel rod 2.2 cladding temperature, 700 mm	°C
22	**T3127**	Ch/Al	Fuel rod 3.12 cladding temperature, 700 mm	°C
23	**T_{sh}7**	WRe	Shroud temperature (opposite fuel rod 3.2), 700 mm	°C
24	**T_{th}7**	Ch/Cop	Thermoinsulation temperature (opposite fuel rod 3.2), 700 mm	°C
25	**T118**	WRe	Fuel rod 1.1 temperature, center line, 800 mm	°C
26	**T248п**	WRe	Fuel rod 2.4 cladding temperature, 800 mm	°C
27	**T248**	Ch/Al	Fuel rod 2.4 cladding temperature, 800 mm	°C
28	**T239**	WRe	Fuel rod 2.3 cladding temperature, 900 mm	°C
29	**T399**	WRe	Fuel rod 3.9 cladding temperature, 900 mm	°C
30	**P10**	-	Pressure sensor near fuel rod 3.2, 1000 mm	MPa
31	**T_{sh}9**	WRe	Shroud temperature (opposite fuel rod 3.8), 900 mm	°C
32	**T_{th}9**	Ch/Cop	Thermoinsulation temperature (opposite rod 3.8), 900 mm	°C
33	**T2110**	WRe	Fuel rod 2.1 cladding temperature, 1000 mm	°C
34	**T3310**	WRe	Fuel rod 3.3 cladding temperature, 1000 mm	°C
35	**T3810**	WRe	Fuel rod 3.8 cladding temperature, 1000 mm	°C
36	**T2611**	WRe	Fuel rod 2.6 cladding temperature, 1100 mm	°C
37	**T3411**	WRe	Fuel rod 3.4 cladding temperature, 1100 mm	°C
38	**T3711**	WRe	Fuel rod 3.7 cladding temperature, 1100 mm	°C
39	**T_{sh}11**	WRe	Shroud temperature (opposite fuel rod 3.1), 1100 mm	°C
40	**T_{th}11**	Ch/Cop	Thermoinsulation temperature (opposite fuel rod 3.1), 1100 mm	°C
41	**T1112.5**	WRe	Fuel rod 1.1 temperature, center line, 1250 mm	°C
42	**T2212.5**	WRe	Fuel rod 2.2 cladding temperature, 1250 mm	°C
43	**T3612.5**	WRe	Fuel rod 3.6 cladding temperature, 1250 mm	°C
44	**T31012.5**	WRe	Fuel rod 3.10 cladding temperature, 1250 mm	°C
45	**p12.5**	-	Pressure sensor near fuel rod 3.7, 1250 mm	MPa
46	**T2513**	WRe	Fuel rod 2.5 cladding temperature, 1300 mm	°C
47	**T3213**	WRe	Fuel rod 3.2 cladding temperature, 1300 mm	°C

48	**T3513**	WRe	Fuel rod 3.5 cladding temperature, 1300 mm	^{o}C
49	**T_{sh}13**	WRe	Shroud temperature (opposite fuel rod 3.6), 1300 mm	^{o}C
50	**T_{th}13**	Ch/Cop	Thermoinsulation temperature (opposite fuel rod 3.6), 1300 mm	^{o}C
51	**T1114B**	WRe	Fuel rod 1.1 temperature, center line, 1400 mm	^{o}C
52	**T1114**	WRe	Fuel rod 1.1 cladding temperature, 1400 mm	^{o}C
53	**T31114**	WRe	Fuel rod 3.11 cladding temperature, 1400 mm	^{o}C
54	**T31'15**	WRe	Fuel rod 3.1 cladding temperature, 1500 mm	^{o}C
55	**p15**	-	Pressure sensor near fuel rod 3.10, 1500 mm	MPa
56	**$T_{st\ out}$**	WRe	Steam temperature at the outlet, steam outlet nozzle, 1425 mm, 0^{o}	^{o}C

The system of measurement includes 39 TCs for measuring the fuel rod cladding temperature at 22 elevations: from -600 to +1500 mm (with 100 mm interval along heated zone); 3 TCs for measuring fuel rod 1.1 temperature, center line; 8 TCs for measuring the shroud and thermoinsulation temperature at 4 elevations (700; 900; 1100 and 1300 mm) and 3 TC for measuring the temperature of steam and argon at the inlet and outlet.

Three TC types were used in the temperature measurement system (see Fig. 8): cable Ch/Al (Ch/Cop) encased into ∅ 1.5 mm stainless steel sheath, with temperature upper limit of effective range to be 1300°C (800°C) and high-temperature WRe thermocouples with W+5%Re/W+20%Re wire encased into ∅ 2.8x0.7 mm zirconium alloy Zr+1%Nb sheath with temperature upper limit of effective range to be 2000^{o}C.

The TCs for cladding temperature measurement were mounted coaxially to the fuel rods on the fuel rods cladding surfaces with ~ 5 mm wide and 0.3 mm thick zirconium band using electrocontact welding. Additionally, the TCs were fastened with Ir wire with diameter 0.3 mm.

The steam-argon mixture pressure was monitored with three pressure sensors at elevations Z = 1000 mm (p10); 1250 mm (p12.5) and 1500 mm (p15). Pressure sampling from the bundle was performed with ∅ 2.8x0.7 mm zirconium alloy Zr+1%Nb tubes. Helium pressure in the fuel rods was monitored with pressure sensor in the compensatory tank (p_{rod}).

PROCESS PARAMETER MONITORING

Collection and storing of the test and facility parameters is carried out with ASNI bench system based on two PC PENTIUM-II program PARAM_19, developed on the basis of package GENIE 3.0, with scanning frequency 2 s.

The bundle electric power is set up with DC generator “Flex Kraft” 2500 A/15 V and is defined according to the instantaneous current $I(\tau)$ and voltage $U(\tau)$, measured with ADP ЛА-1,5PCI PC PENTIUM-II (reading frequency 0.01s) and integrated using Power5V electric power calculating program.

Steam flow rate $G_{st\ in}$ is set up by the water consumption of the steam generation system (Pump 1) and monitored by the volume of water in the Tank 1, steam generator parameters ($N_{el.sg}$, T_{sg}, p_{sg}) and steam parameters upstream and downstream flow meter (T1, p1, T2, p2).

Argon flow rate $G_{Ar\ in}$ is set up by the argon pressure at the gas outlet manifold and is monitored by argon parameters (T3, p3).

The top flooding water flow rate is set up by pressure p7 in Tank 7 and is monitored by water volume in Tank 7 and readings of electronic flowmeter R3.

Water flow rate in cooling jacket of the upper part of the test section is set up by Pump 2, water heating is monitored with thermocouples $T_{cool\ in}3$, $T_{cool\ out}3$ (Fig. 3).

Water flow rate in cooling jacket of the middle part of the test section is set up by Pump 5, water heating is monitored with thermocouples $T_{cool\ in}1$, $T_{cool\ out}1$ (Fig. 4).

The mass of steam condensate after condensing in the condenser 1 is monitored: at the preparatory stage (steam and argon parameters stabilization stage) in Tank 5’ and Tank 6.1., at the stage of bundle heating up to 1470 K, during pre-oxidation and at the temperature phase – in Tank 5.1,…, Tank 5.5, Tank 6.2, at the quenching phase – in Tank 6.3.

Water mass monitoring is carried out after the experiment by weighing with electronic scales ПВ-6 with precision ±0.5 g.

HYDROGEN MEASUREMENT SYSTEM

The system for measuring hydrogen generated in high temperature reaction between steam and the model bundle materials is similar to that used in the experiments SF1 and SF2.

The hydrogen measurement system is located in a bypass to the off-gas line downstream the condenser 1 after the gas mixture parameter control point T10, p10 (Fig. 1). The system operation is based on two measurement techniques: continuous and discrete.

For continuous hydrogen analysis the hydrogen detection system SOV-3 was used. It was developed by SRC RF - IPPE for automatic monitoring of hydrogen content within the containment in NPP. The system operates on conductometric principle and is selective as regards to hydrogen. As the mixture analyzed goes through the sensor cavity, the hydrogen is absorbed by the sensing element made of palladium-silver alloy, increasing its electric resistance until the equilibrium, corresponding to the hydrogen bulk concentration in the gas mixture, is reached. The change of electric resistance of the sensitive element is converted into continuous electric signal displayed on a computer.

Main design parameters of SOV-3:

- gas mixture:
  - carrier gas – argon;
  - monitored gas – hydrogen;
- pressure of gas mixture – 0.15 – 0.35 MPa;
- flow rate of gas mixture – (8 – 25)$\cdot 10^{-5}$ m^3/min;
- measurement range - 5$\cdot 10^{-4}$ – 80% vol.;
- transition time within the concentration range:
  - 5$\cdot 10^{-4}$ – 1$\cdot 10^{-1}$ % vol. ~ 2 min;
  - ≥1$\cdot 10^{-1}$ % vol. – 1 min.

Provided the valve F11 open, the location of SOV-3 hydrogen measurement system in the auxiliary gas conduit enables to monitor the variation of hydrogen concentration throughout the entire experiment.

For discrete hydrogen concentration measurement 10 sampling tanks with volume of 2 liters each (№1, №2,…, №10) are used. Prior the experiment, the tanks are washed with ultra-pure argon and then evacuated. Sampling is carried out using electric valves (V8,…, V17), controlled remotely with the automatic sampling system with preset sampling period and duration. The sampling time is registered by the system gathering the data from the facility.

After the experiment the tanks are evacuated and separated from the gas pipe for the gas mixture analysis using gas chromatograph CHROMATECH-CRYSTAL 5000. The obtained results are synchronized in time with the indications of the continuous control system SOV-3.

PARAMETER-SF3 EXPERIMENT

Experiment scenario

PARAMETER-SF3 experiment was conducted at the PARAMETER test facility of FSUE SRI SIA “LUCH” under computational support by SOCRAT, PARAM-TG, RELAP/SCDAP/SIM MOD3.2, ATHLET-CD, SCDAP/RELAP/IRS codes. The pre-test scenario of the experiment is presented in Table 3.

Table 3

Pre-test scenario of PARAMETER-SF3 experiment

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 at temperature 720 K (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 at inlet - 2/3.5 g/s at temperature 720/770 K)	–	1500-3500
3	FA heating up to 1470 K	770→1470	Steam-argon mixture (argon/ steam flow rate at inlet - 2/3.5 g/s at temperature 720/770 K)	0.25 (initial), 0.1 (final)	3500-7500
4	FA pre-oxidation	~1470	Steam-argon mixture (argon/ steam flow rate at inlet - 2/3.5 g/s at temperature 720/770 K)	–	7500-11500
5	Transient phase	1470→1870	Steam-argon mixture (argon/ steam flow at inlet - 2/3.5 g/s at temperature 720/770 K)	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 ~300 K	–	As soon as saturation temperature will be reached

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

Table 4

PARAMETER-SF3 experiment main events

Current time, s	Events
0	The information and measurement system on
~ 1400	Start of argon supply to the bundle, flow rate ~ 2 g/s with temperature ~ 420°C
~ 2850	Start of steam supply to the bundle, flow ~ 3.5 g/s with temperature ~ 500°C
~ 4500	Heating-up of the bundle to temperature 500±50°C over 300-1300 mm
4506	Beginning of the bundle slow heating-up
9760	Beginning of pre-oxidation phase
13725	Beginning of the bundle heating-up to temperature 1600°C
14470	Shutting of the valve of steam supplied to the bundle
14481	Electric power off
14486	Opening of the top flooding valve
14960	Shutting of the top flooding valve
15064	The information and measurement system off

Experiment conduct

The PARAMETER-SF3 experiment was initiated after checking that the valves were in right positions, and the supply of argon, helium and distilled water was sufficient for carrying out the experiment.

The experiment consisted of five stages:

- *preparatory* (0 – 4506 s) – stabilization of the designed flow rates of argon ($G_{Ar\ in} \approx$ 2 g/s) and steam ($G_{st\ in} \approx$ 3,5 g/s) at FA temperature $T_{FA} \approx 500^oC$, the bundle and technological system check;

- *assembly heating-up to temperature ≈ 1200°C* (4506 – 9760 s);

- *pre-oxidation* (9760 – 13725 s) – FA exposure at temperature ≈ 1200°C (in its hottest spot) for ~ 3970 s. Maximum temperature deviation at the hottest elevation (1250 mm) ~ ± 50°C;

- *transient* (13725 – 14481 s) – bundle temperature increasing to 1600°C in the hottest section;

- *flooding* (14486 – 14960 s) – top flooding of the bundle with water, water flow rate Gtf ≈ 40 g/s.

Preparatory stage

At 0 s the information and measurement system and hydrogen measurement system SOV-3 were turned on, valves V6, V23 were shut, valves V7, V21, V22, V25, V26 V27, V28 were turned on.

At 200 s the argon pre-heater (heater 1) and valves V20 and V2 were turned on, argon flow rate $G_{Ar\ in}$ was set to be ≈ 2.0 g/s at the inlet (Fig. 10).

At 229 s heating-up of the model bundle with argon flow was initiated, electric power ~2000 W was supplied to the bundle (Fig. 11).

At 524 s the heater of the test section lower part was turned on.

At 580 s the main argon heater (heater 2) was turned on for argon heating to designed temperature $T_{Ar\ in} \approx 400^oC$.

At 690 s the thermoinsulation cavity was filled with argon by opening valve V5 in order to set up the specified pressure.

At ~ 1028 s the electronic rotameter R4 at the inlet to the special ventlation showed the gas flow rate ≈ 2 g/s (Fig. 10), which indicated that the test section and technological pipes being filled with argon.

At 1388 s the thermocouple fixed on the body (Fig. 5) had indicated temperature $T_{stbt}4$ ~140°C and the lower part heater have been turned off.

At 1776 s the steam generator and superheater were turned on.

At 2000 s the electric power for the model bundle heating was decreased to ~ 1600 W (Fig. 11).

At 2300 s at cladding temperature ~ 300°C at elevations from 300 to 1500 mm valve V1 was opened, and steam was supplied into the test section (see Fig. 10, 12 – cladding temperature decrease in the period 2400-3000 s resulted from their cooling with steam).

At 3662 s the gas mixture sampling into sampling tank Vol.2 was made.

At ~ 4243 s valves V22, F5, F15 were shut, valve V23 was opened to collect the condensate into Tank 5.1 (Fig. 1)

By ~ 4500 s the cladding temperature at elevations from 800 to 1300 mm reached ~450-500°C (Fig. 12).

Assembly heating up to ≈ 1200°C

From 4506 s at cladding temperature ~450-500°C at elevations from 800 to 1300 mm the electric power was increased to ~ 3000 W (Fig. 11).

From 4905 s the electric power increased to ~ 4000 W (Fig. 11).

At 6703 s the valve V28 was shut – condensate collecting Tank 5.1 was closed.

From 5315 s to 7017 s the electric power stepwise increased from ~ 4000 W to ~ 7000 W (Fig. 11).

From 7029 s to 9898 s the electric power stepwise was increased from ~ 6500 W to ~ 8300 W (Fig. 11).

Pre-oxidation phase

From 9760 s at constant electric power ~ 8300 W (Fig. 11) and maximum cladding temperature 1210°C at elevation 1250 mm (Fig. 15 – T2212,5) the pre-oxidation phase begun.

At 9102 s valve V27 was shut – condensate collecting Tank 5.2 was closed.

At 9735 s gas mixture sampling into sampling tank Vol.2 was made.

Stable behavior of main parameters: argon and steam flow rate ($G_{Ar\ in}$ ≈ 2 g/s, $G_{st\ in}$ ≈ 3.5 g/s), system pressure (~ 0.37 MPa), helium pressure inside the fuel rods (~ 0.56 MPa), argon pressure inside the heat insulation cavity (~ 0.35 MPa) was observed (Fig. 13). However, in some thermocouples reading temperature drop started. To maintain the needed temperature the electric power was increased to ~ 9100 W (Fig. 11)

At 10725 s gas mixture sampling into sampling tank Vol.3 was made.

At 11725 s gas mixture sampling into sampling tank Vol.4 was made.

At 12725 s gas mixture sampling into sampling tank Vol.5 was made.

At 13726 s gas mixture sampling into sampling tank Vol.6 was made.

Lasting for 3965 s, the pre-oxidation phase finished at 13725 s at electric power ~ 9100 W and the maximum temperature ~ 1260°C.

Transient phase

From ~ 13725 s the electric power started to increase. Varying the electric power in the range 9100-18400 W enabled to maintain low rates of cladding heating-up.

At 13750 s the valve V26 was shut – condensate collecting Tank 5.3 was closed.

At 13976 s gas mixture sampling into sampling tank Vol.7 was made.

At 14226 s gas mixture sampling into sampling tank Vol.8 was made.

At 14550 s the argon inlet position was switched to the upper part.

At 14466 s the valves V25 and V18 were shut – condensate collecting Tank 5.4 and Tank 6.2 was closed.

At ~ 14470 s after the bundle had reaching the maximum temperature 1600°C, steam feeding rate the valve V1 have been shut.

At 14476 s gas mixture sampling into sampling tank Vol.9 was made.

At 14481 s electric power was turning off.

Flooding phase

At 14486 s the valve V3 was opened to inject water from Tank 7 for top flooding. Average water flow registered with electronic flowmeter R3 was ~ 40 g/s (Fig. 23). Maximum cladding temperature just before the flooding began was 1578°C (T2513).

At 14726 s gas mixture sampling into sampling tank Vol.10 was made.

At 14960 s after FA temperature drop to ~ 130°C, top flooding water injection valve V3 was shut.

Top flooding had lasted for ~ 470 s.

At 15064 s the information and measurement system and SOV-3 hydrogen measurement system were off.

Experiment results

The experiment results are presented on Fig. 10 – 33.

Fig. 10 and 11 present the results of measurement of the main experiment parameters: flow rate and temperature of argon ($G_{Ar\ in}$, $T_{Ar\ in}$) and of steam ($G_{st\ in}$, $T_{.st\ in}$) at the inlet into the test section; gas mixture flow rate R4 at the inlet into the special ventilation (Fig.10); electric parameters (Fig.11): power (P), current (I), voltage (U).

Fig. 12 and 13 present the thermocouples readings fixed on claddings at the different elevations (Fig. 12) and pressure sensors readings (Fig. 13): in the model bundle (p_{bnl}), in fuel rods (p_{rod}) and the thermoinsulation cavity (p_{th}).

Fig. 14 to 17 give more detailed the cladding thermocouples readings at elevations: Z = (1300 – 1500) mm (Fig. 14), Z = 1250 mm (Fig. 15), Z = (900 – 1100) mm (Fig. 16) and Z = (0 – 800) mm (Fig. 17) in the period 0 to 16000 s.

Volumetric hydrogen concentration measured by the SOV-3 hydrogen measurement devise and in ten sampling tanks (Vol.1,…,Vol.10) are presented in Fig. 18.

Fig. 19 presents the readings of pressure sensors at some elevations of the model bundle: p10 (Z = 1000 mm), p12.5 (Z = 1250 mm), p15 (Z = 1500 mm) and in the thermoinsulation cavity (p_{th}) at the transient and quenching phases.

The readings of thermocouples placed inside the central fuel rod 1.1 in the period 0 to 16000 s are presented in Fig. 20.

The readings of thermocouples maintained on the shroud (T_{sh}) and the test section thermoinsulation (T_{th}) at different elevations, in the period 0 to 16000 s are given in Fig. 21.

Fig. 22 provides the readings of electronic flowmeter of the top flooding system (R3) and level gauge M7 during the quenching phase in the period 14400 to 15000 s.

Fig. 23 to 26 present the readings of thermocouples installed on fuel rod claddings at different elevations during the quenching phase in the period 14400 to 15000 s: Z = (1300 – 1500) mm (Fig. 23), Z = (1000 – 1250) mm (Fig. 24), Z = (500 – 800) mm (Fig. 25 a), Z = (0 – 400) mm (Fig. 25 б) and Z = (-600 – 0) mm (Fig. 26)

Fig. 27 to 28 present the readings of thermocouples located inside and on the cladding of central fuel rod 1.1 (Fig. 27), on the shroud (T_{sh}) and inside the thermoinsulation (T_{th}) of the test section (Fig. 28), during the quenching phase.

Hydrogen generation rate and mass obtained by processing SOV-3 readings are shown in Fig. 29.

Fig. 30 shows the bundle cross-section at elevation Z = 600 mm.

Fig. 31 shows the bundle cross-section at elevation Z = 700 mm.

Fig. 32 shows the bundle cross-section at elevation Z = 800 mm.

Fig. 33 shows the bundle cross-section at elevation Z = 900 mm.

Table 5 provides the condensates masses in the condensate mass control tanks.

Table 5

Results of measurements of water masses in control tanks

No.	Tank	Period of condensate collecting (start – finish), s	Water mass, g
1. Water flow rate			
1	Tank 1 (Steam supply)	2300 - 14470	42934
2	Tank 7 (flooding)	14486 - 14960	19135
3	Steam generator	2300 - 14470	400
2. Condensate collecting			
4	Tank 5'	0 - 4241	2956
5	Tank 6.1	0 - 4241	3440
6	Tank 5.1	4241 - 6701	8709
7	Tank 5.2	6701 - 9101	7872
8	Tank 5.3	9101 - 13748	15240
9	Tank 5.4	13748 - 14464	2350
10	Tank 6.2	4241 - 14464	3426
11	Tank 5.5	14464 - 14960	6199
12	Tank 6.3	14464 - 14960	4332
13	Test section (water mass in the lower part of the bundle)	2300 - 14470	4805

Table 6 presents the results of measuring of the volumetric hydrogen concentration in the sampling tanks of the discrete hydrogen control system and continuous monitoring system (SOV-3).

Table 6

Results of hydrogen measurement

Sample number	Time of sampling start, s	Volumetric hydrogen content in the tank, %	Volumetric hydrogen content according to SOV-3, %
Vol.1	3662	0.37	-
Vol.2	9735	5.46	2.7
Vol.3	10727	4.55	3.43
Vol.4	11727	4.46	3.54
Vol.5	12726	4.00	2.9
Vol.6	13728	4.06	2.73
Vol.7	13978	8.43	6.26
Vol.8	14228	13.78	10.3
Vol.9	14478	18.84	15.2
Vol.10	14728	2.47	2.85

In the course of the experiment at the pre-oxidation phase some thermocouples had failed. They are listed in Table 7.

Table 7

List of the thermocouples failed

No.	Thermo-couple designation	Location	Behavior	Time, s	Condition
1	T1112.5	Z=1250	Readings pulsation	-	
2	T2212.5	Z=1250	Circuit opening	14223	failure
3	T253	Z=300	Readings pulsation	-	
4	T311’5	Z=500	Readings pulsation	-	
5	T239	Z=900	Circuit opening	9770	failure
6	T248п	Z=800	Circuit opening	14500	failure
7	T399	Z=900	Circuit opening	14257	failure
8	T31012.5	Z=1250	Circuit opening	14407	failure

RESULTS OF EXPERIMENTAL DATA PRIMARY PROCESSING

Preparatory stage

Preliminary analysis of results of the PARAMETER-SF3 experiment has shown that at the preparatory stage, according to pretest experiment scenario, the designed parameters of steam and argon at the inlet were set up (Fig. 10): steam flow rate $G_{st\ in}$ ~ 3.5 g/s at $T_{st\ in}$ ~ 520°C; argon flow rate $G_{Ar\ in}$ ~ 2.0 g/s at $T_{Ar\ in}$ ~ 380°C.

By ~ 4506 s at electric power ~ 1600 W (Fig. 11) thermocouples at elevations 900 to 1300 mm showed the settled temperature – 470 to 510°C (Fig. 12) with steam flow rate through the bundle ~ 3.5 g/s (Table 5). The pressures (by pressure sensors readings) were: for steam-gas mixture in the bundle (system pressure) ~ 0.35 MPa, for helium inside the fuel rods ~ 0.43 MPa, for argon in the thermoinsulation cavity ~ 0.4 MPa (Fig. 13).

Pre-oxidation stage

The pre-oxidation stage had lasted for ~ 4000 s (~ 9760 to 13725 s), at fuel rod cladding temperature, according to thermocouple readings at elevations 1250 – 1300 mm, within the range 1170 to 1250°C (Fig. 14, 15), steam flow rate through the bundle ~ 3.6 g/s, and with electric power increase from 8200 to 9100 W.

Five gas mixture samples were taken during the pre-oxidation stage (Table 6, Fig. 18).

Transient stage

The transient stage had lasted for ~ 756 s (~ 13725 to 14481 s). During the transient phase electrical power was increased from ~ 9100 to ~ 12600 W (Fig. 11). Steam flow rate through the bundle was ~ 3.6 g/s (Table 5).

At the moment of power switching-off, the readings of thermocouples in the hottest elevation – 1300 mm were ~ 1600°C (Fig. 14, T2513, rod 2.5, 2nd row).

The maximum thermocouple readings at elevation 1100 mm (Fig. 16) were: in the second row ~ 1500°C (T2611, rod 2.6), in the third row ~ 1460°C (TC T3711, rod 3.7). The readings of thermocouples below elevation 1000 mm didn't exceed 1400°C (Fig. 17).

The maximum heating rate of claddings didn't exceed ~ 0.5°C/s.

Three gas mixture samples were taken during the transient stage (Table 6, Fig. 18).

Flooding stage

At 14486 s as soon as the maximum temperature was achieved 1600°C (thermocouple T2513) (Fig. 14), the top flooding system was switched on, water flow rate was ~ 40 g/s (Fig. 22).

Water injection into the bundle during top flooding resulted in:

- rapid (for approximately 20 s after the flooding start) cooling of claddings at elevations (1250 – 1500) mm to temperature ~130°C (Fig. 23);

- cooling of the fuel rod claddings at elevations (1000 – 1100) mm to temperature ~130°C in approximately (120 – 160) s (Fig. 24);

- cooling of the fuel rod claddings at elevations (500 – 800) mm to temperature ~ 130°C in approximately ~ (200 – 360) s (Fig. 25 a);

- cooling of the fuel rod claddings at elevations (0 – 400) mm to temperature ~ 130°C in approximately ~ (360 – 390) s (Fig. 25 b).

The bundle cooling at elevations (-600 – 0) mm to temperature ~ 130°C, starting from ~ 14700 s to ~ 14880 s, occurred in approximately (330 – 390) s bottom-to-top (Fig. 26).

During flooding, a pressure jump (P_{bnl}) to be ~0.04 MPa caused by steam generation was detected in the bundle.

By the moment of the top flooding system shutdown (14960 s) the bundle temperature was ~ 100°C.

Analysis of SOV-3 hydrogen measurement results showed that ~ 34 g hydrogen was released in the experiment (Fig. 29). The maximum hydrogen generation rate was ~ 0.02 g/s (Fig. 29).

The mass of water collected in the course of top flooding was ~ 4332 g (Tank 6.3, Table 5), and the mass of water collected during water-steam mixture condensation and ejected during top flooding was ~ 6199 g (Tank 5.5, Table 5).

Analysis of water balance in the test facility technological systems has shown that the difference between the masses of consumed water and water collected after the experiment was ~ 3140 g.

Separate analysis of water condensed in Tank 5.1, Tank 5.2, Tank 5.3, Tank 5.4, Tank 5.5 (Table 5) and bundle examination after dismantling have shown that ~ 3140 g water leaked into the thermoinsulation due to the shroud failure in the course of top flooding.

Dismantling, encapsulation and sectioning of the model bundle were carried out after the test.

Cross-sections of the model bundle at elevations Z = 600, 700, 800 and 900 mm are depicted on Fig. 30 to 33.

Primary visual examination of the bundle appearance in the hottest zone revealed significant oxidation and fragmentation of the fuel rod claddings. No melt between the fuel rods not detected.

After thorough examination, fuel rod status description and photography, the bundle and the shroud were separately prepared for further material science study.

FIGURES

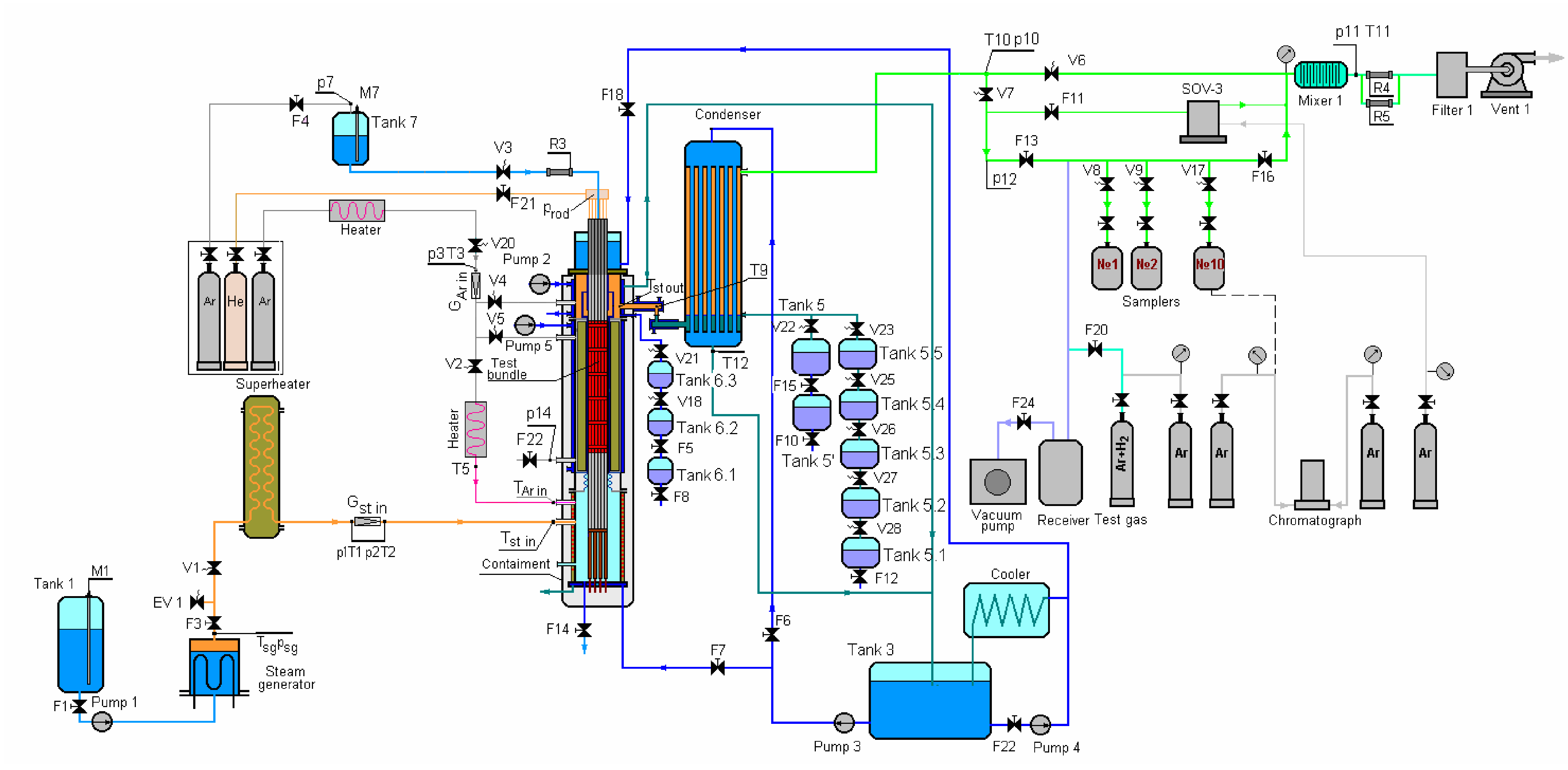
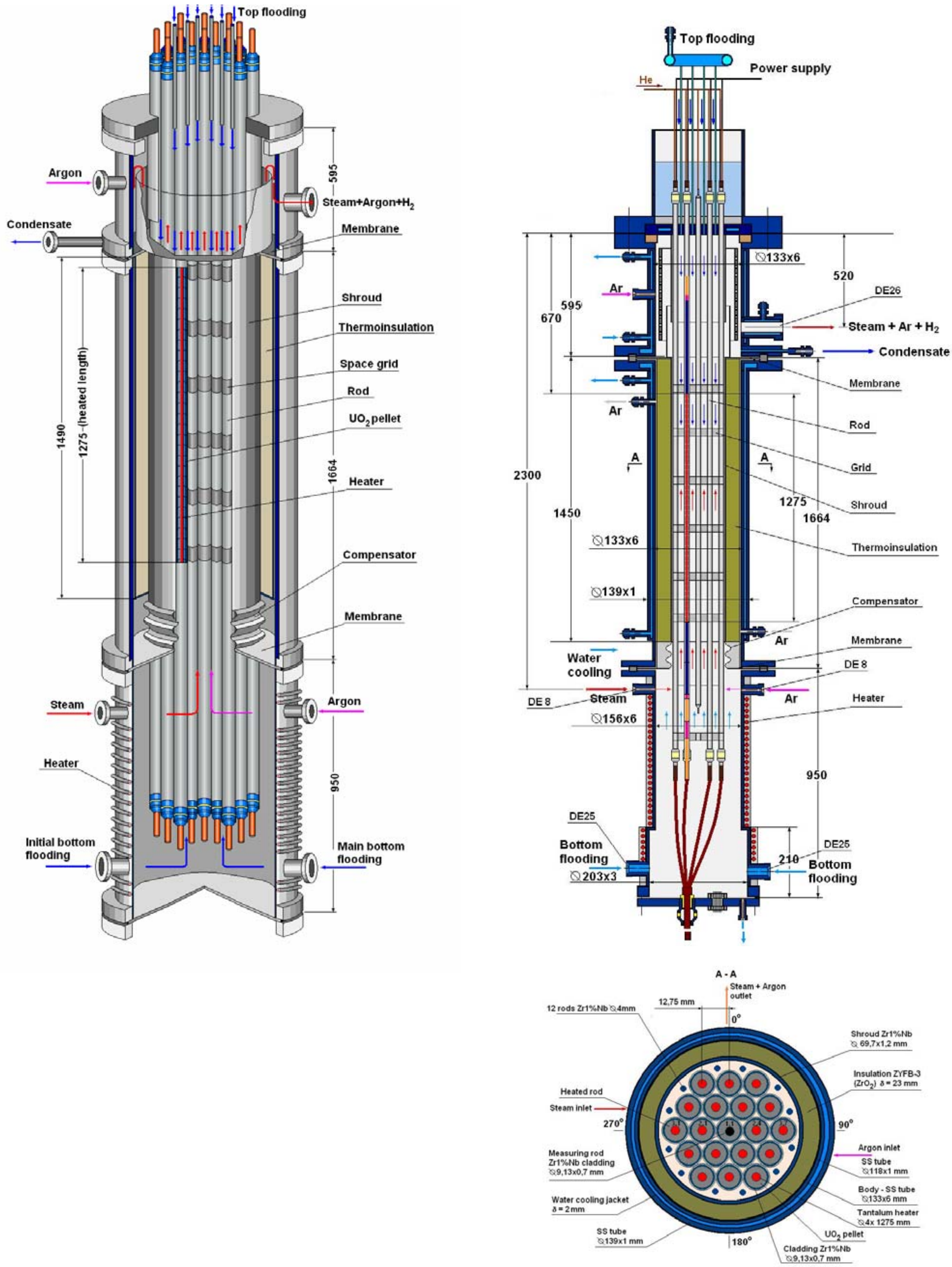


Fig. 1. Flow diagram of the PARAMETER test facility.



General view

Scheme

Fig. 2. General view of the test section.

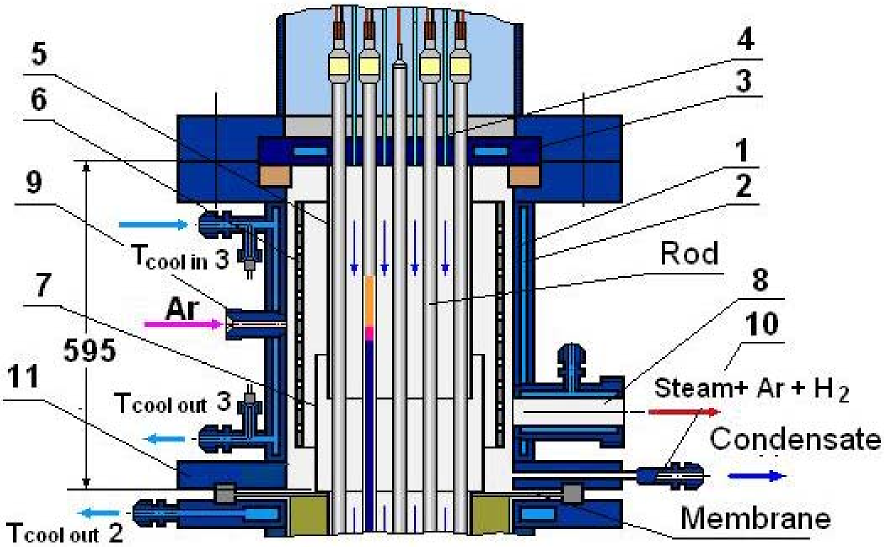


Fig. 3. Test section upper part.

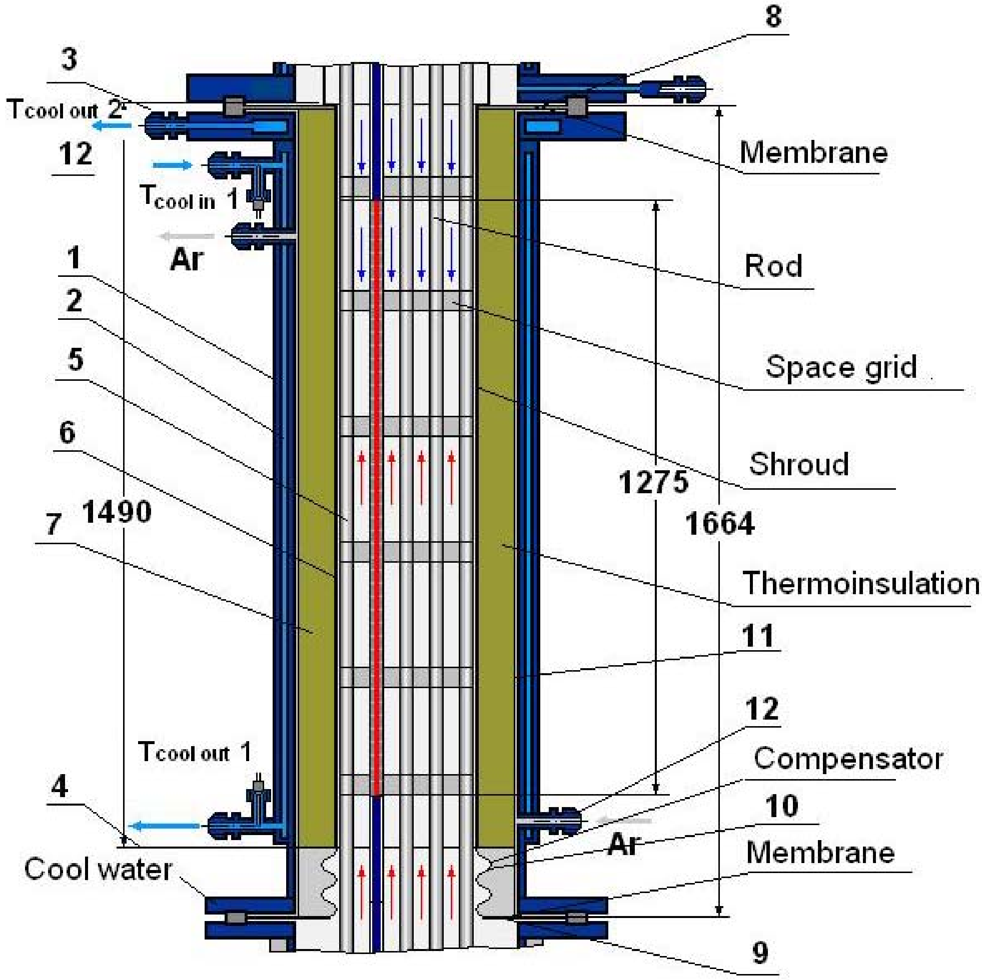


Fig. 4. Test section middle part.

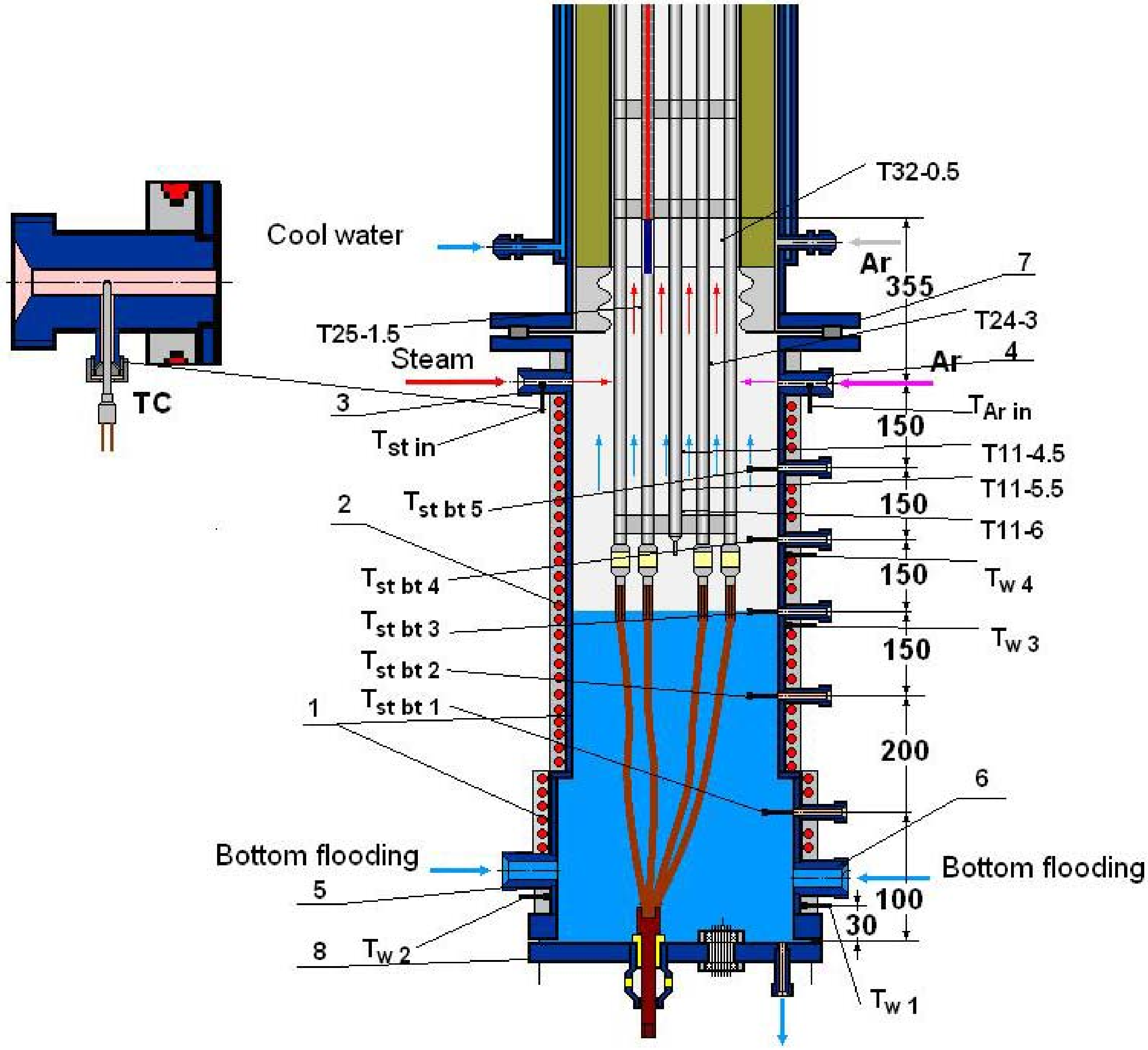
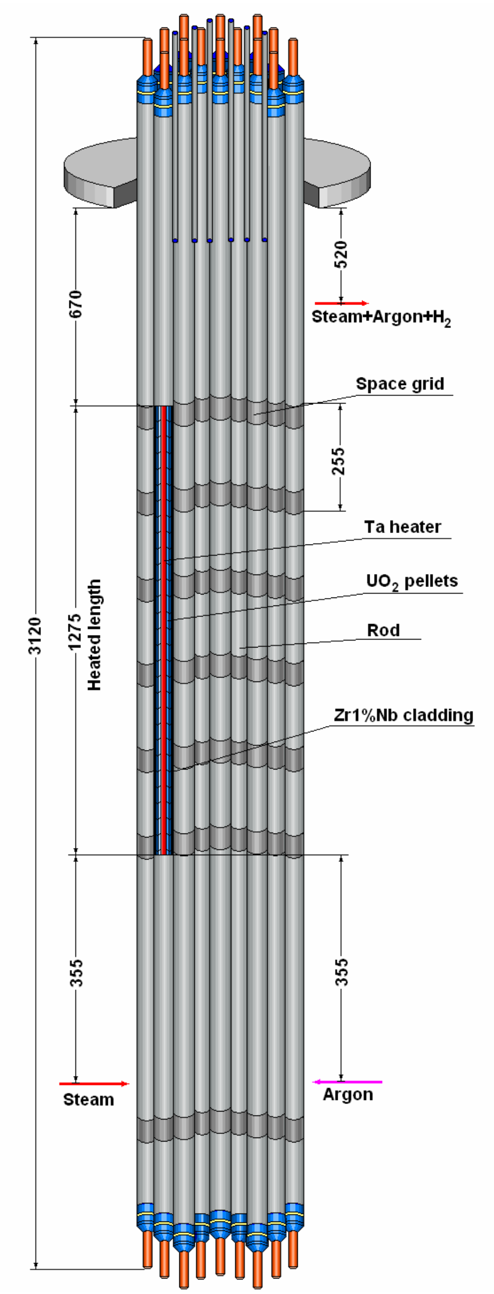
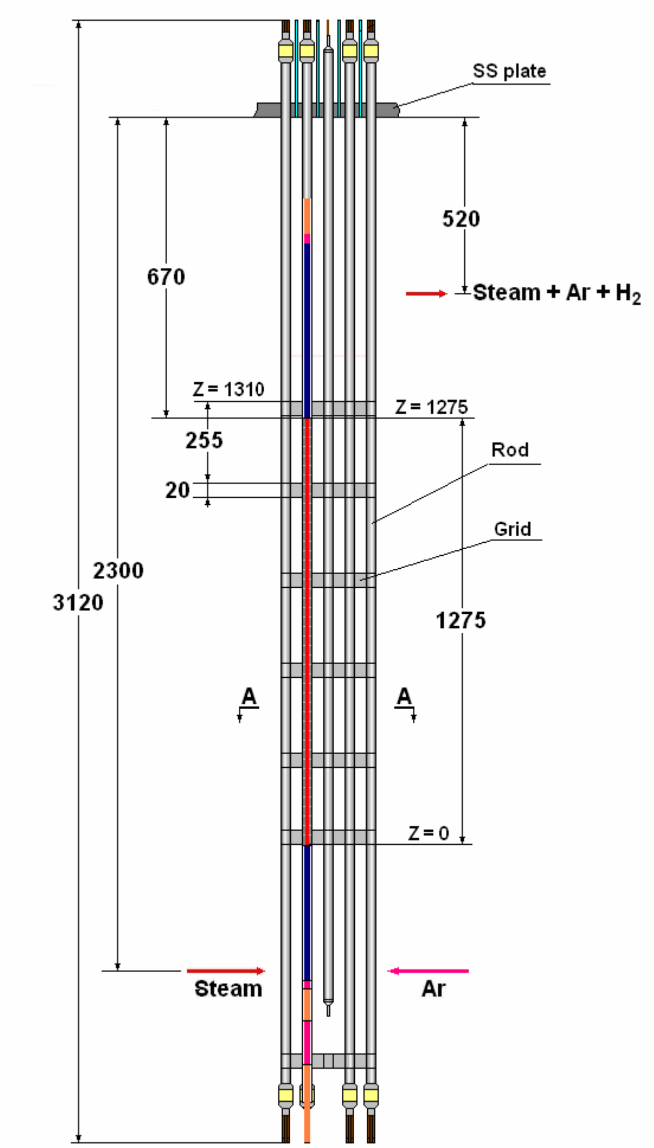


Fig. 5. Test section lower part.

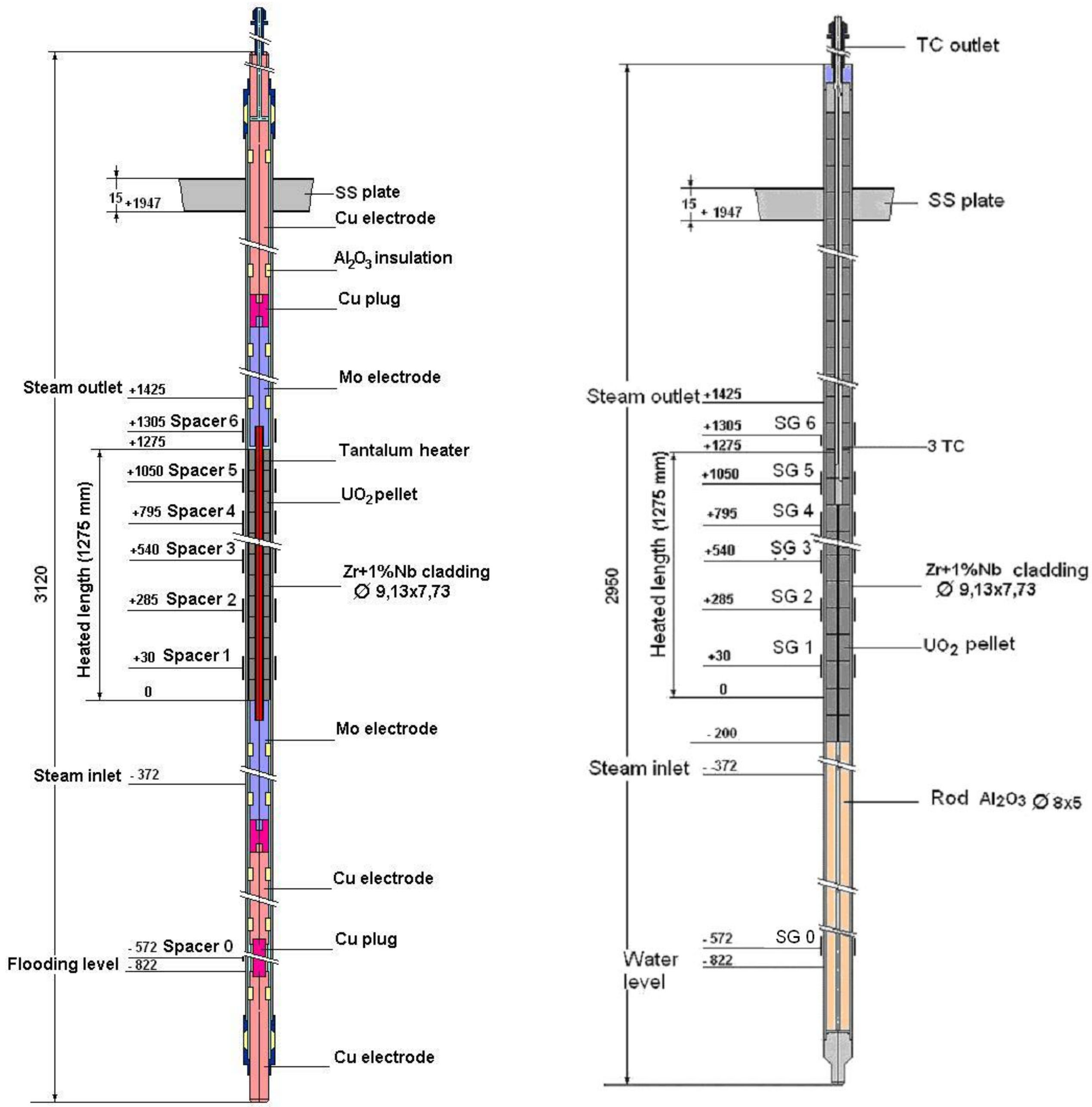


General view



Scheme

Fig. 6. Model FA.



Heated fuel rod

Unheated fuel rod

Fig. 7. Fuel rod simulators.

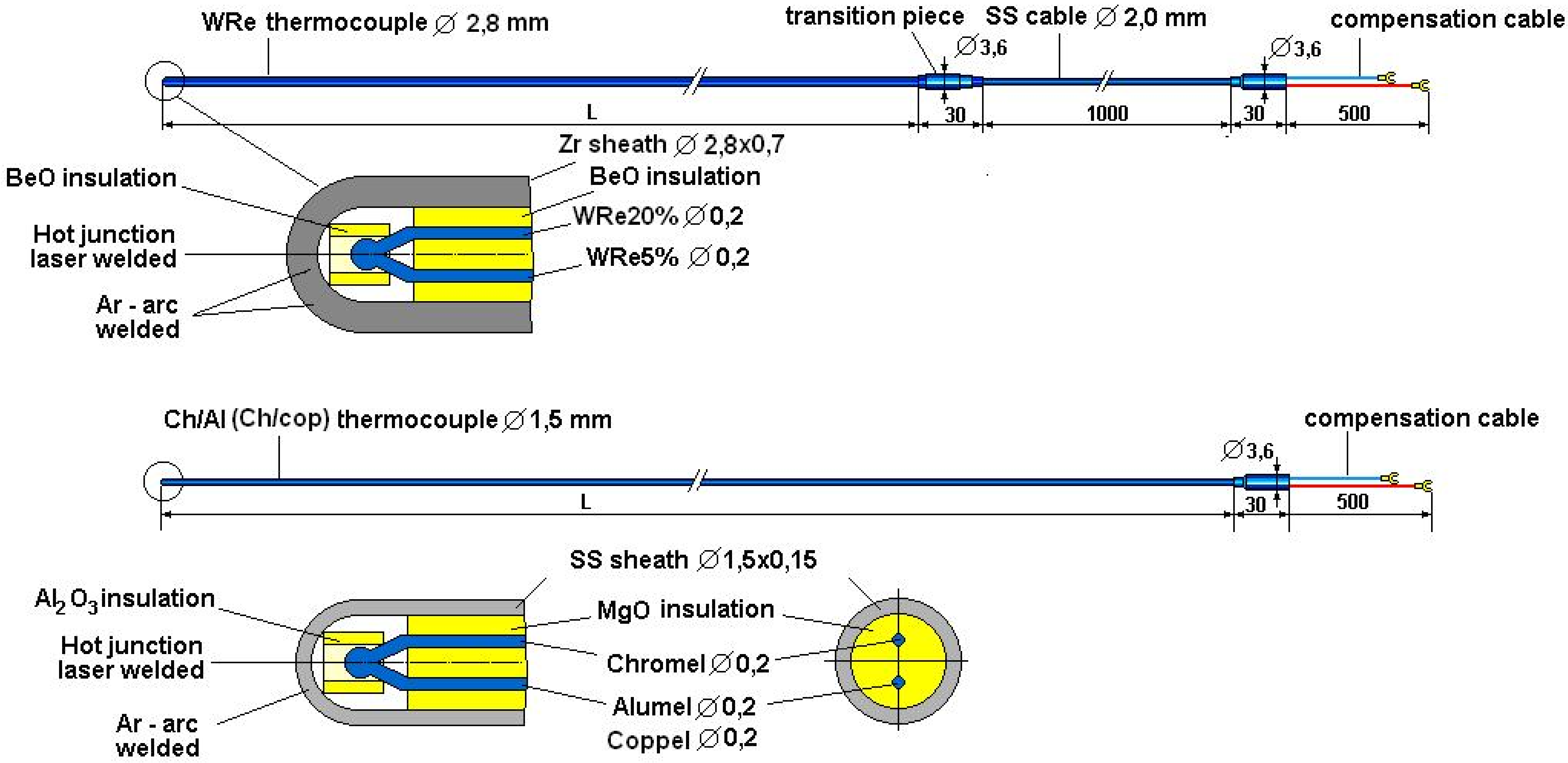


Fig. 8. FA thermocouples.

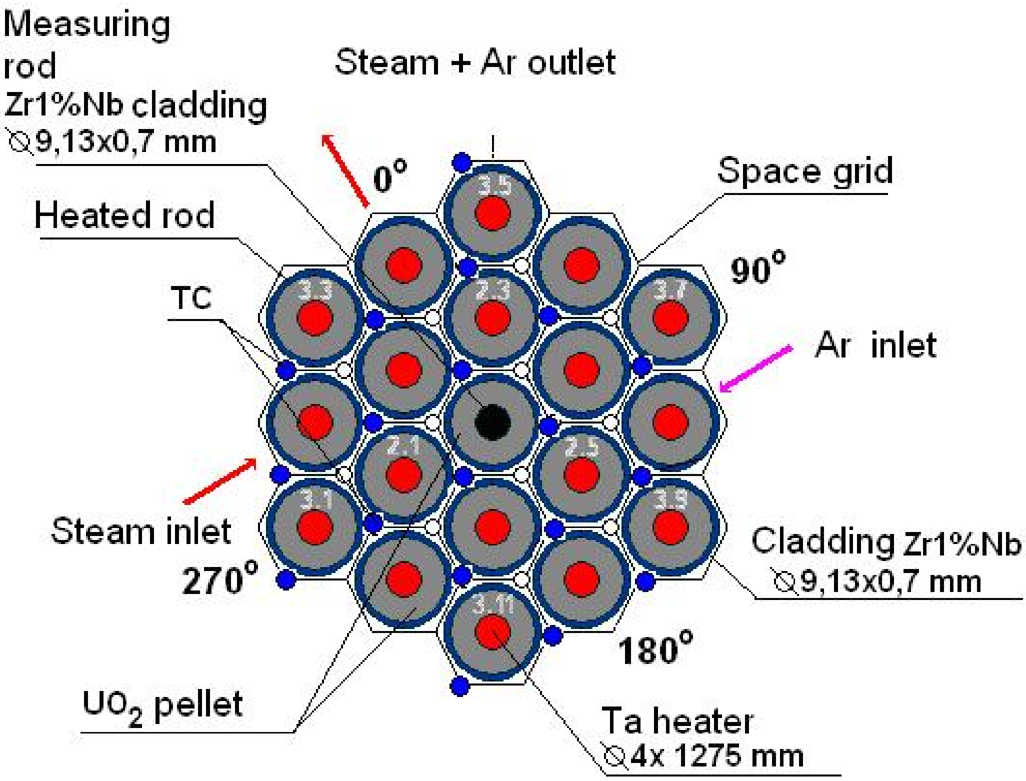


Fig. 9. Thermocouple arrangement (top view).

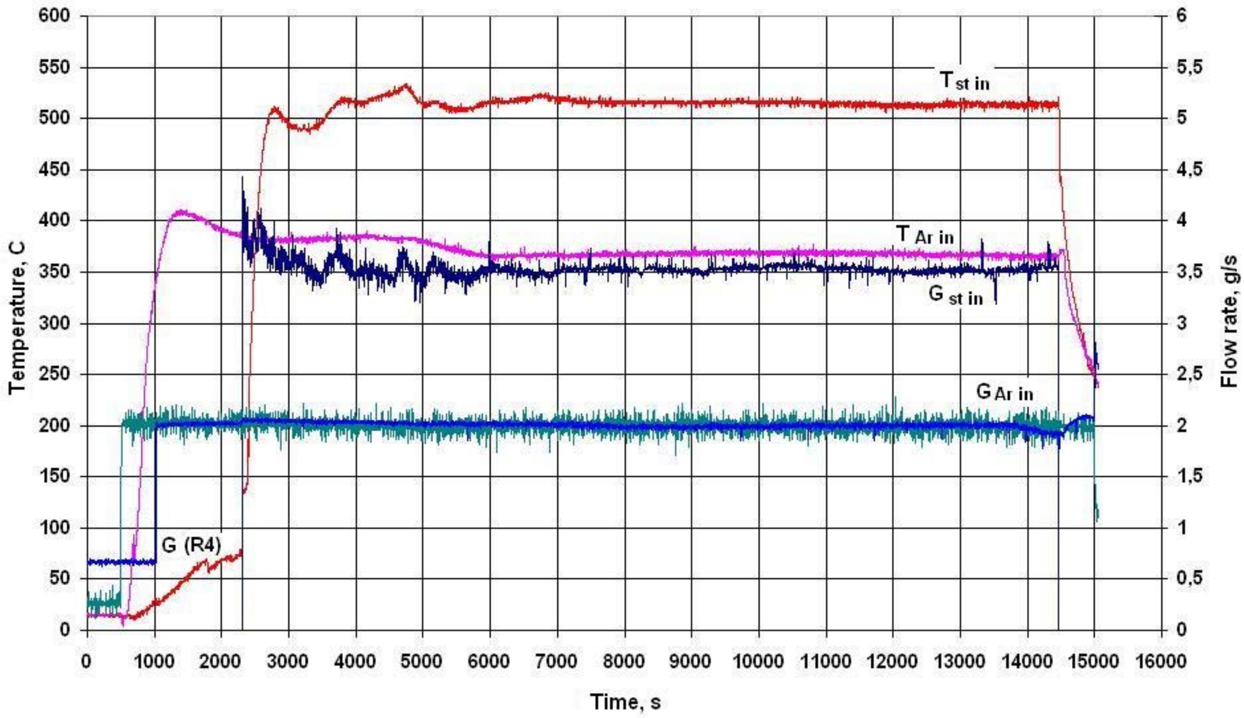


Fig. 10. Steam ($G_{st\ in}$, $T_{st\ in}$) and argon ($G_{Ar\ in}$, $T_{Ar\ in.}$) parameters at the inlet to the test section and steam flow rate ($G(R4)_{Arg\ out}$) at the outlet to the special ventilation.

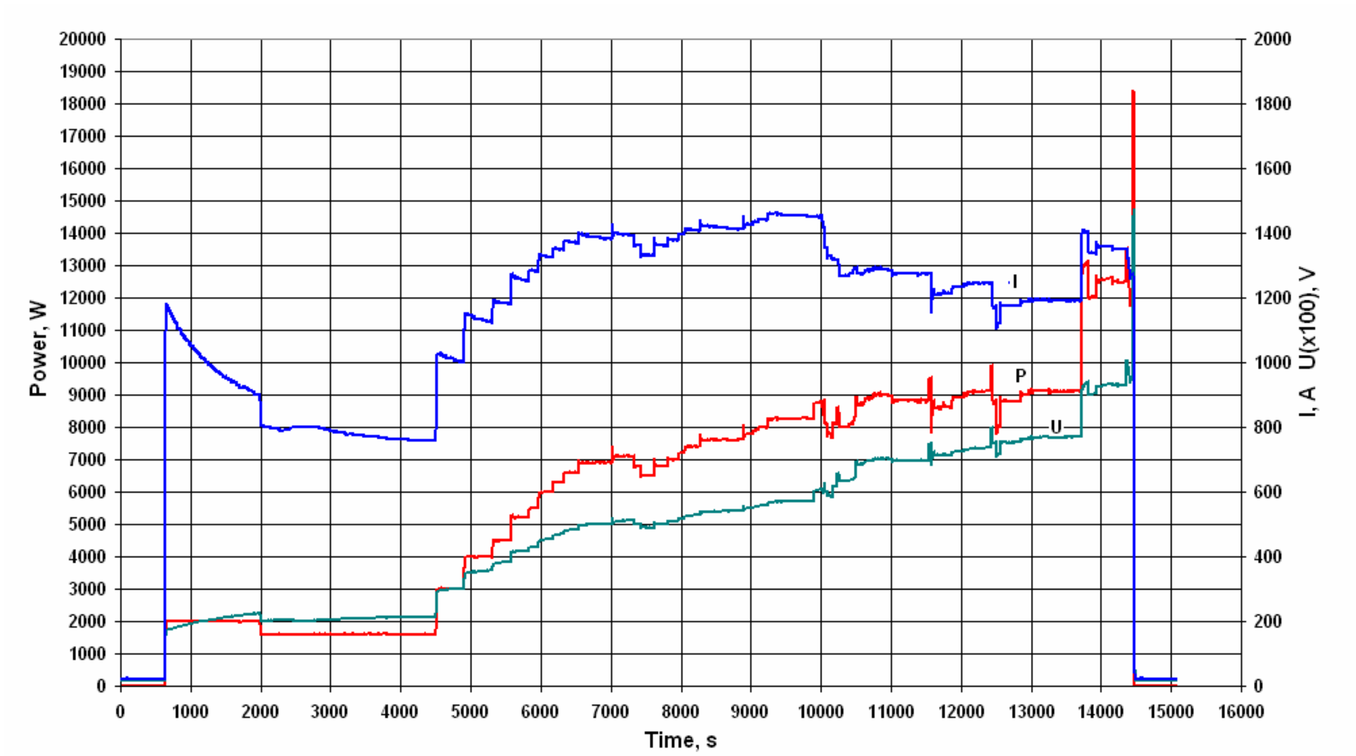


Fig. 11. Power supply.

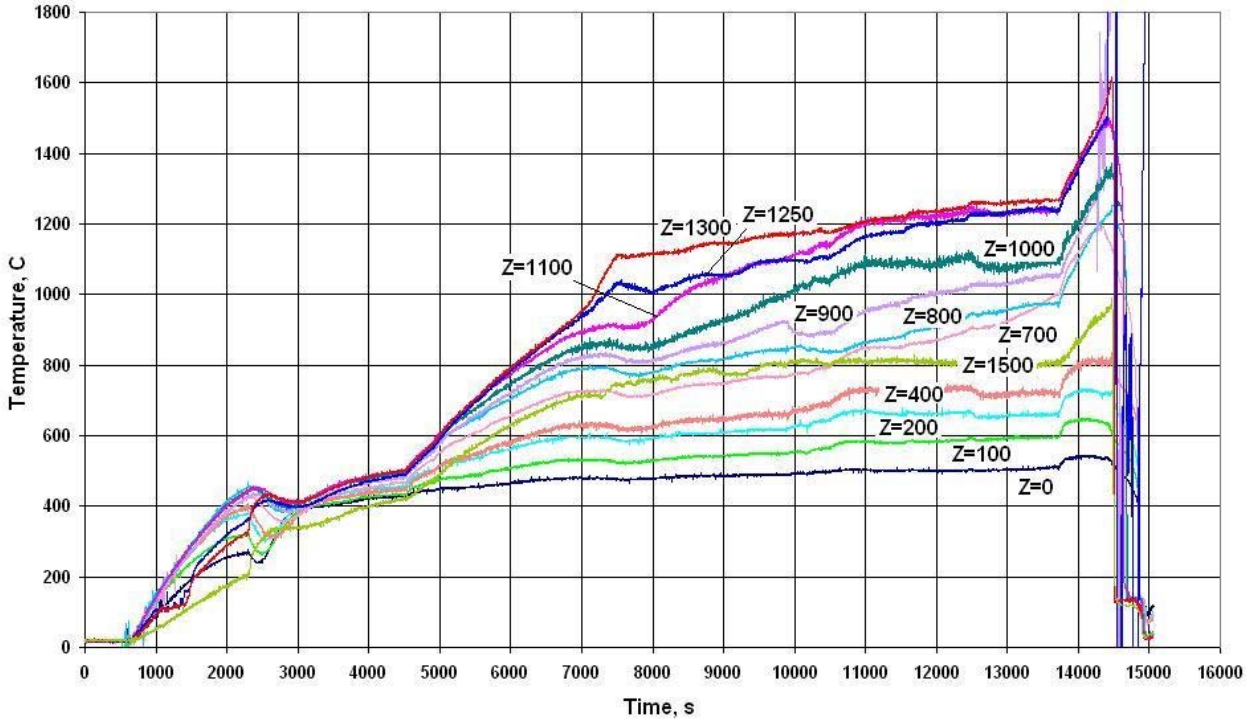


Fig. 12. Readings of thermocouples on fuel rod claddings at different elevations.

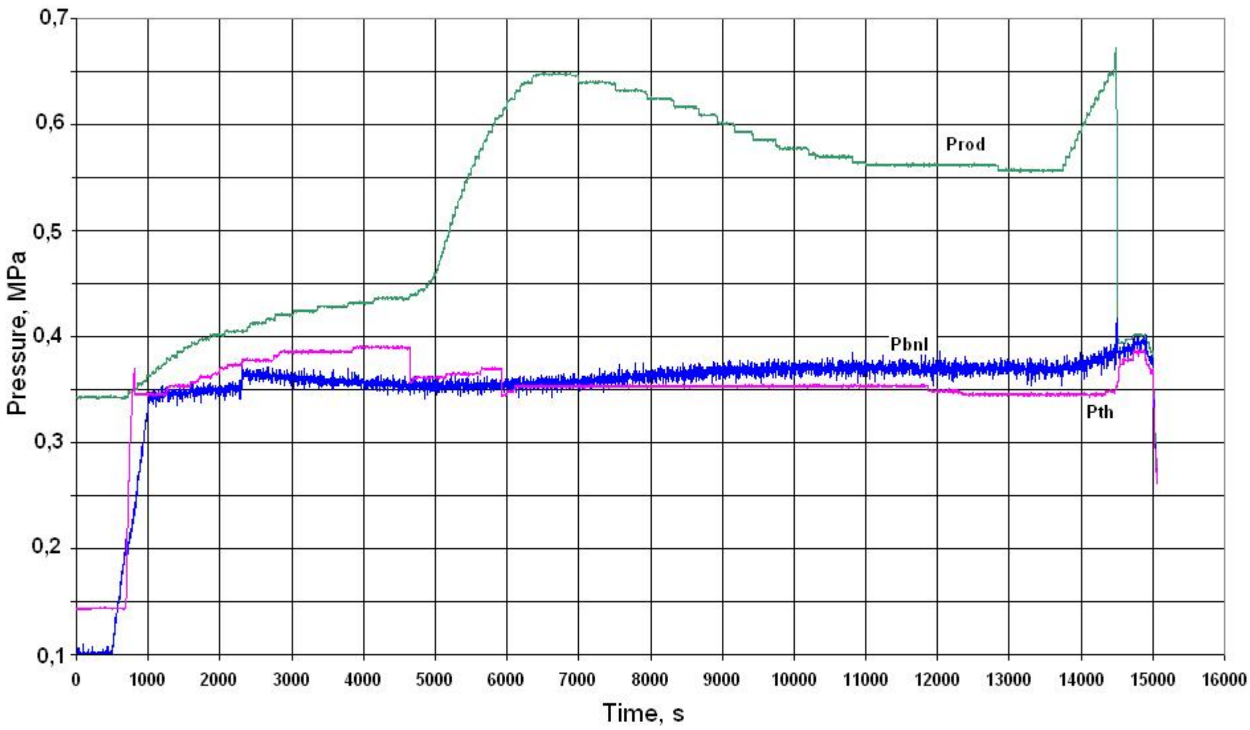


Fig. 13. Readings of pressure sensors in the model bundle (p_{bnl}), fuel rods (p_{rod}) and in the thermoinsulation cavity (p_{th}).

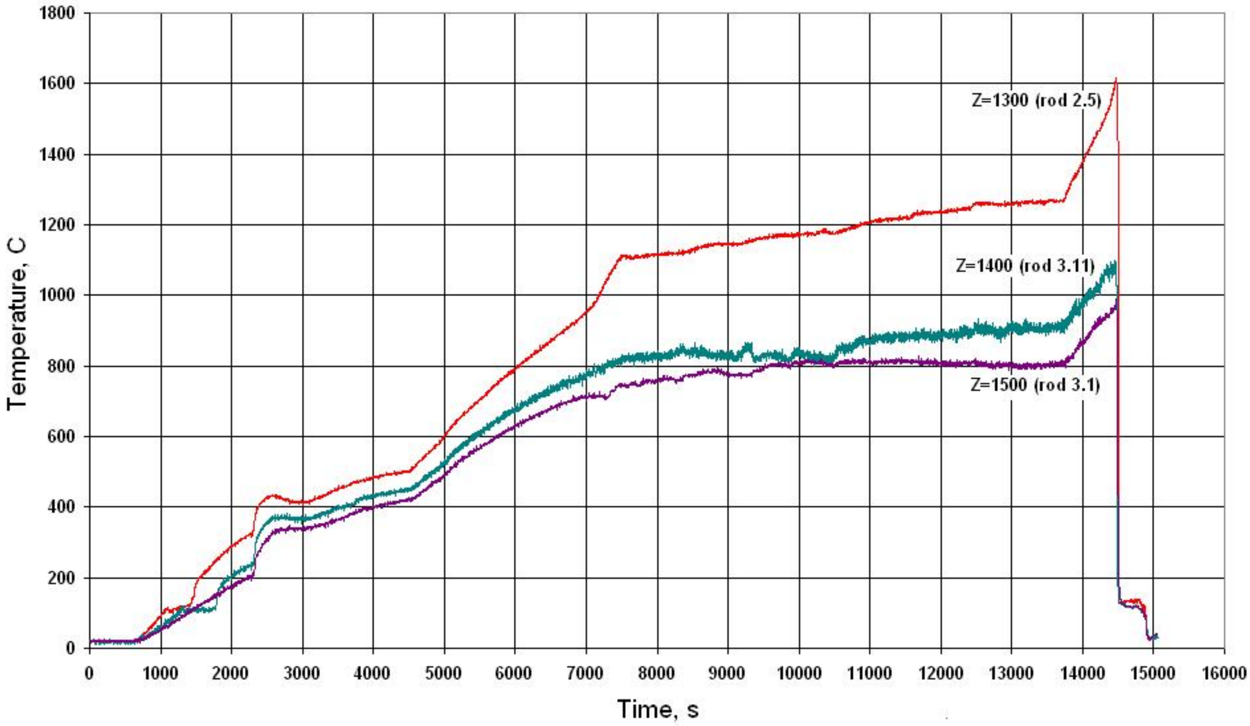


Fig. 14. Readings of thermocouples on fuel rod claddings at elevations
Z = (1300 – 1500) mm.

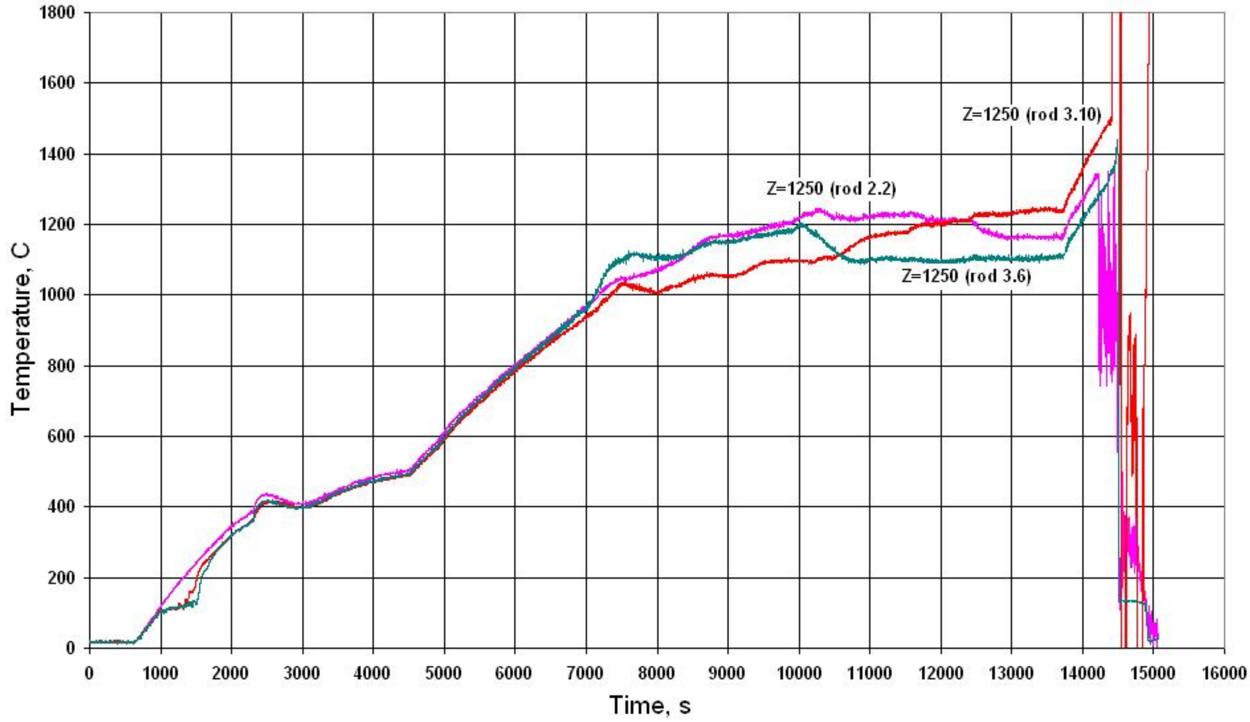


Fig. 15. Readings of thermocouples on fuel rod claddings at elevation Z = 1250 mm.

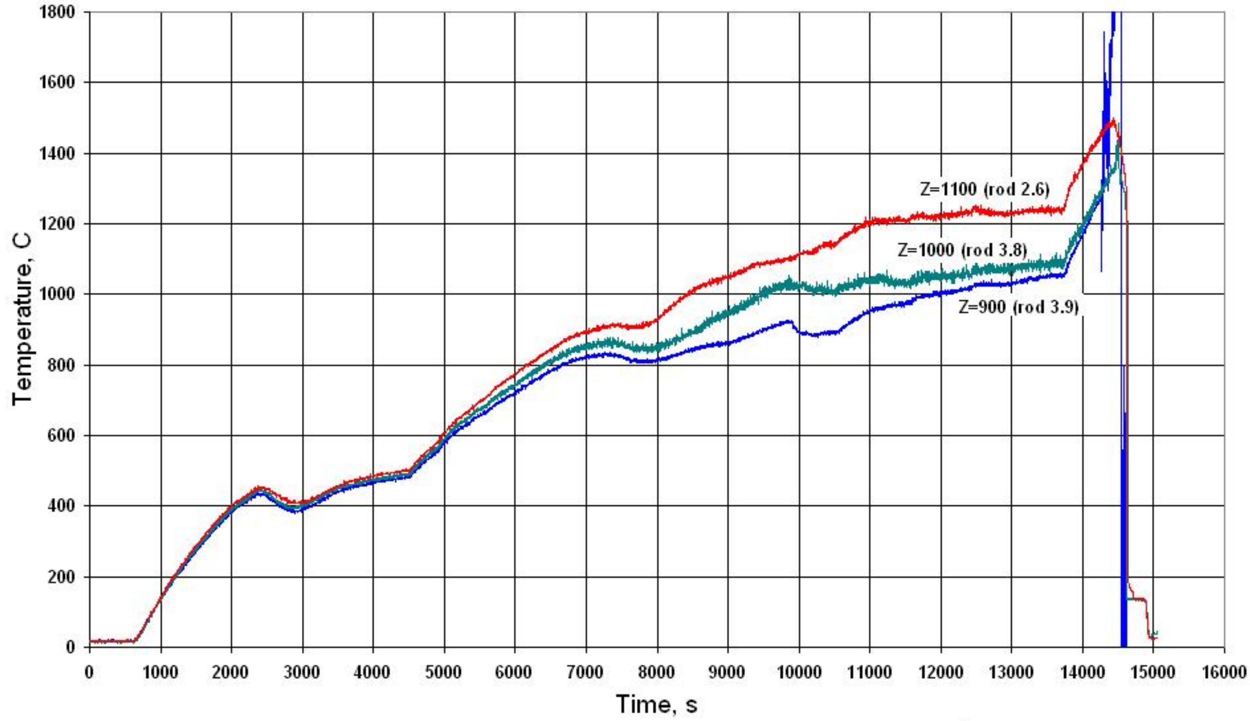


Fig. 16. Readings of thermocouples on fuel rod claddings at elevations Z = (900 – 1100) mm.

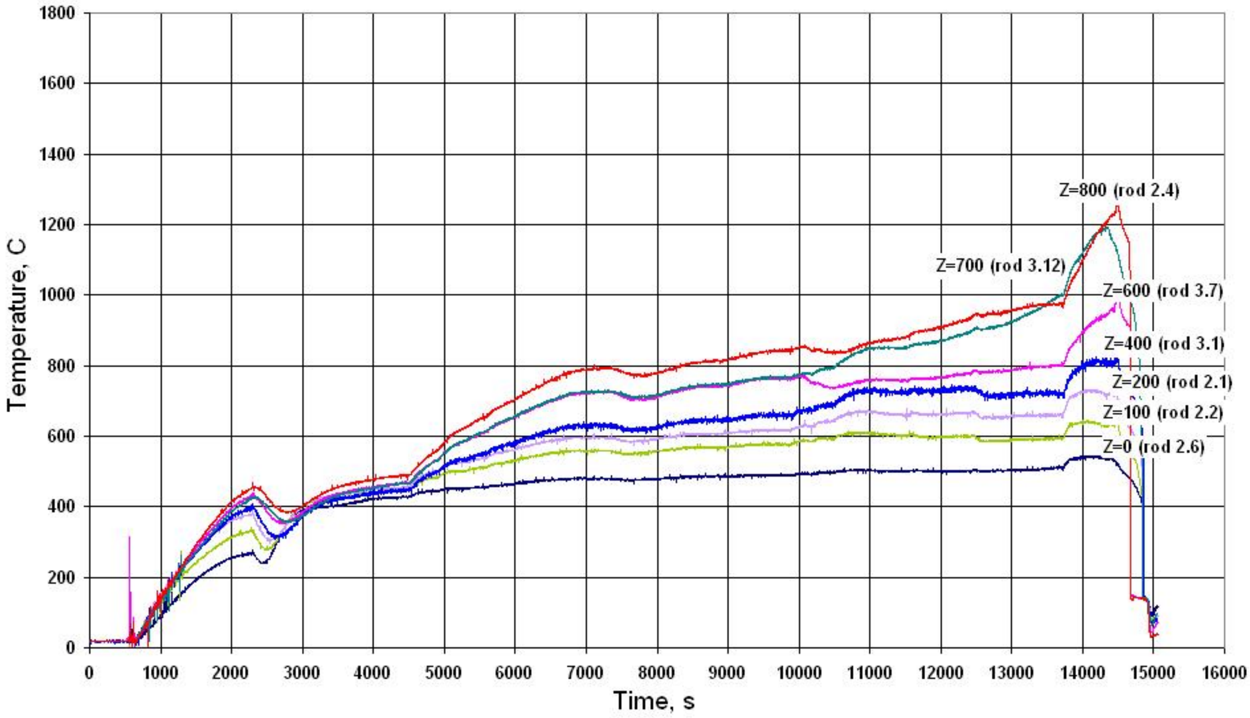


Fig. 17. Readings of thermocouples on fuel rod claddings at elevations Z = (0 – 800) mm.

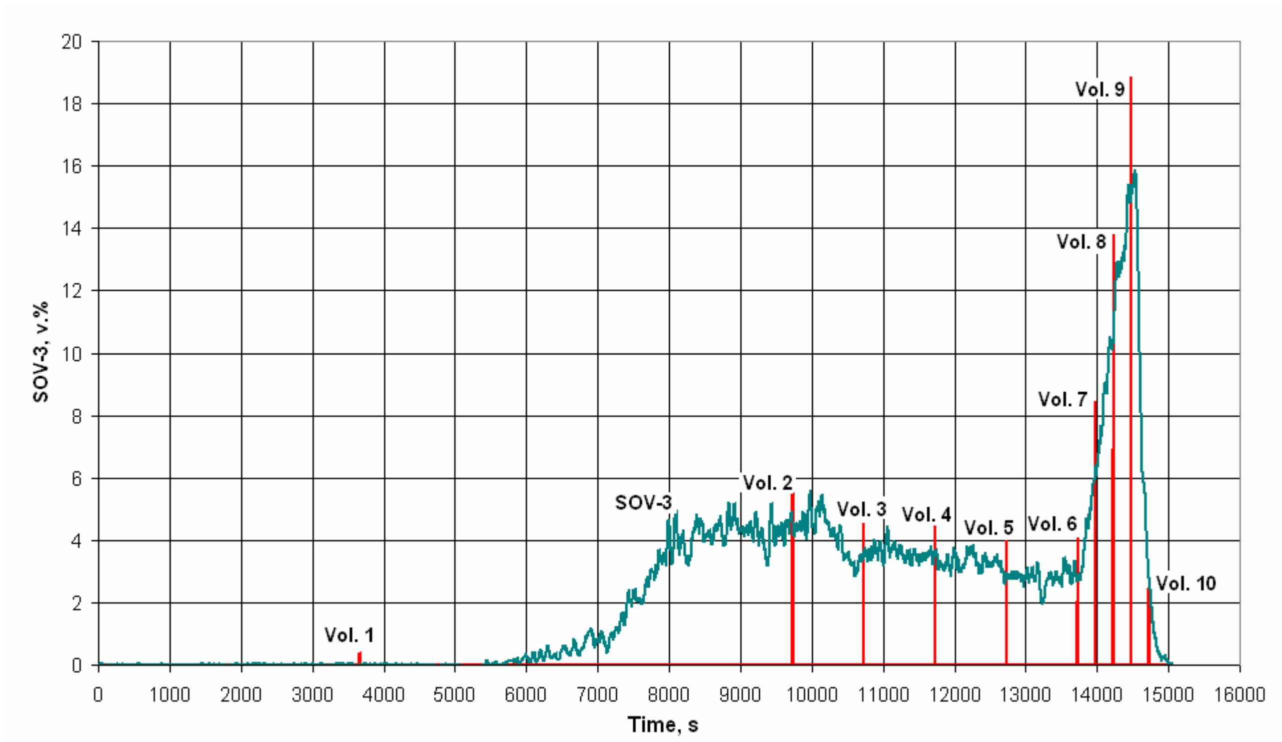


Fig. 18. Volumetric hydrogen concentration measured by continuous (SOV-3) and discrete (Vol.) hydrogen monitoring systems.

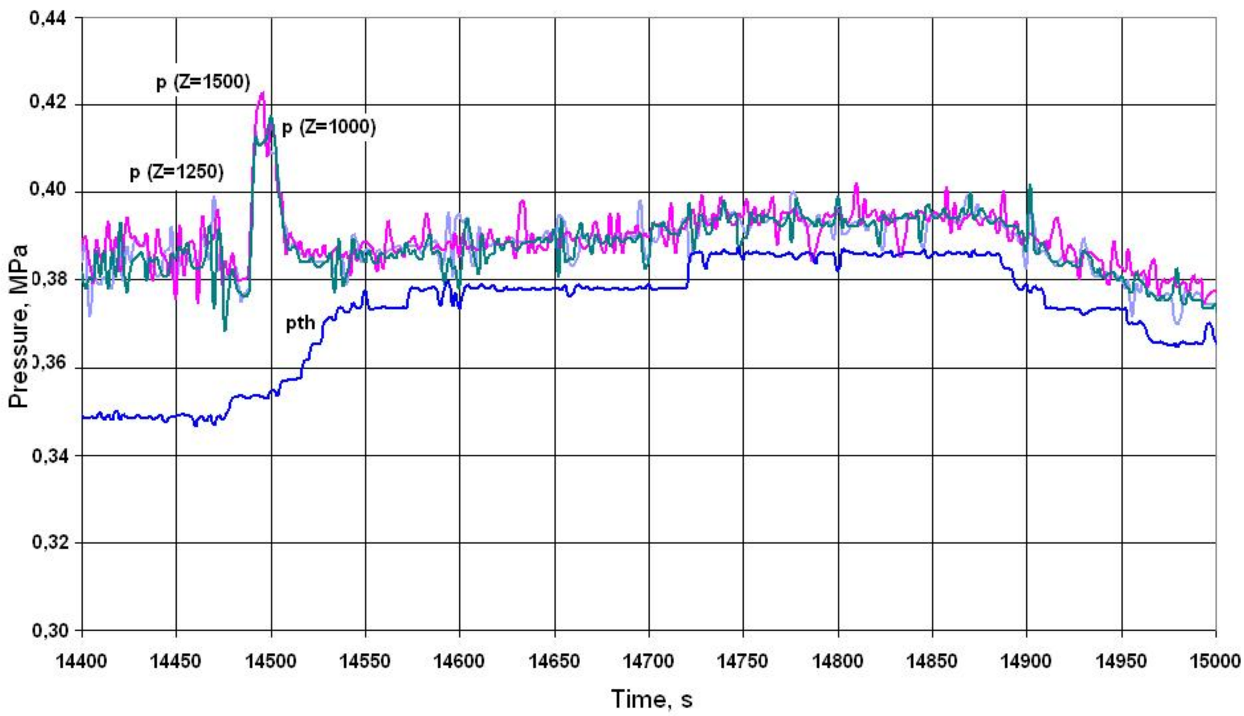


Fig. 19. Readings of pressure sensors at some elevations of the model bundle (Z = 1000, 1250 and 1500 mm) and the thermoinsulation cavity (p_{th}) at transient and quenching phases.

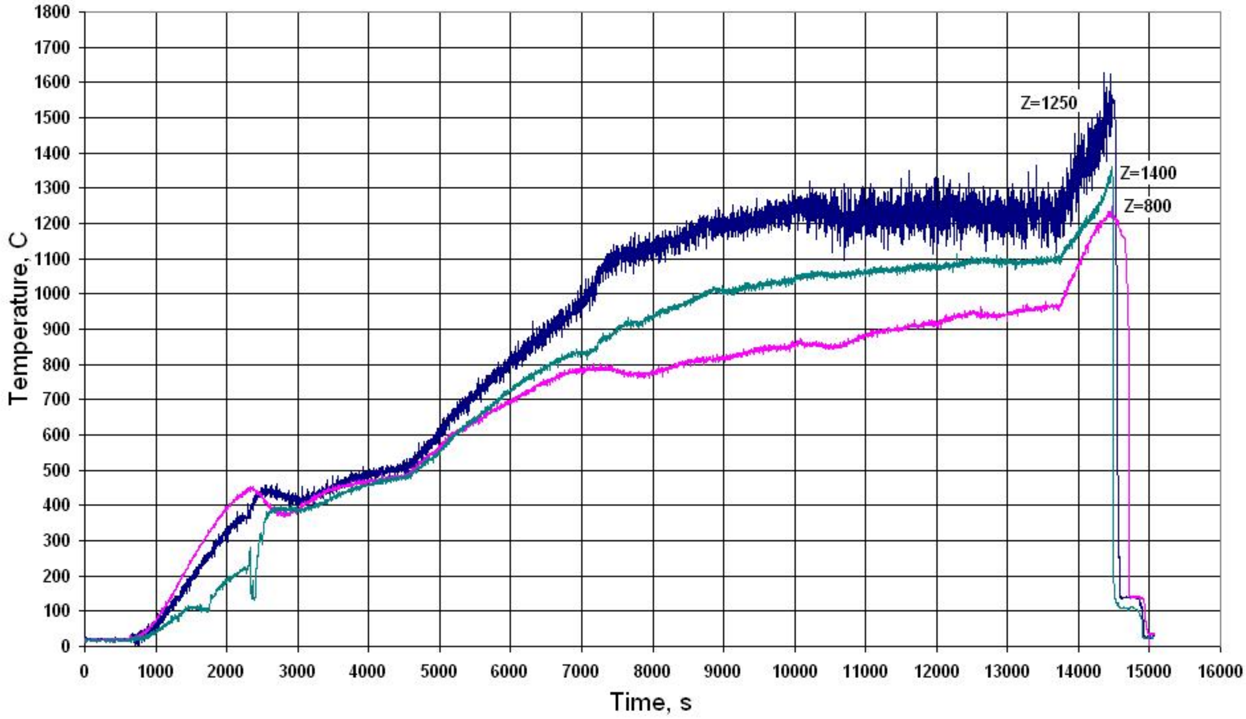


Fig. 20. Readings of thermocouples inside the central fuel rod 1.1.

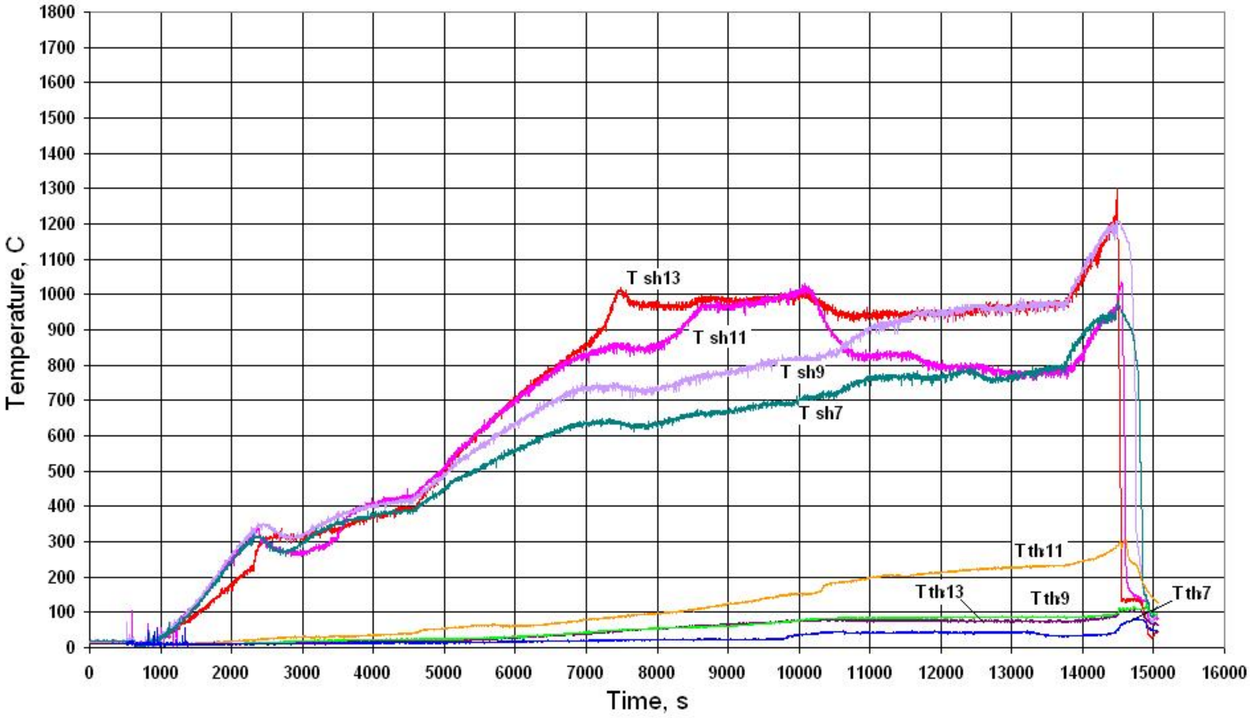


Fig. 21. Readings of thermocouples on the shroud (T_{sh})
and the thermoinsulation (T_{th}) at various elevations.

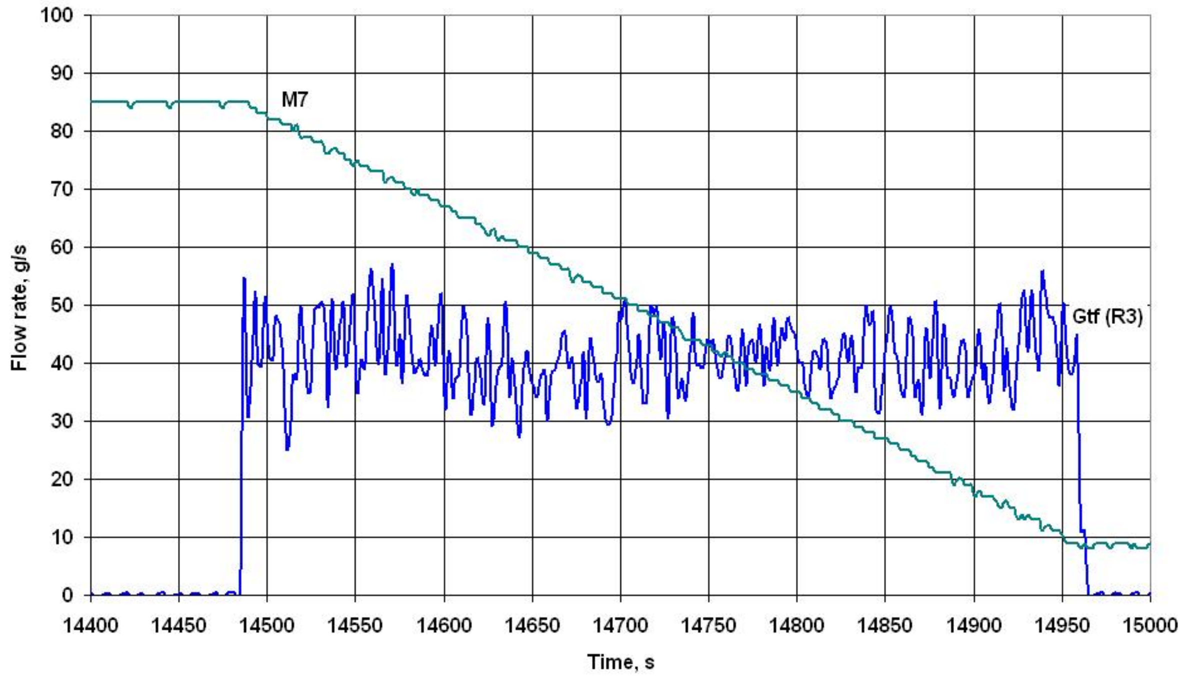


Fig. 22. Readings of electronic flowmeter of the top flooding system (R3) and level gauge (M7).

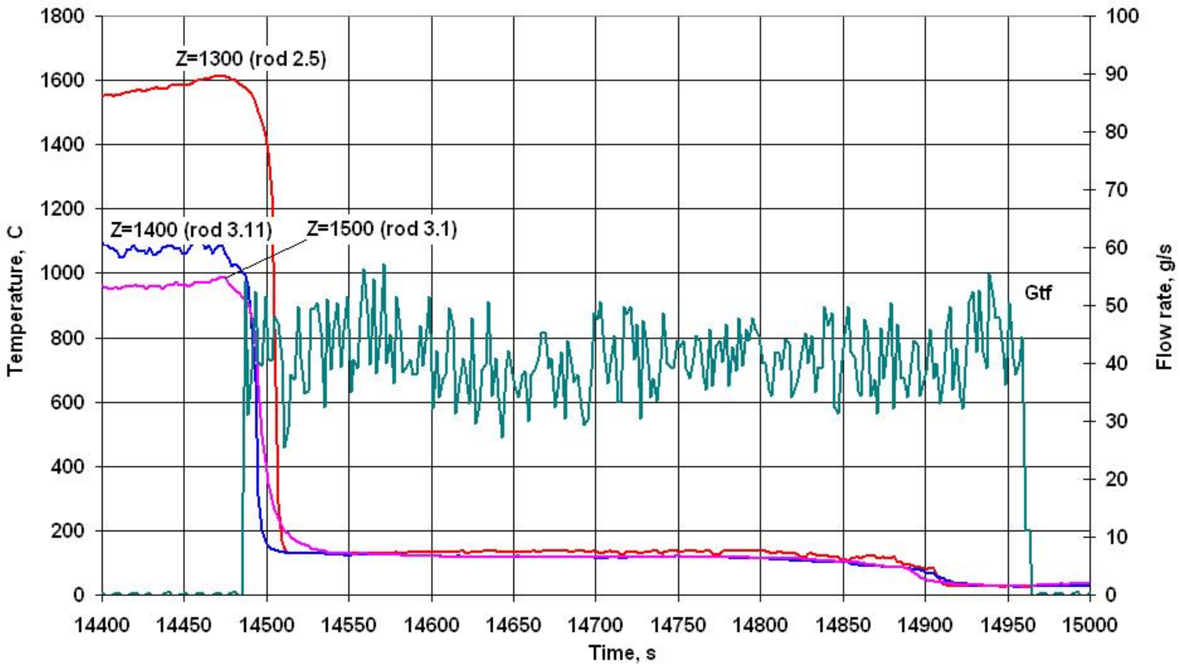


Fig. 23. Readings of thermocouples on fuel rod claddings at elevations Z = (1300 – 1500) mm at the quenching phase.

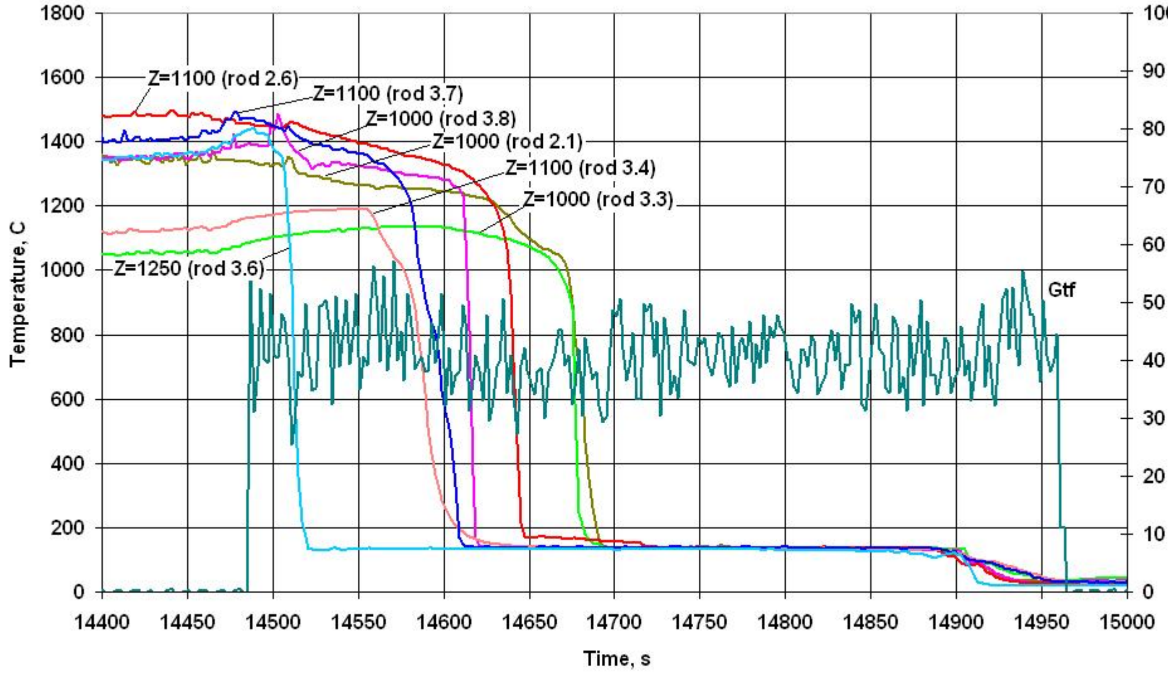
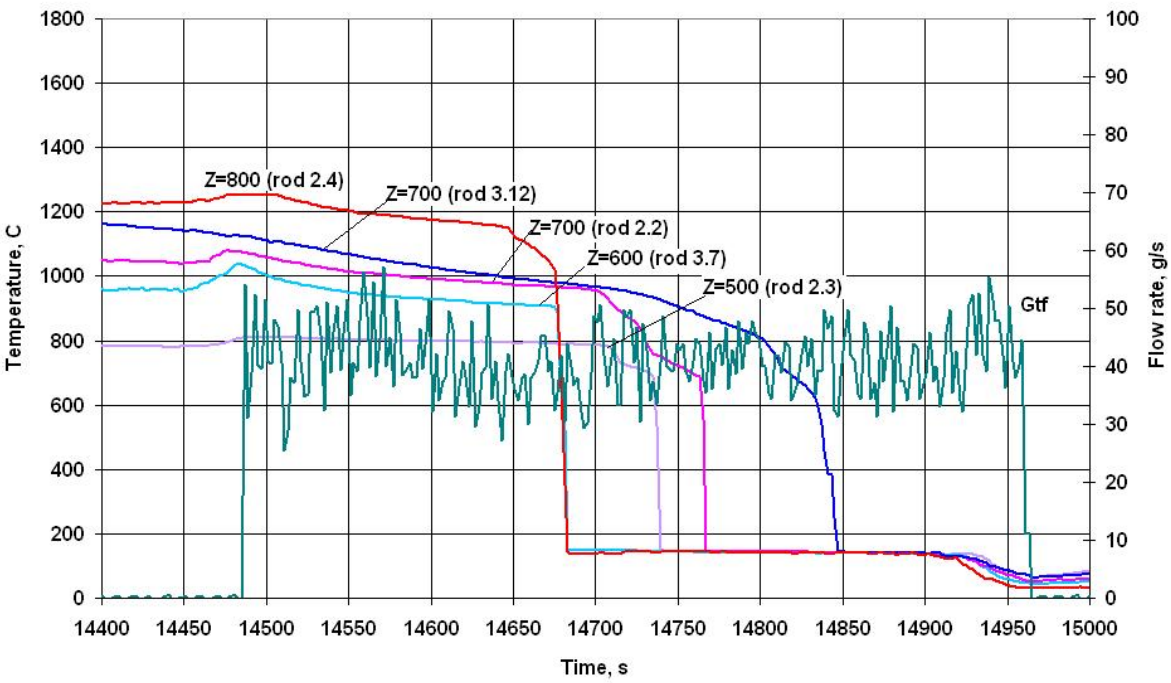
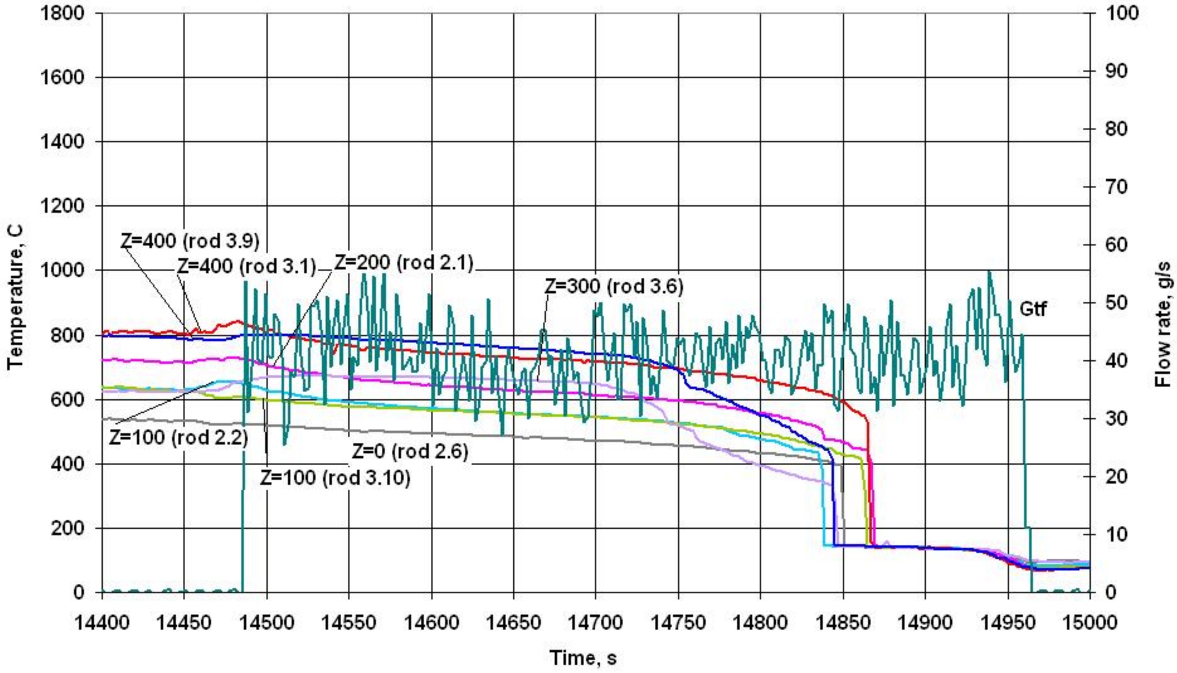


Fig. 24. Readings of thermocouples on fuel rod claddings at elevations Z = (1000 – 1250) mm at the quenching phase.



a)



b)

Fig. 25. Readings of thermocouples on fuel rod claddings at elevations
Z = (500 – 800) mm (a) and Z = (0 – 400) mm (b) at the quenching phase.

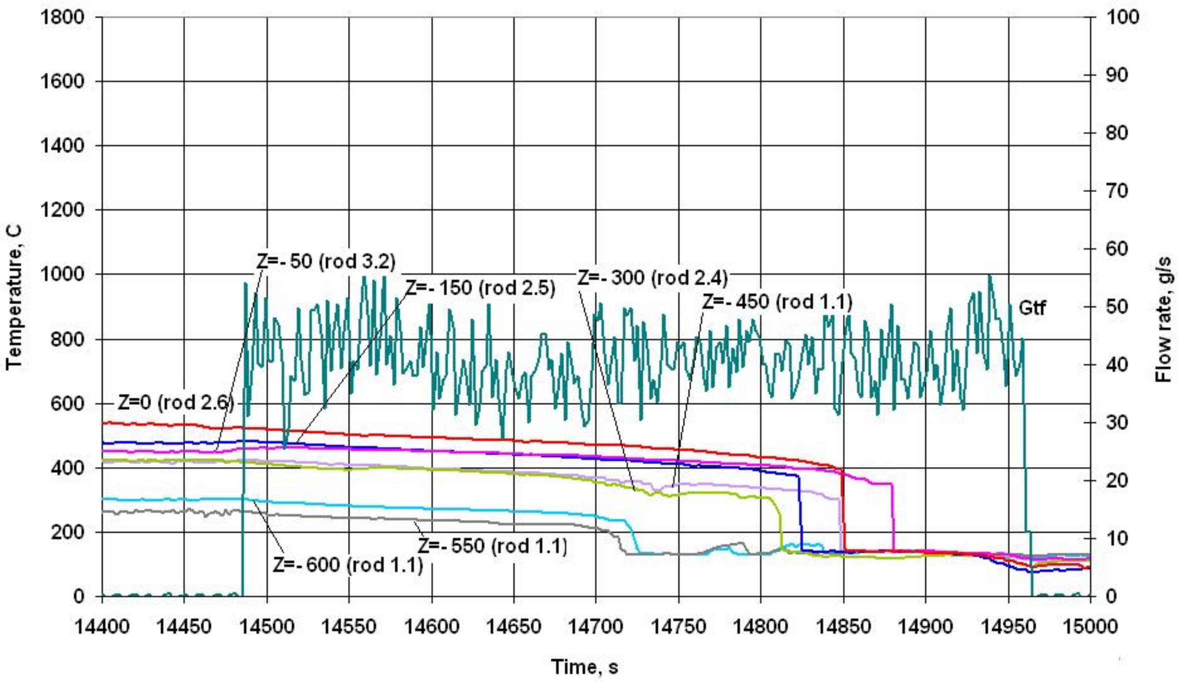


Fig. 26. Readings of thermocouples on fuel rod claddings at elevations
Z = (-600 – 0) mm at the quenching phase.

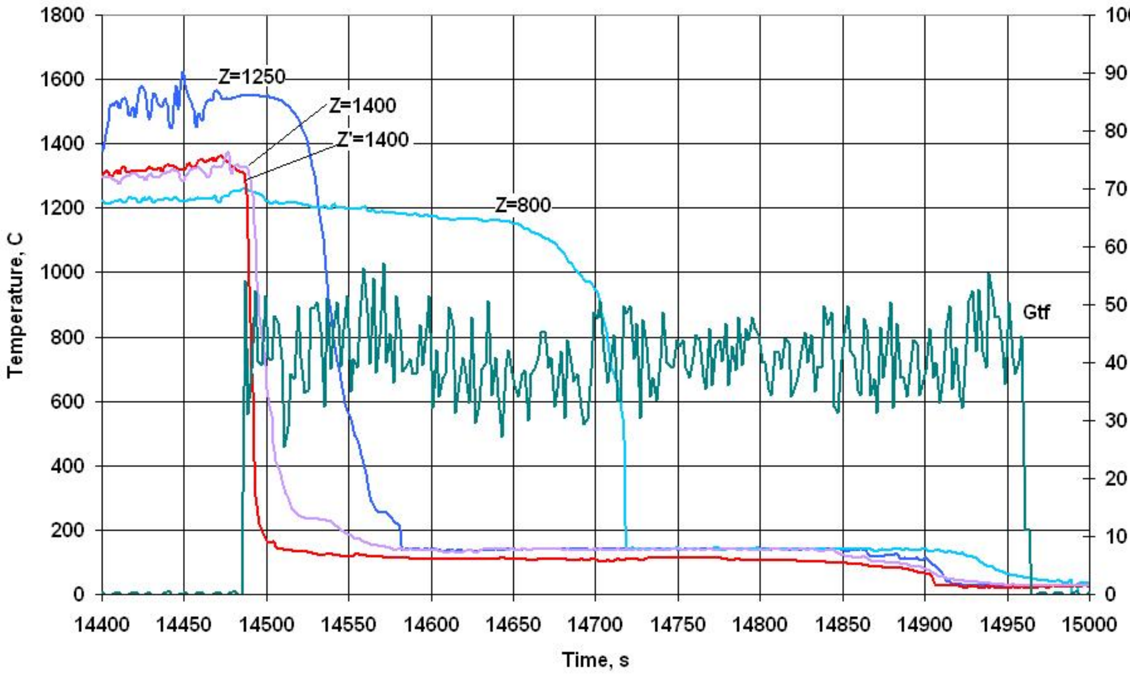


Fig. 27. Readings of thermocouples inside and on the cladding of fuel rod 1.1 at the quenching phase.

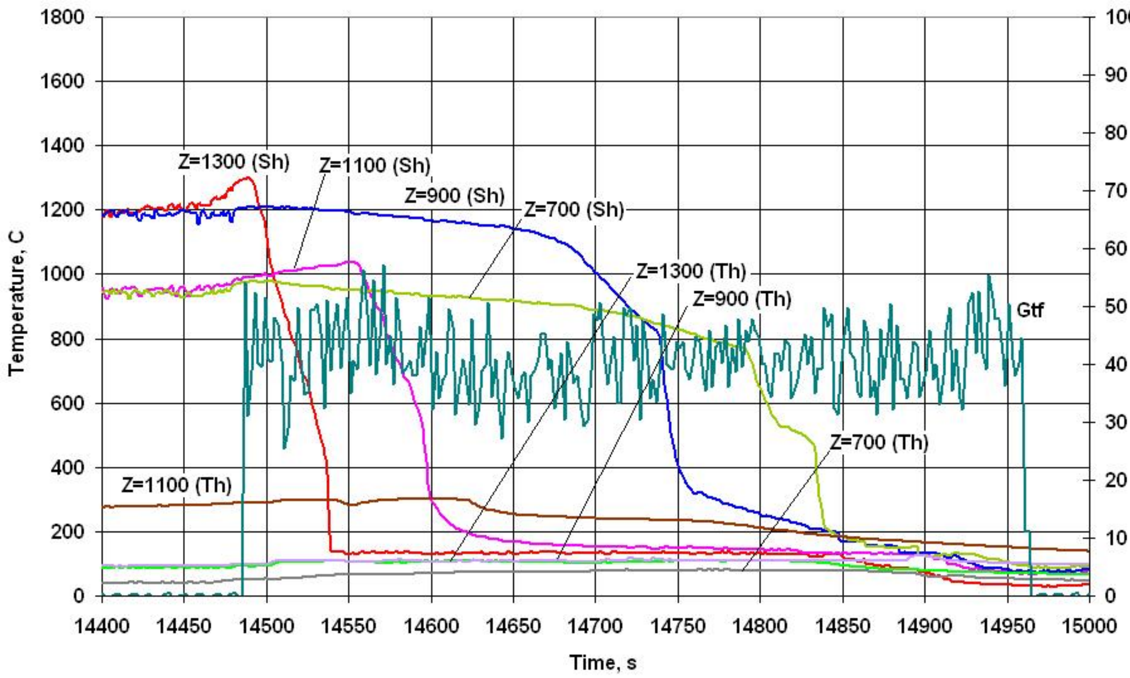


Fig. 28. Readings of thermocouples on the shroud (T_{sh}) and thermoinsulation (T_{th}) at the quenching phase.

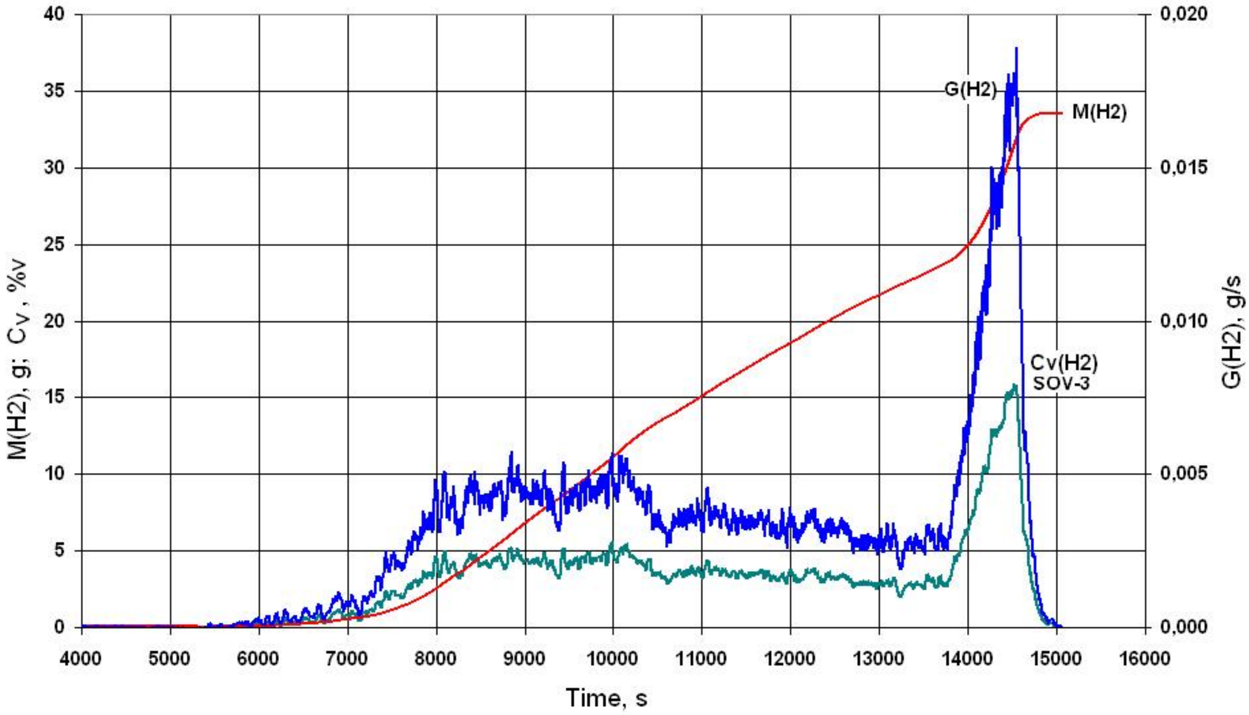


Fig. 29. Released hydrogen mass and generation rate.

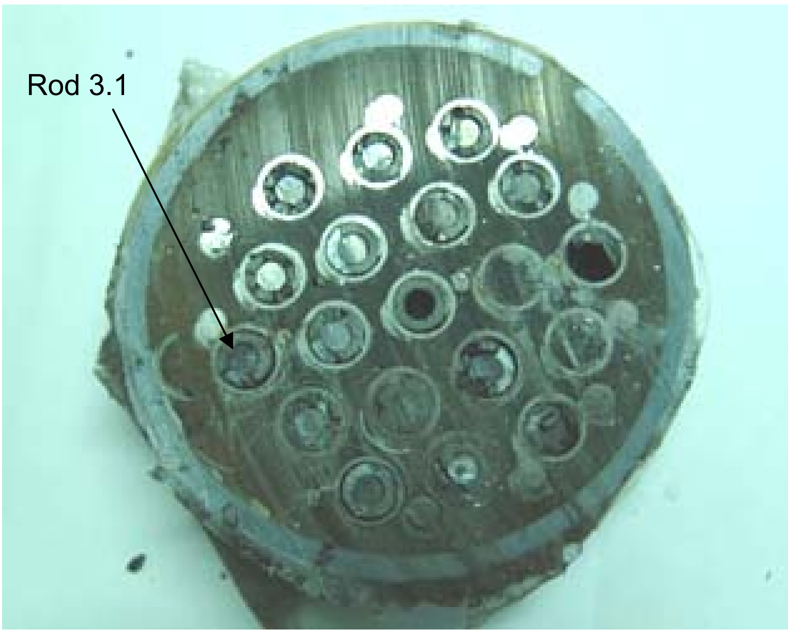


Fig. 30. SF3 bundle cross-section at elevation Z =600 mm.

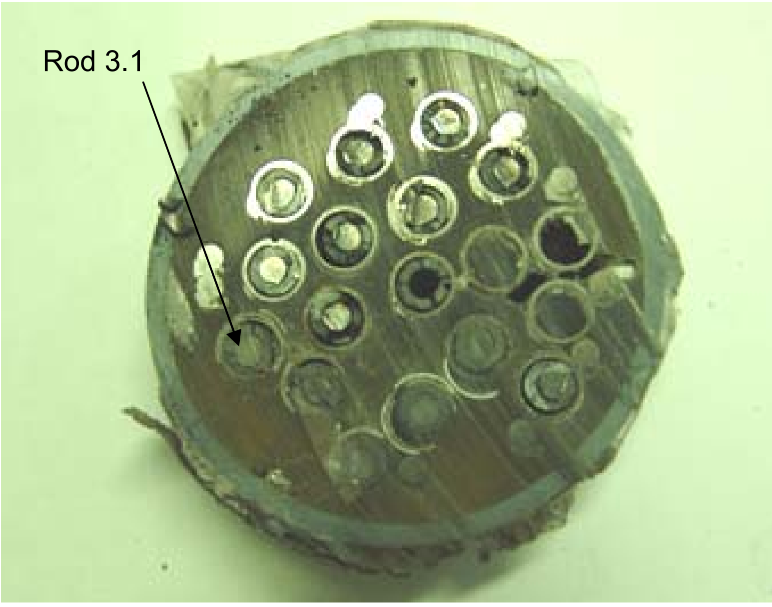


Fig. 31. SF3 bundle cross-section at elevation Z =700 mm.

Fig. 32. SF3 bundle cross-section at elevation Z =800 mm.

Fig. 33. SF3 bundle cross section at elevation Z =900 mm.