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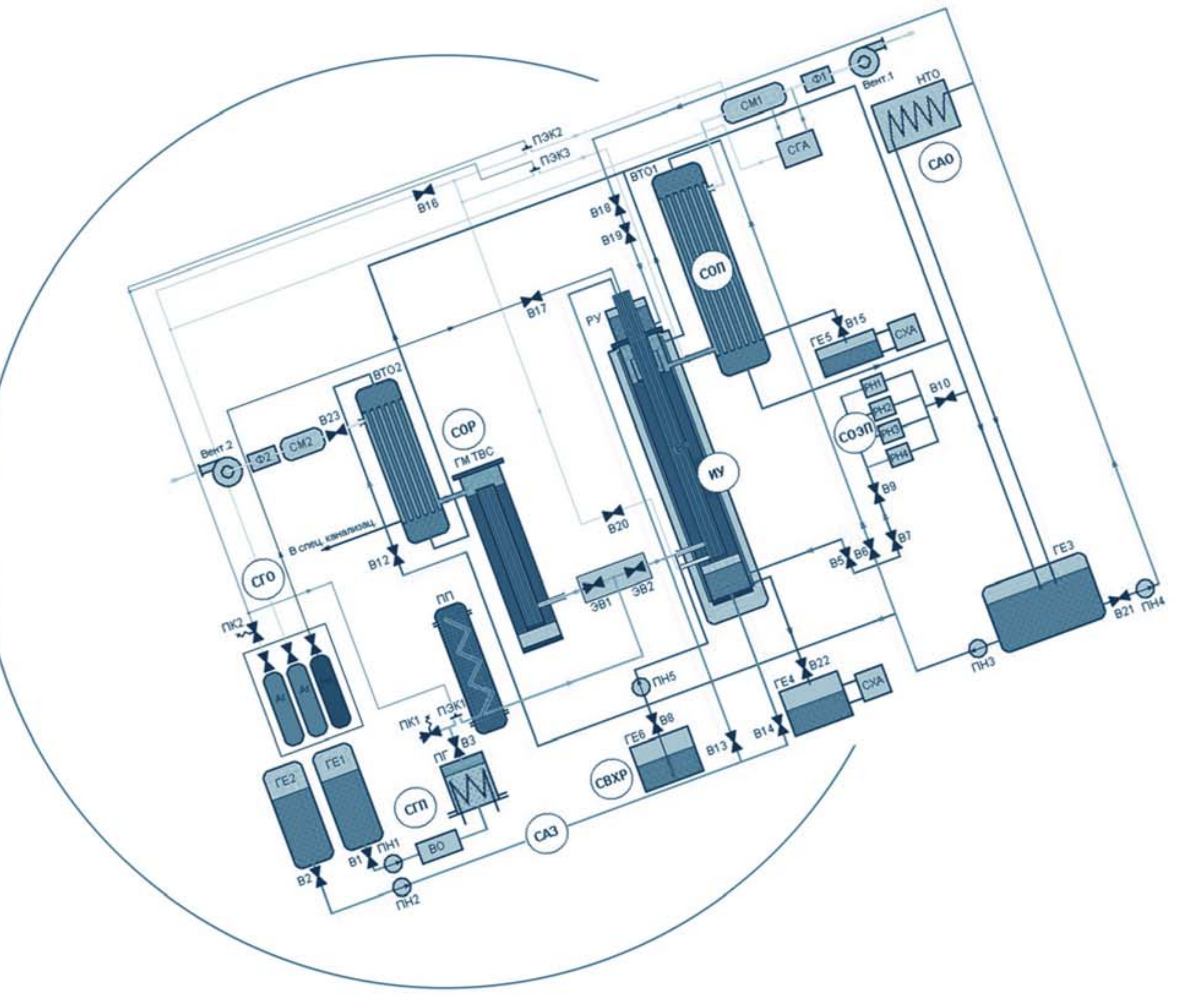
НИИ НПО "ЛУЧ"

PROJECT # 3194

"Fuel assembly tests under severe accident conditions"



2007

PROTOCOL
Of PARAMETER-SF2 Experiment
Results (April 03, 2007)

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

Organizations, which have taken part in the work:
A.A. Botchvar FSUE VNIINM
A.I. Leypunskiy SRC RF IPPE
RRC "Kurchatov Institute"

INTRODUCTION

The PARAMETER-SF2 experiment was performed on April 3, 2007, in the PARAMETER test facility in FSUE SRI SIA “LUCH” in cooperation with IBRAE RAS and FSUE EDO “GIDROPRESS” with participation of A.A. Botchvar FSUE VNIINM, A.I. Leypunskiy SRC RF IPPE, and the methodical support of foreign collaborators (FZK, GRS, EdF, IRSN) according to the Work Plan for ISTC Project # 3194.

The PARAMETER-SF2 experiment was the second one of the two planned experiments within the framework of Project # 3194.

In the SF2 experiment the initial stage of severe accident with large break LOCA was simulated with the core drying, its heating-up to ~ 1500°C and top and bottom water flooding.

The goal of the SF2 experiment was to study the 19-rods model FA of VVER-1000 under the simulated conditions of severe accident including the stages of low rate cooling with top flooding and the high rate cooling with the bottom flooding, and namely:

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

EXPERIMENTAL FACILITY

The PARAMETER-SF2 experiment was conducted in the PARAMETER test facility consisting of the following (see Fig. 1):

- Test section with the model FA;
- The system of electrical heating of the model FA and power supply to the test facility process systems;
- The system of steam generation and condensation;
- The system of the model FA emergency top and bottom 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 the heated carrier gas (argon), used in the system of hydrogen measurement, are supplied from bottom into the test section with the model FA. The steam that has not consumed, argon and hydrogen released in the oxidation reactions come from the top part of the test section into water-cooled condenser. The argon and hydrogen come from the condenser 1 into the system of gas analysis and then into the ventilation system.

The system of steam generation is fed from Pump 1, from Tank 1 (see Fig. 1), its volume being 75 L.

The top flooding is implemented with the independent system comprising water Tank 7 (volume being ~ 23 l and constant pressure p7), electric valve V3 and flow meter R3.

The bottom flooding is implemented with the independent system comprising water Tank 4 (volume being 28 l and constant pressure p8), electric valve V19 and flow meter R2.

In the course of the experiment the monitoring is carried out for the parameters of steam ($G_{st\ in}$, $T_{st\ in}$) and argon ($G_{Ar\ in}$, $T_{Ar\ in}$) at the test section inlet, and of the gas mixture flow rate (G_{Ar}(R4)) at the outlet to special ventilation, as well as the water mass in the main feeding tank (M1, Tank 1), tanks of the top (M7, Tank 7) and bottom (M4, Tank 4) flooding; mass of steam condensate in tanks (Tank 5, Tank 5', Tank 5.1, Tank 5.2, Tank 5.3, Tank 5.4, Tank 5.5), located downstream of condenser 1, mass of discharge water from the test section upper flange (Tank 6) and from the test section lower part (Tank 2).

TEST SECTION

For the PARAMETER-SF2 experiment a new test section has been developed and fabricated in FSUE SRI SIA “LUCH”, the test section structure allows to avoid the undesirable effects occurred in the PARAMETER-SF1 experiment.

The improved test section comprises three parts connected with flange joints (see Fig. 2):

1) Upper part (see Fig. 3) is intended for:

- introducing into the working volume and sealing the fuel rods, thermocouples and tubes of the top flooding system, similar to that used in the SF1 experiment;

- argon supply under bottom flooding;

- removal of steam-gas mixture from the test section to the heat exchanger-condenser;

- removal and control of water volume ejected from the mode assembly under top flooding,

and includes: a body – SS tube ∅ 133x6 mm (1) with the water cooling jacket ∅ 139x1 mm (2), the upper water-cooled flange (3) with the top flooding system including 41 tubes ∅ 4x1 mm (4), the guiding channel (5), the shell (6), the collecting thimble (7), the nozzles of steam-gas mixture outlet (Dnom=26) (8), of argon supply (Dnom=8) (9) under bottom flooding, of water discharge (Dnom=8) (10) ejected from the model assembly under top flooding, and the lower connecting water-cooled flange (11).

2) Central part (see Fig. 4) is intended for:

- arrangement of the tested model assembly, thermoinsulation and the system of test parameters monitoring;

- sealed separation of the cavity of thermoinsulation arrangement;

- compensation of the shroud temperature linear expansions

and includes: a body – SS 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) ∅ 70x2 mm of the model FA, thermoinsulation (7), upper (8) and lower (9) separating membranes, compensating bellows (10), thermoinsulation housing (11), nozzles (12) of argon inlet and outlet from the thermoinsulation cavity.

3) Lower part (see Fig. 5) is intended for:

- separate supply of steam and argon into the model assembly;

- supply of bottom flooding water into the test section;

- heating-up the cold walls of the body lower part to the steam saturation temperature for reducing the condensation of the supplied steam in the test section lower part

and includes: a body (1) – two SS tubes: ∅ 156x6x690 mm, ∅ 203x3x210 mm with the heater (2), nozzles for inlet of steam (3) and argon (4) (Dnom=8 mm), of water of the preliminary (5) and main (6) bottom flooding (2 nozzles Dnom=25 mm), upper connecting flange (7) and lower water-cooled flange (8) for inlet of current leads, thermocouples and water discharge. Temperatures of environment in the lower part of the test section and body are monitored by the measurement system including 9 thermocouples (TC): 5 TC – environment temperature monitoring, 4 TC – body temperature monitoring.

MODEL FA

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

Table 1

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
Height of fuel rods heated, mm	3120
Height of fuel rod unheated, mm	2950
Heater material	tantalum
Sizes of the fuel rod heater, mm:	
diameter/height	4/1275
coordinates	от 0 до 1275
Coordinate of the place of steam/argon inlet (radial), mm	-355 ($270^o/90^o$)
Coordinate of the place 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 $7.6^{-0.03}/4.2^{+0.15}/11^{\pm 0.1}$
Fuel rod unheated	No UO_2 pellets
Spacing grid	
Material	Zr-1%Nb
Height, mm	20
Number, pcs.	6
Distance between grids, mm	255
Coordinates 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
Height, mm	1490

Thermoinsulation	
Material	ZrO_2 ZYFB-3
Thickness, mm	23
Height, mm	1490
Thermoinsulation housing	
Material	Steel 2X18H10T
Thickness, mm	1
Height, mm	1490
Outer diameter/thickness, mm	118/1

The scheme, general view and cross-section of the model FA are presented in Fig. 6, general view of the heated and unheated fuel rod simulators – in Fig. 7. All fuel rod simulators (except for the central unheated fuel rod) are combined into one heating section.

In the upper part of the model FA there is the water injection system (see Fig. 2, 3), comprising 41 tubes ∅ 4x1 mm in the test section upper flange, the guiding tube and the collecting cylinder.

Each fuel rod of the assembly is equipped in its upper part with the helium filling device including the capillary tube ∅ 1.6x0.3 mm with the length of ~1500 mm. All the capillaries are connected to the common compensatory volume of ~10 L.

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

No.	Designa-tion	Type	Purpose and location	Output signal
1	**$T_{st\ in}$**	Ch/Al	Steam temperature at the inlet of the test section, steam inlet nozzle – 355 mm, 270°	^oC
2	**$T_{Ar\ in}$**	Ch/Al	Argon temperature at the inlet of the test section, argon inlet nozzle – 355 mm, 90°	^oC
3	**T11-6**	Ch/Al	Fuel rod cladding temperature 1.1, -600 mm	^oC
4	**T11-5.5**	Ch/Al	Fuel rod cladding temperature 1.1, -550 mm	^oC
5	**T11-4.5**	Ch/Al	Fuel rod cladding temperature 1.1, -450 mm	^oC
6	**T24-3**	Ch/Al	Fuel rod cladding temperature 2.4, -300 mm	^oC
7	**T25-1.5**	Ch/Al	Fuel rod cladding temperature 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	Fuel rod cladding temperature 3.2, -50 mm	^oC
10	**T260**	Ch/Al	Fuel rod cladding temperature 2.6, 0 mm	^oC

11	**T230.5**	Ch/Al	Fuel rod cladding temperature 2.3, 50 mm	^oC
12	**T221**	Ch/Al	Fuel rod cladding temperature 2.2, 100 mm	^oC
13	**T3101**	Ch/Al	Fuel rod cladding temperature 3.10, 100 mm	^oC
14	**T212**	Ch/Al	Fuel rod cladding temperature 2.1, 200 mm	^oC
15	**T352**	Ch/Al	Fuel rod cladding temperature 3.5, 200 mm	^oC
16	**p2**	-	Pressure sensor near fuel rod 3.7, 200 mm	MPa
17	**T253**	Ch/Al	Fuel rod cladding temperature 2.5, 300 mm	^oC
18	**T363**	Ch/Al	Fuel rod cladding temperature 3.6, 300 mm	^oC
19	**T314**	Ch/Al	Fuel rod cladding temperature 3.1, 400 mm	^oC
20	**T394**	Ch/Al	Fuel rod cladding temperature 3.9, 400 mm	^oC
21	**T235**	Ch/Al	Fuel rod cladding temperature 2.3, 500 mm	^oC
22	**T3115**	Ch/Al	Fuel rod cladding temperature 3.11, 500 mm	^oC
23	**T376**	Ch/Al	Fuel rod cladding temperature 3.7, 600 mm	^oC
24	**T227**	Ch/Al	Fuel rod cladding temperature 2.2, 700 mm	^oC
25	**T397**	Ch/Al	Fuel rod cladding temperature 3.9, 700 mm	^oC
26	$T_{sh}7$	WRe	Shroud temperature (opposite of fuel rod 3.2), 700 mm	^oC
27	$T_{th}7$	Ch/Cop	Thermal insulation temperature (opposite of fuel rod 3.2), 700 mm	^oC
28	$T_{st}7.75$	WRe	Steam temperature, 775 mm	^oC
29	**T117.75**	WRe	Fuel rod cladding temperature 1.1, 775 mm	^oC
30	**T257.75**	WRe	Spacing grid temperature, 775 mm	^oC
31	**T369**	WRe	Fuel rod cladding temperature 3.6, 900 mm	^oC
32	**T389**	WRe	Fuel rod cladding temperature 3.8, 900 mm	^oC
33	**p9**	-	Pressure sensor near fuel rod 3.11, 900 mm	MPa
34	$T_{sh}9$	WRe	Shroud temperature (opposite of fuel rod 3.8), 900 mm	^oC
35	$T_{th}9$	Ch/Cop	Thermal insulation temperature (opposite of fuel rod 3.8), 900 mm	^oC
36	**T1110.3**	WRe	Fuel rod cladding temperature 1.1, 1030 mm	^oC
37	**T2110.3**	WRe	Spacing grid temperature, 1030 mm	^oC
38	$T_{st}10.3$	WRe	Steam temperature, 1030 mm	^oC
39	**T1111**	WRe	Fuel rod cladding temperature 1.1, 1100 mm	^oC
40	**T2111**	WRe	Fuel rod cladding temperature 2.1, 1100 mm	^oC
41	**T2411**	Ch/Al	Fuel rod cladding temperature 2.4, 1100 mm	^oC
42	**T3311**	Ch/Al	Fuel rod cladding temperature 3.3, 1100 mm	^oC
43	**T31011**	WRe	Fuel rod cladding temperature 3.10, 1100 mm	^oC
44	**T31211**	WRe	Fuel rod cladding temperature 3.12, 1100 mm	^oC
45	$T_{sh}11$	WRe	Shroud temperature (opposite of fuel rod 3.1), 1100 mm	^oC
46	$T_{th}11$	Ch/Cop	Thermal insulation temperature (opposite of fuel rod 3.1), 1100 mm	^oC
47	**T2312.5**	WRe	Fuel rod cladding temperature 2.3, 1250 mm	^oC
48	**T2512.5**	PtRh	Fuel rod cladding temperature 2.5, 1250 mm	^oC
49	**T2612.5**	Ch/Al	Fuel rod cladding temperature 2.6, 1250 mm	^oC

50	**T3212.5**	WRe	Fuel rod cladding temperature 3.2, 1250 mm	^oC
51	**T3412.5**	PtRh	Fuel rod cladding temperature 3.4, 1250 mm	^oC
52	**T31112.5**	Ch/Al	Fuel rod cladding temperature 3.11, 1250 mm	^oC
53	**p12.5**	-	Pressure sensor near fuel rod 3.6, 1250 mm	MPa
54	**T1112.85**	WRe	Fuel rod cladding temperature 1.1, 1285 mm	^oC
55	**T2312.85**	WRe	Spacing grid temperature, 1285 mm	^oC
56	**T_{st}12.85**	WRe	Steam temperature, 1285 mm	^oC
57	**T3113**	Ch/Al	Fuel rod cladding temperature 3.1, 1300 mm	^oC
58	**T3513**	Ch/Al	Fuel rod cladding temperature 3.5, 1300 mm	^oC
59	**T3713**	Ch/Al	Fuel rod cladding temperature 3.7, 1300 mm	^oC
60	**T_{sh}13**	WRe	Shroud temperature (opposite of fuel rod 3.6), 1300 mm	^oC
61	**T_{th}13**	Ch/Cop	Thermal insulation temperature (opposite of fuel rod 3.6), 1300 mm	^oC
62	**T2314**	Ch/Al	Fuel rod cladding temperature 2.3, 1400 mm	^oC
63	**T2115**	Ch/Al	Fuel rod cladding temperature 2.1, 1500 mm	^oC
64	**T2515**	Ch/Al	Fuel rod cladding temperature 2.5, 1500 mm	^oC
65	**p15**	-	Pressure sensor near fuel rod 3.9, 1500 mm	MPa
66	**$T_{st\ out}$**	Ch/Al	Steam temperature at the outlet of the test section, steam outlet nozzle, 1425 mm, 0^o	^oC

The system of measuring the testing parameters of the model assembly includes 44 TCs for measuring the cladding temperature of fuel rods located at 22 levels: from -600 to +1500 mm (with a pitch of 100 mm on the heater section); 3 TCs for measuring the temperature of spacing grids at 3 levels (775; 1030; 1285 mm); 8 TCs for measuring the temperature of cladding and thermal insulation at 4 levels (700; 900; 1100 and 1300 mm); 3 TCs for measuring the steam temperature in FA at three levels (775; 1030; 1285 mm) and 3 TCS for measuring the steam and argon temperature at the test section inlet and outlet.

In the system of measuring the assembly temperature the TCs of four types were used (see Fig. 8): cable Ch/Al (Ch/Cop) in the SS jacket ∅ 1.5 mm with the limit of measured temperatures of 1300^oC (800^oC) and high-temperature thermocouples: WRe – W+5%Re/W+20%Re in zirconium alloy Zr+1%Nb jacket ∅ 2.8x0.7 mm and PtRh – Pt + 6%Rh/Pt + 30%Rh with the limit of measured temperatures to 2000^oC.

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

TCs for measuring the temperature of spacing grids were placed in cells inside the spacing grid (see Fig. 9).

Pressure of steam-argon mixture was monitored with five pressure sensors at the levels of Z = -150 mm (p-1,5); 200 mm (p2); 900 mm (p9); 1250 mm (p12.5) and 1500 mm (p15). Helium pressure in fuel rods was monitored with pressure sensor in the compensatory volume (p_{rod}).

PROCESS PARAMETER MONITORING

Collection and registration of testing parameters and PARAMETER facility parameters is made by the bench system ASNI on the base of two PCs PENTIUM-II with software PARAM_19, developed on the basis of code package GENIE 3.0, with frequency of inquiry of 2 s.

FA electric power is set by the direct current generator “Flex Kraft” 2500 A/15 V and determined by prompt values of current $I(\tau)$ and voltage $U(\tau)$ on FA, measured with the use of ADP ЛА-1,5PCI PC PENTIUM-II (frequency of inquiry is 0,01 s) and integrated by electric power calculation program Power5V.

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

Argon flow rate $G_{Ar\ in}$ is set by argon pressure at the outlet of gas manifold and monitored by argon parameters on the flow metering section (T3, p3) and indications of electron flow meter R4.

The top flooding water flow rate is set by the pressure p7 in Tank 7 and monitored by water volume in Tank 7 and indications of electron flow meter R3.

The bottom flooding water flow rate is set by the pressure p8 in Tank 4 and monitored by water volume in Tank 4 and indications of electron flow meter R2.

Mass of steam condensate after condensation in condenser 1 is monitored: at the preparatory stage (the stage of stabilization of steam and argon parameters) – in Tank 5’, at the stages of reaching the preoxidizing phase, at the preoxidizing phase and the transient phase - in Tank 5.1,…, Tank 5.5, at the flooding phase - in Tank 5. The mass of water in the test section after flooding phase is monitored in Tank 2, mass of water ejected from the assembly under flooding – in Tank 6.

Water masses is checked after the experiment by weighing on electronic balance ПВ-6 with an accuracy to ±0.5 g.

HYDROGEN MEASUREMENT SYSTEM

The system of measuring the hydrogen generated in high-temperature interaction of steam with materials of the model FA, including fuel rod claddings, spacing grids, shroud and protective jackets of thermocouples, is similar to the system used in performing the SF1 experiment.

The hydrogen measurement system is located downstream of condenser 1 in additional gas path of the PARAMETER test 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 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.

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.

After the experiment the tanks are sealed and disconnected from the gas path with subsequent analysis of gas mixtures with the help of gas chromatograph CHROMATEC-CRYSTAL 5000. The obtained results are synchronized in time with the indications of the continuous registration system SOV-3.

PARAMETER-SF2 EXPERIMENT

Experiment scenario

PARAMETER-SF2 experiment was performed on April, 3, 2007, in the PARAMETER test facility in FSUE SRI SIA "LUCH" with the analytic support of the specialist groups performing the calculations using the computer codes RATEG/SVECHA, PARAM-TG and ICARE/CATHAR. The pre-test scenario of the experiment is presented in Table 3.

Table 3

Pre-test scenario of PARAMETER-SF2 experiment

No.	Stage	Main parameters			
		FA temperature, °C	Environment	Heating rate, °C/s	Time, s
1	***Heating of the assembly within argon***	20-100	Argon flow at temperature to 400°C (argon flow rate is 2 g/s)	–	0-1000
2	***Heating of the assembly within the steam and argon flow***	100-500	Steam-argon mixture (argon/steam flow rate is 2/3.3 g/s)	_	1000-4000
3	***Heating of the assembly up to 1200°C***	500-1200	Steam-argon mixture (argon/steam flow rate is 2/3.3 g/s)	~0.3	4000-6000
4	***Pre-oxidation of the assembly***	~ 1200	Steam-argon mixture (argon/steam flow rate is 2/3.3 g/s)	–	6000-10000
5	***Heating of the assembly up to 1500°C***	1200-1500	Steam-argon mixture (argon/steam flow rate is 2/3.3 g/s)	~0.3	10000-11000

6	***Top flooding of the assembly (when the assembly reaches the temperature T_{max}=1500^{o}C)***	Till complete cooling of the assembly	Water (flow rate of 40 g/s per assembly)	–	Duration of flooding ~ 150 s
7	***Bottom flooding of the assembly (in 50 s after the beginning of the top flooding or when the assembly temperature decreases less ≈630^{o}C at the level of 1250 mm)***	Till complete cooling of the assembly	Water (flow rate of 100 g/s per assembly)	–	Duration of flooding ~ 100 s

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

Table 4

Main events of PARAMETER-SF2 experiment

Moment of time, s	Events
0	Switching on the information and measurement system
~ 2200	Supply of argon into the assembly with the flow rate of ~ 2 g/s at temperature of ~ 420^{o}C
~ 5500	Supply of steam into the assembly with the flow rate of ~ 3.5 g/s at temperature of ~ 500^{o}C
~ 5800	Heating the assembly to temperature of 500±50^{o}C at the level of 300-1300 mm
~ 8680	Increase in temperature and heating the assembly at 700±50^{o}C at the level of 1100-1300 mm
5908	Beginning of the assembly slow heating-up
11900	Beginning of the preoxidizing phase
15300	Beginning of the assembly heating-up to temperature of 1500^{o}C
16497	Electric power is off
16514	Closure of the valve of steam supply into the assembly
16508	Opening of the top flooding valve
16535	Opening of the bottom flooding valve
16626	Closure of the top and bottom flooding valves
17123	Switching off the information and measurement system

Experiment description

The PARAMETER-SF2 experiment was started after checking the correct position of the valves, presence of argon, helium and distilled water inventory sufficient for starting the experiment.

The experiment included four stages:

- *preparatory stage* (0 – 11900 s – stabilization of the assigned flow rates of argon ($G_{Ar\ in}$ ≈ 2 g/s) and steam ($G_{st\ in}$ ≈ 3.5 g/s) at FA temperature T_{FA} ≈ 500°C, check of the state of the assembly and process systems at FA temperature T_{FA} ≈ 700°C, heating-up the assembly to temperature of ≈ 1200°C in the hottest zone;

- *pre-oxidation phase* (11900 – 15300 s) – FA holding at temperature of ≈ 1200°C in the hottest zone during ~ 3400 s. Maximum deviations of temperature in the hottest section (1250 mm) were ~ ± 50°C;

- *transient phase* (15300 – 16510 s) – rise of FA temperature in the hottest section to 1500°C;

- *flooding:*

- top flooding (16512 – 16628 s) – top water flooding of the assembly with the flow rate of Gtf ≈ 40 g/s;

- bottom flooding (16536 – 16628 s) – bottom water flooding of the assembly with the flow rate of Gbf ≈ 130 g/s.

Preparation stage

At 0 s the information and measurement system and system of hydrogen detection SOV-3 were switched on, the valves V21, V25, V26, V27 and V28 open.

From 56 to 206 s the argon was supplied into the thermal insulation cavity twice, having opened the valve V5, to set the assigned pressure.

At 368 s the valve V2 was opened and the preliminary argon flow rate $G_{Ar\ in}$ ≈ 1.1 g/s into the model assembly was set (~ 380 s) for cleaning of steam-gas paths (see Fig. 10).

At 642 s the argon heater was switched on for heating the argon to the assigned temperature $T_{Ar\ in}$ ≈ 400°C.

At 1060 s the model FA heating in argon flow was started – the electric power of ~ 1600 W was supplied to FA (see Fig. 11).

At ~ 1498 s the pressure p3 was increased for increasing the argon flow rate into the assembly. At 1558 c, for acceleration of argon pressure setting in the assembly, the valve V7 was closed at 210 s, and after its opening the test electronic rotameter R4, at the outlet to special ventilation, recorded the assigned argon flow rate $G_{Ar}(R4) \approx 2$ g/s at ~ 1770 s (see Fig. 10).

At 2132 s the valve V22 was opened for collecting the condensate into Tank 5' (see Fig. 1).

At 2472 s at FA temperature of ~ 400^{o}C in sections at the levels of 300-1250 mm the valve V1 was opened and the steam was supplied to the FA test section (see Figs. 10, 12 – decrease in FA temperature within the time interval of 2500-3700 s is caused by FA cooling with steam flow).

By ~ 5000 s the FA temperature in sections at the level of 1100-1300 mm reached ~500±50^{o}C (see Fig. 12).

At ~ 4999 s the valves V22, V24 were closed and the valve V23 was opened for condensate discharge into Tank 5.1 (see Fig. 1).

From ~ 5114 to 5420 s the bottles with technical argon were switched over to the bottles with high purity argon.

At 5799 s the valve V28 was closed – the condensate collection into Tank 5.1 was stopped.

By ~5800 s the stable behaviour of the main parameters was observed: at the settled flow rates of argon and steam ($G_{Ar\ in} \approx 2$ g/s, $G_{st\ in} \approx 3.5$ g/s) the FA temperature (T_{FA}) was ~ 500±50^{o}C practically along the whole length of the active part (300-1300 mm) (see Fig. 12); the pressure of steam-gas mixture in FA was ~ 0.3 MPa, the pressure of helium inside fuel rods was ~ 0.3 MPa, the pressure of argon in the thermal insulation cavity was ~ 0.3 MPa (see Fig. 13).

From ~ 5908 to ~7420 s the stepwise increase in the assembly power was made from ~ 1600 W to ~ 3600 W with a step of ~ 500 W (see Fig. 11).

At 7501 s the valve V27 or the condensate collection into Tank 5.2 was closed (see Fig. 1).

At ~ 8680 s with the assembly power of ~ 3600 W the assembly temperature in sections 900-1300 mm was settled at the level of 700±50^{o}C (see Fig. 12).

From ~ 8906 to ~12255 s the stepwise power increase of the assembly was made from ~ 3600 W to ~ 6600 W, and temperature of fuel rod claddings, by indications of thermocouples in the assembly sections 1250-1300 mm, increased to ~ 1170^{o}C in the second row, to ~ 1100^{o}C in the third row (see Fig. 15). With this, at ~11896 s in the section at the level of 1250 mm the following temperature was recorded by thermocouples (see Fig. 15):

- ~1200°C (T2612.5 – fuel rod 2.6 of the second row);

- ~1170°C (T31112.5 – fuel rod 3.11 of the third row).

At 10000 s the valve V26 for the condensate collection into Tank 5.3 was closed (see Fig. 1).

Pre-oxidation phase

Beginning from ~ 12000 s the assembly pre-oxidation phase was started (at ~11896 s the thermocouple T2612.5 in the section at the level of 1250 mm recorded the temperature of fuel rod cladding being ~1200°C).

At 12448 s the valve V25 for the condensate collection into Tank 5.4 was closed (see Fig. 1).

From ~12257 to ~13300 s the stepwise power increase of the assembly was made from ~ 6600 to ~ 8300 W, with this, by ~13600 s the maximum temperature of fuel rod cladding in the assembly section 1250 mm was ~ 1270°C by indications of thermocouples (TC T2312.5, fuel rod 2.3 of the 2nd row, Fig. 15). Temperature of claddings of the rest of fuel rods did not exceed ~ 1200°C (see Fig. 15).

At 12971 s, with the beginning of hydrogen registration by SOV-3 system, the automatic sampling system was switched on with the time of gas sampling being 8 s and frequency of 750 s (Vol.1 - Vol.4), 250 s (Vol.5) and 500 s (Vol.6 - Vol.7) (see Fig. 18).

At 12976 s the gas sampling into tank Vol.1 was started.

For stabilization of the conditions the assembly power was decreased to ~ 8000 W from ~ 13366 s to ~ 13577 s, and from ~ 14160 s it was increased to ~ 8240 W and kept at this level till 15300 s (see Fig. 11). Temperature of fuel rod claddings at the levels of 1100-1300 mm under these conditions was 1150-1250°C in the second row, by indications of thermocouples, and 1070-1180°C in the third row (see Fig. 15, 16).

At 13726 s the gas sampling into tank Vol.2 was started.

At 14476 s the gas sampling into tank Vol.3 was started.

The duration of the preoxidizing stage was ~ 3400 s, maximum deviation of temperature in the hottest section (1250 mm) was ~70°C (TC T2312.5, fuel rod 2.3 of the 2nd row, Fig. 15).

At 15000 s the valve V23 was closed. the condensate collection into Tank 5.5 was stopped. Due to failure of the valve V20 of Tank 6 the condensate was drained from Tank 5' and the valves V22 and V24 were opened for condensate collection into Tank 5' (see Fig. 1).

At 15226 s the gas sampling into tank Vol.4 was started.

Transient phase

From ~ 15300 to ~ 15930 s the stepwise power increase was made from ~ 8300 W to ~ 10500 W, that was kept at this level for ~ 560 s (see Fig. 11). With this, the maximum FA temperature in the hottest section (1250 mm) increased to 1480°C by ~ 16500 s (T2312.5, fuel rod 2.3 of the 2nd row, see Fig. 15). At the same time the maximum cladding temperature of fuel rods of the third row was ~ 1430°C (TC T3212.5, fuel rod 3.2 of the 3rd row, Fig. 15).

At 15476 s the gas sampling into tank Vol.5 was started.

In the course of rise of the FA temperature the increase in pressure occurs: of steam-gas mixture in FA – from ~ 0.30 to ~ 0.32 MPa; of helium inside fuel rods – from ~ 0.30 to ~ 0.31 MPa (see Fig. 19). The pressure in the thermal insulation cavity did not change.

In the course of temperature rise the SOV-3 system registered the increase in volumetric hydrogen concentration (see Fig. 18).

At 15978 s the gas sampling into tank Vol.6 was started.

At 16478 s the gas sampling into tank Vol.7 was started.

Flooding

At ~ 16497 s, when the assembly reached the maximum temperature of 1480°C, the electric power was switched off and at 16508 s the valve V3 was opened for supply of top flooding water from Tank 7. The average water flow rate, registered by electronic flow meter R3, was ~ 41 g/s (see Fig. 23).

In the course of top flooding the model assembly thermocou0ples registered the successive temperature decrease at the following levels: 1500 – 1400 mm (see Fig. 24), 1300 mm (see Fig. 25a), 1250 mm (see Fig. 25b), over the height of the central fuel rod 1.1 (see Fig. 30), at the level of 1285 mm of the upper spacing grid (see Fig. 31) and at the level of 1300 mm of the shroud (see Fig. 32).

At ~ 16508 s the valve V24 for the condensate collection into Tank 5' was closed and the condensate collection was continued into Tank 5 (see Fig. 1).

From 16514 s the stepwise switching off the steam generation system was made: the steam generator power supply was switched off and the valve V1 was closed; at 16516 s the steam superheater power supply was switched off; at 16520 s the water supply to steam generator was stopped (trip of Pump 1).

At 16514 s the power supply to the argon heater was also switched off.

At ~ 16529 s the valve V4 for argon supply to the test section upper part was opened.

At ~ 16535 s, after decrease in the assembly temperature in section 1285 mm (T2312.85, spacing grid, fuel rod 2.3, see Fig. 31) to ~ 700^{o}C the valve V19 for supply of the bottom flooding water from Tank 4 was opened. The average water flow rate, registered by electronic flow meter R2 in the course of flooding, was ~ 130 g/s (see Fig. 23).

In the course of the bottom flooding the model assembly thermocouples registered the successive temperature decrease at the following levels: -600 – 0 mm (see Fig. 28), 0 – 700 mm (see Fig. 27), 900 – 1100 mm (see Fig. 26).

In the course of the flooding phase the pressure jumps in the assembly were registered in ~ 2 s after beginning of the top flooding and in ~ 50 s after beginning of the bottom flooding (see Fig. 29).

At 16626 s after decrease in the assembly temperature to ~ 120^{o}C the valves V3 and V19 for supply of the top and bottom flooding water were closed. Duration of the top flooding was ~ 120 s, and duration of the bottom flooding was ~ 93 s.

At 17123 s the information and measurement system and the system of hydrogen detection SOV-3 were switched off.

Experiment results

The experiment results are presented in Figs. 10 – 38.

In Figs. 10 and 11 the results are presented on measuring the main parameters of the experiment: flow rate and temperature of argon ($G_{Ar\ in}$, $T_{Ar\ in}$) and steam ($G_{st\ in}$, $T_{st\ in}$) at the test section inlet; flow rate of gas mixture (G_{Ar}(R4)) at the outlet to special ventilation (Fig. 10); the assembly electric parameters (Fig.11): power (P), current (I), voltage (U).

Figs. 12 – 13 present the indications of thermocouples over the height of fuel rod claddings (Fig.12) and of pressure sensors (Fig. 13): in the model assembly (p_{bnl}), fuel rods (p_{rod}), thermoinsulation cavity (p_{th}).

Figs. 14 – 17 give the more detailed presentation of thermocouple indications on fuel rod claddings at the following levels: Z = (1400 – 1500) mm (Fig. 14), Z = (1250 – 1300) mm (Fig. 15), Z = (900 – 1100) mm (Fig. 16) and Z = (0 – 700) mm (Fig. 17) within the time interval of 10000 – 18000 s.

Fig. 18 presents the results of measuring the volumetric hydrogen concentration by the system of hydrogen detection SOV-3 and in seven sampling tanks (Vol.1,…,Vol.7).

Fig. 19 presents the indications of pressure sensors in fuel rods (p_{rod}), at different elevations: p-1.5 (Z = -150 mm), p2 (Z = 200 mm), p9 (Z = 900 mm), p12.5 (Z = 1250 mm), p15 (Z = 1500 mm) and in thermal insulation cavity (p_{th}) within the time interval of 10000 – 18000 s.

Fig. 20 presents the indications of thermocouples on the inside surface of cladding of the central measuring fuel rod 1.1 within the time interval of 10000 – 18000 s.

Fig. 21 presents the indications of thermocouples on three upper spacing grids (Z = 775, 1030, 1285 mm) of the model assembly within the time interval of 10000 – 18000 s.

Fig. 22 presents the indications of thermocouples over the height of the shroud (T_{sh}) and the test section thermal insulation (T_{th}), within the time interval of 10000 – 18000 s.

Fig. 23 presents the indications of electronic flow meters of the top (R3) and bottom (R2) flooding at the stage of flooding within the time interval of 16500 – 16640 s.

Figs. 24 – 28 present the indications of thermocouples over the height of fuel rod claddings at the following levels: Z = (1400 – 1500) mm (Fig. 24), Z = 1300 mm (Fig. 25a), Z = 1250 mm (Fig. 25b), Z = (900 – 1100) mm (Fig. 26), Z = (0 – 700) mm (Fig. 27) and Z = (-600 – 0) mm (Fig. 28) at the stage of flooding within the time interval of 16500 – 16640 s.

Fig. 29 presents the indications of the pressure sensors over the height of the model assembly path (p-1.5 (Z = -150 mm), p2 (Z = 200 mm), p9 (Z = 900 mm), p12.5

(Z = 1250 mm), p15 (Z = 1500 mm)), in fuel rods (p_{rod}) and in thermal insulation cavity (p_{th}) at the stage of flooding within the time interval of 16500 – 16640 s.

Fig. 30 presents the indications of the pressure sensors over the height of the inside surface of the cladding of the central measuring rod 1.1 at the stage of flooding within the time interval of 16500 – 16640 s.

Fig. 31 presents the indications of thermocouples on three upper spacing grids (Z = 775, 1030, 1285 mm) at the stage of flooding within the time interval of 16500 – 16640 s.

Fig. 32 presents the indications of thermocouples over the height of shroud (T_{sh}) and the test section thermal insulation (T_{th}) at the stage of flooding within the time interval of 16500 – 16640 s.

Fig. 33 presents the indications of thermocouples measuring the steam temperature (T_{st}) in sections of the model assembly Z = 775 mm and Z = 1030 mm and the temperature of steam-gas mixture at the assembly outlet ($T_{st\ out}$) in section Z = 1425 mm at the stage of flooding.

Fig. 34 presents the rate of hydrogen generation and the mass of hydrogen released.

Fig. 35 presents the general view of FA shroud after tests and cutting.

Figs. 36 – 38 present the assembly cross-sections after tests and conservation at the levels of ~ 1100 mm (Fig. 36), ~ 1250 mm (Fig. 37), ~ 1300 mm (Fig. 38).

Table 5 gives the masses of condensates discharged from the tanks of the condensate mass control.

Table 5

Results of measurements of water masses in control tanks

No.	Tank	Time of condensate collection, s	Condensate mass, g
1	Tank 5’	2472 – 4999	8640
2	Tank 2	4999	136
3	Tank 5.1	4999 – 5799	2775
4	Tank 5.2	5799 – 7501	6065
5	Tank 5.3	7501 – 10000	9109
6	Tank 5.4	10000 – 12448	8912
7	Tank 5.5	12448 – 15000	9268
8	Tank 5’	15000 – 16514	5291
9	Tank 5	after 16628	6506

10	Tank 2	after 16628	9954
The total amount discharged from tanks after the experiment:			66656

Table 6 gives the results of measuring the volumetric hydrogen concentration in the sampling tanks of the discrete hydrogen control system.

Table 6

Results of analysis of samples of the discrete hydrogen control system

Sample No.	Time of test samples, s	Volumetric hydrogen content, %
Vol.1	12976	4.56
Vol.2	13726	5.55
Vol.3	14476	4.09
Vol.4	15226	3.07
Vol.5	15476	3.24
Vol.6	15978	6.75
Vol.7	16478	12.78

Table 7 presents the list of unreliable or failed thermocouples.

Table 7

List of unreliable or failed thermocouples.

No.	Thermo-couple designation	Location	Behavior	Time, s	State
1	T3513	Fuel rod 3.5 Z=1300 mm	Fault of electric contact in hot junction	from ~ 2549	Failure
2	T_{st}12.85	Z=1285 mm	Open-circuit	from ~ 2543	Failure
3	T369	Fuel rod 3.6 Z=900 mm	Fault of electric contact in fuel rod heater	from ~ 6307	-
4	T117.75	Fuel rod 1.1 Z=775 mm	Loss of thermal contact with the cladding	from ~ 6667	-
5	T_{sh}13	Shroud Z=1300 mm	Loss of thermal contact with the shroud	from ~ 8287	-
6	T1111	Fuel rod 1.1 Z=1100 mm	Loss of thermal contact with the cladding	from~ 11800	-
7	T31112.5	Fuel rod 3.11 Z=1250 mm	Loss of thermal contact with the cladding	from~ 11980	-
8	T394	Fuel rod 3.9 Z=400 mm	Fault of electric contact in fuel rod heater	from ~15547	-
9	T397	Fuel rod 3.9 Z=700 мм	Fault of electric contact in fuel rod heater	from ~15547	-
10	T_{st}10.3	Z=1030 mm	Open-circuit	from ~16513	Failure
11	T2612.5	Fuel rod 2.6 Z=1250 mm	Open-circuit	from ~16529	Failure

12	$T_{th}9$	Thermal insulation Z=900 mm	Pulsations of indications ~ ± 50°C	-	-
13	T24-3	Fuel rod 2.4 Z=-300 mm	Pulsations of indications ~ ± 100°C	-	Failure
14	T31013	Fuel rod 3.10 Z=1300 mm	Pulsations of indications ~ ± 100°C	-	Failure
15	T352	Fuel rod 3.5 Z=-200 mm	Pulsations of indications ~ ± 100°C	-	Failure

RESULTS OF THE EXPERIMENTAL DATA PRIMARY PROCESSING

Preparatory stage

Preliminary analysis of the results of the experiment PARAMETER-SF2 showed that, according to the pre-test scenario, at the preparatory stage the assigned parameters of steam and argon were set at the test section inlet (Fig. 10): steam flow rate of $G_{st\ in}$ ~ 3.5 g/s at $T_{st\ in}$ = 530°C; argon flow rate of $G_{Ar\ in}$ ~ 2.0 g/s at $T_{Ar\ in}$ = 400°C.

By the end of the preparatory stage (~ 8680 s) at the assembly power of ~ 3600 W the thermocouples at the levels of 900 – 1300 mm registered the settled temperature of 700±50°C (see Fig. 12) with the steam flow rate through the assembly being ~ 3.56 g/s (see Table 5). Pressures (by indications of pressure sensors) were: ~ 0.30 MPa – of steam-gas mixture in the FA path; ~ 0.30 MPa – of helium inside fuel rods; ~ 0.30 MPa – of argon in the thermal insulation cavity (Fig. 13).

Pre-oxidation phase

Duration of the pre-oxidation phase was ~ 3400 s (~ 11900 - 15300 s) at temperature of fuel rod claddings, by indications of thermocouples at the levels of 1250 – 1300 mm, being ~ 1200°C and the steam flow rate through the assembly being ~ 3.64 g/s (see Table 5). Maximum deviation of cladding temperature in the hottest section (1250 mm) was ~ +70°C (TC T2312.5, fuel rod 2.3 of the 2nd row, Fig. 15).

At the preoxidizing stage four samples of gas mixture was taken (see Table 6, Fig. 18). On the basis of the analysis of results of hydrogen measurement by SOV-3 system it was found out that at the preoxidizing stage (before ~ 15300 s) ~ 15 g of hydrogen was generated, and according to the results of the analysis of the discrete system samples at this stage ~ 17 g of hydrogen was released (see Fig. 34).

Transient phase

Duration of the transient phase was ~ 1200 s (~ 15300 – 16497 s) with increase in the assembly power from ~ 8300 to ~ 10500 W (Fig. 11) and the steam flow rate through the assembly of ~ 3.49 g/s (see Table 5).

At the moment of switching the power the indications of thermocouples in the hottest section 1250 mm were the following (Fig. 15): in the second row ~ 1480°C (T2312.5, fuel rod 2.3 of the 2nd row), in the third row ~ 1430°C (TC T3212.5, fuel rod 3.2 of the 3rd row).

At the level of 900 – 1100 mm the maximum indications of thermocouples were the following (Fig. 16): in the second row ~ 1410°C (T2111, fuel rod 2.1 of the 2nd row), in the third row ~ 1270°C (TC T3311, fuel rod 3.3 of the 3rd row). Indications of the thermocouples located below the level of 700 mm did not exceed 1000°C (Fig. 17).

Average rate of cladding heating was ~ 0.20 – 0.25°C/s.

At the transient phase three samples of gas mixture were taken (see Table 6, Fig. 18). On the basis of the analysis of the results of hydrogen measurement by SOV-3 system it was found out that at transient phase (till ~ 16500 s) ~ 9 g of hydrogen was generated, the results of analysis of the discrete system samples show that at this stage ~ 11 g of hydrogen was released (see Fig. 34). Maximum rate of hydrogen generation was ~ 0,012 and ~ 0,015 g/s, respectively (see Fig. 34).

Flooding

At 16508 s, when the thermocouple T2312.5 registered the maximum temperature of 1480°C (Fig. 15), the top water supply system was switched on with the flow rate Gtf(R3) = ~ 41 g/s (Fig. 23).

Water supply into the assembly under top flooding resulted in the following:

- quenching (during ~ 10 s after the beginning of flooding) of claddings at the levels of 1500 – 1300 mm to temperature of ~100°C (Fig. 24, 25a);

- cooling the fuel rod claddings at the level of 1250 mm to temperature of ~ 200 – 700°C during ~ 40 s (Fig. 25b).

The effect of top flooding on temperature behaviour of claddings of the fuel rods of the second and third rows at the level of 1100 mm was not recorded by thermocouples (Fig. 26).

Water supply into the assembly under bottom flooding resulted in successive cooling of claddings at the levels of 0 – 1100 mm. The front of cooling to temperature of ~150°C moved from the level of 0 mm to the level of 700 mm at a rate of ~ 90 mm/s, and from level 700 mm to level 900 mm – at a rate of ~ 5 mm/s (Fig. 26, 27).

In the course of the experiment the pressure jumps were registered in the assembly (P_{bnl}), as well as decrease in the average flow rate of the bottom flooding water caused by evaporation process:

- to ~ 0,4 MPa during ~ 20 s in ~ 2 s after starting the top flooding (Fig. 29);

- to ~ 0,6 MPa during ~ 50 s in ~ 50 s after starting the bottom flooding (Fig. 29);

- to ~ 110 g/s in ~ 50 s after starting the bottom flooding (Fig. 29).

Bottom flooding resulted in intensive evaporation in the assembly lower part and in displacing the top flooding water from the assembly that, in its turn, resulted in repeated rise of temperature in the assembly upper part:

- to ~500°C at the level of 1300 mm (Fig. 25);
- to ~1000°C at the level of 1250 mm (Fig. 25).

By the moment of switching off the top and bottom flooding systems (16626 s) the assembly temperature was ~ 100 – 120°C.

The total mass of the condensed steam-water mixture, collected in the course of t the flooding stage, was ~ 6506 g (Tank 5, Table 5).

The analysis of water balance at the flooding stage shows that after completion of the experiment the following amount (Table 5) was drained from Tank 5 and test section (Tank 2):

6506 g (Tank 5) + 9954 g (Tank 2) ≈ 16460 g.

The post-test measurement of water losses in tanks of top (Tank 7) and bottom (Tank 4) flooding (Fig. 1) showed that the total water flow rate for the flooding was:

4984 g (Tank 7) + 12015 g (Tank 4) ≈ 16999 g,

i.e. the balance of flooding water is in agreement with the accuracy of ~ 3%. Some disagreement in the balance could be caused by water loses in gas and steam lines of the test facility under draining the test section.

After the tests the dismantling, conservation and cutting of the assembly were performed.

Analysis of the shroud state showed (Fig. 35) that it kept its integrity and leak tightness, there is a thin oxide layer on its outer surface, and its diameter at the level of 900 – 1300 mm increased by ~ 2 mm.

Visual examination of the state of the assembly structural materials at the levels of 1100 – 1300 mm showed (Fig. 36 – 38) that the fuel rod claddings were oxidized considerably and partially fragmented, there is no melt in the space between fuel rods.

FIGURES

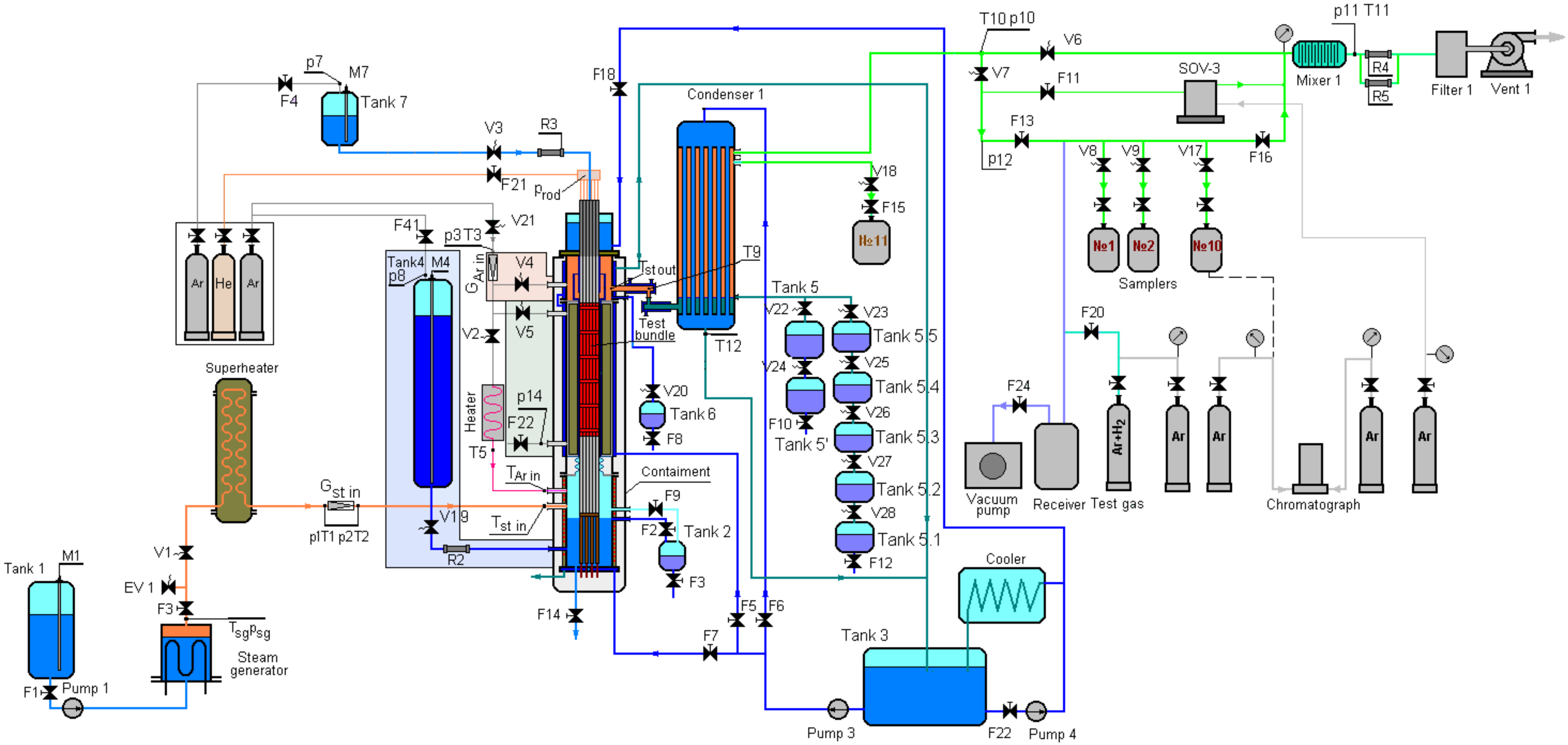
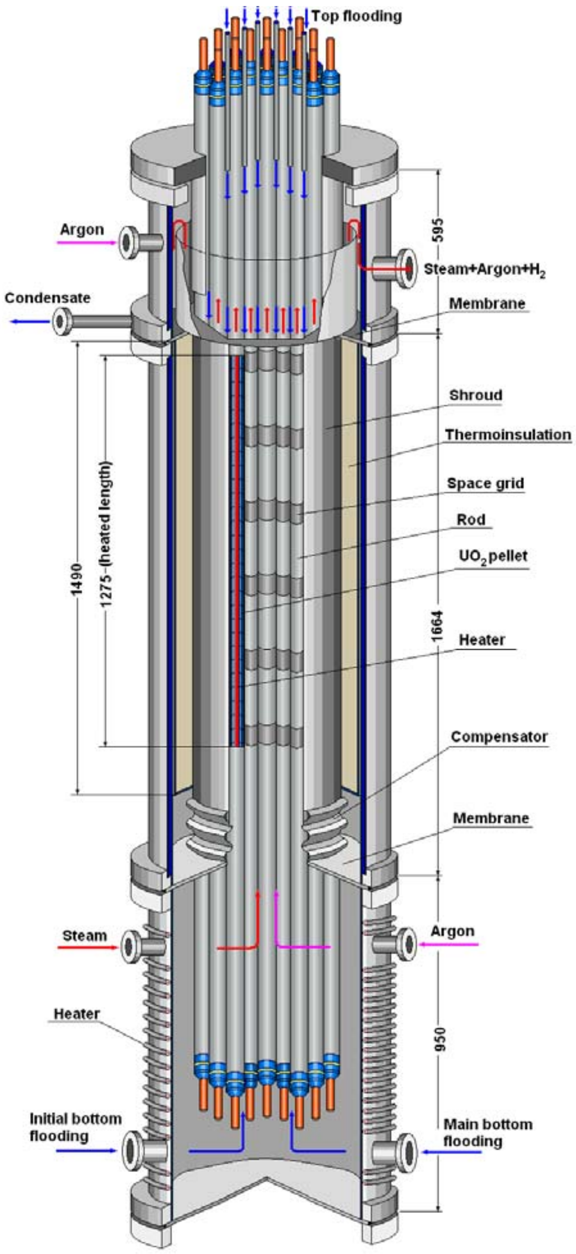
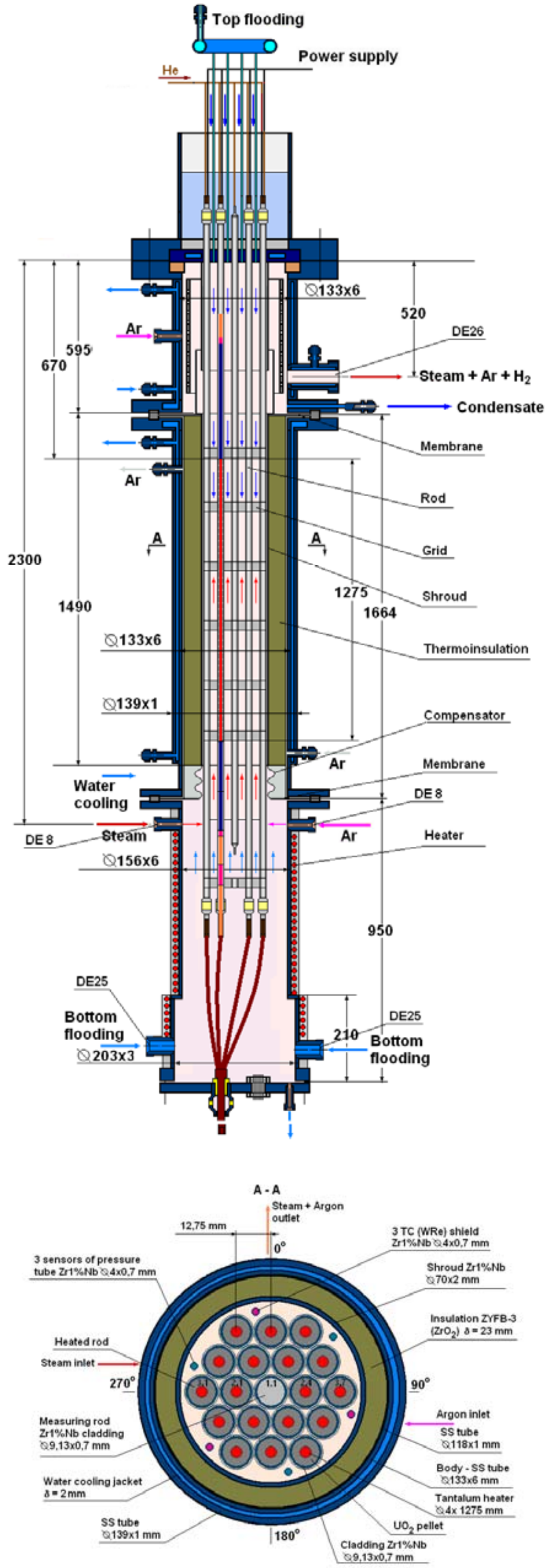


Fig. 1. Functional diagram of PARAMETER test facility.



General view



Layout

Fig. 2. General view of the test section.

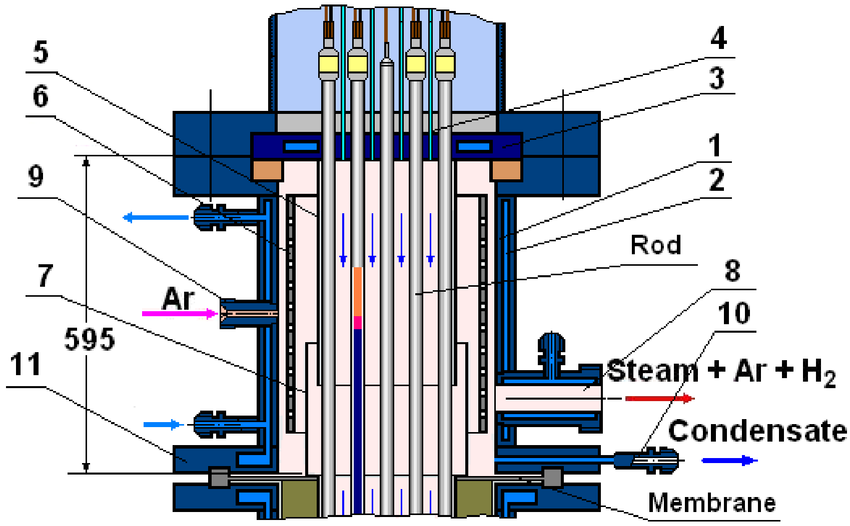


Fig. 3. Upper part of the test section.

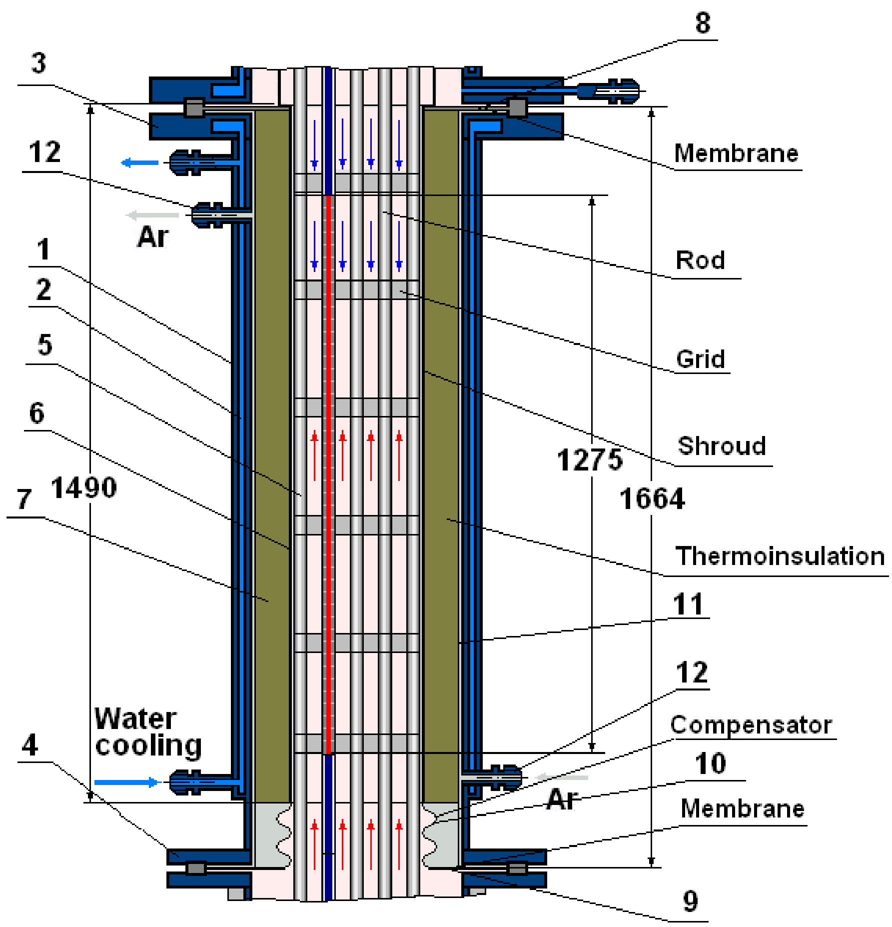


Fig. 4. Central part of the test section.

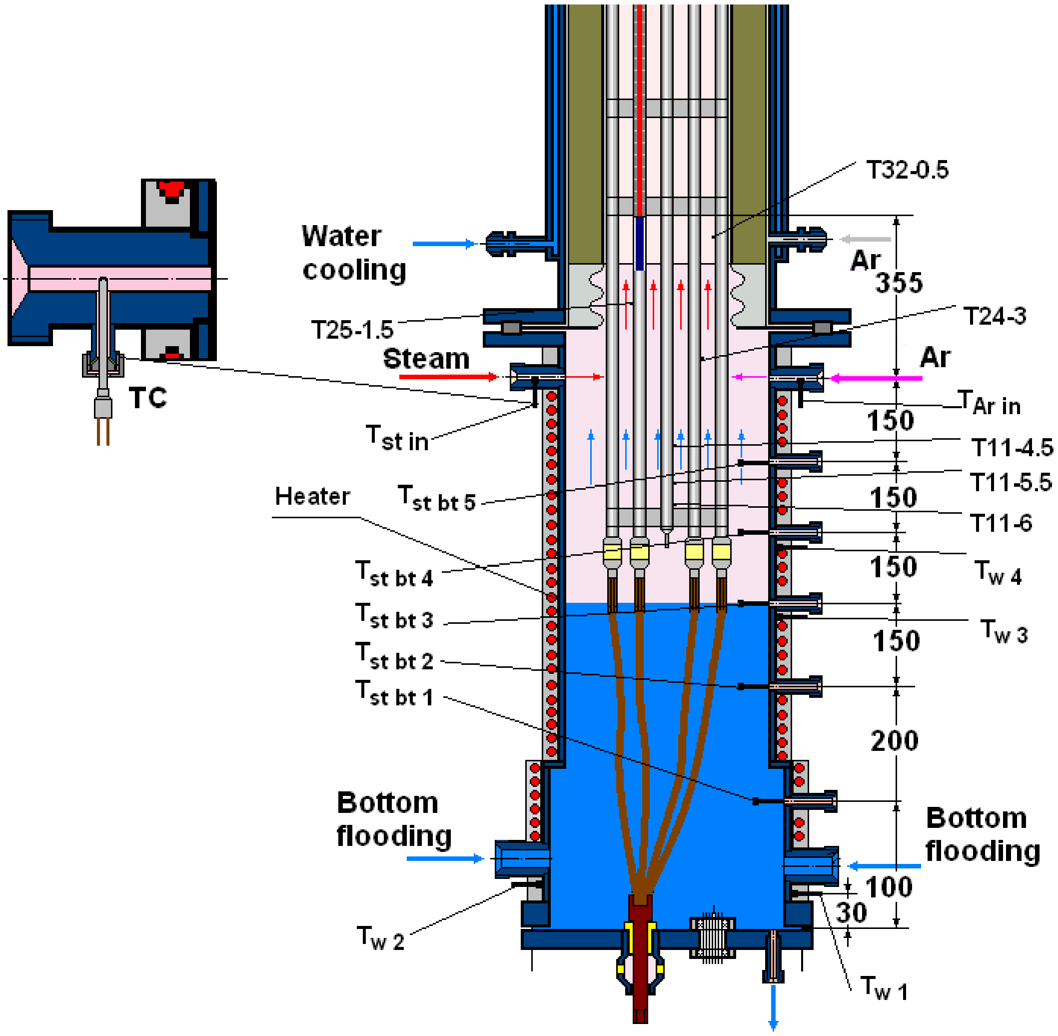
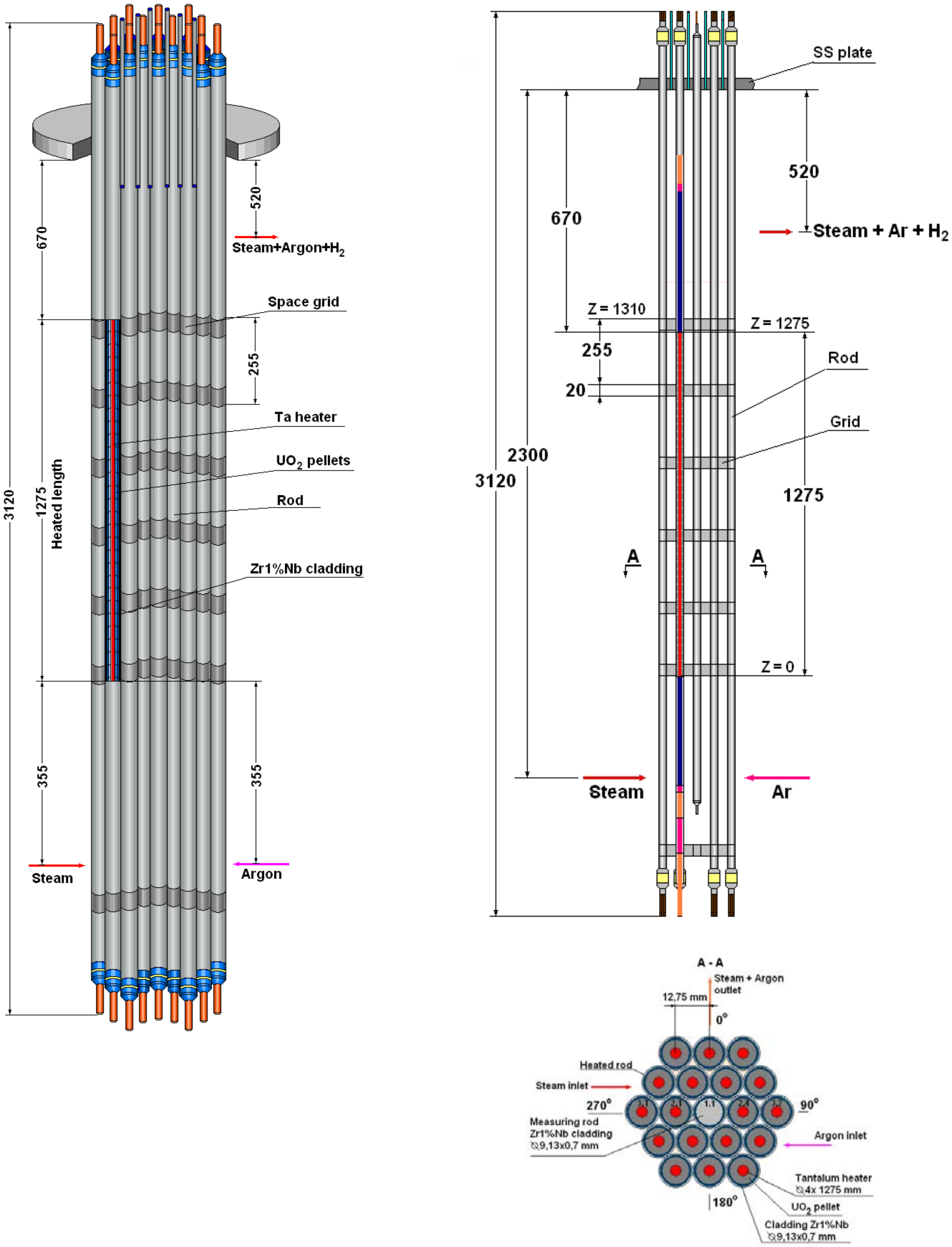


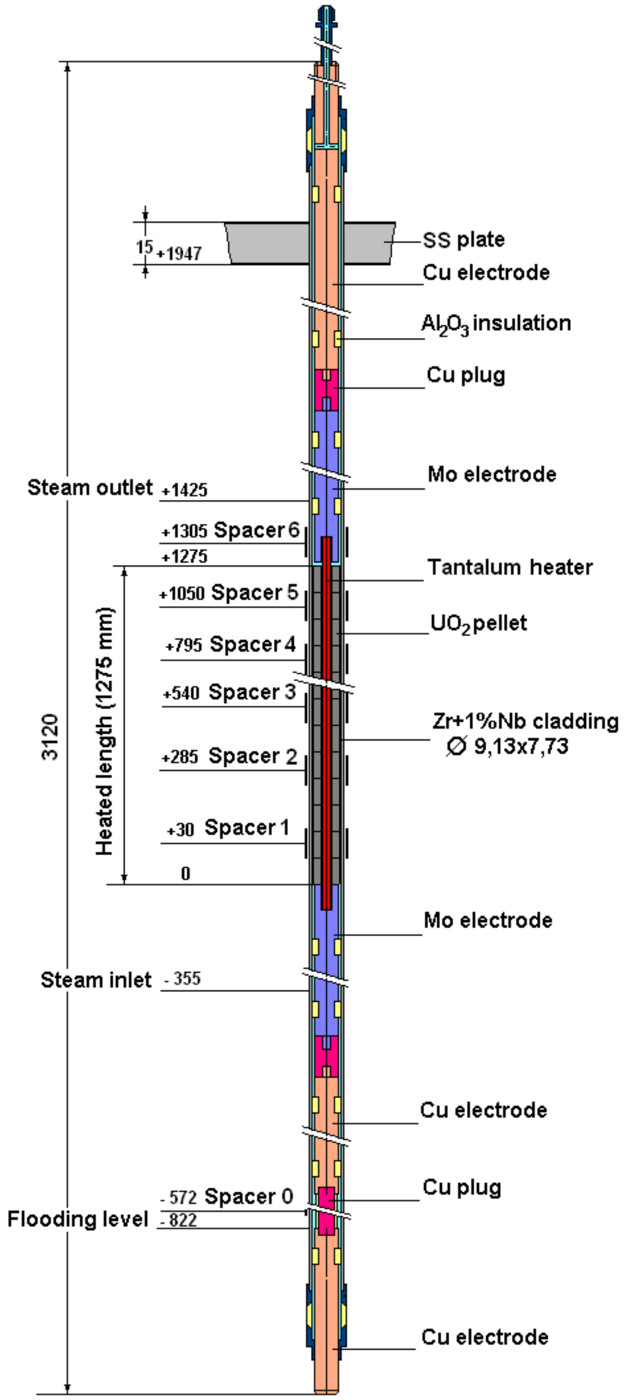
Fig. 5. Lower part of the test section.



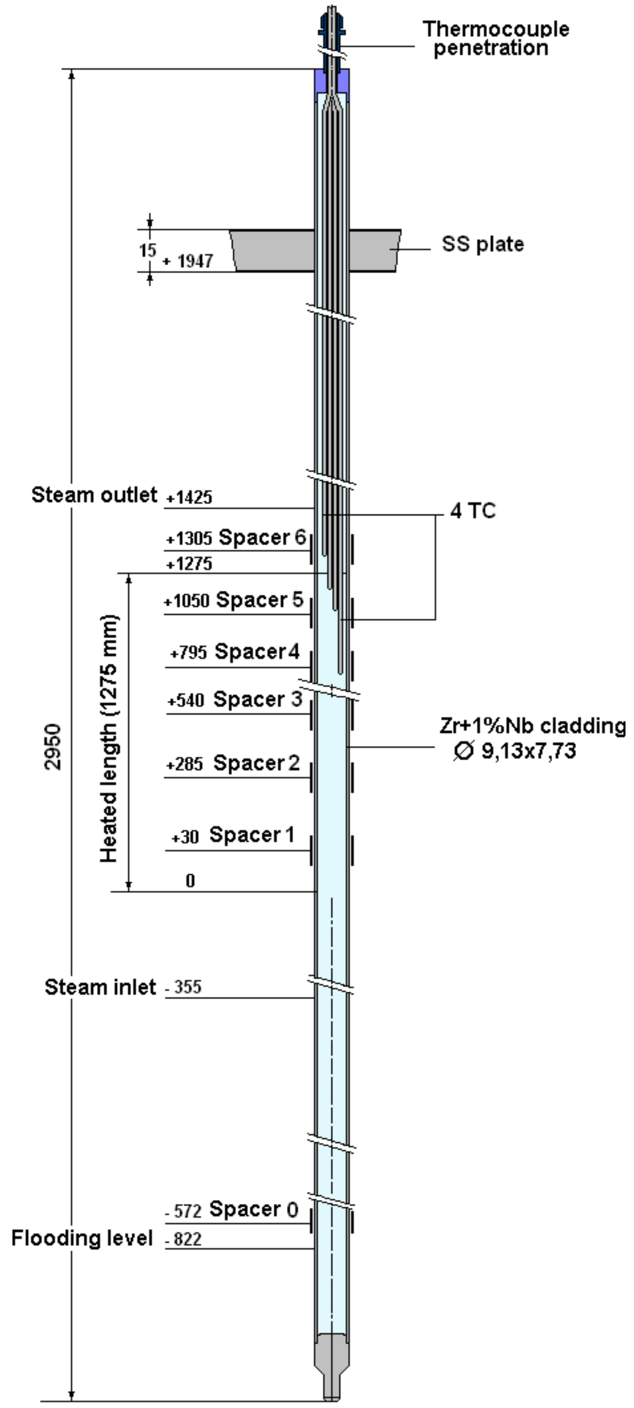
General view

Layout

Fig. 6. Model FA.



Heated fuel rod



Unheated fuel rod

Fig. 7. Fuel rod simulators.

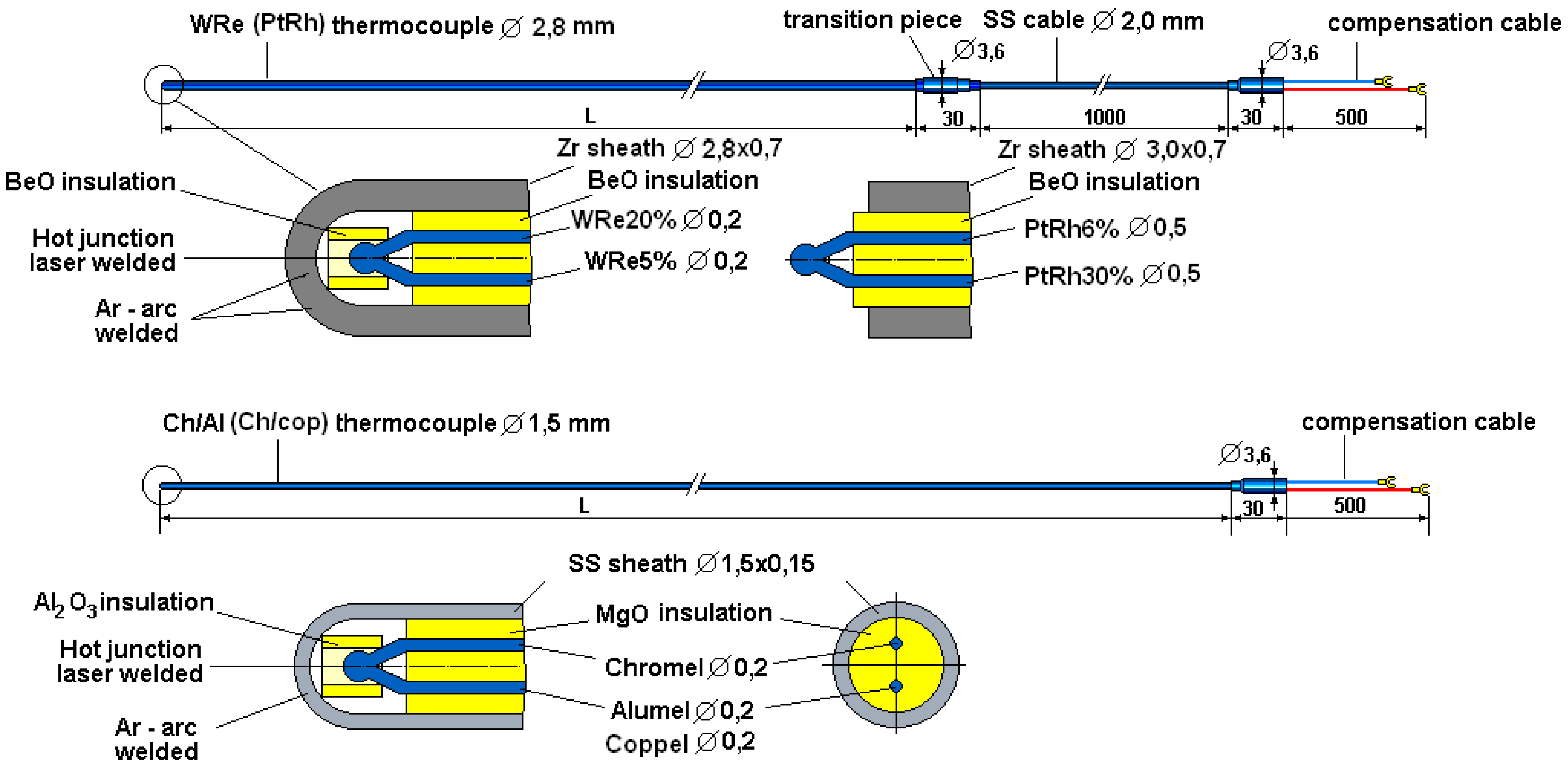


Fig. 8. FA thermocouples.

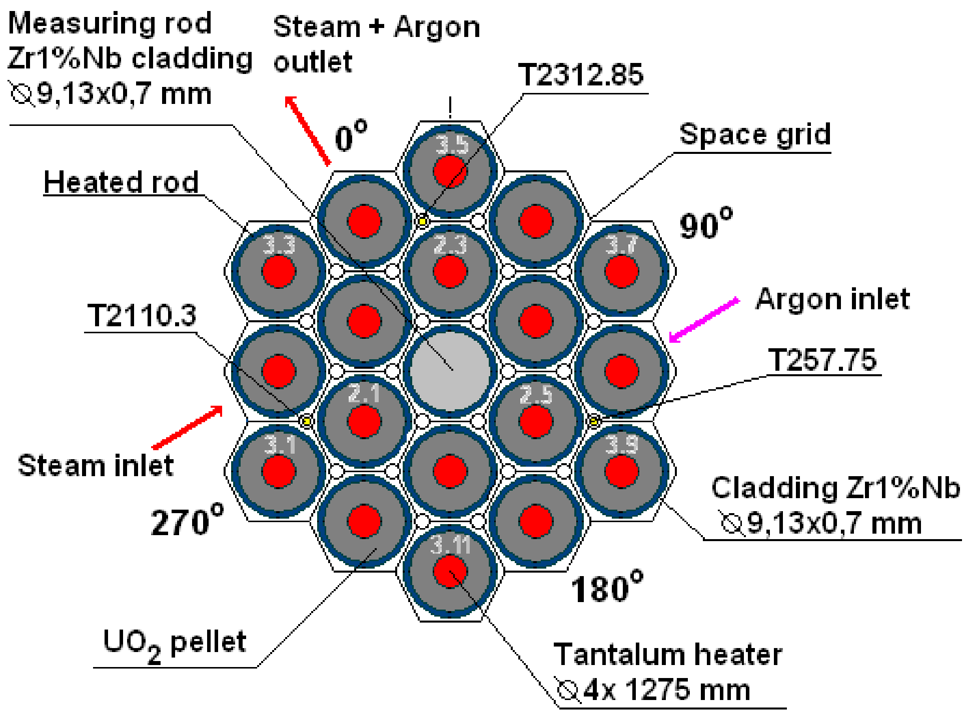


Fig. 9. Thermocouples in the spacing grid.

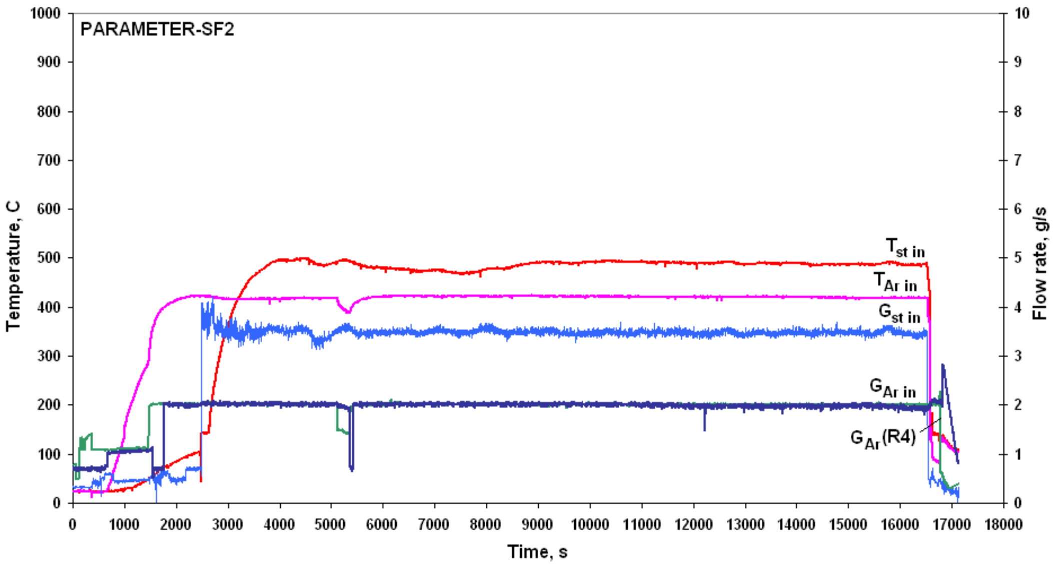


Fig. 10. Parameters of steam ($G_{st\ in}$, $T_{st\ in}$) and argon ($G_{ar\ in}$, $T_{ar\ in}$) at the test section inlet and argon flow rate (G_{ar}(R4)) at the outlet to special ventilation.

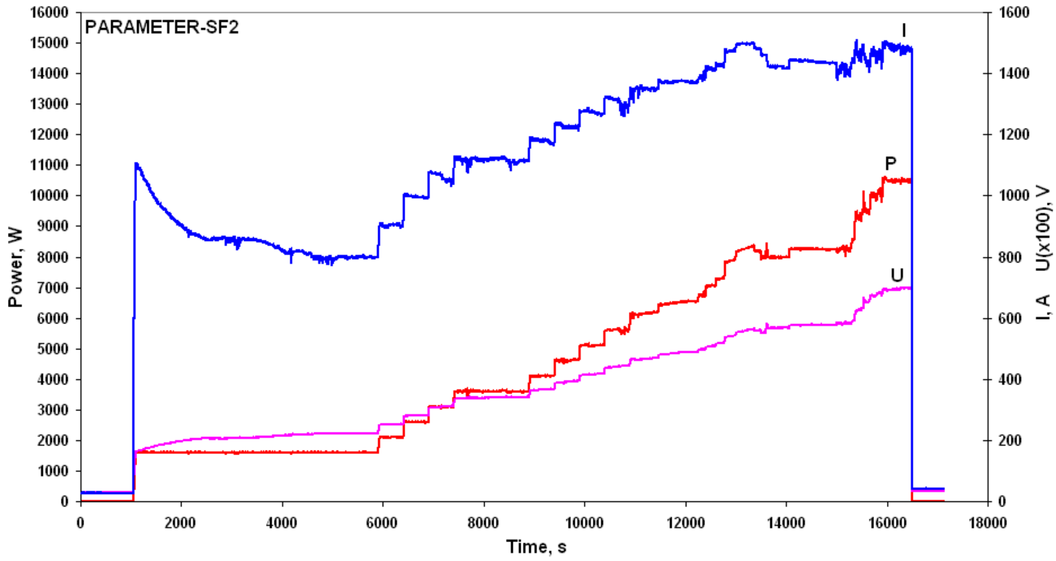


Fig. 11. FA electric parameters.

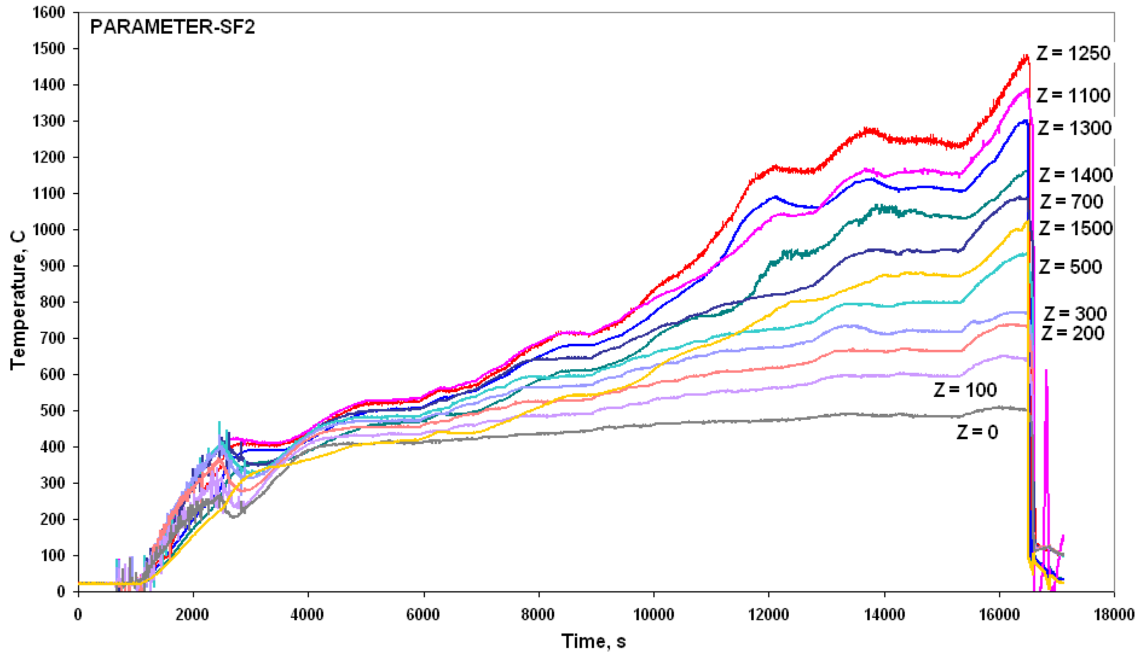


Fig. 12. Indications of thermocouples located over the height of fuel rod claddings.

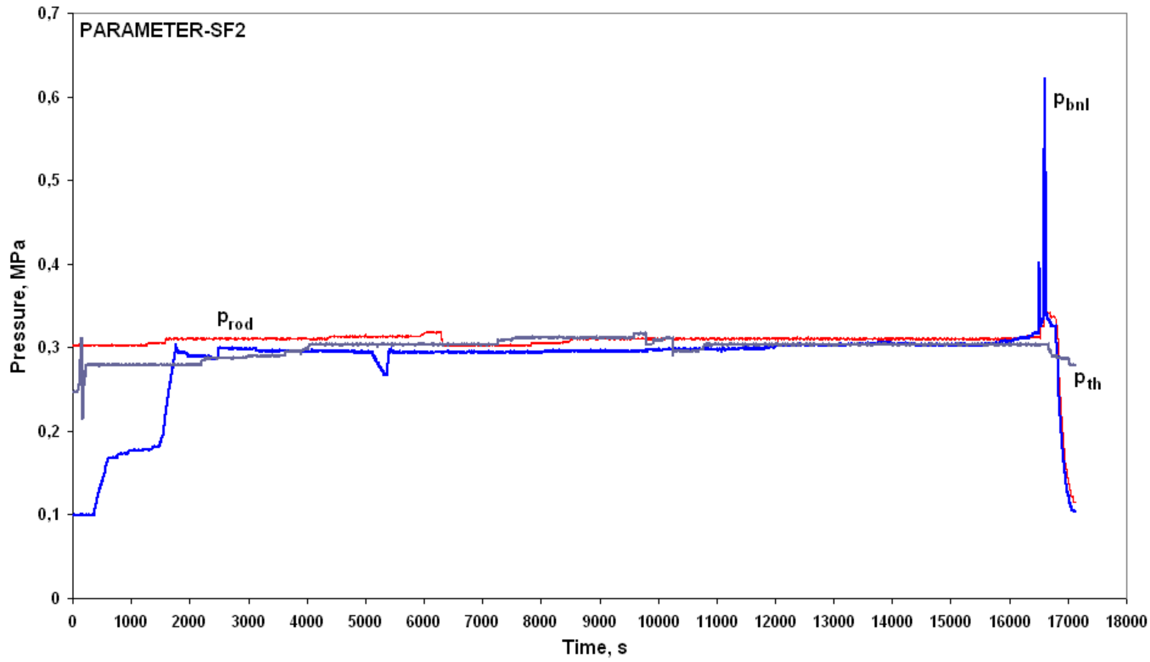


Fig. 13. Indications of pressure sensors in the model assembly (p_{bnl}), fuel rods (p_{rod}) and thermal insulation cavity (p_{th}).

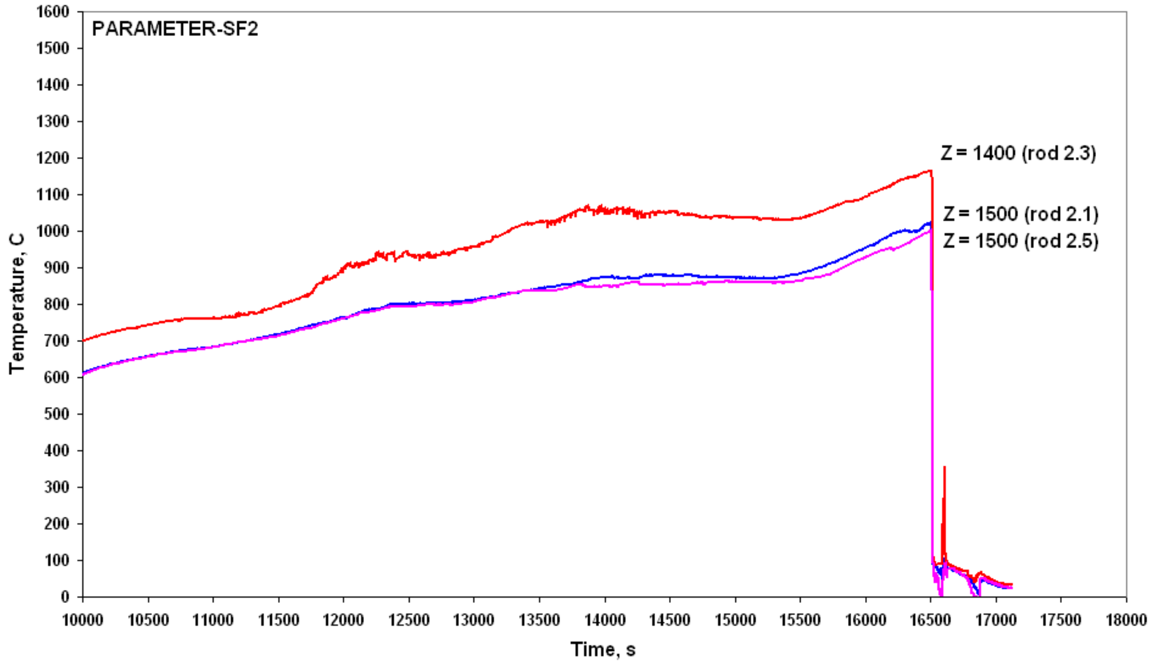


Fig. 14. Indications of thermocouples on fuel rod claddings at levels Z = (1400 – 1500) mm of the model FA.

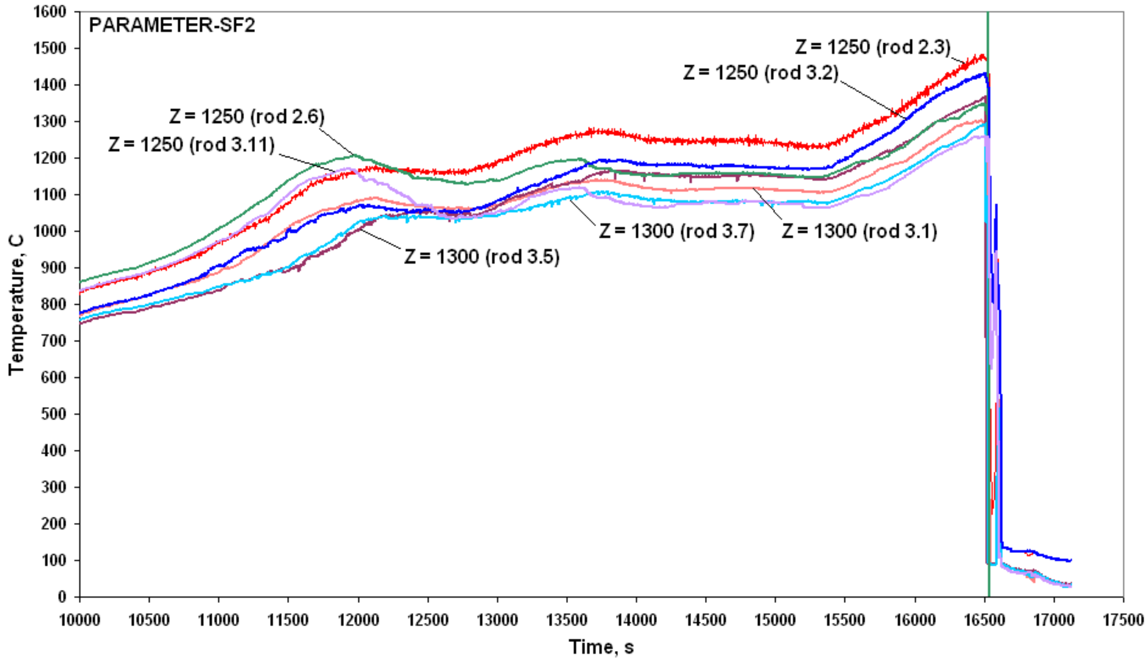


Fig. 15. Indications of thermocouples on fuel rod claddings at levels Z = (1250 – 1300) mm of the model FA.

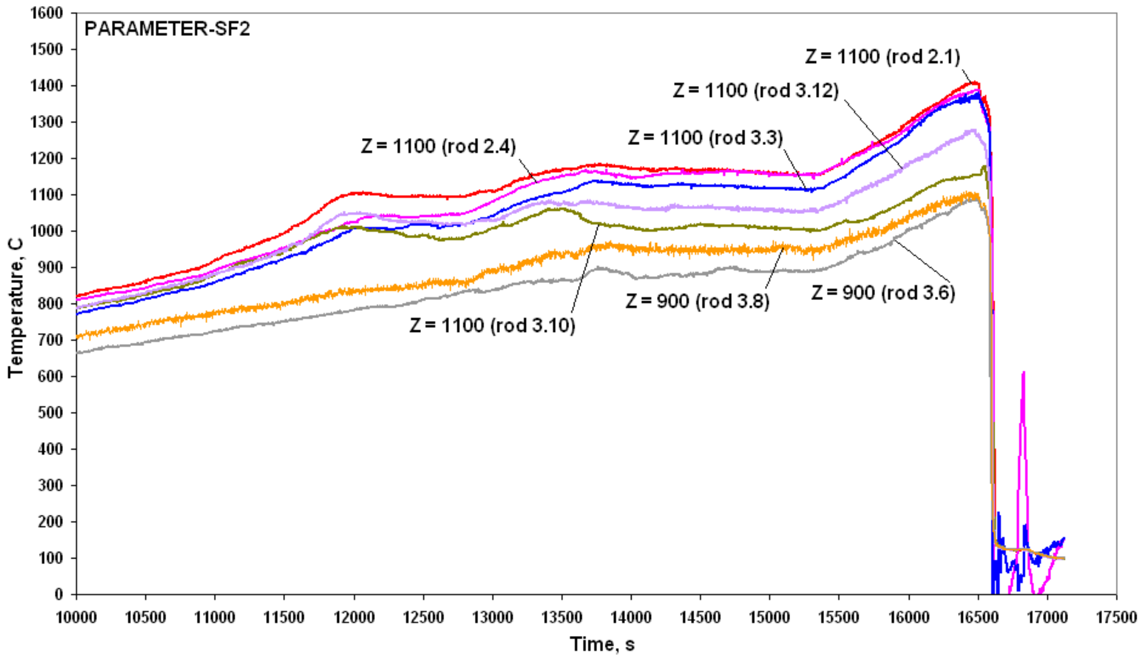


Fig. 16. Indications of thermocouples on fuel rod claddings

at levels Z = (900 – 1100) mm of the model FA.

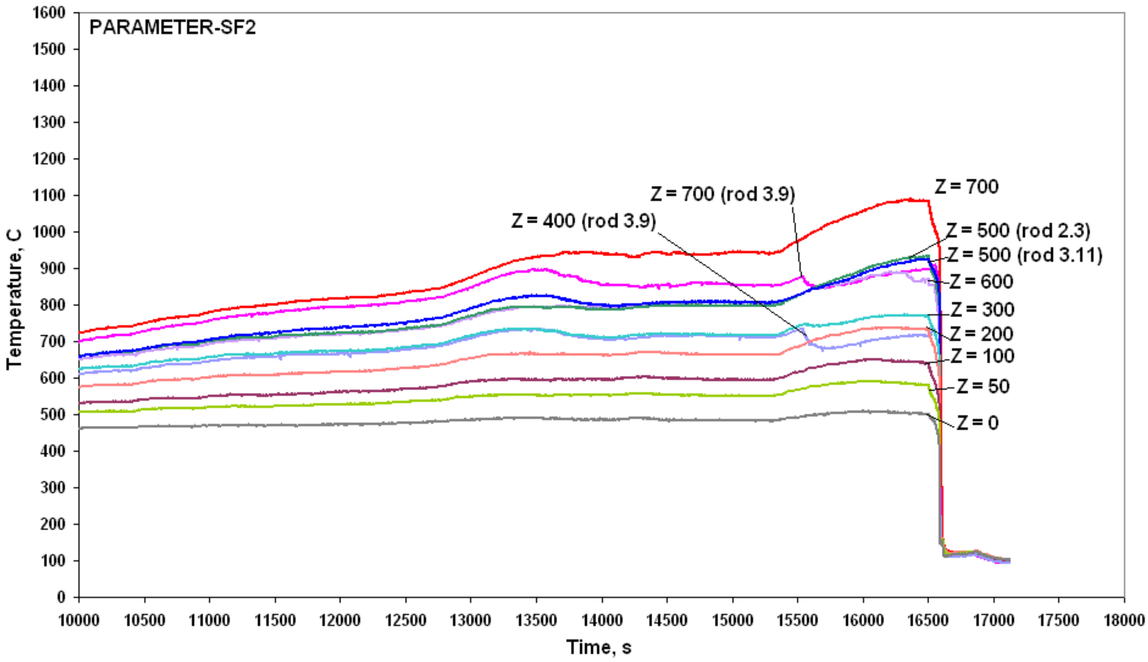


Fig. 17. Indications of thermocouples on fuel rod claddings

at levels Z = (0 – 700) mm of the model FA.

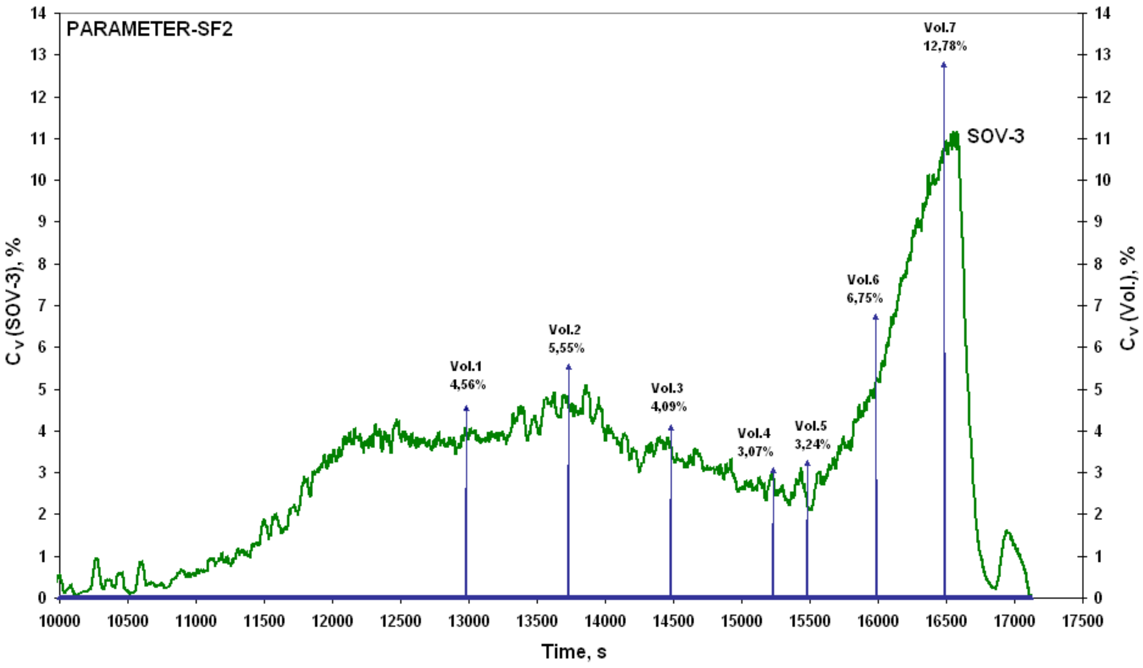


Fig. 18. Variation of volumetric hydrogen concentration versus time (Vol1, …, Vol7 – gas sampling (duration 8 s)).

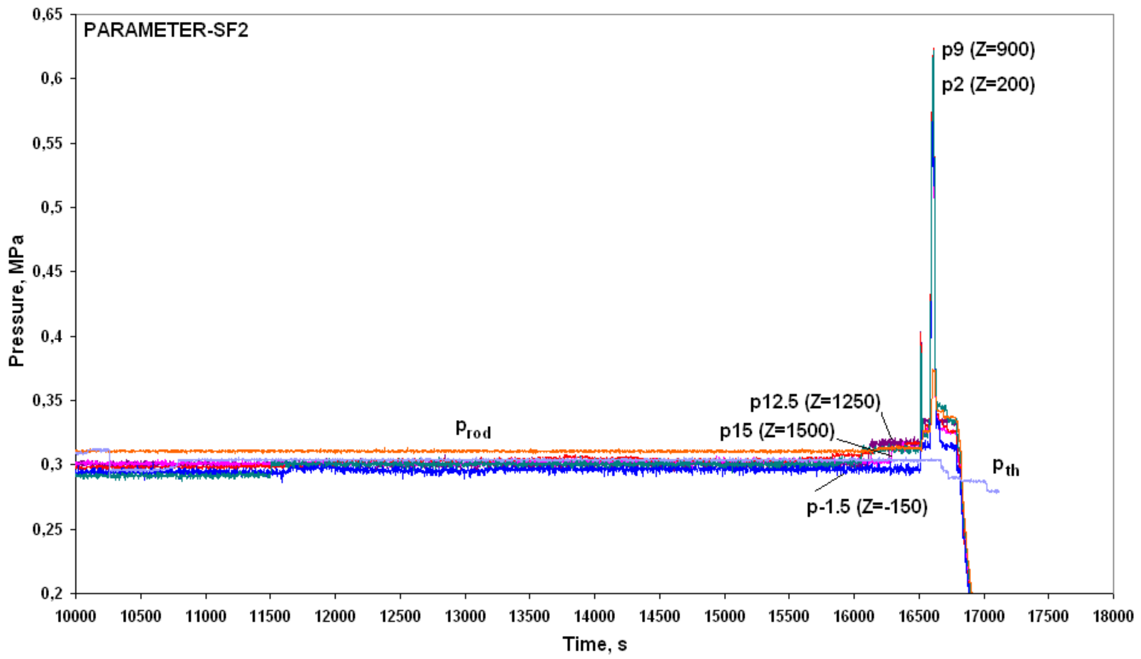


Fig. 19. Indications of pressure sensors over the assembly height (p-1.5, p2, p9, p12.5, p15), in fuel rods (p_{rod}) and thermoinsulation cavity (p_{th}).

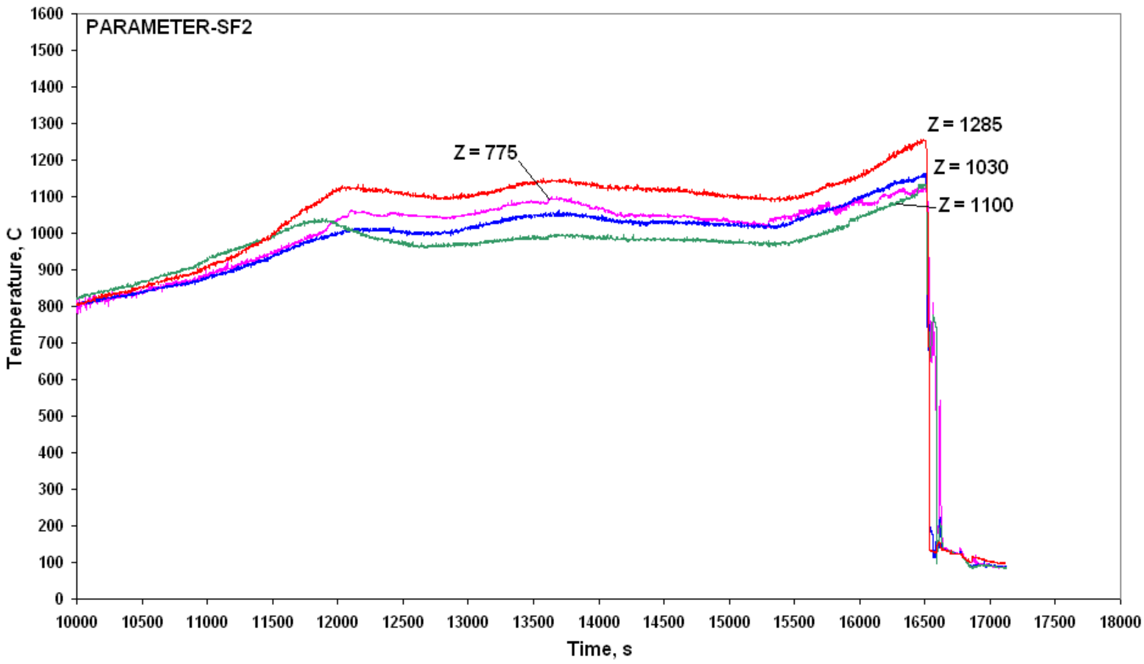


Fig. 20. Indications of thermocouples on cladding of the central measuring rod 1.1.

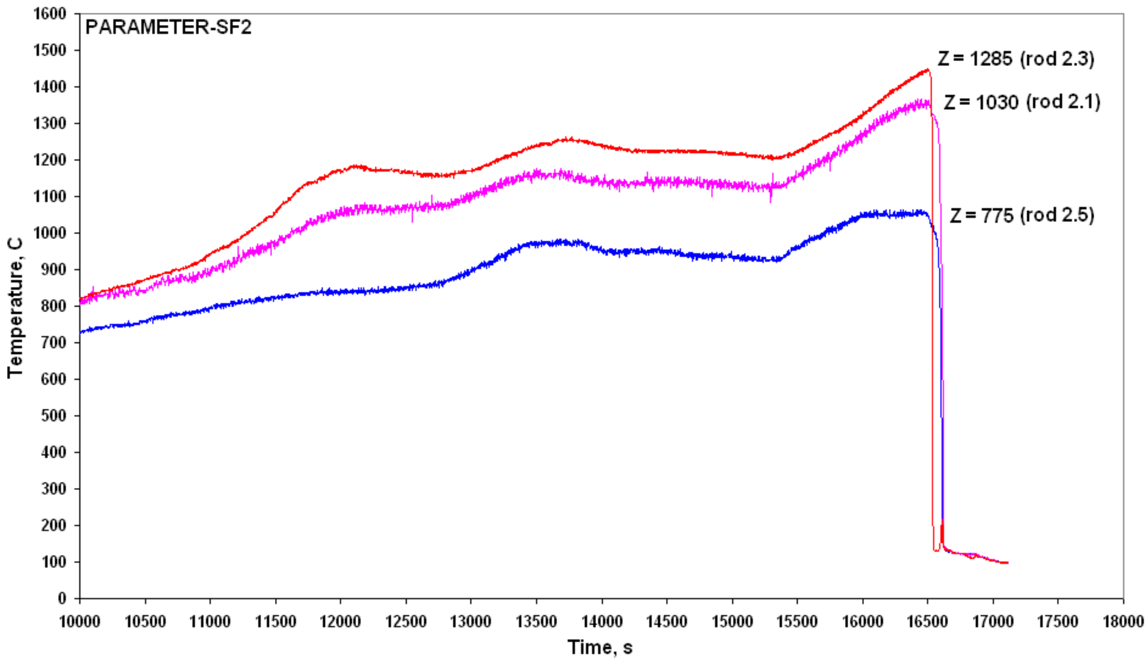


Fig. 21. Indications of thermocouples on spacing grids located at levels Z = (775, 1030 and 1285) mm.

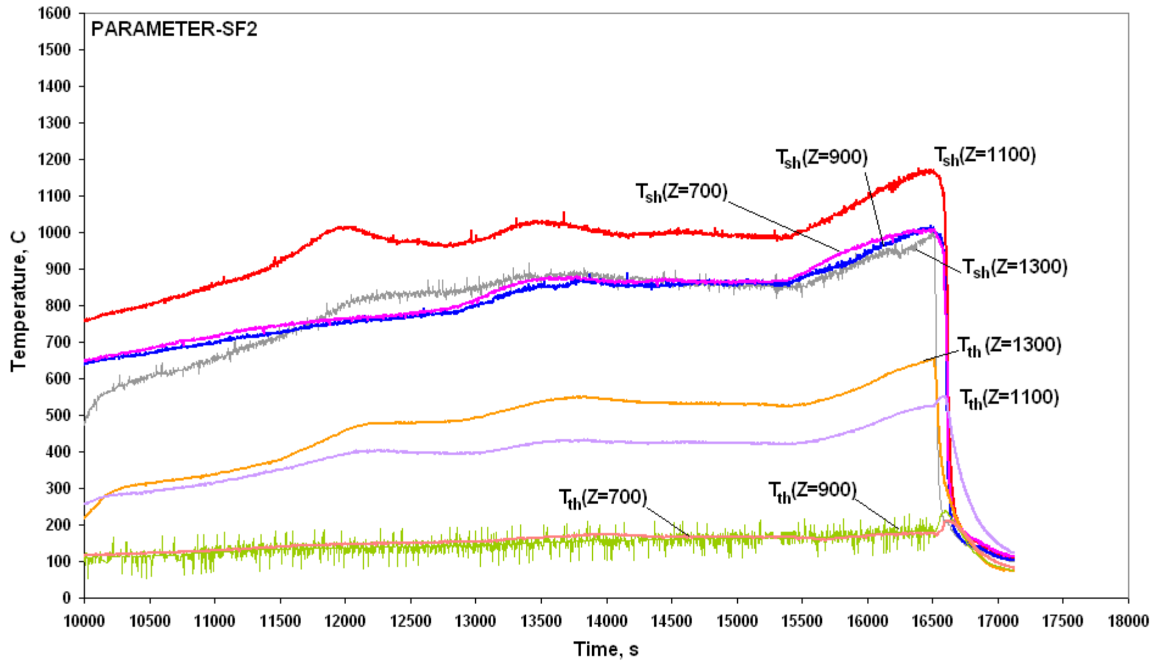


Fig. 22. Indications of thermocouples over the height of shroud (T_{sh}) and thermoinsulation (T_{th}) of the test section.

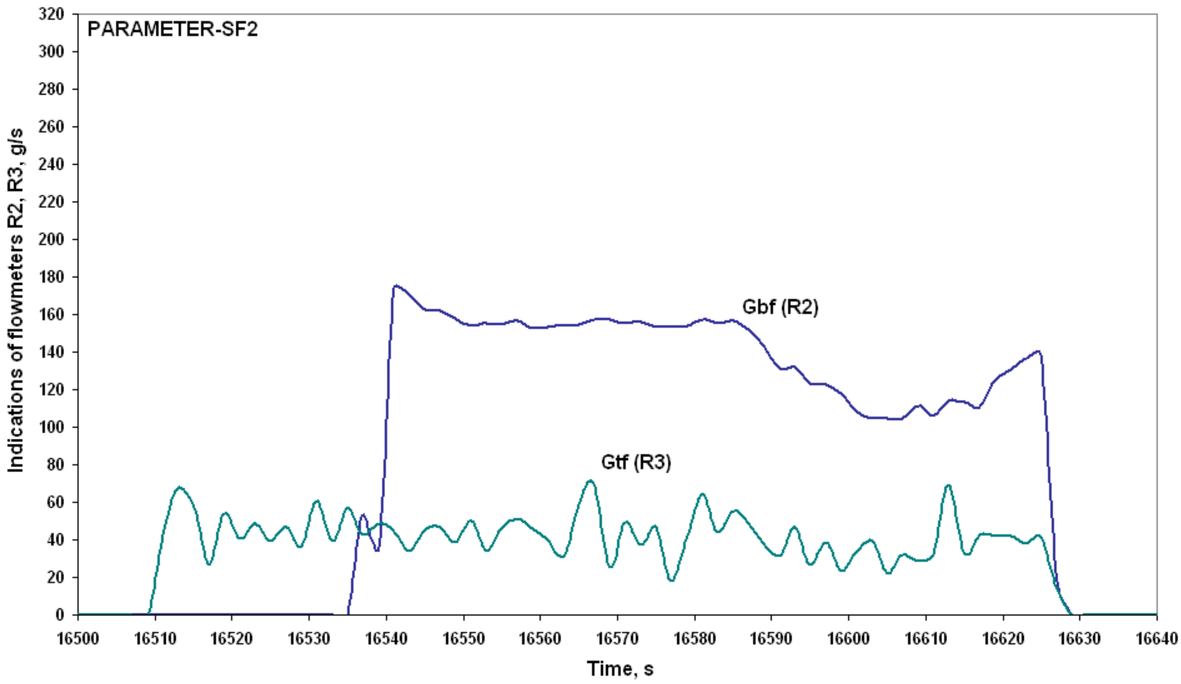


Fig. 23. Indications of electronic flow meters of the top (R3) and bottom (R2) flooding systems.

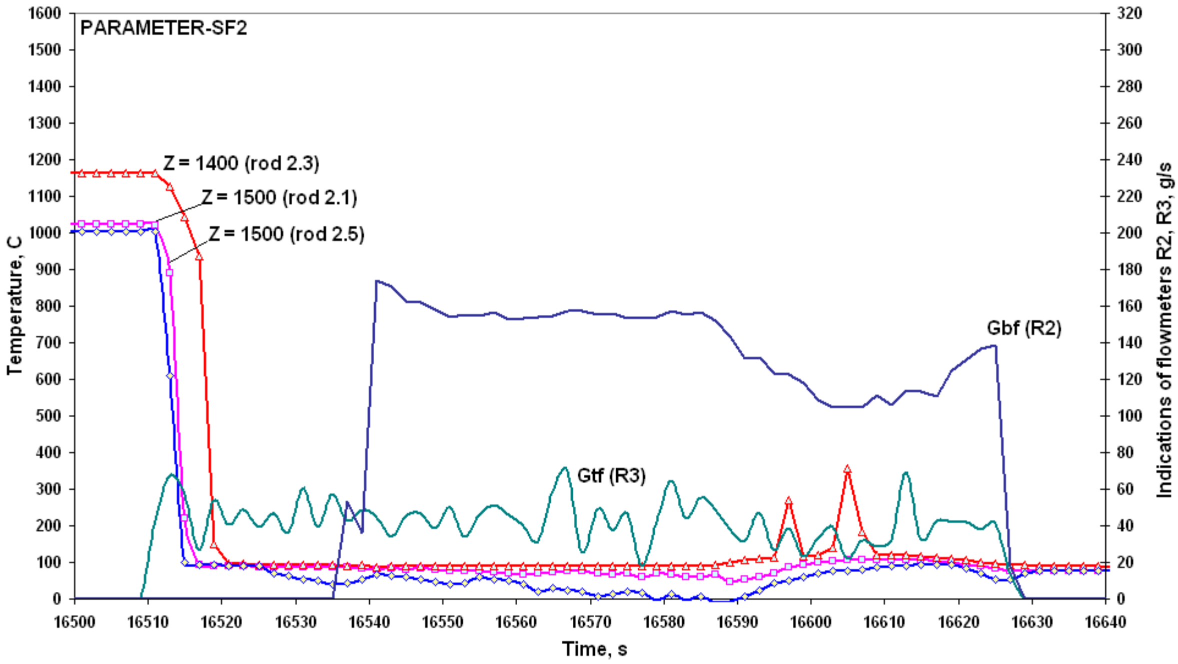
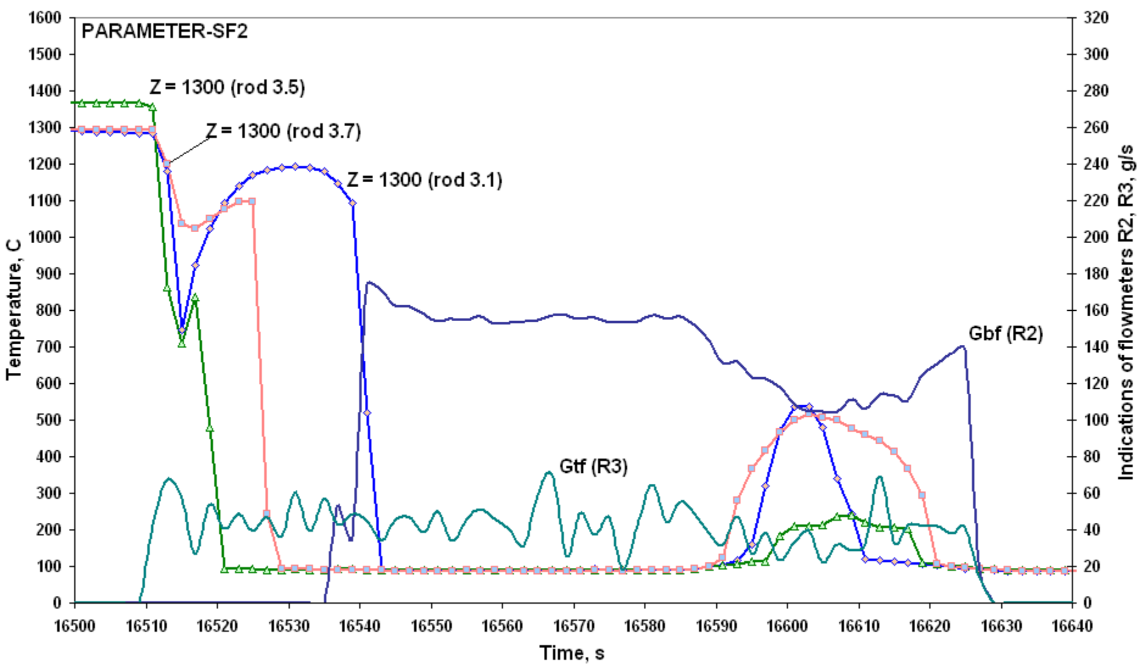
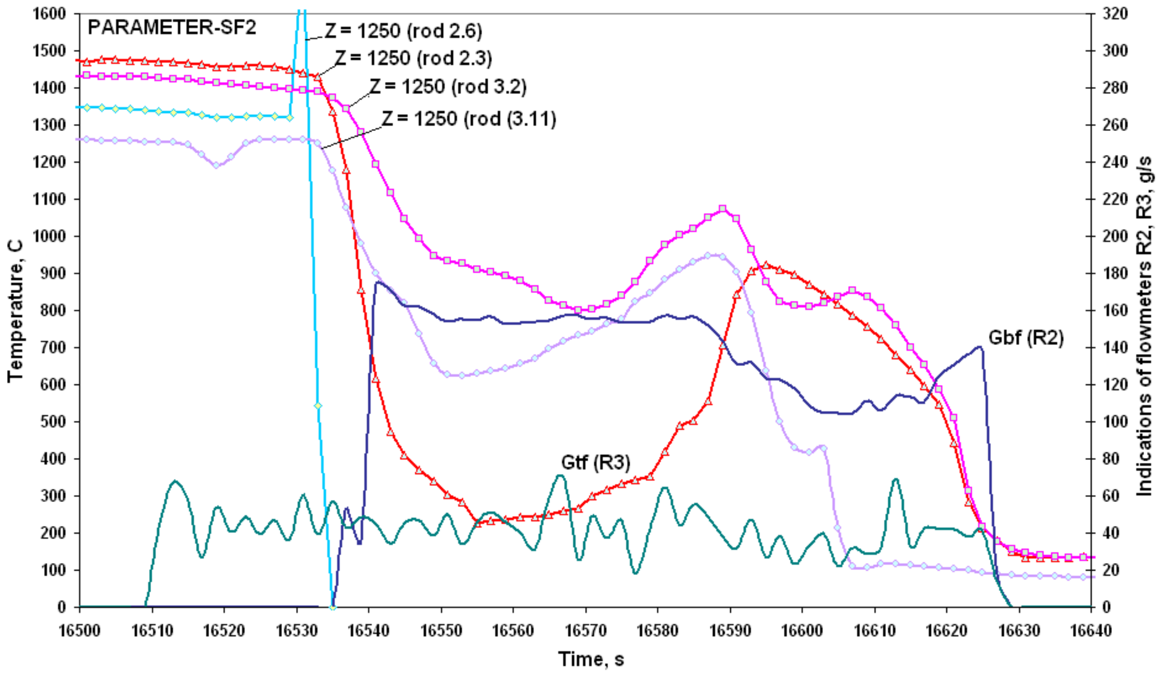


Fig. 24. Indications of thermocouples on fuel rod claddings at levels Z = (1400 – 1500) mm at the flooding stage.



a)



b)

Fig. 25. Indications of thermocouples on fuel rod claddings at levels Z = 1300 mm (a) and Z = 1250 mm (b) at the flooding stage.

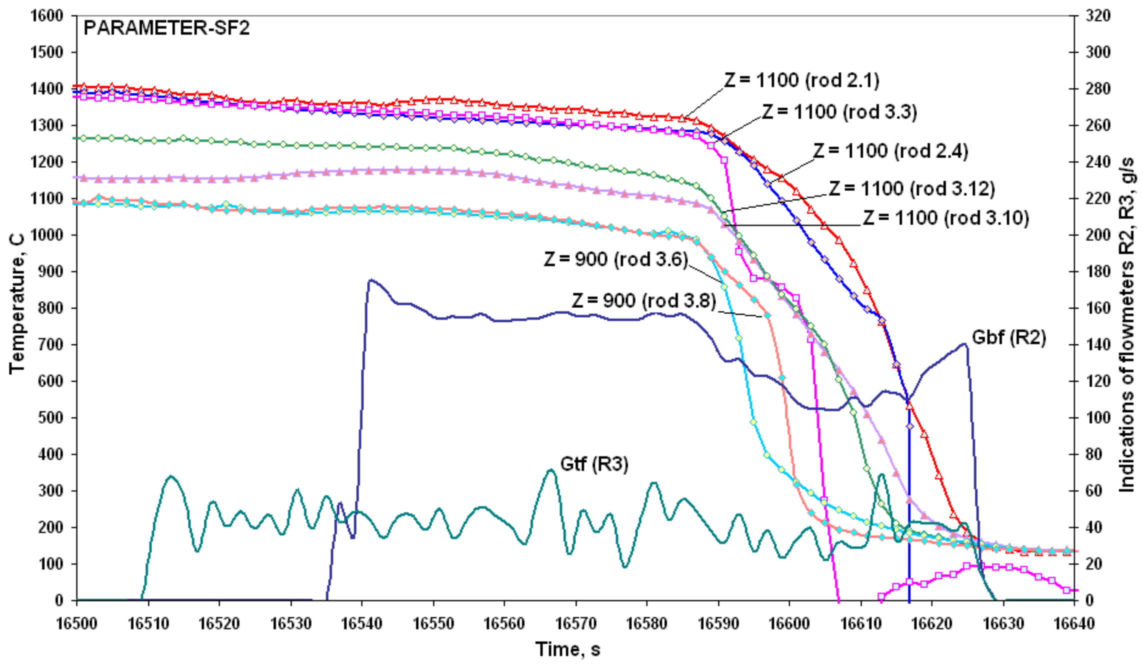
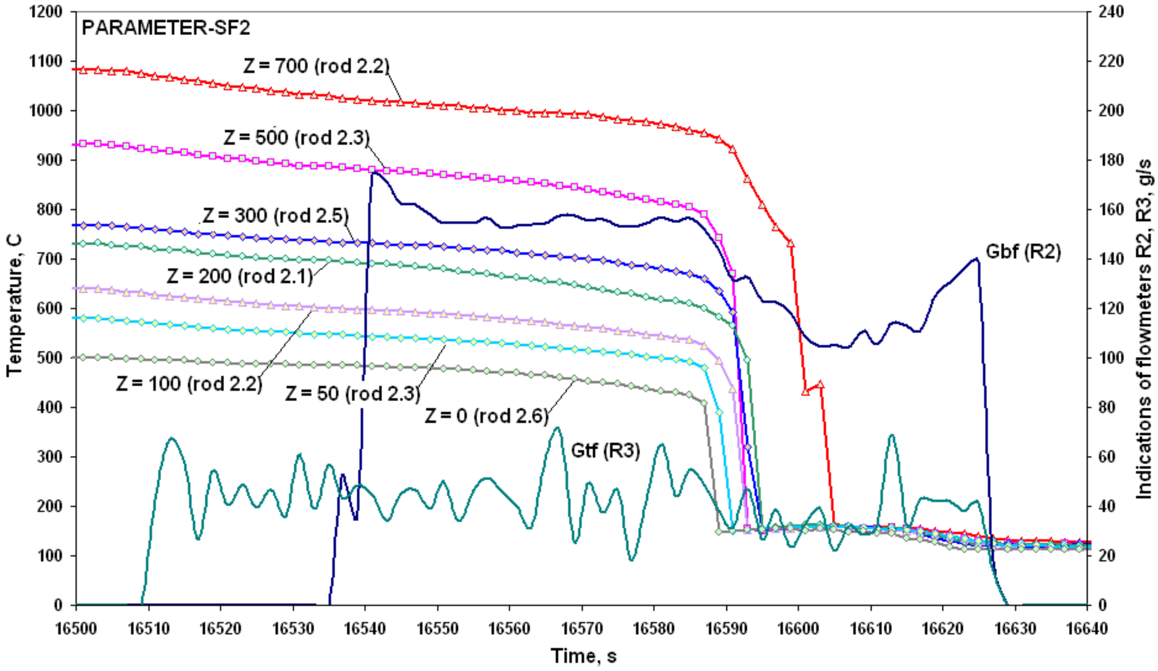
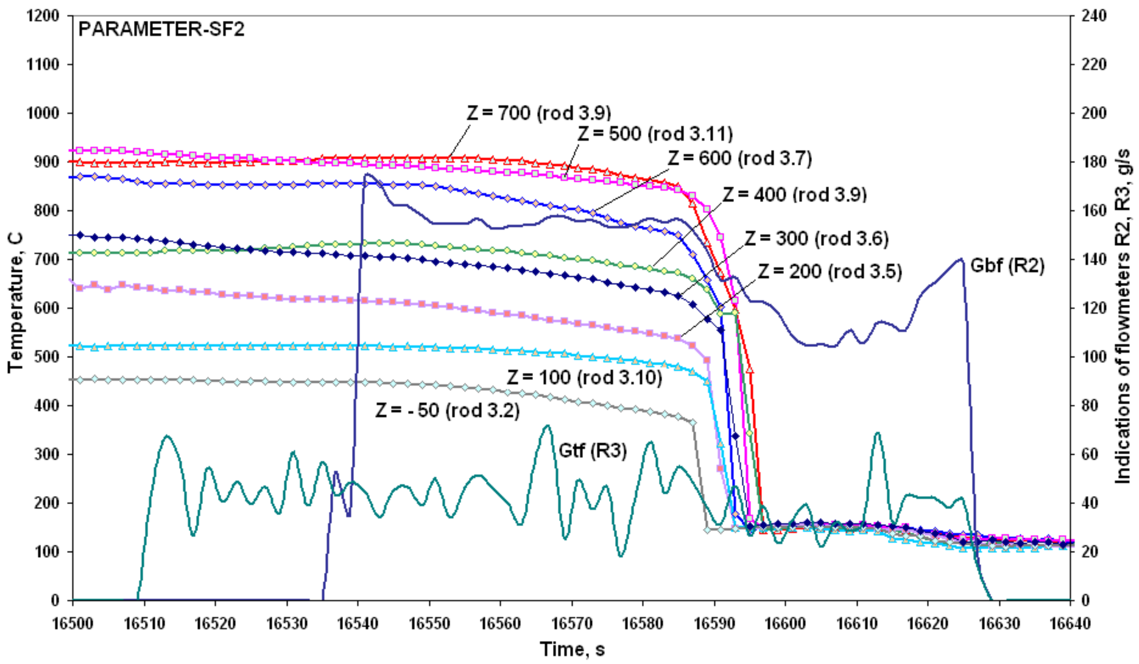


Fig. 26. Indications of thermocouples on fuel rod claddings at levels Z = (900 – 1100) mm at the flooding stage.



a)



b)

Fig. 27. Indications of thermocouples on claddings of fuel rods of the second (a) and the third (b) rows in the assembly heated zone at levels Z = (0 – 700) mm at flooding stage.

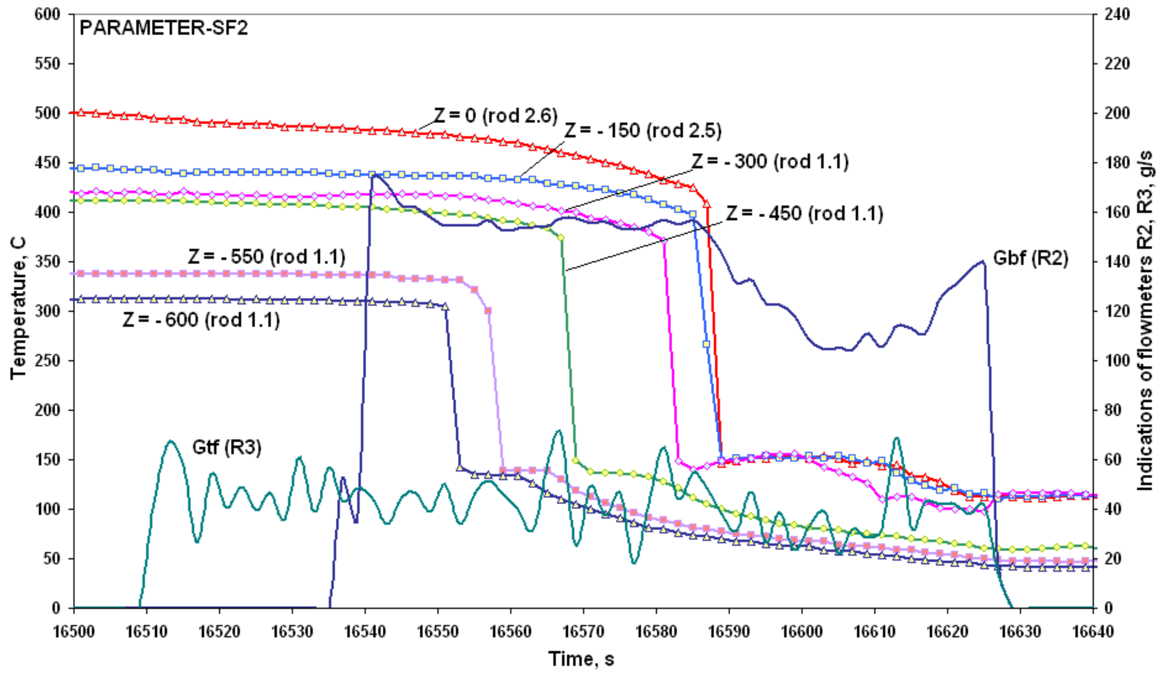


Fig. 28. Indications of thermocouples on claddings of fuel rods outside the assembly heated zone at levels Z = (-600 – 0) mm at the flooding stage.

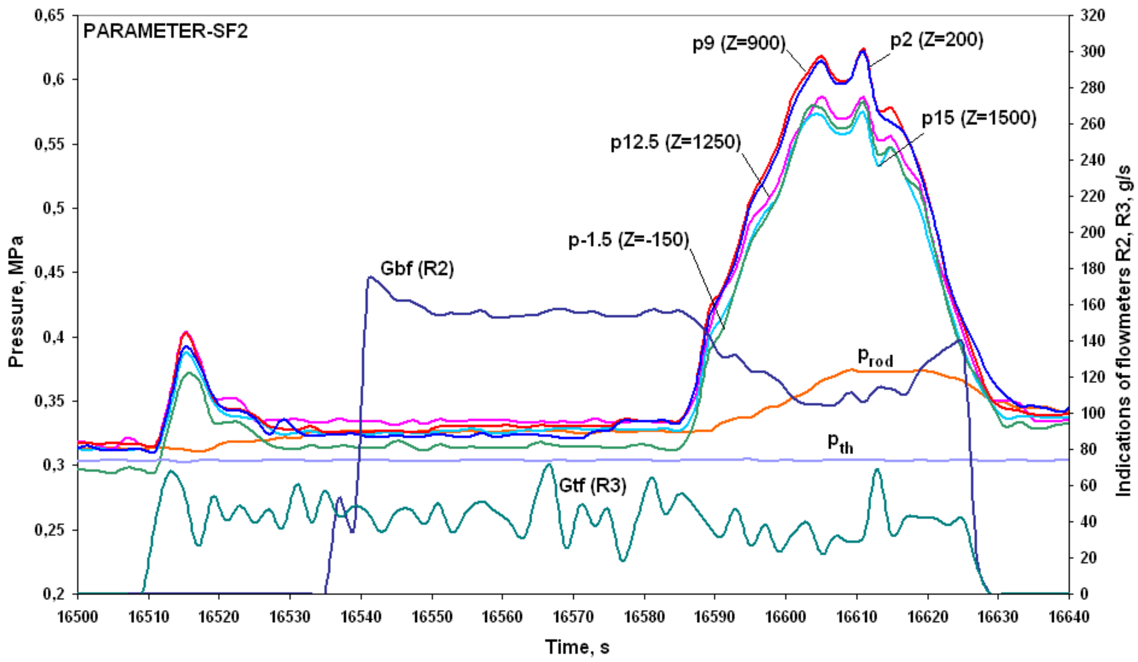


Fig. 29. Indications of pressure sensors over the model assembly path (p-1.5, p2, p9, p12.5, p15), in fuel rods (p_{rod}) and thermal insulation cavity (p_{th}) at the flooding stage.

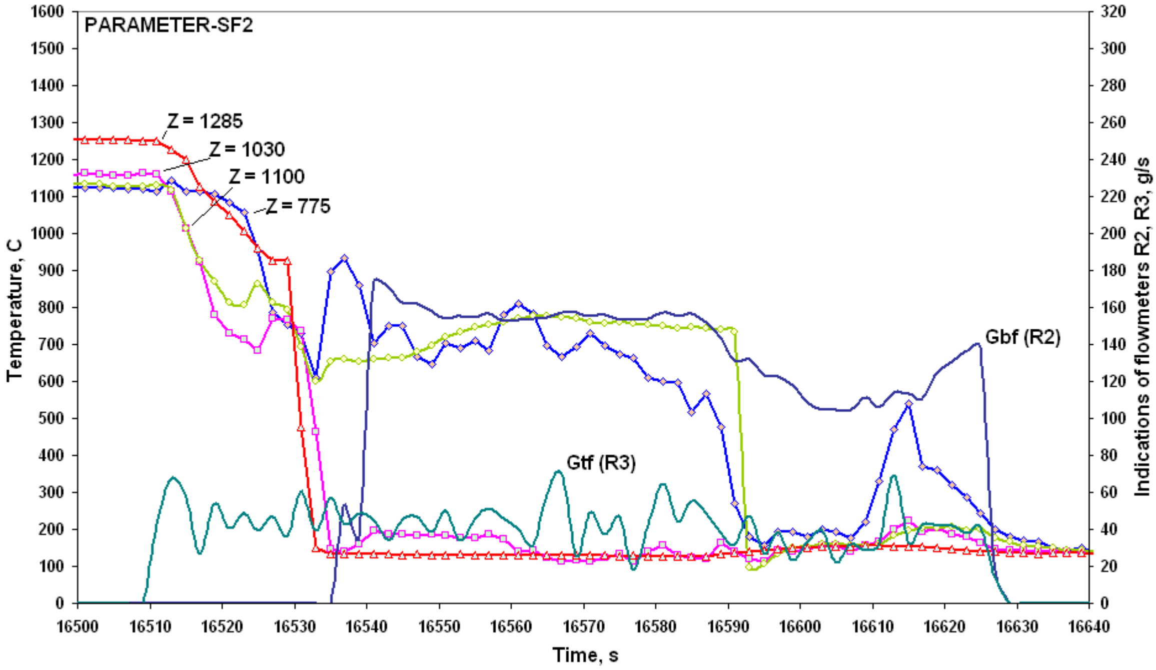


Fig. 30. Indications of thermocouples over the height of the central rod 1.1 at the flooding stage.

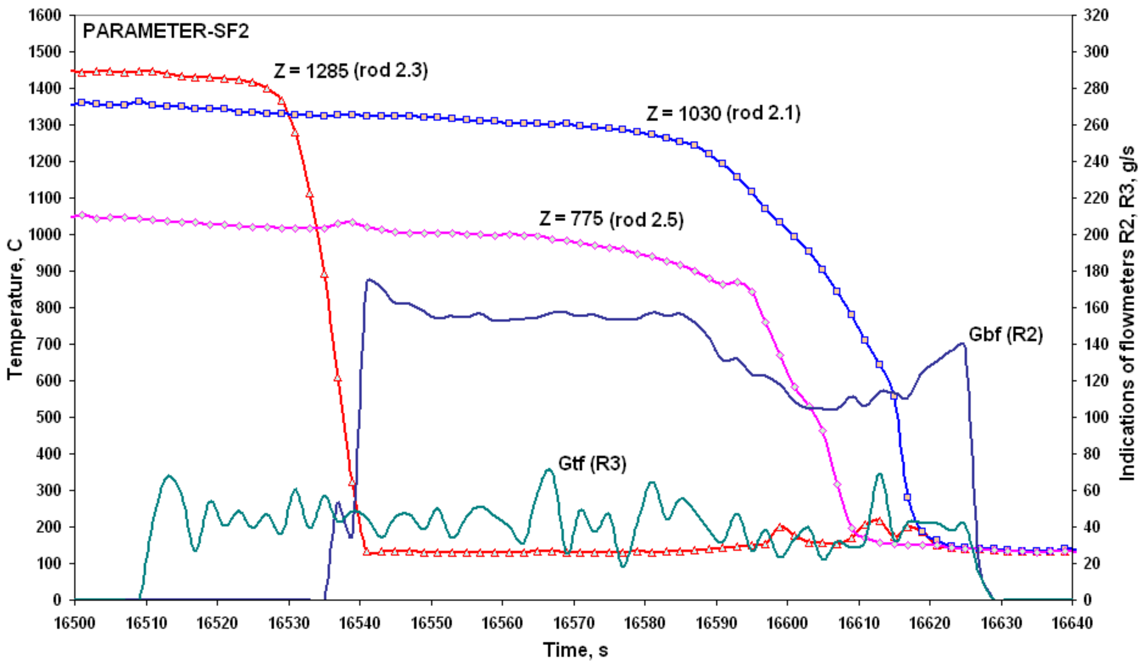


Fig. 31. Indications of thermocouples on three upper spacing grids at levels Z = (775, 1030, 1285) mm at the flooding stage.

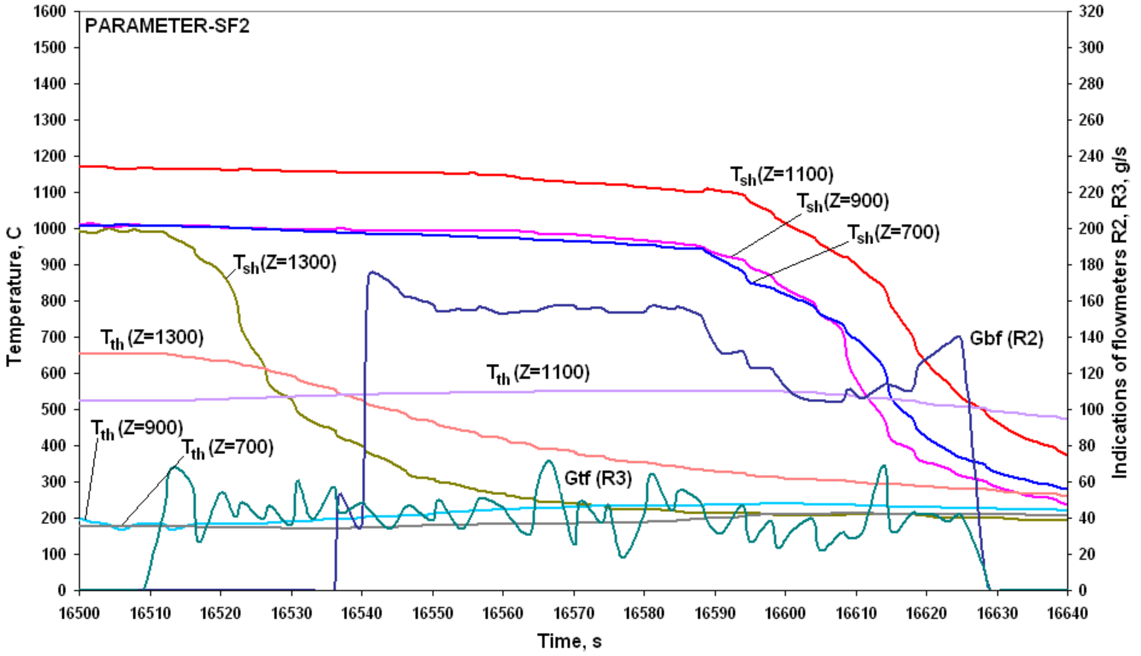


Fig. 32. Indications of thermocouples over the height of shroud (T_{sh}) and thermoinsulation (T_{th}) of the test section at the flooding stage.

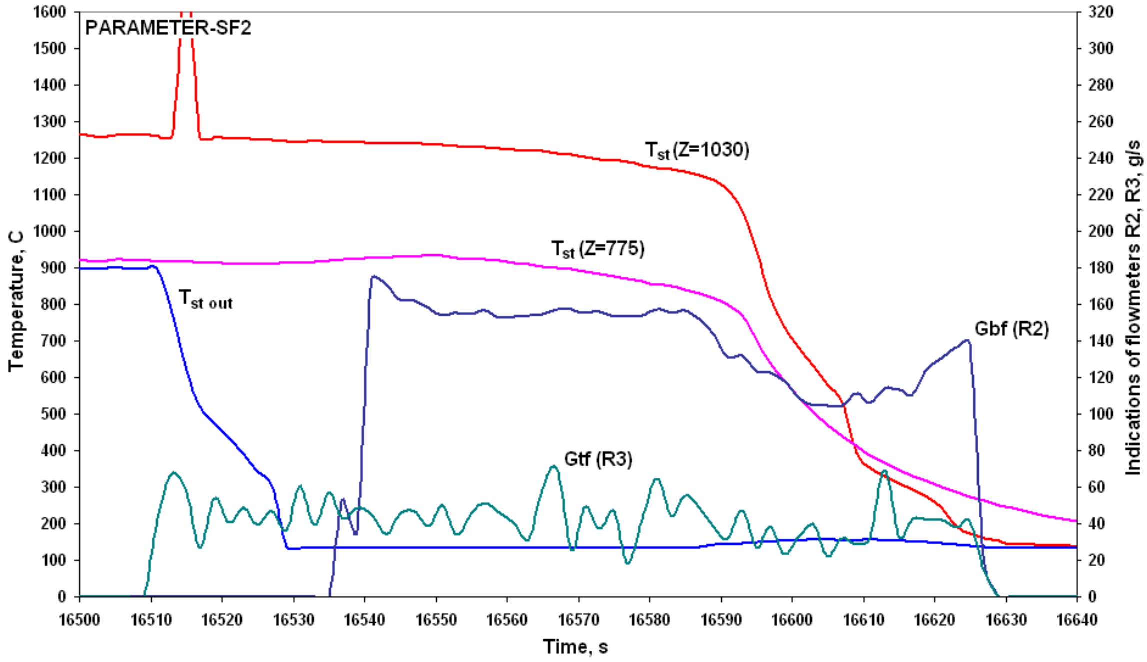


Fig. 33. Indications of thermocouples measuring the temperature of steam (T_{st}) at levels Z = (775, 1030) mm and of steam-gas mixture ($T_{st\ out}$) at level Z = 1425 mm at the flooding stage.

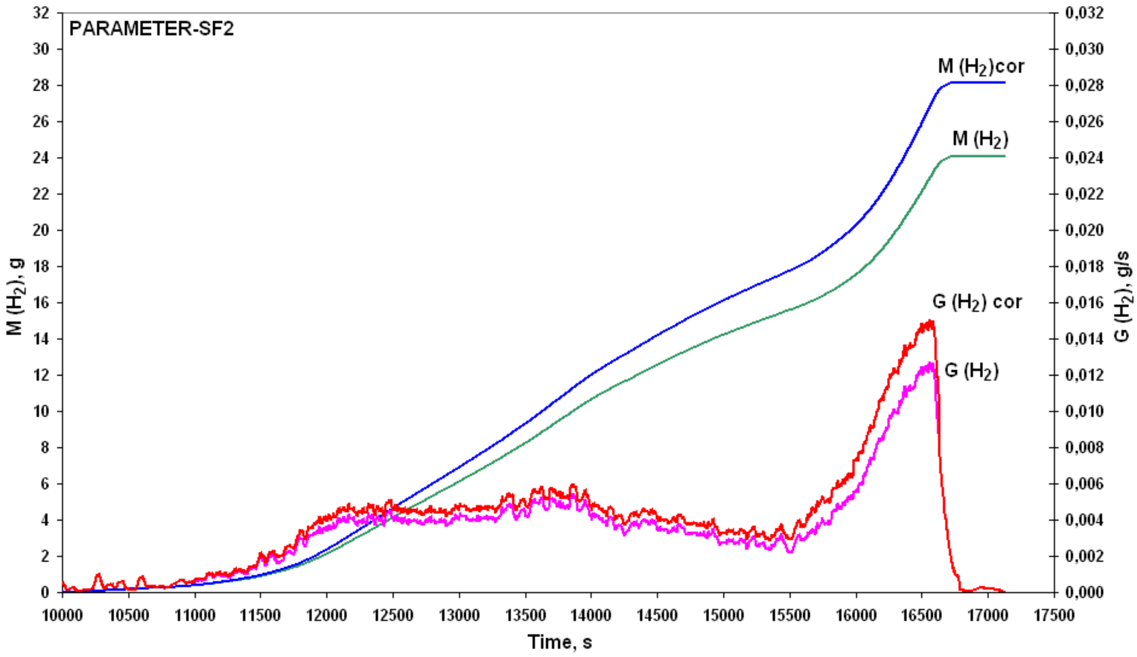


Fig. 34. Regeneration rate and mass of evolved hydrogen.

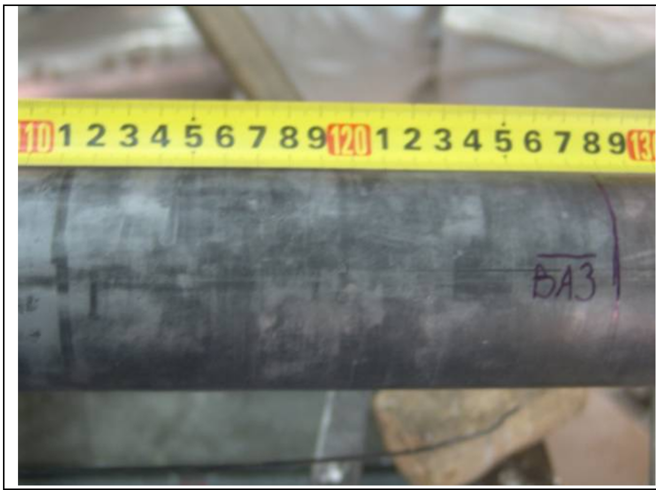
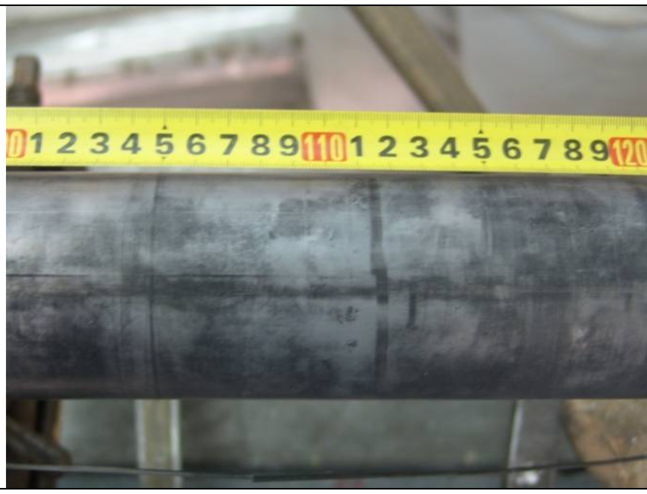
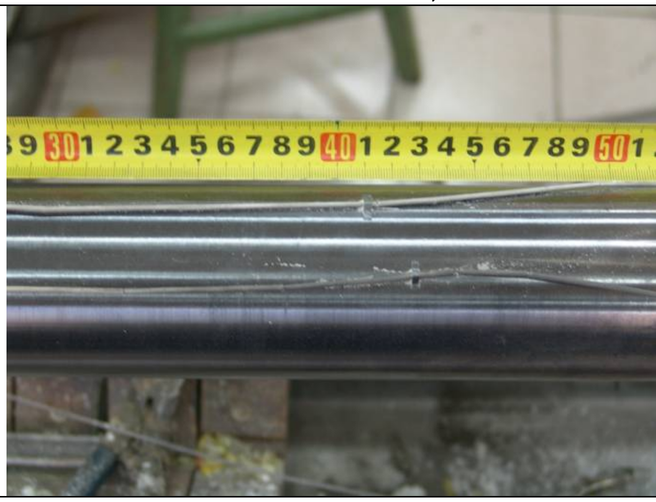
	
1300 – 1100 mm;	1200 – 1000 mm;
	
1000 – 900 mm;	800 – 700 mm;
	
600 – 500 mm;	500 – 300 mm;

Fig. 35. External appearance of the shroud after the tests.

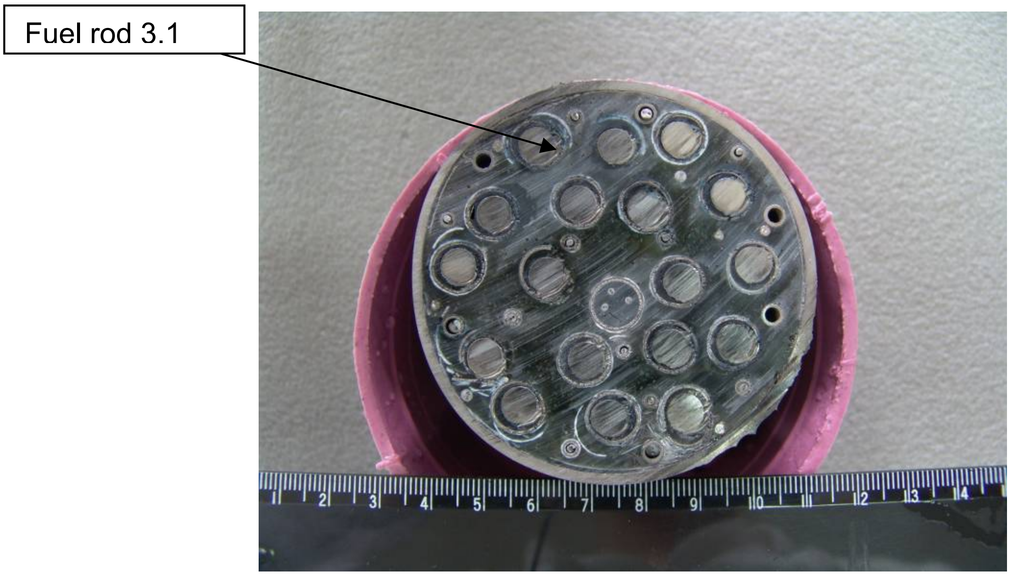


Fig. 36. The assembly cross-section at the level of ~ 1300 mm.

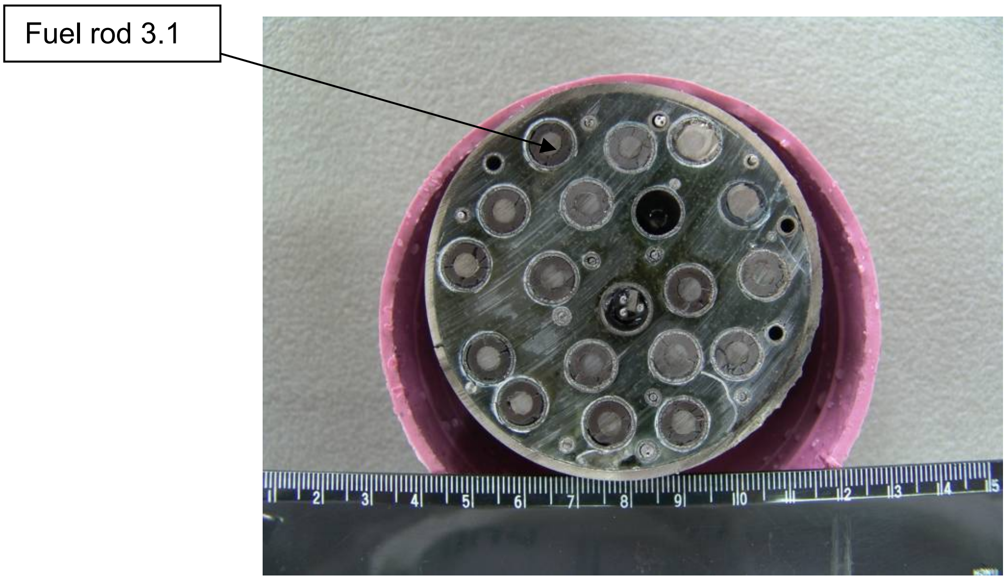


Fig. 37. The assembly cross-section at the level of ~ 1250 mm.

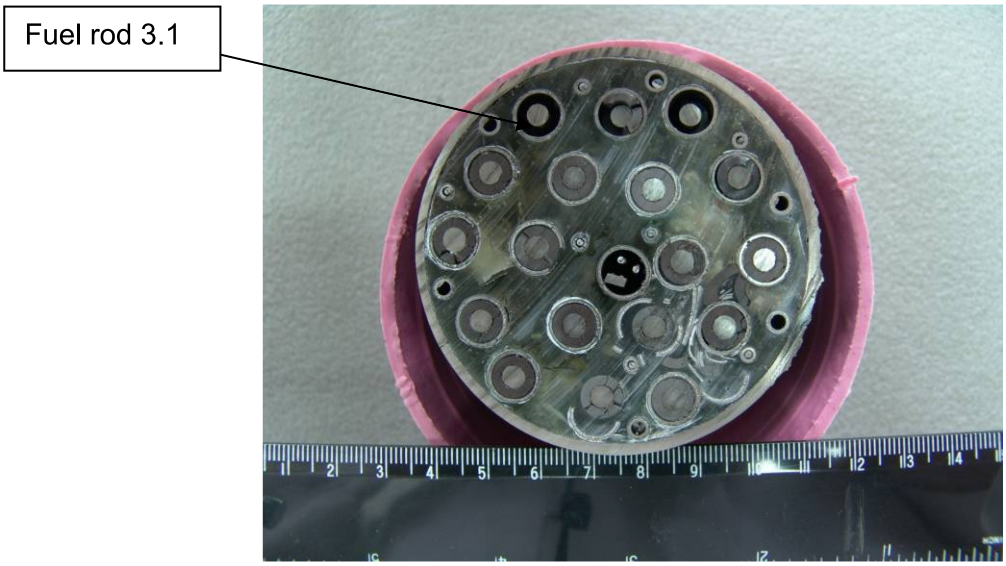


Fig. 38. The assembly cross-section at the level of ~ 1100 mm.