PROJECT # 3690

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

2009

НИИ НПО "ЛУЧ"

# PROTOCOL

## of PARAMETER-SF4 Experiment Results

**CONTENTS**

## INTRODUCTION

The PARAMETER-SF4 experiment was performed at the PARAMETER test facility in FSUE SRI SIA “LUCH” according to the Work Plan for ISTC Project # 3690.

The PARAMETER-SF4 experiment is the last experiment from the two experiments planned under Project # 3690.

In the PARAMETER-SF4 experiment the stage of severe LOCA was simulated with a core drying out, its heating-up to ~ 1750°C in the air flow and water flooding from bottom.

The PARAMETER-SF4 experiment was conducted to study the behaviour of 19-rods model FA of VVER-1000 under simulated conditions of severe accident with air ingress, including:

- Study of temperature behaviour of an assembly under conditions of air ingress and subsequent bottom flooding;
- Post-test study of oxidation degree of the structural components of the model FA of VVER-1000 and structural-phase changes in the model FA claddings;
- Study of the time history of oxygen consumption and hydrogen release.

## 1. EXPERIMENTAL FACILITY

The PARAMETER-SF4 experiment was performed at the PARAMETER test facility. The following equipment was used (see Figure 1):

- Test section with the model FA;
- System for the model FA electric heatup and the facility process system power supply;
- Steam generation and condensation system;
- System for the model FA bottom flooding;
- Argon and helium gas supply system;
- System of air supply;
- System of hydrogen analysis;
- System of air analysis at the assembly outlet;
- Data retrieval and instrumentation system.

The superheated steam from the system of steam generation and the heated carrier gas (argon) are supplied at the bottom of the test section with the model FA. The non-reacted steam, argon and hydrogen generated in the steam-zirconium reaction enter the water-cooled condenser 1. Argon, air and hydrogen come from condenser 1 into the system of gas analysis and then into the special ventilation system.

The steam generation system is fed with water using the Pump 1 from the Tank 1 (see Figure 1) with capacity of 75 L.

Bottom flooding is provided with an independent system including Tank 4 with capacity of ~ 23 L at constant pressure p8, motor-operated valve V19 and the flow meter R2.

The synthesized air (20%$O_2$+80%$N_2$) is supplied through the fragment of the central rod simulator (see Figure 7) from the test section lower part using the independent air supply system including the bottle with air, motor-operated valve V3 and the flow meter R6. At the assigned time moment the valve V3 is opened (see Figure 1), the air with calibrated flow rate passes through the measuring device ($T_{air}$, $p_{air}$) and the electron flow meter R6 (in addition the air flow rate is controlled by measured mass of air the tank using the electronic balance PV-6 with an accuracy to ±0.5 g), gets into the central fuel rod lower part, then enters into space between rods in the assembly lower part through 12 radial holes ∅ 1.5 mm in the central fuel rod cladding.

In the course of the experiment the parameters of steam ($G_{st\ in}$, $T_{st\ in}$), argon ($G_{Ar\ in}$, $T_{Ar\ in}$) and air flow rate ($G_{air\ in}$) at the test section inlet are monitored, as well as the flow rate of gas mixture (G(R4)) and concentration of oxygen in gas mixture – at the outlet (inlet of special ventilation), water mass in the main supplying tank (M1, Tank 1) and the bottom flooding tank (M4, Tank 4); mass of 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 of the condenser 1, and mass of discharge water from the test section upper flange (Tank 6.1, Tank 6.2, Tank 6.3).

## 2. TEST SECTION

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

1) Upper part (see Figure 3) is intended for:

- insertion into the working volume and sealing of fuel rods, thermocouples and tubes of the top flooding system;
- argon supply at flooding stage;
- outlet of steam-gas mixture from the test section into the heat exchanger-condenser;
- removal and control of water volume ejected from the model assembly during top flooding,

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

2) Middle part (see Figure 4) is intended for:

- arrangement of the model assembly, thermal insulation and control system of test parameters;
- sealed partition of thermal insulation cavity;
- compensation of the shroud thermal linear expansions

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

3) Lower section (see Figure 5) is intended for:

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

- heating-up of cold walls of the body lower part to the steam saturation temperature for reducing condensation of the supplied steam in the test section lower part and includes: a body (1) – two stainless steel tubes: ∅ 156x6x690 mm, ∅ 203x3x210 mm with a heater (2), pipe sleeves for supply of steam (3) and argon (4) (Dnom=8 mm), water (2 pipe sleeves Dnom=25 mm) of bottom (5) and emergency flooding (6), upper connecting flange (7) and lower water-cooled flange (8) for insertion of leads, thermocouples, system of air supply and water discharge. Environmental temperatures in the lower part of the test section and body are monitored with the help of measurement system including nine thermocouples (TC): five TCs - environmental temperature monitoring, four TCs – body temperature monitoring.

## 3. 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 heated fuel rods | 18 |
| Number of unheated fuel rods | 1 |
| FA spacer grid pitch, mm | 12.75 |
| Outside/inside diameter of fuel rod cladding, mm | 9.13/7.73 |
| Cladding material | Zr-1%Nb |
| Length of fuel rods heated, mm | 3120 |
| Length of fuel rod unheated, mm | 3050 |
| 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 the place of air inlet (axial), mm | - 120 |
| 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<br>outer diameter/central hole diameter/height, mm | $UO_2$ pellets with holes<br>$7.6^{-0.03}/4.2^{+0.15}/11^{\pm0.1}$ |
| Fuel rod unheated<br>outer diameter/central hole diameter/height, mm | $UO_2$ pellets with holes<br>$7.6^{-0.03}/4.2^{+0.15}/11^{\pm0.1}$ |
| **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 grid (lower) | 30 |
| of the sixth grid (upper) | 1305 |
| **FA Shroud** | |
| Material | Zr-1%Nb |

| | |
|---|---|
| Dimension: 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 diagram, general view and cross-section of the model FA are shown in Figures 6 and 2, general view of heated and unheated fuel rod simulators – in Figure 7.

In the unheated fuel rod simulator the fuel column (pellets) height is 2100 mm from the elevation Z = -100 mm. Below elevation of -100 mm there are 12 radial holes ∅ 1.5 mm drilled on the unheated fuel rod cladding through which the air gets into the assembly lower part.

All fuel rod simulators (except for the central unheated fuel rod) are combined into one heated section.

Each fuel rod of the assembly is equipped in its upper part with a device for helium filling and internal pressure control, including a capillary of ∅ 1.6x0.3 mm and length of ~1500 mm.

## 4. TEMPERATURE MEASUREMENT SYSTEM

Structure and composition of temperature measurement system for the test section and model FA are presented in Table 2.

Table 2

List of instrumentation

| No. | Designation | Type | Purpose and location | Output signal |
|---|---|---|---|---|
| **1** | **$T_{st\ in}$** | Ch/Al | Steam temperature at the inlet, steam inlet nozzle, - 372 mm, 270° | $^oC$ |
| **2** | **$T_{Ar\ in}$** | Ch/Al | Argon temperature at the inlet, argon inlet nozzle, - 372 mm, 90° | $^oC$ |
| **3** | **T11-6** | Ch/Al | Fuel rod 1.1 cladding temperature, -600 mm | $^oC$ |
| **4** | **T11-5.5** | Ch/Al | Fuel rod 1.1 cladding temperature, -550 mm | $^oC$ |
| **5** | **T11-4.5** | Ch/Al | Fuel rod 1.1 cladding temperature, -450 mm | $^oC$ |
| **6** | **T24-3** | Ch/Al | Fuel rod 2.4 cladding temperature, -300 mm | $^oC$ |
| **7** | **T25-1.5** | Ch/Al | Fuel rod 2.5 cladding temperature, -150 mm | $^oC$ |
| **8** | **T32-0.5** | Ch/Al | Fuel rod 3.2 cladding temperature, -50 mm | $^oC$ |
| **9** | **T260** | Ch/Al | Fuel rod 2.6 cladding temperature, 0 mm | $^oC$ |
| **10** | **T221** | Ch/Al | Fuel rod 2.2 cladding temperature, 100 mm | $^oC$ |

| | | | | |
|---|---|---|---|---|
| **11** | **T3101** | Ch/Al | Fuel rod 3.10 cladding temperature, 100 mm | $^oC$ |
| **12** | **T212** | Ch/Al | Fuel rod 2.1 cladding temperature, 200 mm | $^oC$ |
| **13** | **T352** | Ch/Al | Fuel rod 3.5 cladding temperature, 200 mm | $^oC$ |
| **14** | **T253** | Ch/Al | Fuel rod 2.5 cladding temperature, 300 mm | $^oC$ |
| **15** | **T363** | Ch/Al | Fuel rod 3.6 cladding temperature, 300 mm | $^oC$ |
| **16** | **T314** | Ch/Al | Fuel rod 3.1 cladding temperature, 400 mm | $^oC$ |
| **17** | **T3124** | Ch/Al | Fuel rod 3.12 cladding temperature, 400 mm | $^oC$ |
| **18** | **T225** | WRe | Fuel rod 2.2 cladding temperature, 500 mm | $^oC$ |
| **19** | **T311'5** | WRe | Fuel rod 3.11 cladding temperature, 500 mm | $^oC$ |
| **20** | **$T_{sh}5$** | WRe | Shroud temperature (opposite to fuel rod 3.2), 500 mm | $^oC$ |
| **21** | **T116** | WRe | Fuel rod 1.1 temperature, center line, 600 mm | $^oC$ |
| **22** | **T346** | WRe | Fuel rod 3.4 cladding temperature, 600 mm | $^oC$ |
| **23** | **T376** | WRe | Fuel rod 3.7 cladding temperature, 600 mm | $^oC$ |
| **24** | **T117** | WRe | Fuel rod 1.1 temperature, center line, 700 mm | $^oC$ |
| **25** | **T237** | WRe | Fuel rod 2.3 cladding temperature, 700 mm | $^oC$ |
| **26** | **T387** | WRe | Fuel rod 3.8 cladding temperature, 700 mm | $^oC$ |
| **27** | **$T_{sh}7$** | WRe | Shroud temperature (opposite to fuel rod 3.2), 700 mm | $^oC$ |
| **28** | **$T_{th}7$** | Ch/Co | Thermoinsulation temperature (opposite fuel rod 3.2), 700 mm | $^oC$ |
| **29** | **T118** | WRe | Fuel rod 1.1 temperature, center line, 800 mm | $^oC$ |
| **30** | **T328** | WRe | Fuel rod 3.2 cladding temperature, 800 mm | $^oC$ |
| **31** | **T248** | WRe | Fuel rod 2.4 cladding temperature, 800 mm | $^oC$ |
| **32** | **T239** | WRe | Fuel rod 2.3 cladding temperature, 900 mm | $^oC$ |
| **33** | **T399** | WRe | Fuel rod 3.9 cladding temperature, 900 mm | $^oC$ |
| **34** | **P10** | - | Pressure sensor near fuel rod 3.2, 1000 mm | MPa |
| **35** | **$T_{sh}9$** | WRe | Shroud temperature (opposite to fuel rod 3.8), 900 mm | $^oC$ |
| **36** | **$T_{th}9$** | Ch/Co | Thermoinsulation temperature (opposite rod 3.8), 900 mm | $^oC$ |
| **37** | **T2110** | WRe | Fuel rod 2.1 cladding temperature, 1000 mm | $^oC$ |
| **38** | **T3310** | WRe | Fuel rod 3.3 cladding temperature, 1000 mm | $^oC$ |
| **39** | **T3810** | WRe | Fuel rod 3.8 cladding temperature, 1000 mm | $^oC$ |
| **40** | **T2611** | WRe | Fuel rod 2.6 cladding temperature, 1100 mm | $^oC$ |
| **41** | **T3411** | WRe | Fuel rod 3.4 cladding temperature, 1100 mm | $^oC$ |
| **42** | **T3711** | WRe | Fuel rod 3.7 cladding temperature, 1100 mm | $^oC$ |
| **43** | **$T_{sh}11$** | WRe | Shroud temperature (opposite to fuel rod 3.1), 1100 mm | $^oC$ |
| **44** | **$T_{th}11$** | Ch/Co | Thermoinsulation temperature (opposite fuel rod 3.1), 1100 mm | $^oC$ |
| **45** | **T2212.5** | WRe | Fuel rod 2.2 cladding temperature, 1250 mm | $^oC$ |
| **46** | **T3612.5** | WRe | Fuel rod 3.6 cladding temperature, 1250 mm | $^oC$ |
| **47** | **T31012.5** | WRe | Fuel rod 3.10 cladding temperature, 1250 mm | $^oC$ |
| **48** | **p12.5** | - | Pressure sensor near fuel rod 3.7, 1250 mm | MPa |
| **49** | **T2513** | WRe | Fuel rod 2.5 cladding temperature, 1300 mm | $^oC$ |
| **50** | **T3213** | WRe | Fuel rod 3.2 cladding temperature, 1300 mm | $^oC$ |

| | | | | |
|---|---|---|---|---|
| **51** | **T3513** | WRe | Fuel rod 3.5 cladding temperature, 1300 mm | $^{o}$C |
| **52** | **$T_{sh}$13** | WRe | Shroud temperature (opposite fuel rod 3.6), 1300 mm | $^{o}$C |
| **53** | **$T_{th}$13** | Ch/Co | Thermoinsulation temperature (opposite fuel rod 3.6), 1300 mm | $^{o}$C |
| **54** | **T1114** | WRe | Fuel rod 1.1 cladding temperature, 1400 mm | $^{o}$C |
| **55** | **T31114** | WRe | Fuel rod 3.11 cladding temperature, 1400 mm | $^{o}$C |
| **56** | **T31'15** | WRe | Fuel rod 3.1 cladding temperature, 1500 mm | $^{o}$C |
| **57** | **p15** | - | Pressure sensor near fuel rod 3.10, 1500 mm | MPa |
| **58** | **$T_{st\ out}$** | WRe | Steam temperature at the outlet, steam outlet nozzle, 1425 mm, 0$^{o}$ | $^{o}$C |

The measurement system includes 40 TCs for measurement 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; 5 TCs for measurement the shroud temperature; 4 TCs for measurement the thermoinsulation temperature at 5 elevations (500, 700; 900; 1100 and 1300 mm) and three TCs for measuring the temperature of steam and argon at the inlet and outlet.

In the system of the assembly temperature measurement the TCs of three types were used (see Figure 8): cable Ch/Al (Ch/Co) in stainless steel sheath ∅ 1.5 mm with the upper limit of effective range of 1400°C (800°C), and high-temperature WRe thermocouples with W+5%Re/W+20%Re wire encased into ∅ 2.8x(0.6-0.7) mm zirconium alloy Zr+1%Nb sheath with the upper limit of measured temperatures to 2000°C.

TCs for measurement of cladding temperatures were fixed in alignment with fuel rods on surface of fuel rod claddings using the zirconium strip with the width of ~5 mm and thickness of 0.3 mm with the help of electric-resistance welding, additionally the TCs were fixed by Ir (Iridium) wire with diameter of 0.3 mm.

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 FA is made with the help of tubes of alloy Zr+1%Nb ∅ 2.8x0.7 mm. Helium pressure in fuel rods was monitored by pressure sensors (p11, p21 – p312).

## 5. MONITORING OF PROCESS PARAMETERS

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

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

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

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

Bottom flooding water flowrate is set by pressure p8 in hydroaccumulator Tank 4 and monitored by water volume in Tank 4 and indications of electron flowmeter R2.

Cooling of the upper and middle part of the body is performed separately, water used as a coolant that flows from top to bottom.

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

Water flow rate in cooling water from top to bottom of the test section middle part body is set by the Pump 5, heating-up of cooling water is monitored with thermocouples $T_{cool\ in}1$, $T_{cool\ out}1$ (see Figure 4).

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 hydroaccumulators Tank 5’, Tank 6.1; at the stages of reaching the pre-oxidation phase, at the pre-oxidation phase and the cool down phase – in Tank 5.1,…, Tank 5.5, Tank 6.2; at the flooding phase – in Tank 5. Mass of water ejected from the assembly under flooding – in Tank 6.3.

Water masses are checked after the experiment by weighing with electronic balance PV-6 with precision to ±0.5 g.

## 6. HYDROGEN MEASUREMENT SYSTEM

The system to measure the hydrogen content that is generated in the course of high temperature interaction of steam and the model FA materials is similar to that used in the experiments SF1, SF2, SF3.

The hydrogen measurement system is located downstream the condenser 1 in a bypass to the off-gas line subsequent to the point of monitoring the gas mixture parameters T10, p10 (see Figure 1). The system operation is based on two methods of measurement: continuous and discrete.

For continuous hydrogen measurement SOV-3 system 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.

Main design parameters of SOV-3:

- gas mixture:
  - carrier gas – argon;
  - monitored gas – hydrogen;
- mixture pressure – 0.15 – 0.35 MPa;
- mixture flowrate – $(8 – 25)\cdot10^{-5}$ $m^3$/min;
- effective range - $5\cdot10^{-4}$ – 80 vol.%;
- transition time within the concentration range:
  - $5\cdot10^{-4} – 1\cdot10^{-1}$ vol.% ~ 2 min;
  - $\geq1\cdot10^{-1}$ vol.% – 1 min.

The location of SOV-3 hydrogen measurement system in the bypass enables to monitor the hydrogen content variation with F11 valve open within the entire course of the experiment.

In case of the discrete method of hydrogen concentration measurement, 9 sampling tanks are used (No.11, No.12,…, No.19) with 2 L volume each. Before the experiment the tanks are washed with high purity argon and vacuumized. Sampling is performed with the help of motor-driven valves (V8,…, V17), remotely controlled with automatic sampling system and with the assigned sampling interval and duration. The sampling time is recorded by the facility data acquisition system.

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.

## 7. OXYGEN MEASUREMENT SYSTEM

The system to measure the content of oxygen not reacted with zirconium FA components (fuel rod claddings, spacer grids, model assembly shroud) as well as system to measure the hydrogen content is based on two methods of measurement: continuous and discrete.

Air flow rate through the model assembly is assigned at the test section inlet by pressure of the air from the gas tank and measured at the flow metering section by the inlet pressure ($p_{air}$) and temperature ($T_{air}$) and electronic flow meter IN FLOW of Bronkhorst company with main design parameters:

- gas monitored – (20 %) $O_2$ + (80 %) $N_2$;
- effective range – 0 - 3.75 kg/h;
- measurement accuracy – ±0,5 %.

For continuous oxygen measurement at the model assembly outlet the OLCT20 device of OLDHAM company is used. The OLCT20 device is located downstream the mixer in a gas line of the facility (Figure 1). The device setting point is chosen according to operation condition OLCT20 at which pressure of the gas mixture transiting through the device, should not exceed 0.11 MPa.

Main design parameters of the OLCT20 device:

- gas monitored – $O_2$;
- effective range – 0 - 30 % vol.;
- permissible limits of main error – ± 5%.

The discrete system to measure the oxygen content is similar to the hydrogen measurement system and is located downstream the condenser 1 in a bypass to the off-gas line subsequent to the point of monitoring the gas mixture parameters T10, p10 (see Figure 1). In case of the discrete method of oxygen concentration measurement 10 sampling tanks are used (No.1, No.2,…, No.10) with 2 L volume each. Before the experiment, the tanks are washed with high purity argon and vacuumized. Sampling is performed with the use of automatic sampling system and with the assigned sampling interval and duration. The sampling time is recorded by the facility data acquisition system.

After the experiment the tanks are sealed and disconnected from the gas duct for a subsequent analysis of gas mixtures using the gas chromatograph CHROMATECH-CRYSTAL 5000.

## 8. PARAMETER-SF4 EXPERIMENT

### 8.1. Experiment scenario

PARAMETER-SF4 experiment was performed on 21.07.2009 at PARAMETER test facility in FSUE SRI SIA "LUCH" with the analytical support of work teams that perform calculations with SOCRAT, PARAM-TG, RELAP/SCDAP/SIM MOD3.2, ATHLET-CD, SCDAP/RELAP/IRS, ICARE/CATHARE, MAAP4 computer codes. Pre-test scenario of the experiment is provided in Table 3.

Table 3

Pre-test scenario of PARAMETER-SF4 experiment

| No. | Stage | Main parameters | | | |
|---|---|---|---|---|---|
| | | FA temperature, K | Medium | Heating rate, K/c | Time, s |
| 1 | Joule heating up of FA in argon flow | ~300-670 | Argon at temperature 720 K (argon flowrate - 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 flowrate at inlet - 2/3.5 g/s at temperature 720/770 K) | | 1500-3500 |
| 3 | FA heating up to 1470 K (transient phase I) | 770→1470 | Steam-argon mixture (argon/steam flowrate at inlet - 2/3.5 g/s at temperature 720/770 K) | 0.3 (beginning), 0.1 (end) | 3500-8000 |
| 4 | FA pre-oxidation | ~1470 | Steam-argon mixture (argon/steam flowrate at inlet - 2/3.5 g/s at temperature 720/770 K) | | 8000-14000 |
| 5 | FA cool down to 1170 K (transient phase II) | 1470→1170 | Steam-argon mixture (argon/steam flowrate at inlet - 2/3.5 g/s at temperature 720/770 K) | | 14000-16000 |

| | | | | | |
|---|---|---|---|---|---|
| **6** | Air ingress | 1170→2020 | Air-argon mixture (argon/air flowrate at inlet - 2/0.5 g/s at temperature 720/300 K) | ~0.3 | As soon as FA will reach temperature of 2020K |
| **7** | FA bottom flooding (as soon as FA will reach Tmax=2020 K) | Up to saturation | Water (flowrate of 80 g/s at temperature ~300 K) | | As soon as saturation temperature will be reached |

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

Table 4

PARAMETER-SF4 experiment main events

| Current time, s | Events |
|---|---|
| **0** | Data retrieval and instrumentation system switched on. Argon supply into the test section and the assembly with the flow rate of ~ 0.76 g/s for filling the gas lines |
| **~ 686** | Argon supply into the assembly with the flow rate of ~ 2 g/s at temperature of ~ 280°C |
| **~ 1716** | Steam supply into the assembly with the flow rate of ~ 3.5 g/s at temperature of ~ 500°C |
| **~ 3516** | FA heatup to temperature 500±50°C at elevations 500-1300 mm |
| **4050** | Beginning of slow heating of assembly |
| **~ 8000** | Beginning of pre-oxidation phase |
| **13886** | Beginning of decrease in the assembly temperature to ~ 900°C |
| **16022** | Closing of the valve of steam supply into the assembly |
| **16035** | Air supply into the assembly with the flow rate of ~ 0.5 g/s |
| **16355** | Electric power increase |
| **17412** | Electric power switched off |
| **17434** | Opening of the bottom flooding valve |
| **17511** | Closing of the valve of air supply into the assembly |
| **17908** | Closing of the bottom flooding valve |
| **18520** | Data retrieval and instrumentation system switched off |

### 8.2. Experiment description

The PARAMETER-SF4 experiment was started after checking the correct position of the valves, availability of argon, helium, air and distilled water inventory sufficient for startup.

The experiment consisted of six stages:

- *preparation stage* (0 – 4506 s) – stabilization of assigned flowrates of argon ($G_{Ar\ in}$ ≈ 2 g/s) and steam ($G_{st\ in}$ ≈ 3.5 g/s) at FA temperature ($T_{FA}$) ≈ 500$^o$C, check of state of the assembly and process systems;

- *assembly heating-up to temperature of ≈ 1200$^o$C* (4506 – 8000 s);

- *pre-oxidation* (8000 – 13886 s) – FA holding at temperature ≈ 1200$^o$C at the hottest zone for ~ 6000 s. The maximum temperature deviations in the hottest cross-section (1250 mm) – ~ ± 50$^o$C;

- *cooling down of the assembly to temperature $T_{FA\ Max}$ ≈ 900$^o$C* (from 13886 to 16355 s);

- *air ingress into FA* (16035 – 17511 s) with subsequent (from 16355 to 17434 s) assembly heating-up to maximum temperature of ~ 1740$^o$C at the hottest zone;

- *flooding* (17434 – 17908 s) – assembly bottom flooding at the flow rate of Gbf ≈ 80 g/s.

*Preparation stage*

At 0 s the Data retrieval and instrumentation system, the SOV-3 system for hydrogen content measurement were switched on, valves V6, V23 were closed, valves V7, V22, V21, V25, V26 V27, V28 were opened.

At 30 s the test section lower part heater was switched on.

At 50 s the heater (see Figure 1) for argon heating up to the assigned temperature of $T_{in.Ar}$ ≈ 280$^o$C was switched on.

At 54 s the argon was supplied into the heat insulation cavity with opening of the valve V5 to set the assigned pressure.

At ~ 160 s the model FA heating in argon flow was started – electric power of ~ 2000 W was supplied to FA (see Figure 11).

At ~ 700 s the valve V7 was opened with setting argon flow rate of $G_{arg\ in}$ ≈ 2.0 g/s at the model assembly inlet (see Figure 10).

At ~ 700 s the gas flow rate of ~ 2 g/s at the outlet to special ventilation was recorded by the control electronic rotameter R4 (see Figure 10) that was indicative of filling the test section and technological pipes with argon.

At 1100 s the steam generator and steam-superheater were switched on.

At 1440 s at the cladding temperature of ~ 500±50$^o$C at elevations 500-1250 mm the valve V1 was opened and the steam was supplied into the test section.

At 2090 s the valve V20 was closed and the valves V22, V24 were opened.

At 3447 s the valve V22 was closed and the valve V23 was opened – the condensate collection into the Tank 5.1 was started (see Figure 1).

*Assembly heating-up to temperature of ≈ 1200°C*

From 4050 to 8456 s at the cladding temperatures of ~450-500°C at elevations of 800-1300 mm the electric power was increased in the stepwise manner to ~ 7500 W (see Figure 11).

By ~ 4100 s the cladding temperatures at elevations of 500-1300 mm reached ~450-500°C (see Figure 12).

At 6437 s the valve V28 was closed – the condensate collection Tank 5.1 was shut off.

At the stage of the assembly heating-up two samples of gas mixture were taken: to the sampling tank Vol.11 (at 4553 s); to the sampling tank Vol.12 (at 6545 s).

*Pre-oxidation*

From ~ 8000 s at electric power of ~ 7500 W (see Figure 11) and maximum cladding temperature of 1150°C at elevation of 1250 mm (see Figure 15 – T31012.5) the pre-oxidation stage started.

At 8542 s the sampling of gas mixture into the sampling tank Vol.13 was made.

At 9437 s the valve V27 was closed – the condensate collection Tank 5.2 was shut off.

The stable behaviour of the main parameters was observed: flow rates of argon and steam ($G_{arg\ in} \approx 2$ g/s, $G_{st\ in} \approx 3.5$ g/s); pressure of steam-gas mixture in FA – ~ 0.38 MPa, of helium inside fuel rods – ~ 0.48 MPa, of argon in thermal insulation cavity – ~ 0.43 MPa (see Figure 13). To maintaining the assigned temperature the electric power was changed within the range from ~ 7500 W to ~ 7700 W (see Figure 11).

At 10542 s the gas mixture sample was taken into sampling tank Vol.14.

At 12437 s the valve V26 was closed – the condensate collection Tank 5.3 was shut off.

At 12512 s the gas mixture sample was taken into sampling tank Vol.15.

At 14522 s the gas mixture sample was taken into sampling tank Vol.16.

At 15437 s the valve V25 the valve – the condensate collection Tank 5.4 was shut off.

At 15967 s the gas mixture sample was taken into sampling tank Vol.17.

The pre-oxidation stage with duration of ~ 6000 s ended at 13886 s at maximum cladding temperature of ~ 1235°C (T31012.5, Figure 12).

*Cooling down of the assembly to temperature $T_{FA\ Max} \approx 900^oC$*

Starting from 13886 to 16355 s the electric power was decreased gradually from 7890 W to ~ 4000 W that resulted in decrease in maximum cladding temperature from ~ 1235 to ~ 900°C (T31012.5, see Figure 12).

At ~ 16000 s the valve F11 was shut off and, accordingly, the gas line with the hydrogen analyzer SOV-3 was switching off.

*Air ingress into FA*

At 16035 s the air was supplied into the assembly with the flow rate of ~ 0.48 g/s.

Starting from 16355 s to 17412 s the electric power was gradually increased from 4090 W to 6000 W. With this, the hottest zone began to increase from the elevation of Z=800 mm and then the front of temperature increase began to shift down (see Figures 25 - 26).

At 16490 s the valve F11 was opened and from 16494 s the sampling and oxygen measurement with OLST20 device were started. At 17511 s the valve of air supply into the assembly was closed. The entire time of air supply was 1476 s. During the air ingress 10 samplings were made:

At 16494 s the gas mixture sample was taken into sampling tank Vol.1.

At 16594 s the gas mixture sample was taken into sampling tank Vol.2.

At 16794 s the gas mixture sample was taken into sampling tank Vol.3.

At 16894 s the gas mixture sample was taken into sampling tank Vol.4.

At 16894 s the gas mixture sample was taken into sampling tank Vol.5.

At 16994 s the gas mixture sample was taken into sampling tank Vol.6.

At 17094 s the gas mixture sample was taken into sampling tank Vol.7.

At 17194 s the gas mixture sample was taken into sampling tank Vol.8.

At 17294 s the gas mixture sample was taken into sampling tank Vol.9.

At 17394 s the gas mixture sample was taken into sampling tank Vol.10.

*Flooding*

At 17412 s, with reaching the maximum assembly temperature $T_{FAMax}$ = 1740°C, the electric power was switched off and at 17434 s the valve V19 of the bottom flooding system was opened. For 22 seconds between electric power switching off and flooding onset the following actions were conducted:

- oxygen measurement device was switched off;
- condensate collection line V23 was shut off;
- condensate collection line for flooding stage was opened (valves V22, V20);

- hydrogen measurement device was switched on (SOV-3);
- argon injection was switched from the lower to the upper part.

Water flow rate recorded by the electronic flow meter R2 is shown in Figure 24.

In the course of flooding the sampling of gas mixture was made into two sampling tanks Vol.18 (17475 s) and Vol.19 (17501 s).

At 17908 s following decrease in the assembly temperature the valve V19 for bottom flooding water supply was closed.

Duration of the bottom flooding was ~ 474 s.

At 18520 s the Data retrieval and instrumentation system and hydrogen and oxygen measurement system were switched off.

**8.3. Experiment results**

The experiment results are presented in Figures 10 – 32.

In Figures 10 and 11 the results of measurement of the main experimental parameters are given: flow rate and temperature of argon ($G_{arg\ in}$, $T_{in.Ar}$) and steam ($G_{st\ in}$, $T_{in.st.}$) at the test section inlet; gas mixture flow rate G(R4) at outlet to special ventilation (Figure 10); electric parameters (Figure 11): power (P1), current (I1), voltage (U1).

Figures 12 – 13 present the thermocouples readings arranged over the height of fuel rod claddings (Figure 12), and of pressure sensors (Figure 13): in the model assembly (p12.5, p15) and thermal insulation cavity ($p_g$) – (Figure 13a), in fuel rods (p11, p21 – p312) – (Figure 13b).

Figures 14 – 17 give the more detailed claddings thermocouples readings fixed at the elevations: Z = (1300 – 1500) mm (Figure 14), Z = (900 – 1250) mm (Figure 15), Z = (400 – 800) mm (Figure 16) and Z = (0 – 300) mm (Figure 17), within the time interval of 0 – 18000 s.

Figure 18 presents volumetric oxygen concentration measured with OLCT20 device and in sampling tanks, and air flow rate at the test section inlet G(R6). The on-line Indications of OLCT20 device are presented. It is necessary to take into account a transportation time to compare continuous (OLCT20) and discrete (Sampling) oxygen monitoring systems indications.

Figure 19 presents volumetric hydrogen concentration measured with SOV-3 device and in sampling tanks, and the flooding water flow rate G(R2).

Figure 20 presents indications of pressure sensors at various elevations of the model assembly: p12.5 (Z = 1250 mm), p15 (Z = 1500 mm), and flooding water flow rate G(R2) at the cool-down, air ingress and flooding stages.

Figure 21 presents the thermocouples readings installed inside the central fuel rod 1.1 at elevations Z = 600, 700 and 800 mm within the time interval of 0 – 18000 s.

Figure 22 presents readings of the thermocouples maintained on the shroud ($T_{shr}$) and in the test section thermal insulation ($T_{ins}$) at various elevations within the time interval of 0 – 18000 s.

Figure 23 presents indications of the electronic flow meter of the air supply system (R6) and of the oxygen measurement device OLCT20 at the cool-down, air ingress and flooding stages, within the time interval of 15500 – 17700 s.

Figure 24 presents indications of the electronic flow meter of the bottom flooding system R2 and of the flow meter M4 at the flooding stage within the time interval of 17400 – 18000 s.

Figures 25 – 27 present the claddings thermocouples readings at the cool-down and air ingress stages within the time interval of 14000 – 17600 s at various elevations over the assembly height: at elevations Z = (1100 - 1500) mm – Figure 25; (0 - 900) mm – Figure 26, and over the heated length of the assembly – Figure 27.

Figure 28 presents the generation rate G(H2) and total mass of the released hydrogen M(H2) obtained by processing the indications of SOV-3 device.

Table 5 presents the condensate water mass in control tanks.

Table 5

Results of water mass measurement in control tanks

| No. | Tank | Time of condensate collection (beginning – end), s | Water mass, g | Steam flow rate by the results of discharge, g/s |
|---|---|---|---|---|
| **1** | Tank 5.1 | 3447 - 6437 | 10465 | 3.50 |
| **2** | Tank 5.2 | 6437 - 9437 | 10614 | 3.54 |
| **3** | Tank 5.3 | 9437 - 12437 | 10298 | 3.43 |
| **4** | Tank 5.4 | 12437 - 15437 | 10062 | 3.35 |

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

Table 6

Results of samples analysis of discrete monitoring system and indications of the continuous hydrogen monitoring system

| Sample No. | Beginning of sampling, s | Volumetric hydrogen content in tanks, % | Volumetric hydrogen content by indications of SOV-3, % |
|---|---|---|---|
| **Vol.11** | 4553 | 0,1 | 0 |
| **Vol.12** | 6545 | 0,6 | 3,8 |
| **Vol.13** | 8542 | 1,1 | 2,6 |
| **Vol.14** | 10542 | 1,2 | 2,9 |
| **Vol.15** | 12512 | 1,0 | 2,6 |
| **Vol.16** | 14522 | 0,4 | 1,0 |
| **Vol.17** | 15967 | 0,1 | 0 |
| **Vol.18** | 17475 | 9,2 | 7,5 |
| **Vol.19** | 17501 | 28,1 | 8,1 |

Table 7 presents the measurement results of volumetric oxygen and nitrogen concentration of sampling tanks of discrete monitoring system and with the system of continuous monitoring OLCT20.

Table 7

Results of samples analysis of discrete monitoring system of oxygen and nitrogen and indications of the OLCT20 device

| Sample No. | Beginning of sampling, s | Volumetric oxygen content in tanks, % | Volumetric nitrogen content in tanks, % | Volumetric oxygen content by indications of OLCT20, % |
|---|---|---|---|---|
| **Vol.1** | 16494 | 2,9 | 11,6 | 4,1 |
| **Vol.2** | 16594 | 2,3 | 9,7 | 3,9 |
| **Vol.3** | 16694 | 2,2 | 9,7 | 3,7 |
| **Vol.4** | 16794 | 2,0 | 9,9 | 3,4 |
| **Vol.5** | 16894 | 0 | 9,6 | 2,6 |
| **Vol.6** | 16994 | 0 | 9,6 | 1,4 |
| **Vol.7** | 17094 | 0 | 9,0 | 0,2 |
| **Vol.8** | 17194 | 0 | 8,2 | 0 |
| **Vol.9** | 17294 | 0 | 7,4 | 0 |
| **Vol.10** | 17394 | 0 | 7,2 | 0 |

### 8.4. Results of primary processing of experimental data

*Preparation stage*

Preliminary analysis of results of the PARAMETER-SF4 experiment has shown that according to the pre-test scenario at the preparation stage the assigned parameters of steam and argon at the test section were set (Figure 10): steam flow rate $G_{st\ in}$ ~ 3.5 g/s at $T_{st\ in}$ ~ 530°C; argon flow rate $G_{arg\ in}$ ~ 2.0 g/s at $T_{arg\ in}$ ~ 280°C. $T_{arg\ in}$ was below the assigned temperature by ~ 100°C due to heat losses to the argon duct shut off valve that was installed before performing the SF4 experiment.

By ~ 3000 s at the assembly power of ~ 2000 W (Figure 11) the thermocouples at elevations 0 – 1300 mm registered the settled temperature of 400 - 500$^{o}$C (see Figure 12) with the steam flow rate through the assembly being ~ 3.5 g/s (see Table 5). Pressure (by indications of pressure sensors) were: ~ 0.35 MPa – of steam-gas mixture in FA path; ~ 0.48 MPa – of helium inside fuel rods; ~ 0.4 MPa – of argon in thermal insulation cavity (Figure 13).

*Pre-oxidation stage*

Duration of the pre-oxidation stage was ~ 6000 s (~ 8000 - 13886 s) at temperature of fuel rod claddings ~ 1100 – 1200$^{o}$C, by thermocouples readings located at elevations (1250 - 1300) mm, (Figure 12), and steam flow rate through the assembly was ~ 3.5 g/s at change in electric power from ~ 7500 to ~ 8500 W.

At the pre-oxidation stage seven samples of gas mixture were taken (see Table 6, Figure 18).

*Cool-down stage*

Duration of the cool down stage was ~ 2469 s (~ 13886 – 16355 s) at decrease in the assembly power from ~ 7890 to ~ 4000 W (Figure 11). The steam flow rate through the assembly was ~ 3.4 g/s (see Table 5).

By the moment of power decrease to ~ 4000 W the maximum temperature (thermocouple T31012.5, see Figure 12) in the hottest zone at 1250 mm were ~ 900$^{o}$C.

At the moment of the assembly temperature decrease to ~ 900$^{o}$C the steam supply to the assembly was switched off (16022 s) and air ingress with the flow rate of ~ 0.48 g/s was started (see Figure 18).

At the phase of air ingress ten samples of gas mixture were taken (see Table 7, Figure 18).

At the phase of air ingress both methods (continuous and discrete) indicated decrease in concentration of oxygen down to ~ 0 % vol. (see Figure 18) and of nitrogen – from ~ 11.6 % vol. to ~ 7.2 % vol. (see Table 7).

*Flooding stage*

At 17412 s, when the thermocouple T311'5 at elevation of 500 mm recorded the maximum temperature of 1750$^{o}$C (Figure 12), the electric power was switched off (see Figure 11), and at 17434 s the bottom flooding system valve V19 was opened.

The system of water flooding from bottom provided for the average flow rate of ~ 80 g/s (Figure 24). In the course of flooding the system of continuous hydrogen monitoring SOV-3 was switched on and two gas mixture samples were taken.

After water injection was initiated, thermocouples started to indicate cladding temperature degrease at elevations of 0 – 200 mm. The claddings at elevation of 400 mm exhibited temperature escalation, so in about 10-15 s the temperature reached upper limits of the thermocouples effective range (1400°C). Claddings at the elevations of 500-700 mm continued to heat up. One can see numerous thermocouples failures but some unfailed thermocouples suggest that zirconium melting point was reached before air switching off.

Claddings at the elevations above 800 mm at the beginning revealed quite slow but stable cooling down. But from about 17540 s they started to reheat. At that time a sharp system pressure increase was observed (by~ 0.7 MPa, Figure 20). Rapid heat up was followed by temperature escalation, so claddings temperatures reached upper limits of the thermocouples effective range (2000°C) very fast.

Altogether the sharp system pressure increase and high assembly temperature resulted in damage of the shroud and a part of gas duct in the facility that lead to water leak and made impossible to evaluate of steam-water balance at the flooding stage.

Preliminary analysis of the results of hydrogen measurement by SOV-3 system showed that at the pre-oxidation stage the hydrogen was generated in the amount of ~ 21 g (Figure 28), and at the flooding stage – ~ 86 g. Maximum rate of hydrogen generation at the flooding stage was ~ 0.6 g/s (see Figure 28).

Separate analysis of water condensed in Tank 5.1, Tank 5.2, Tank 5.3, Tank 5.4 (Table 5) showed that the average steam flow through the assembly was ~ 3.5 g/s.

After completion of tests the model assembly was encapsulated, dismounted and sectioned.

# 9. PRELIMINARY RESULTS OF MATERIAL STUDIES

## 9.1. Methods of the model FA encapsulation and sectioning

Encapsulation of the model FA was made inside the test section (before its withdrawal from the test section) to keep the bundle integrity. FA encapsulation procedure included resin supply in lower part of the bundle, that is bottom-top filling. Following this procedure, the bundle was filled up to elevations of ~ 250 …300 mm, and after that resin level rise stopped evidently due to flow path blockage at lower elevation. To complete the bundle encapsulation, resin was injected in the upper part.

After the compound hardened, the assembly was removed from the test section and cut over the height into fragments and slabs. The cross-section cuts were made with the use of cutting-off machine Delta-Abrasimet with diamond blade of thickness 1.7 mm. Thickness of cross section slabs was chosen to be 15…20 mm to be ensured in their integrity keeping during their cutting out (to avoid their transverse cracking and spilling out of FA components).

To remove voids and cavities remained after FA filling with the compound the cross section slabs vacuum impregnation was made with epoxy resin EPO – THIN at the "Buehler" impregnator. Then the cross section slabs have been ground and polished.

The macro photos of the ground cross section slabs were taken by the digital camera SONY (8 mps) (Figure 30). Further on, the available macrographs were used for comparative evaluation of the assembly damage degree at different elevations.

## 9.2. Description of the assembly posttest appearance

After the test section was disassembled, the encapsulated assembly was withdrawn and thermal insulation impregnated with epoxy resin was removed from the shroud surface (where it was possible), the following was revealed (Figure 29):

- below 200 mm elevations the shroud looks like undamaged, its outer surface have metallic lustrous appearance;
- over the elevations Z = 300…600 mm the thermal insulation looked like dark, and ceramic dark-grey melt was found under the thermoinsulation;
- over the elevations Z = 600…1200 mm the shroud surface is covered with tightly stuck layer of heat insulation impregnated with resin that makes the analysis of appearance difficult.

## 9.3. Methods of material studies of the model FA

The given work deals with the preliminary analysis of four cross-section slabs from the upper and lower part of the assembly.

The studies were performed for the cross-sections Z = 130, 260, 300 and 1200 mm (4 pcs. in all). In each section the structures of fuel rod simulators, zirconium structural components, and melt are presented.

Metallographic analysis of cross section slabs was performed with the optical microscope OLYMPUS using the computer code package OMNIMET. Electron microscope studies of cross-sections were performed with the scanning electron microscope JEOL JSM – 6460 LV, X-ray microanalysis – with the help of EDX-adapter OXFORD.

**9.4. Structural analysis of cross-sections**

*At the elevation Z = 130 mm (top view)* the assembly has no any visible damages practically (in the given section all fuel rod cladding and periphery rods kept their integrity, Figures 31, 32). Some pellets of uranium dioxide have cracks. There are no fuel fragments in some pellets. However crumbling of pellets occurred probably in the course of the assembly cutting or preparing of slabs.

The oxide scale on fuel rod claddings is thin and well connected with metallic layer (Figure 5a), the measured thickness of zirconium oxide varies within the range of 4 – 9 $\mu$m.

At the given elevation the strongly oxidized fragment of the spacer grid is revealed (Figure 33 b), that relocated evidently from the higher elevations.

*At the elevation Z = 260 mm* the following was revealed:

- presence of large amount of melt in space, between rods, dissolving fuel rod claddings (Figures 34, 35). EDX analysis of the melt indicates that it is metallic and have (U,Zr,O) composition (Figure 38). Formation of cracks in the solidified melt is a sign of its brittleness due to high content of the dissolved oxygen;
- oxidation of zirconium structural components and melt (Figure 36);
- presence of melt in fuel-clad gaps in some fuel rods;
- interaction of some claddings of fuel rod with $UO_2$ pellets (Figure 37). Study of fuel rods cross-sections show the phases typical for Zr – $UO_2$ interaction and outer oxidation (Figure 37b).

*At the elevation Z = 300 mm (bottom view)* practically all structural components of the model FA (including heaters) are degraded. One can see remains of two fuel rods only, Figure 39). The melt is porous. EDX analysis indicates that the melt contained not only uranium, zirconium, oxygen, but significant amount of tantalum as well (Figure 40). At the elevation Z = 1200 mm (bottom view) the state of the assembly is characterized by complete absence of zirconium structural components (FA shroud, fuel rod claddings, spacer grids, thermocouples sheath) that is indicative of considerable exceeding the zirconium melting temperature (Figure 41) though molten pool are absent. Remained fuel stacks (12 out of 18) are kept only due to tantalum heaters being in the given case the skeleton for the assembly. In some regions of the given section the remains of oxide scales of fuel rod claddings and shroud are revealed (Figures 41, 42). Diameter of fuel pellets is less than original one noticeably due to dissolution of uranium dioxide by the melted zirconium that evidently relocated down on the fuel column surfaces (Figure 42). The traces of melt was found in the fuel-heater gap, the diameter of some heaters is less than original one as well.

# FIGURES

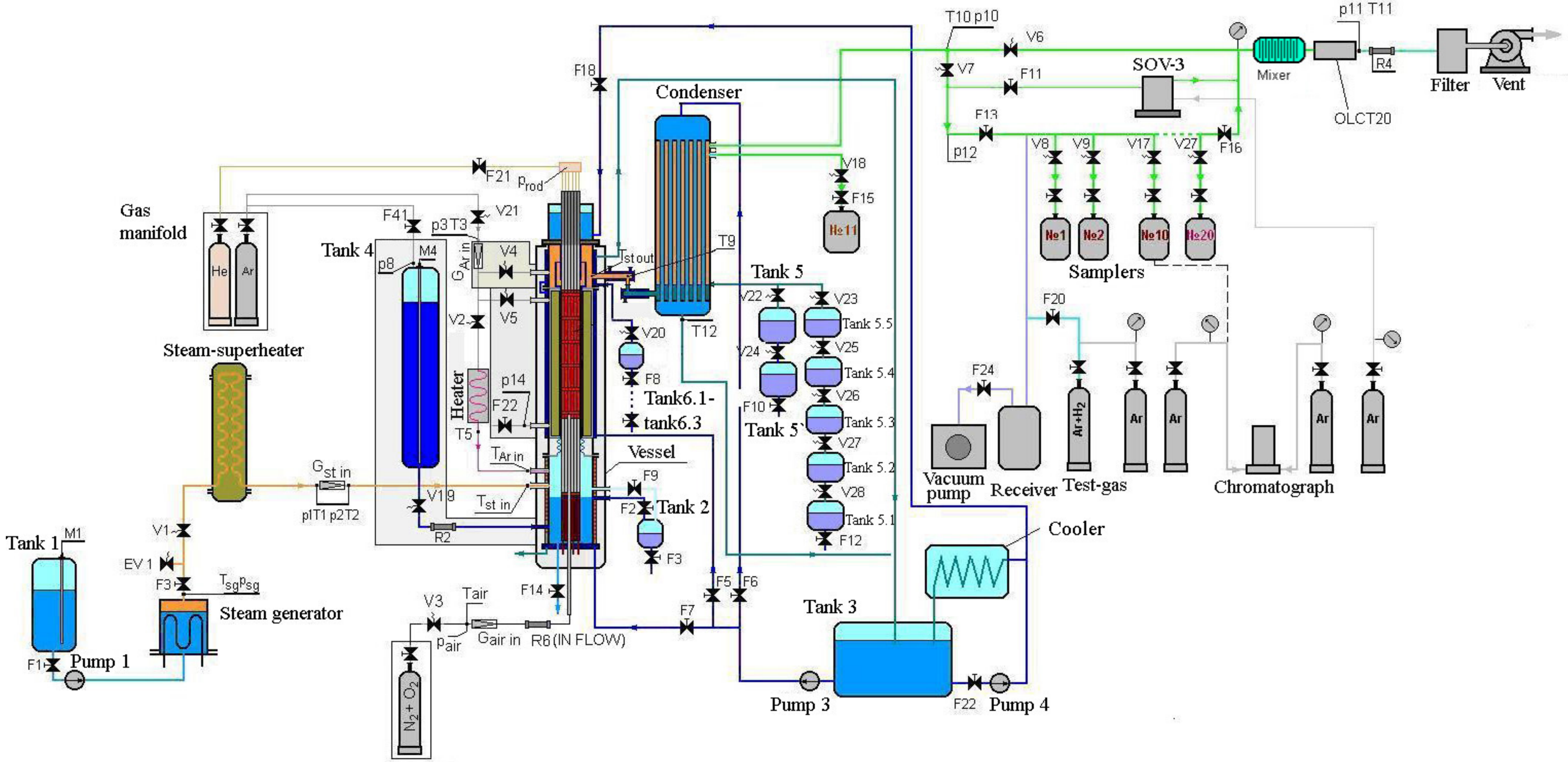
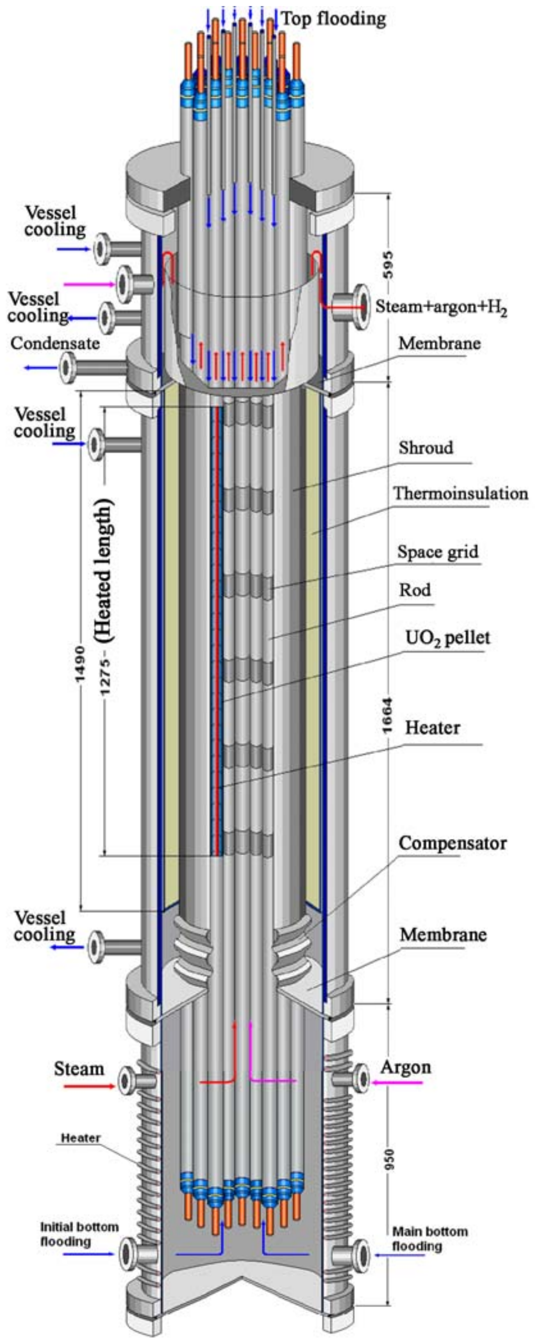
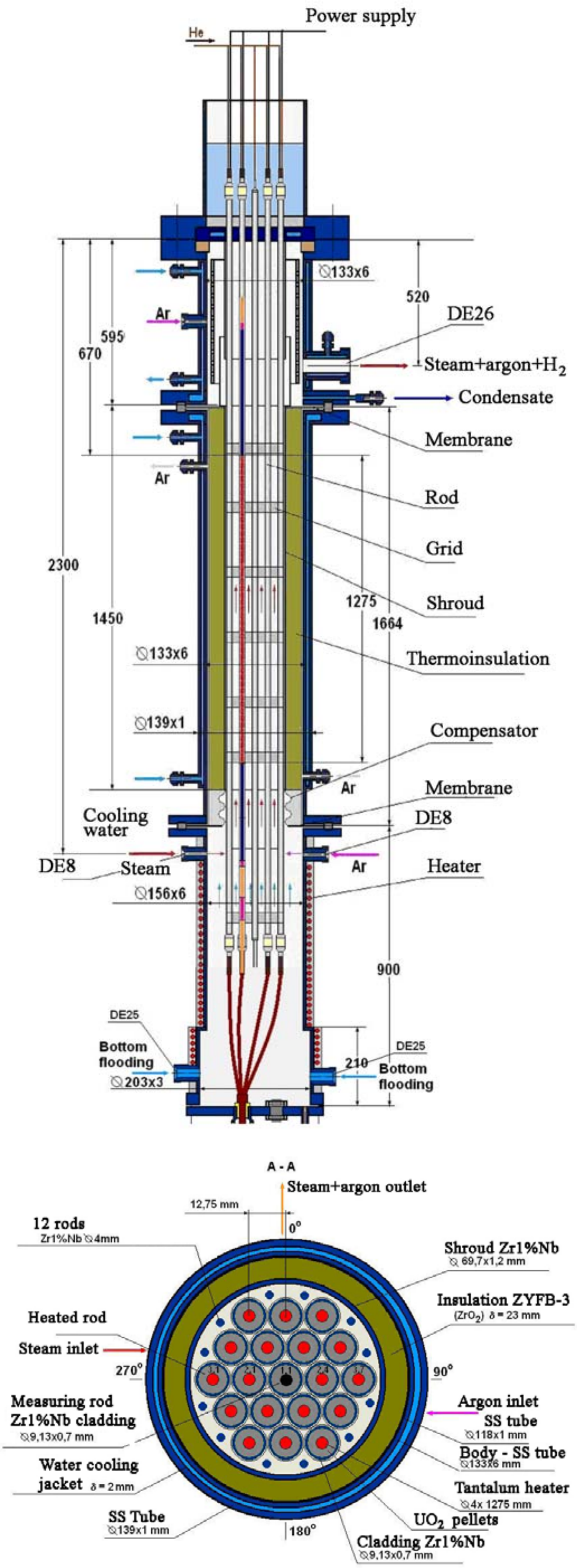



Figure 1. Functional diagram of the PARAMETER test facility.




General view




Schematic

Figure 2. Test section general view.

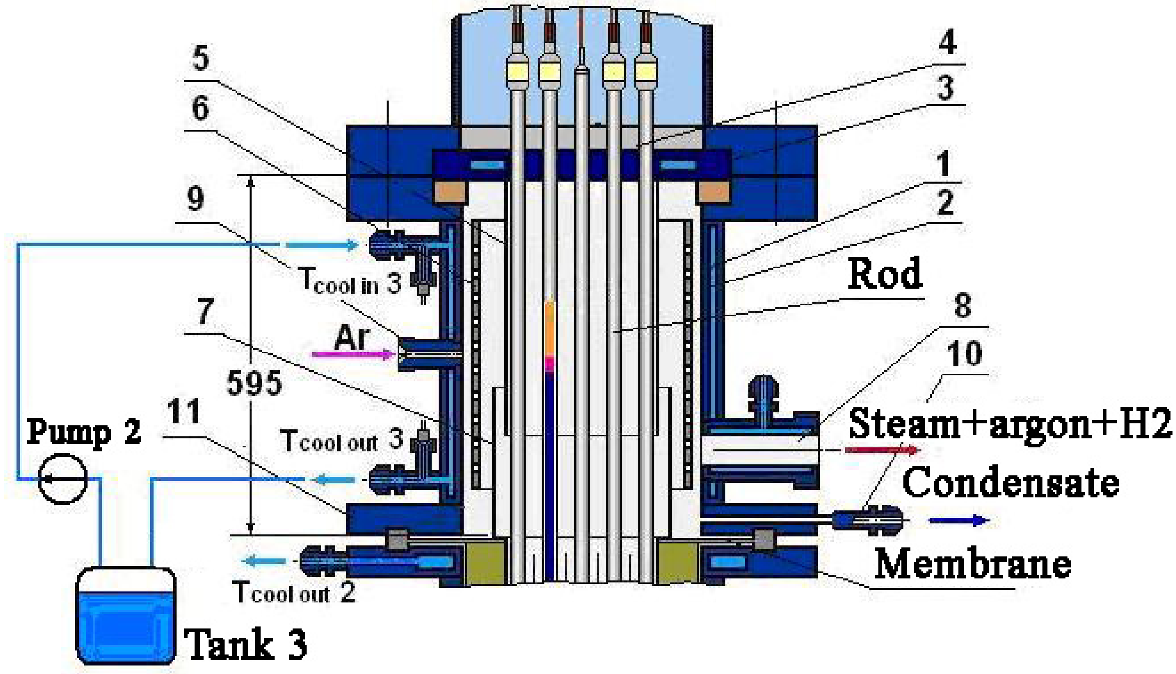



Figure 3. Test section upper part.

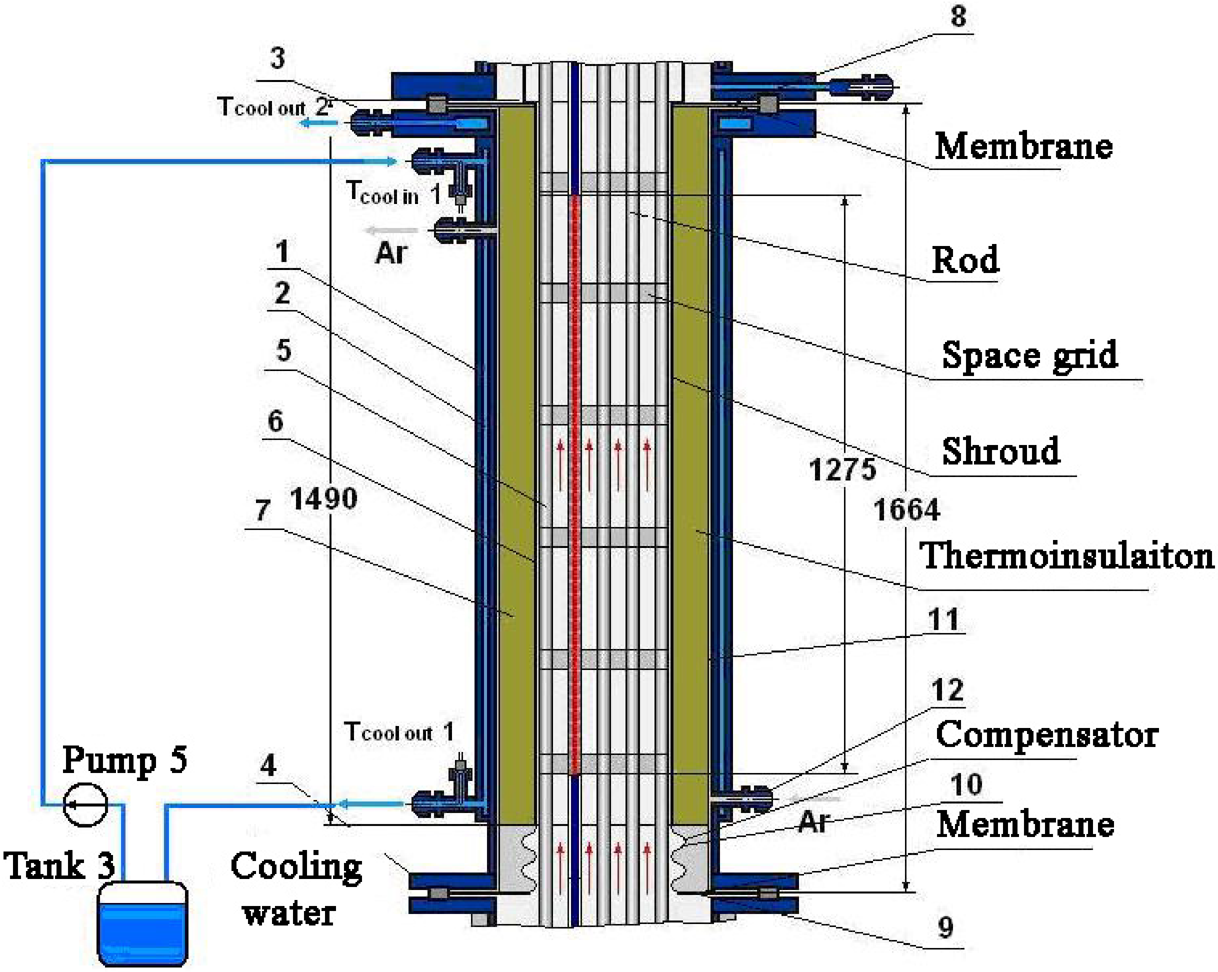



Figure 4. Test section middle part.

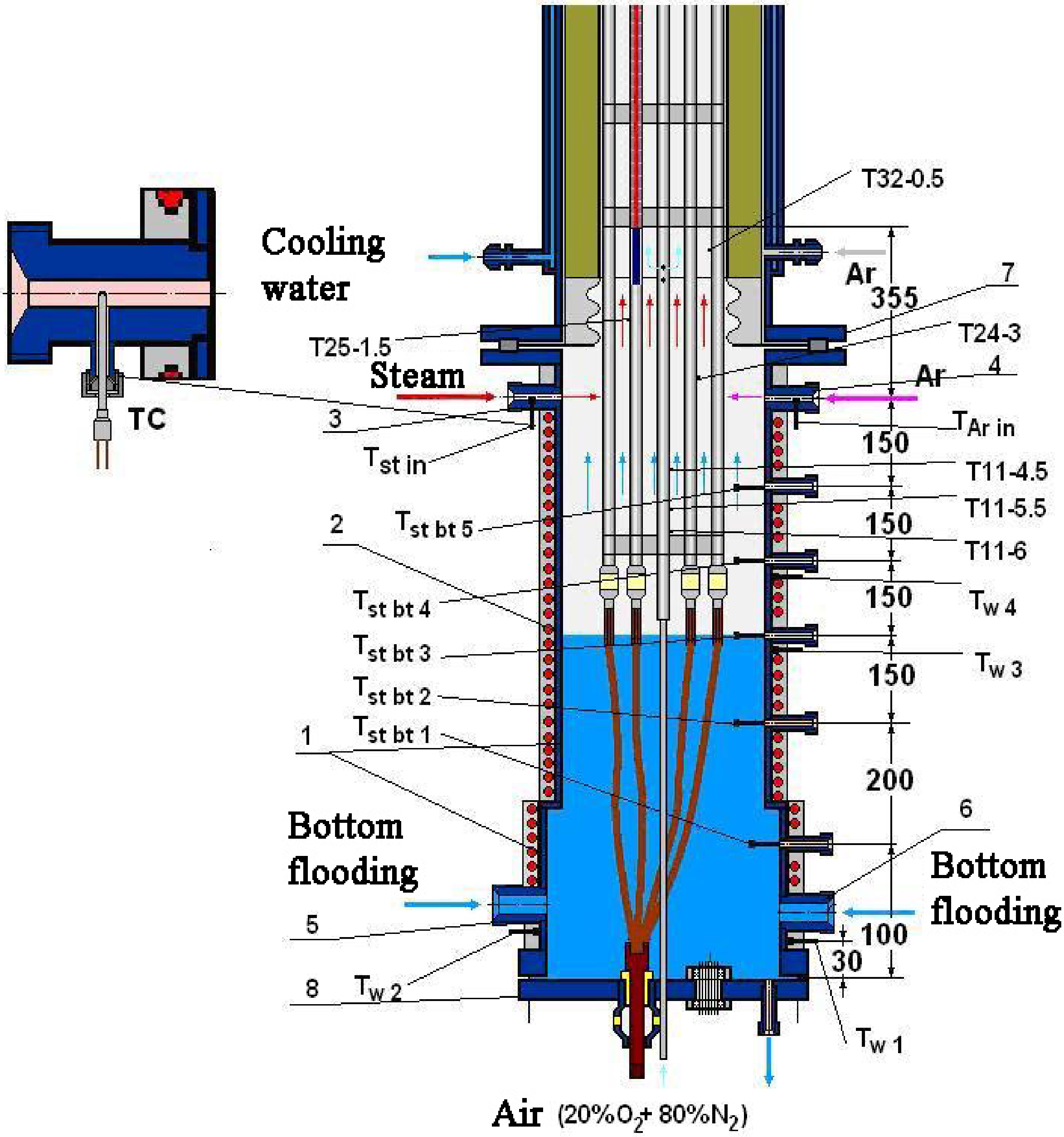
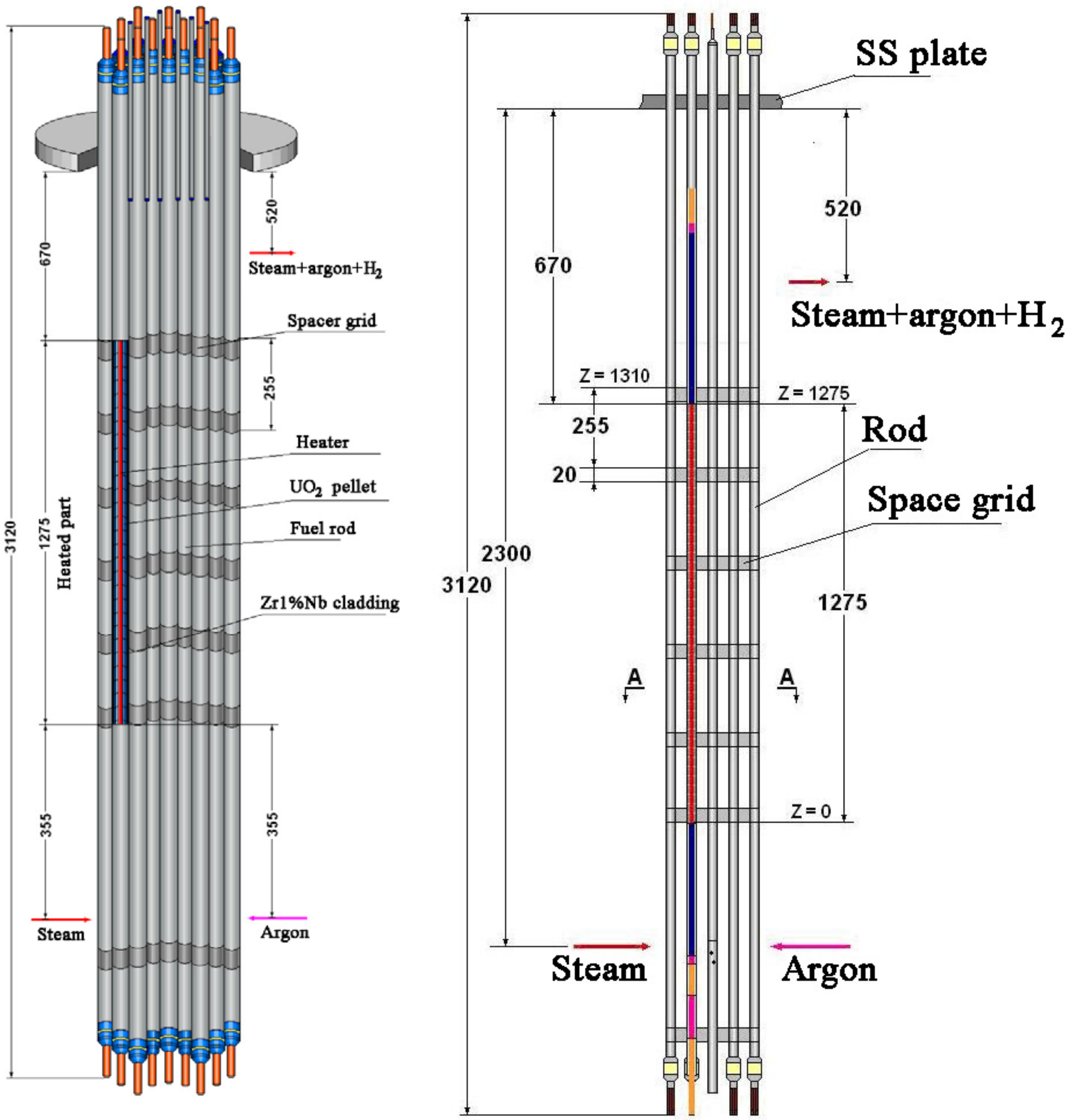
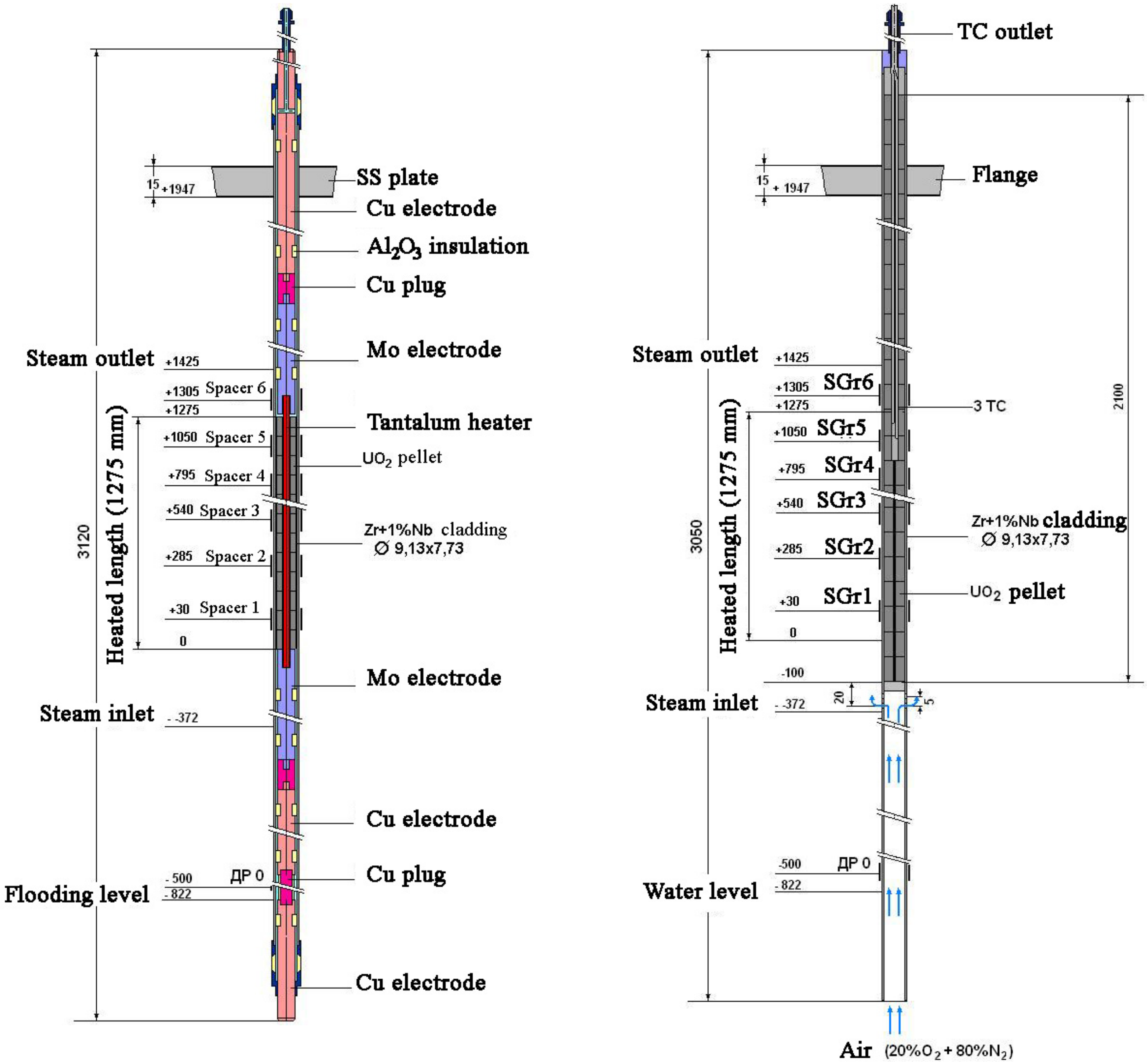



Figure 5. Test section lower part.




General view Schematic

Figure 6. Model FA.




Heated fuel rod

Unheated fuel rod with air supply system

Figure 7. Fuel rod simulators.

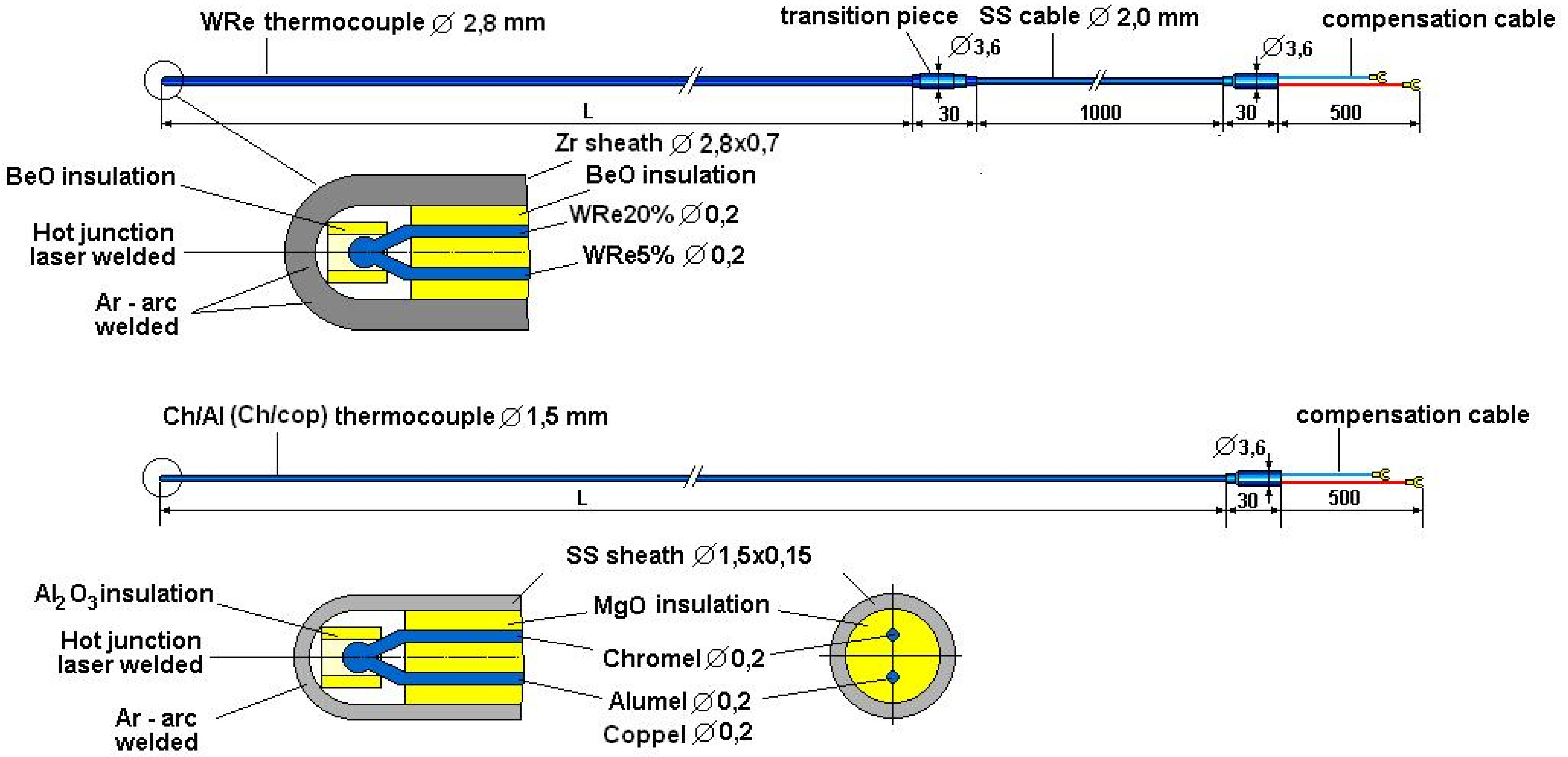



Figure 8. FA thermocouples.

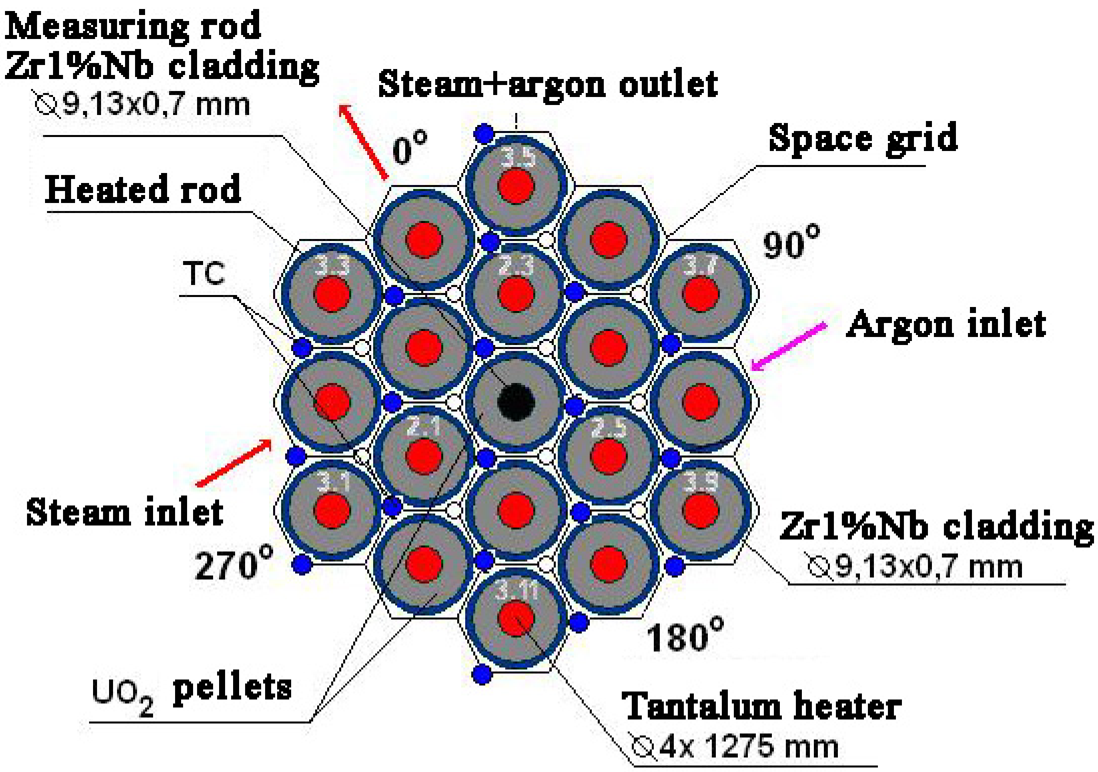



Figure 9. Thermocouples arrangement in the assembly cross-section (top view).

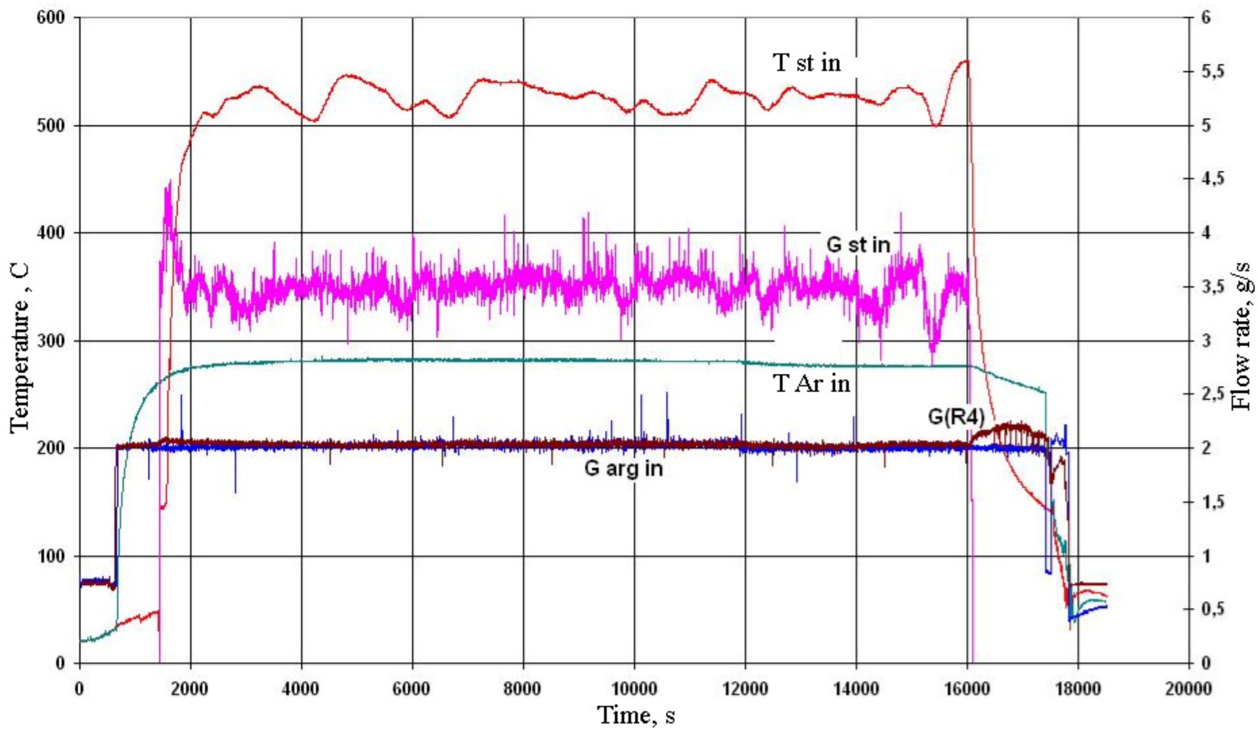



Figure 10. Parameters of steam ($G_{st\ in}$, $T_{st\ in}$) and argon ($G_{arg\ in}$, $T_{arg\ in}$) at the test section inlet and gas mixture flow rate G(R4) at the outlet to special ventilation.

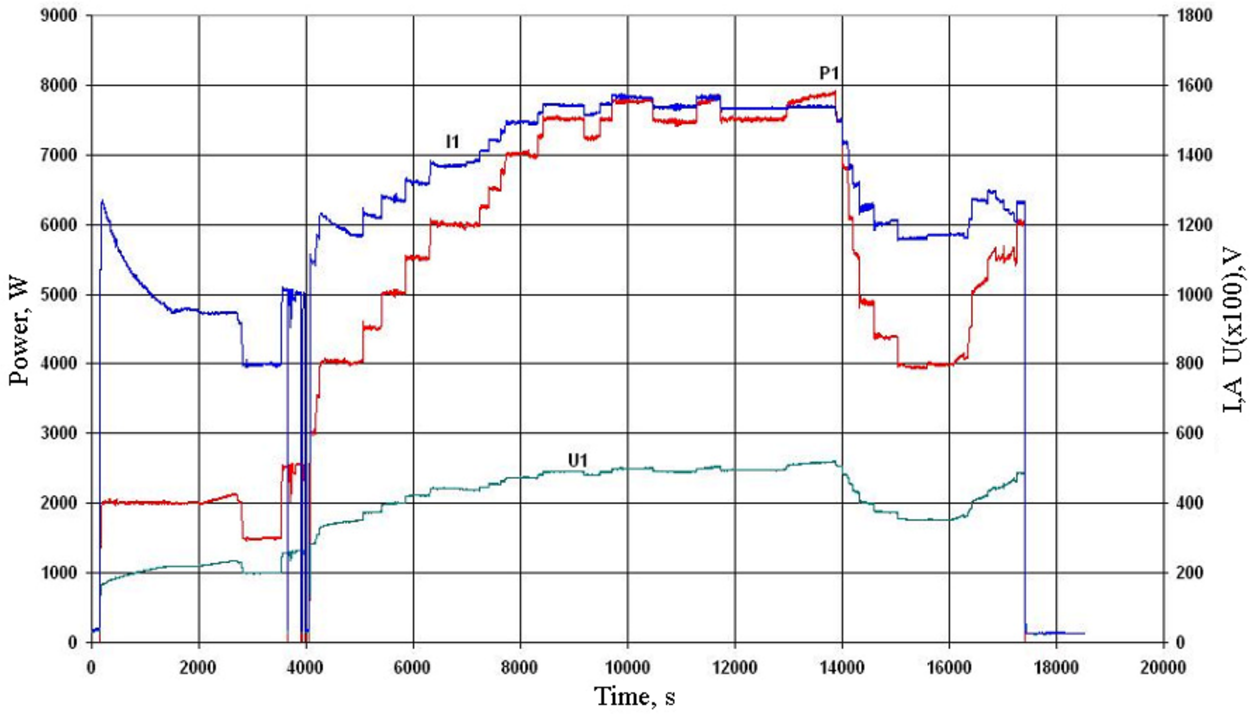



Figure 11. Parameters of electrical power.

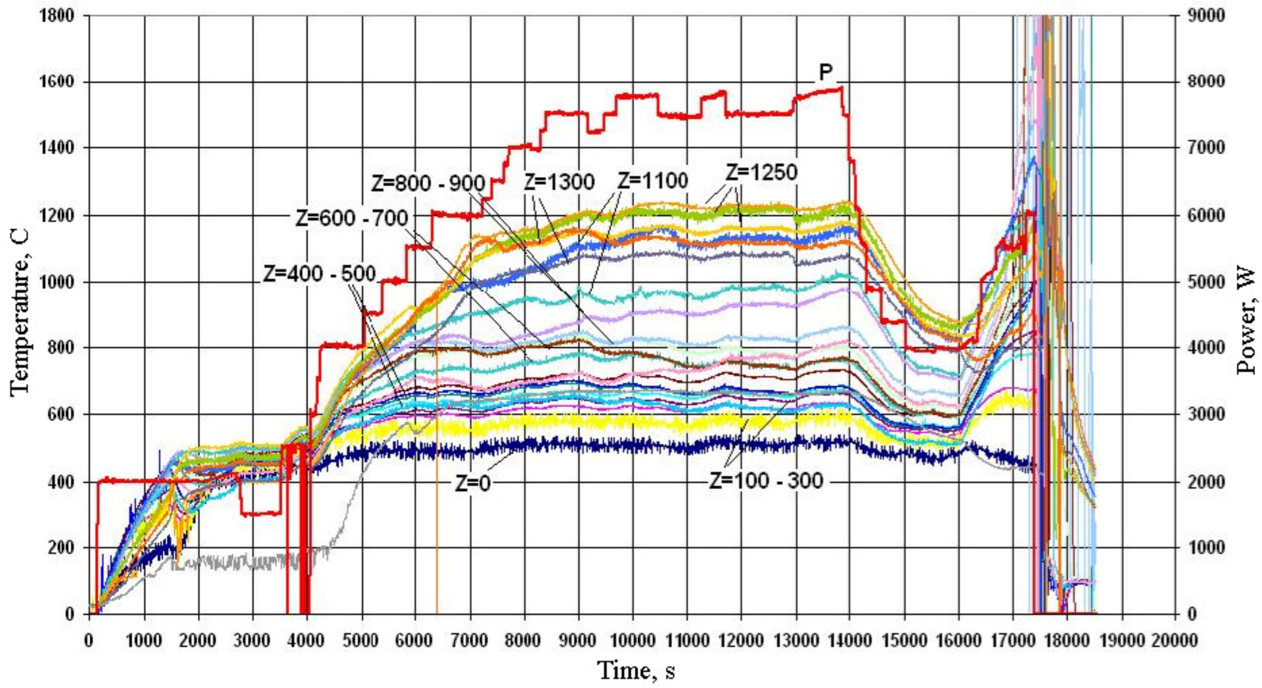
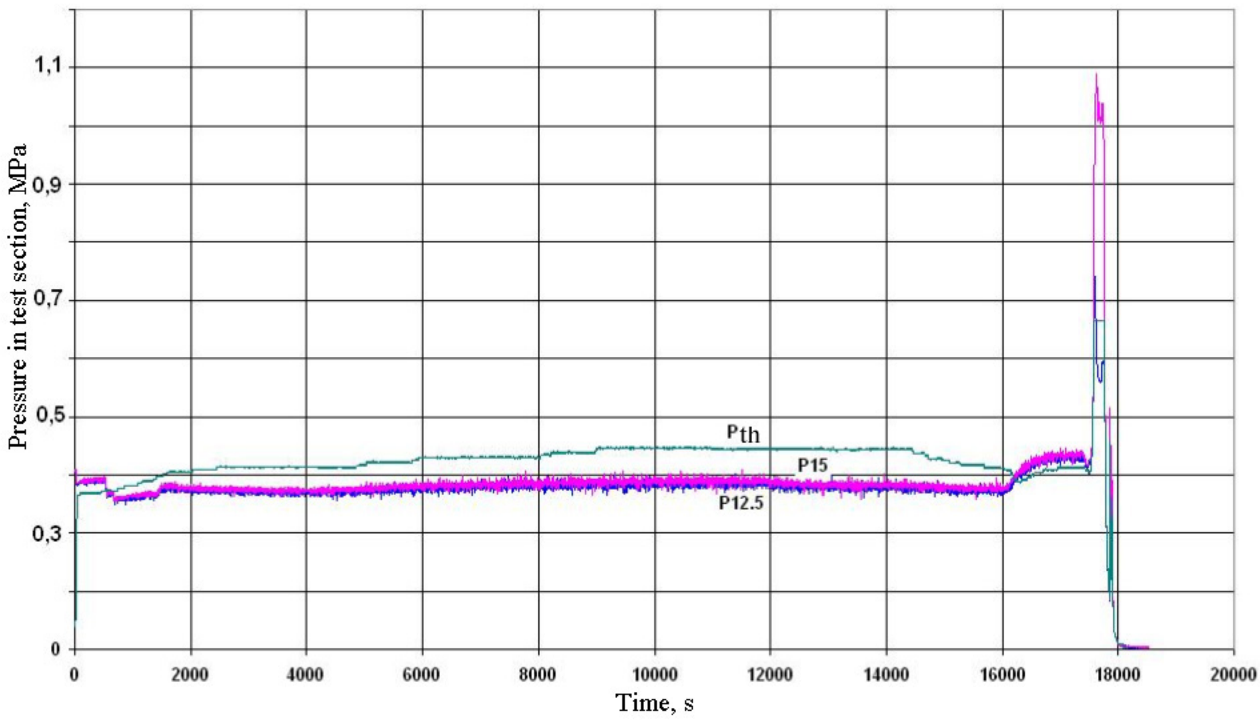
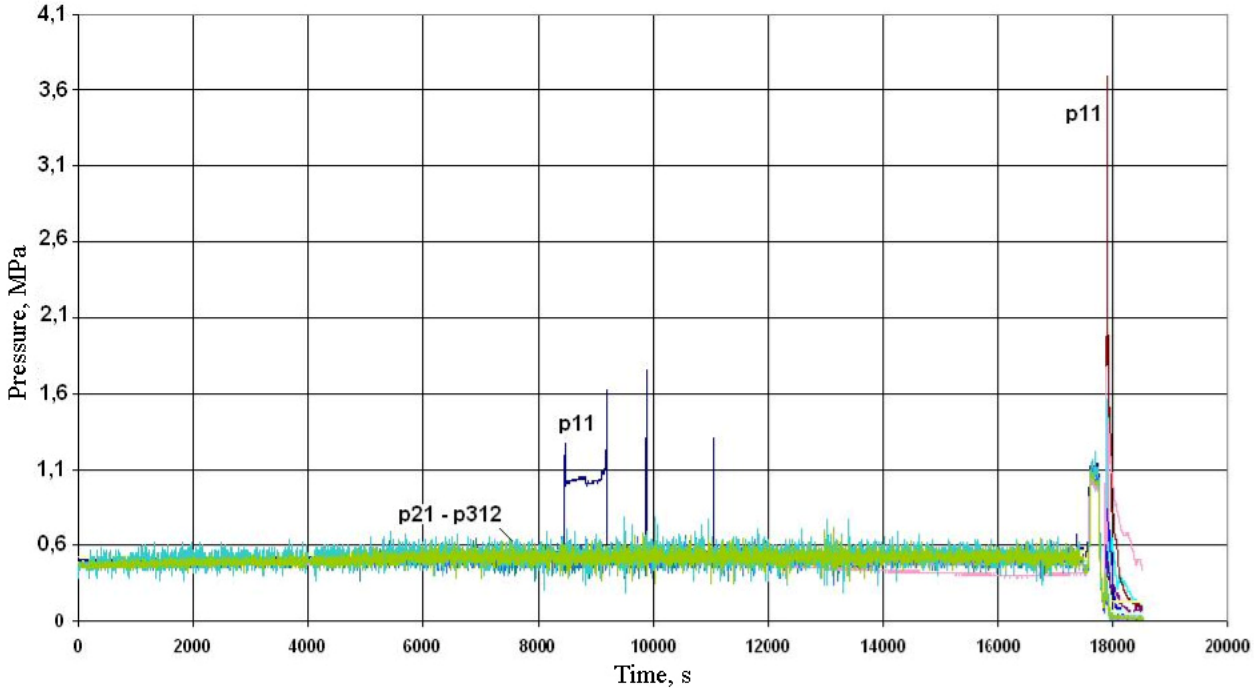



Figure 12. Thermocouples readings located over the height of fuel rods, and electric power supply (P).




a)




b)

Figure 13. Indications of pressure sensors: (a) – in the model assembly at elevations Z=1500 and 1250 mm and in thermoinsulation cavity ($p_{ins}$);
(b) – in fuel rods (p11, p21 – p312).

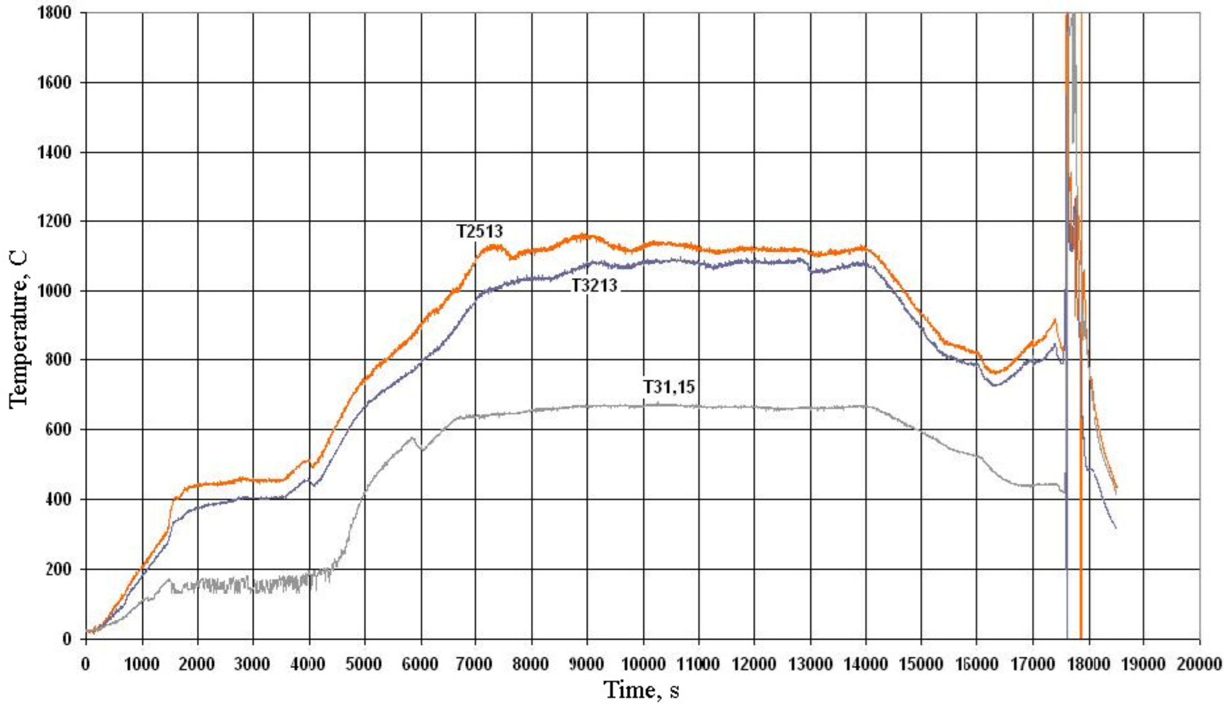



Figure 14. Thermocouples readings located on fuel rod claddings at elevations Z = (1300 – 1500) mm.

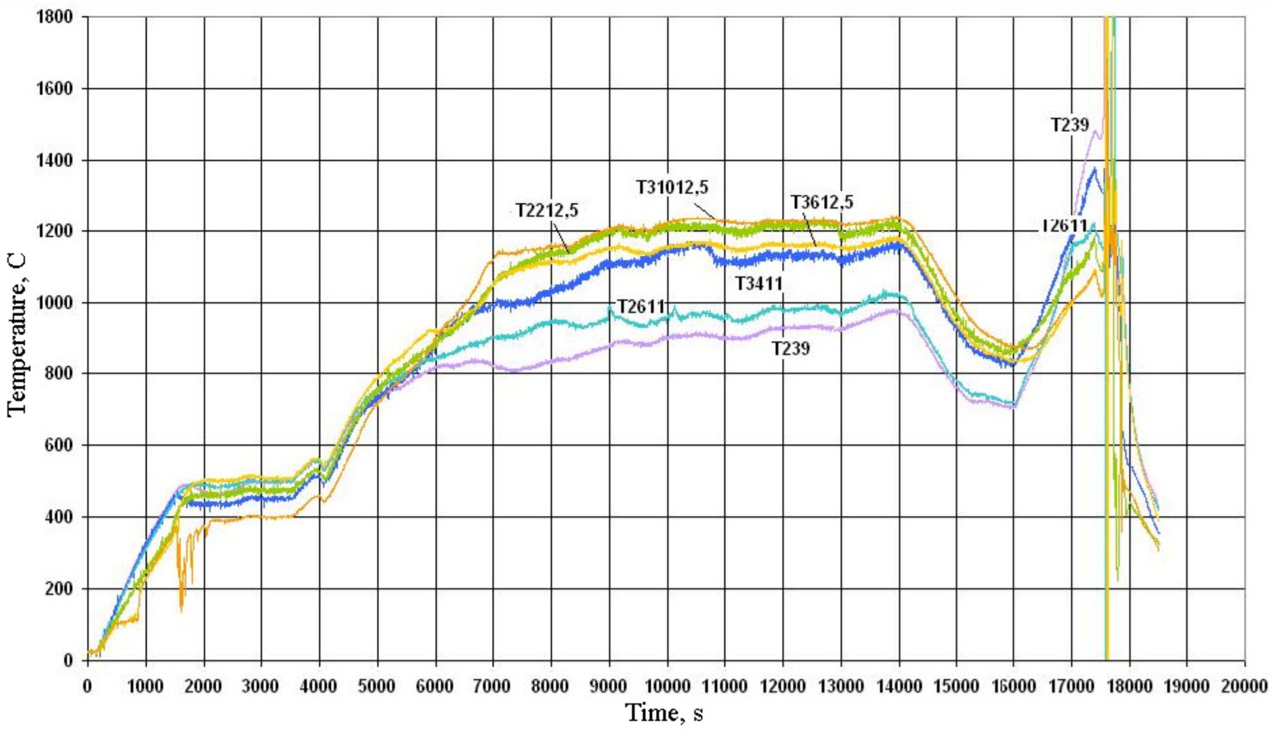



Figure 15.Thermocouples readings located on fuel rod claddings at elevations Z = (900 – 1250) mm.

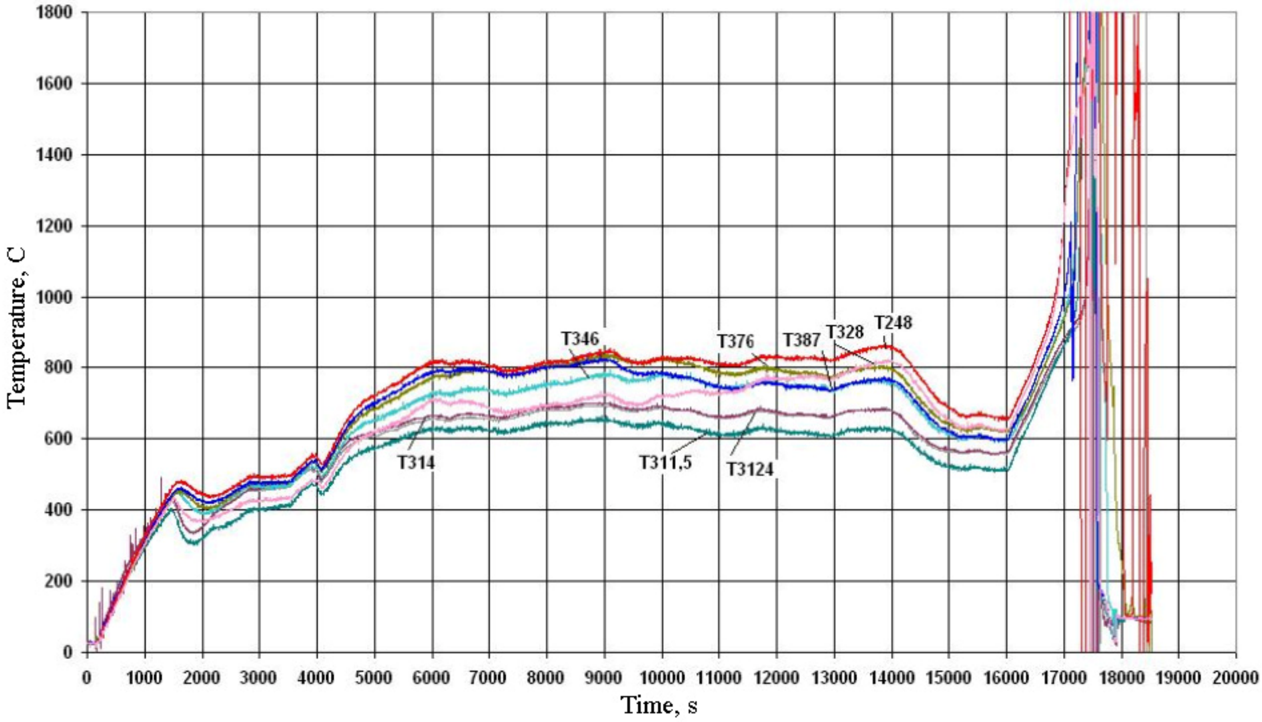



Figure 16. Thermocouples readings located on fuel rod claddings at elevations Z = (400 – 800) mm.

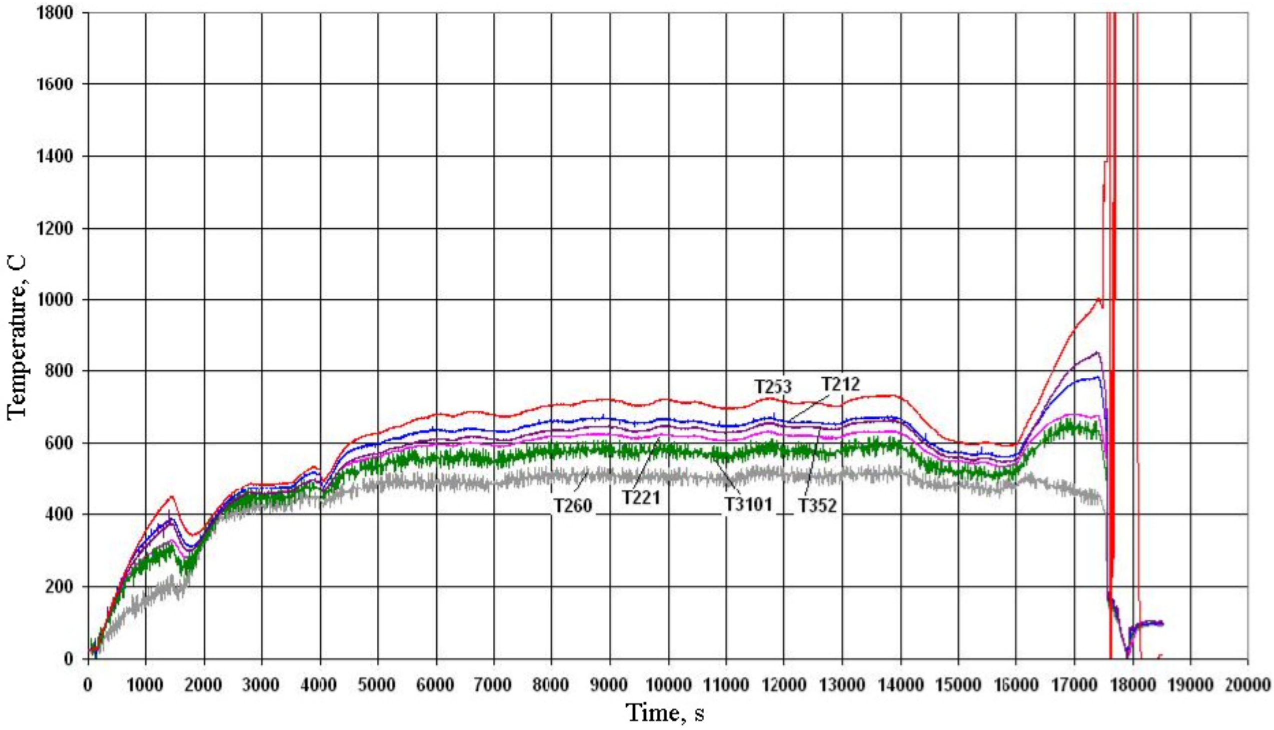



Figure 17. Thermocouples readings located on fuel rod claddings at elevations Z = (0 – 300) mm.

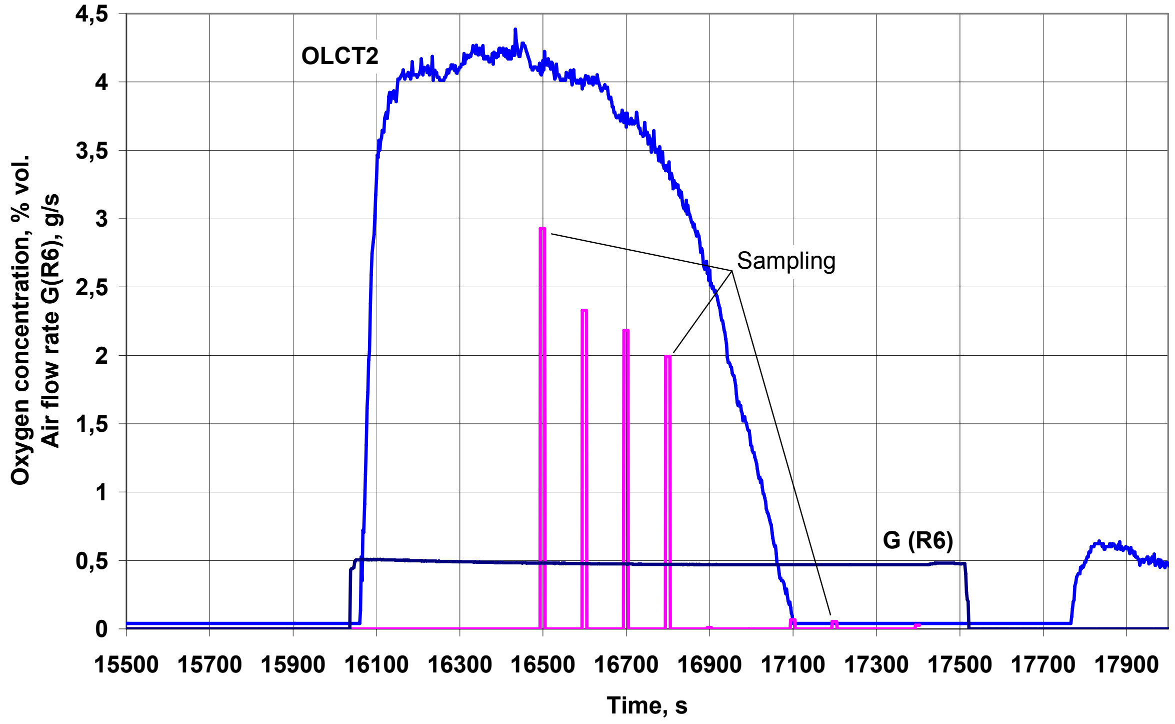



Figure 18. Volumetric oxygen concentration measured with the systems of continuous (OLCT20) and discrete (Sampling) oxygen monitoring and air flow rate at the test section inlet G(R6).

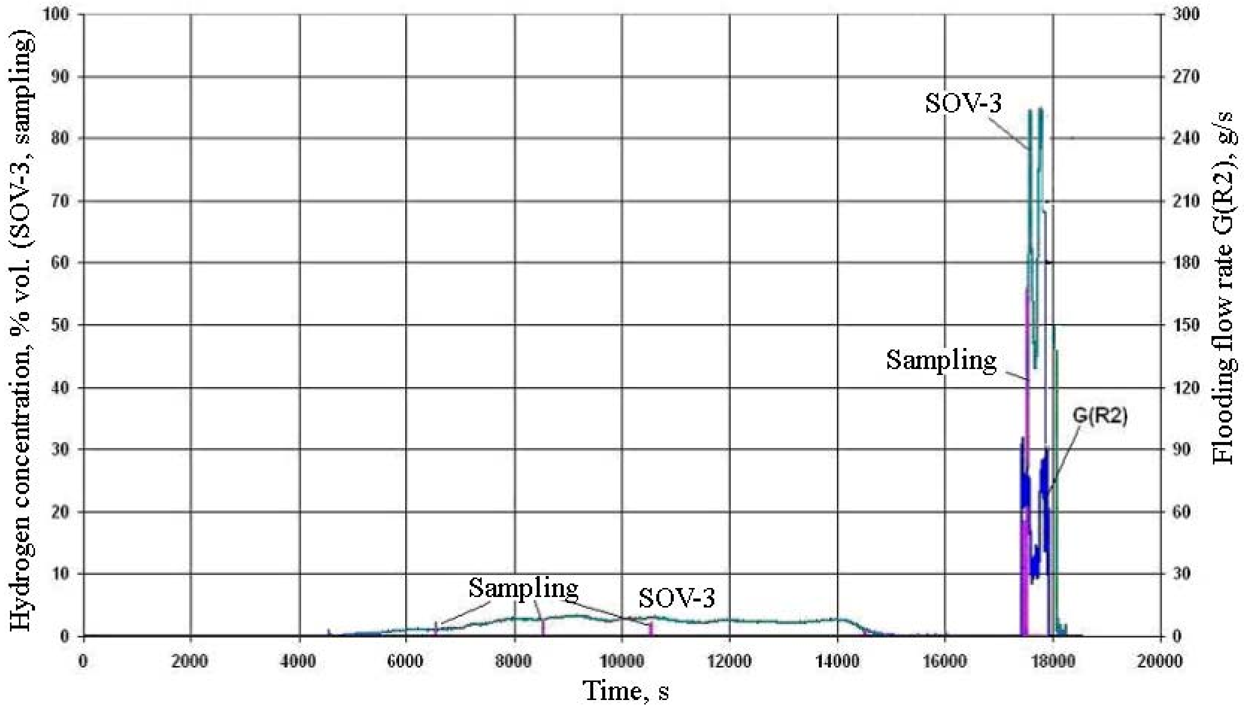



Figure 19. Volumetric hydrogen concentration measured with the systems of continuous (SOV-3) and discrete (Sampling) hydrogen monitoring, flooding water flow rate G(R2).

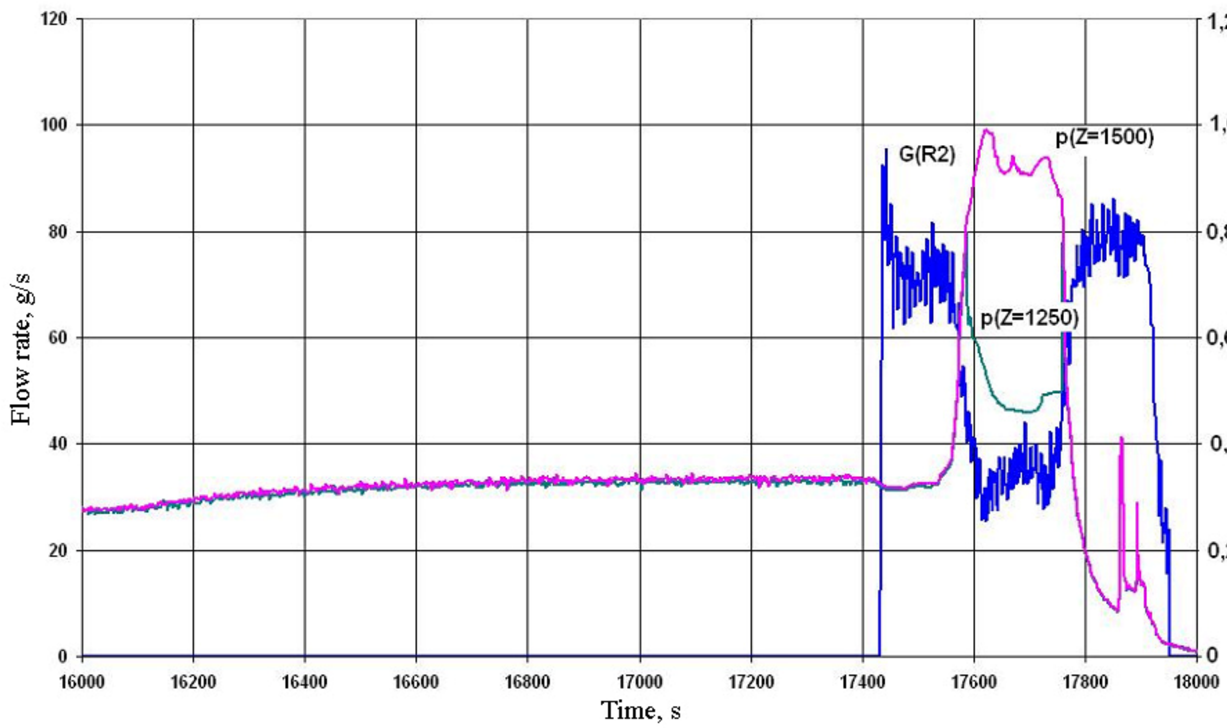



Figure 20. Indications of pressure sensors in the model assembly at elevations Z = 1250 and 1500 mm and flooding water flow rate G(R2) at the cool down, air ingress and flooding phases.

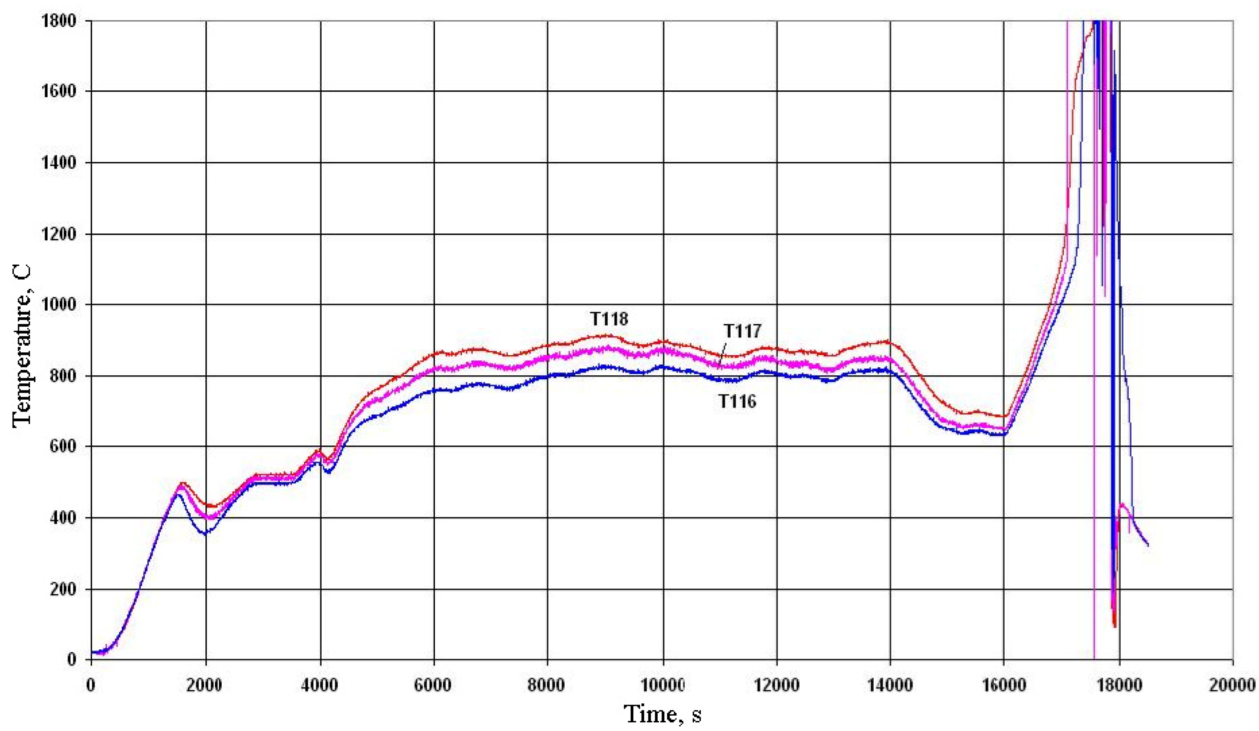



Figure 21. Thermocouples readings inside central fuel rod 1.1.

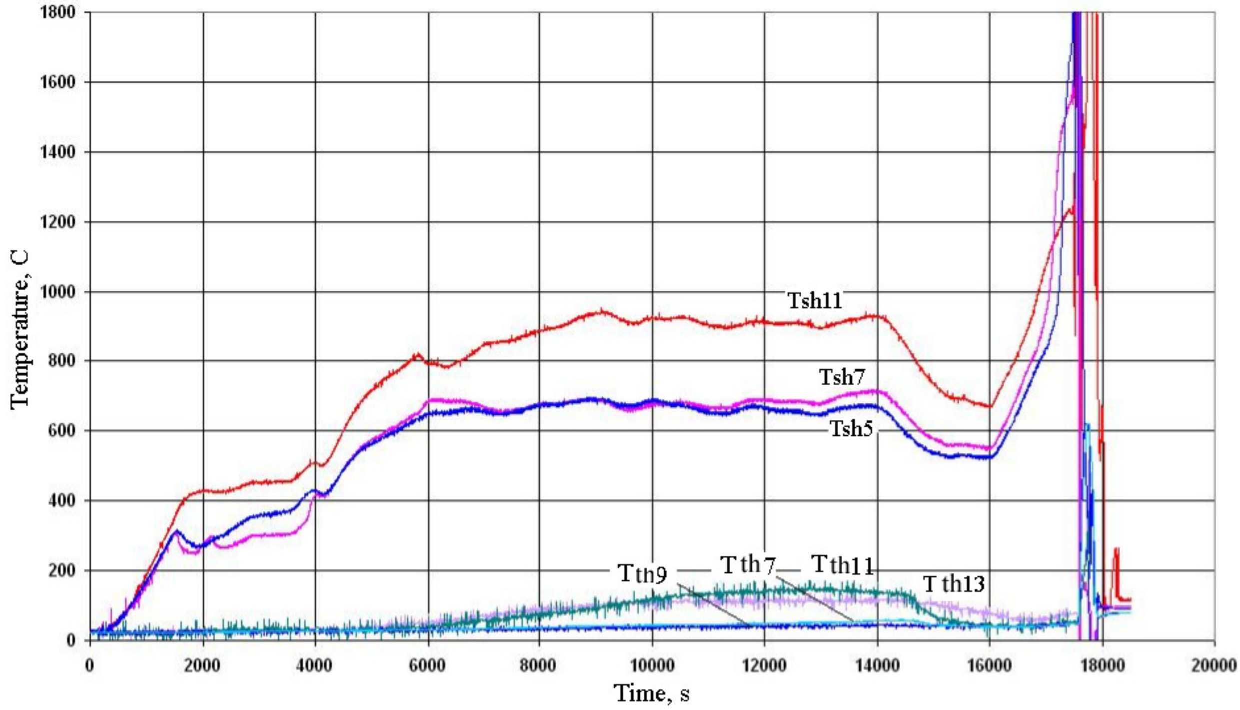



Figure 22. Thermocouples readings located on the shroud ($T_{sh}$) and thermoinsulation ($T_{th}$) of the test section at different elevations.

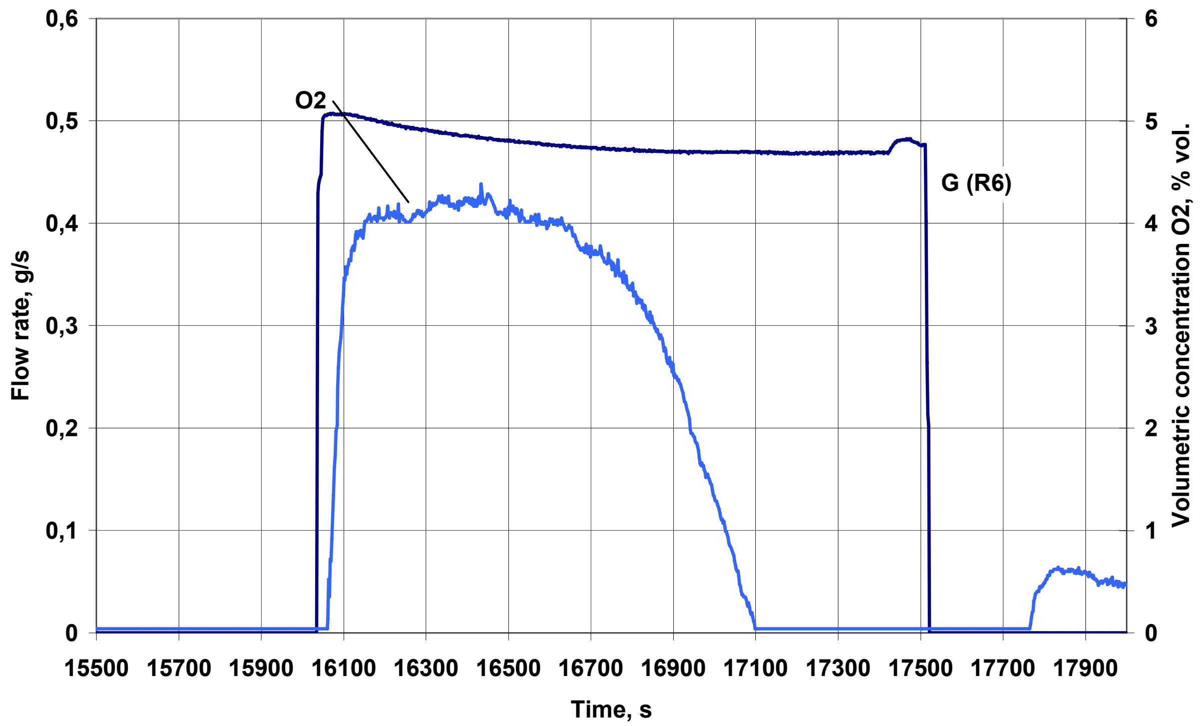



Figure 23. Indications of electronic flow meter of the air supply system (R6) and oxygen measurement device (O2) OLCT20.

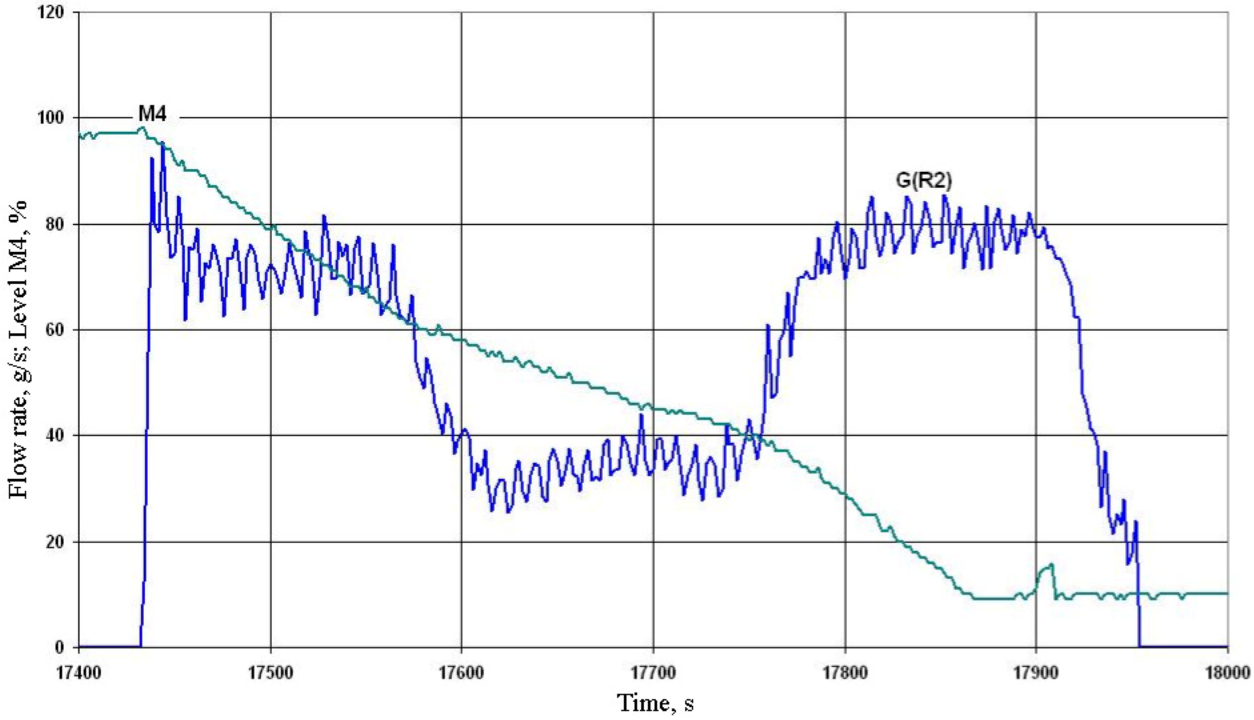



Figure 24. Indications of electronic flow meter of the bottom flooding system R2 and level meter M4.

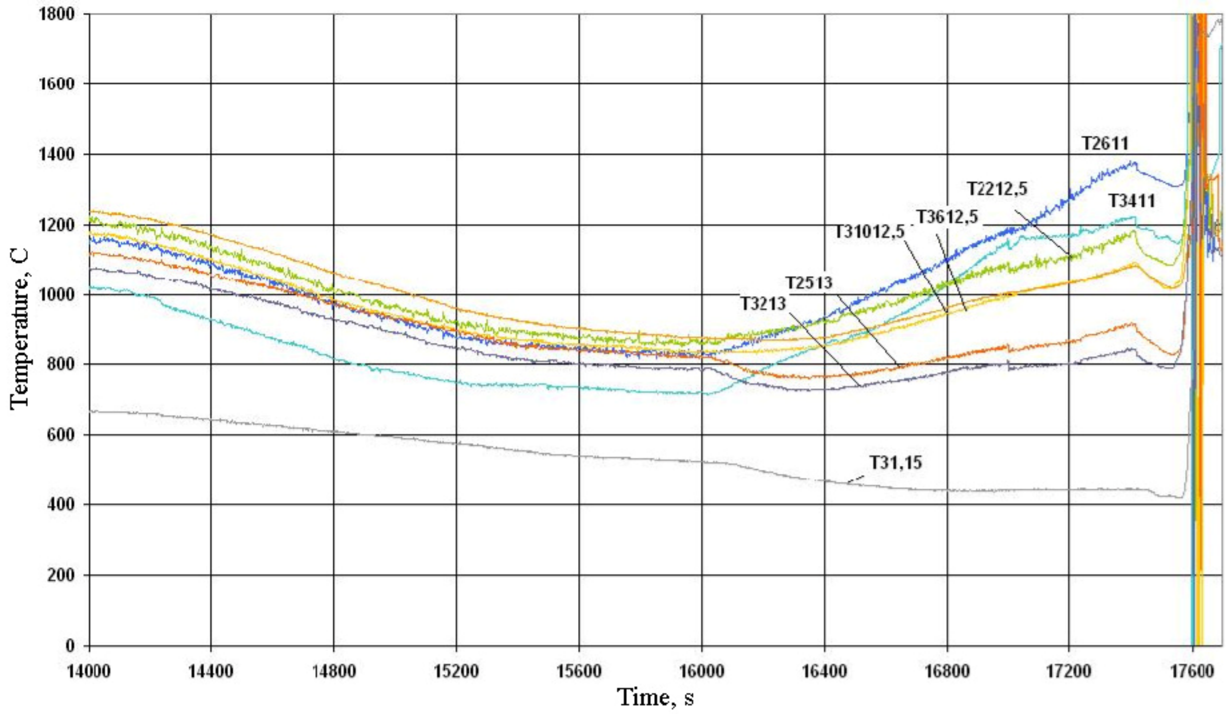



Figure 25. Thermocouples readings located on fuel rod claddings at elevations Z = (1100 - 1500) mm.

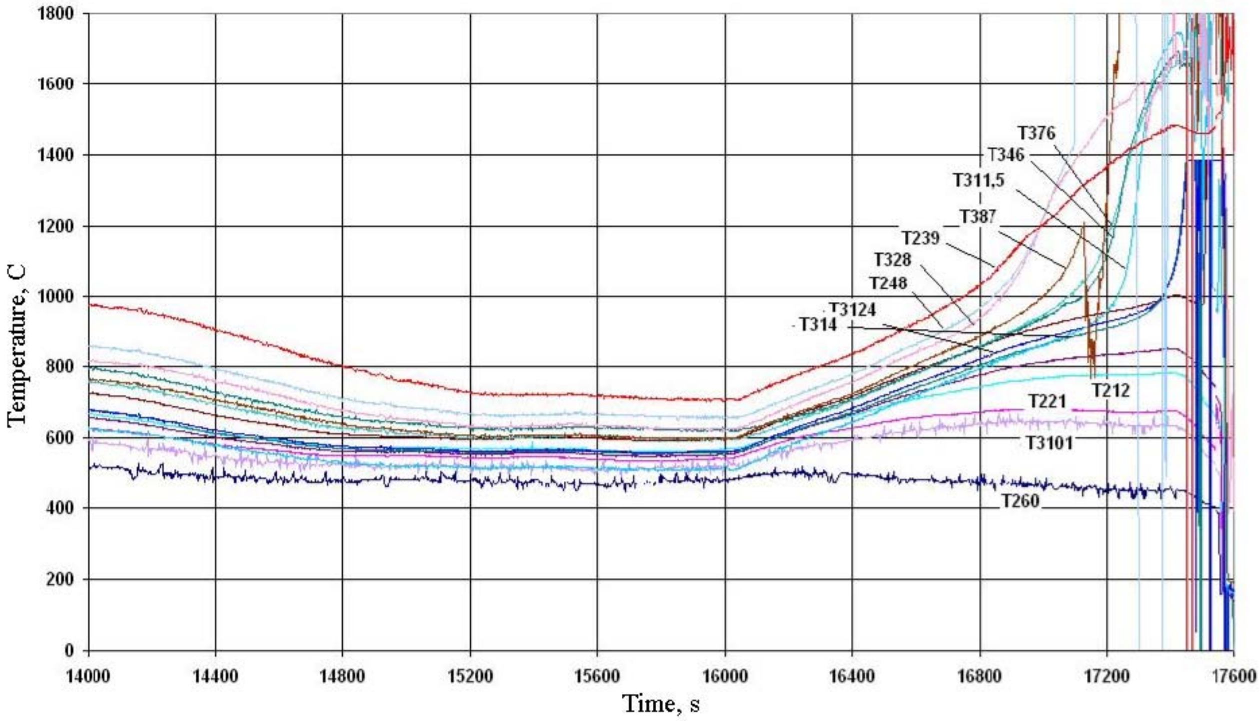



Figure 26. Thermocouples readings located on fuel rod claddings at elevations Z = (0 - 900) mm.

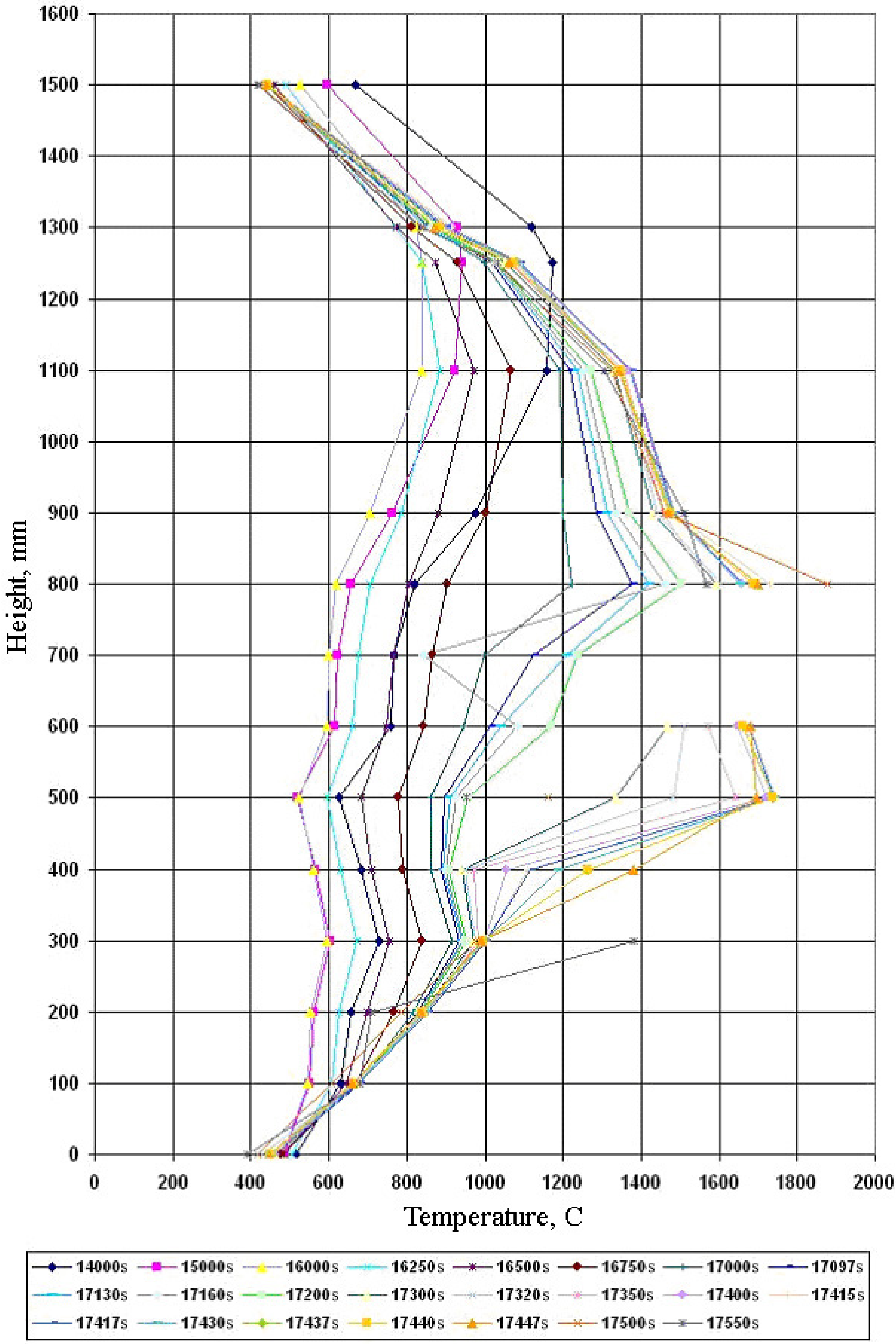



Figure 27. Axial cladding temperature profile evolution within the time interval of 14000 – 17550 s.

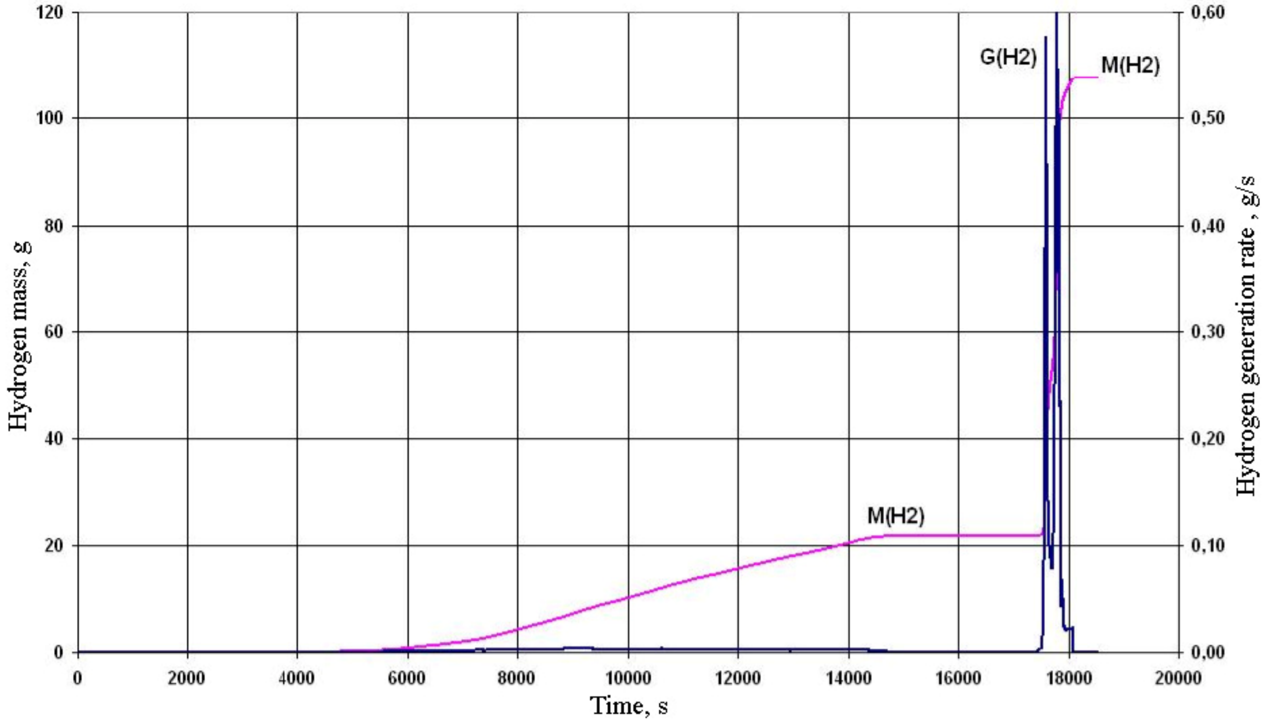



Figure 28. Released hydrogen mass and generation rate.

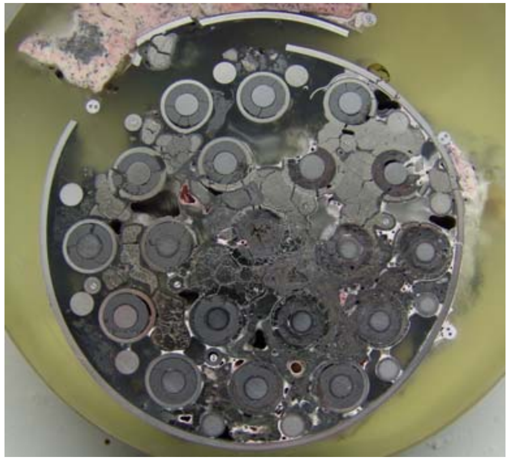
Z = 300…700 mm

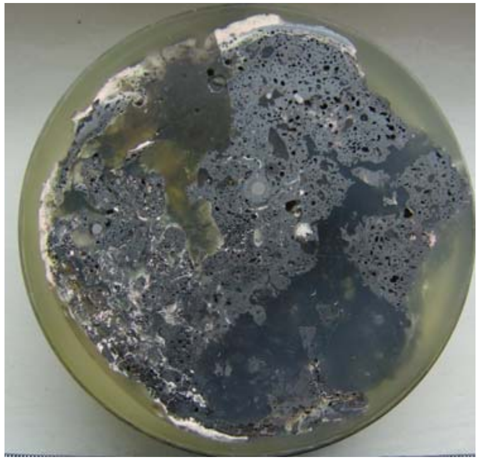
Z = 800…1200 mm

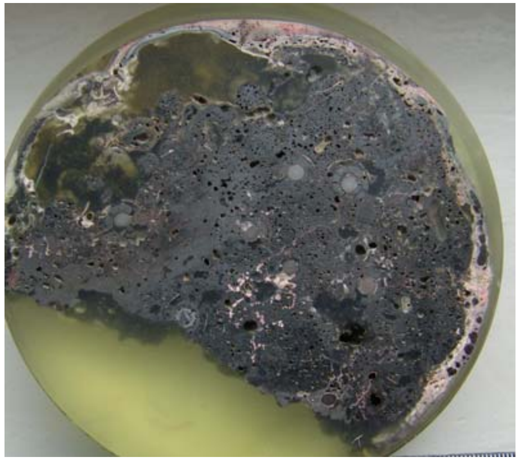
Z = 1200…1400 mm

Figure 29. Photos of the assembly appearance over elevations Z ~ 0…1400 mm
after encapsulation and withdrawal from the test section


130 mm


260 mm


300 mm


380 mm


600 mm


1200 mm

Figure 30. Photos of the assembly cross-sections over elevations Z ~ 130…1200 mm.

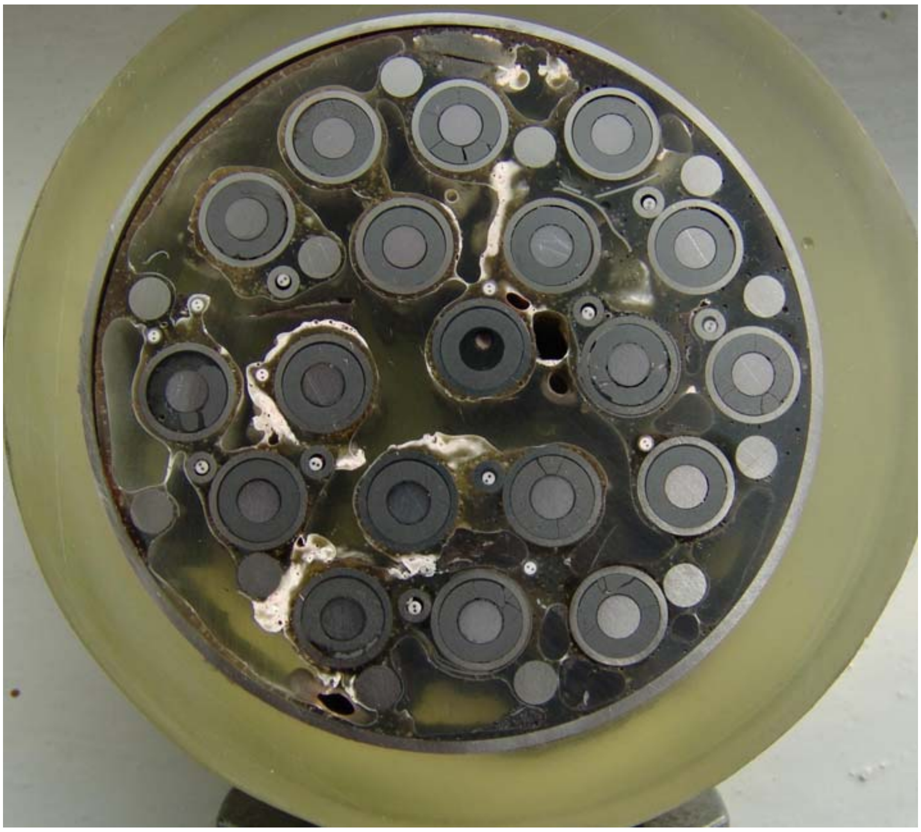


Figure 31. Assembly cross-section at the elevation of Z = 130 mm (top view).

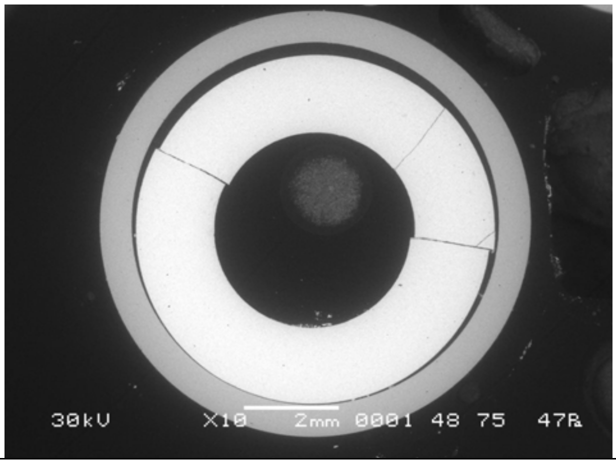
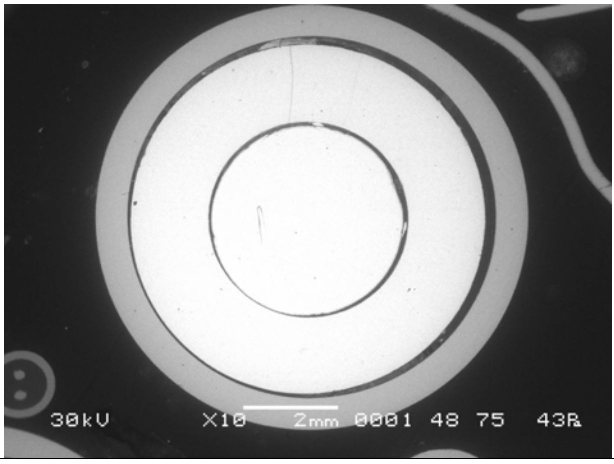
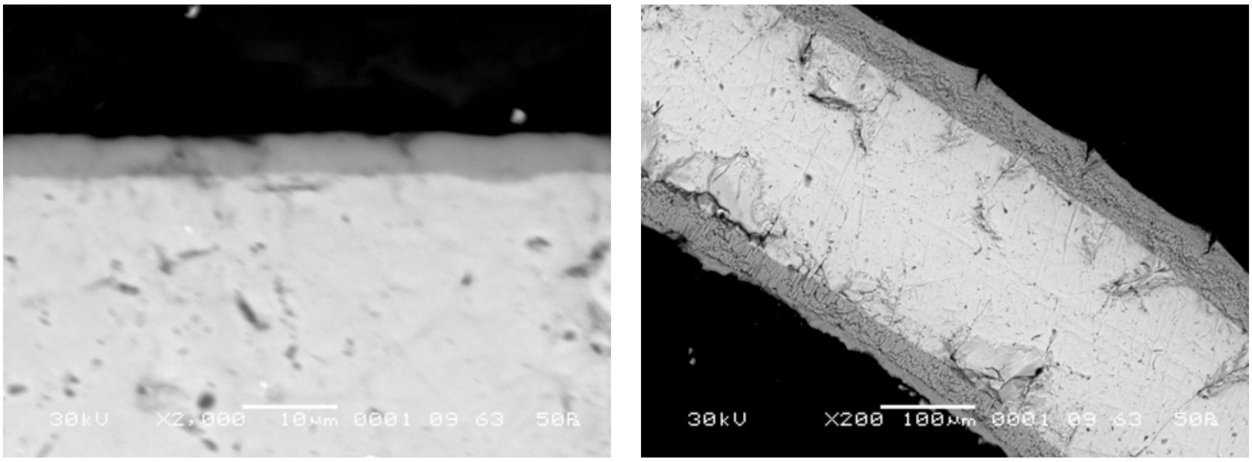
| | |
|---|---|
|  |  |
| a | b |

Figure 32. Photos of fuel rod simulators at the elevation of Z = 130 mm:

a – fuel rod 1.1; b – fuel rod 2.4.




a b

Figure 33. Structure of oxide scales on surfaces of zirconium structural components at the elevation of Z = 130 mm:
a – fuel rod 2.4; b – spacer grid fragment.

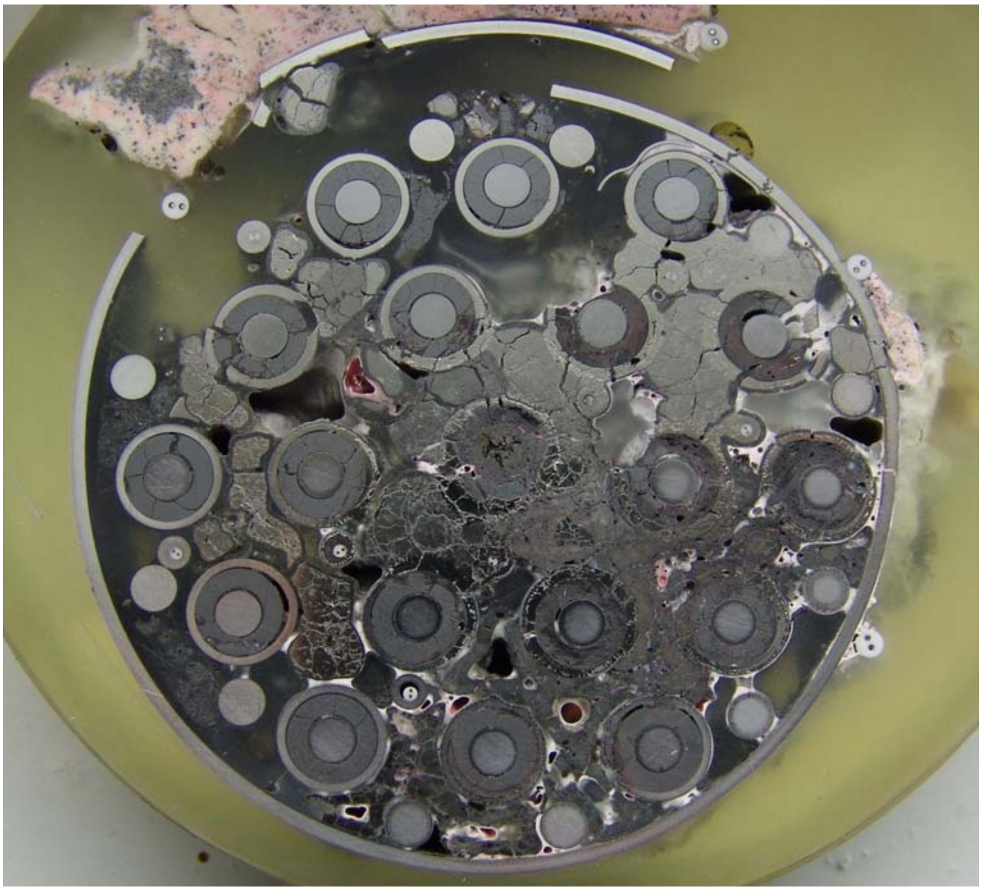
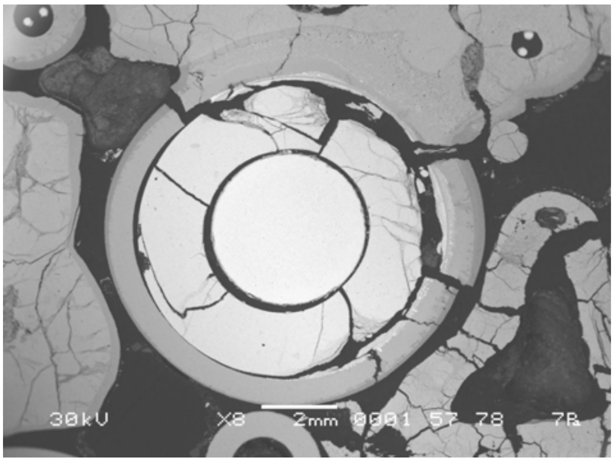
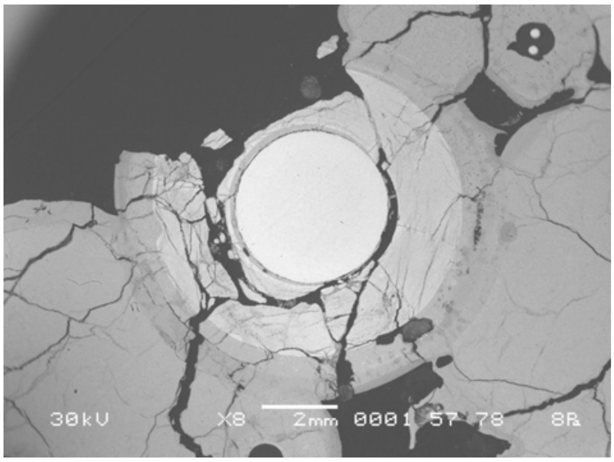


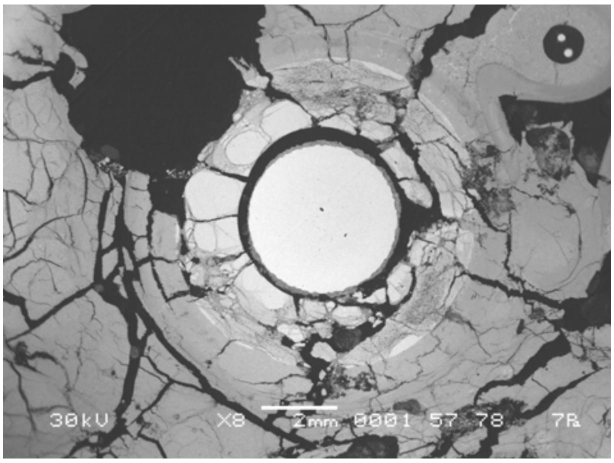
Figure 34. Assembly cross-section at the elevation of Z = 260 mm (top view).



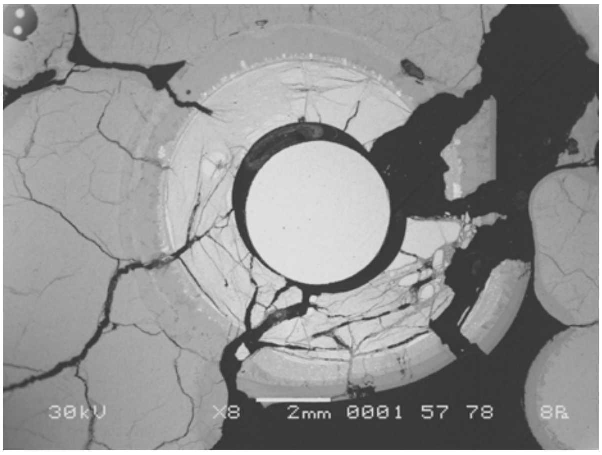
a



b



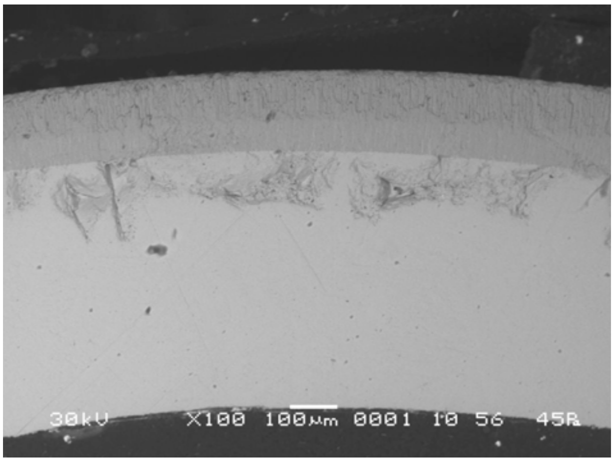
c



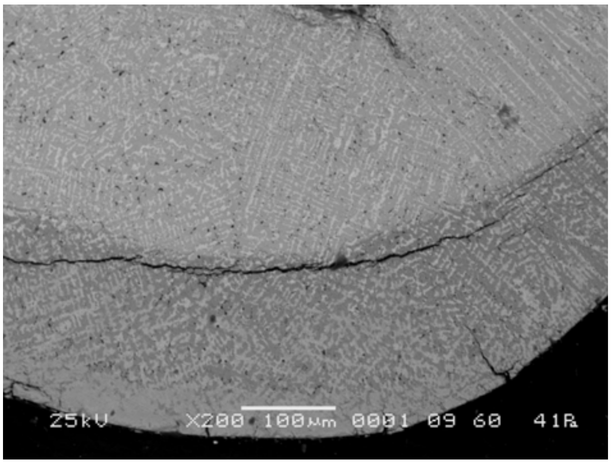
d

Figure 35. Cross-section of fuel rod simulators at the elevation of Z = 260 mm:

a – fuel rod 2.1;  b – fuel rod 2.4; c – fuel rod 2.5; d – fuel rod 3.8.

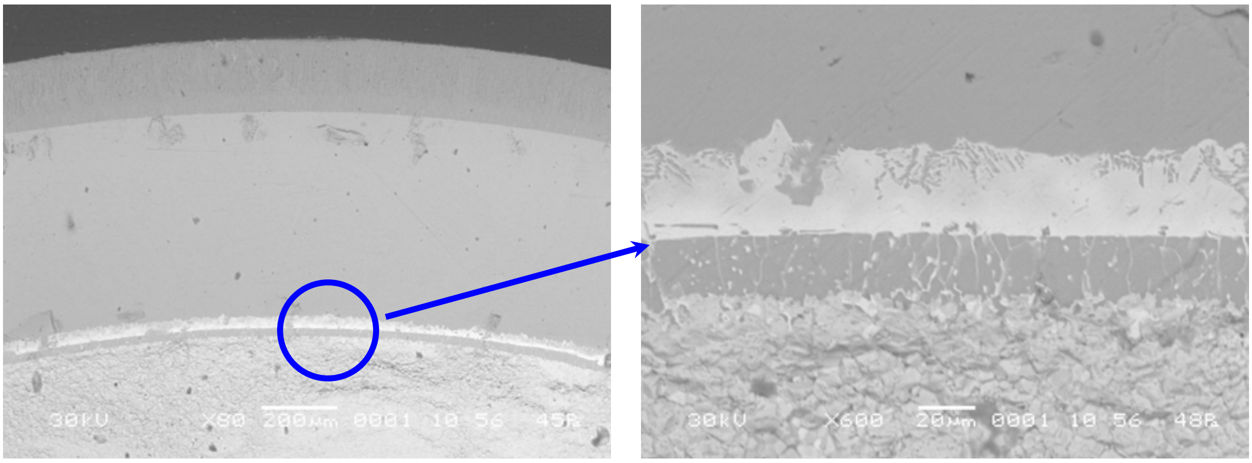


a



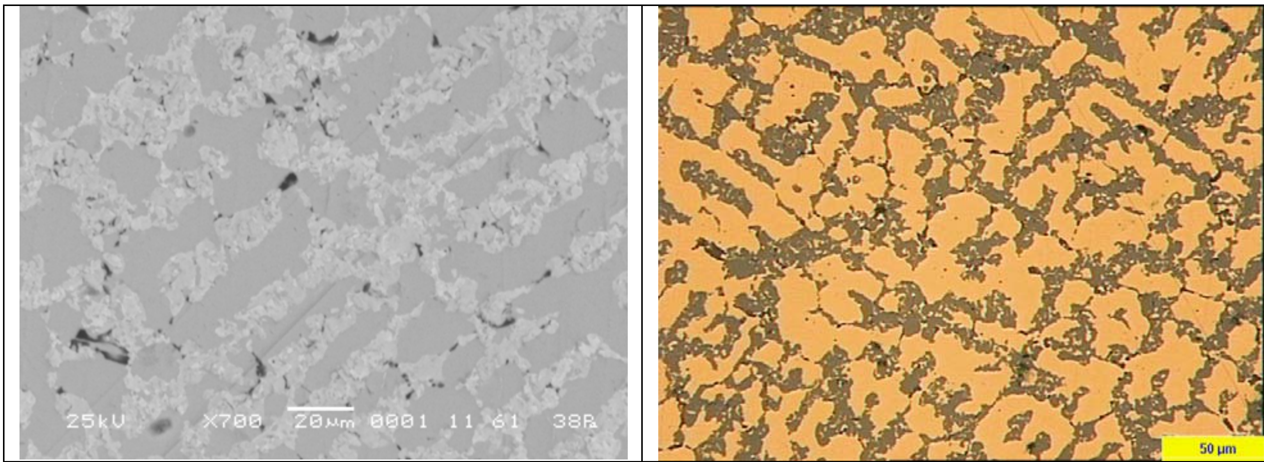
b

Figure 36. Structure of the remained claddings of fuel rod simulators and their oxide scales at the elevation of Z = 260 mm: a – fuel rod 2.2; b – fuel rod 2.3.




a b

Figure 37. Layers formed due to fuel-clad interaction at the elevation of Z = 260 mm:
a – fuel rod 2.2x80; b – fuel rod 2.2 x600.




a b

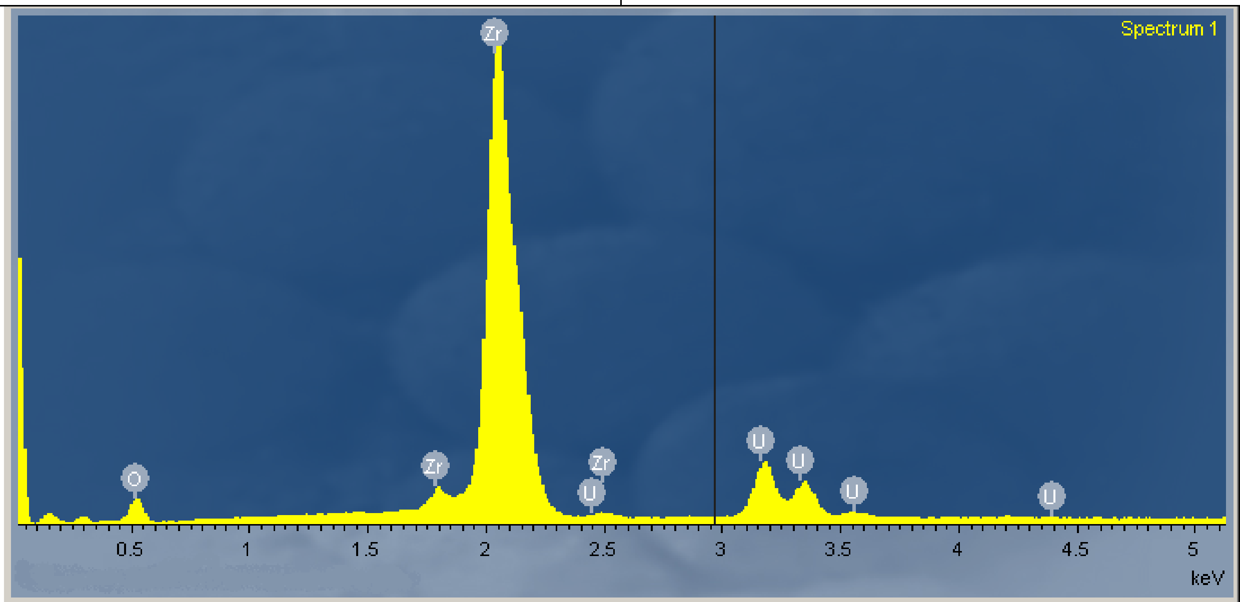



Figure 38. Structure of the melt (U,Zr,O) located in inter-rod space between rods at the elevation of Z = 260 mm:

a – electronic microscopy x700; b – optical microscopy x 500.

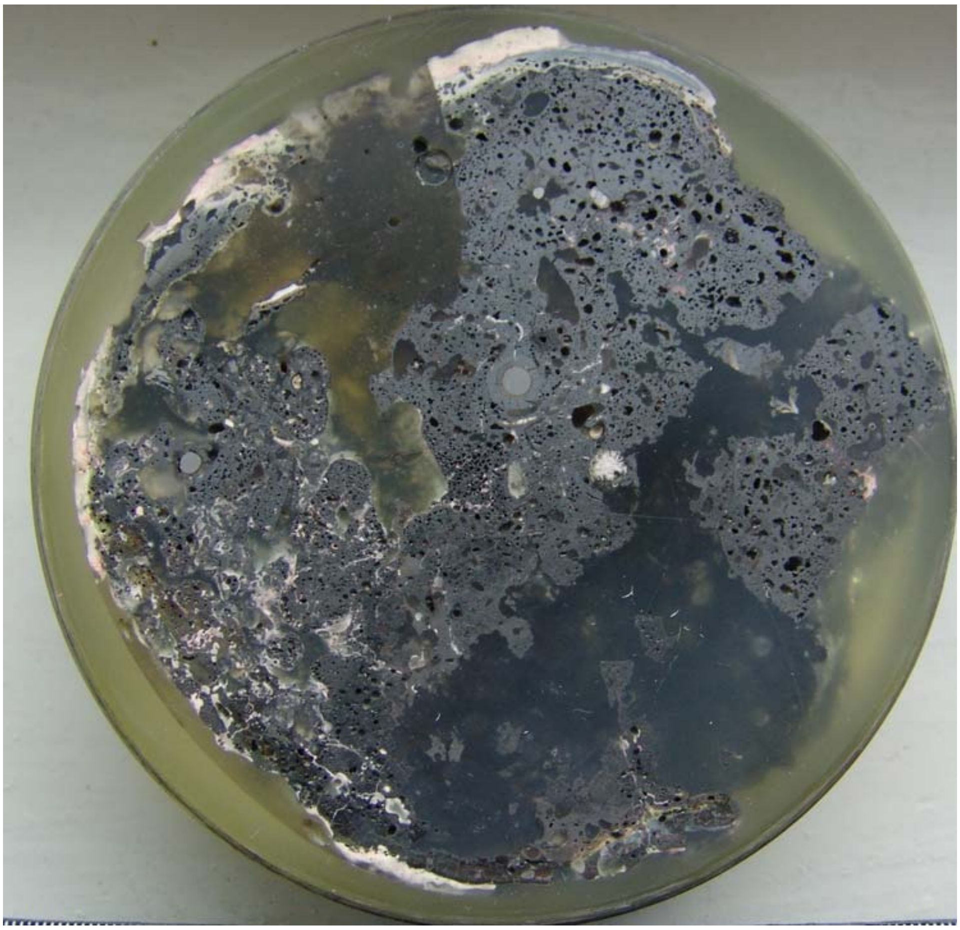


Figure 39. Assembly cross-section at the elevation of Z = 300 mm (bottom view).

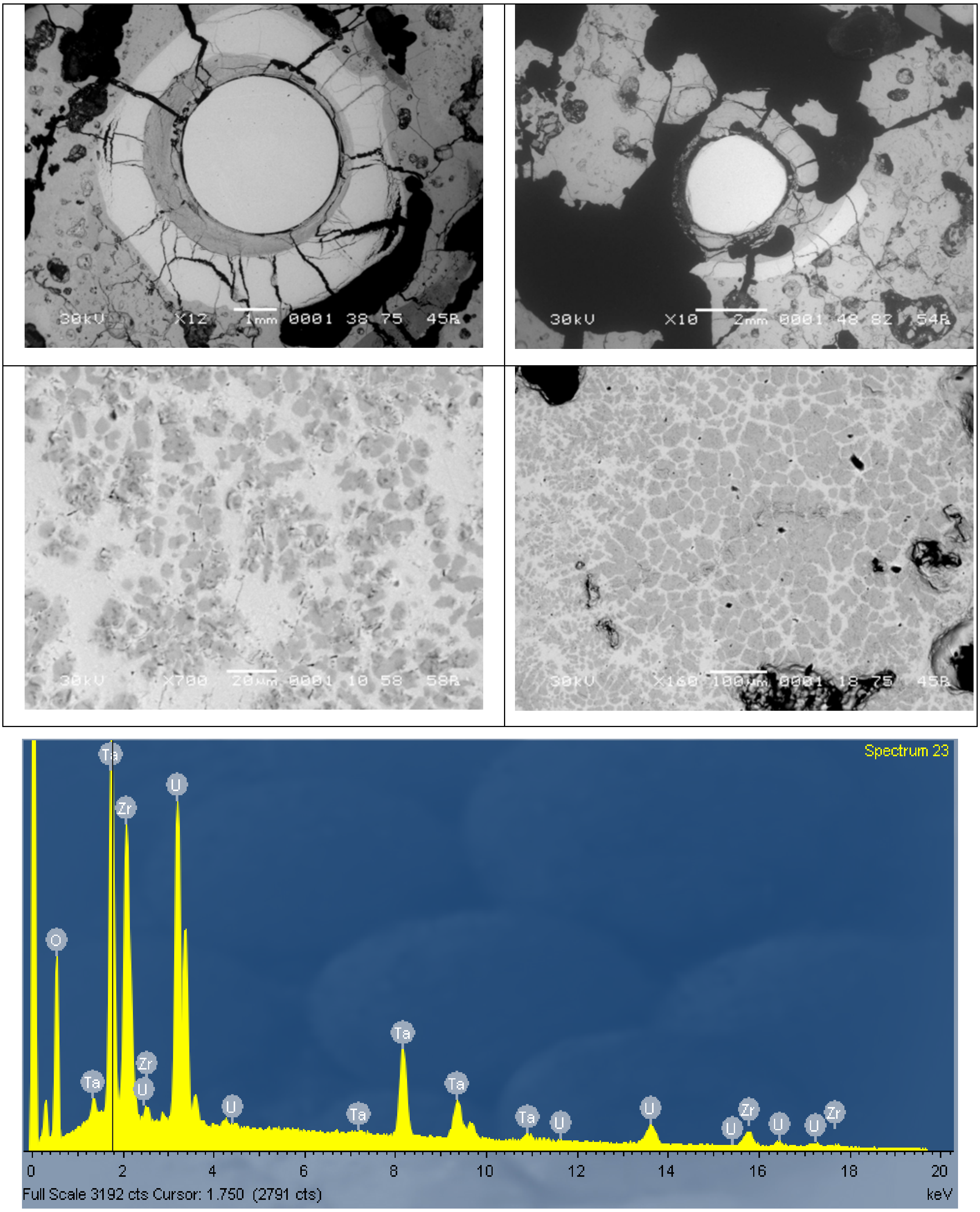



Figure 40. Cross-section of fuel rod simulators and structure of the melt at the elevation of Z = 300 mm.

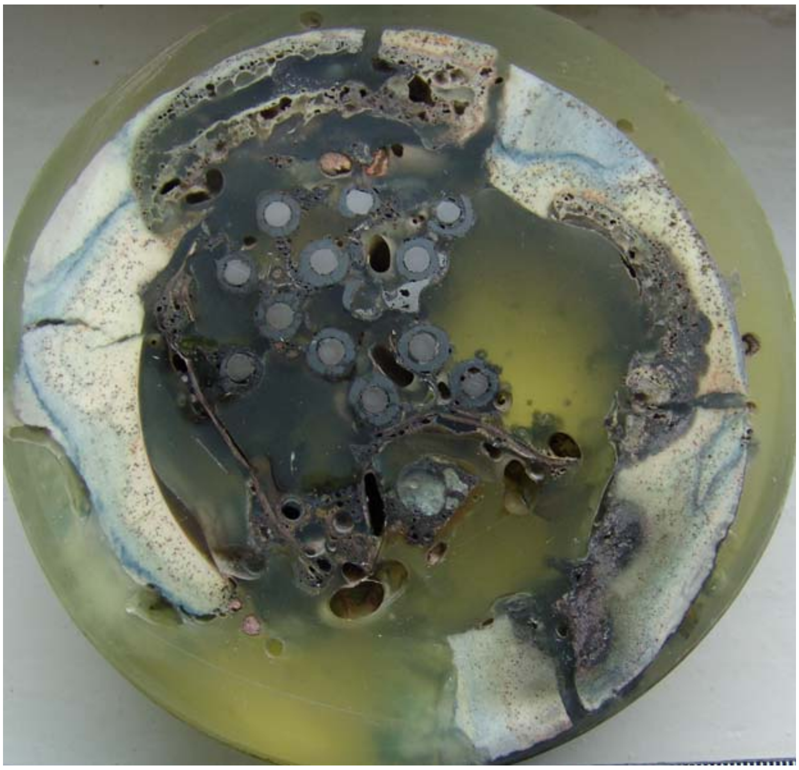


Figure 41. Assembly cross-section at the elevation of Z = 1200 mm (bottom view).

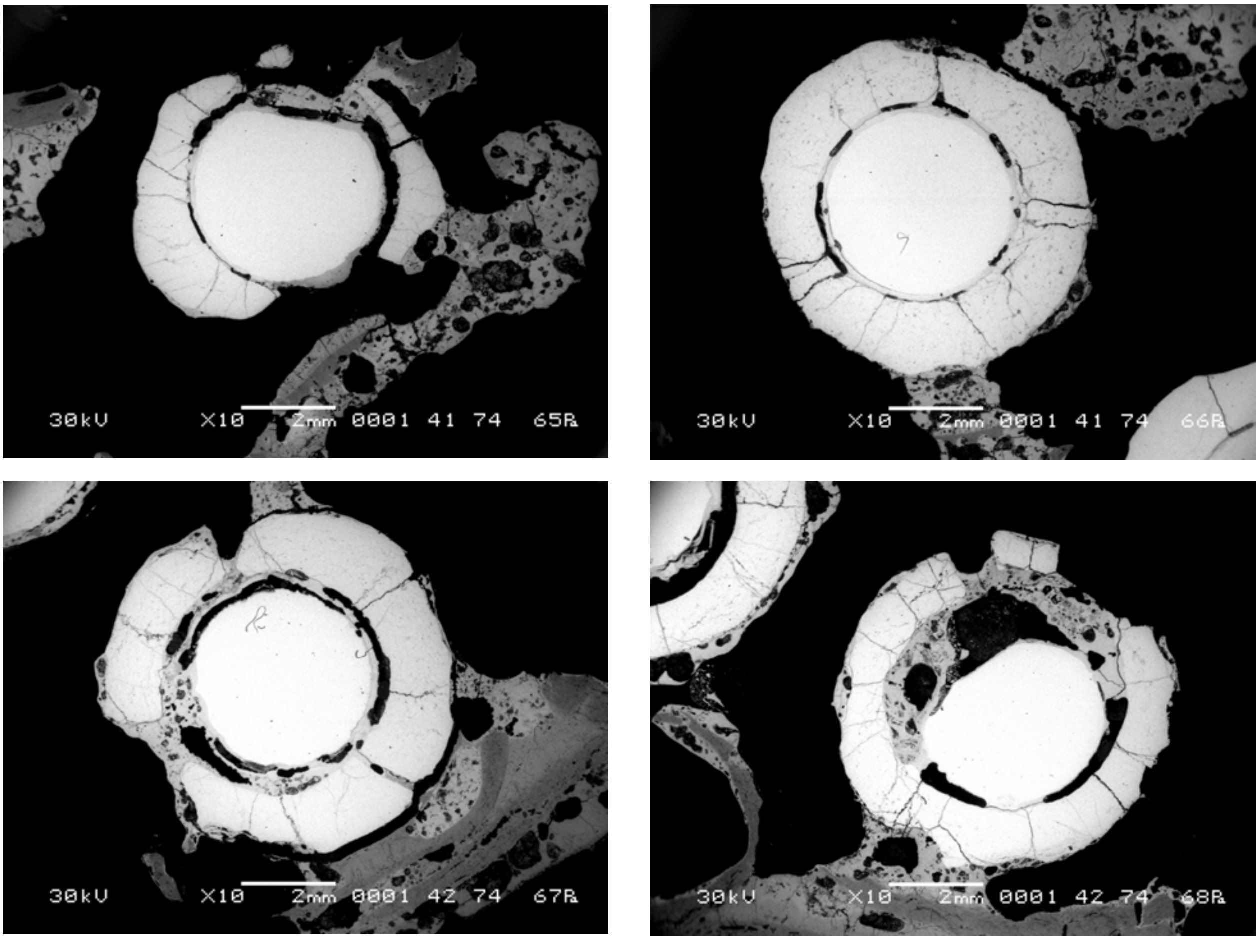



Figure 42. Cross-section of fuel rod simulators at the elevation of Z = 1200 mm.