ISTC Project No. 3690

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

Final Project Technical Report

on the work performed from Dec 01, 2007 to Nov 30, 2009

Federal State Unitarian Enterprise Scientific Research Institute Scientific Industrial Association "LUCH"

Project Manager	**Nalivaev Vladimir Ivanovich Ph.D.**	
Director	**Alekseev Sergey Vladimirovich Professor, PhD.**	

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Project Manager	Nalivaev Vladimir Ivanovich
phone number:	+7 (4967) 69-2792
fax number:	+7 (4967) 54-8589
e-mail address:	dvp@luch.podolsk.ru
Leading Institute:	FSUE SRI SIA "LUCH" Zheleznodorozhnaya 24, Podolsk, Moscow region, 142100, Russian Federation +7 (495) 715-9546 dvp@luch.podolsk.ru
Participating Institutes:	IBRAE RAS B. Tulskaya 52, Moscow, 115191, Russian Federation (495) 955-2324 ksv@ibrae.ac.ru EDO "GIDROPRESS" Ordzhonikidze 21, Podolsk, Moscow region, 142103, Russian Federation (495) 502-7918 semish@grpress.podolsk.ru
Foreign Collaborators:	STUCKERT, Juri Hermann-von-Helmholtz Pl. 1, Eggenstein-Leopoldshafen, 76344, Germany +49 7247 82 2558 juri.stuckert@imf.fzk.de TROMM, Thomas-Walter Hermann-von-Helmholtz Pl. 1, Eggenstein-Leopoldshafen, 76344, Germany +49 7247-82-5509 walter.tromm@nuklear.fzk.de BOTTOMLEY, David Hermann-von-Helmholtz Pl. 1, Karlsruhe, 76125, Germany (49) 7247 952 364 David.Bottomley@ec.europa.eu LAMY, Jean-Sylvestre 1 avenue du General de Gaulle, Paris, Clamart CEDEX, 92141, France 33 1 47 65 40 59 jean-sylvestre.lamy@edf.fr ALLELEIN, Hans-Josef Schwertnergasse, 1, Kologne, 50667, Germany 49 221 2068 770 Hans-Josef.Allelein @ grs.de TRAMBAUER, Klaus POB 1221, Garching, 85738, Germany 49(89)32004-436

klaus.trambauer@grs.de
BIRCHLEY, Jonathan
Villgen, 5232, Switzerland
+41(56)310-2724
jonathan.birchley@psi.ch
SEILER, Jean-Marie
17 rue des Martyrs, Grenoble cedex 9, 38054, France
+33(4)3878-3023
jean- marie.seiler@cea.fr
GROUDEV, Pavlin
72 Tzarigradsko shaussee, Blvd., room 108, Sofia
1784, Bulgaria
+359(2)959-5000/585
pavlinpg@inrne.bas.bg
HOZER, Zoltán
Konkoly Thege Miklós út 29-33, Будапешт, H-2040, Венгрия
+36(1)392-2294
hozer@aeki.kfki.hu

Keywords:

VVER-1000, fuel assembly, severe accident, top quenching, bottom quenching, tests, PARAMETER test facility.

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1. Brief description of the work plan: objective, expected results, technical approach

The objective of the Project is the study of behaviour of two 19-fuel rod model FAs of VVER-1000, completed with standard reactor structural materials (fuel rod claddings of alloy Zr+1%Nb, fuel pellets of uranium dioxide, spacing grids and shroud of alloy Zr+1%Nb), under the initial stage of severe accident with top quenching (experiment PARAMETER-SF3) and with bottom quenching (experiment PARAMETER-SF4).

Expected results within the framework of the project:

- Information will be obtained and systematized on behaviour on model FA under severe accident during top quenching.
- Database for verification of severe accident codes (SOCRAT, ATHLET, ICARE-CATHARE etc) will be broadened.
- Information will be obtained on behaviour on model FA under severe accident during bottom quenching the assembly, heated to ~1750°C in an air environment.

The scope of activities within 24 months includes post-test material analysis of VVER-1000 model FA, subjected to tests in experiment PARAMETER-SF2, preparation and performing the two experiments at the PARAMETER test facility – the tests of two 19-fuel rod model FAs of VVER-1000:

1) the assembly heated to ~1600°C (PARAMETER-SF3);
2) the assembly heated to ~1750°C (PARAMETER-SF4).

In experiment SF4, after a pre-oxidation stage, the assembly is cooled up to ~900°C, the steam switching off and air ingress (flowrate is ~0.5 g/s), then the assembly is heated up to ~1750°C.
The methodology of the tasks realization under the Project includes the following main stages:

- development of the scenario and main goals of the experiment;
- development of the calculated model and carrying out the calculations of test conditions and parameters of the experiment on the basis of computer codes SOCRAT, RELAP/SCADSIM, ICARE – CATHARE;
- preparation of the model fuel assembly and facility process systems to the tests;
- complex pre-operational work (functional check of the process and information-measuring systems of the test facility systems, adjustment of testing conditions for the process systems and technical parameters of model FA);
- performing the experiments, processing of results;
- post-tests material studies.

Technical realization of the project tasks is carried out using the PARAMETR facility of FSUE SRI SIA “LUCH”. The facility is intended for research of behavior of model FA of VVER reactors under conditions simulating various stages of LOCA-type events.

2. Experimental investigations

2.1. Posttest material analysis of model FA, subjected to tests in experiment PARAMETER-SF2

PARAMETER-SF2 experiment was performed with the aim of studying the behaviour of a 19-rod model FA of VVER-1000 under simulated severe accident conditions. In the experiment the initial stage of severe accident was simulated with large coolant leak from the primary circuit of VVER-1000 RP when the core drying occurs as well as its heating-up to ~ 1500°C and top and bottom water quenching.

After the experiment the test section was disassembled and the state of model FA inside the test section was fixated with a compound (epoxy resin ЭД-20) in vertical position.
After the compound hardened, the assembly was removed from the test section, photographed in detail and cut over the height into slabs. Sectioning of the bundle was done 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 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).
Methodical approaches to material studies of the assembly are developed on the basis of the analysis of results of measurement of fuel rod cladding temperature in the PARAMETER-SF2 experiment.
According to the thermocouple readings, the hottest zone location corresponds to the assembly upper part at 900…1300 mm elevations. So, in this part of the assembly, one should expect the highest degree of oxidation of the shroud and claddings. Therefore, the metallographic measurements of layers thickness in this area were done with more detail.
For all cross section slabs the thickness of metal layers and dense oxide of fuel rod claddings were measured. The measurements were done on each cladding in four directions around rods and averaged.
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 studies of the assembly zirconium structural components were performed on specimens cut out of the shroud (Z ~ 250, 500, 900 and 1200 mm, specimen size – 15x20 mm). We did not manage to prepare similar specimens of claddings because any attempt to withdraw claddings from cross section slabs resulted in cladding damage.
Phase analysis of specimens by X-ray was performed on the external shroud surface, as well as at a depth of 30 and 200 μm from the external surface and in the middle of the shroud thickness (~1000 μm).
X-ray of specimens was performed with the diffractometer DRON-6 basing on CuKα – radiation. The amount of ZrH_2 phase was measured by ratio of integral intensities of analytical lines. Line (111) – the most intensive in the diffraction spectrum of ZrH_2, was used as the analytical line. Measurements were performed in each studied section in layer-by-layer radiography phase analysis. The most suitable specimens for performing the quantitative X-ray phase analyses are powders. Owing to this, at the elevations (Z ~ 250, 500, 900 and 1200 mm) measurements of ZrH_2 phase content were performed also on powder samples. Lattice periods of β - and ω - phases were determined with an error of ±0.01 Å.
Accuracy of determination of a and c periods of α-solid solution depended on the width of diffraction lines, i.e. on the degree of the lattice distortion. In the most favourable cases an error in determination of a and c periods did not exceed ±0.001 Å.

2.2. PARAMETER-SF3 experiment

The PARAMETER-SF3 experiment was performed on October 31, 2008. In PARAMETER-SF3 experiment the initial stage of severe accident with LB LOCA was simulated when the core drying occurs, then its heating-up to ~1600°C and top water flooding.
The experiment included five stages:

- preparatory stage (0-4506 s) – stabilization of the assigned flow rates of argon ($G_{Ar\ in}$ ≈ 2 g/s) and steam (Gst in ≈ 3.5 g/s) at FA temperature T_{FA} ≈ 500°C, check of the state of the assembly and process systems;
- assembly heating up (4506-9760 s) to ≈ 1200°C;
- pre-oxidation (9760-13725 s) – FA holding at temperature of ≈ 1200°C in the hottest zone during ~3970 s. Maximum deviations of temperature in the hottest section (1250 mm) were ~ ± 50°C;
- heating up (13725-14481 s) – rise of FA temperature in the hottest section to 1600°C;
- flooding (14486-14960 s) – top water flooding of the assembly with the flow rate ≈ 40 g/s.

The main FA parameters are shown in Fig. 1–4.

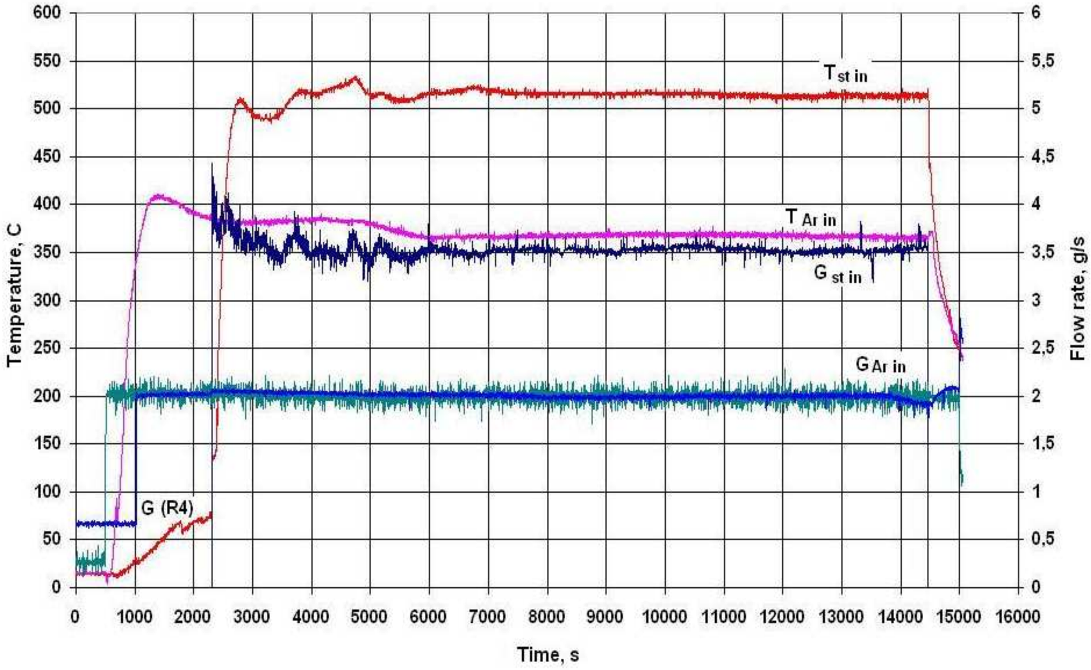

Fig. 1. Parameters of steam and argon at the test section inlet.

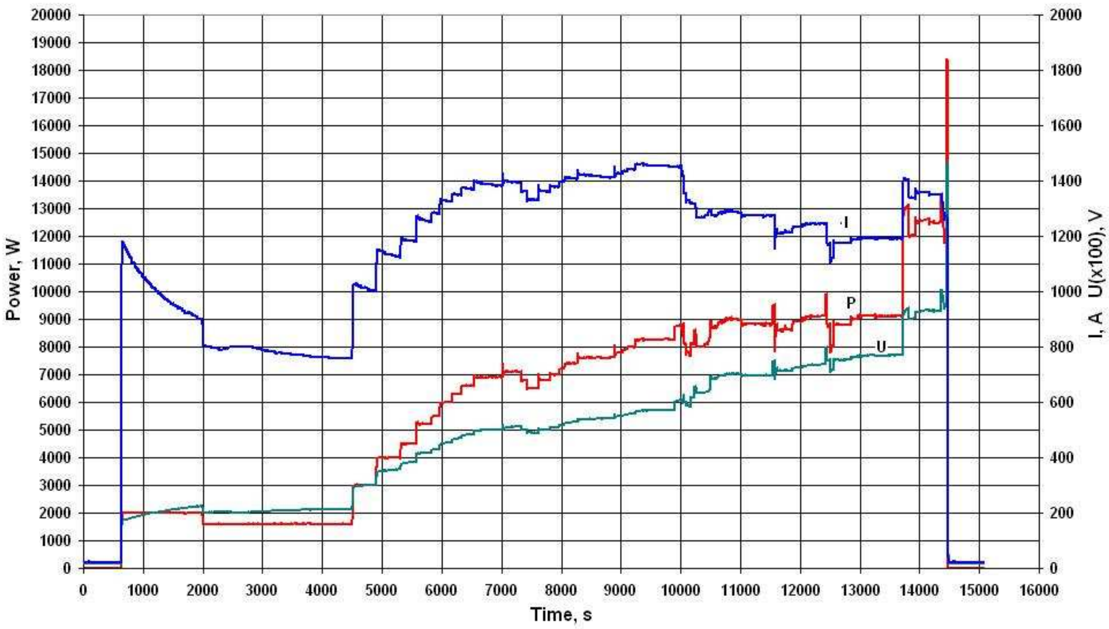

Fig. 2. FA electric parameters: power (P), current (I) and voltage (U).

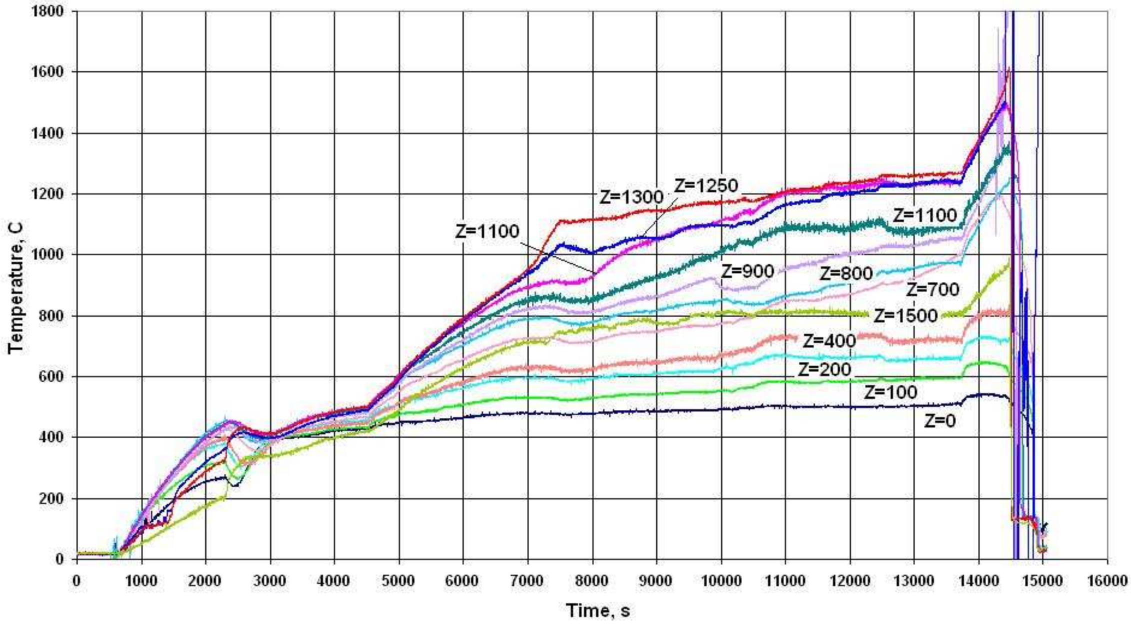

Fig. 3. Indications of thermocouples located over the height of fuel rod claddings.

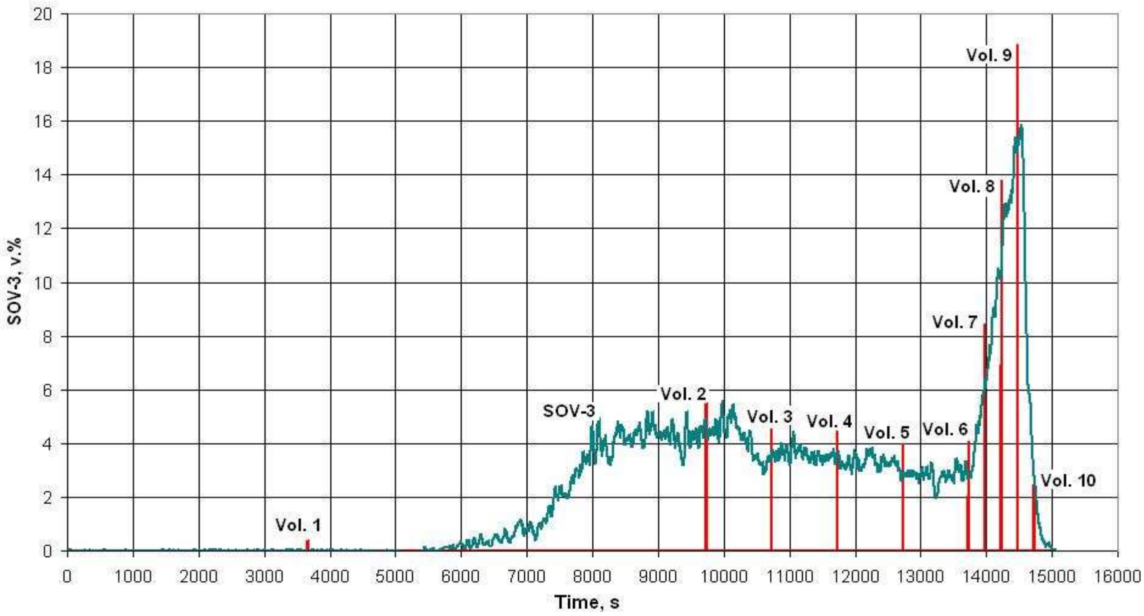

Fig. 4. Variation of volumetric hydrogen concentration under the indications of systems continuous (SOV-3) and discrete (Vol.) control of hydrogen.

Measurements of volumetric hydrogen concentration were carried out by the system SOV-3 at all stages of the experiment. At stages pre-oxidization, heating of the assembly to ~1600°C and flooding 10 test samples was performed. Indications of SOV-3 and the results of test samples analysis are in close agreement (see Fig. 4).

2.3. PARAMETER-SF4 experiment

The PARAMETER-SF4 experiment was performed on July 21, 2009 at PARAMETER test facility in FSUE SRI SIA "LUCH" with the analytical support of the work teams that perform calculations with SOCRAT (IBRAE), ICARE/CATHARE (RRC KI – IRSN), ATHLET-CD

(GRS), RELAP/SCDAPSIM MOD3.2 (OKB «GIDROPRESS»), MAAP4 (EdF), SCDAP/RELAP/FZK-PSI (PSI), PARAM-TG (SRI SIA «LUCH») computer codes. In the PARAMETER-SF4 experiment the stage of severe accident with LB LOCA was simulated when the core drying occurs, its heating-up to ~1750°C in the air flow, and bottom water flooding.

The PARAMETER-SF4 experiment included six stages:

- preparatory stage (0-4506 s) – stabilization of the assigned flow rates of argon (≈ 2 g/s) and steam (≈ 3.5 g/s) at FA temperature ≈ 500°C, check of the state of the assembly and process systems;
- assembly heating up (4506-8000 s) to ≈ 1200°C;
- pre-oxidation (8000-13886 s) – FA holding at temperature of ≈ 1200°C in the hottest zone during ~6000 s. Maximum deviations of temperature in the hottest section (1250 mm) were ~ ± 50°C;
- decrease of FA temperature (13886-16355 s) to ≈ 900°C;
- air ingress into FA (16035-17511 s) and rise of FA temperature in the hottest section (16355-17434 s) to 1740°C;
- flooding (17434-17908 s) – bottom water flooding of the assembly with the flow rate ≈ 80 g/s.

The main FA parameters are shown in Fig. 5–8.

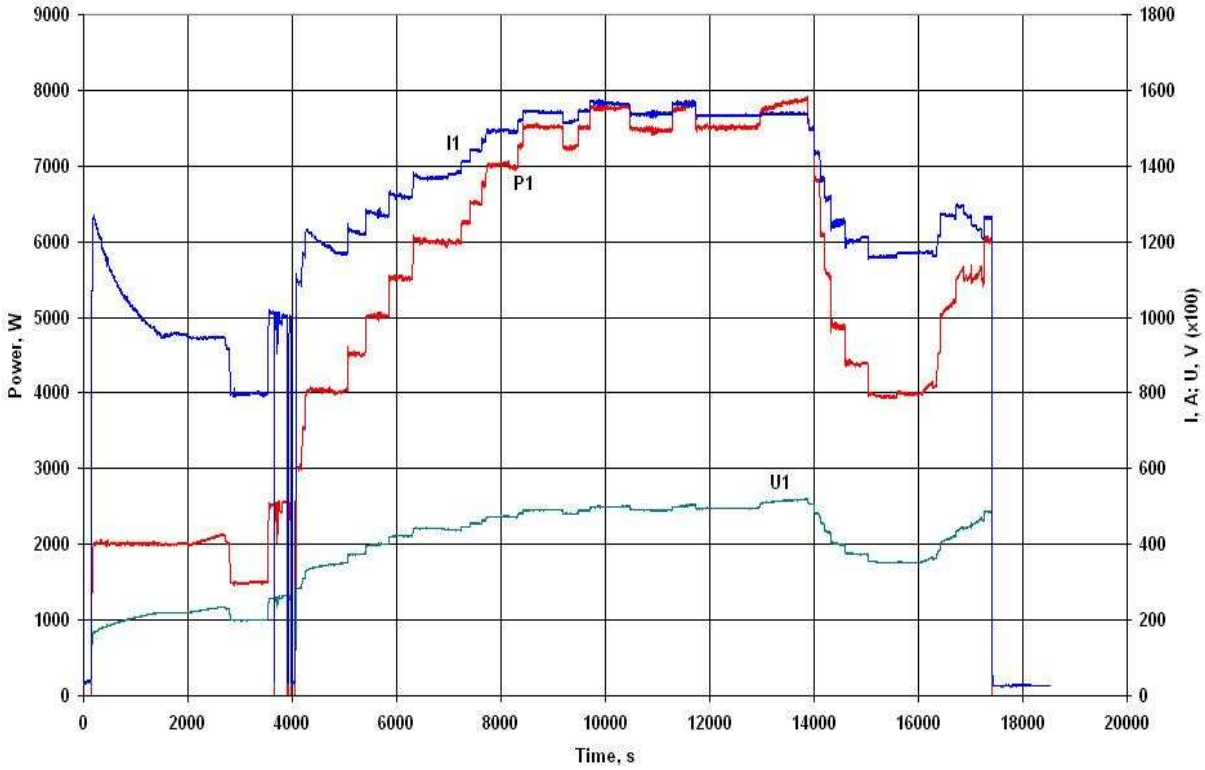

Fig. 5. FA electric parameters: power (P1), current (I1) and voltage (U1).

In the course of the experiment the two systems of hydrogen registration were used: continuous – SOV-3 and discrete – sampling system (8 test samples), that recorded hydrogen generation at the phase of pre-oxidization (6 test samples) and temperature rise (2 test samples).

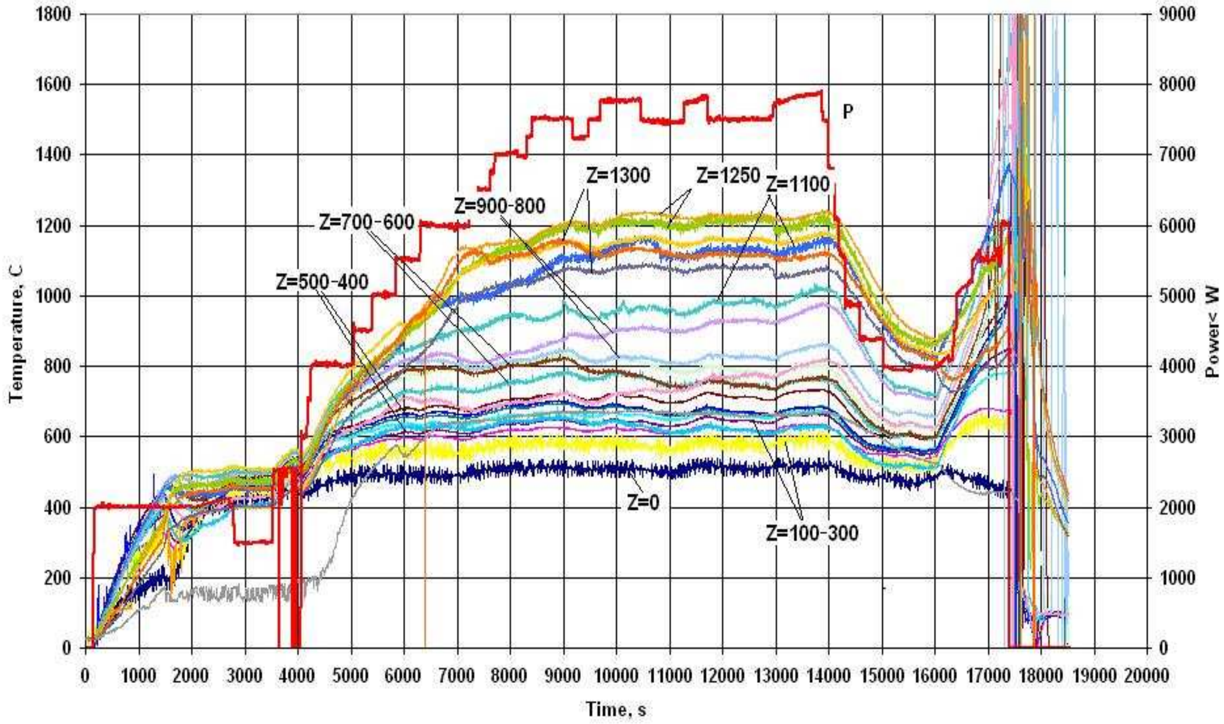

Fig. 6. Indications of thermocouples located over the height of fuel rod claddings.

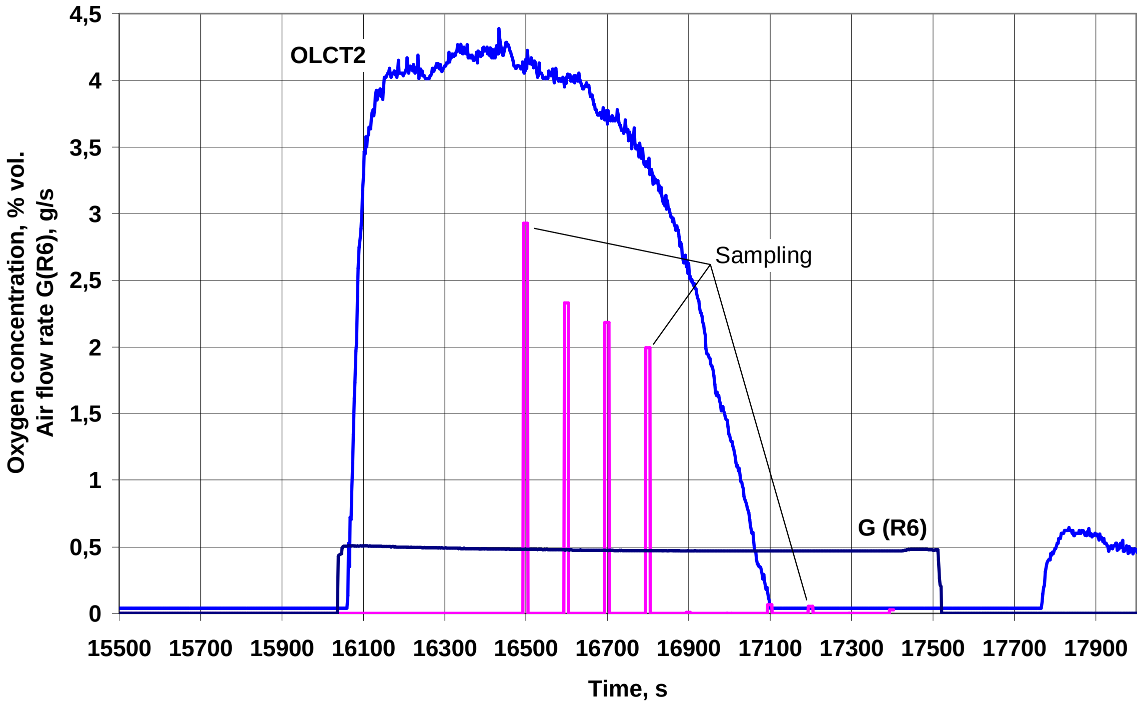

Fig. 7. Volumetric oxygen concentration measured with the systems of continuous (OLCT20) and discrete (Sampling) oxygen monitoring and air flow rate at the test section inlet G(R6).

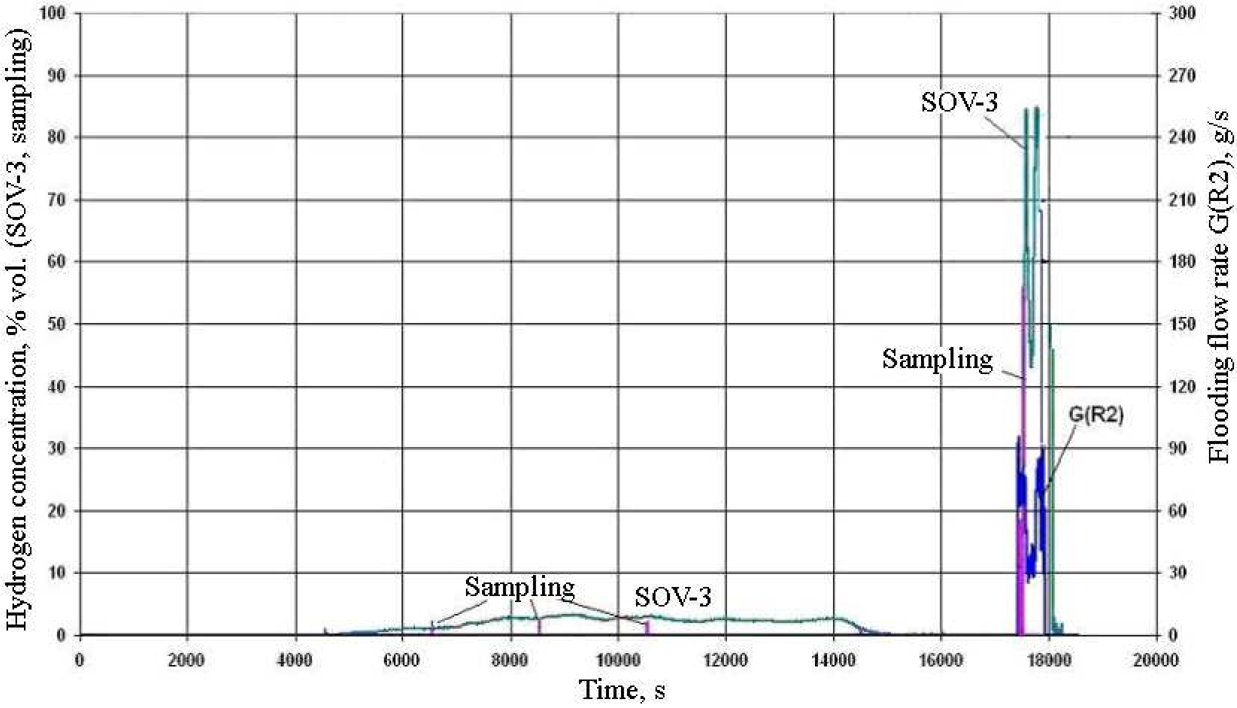

Fig. 8. Volumetric hydrogen concentration measured with the systems of continuous (SOV-3) and discrete (Sampling) hydrogen monitoring, flooding water flow rate G(R2).

3. Results

1. The tests of two 19-rod model assemblies of VVER-1000 completed with the standard reactor structural materials were performed under the conditions of severe accident with the top quenching of FA heated to the temperature of ~1600°C (PARAMETER-SF3 experiment) and with bottom flooding of the assembly heated to the temperature of ~1750°C in air flow (PARAMETER-SF4 experiment). The full information on the results of the experiments is presented in the “Protocol of PARAMETER-SF3 experiment results” and the “Protocol of PARAMETER-SF4 experiment results”.

In PARAMETER-SF3 experiment, on the whole, the stages of heating and pre-oxidation of the model assembly were realized successfully and the pre-test studies enabled to bring the plant to the heating stage at the required rate of temperature rise. The top flooding was successful. Analysis of SOV-3 hydrogen measurement results showed that ~ 34 g hydrogen was released in the experiment (Fig. 9). The maximum hydrogen generation rate was ~ 0.02 g/s (See Fig. 9).

Analysis of the results of post-test material studies of the model assembly after SF3 experiment showed the following:

- the state of the assembly lower part (0…400 mm) does not differ practically from the initial state, and the oxide thickness on the outer surface does not exceed 2-10 μm;
- within the elevation range of 500…1300 mm there is a multi-layer separating zirconium dioxide on fuel rod claddings;
- in the studied assembly cross-sections (900…1300 mm) a substantial irregularity of oxidation of fuel rods is observed;
- the mass of generated hydrogen, estimated “from above”, corresponds to the value of ~42 g. For comparability with the mass measured in the experiment (See Fig. 9) it is necessary to

consider additionally the mass of hydrogen absorbed by FA components , at least due to the shroud hydrogenation.

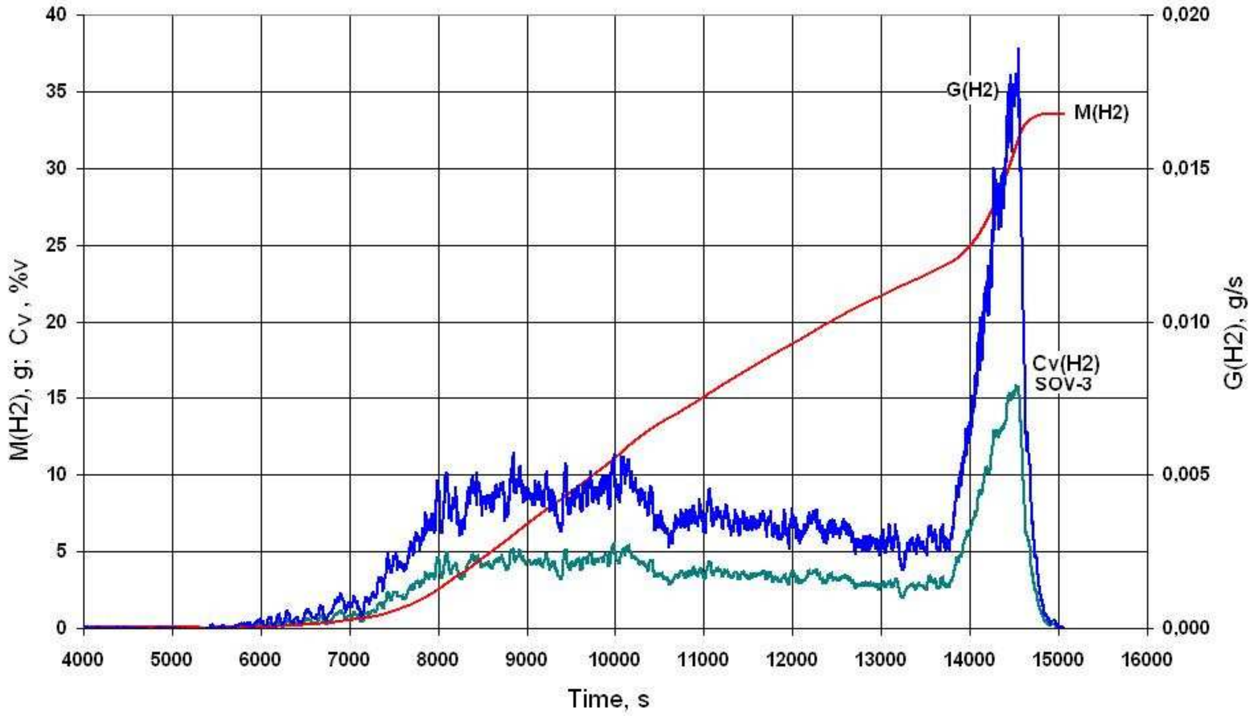

Fig. 9. Released hydrogen mass and generation rate.

In PARAMETER-SF4 experiment the work was performed on studying the possible flooding of the assembly actively oxidized with steam-air mixture in the region of unstable development of the fuel rod temperature escalation process. When the thermocouple at elevation of 500 mm recorded the maximum temperature of 1750°C, the electric power was switched off and the bottom flooding system was opened. The system of water flooding from bottom provided for the average flow rate of ~ 80 g/s.

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.

Claddings at the elevations above 800 mm at the beginning revealed quite slow but stable cooling down. But through ~100 s they started to reheat. Rapid heat up was followed by temperature escalation, so claddings temperatures reached upper limits of the thermocouples effective range (2000°C) very fast.

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 (Fig. 10), and at the flooding stage – ~ 86 g. Maximum rate of hydrogen generation at the flooding stage was ~ 0.6 g/s (See Fig. 10).

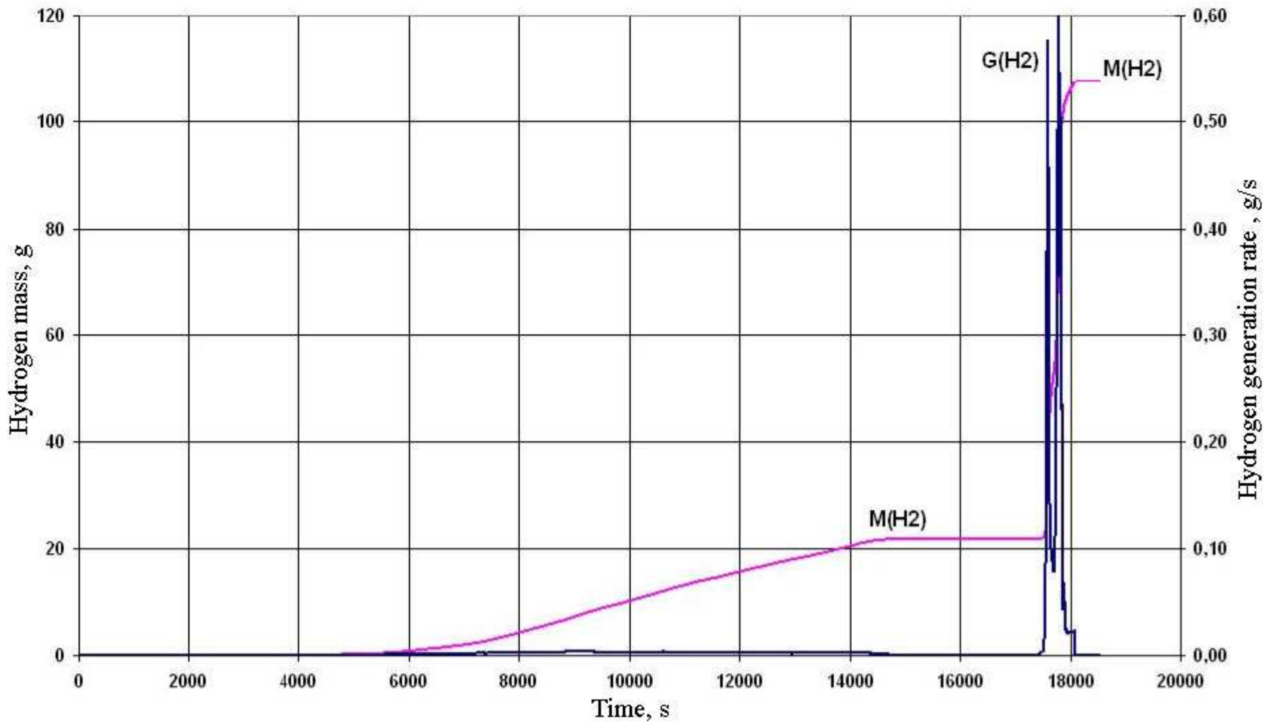

Fig. 10. Released hydrogen mass and generation rate (SF4).

Analysis of post-test material studies of SF4 model FA showed that:

- extensive damage of fuel rods (Z = 250…1400 mm);
- oxidation and melting of claddings and shroud;
- formation of large amount of the melt, its relocation downwards and solidification in the assembly lower part;
- heaters oxidation and dissolution by the melt.

2. Analysis of posttest material studies of SF2 model FA showed that the assembly axial temperature profile led to different degree of its damages.
The state of the lower part of heated zone (Z = 0…400 mm) does not practically differ from the original state, and oxide thickness on the external surface does not exceed 5…10 μm.
At 500…1300 mm elevations there is a multilayered spalled off zirconium dioxide.
Thicknesses of the compact oxide and the remained metal part of claddings were measured on each fuel rod and. Results of these measurements are presented in the form of plots (Fig. 11 – 14).

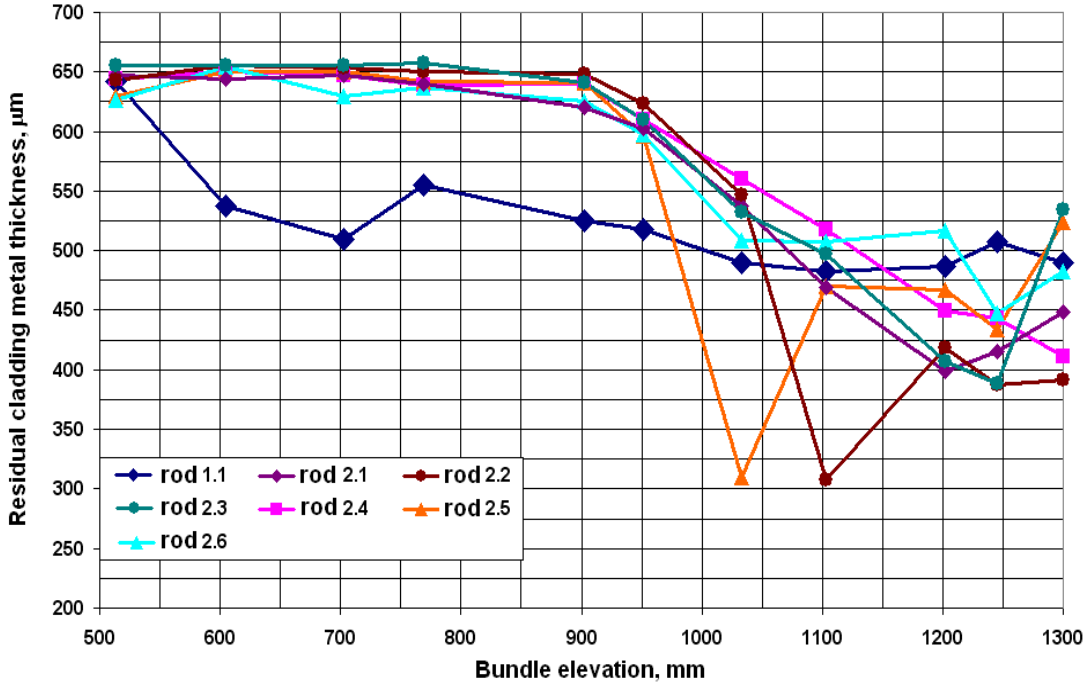

Fig. 11. Distribution of thickness of the remained metal part of claddings of fuel rods in the second row over heated zone.

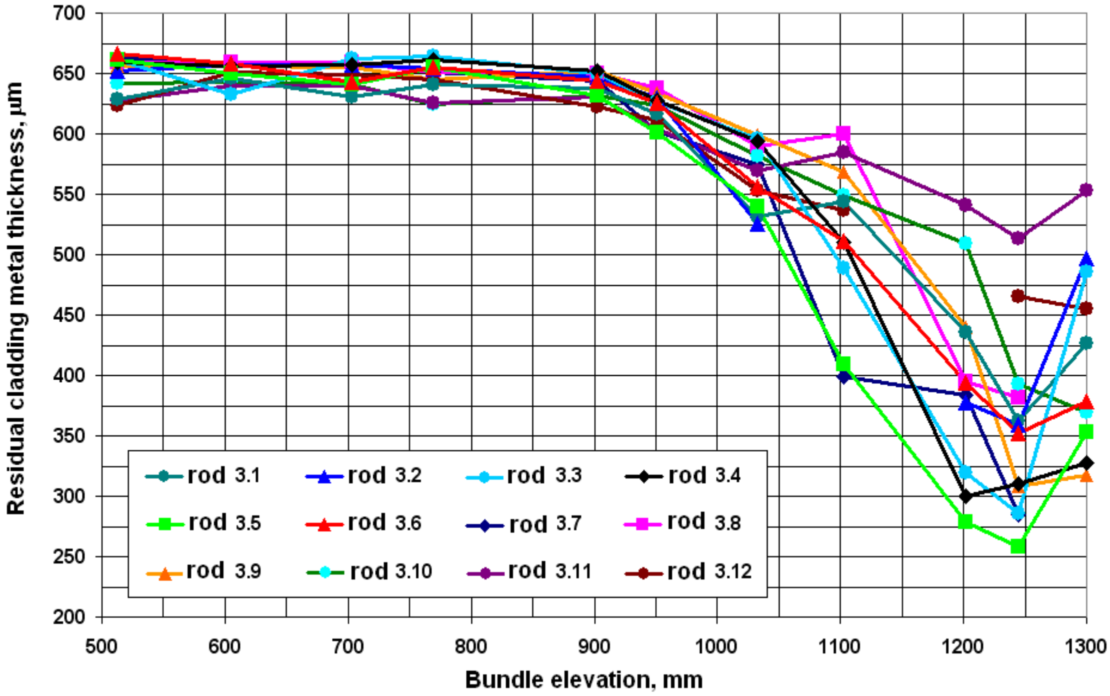

Fig. 12. Distribution of thickness of the remained metal part of claddings of fuel rods in the third row over heated zone.

Comparison of the results of metallographic studies and thermocouples indications allow supposing that pronounced breakaway oxidation over such an extended zone would occurred during the pre-oxidation phase.

In the middle part of heated zone (Z = 500…800 mm) the fuel rod simulators are displaced relative to the original arrangement, the external claddings surface is covered with multilayered zirconium dioxide, separating from metal surface, but its thickness does not exceed ~ 100 μm.

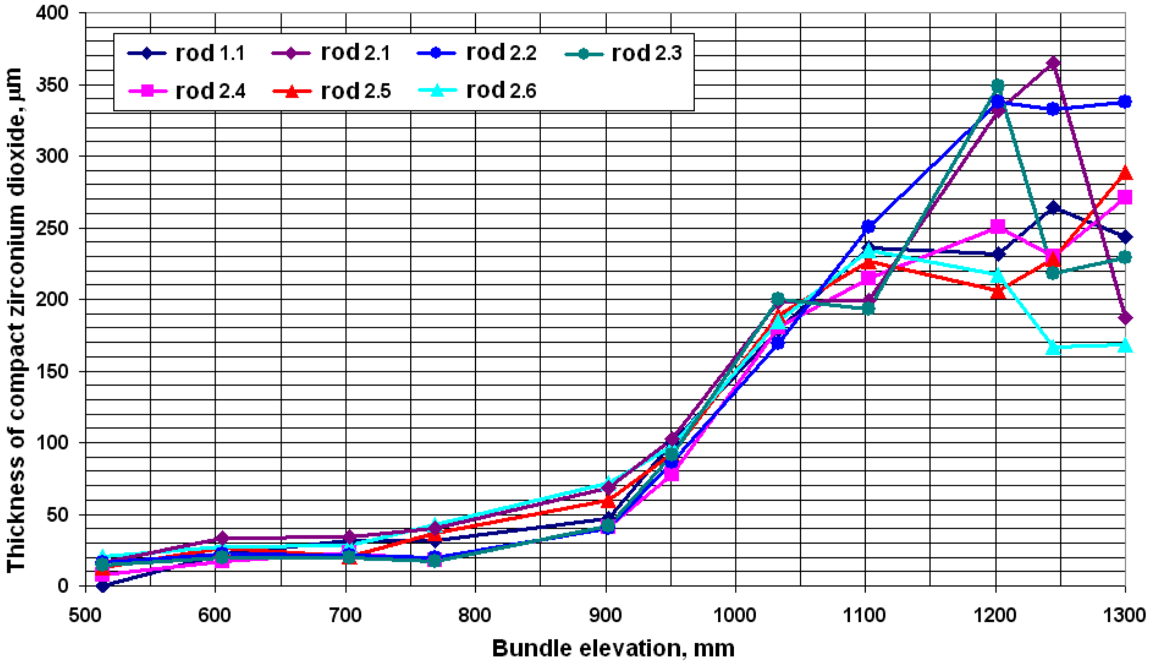

Fig. 13. Distribution of thickness of the compact ZrO_2 layer on external surface of fuel rods in the second row over heated zone.

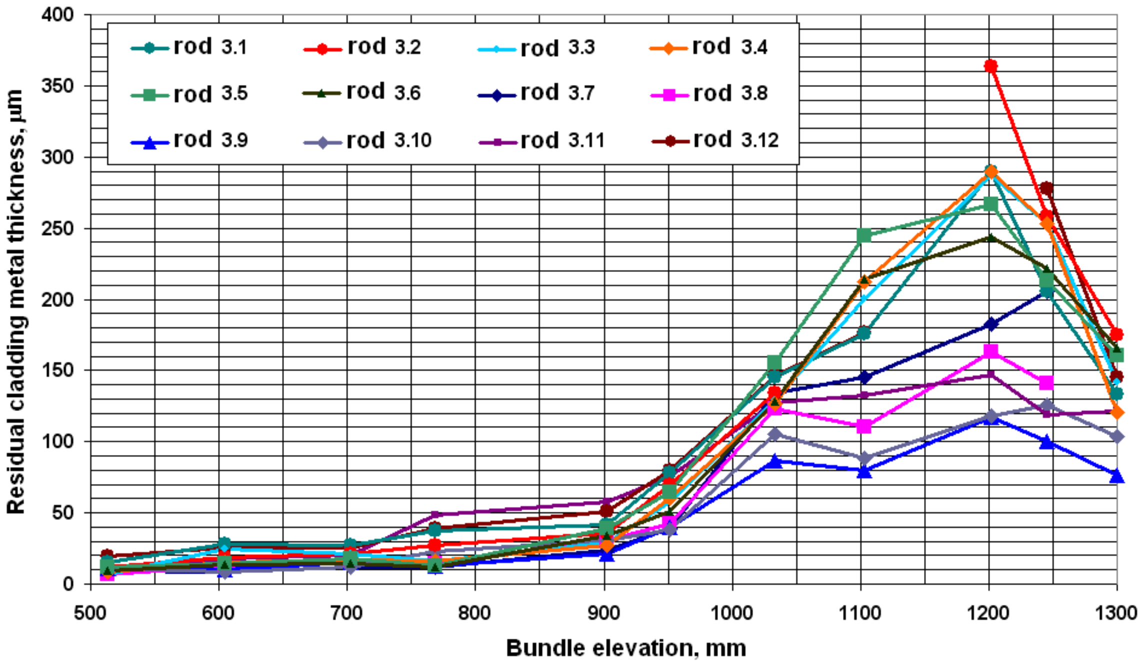

Fig. 14. Distribution of thickness of the compact ZrO_2 layer on external surface of fuel rods in the third row over heated zone.

In the upper part of heated zone (Z = 900…1300 mm) the original arrangement is greatly distorted. The claddings are oxidized both on the external (to 650 μm), and on the internal (to 50 μm) surfaces. Zirconium dioxide has different morphology. The metal part of the

claddings presents the oxygen-stabilized α phase (α - Zr (O)). The fuel rod claddings are embrittled, i.e. have through wall cracks, however fragmentation of fuel rods is limited. No fuel relacation and fuel-clad interaction are revealed in the assembly.
On the basis of the results of metallographic studies the evaluation was done for the maximum possible hydrogen mass that could release into steam-gas environment during the experiment. Taking into account the results of measurement of hydrogen content in the shroud, the upper limits of total hydrogen mass in the steam-gas environment can be estimated to be 31 g. The assessed value is in a good agreement with the results of measurements (~ 28 g).

4. Conclusion

The performed experiments PARAMETER-SF3 and PARAMETER-SF4 enabled to:

– obtain the information on the behaviour of structural components of 19-rods model FA of VVER-1000 overheated to ~ 1600°C during top quenching;
– study the temperature behaviour of the model FA of VVER-1000 under the conditions of air oxidation and subsequent bottom quenching;
– obtain the information on the degree of oxidation of structural components of the model FA of VVER-1000 and structural-phase changes in claddings of the model FA of VVER-1000 by the results of post-test studies;
– study the time history of oxygen absorption and hydrogen release.

Results of tests are intended for better understanding of the phenomenology of the processes occurring during water flooding of the core overheated under severe LOCA at NPP with VVER and under similar situations at PWR, and can be used for verification of computer codes.

5. References

None.

Attachment 1: List of published papers and reports with abstracts

1. Report on research work under the ISTC Project #3690 "Analysis of material studies of WWER-1000 model assembly tested at the PARAMETER-SF2 experiment under the conditions of severe accident with top and bottom flooding", 2008

The report presents the results of material studies of a 19-rod model assembly of WWER-1000 after the PARAMETER-SF2 experiment under the conditions of initial stage of severe accident with the combined top and bottom quenching of FA overheated to 1500°C.
The objective of material studies was a description of the post-test state of the model assembly and analysis of its components (structure, oxidation, fragmentation).
The studies included the following:

- encapsulation and sectioning of the model FA;
- preparation of cross section slabs;
- optical and electronic microscopy;
- X-ray analysis;

- analysis of the obtained results.

2. Protocol of PARAMETER-SF3 Experiment Results

The PARAMETER-SF3 experiment was performed on October 15, 2008. In PARAMETER-SF3 experiment, the initial stage of severe accident with LB LOCA was simulated when the core drying occurs, then its heating-up to ~ 1600°C and top water flooding.
SF3 experiment was performed with the aim of studying the behaviour of a 19-rods model FA of VVER-1000 under simulated severe accident conditions including the stage of low rate top flooding, and namely:

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

3. The report “Pre- and post-test calculations of experiments of a series PARAMETER-SF within the framework of the ISTC project #3690”. Annex 1 to final report under Project No.3690, 2009

The pre- and post-test calculations of experiments PARAMETER-SF2 (post-test analysis), -SF3 were performed With this aim the widely used computer code for NPP safety assessment (SOCRAT, ICARE/CATHARE, RELAP/SCDAPSIM MOD3.2) were applied, as well as engineering code PARAM-TG, developed directly for numerical analysis of PARAMETER facility. Collaborators of the Project also took part in calculational studies - GRS (Germany), using ATHLET-CD code, and PSI (Switzerland) with the code SCDAP/RELAP/FZK-PSI.
Results of the post-test calculational analysis, performed within the framework of ISTC Project #3690, showed that in spite of complexity of the experiments, the sets of experimental data are in mutual consistency and can be used in verification of the codes, their thermohydraulic models and physical-chemical models under severe accident conditions including the flooding stage.

4. The report “Post-test analysis of material studies of VVER-1000 model assembly tested at the PARAMETER-SF3 experiment under the conditions of severe accident with top flooding”. Annex 2 to final report under Project No.3690

The report presents the results of material studies of a 19-rod model assembly of VVER-1000 after the PARAMETER-SF3 experiment under the conditions of initial stage of severe accident with the top quenching of FA overheated to 1600°C.
The objective of material studies was a description of the post-test state of the model assembly and analysis of its components (structure, degree of oxidation, fragmentation).
The studies included the following:

– description of external appearance, encapsulation and sectioning of the model FA;
– preparation of cross section slabs;

– optical and electronic microscopy;
– analysis of the obtained results.

5. Protocol of PARAMETER-SF4 Experiment Results

The PARAMETER-SF4 experiment was performed at the test facility PARAMETER in FSUE SRI SIA “LUCH” on 21 July, 2009, with analytical support of the teams executing the calculations on codes SOCRAT (IBRAE), ICARE/CATHARE (RRC KI – IRSN), ATHLET-CD (GRS), RELAP/SCDAPSIM MOD3.2 (OKB “GIDROPRESS”), MAAP4 (EdF), SCDAP/RELAP/FZK-PSI (PSI), PARAM-TG (SRI SIA “LUCH”). In the PARAMETER-SF4 experiment, the stage of severe LOCA with a core drying out, its heating-up to ~ 1750°C in the air flow and water flooding from bottom was simulated.

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.

6. L.S. Degtyareva, V.P. Deniskin, D.N. Ignatiev, V.S. Konstantinov, V.I. Nalivaev, N.Ya. Parshin, E.B. Popov, D.M. Soldatkin, V.N. Turchin (FSUE “SRI SIA “LUCH”), A.D. Vasilev, A.E. Kiselev, D.Yu. Tomashchik, T.A. Yudina (IBRAE RAS), V.P. Semishkin, E.A. Frizen, V.V. Shchekoldin (OKB “GIDROPRESS”). Final Report on scientific work under ISTC Project No.3690 “Studies of fuel assemblies under severe accident top quenching conditions in the PARAMETER-SF test series”

The Final Report deals with the results of the computational and experimental studies performed according to the Work Plan of ISTC Project No. 3690 “Studies of fuel assemblies under severe accident top quenching conditions in the PARAMETER-SF test series”. The Project was executed jointly by three organizations: FSUE “SRI SIA “LUCH”, IBRAE RAS, OKB “GIDROPRESS” with participation of the leading specialists from JSC “VNIINM”, RRC “Kurchatov Institute”, A.I. Leipunsky SRC RF - IPPE and under methodical support of foreign collaborators (FZK, GRS, JRC-ITU, PSI, EdF, CEA, AEKI, INRNE).

Within the framework of the Project two experiments of PARAMETER-SF series (SF3 and SF4) were conducted as well as material studies of the model assembly tested in the SF2 experiment under the preceding ISTC Project No. 3194 were done. The tested bundles were made up of 19 fuel rod simulators. The bundles are identical to those used in VVER-1000 with respect to material and dimensions.

In PARAMETER-SF2 experiment, the initial stage of severe LB LOCA accident is studied when top and bottom flooding with water is initiated after core drying and its heating-up to ~ 1500°C.

In PARAMETER-SF3 experiment, the specific peculiarities of cooling and changes in structure of materials of VVER-1000 assembly under the conditions of severe accident with top flooding of the assembly heated to temperature of ~1600°C were investigated.

The possibility of assembly flooding intensively oxidized with steam-air mixture when unstable cladding temperature escalation occurs was in focus of the PARAMETER-SF4 experiment.

Results of the tests are intended for studying the processes occurring during water flooding of the overheated core in the course of severe LOCA accident at the NPP with VVER, and under similar situations in PWR, and could be used for verification of computer codes.

7. V. Nalivaev, A. Kiselev, J.-S. Lamy, S. Marguet, V. Semishkin, J. Stuckert, K. Trambauer, T. Yudina, Yu. Zvonarev. The PARAMETER test series. ERMSAR 2008, Nesseber, Bulgaria, 23-25 September 2008

The PARAMETER programme investigates phenomena associated with reflood of a degrading VVER like core under postulated severe accident conditions, in the early phase where the geometry is still mainly intact. The studies were performed according to the Work Plan of ISTC Project No.3194 "Fuel assembly tests under severe accident conditions". The objective of the presented out-of-pile test series is experimental and computational investigation of 19-fuel rods bundle behavior under severe accident conditions including the stage of low rate flooding from bundle top or high-rate flooding from bundle bottom and bundle top. The project was realized jointly by the leading organizations of the Federal Atomic Energy Agency of the Russian Federation: FSUE EDO "GIDROPRESS"; IBRAE RAS, FSUE SRI SIA "LUCH". The project was performed under financial support by ISTC and in close cooperation with leading European R&D organizations such as FZK, GRS (Germany), CEA, EdF, IRSN (France).

The paper provides the information on scope of work as already completed or planed in framework of PARAMETER-SF test series. Some outcomes from PARAMETER-SF1 and PARAMETER-SF2 tests are presented for discussion. In the PARAMETER-SF1 experiment, the behaviour of VVER-1000 assembly overheated to 2000ºC under top flooding conditions was studied. In another PARAMETER-SF2 experiment, the efficiency of the combined top and bottom flooding was studied for the VVER-1000 assembly overheated to 1500ºC. An outlook is given on future experiments PARAMETER-SF3 (top flooding) and PARAMETER-SF4 (air ingress).

The experimental part of PARAMETER project is supported by intensive analytical work. For that, widely used codes for NPP safety assessment were involved. Considerable contribution for success of the PARAMETER project was done by teams from Russia (SOCRAT, PARAM-TG, ICARE/CATHARE codes), France (MAAP4) and Germany (ATHLET-CD). So in the paper some results of pre- and posttest modeling and outcomes from code-to-code and code-to-data comparisons are presented for both SF1 and SF2 tests as well.

8. M. Steinbrück, M. Grosse, J. Stuckert, J. Birchley, T. Haste, Z. Hozer, N. Vér, V.I. Nalivaev, V.P. Semishkin, A.V. Goryachev, C. Duriez, A.E. Kisselev, M.S. Veshchunov. Comparative studies of high-temperature oxidation and quench behaviour of Zircaloy-4 and E110 cladding alloys. ERMSAR 2008, Nesseber, Bulgaria, 23-25 September 2008

The zirconium based alloys Zircaloy-4 and E110 are the classical materials used for fuel rod cladding in Western pressurised water reactors (PWR) and Russian RMBK and VVER reactors, respectively. This paper deals with overview of current investigations on high-temperature oxidation of the both alloys.
Results of separate effect tests, single rods tests, and test performed at large-scale facilities are presented. Special attention is devoted to high temperature oxidation kinetics, hydrogen release and its uptake by claddings, as well as cladding behaviour during flooding.
Regarding considered parameters, the results evidence that materials behaviour is similar if thick protective oxide scale is grown on cladding surface. Major differences are exhibited due to breakaway effect that leads to enhanced oxidation kinetics and increased hydrogen uptake by metallic part of claddings, and then to embrittlement and earlier failure of cladding. Temperature range where breakaway oxidation occurs is different for the considered alloys.
Overview of oxidation models based on correlations, models of mechanical behaviour during flooding is presented, effect of fuel burn up is discussed.

9. M. Steinbrück, J. Birchley, A.V. Boldyrev, A.V. Goryachev, M. Grosse, T.J. Haste, 1, Z. Hózer, A.E. Kisselev, V.I. Nalivaev, V.P. Semishkin, L. Sepold, J. Stuckert, N. Vér and M.S. Veshchunov. High-Temperature Oxidation And Quench Behaviour Of Zircaloy-4 And E110 Cladding Alloys. PROGRESS IN NUCLEAR ENERGY Volume: 52 Issue: 1 Pages: 19-36, Published: JAN 2010

The zirconium based alloys Zircaloy-4 and E110 are the classical materials used for fuel rod cladding in Western pressurised water reactors (PWR) and Russian RBMK and VVER reactors, respectively. This paper deals with overview of current investigations on high-temperature oxidation of the both alloys.
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Regarding considered parameters, the results evidence that materials behaviour is similar if thick protective oxide scale is grown on cladding surface. Major differences are exhibited due to breakaway effect that leads to enhanced oxidation kinetics and intensified hydrogen uptake by metallic part of claddings, and then to embrittlement and earlier failure of cladding. Temperature range where breakaway oxidation occurs is different for the considered alloys.
Overview of oxidation models based on correlations, models of mechanical behaviour during flooding is presented, effect of fuel burn up is discussed.

Attachment 2: List of presentations at conferences and meetings with abstracts

1. Post-test examination of the SF2 fuel assembly. D.N. Ignatiev. 13th International QUENCH Workshop, November 20-22, 2007, Karlsruhe, Germany.

While developing engineering solutions and measures to manage a beyond design basis and severe accident stages the information is required on thermo-mechanical behavior of the core structural components under water flooding from top and bottom and how the core conditions affect rate, ways and methods of cooling.

In this connection, in the ISTC Project #3194 first out-of-pile test of behavior of fuel assemblies made of standard structural materials used for VVER-1000 (Zr+1%Nb-alloy fuel cladding, uranium dioxide fuel pellets and guiding tubes made of Zr+1%Nb alloy) under simulated conditions of a severe accident including the stage of low rate flooding from the top (SF1) was carried out.

Basic stages of the experiment were:

- oxidation phase ($T_{мах}$ ~ 1200°C during 3000…4000 s);
- transient phase ($T_{мах}$ ~ 1500°C, heating rate ~ 5°C/s);
- simultaneous top and bottom flooding.

In this report presented:

- results of bundle cutting and material investigations of the SF1 fuel assembly with optical and electron microscopy.
- careful description of the three cross section appearance after test;
- prior analysis of results.

2. Pre- and post-test calculations on PARAM-TG code in basis of model FA tests regimes in conditions DBA and BDBA at the PARAMETER test facility. L.S. Degtyareva, N.Ya. Parshin, E.B. Popov, D.N. Soldatkin. 13th International QUENCH Workshop, November 20-22, 2007, Karlsruhe, Germany.

PARAMETER facility is appropriate to conducting experiments that simulate all accident process stages with model fuel assemblies from the initial stage to the stage of severe accident.

PARAM-TG code was developed to accompany by the calculations above experiments. The computer code unique feature is the description in detail of test section and of model fuel assembly geometry. Every fuel rod, all hydraulics channels between neighboring fuel rods, thermocouples, all of these are taken into consideration.

By means of PARAM-TG code it was calculated the following:

- temperature fields in model fuel assemblies for experiment scenarios validation;
- experiment parameters to validate scenarios;
- post-test calculations with taking into account particular features of conducting experiments.

For the first time the accident initial stage that lasts only 15-25 s could been reproduced at first by means of the numerical modeling and then for the bundle test. It was shown that at the initial stage in principle fuel cladding ballooning and ballooning with depressurization was possible for the most energy released fuel rods.

More than ten experiments were conducting for 19- and 37-rods model assemblies to study separate aspects of design basis accident. Fuels cladding ballooning, depressurization and oxidation range of fuel cladding, blockage of flow area and so on were investigated in the wide range of temperatures, heating rates and pressures inside the fuel cladding.

For the first during the investigation under severe reactor accident conditions the overheated to 2000°C 19-rods bundle was flooded by water from the top and also the same bundle heated to 1500°C was flooded simultaneously from the bottom and from the top.

3. Related thermal-mechanical and heat transfer processes in WWER core during LOCA. E. Frizen, V. Semishkin, A. Churkin. 13th International QUENCH Workshop, November 20-22, 2007, Karlsruhe, Germany.

WWER primary coolant fast pressure decrease and core heat-up is available under design and beyond design-basis primary LB LOCA. Gas gauge pressure affects fuel rod cladding internal surface under these conditions that results in tension hoop stresses. Increase of fuel rod cladding deformation starts as a result. Creep strain increase is enhanced at high temperatures and local fuel rod cladding ballooning with FA flow area partial blockage and also loss of cladding integrity can be available in the course of time. Fuel rod cladding ballooning is changes heat-transfer conditions inside fuel rod because of its geometry variation as well as heat release outside fuel rod because of fuel rod bundle flow area partial blockage and primary coolant redistribution over FA cross-section. Uncertainty of specified processes for core simulation in a channel approximation requires conservative methods and assumptions to be applied. Partial removal of the above uncertainties using advanced calculated methods allows to enhance the quality of calculation analyses for WWER RP designs. Problems of fuel rod-primary coolant heat exchange and fuel rod thermal conductivity on the one hand both problems of strain in fuel pellets and fuel rod cladding on the other hand are interdependent since continuous and fast variation of fuel pellet and fuel rod cladding geometry is available during heat removal from fuel rods under design and beyond design-basis accidents. Fuel rod codes TVEL-3 and TVEL-3/2 have been developed for solution of such problems within the framework of safety analyses using thermal-hydraulic codes.

4. Computational assessment of PARAMETER-SF experiments. T. Yudina. 13th International QUENCH Workshop, November 20-22, 2007, Karlsruhe, Germany.

Some results of pre- and post-test calculations performed using RATEG/SVECHA (SOCRAT), RELAP, MELCOR 1.8.5, ICARE/CATHARE, ATHLET, MAAP4, PARAM TG codes are presented. Applying of integral severe fuel damage codes in the pre-test calculations allow blindly assessing quality of the corresponding models. The runs were done by teams from IBRAE, RRC KI, “GIDROPRESS”, SRI “LUCH”, GRS, EdF.

Upon the PARAMETER-SF1 pre- and post-test runs analysis one can conclude that at preheating, preoxidation phases and at the beginning of transient stage the used codes predications with respect to the bundle temperature and hydrogen release agree to each other and to measured data as well. Calculated results at flooding stage are rather different and far away from experimental data. Some codes don’t predict release of extra hydrogen at all. Other predictions can be characterized by large – by factor of 1.5.Obviously, different approaches are applied in the codes to treat thermohydraulic processes at quench phase, the approaches are not well verified, the models need improving.

The scope of the PARAMETER-SF2 pre-test numerical analysis included assessment of required power level for the pre-oxidation phase (~1470 K), assessment of acceptable temperatures deviation and delay of water injection beginning, pre-injected water level assessment – to avoid unexpected early flooding from bottom by steam or flashing. At blind phase of calculations applied system codes SOCRAT and ICARE/CATHARE predict similar total hydrogen release of about 23 g. Uncertainties in relation to treatment of some processes during top flooding are taken into account in developed scenario of combined flooding.

5. Status of the ISTC project #3690 on the "Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and -SF4 experiments). V.I. Nalivaev, T.A. Yudina. 13-th CEG-SAM Meeting, March 5-7, 2008, Budapest, Hungary.
The general information will be presented about status of the ISTC project #3690 on the "Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and -SF4 experiments).
As well the main results of preparation of the PARAMETER-SF3 test will be discussed. The presentation will contain the information about PARAMETER facility modification, improvements done with its instrumentation and bundle assembling. Some results of PARAMETER-SF2 post-test material investigation will be shown.
Generally the following basic parameters of the experiment are proposed for PARAMETER-SF3 test:

- Test bundle of VVER-1000 type - (18 heated rods and 1 unheated rod);
- Coolant flow rate (argon/steam) - 2/3.5 g/s;
- Temperature of the bundle on pre-oxidation phase - 1470 K;
- Time of pre-oxidation - 3000 s;
- Cladding heat up rate - 0.5 K/s;
- Maximum cladding temperature - 1870 K;
- Water flow rate on quench stage (from top) - 40 g/s.

6. PARAMETER-SF3 test scenario and results of SF3 pre-test numerical modeling. A.E. Kiselev. 13-th CEG-SAM Meeting, March 5-7, 2008, Budapest, Hungary.

Main goal of the pre-test calculations was the PARAMETER-SF3 experiment scenario justification and development of requirements to measurement systems. On the basis of occur physical-chemical processes contribution assessment by SOCRAT and ICARE/CATHARE the electric power supply mode which results in the temperature scenario anticipated with the project collaborators is developed. It was shown that the hottest zone should be expected at the 1200-1300 mm elevations. Proposed flood scheme will allow getting data on bundle cooling down processes during top quenching.

7. Specification for numerical simulation of PARAMETER facility; Tests SF3 and SF4. T.A. Yudina. 13-th CEG-SAM Meeting, March 5-7, 2008, Budapest, Hungary.

To provide code users with technical information about PARAMETER facility Specification on simulation of PARAMETER facility is presented. Modifications of the facility, the bundle and the test section made for PARAMETER-SF3 experiment performance are shown. Special attention is devoted to description of a water injection system developed to realize top flooding and to description initial and boundary conditions (cooling jacket, bottom sections, thermal insulation). In the course of analysis of top flood experiments had been performed at PARAMETER facility spacer grids effects on cooling front propagation as well as peculiarities of facility design were found. Accordingly the recommendations to code users to account for these effects in nodalization scheme are given. To realize the PARAMETER-SF3 scenario that had been anticipated with the project collaborators an electric power supply mode is proposed. For comparison analysis of pre- and post-test numerical results by various codes a matrix of output calculated data is developed.

8. Status of the ISTC project #3690 on the “Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and -SF4 experiments). V.I. Nalivaev. 14-th CEG-SAM Meeting, September 9-11, 2008, Kiev, Ukraine.

The main results of the PARAMETER-SF3 experiment in the report are submitted:

- sequence of events of the test;
- input parameters of steam and argon;
- temperature of rod claddings;
- parameters of system of the top flooding.

During of test the following parameters have been achieved:

- input steam flow rate in the bundle ~3.5 g/s;
- input argon flow rate ~2 g/s;
- stabilization of parameters of preoxidation phase is carried out during 3970 s with temperature of claddings ~1200°C;
- at the transient phase the temperature of claddings up to 1600°C is achieved.

It is carried out the top flooding with flow rate ~40 g/s during 474 s of the bundle heated up to 1600°C.

9. Results of post-test examinations of SF2 fuel bundle and numerical simulations of the experiments PARAMETER-SF3 and -SF4. A. Kiselev. 14-th CEG-SAM Meeting, September 9-11, 2008, Kiev, Ukraine.

Status of results of PARAMETER-SF2 post-test investigation are shown. As well the presentation deals with the comparative analysis of the results of the PARAMETER-SF2 post-test and the PARAMETER-SF3 pre-test calculations performed by SOCRAT, ICARE, RELAP, PARAM-TG and ATHLET codes.

Need of PARAMETER-SF2 post-test calculations results from comparison of the PARAMETER-SF2 pre-test calculated results with the experimental data which reveals that experimental electric power at the pre-oxidation and the transient phase higher than calculated one. Post-test calculations were performed on the basis of the exact PARAMETER-SF2 experimental data on power history, mass flow rates, inlet temperature (except RELAP code). In the course of the PARAMETER-SF2 post-test calculations heat loss in the external resistances (leads and electrodes) and radial heat loss through the shroud poor known were improved. Heat loss in the external resistance is assessed to be about 1.5 kW at the pre-oxidation and the transient phases. Scattering in calculated Joule heating power doesn’t exceed 0.5 kW. Radial

loss through the shroud is assessed to be 1.5 1 kW.
All codes well reproduce temperature evolution of the bundle heated part besides the “hump” in experimental temperature at ~12000 s. Calculated maximal temperatures before flooding onset correspond to experimental one (~1770 K). RELAP code demonstrates too fast runaway at the transient phase, and earlier electric power switching off is needed to fit experimental maximum temperature.
At the flooding stage all codes predict practically no hydrogen release. Some hydrogen increasing in SOV-3 device indications at that phase might be result of time delay connected with hydrogen transport from source to the hydrogen measurement device. The best coincidence between experimental hydrogen mass and calculated one is achieved in the calculations by ICARE code for the entire experiment. 28 g of hydrogen mass was measured at the end of the experiment; ICARE demonstrates 25.5 g. ATHLET and SOCRAT codes show lower hydrogen release. One of the possible ways to improve the calculated results is based on the clarification of “hump” causes.
Input decks for PARAMETER-SF3 pre-test calculations were derived from the PARAMETER-SF2 post-test calculations and were adjusted to the special proposed initial and boundary conditions of the PARAMETER-SF3 test. The presentation is provided the analysis of heat balance and temperature over heated zone calculated by different codes. Presented data are used for justification of the test scenario.

10. Results of PARAMETER-SF2 material investigations. A. Kiselev. 14th International QUENCH Workshop, 4-6 November, 2008, Karlsruhe, Germany.

Results of the PARAMETER-SF2 bundle material investigations on the FA structural elements status with emphasis on cladding oxide scale, their measured thicknesses, zirconium dioxide thickness distribution over cross-sections and along heated zone are presented.
Visual inspection of the shroud revealed that it maintained integrity after the experiment; its external surface is covered with a thick zirconium dioxide layer. Its cracking during cutting off indicates significant oxygen content in the metal and possible zirconium hydrides formation.
Over 500…1300 mm elevations, claddings exhibit multilayer spalled off zirconium dioxide, its external layers detached partially from claddings, some of them were lost. Comparison of the material study results and thermocouple readings during the experiment suggests that so extended zone with breakaway effect was formed during the bundle preoxidation.
Over upper part of the bundle (900…1300 mm), internal layer of oxide scale represents a compact well connected with metallic substrate zirconium dioxide that would be grown at the transient phase. At the hottest zone, compact oxide demonstrates crack in azimuthal direction and tends to separation of its external part. One can conclude that the effect resulted from thermal shock during upper flooding. One can find cladding internal oxidation but it is weak.
Averaged oxide scale thickness estimation was done using metallic layer thickness measured. Oxide scale thickness increases as elevation raises, its maximum corresponds 1250 mm elevation (the hottest elevation).
Cladding metallic part over 900…1300 mm represents α phase stabilized

with oxygen (α - Zr (O)). Claddings is brittle (have through-wall cracks) but their fragmentation is limited. No fuel relocation and fuel-cladding interaction was observed.

11. Results of pre- and posttest calculations of PARAMETER-SF experiments. T. Yudina. 14th International QUENCH Workshop, 4-6 November, 2008, Karlsruhe, Germany.

Comparison analysis of numerical investigations of PARAMETER-SF2 and PARAMETER-SF3 tests performed in the framework of ISTC Project#3690 by the project participants (IBRAE, Hydropress, Kurchatov's Institute) and collaborators (GRS, PSI) is presented. Used codes were SOCRAT, ICARE/CATHARE, RELAP/SCDAPSIM, ATHLET-CD, SCDAP/RELAP/IRS which apply in reactor calculations.
For the both experiments, heat sources power over heated zone and effect of different kind of heat losses on the bundle temperature behaviour at different tests phases are analyzed. Calculated data on temperature and hydrogen release are presented as well.
Comparison of PARAMETER-SF2 calculated and measured data allows conclusion about adequacy of codes modeling of this test.
PARAMETER-SF3 pretest calculations with different codes reveal rather large scattering in hydrogen release (varies 13 g (SCDAP/RELAP/IRS) to 32 g (RELAP/SCDAPSIM)). It can be explained rather large scattering of predicted temperature to be 120-130 K at some elevations at preoxidation phase.

12. Status of the ISTC project #3690 on the "Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and PARAMETER-SF4 experiments); Results of PARAMETER SF3 experiment. V.I. Nalivaev. 15th CEG-SAM Meeting, 10-12 March 2009, Villigen, Switzerland.

1. Experiment PARAMETER-SF3 on simulating the initial stage of severe accident, including the stage of the top flooding, has been carried out.
2. The main parameters of experiment:
- the steam flow rate ~ 3.5 g/s at temperature ~ 500 °C;
- the argon flow rate ~ 2.0 g/s at temperature ~ 400 °C;
- the duration of the pre-oxidation stage ~ 3970 s at temperature ~ 1200 °C;
- the maximal temperature of the bundle - 1600°C at maximal heating rate ~ 0.5 °C/s.
3. The total of hydrogen measured by continuous monitoring systems of hydrogen (SOV-3), has not exceeded ~34 g.
4. The cooling overheated up to ~ 1600°C of the bundle has been achieved for ~ 470 s at the water flooding from top with flow rate ~ 40 g/s.
5. Conservation and preliminary cutting of the bundle has been carried out.

13. Results of PARAMETER –SF3 pre- and post-test numerical modeling. A. Kiselev. 15th CEG-SAM Meeting, 10-12 March 2009, Villigen, Switzerland.

Comparison analysis of PARAMETER-SF3 test numerical investigation performed in the framework of ISTC Project #3690 is presented. The calculations were done with SFD codes applied for severe accident analysis on NPP: SOCRAT, ICARE/CATHARE, RELAP/SCDAPSIM, ATHLET-CD, SCDAP/RELAP/IRS.

To estimate poor known values of external resistances and heat losses through thermoinsulation in PARAMETER facility that effect on calculation results, PARAMETER-SF2 posttest analysis was made.

Input decks for PARAMETER-SF3 pretest calculations were derived from ones for PARAMETER-SF2 posttest analysis considering PARAMETER-SF3 boundary conditions.

Predicted temperature deviation at preoxidation phase doesn't exceed 120-130 K for heated part except the elevations of 1000-1100 mm. The most codes indicate that the hot spot location would be at 1250 mm elevation, and it agrees with PARAMETER-SF2 test results. SCDAP/RELAP/IRS code calculates the hottest zone location lower (at 1100 mm elevation), and steep gradient in axial temperature profile at 1100-1300 mm elevations. Obviously, upper edge modeling of heated zone (including upper edge of thermoinsulation) done with SCDAP/RELAP/IRS code needs to be improved.

Predicted hydrogen production is estimated to be 13 g (SCDAP/RELAP/IRS) to 32 g (RELAP/SCDAPSIM). Such calculated mass deviation can be explained by deviation in predicted temperatures. Comparison of calculated total hydrogen mass and cladding oxide scale thickness indicates that oxidation model in ICARE/CATHARE code differs significantly from other ones regarding oxygen consumption in α-phase of zirconium.

Analysis of temperature data predicted by the codes allows concluding that proposed electric power mode in whole meets anticipated temperature scenario, but due to calculated temperature scattering with trend to underestimation of designed temperature, calculated electrical power correction would be needed during the experiment.

14. Post-test examination of the PARAMETER-SF2 and –SF3 fuel assemblies. T. Yudina. 15th CEG-SAM Meeting, 10-12 March 2009, Villigen, Switzerland.

Status of material investigations being performed in frame of ISTC project #3690 is presented.

In the first part of presentation the general information about results of SF2 bundle materials studies and overview of correspondent formal report are provided (scientific aspects of the investigations were discussed at 14th International QUENCH Workshop Karlsruhe, 4-6 November 2008). Correspondent report will be distributed among the collaborators at 15th CEG-SAM meeting, Switzerland.

In the second part preliminary results of SF3 material investigations are discussed for cross-sections at 800, 1000, 1250, 1300 mm. Briefly, they could be summarized as following:

- SF3 shroud was found failed, weak external oxidation (up to 15 µm) was revealed over 1100-1250 mm.
- SF3 bundle revealed pronounced breakaway oxidation of claddings, shroud, and peripheral rods at the elevations studied.
- Cladding oxide at 1250 and 1300 mm elevations consists of inner compact oxide with columnar structure and earlier grown fine multilayered oxide spalled off; at 800 and 1000 mm compact oxide was found on metallic substrate of some claddings.
- On metallic layer of some claddings at 1250 and 1300 mm, mixed

ZrO_2+αZr(O) layer was observed that probably formed due to transformation of unstable cubic modification into tetragonal form under precipitation of α-phase.

- Both peripheral rods and claddings oxide layer thickness distribution was inhomogeneous.
- Maximum location of cladding oxide thickness calculated on metallic layer thickness measured corresponds to the hottest zone (1300 mm).

15. Status of the ISTC project #3690 on the “Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and PARAMETER-SF4 experiments); Results of PARAMETER SF3 experiment. V.I. Nalivaev. 15th CEG-SAM Meeting, 10-12 March 2009, Villigen, Switzerland.

Objective of project: The study of behaviour of two 18-rods simulators fuel assembly VVER-1000 completed with standard constructional materials (constructional, fuel and absorber elements on basis of B_4C) under severe accident conditions at the top flooding.
The mane tasks of the Project:
Task 1. The first year of the Project
The study of change of structure of materials of fuel assembly VVER-1000 with absorber element under initial stage of severe accident conditions at the top flooding of assembly, heated up to temperature less 1250°C (PARAMETER-SF5):
- Preparation and carrying out of PARAMETER-SF5 experiment.
- Post-test the material analysis.
- Processing results of PARAMETER-SF5 experiment.

Task 2. The second year of the Project
The study of change of structure of materials of fuel assembly VVER-1000 with absorber elements under severe accident conditions at the top flooding of assembly, heated up to temperature less 1450°C (PARAMETER-SF6):
- Preparation and carrying out of PARAMETER-SF6 experiment.
- Post-test the material analysis.
- Processing results of PARAMETER-SF6 experiment.
- Preparation and release of the final report.

At realization of the Project:

- The information on behaviour of fuel assembly with absorber rod on a basis B_4C under accident conditions at the top flooding is received and systematized.
- Are investigated a degree of oxidation of cladding on length absorber rod depending on temperature and a degree of fusion of metal of the cladding directing pipes and materials of the absorber rod.
- The structure of the hardened mixes after running off fusion is received.
- The database for verification accident codes (SOCRAT, ATHLET, ICARE-CATHARE, etc.) is expanded.

The received results can be used for a substantiation of safety of reactors such as VVER (PWR).
Participants of the Project
The mane participants:
FSUE SRI SIA “LUCH” – carrying out of experiments, post-test

calculation and material analysis;
IBRAE RAS – development of scenario of experiments, the pre-test and post-test analysis;
OKB "GIDROPRESS" – development of scenario of experiments, the analysis of a degree of conformity of experiments, pre-test and post-test analysis.

Leading experts of the organizations:
VNIINM, SRC RF - IPPE, RRC "Kurchatov institute", Open Society «Moscow factory of polymetals».

Time of realization of the Project - 24 months. The expected volume of financing - $ 600 thousand.

16. Experimental results of complex starting-up and adjustment actions on preparation of the PARAMETER-SF4 Experiment. V.S. Konstantinov. PARAMETER Status Meeting. 29 July, 2009, Podolsk, Russian Federation.

In the report are submitted results of complex starting-up and adjustment actions on preparation for PARAMETER-SF4 experiment on studying behaviour 19-rods bundle of VVER-1000, by the completed standard constructional materials, under accident conditions are submitted at input of air and bottom flooding.

The complex of actions included:
- Definition of parameters of system of the bottom flooding;
- Installation of the flow rate of argon;
- Working off of system of steam generation;
- Working off of system of the analysis of oxygen

Parameters are experimentally fulfilled:
- The coolant - steam / argon;
- Parameters of the coolant:
  Steam – 3.5 g/s (500±50°C);
  Argon – 2 g/s (280±20°C);
  Air (20%O_2+80%N_2) – 0.5 g/s;
- Speed of heating of rods – ~ 0.5 K/s;
- The maximal cladding temperature – ~700 K.

Readiness for carrying out of experiment PARAMETER-SF4 is reported.

17. Preliminary results of the PARAMETER-SF4 test. V.I. Nalivaev. PARAMETER Status Meeting. 29 July, 2009, Podolsk, Russian Federation.

The PARAMETER-SF4 experiment was performed on July 21, 2009 at PARAMETER test facility.

The objective of PARAMETER-SF4 experiment: The investigation of behavior of a 19-rods model fuel assembly (FA) of VVER-1000, completed with standard reactor structural materials (fuel rod claddings of alloy Zr+1%Nb, fuel pellets of uranium dioxide, spacer grids and shroud of alloy Zr+1%Nb), under conditions of severe accident (T_{FA} = 1750°C) with air ingress and following bottom flooding

The main parameters of experiment:
- the steam flow rate ~ 3.5 g/s at temperature ~ 500 °C;
- the argon flow rate ~ 2.0 g/s at temperature ~ 280 °C;
- the duration of the pre-oxidation stage ~ 6000 s at temperature ~ 1200 °C;
- the air (20%O_2+80%N_2) flow rate ~ 0.5 g/s;
- the maximal temperature of the bundle - 1750°C.

The cooling overheated up to ~ 1750°C of the bundle has been achieved for ~ 470 s at the water flooding from bottom with flow rate ~ 80 g/s.

18. PARAMETER-SF4 pretest calculations. D.Tomashchic. PARAMETER Status Meeting. 29 July, 2009, Podolsk, Russian Federation.

Main results of variant calculations performed to optimize PARAMETER-SF4 test scenario are presented and analyzed. Fitted parameters were air ingress, argon ingress, steam ingress, and electrical power. All calculations were performed with integral codes applied for severe accident analysis at NPP:

- SOCRAT, ICARE/CATHARE, RELAP/SCDAPSIM – by the project participants,
- ATHLET-CD, SCDAP/RELAP/IRS, MAAP4 - by the project collaborators.

Comparison analysis of final calculations with air flow rate to be 0.5 g/s and electrical power to be 5.5 kW at air ingress phases is presented. Most codes predict hot spot shift to 700-500 mm. Some codes with air oxidation models predict short term cladding escalation up to 2000°C at flooding stage. SOCRAT code predicts peripheral rods to achieve zirconium melting point at 500-900 mm at quenching stage due to oxide scale dissolution under oxygen starvation conditions. Hydrogen production at flood stage is about 5 g, but may be higher (30-60 g) if bundle temperature achieves zirconium melting point and direct contact of melt with steam takes place.

19. Pretest studies of PARAMETER SF4 scenario with ICARE/CATHARE V2. A.Volchek, Yu. Zvonarev, O.Coindreau (IRSN), F. Fichot (IRSN). PARAMETER Status Meeting. 29 July, 2009, Podolsk, Russian Federation.

Coupled ICARE/CATHARE code, developed by IRSN, is used in NSI RRC KI for interpretation of available experimental data and for the analyses of accident transients on VVER-type NPPs. In the frame of ongoing ISTC project on PARAMETER SF experimental series NSI RRC KI contributed to the code validation with a number of examinations of previous tests from SF1 to SF3. The planning experiment for 2009 was the experiment SF4 with air ingress after substabtial steam oxidation phase realized on high temperature plateau. Basing on recently developed at IRSN model of Zirconium oxidation in air it was decided by IRSN and NSI RRC KI experts to provide help to SIA “LUCH” experimental team (Podolsk, Russia) in the elaboration of the PARAMETER SF4 experimental test protocol.
Following the goal, a number of ICARE/CATHARE V2 simulations were performed by NSI RRC KI in order to predict and verify the likely key-events and parameters. For pretest the following parameters were considered: input mass flow rates, starvation period, axial temperature profile etc. Our examination with ICARE/CATHARE allowed obtaining following results for pretest studies:
Air oxidation model switch off

- When steam is switch off then the temperature increases up to 2100 K in 2000 seconds;
- The hottest zone is shifted to lower elevations;
- Maximum temperatures can be obtained at 1100 mm due to low coolant flow;
- At low electrical powers (973 K) the temperatures of air injection

phase may be too low for intensive air oxidation reaction;
- Temperatures at air injection phase are very sensitive to variation of electrical power.

Air oxidation model switch on
- Air oxidation reaction firstly started at hottest elevations;
- Peak of the air oxidation in simulation was shifted to much lower region (between 500 and 600 mm) - starvation conditions;
- Preliminary experimental finding**:** Peak of the air oxidation at 500 mm;
- Before quenching temperature rate growth was up to 6 K/s;
- Predicted oxide scale thickness - relatively small increase at initially heated zone (900 – 1300 mm);
- Initial ZrO_2 thickness in sharp escalation zone ~ 50 μm.

The results obtained allowed to provide recommendations to "LUCH" experimentalists regarding test scenario. The test scenario was approved as a result of cooperation of research groups from different countries, with frequent and direct exchanges between Institutes involved in analytical support and LUCH experimental team.

20. Studies of VVER-1000-type fuel rods under BDBA conditions with top, bottom and combined flooding in the PARAMETER facility. Degtyareva L.S., Konstantinov V.S., Nalivaev V.I., Parshin N.Ya., Kiselev A.E., Yudina T.A., Semishkin V.P. International scientific and technical meeting «Computational and experimental studies of LWR fuel element behavior under beyond design basis accidents and reflood conditions», July 27-28, 2009, IBRAE RAS, Moscow, Russian Federation,

Main results of experimental investigations of VVER-1000-type fuel bundles under BDBA conditions are in focus of the presentation. The tests are performed at the PARAMETER facility under analytical support of IBRAE RAS and OKB "GIDROPRESS".

Three VVER-1000-type bundles made up of 19 fuel rods were tested under BDBA conditions in the framework of ISTC Project.

The test protocol provided the following phase:
- preliminary one to stabilize designed steam and argon flow rates at bundle temperature ~500°C;
- heat up of bundle to temperature ~1200°C to grow claddings oxide thickness ~200-250 μm;
- heat up of bundle to target temperature provided by test scenario;
- flooding.

In the first of three experiments (PARAMETER-SF1), a bundle was heated up to maximum temperature over 2000°C and then was quenched with water from top. In the second test (PARAMETER-SF2), a bundle was preoxidized as well but maximum temperature at transient phase was reduced to 1500°C and flooding of bundle from top and bottom was realized. The third bundle (PARAMETER-SF3 test) was heated up to 1600°C to avoid bundle elements melting and was quenched with water from top. After testing, the bundles were encapsulated by filling with epoxy for subsequent material investigations.

Performed tests demonstrated strong effect of melt on hydrogen release, it allows conclusion that BDBA can be managed if temperature does not exceed zirconium melt point (2000°C). Material studies results will supplement the data base to verify numerical codes under tested temperature conditions.

21. Status of the ISTC project #3690 on the "Fuel assemblies behaviour under severe accident top quenching conditions in the PARAMETER-SF test series (PARAMETER-SF3 and PARAMETER-SF4 experiments); Results of PARAMETER-SF4 experiment. V.I. Nalivaev. 16th CEG-SAM Meeting, September 8-9, 2009, Moscow, Russian Federation.

The objective of PARAMETER-SF4 experiment: The investigation of behavior of a 19-rods model fuel assembly (FA) of VVER-1000, completed with standard reactor structural materials (fuel rod claddings of alloy Zr+1%Nb, fuel pellets of uranium dioxide, spacer grids and shroud of alloy Zr+1%Nb), under conditions of severe accident (T_{FA} = 1750°C) with air ingress and following bottom flooding.

At preparation of experiment:
1. It is made and established in the PARAMETER facility the 19-rods bundle VVER-1000 for carrying out of the PARAMETER-SF4 experiment under severe accident, including stages of ingress of air and a bottom flooding.
2. Submission of argon flow (Garg = 2 g/s, Targ = 280±20°C) and steam flow (Gst = 3,5 g/s, Tst = 500±50°C) in the test bundle is provided.
3. The system of bottom flooding (Gbf = 80 г/c flow rate) of test bundle is checked up.
4. The system of ingress (Gair=0.5 g/s) of air (20%O_2+80%N_2) in the test bundle is checked up.
5. Calibration of system of the gas analysis on reference gas mixes (Ar+XH_2, X = 5,56; 10,4; 22,3; 39,2; 41,1 %v.) is carried out.

July 21, 2009 PARAMETER-SF4 experiment has been carried out.
The main parameters of experiment:
- the steam flow rate ~ 3.5 g/s at temperature ~ 500 °C;
- the argon flow rate ~ 2.0 g/s at temperature ~ 280 °C;
- the duration of the pre-oxidation stage ~ 6000 s at temperature ~ 1200 °C;
- the maximal temperature of the bundle - 1750°C.

The cooling overheated up to ~ 1750°C of the bundle has been achieved for ~ 470 s at the water flooding from bottom with flow rate ~ 80 g/s.
Conservation and preliminary cutting of the bundle has been carried out.

22. Results of PARAMETER–SF3/SF4 pre- and post-test numerical modeling. D. Tomashchic. 16th CEG-SAM Meeting, September 8-9, 2009, Moscow, Russian Federation.

Main results of variant calculations performed to optimize PARAMETER-SF4 test scenario are presented and analyzed. Fitted parameters were air ingress, argon ingress, steam ingress, and electrical power. All calculations were performed with integral codes applied for severe accident analysis at NPP:

- SOCRAT, ICARE/CATHARE, RELAP/SCDAPSIM – by the project participants,
- ATHLET-CD, SCDAP/RELAP/IRS, MAAP4 - by the project collaborators.

Comparison analysis of final calculations with air flow rate to be 0.5 g/s and electrical power to be 5.5 kW at air ingress phases is presented. Most codes predict hot spot shift to 700-500 mm. Some codes with air oxidation models predict short term cladding escalation up to 2000°C at flooding stage. SOCRAT code predicts peripheral rods to achieve zirconium melting point at 500-900 mm at quenching stage due to oxide scale dissolution under oxygen starvation conditions. Hydrogen production at flood stage is about 5 g, but may be higher (30-60g) if bundle temperature achieves zirconium melting point and direct contact of melt with steam takes place.

23. Post-test examinations of the PARAMETER-SF fuel assemblies. T. Yudina. 16th CEG-SAM Meeting, September 8-9, 2009, Moscow, Russian Federation.

Brief overview of current state of ISTC Project#3690 regarding material investigation is presented.
The first part of the presentation contains general information on PARAMETER-SF2 fuel bundle material studies.
In the second part, PARAMETER-SF3 bundle material investigation results are discussed. They can be summarized as follow:

- SF3 shroud was found failed, weak external oxidation (up to 15 µm) was revealed.
- 13 SF3 bundle cross-sections over 400-1500 mm elevations were examined.
- SF3 claddings, shroud, peripheral rods reveal pronounced breakaway oxidation. Cladding oxide scale over 900-1300 mm includes inner compact oxide with columnar structure on the metallic layer and external multi-layer spalled off oxide.
- Weak cladding internal oxidation.

Metal layer, compact oxide thicknesses were measured for claddings, peripheral rods, shroud, heaters, electrodes at examined elevations.

24. Short overview on the PARAMETER program at LUCH. A. Kiselev. 15th International QUENCH Workshop, November 3-5, 2009, Karlsruhe, Germany.

Short overview of experiments conducted at PARAMATER Facility is presented. Capability of PARAMATER facility (FSUE EDO LUCH) allows performing of fuel bundle testing under conditions that are very close to calculated ones in VVER-like core during both design basic and beyond basic accidents. In the framework of ISTC Projects, PARAMETER-SF1, -SF2, -SF3, and -SF4 tests series was done. The experiments were executed with aim of studying of VVER-1000 fuel bundle made up of 19 fuel rods under severe accident conditions including low rate cooling down phase during quenching from top and bottom, and namely:

- investigation of the bundle structure components (fuel pellets and claddings, shroud, spacer grids);
- investigation of oxidation degree of the bundle structure components;
- investigation of material interaction and structure-phases change (fuel pellets and claddings);
- investigation of hydrogen release.

Data obtained at PARAMATER facility can be include in data basis for verification of best estimation SFD codes.

25. Post-test examination of the PARAMETER-SF4 fuel assembly. D. Ignatiev. 15th International QUENCH Workshop, November 3-5, 2009, Karlsruhe, Germany.

Эксперимент SF-4 и предварительные посттестовые материаловедческие исследования проведены в соответствии с рабочим планом проекта МНТЦ # 3690 «Исследование модельных ТВС в условиях тяжелой аварии с заливом сверху в серии экспериментов PARAMETER SF».

Эксперимент SF-4 был проведен с целью исследования поведения 19-твэльной модельной ТВС ВВЭР в имитационных условиях тяжелой аварии включая доступ воздуха и залив сверху, а именно:

- Исследование поведения структурных компонент 19-твэльной модельной ТВС ВВЭР-1000 в условиях доступа воздуха и залива сверху.
- Исследование степени окисления структурных компонент 19-ти твэльной модельной ТВС ВВЭР-1000.
- Исследование взаимодействий и структурно-фазовых превращений в материалах модельной ТВС ВВЭР-1000 (топливные таблетки и оболочки).
- Исследование динамики выхода водорода.

Основные результаты предварительных материаловедческих исследований четырех поперечных сечений (Z = 130, 260, 300 и 1200 мм) следующие:

- На уровне 130 мм разрушения отсутствуют. Конфигурация сборки сохранилась. Толщина оксидного слоя составляет 5…10 мкм.
- На уровне 260 мм стекшие массы металлического расплава (U,Zr,O) образовали блокировку, которая заполнила практически все проходное сечение. Этот расплав имеет разные оттенки и сетку трещин. Взаимодействие с расплавом происходило как снаружи, так и изнутри оболочек.
- На уровне 300 мм были обнаружены только два фрагмента твэла, причем топливо их было частично растворено. Больше никаких конструкционных или топливных элементов обнаружено не было. Присутствующий расплав существенно отличается от металлического (U,Zr,O) по цвету и макроструктуре (очень высокая пористость). Расплав имеет сложный состав, поскольку танталовые нагреватели и теплоизоляция ZrO_2 растворены.
- На уровне 1200 мм (верх нагреваемой зоны) сборка слабо сохранила первоначальную конфигурацию. Топливные стержни (12 из 18) существенно повреждены из-за окисления оболочек, расплавления и растворения топлива. Обечайка и периферийные стержни были расплавлены и разрушились. В сечении обнаружены только остатки оксида с поверхности обечайки. Целостность оставшихся твэлов сохранена лишь за счет нагревателей.

26. Comparison results of pretest PARAMETER-SF4 test numerical modeling. T.Yudina. 15th International QUENCH Workshop, November 3-5, 2009, Karlsruhe, Germany.

In July 2009 year in the framework of ISTC Project #3690 at PARAMETER facility at FSUE EDO LUCH, PARAMETER-SF4 experiment aimed at study of VVER fuel bundle behaviour under severe accident conditions with

air ingress was conducted. Comparison analysis of SF4 pretest calculations done to determine the test scenario is presented; the scenario acceptable criteria are discussed. All runs were performed with integral codes applied for reactor calculations: SOCRAR, ICARE/CATHARE, RELAP/SCDAPSIM, ATHLET-CD, SCDAP/RELAP/IRS, and MAAP4.
For analysis of the codes capability to treat main phenomena that is important in severe accident including air oxidation, correspondent measured data are presented. It was demonstrated that the bundle behaviour predicted at all phases corresponds to the test data except for flooding stage. To analyze processes occurred at flooding stage, numerical investigations with the boundary conditions that is corresponds exactly to the test ones are needed.

27. Main results of RELAP/SCDAPSIM calculation analysis of the PARAMETER-SF experiments. V.V. Shchekoldin, V.P. Semishkin. 15th International QUENCH Workshop, November 3-5, 2009, Karlsruhe, Germany.

The experiments at PARAMETER facility devoted to research of bundle flooding processes at rod cladding temperatures above 1600 K. Experiments with bottom, top, and both flooding were done.
Main objective of participation in this experimental program is performing RELAP/SCDAPSIM MOD3.2 (RELAP) calculations in order to assess its capabilities in area of VVER type reactor modelling. The calculation results were used in developing of experimental scenarios.
Results of pre- and post-test analysis of SF1, SF2 and SF3 experiments using RELAP/SCDAPSIM MOD3.2 are presented in the paper. It is stated as a result of calculated and experimental data comparison that RELAP is capable to model main phenomena in the experiments such as: zirconium oxidation, temperature changes, flooding, hydrogen generation. Steam flow rate, power supplied, geometry, code parameters impact on bundle temperatures and other results are analysed basing on calculations performed.
RELAP code applicability for VVER type rod bundles and issues of experimental and calculation results extending to real plant are considered in the paper. In particular, it is stated based on experimental data of flooding the bundle heated up to 1800 K that there is a possibility to flood from the top a core heated up to such temperatures.
The work done allows to significantly improve methodology of VVER severe accident analysis using RELAP/SCDAPSIM, it also allows to adopt the code capabilities for this type of reactor.

Attachment 3: Information on patents and copy rights

Copy rights which may be obtained as a result of the project:

1. Information on the behaviour of structural components of 19-rods model FA of VVER-1000 overheated to ~ 1600°C during top quenching;

2. Information on the temperature behaviour of the model FA of VVER-1000 under the conditions of air oxidation and subsequent bottoms quenching.