INTERNATIONAL SCIENCE & TECHNOLOGY CENTER

THE PROJECT 1648.2

"Examination of the VVER fuel behavior under the severe accidents. Reflooding stage"

Annual report 2005

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Content

STAGE A. Spent ROD-QUENCH

Introduction

The core reflood is one of the ways to terminate the LOCA accident at the VVER reactors. During the reflood the oxidized fuel rods are subjected to the thermal shock that leads to the additional fuel rod cladding damage and hydrogen generation that cause the risk of explosive gas mixture formation in the containment. The Karlsruhe Research Center (FZK) implements the QUENCH Program on examination of the PWR fuel rods behavior under the core flooding conditions [1]. In the frame of ISTC 1648.2 Project the similar investigations are planned with regard to VVER fuel rods. The 1648.2 Project Stage A "Spent ROD-QUENCH: Examination of the behavior of the irradiated fuel rod fragments under the re-flooding conditions", is aimed at investigation of performance of VVER-1000 spent fuel rod simulators with a burnup of 45-50MW*d/kgU as well as hydrogen generation under the simulated core reflood conditions. These tests are planned to create a database complimentary to the data on fresh fuel rod simulators to be obtained during the large-scale test at the QUENCH facility at FZK also planned in the frame of ISTC 1648.2 Project. On the test rig trial run stage the tests with fresh fuel rod simulators are planned with aim of adjustment of the test regimes and obtain the reference data with respect to following tests with irradiated simulators and comparison with the similar tests being fulfilled at FZK.

In this report the results of the first trial run tests with unirradiated fuel rod simulators those show the created test rig performance are given.

1. Preparation of specimens

The test specimens (Fig. 1) were made of a certified fuel rod tube of E110 alloy filled with genuine VVER-1000 pellets of unirradiated uranium dioxide. The tube length was of 150 mm, outer diameter – 9.1 mm, wall thickness – 0.69 mm. The outer diameter of the fuel pellet was of 7.56 mm, diameter of the central hole – 2.4 mm and the average pellet height – 11 mm. The end plugs were welded to the tube ends to attach the specimen to the suspension and hold fuel stack. Prior to the specimen fabrication, the claddings were oxidized in the oxygen-argon medium at 1200 °C during 100 s to prevent the formation of eutectic with the material of thermocouples. According to the weighting and metallography, the oxide film thickness made up 10-20 μm.

Fig. 1. Preliminary oxidized specimen appearance before the test

The specimen was fixed to the suspension so as to move it during the experiment. Each specimen was equipped with four thermocouples. To measure the temperature in the center of the fuel column, a W/Re shielded thermocouple of 1.6 mm in diameter located in the central hole at the half-height of the fuel stack (75 mm) was used. Unshielded Pt/Rh thermocouples were installed at the elevations of 25, 75 and 125 mm at the cladding outer surface. The diameter of TC electrodes was of 0.2 mm. Junction of thermocouples were fixed to the specimen with Pt/Rh wire.

2. Test rig and test conditions

The simplified diagram of the test rig is shown in the figure 2. The test rig comprises a heating unit with a flooding tank, gas lines, steam generator, system of specimen displacement and computer system to control the experiment.

The heating unit is based on the resistive heating furnace. A ceramic tube with a specimen inside is used as a unit operating channel. The specimen is located vertically. The operating channel is located in a tubular molybdenum heater surrounded with heat shields and thermal insulation. The specimen is flooded by means of its movement into the flooding tank filled with water at a prescribed speed up to the complete immersion.

In the Figure 3 the temperature distribution along the specimen in the heating unit under the stationary conditions is shown. The temperature distribution is symmetrical with regard to the temperature maximum that coincides with the specimen center. The temperature gradient along the specimen does not exceed 72 °C at the central cross-section temperature of 1400 °C.

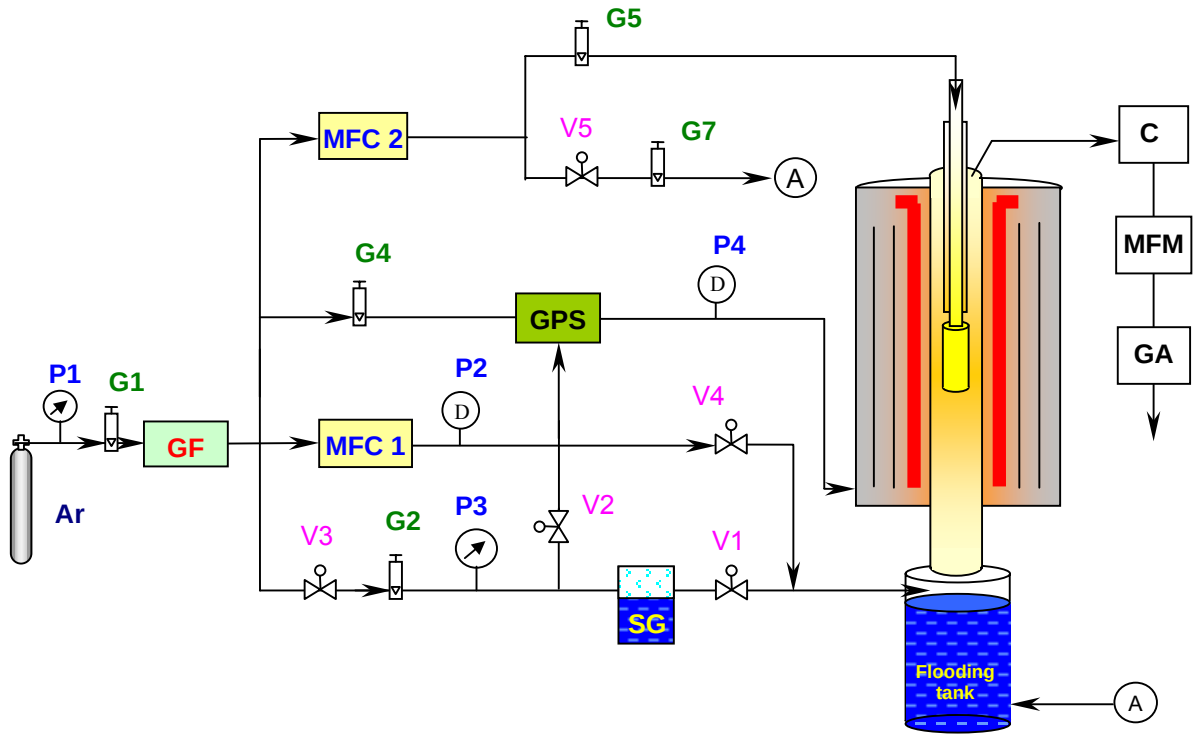


Fig. 2. Test rig diagram.

GF – getter filter; P1, P3 – pressure gauges; P2, P4 – pressure sensors; G1 – G7 – flowmeters; V1 – V5 – electromagnetic valves; MFC 1, MFC 2 – mass flow meter/controller; MFM - mass flow meter; SG – steam generator; C – condenser; GA – gas analyzer, GPS – gas pressure stabilizer.

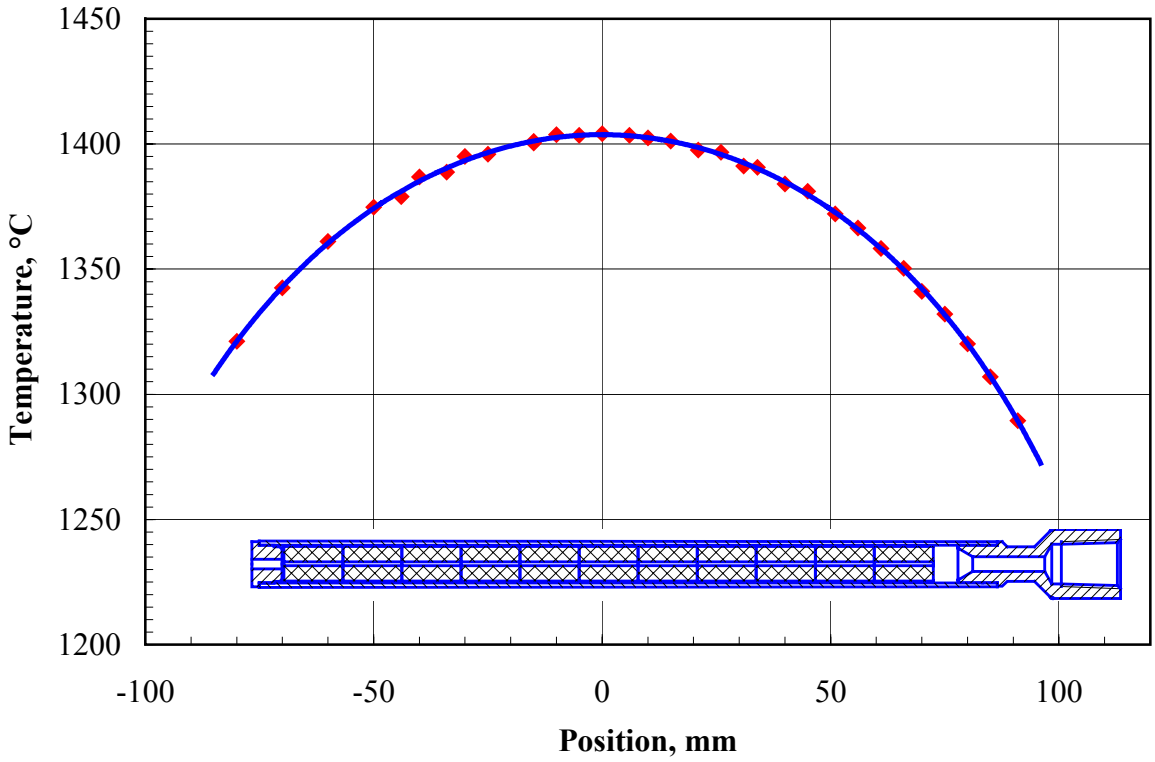


Fig. 3. Temperature distribution along the heating unit.

The hydrogen concentration in the carrier-gas (argon) was measured by means of the gas analyzer with error of ±5%. The gas pressure stabilizer was used in the gas lines to maintain the pressure differential between the channel and heater cavity to prevent the steam penetration to the heater. The inner volume of the suspension and specimen was purged with argon with a flow rate of about 300 ml/min. The purging was switched off at the beginning of the suspension movement.

So as to simulate the flooding conditions, the suspension with specimen was moved by step motor and under the control of the experiment control system. The specimen was quickly (1 s) moved from the heater area to the flooding tank and then it was immersed slowly (15 mm/s) into water at a depth of 160 mm.

The facility allows the following experiment procedure to be implemented:

1. specimen is heated up to 600 °C in the inert medium (argon);
2. steam is supplied with a flow rate of about 0.04 g/s with the following temperature rise up to 1400 °C and heating rate of about 1.5 °C/s;
3. specimen is subjected to isothermal exposure at 1400 °C in the steam-argon medium within the prescribed period of time to achieve the target oxide film thickness;
4. steam supply from the steam generator is switched off and the flooding temperature at the heat up rate of about 1.5 °C/s is achieved;

5. specimen is dropped into the flooding tank at a rate of 245 mm/s and the heater is switched off;
6. specimen is immersed into water heated up to 90 °C at a rate of 15 mm/s.

3. Test results

The test with the preliminary oxidation of simulator in the steam-argon medium within 800 s and a flooding temperature of 1400 °C was performed (sample 1). Two experiments were performed with the preliminary oxidation during 240 s and flooding temperature of 1600 °C (samples 2, 3). In Figure 4 the temperature conditions and hydrogen concentration in the carrier-gas during the tests are shown. The temperatures on the cladding surface and in the simulator fuel column center as well as hydrogen generation rate during the flooding are shown in Figure 5. The moment of steam supply starting is taken as a zero coordinate of abscissa in Figures 4-6. The lower thermocouple on the cladding of sample 3 failed at the beginning of the experiment and two other thermocouples failed during the sample flooding. The hydrogen rate shown in Fig.5 is plotted in consideration of gas delivery time to the analyser.

During heating up to flooding temperature the steam supply from the steam generator was terminated but the operating channel medium still contained a small amount of steam due to water evaporation in the flooding tank. It contributed to a certain degree to the generation of oxide film and hydrogen release for samples 2 and 3.

The integral hydrogen release during the experiment is presented in Figure 6. The hydrogen release curves have the similar shape at the oxidation stage that is good evidence of the oxidation conditions reproducibility. As compared to the experiments performed at FZK using the facility with inductive heating and cooling of specimens by steam[2], an obvious increase of the hydrogen concentration can be observed in the carrier gas during the specimen flooding. The experimental conditions and sample test results are listed in the following.

The experiments being finished, the samples were subjected to visual control (Fig. 7). Samples No 1 and 2 did not damage during the test. Sample No3 is damaged; the fracture line is at 7-10 mm from the lower end.

The samples had glittering light-gray pinkish exfoliating oxide film. Black uniform oxide film can be seen on the areas where the light film exfoliated. When the end plugs of sample 1 were cut off and the fuel was removed, there are remain several pellets in the cladding coherent tightly with the cladding. At the sample 1 elevation of 60mm there was a transversal crack extending the half of the perimeter. As for samples 2 and 3, no visible cracks were revealed. The uranium dioxide pellets remained intact and no cracks were revealed.

Cotton plugs wetted with acetone were used to visualize the through cracks in the cladding. Sample 1 had a net of cracks in the center. One transversal through crack was revealed in sample 2.

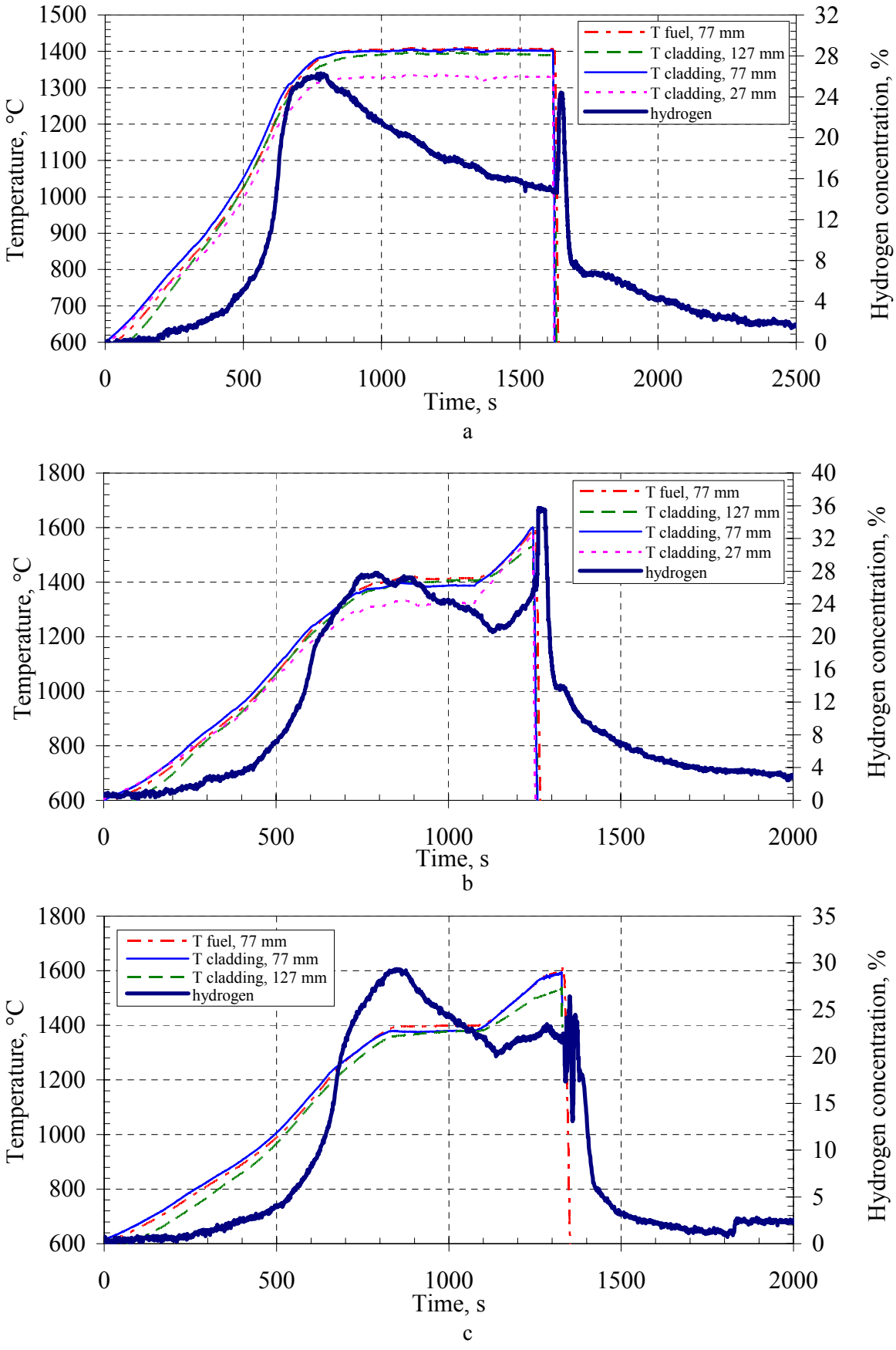
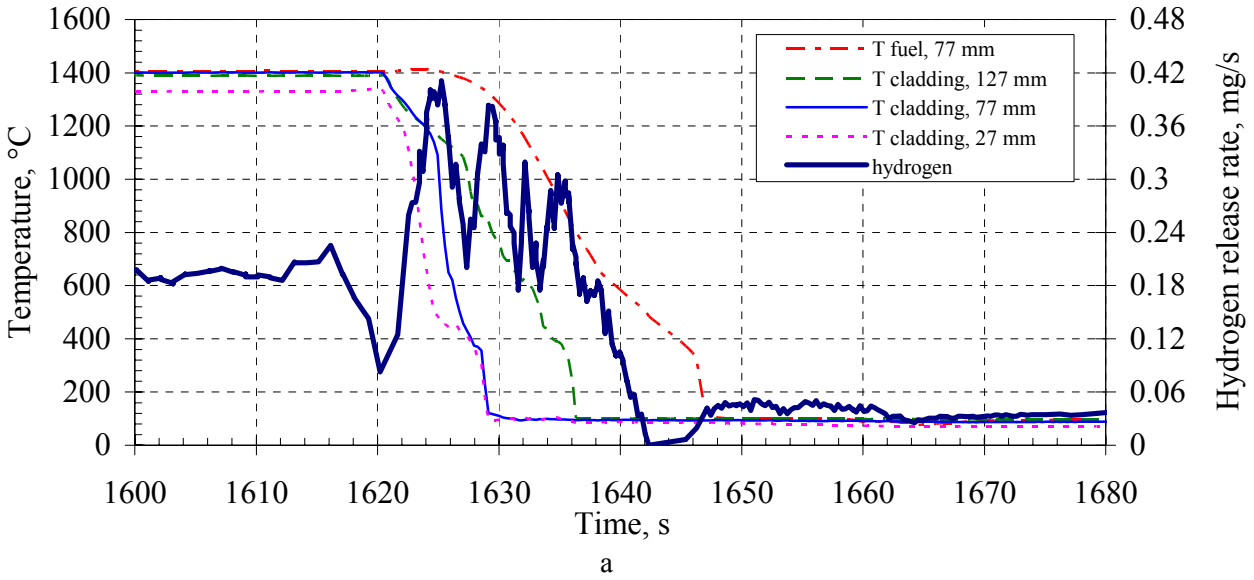
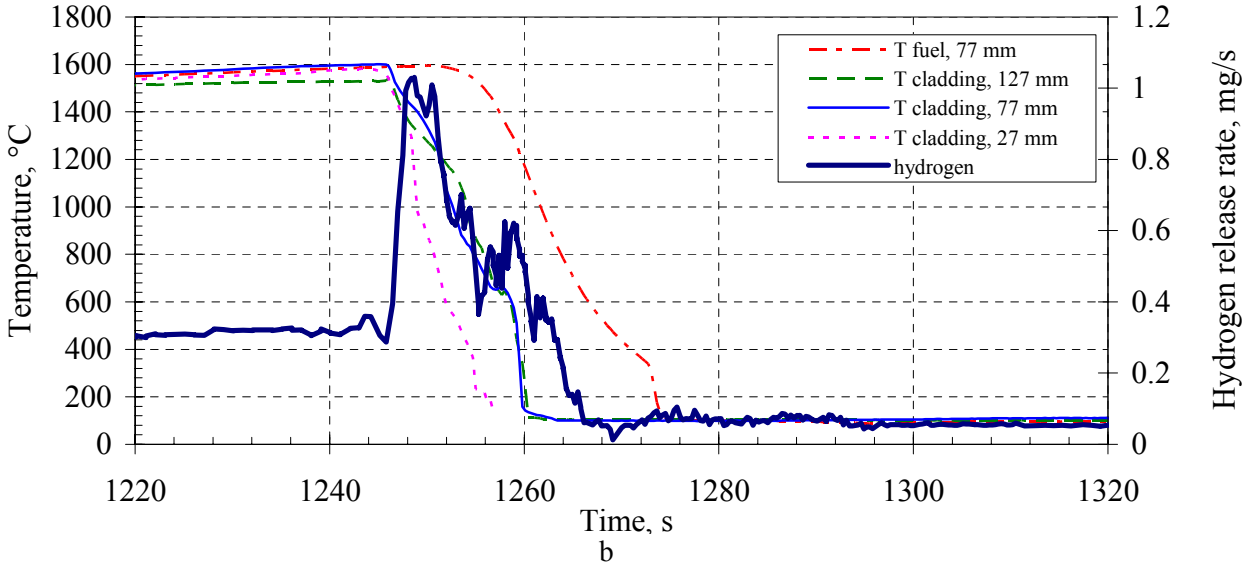


Fig. 4. Temperature and hydrogen concentration

experiment with sample 1, oxidation time 240 s, flooding temperature 1400 °C (a), experiment with sample 2, oxidation time 800 s, flooding temperature 1600 °C (b), experiment with sample 3, oxidation time 800 s, flooding temperature 1600 °C (c).





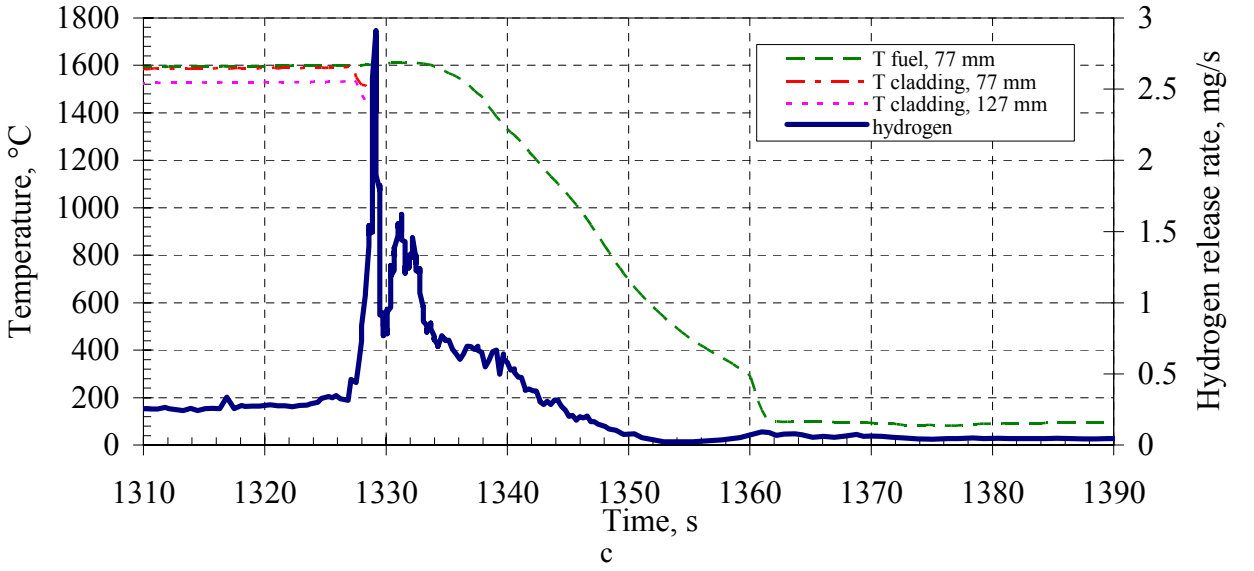


Fig. 5. Temperature and hydrogen release rate at the flooding of simulator in experiment with sample 1, oxidation time 240 s, flooding temperature 1400 °C (a), in experiment with sample 2, oxidation time 800 s, flooding temperature 1600 °C (b), in experiment with sample 3, oxidation time 800 s, flooding temperature 1600 °C (c).

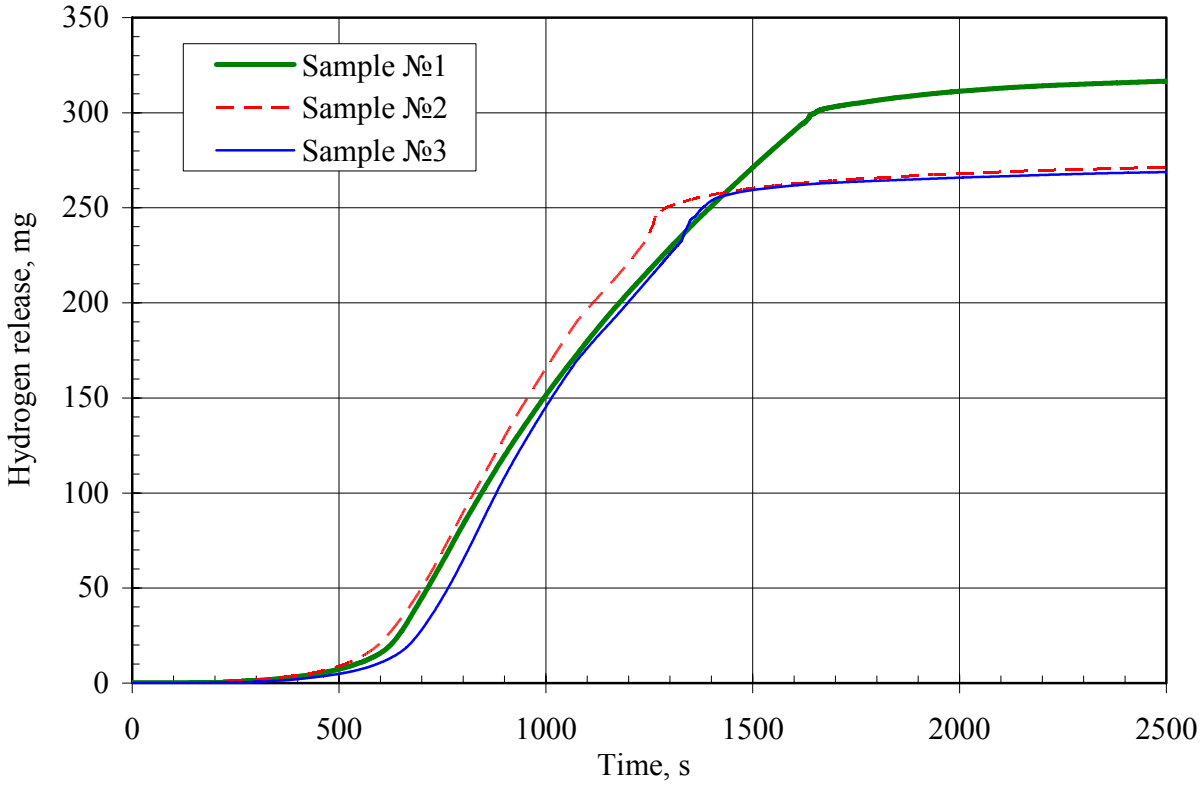


Fig. 6. Integral hydrogen release

Table 1

Experimental conditions and results

No of sample		**1**	**2**	**3**
Oxidation time at 1400 °C, s		800	240	240
Flooding temperature, °C		1400	1600	1600
Total hydrogen release, mg		320	276	270
Hydrogen release at flooding, mg		25	35	38
ECR, %		32	30	-
Thickness of ZrO_2 outer layer along the sample*, μm	**top**	202	183	-
	center	201	216	-
	bottom	167	165	-
Cladding metal thickness along the sample *, μm	**top**	581	591	-
	center	574	571	-
	bottom	591	602	-

* - the section coordinate is given from the sample lower end
Sample No1: upper cross-section 114 mm, central cross-section 57 mm, lower cross-section 27 mm.
Sample No2: upper cross-section 127 mm, central cross-section 77 mm, lower cross-section 27 mm

Samples 1 and 2 were cut in fragments for metallography and ECR determination. When cutting sample No1 by diamond disk, brittle fracture of the cladding was observed as compared to sample No 2. Some non-oxidized rough areas can be seen on the inner surface of fragments. They are oriented along the sample axis and probably resulted from the fuel-to-cladding interaction.

The ECR was determined on a fragment (sub-sample) cut off from the cladding center of samples No1 and 2 according to the results of the sub-sample mass increment at its complete oxidation up to stoichiometric zirconium dioxide

$$ECR = \left(1 - \frac{\Delta m_{ex} \cdot \mu_{Zr}}{2 \cdot l_{sub} \cdot \rho_l \cdot \mu_O}\right) \cdot 100\%$$

where: Δm_{ex} – sub-sample weight gain during extra oxidation, g;

l_{sub} – sub-sample length, mm;

m_{sub} – sub-sample mass; g;

ρ_l - cladding linear density, g/mm;

μ_{Zr} , μ_O – molar mass of zirconium and oxygen, respectively, g/mol

To determine, the sub-samples were selected at the coordinates of 67-86 mm and 85-107 mm along the samples No1 and 2 correspondingly. The ECR determination results of the tested samples No1 and 2 are presented in table 1.

The metallography was performed in three cross-sections at the elevations 27, 57 and 114 mm for sample 1 and 27, 77 and 127 mm for sample 2 (Fig. 8). Figure 7 presents a cross-section of sample 1 with a pellet coherent tightly with the cladding. The cracks in the cladding are observed in the areas of tight contact with fuel.

Figures 9 and 10 present the sample cladding structures after tests. The solid oxide film without any tangential cracks is observed on the samples. In the cladding of both samples there are radial cracks spreading from the inner surface to the outer oxide film. The majority of cracks end in the oxide layer. There are no any oxide films on the crack surfaces. The thickness of oxide films and metal part of the cladding is presented in Table 1.

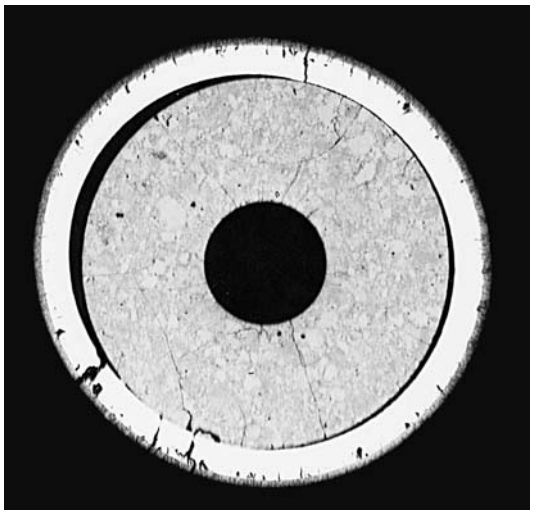


Fig. 7. Cross-section of sample No1 with a pellet coherent tightly with the cladding (57 mm).

Sample No1
Oxidation time 800 s,
flooding temperature 1400 °C

Without crack visualization With crack visualization

Sample No2
Oxidation time 240 s,
flooding temperature 1600 °C

Without crack visualization With crack visualization

Sample No3
Oxidation time 240 s,
flooding temperature 1600 °C

Without crack visualization

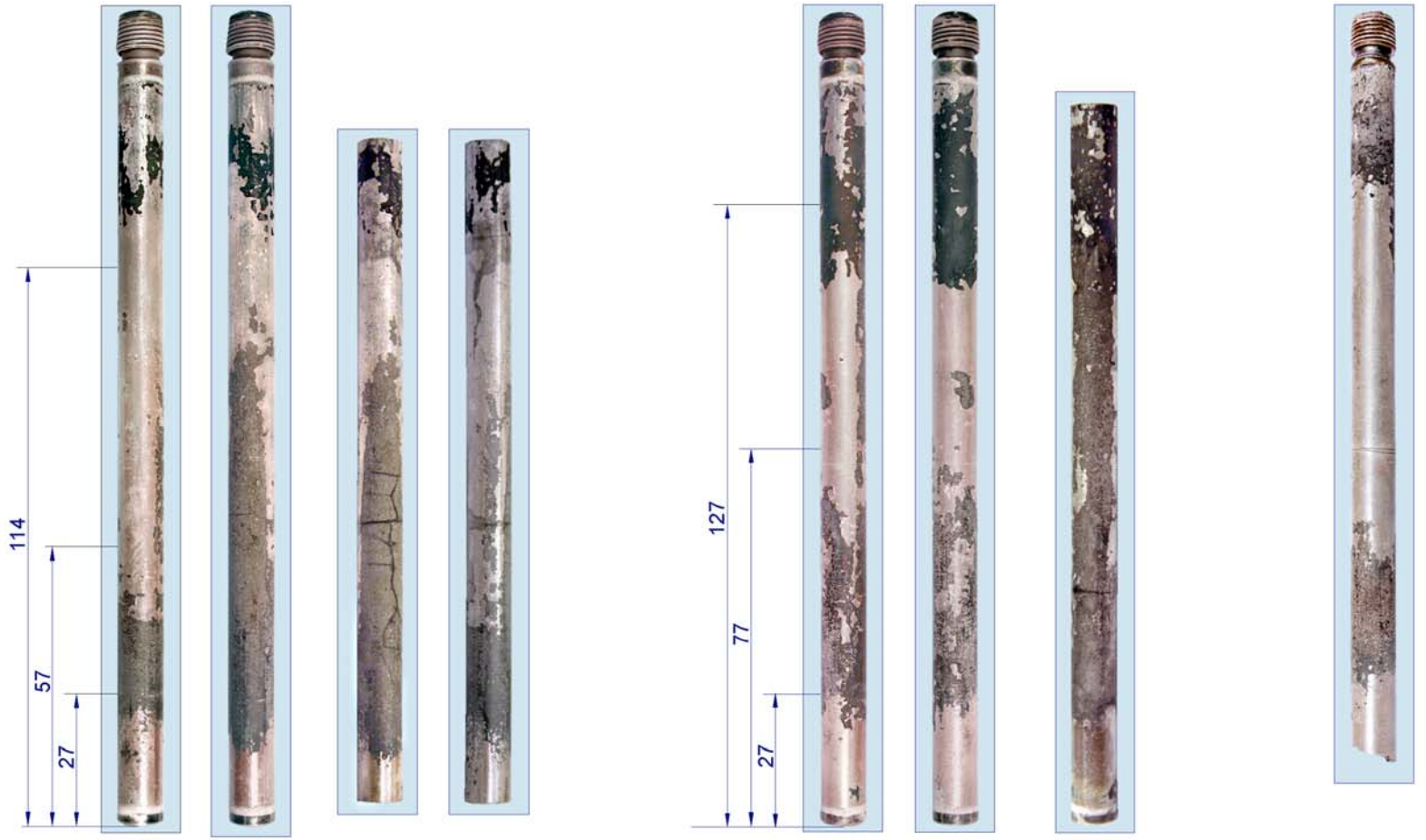
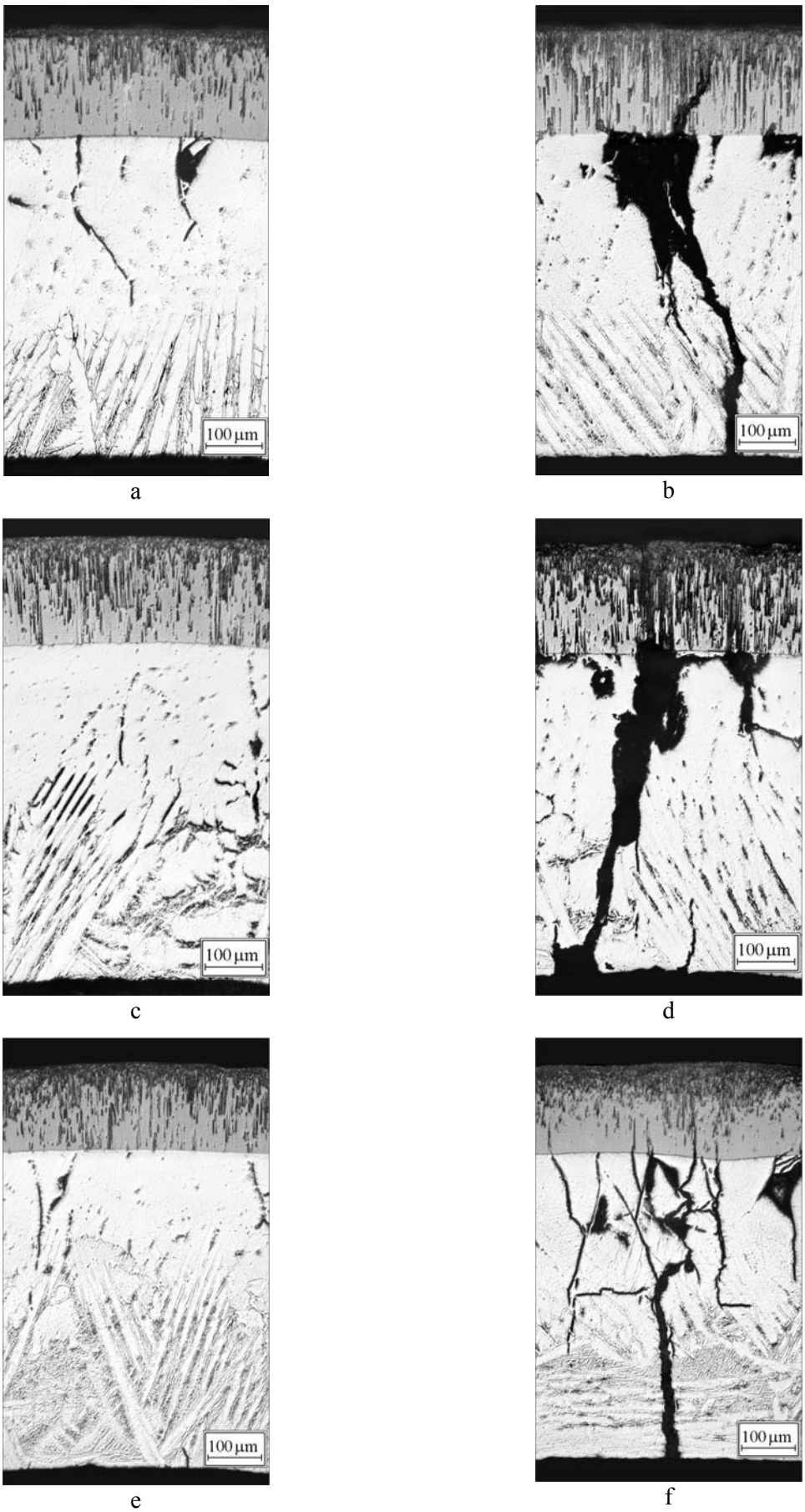


Fig. 8. Sample claddings appearance after tests

the positions of metallography cross-section are pointed by arrows

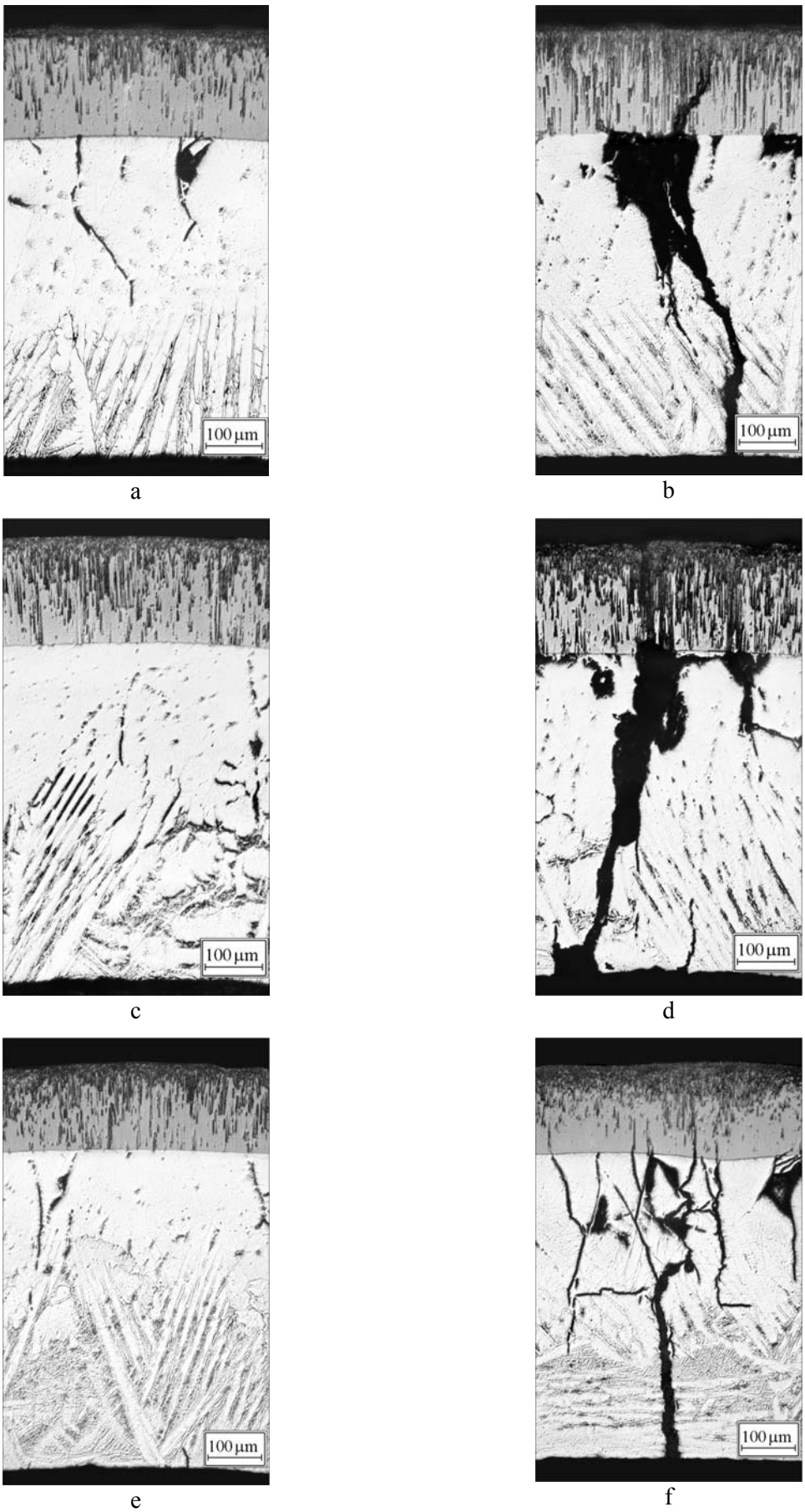


a b c d e f

Fig. 9. Oxide film on sample 1

(oxidation time 800 s, flooding temperature 1400 °C)

at the elevations 114 mm (a, b), 57 mm (c, d) and 27 mm (e, f)



a b c d e f

Fig. 9. Oxide film on sample 1

(oxidation time 800 s, flooding temperature 1400 °C)

at the elevations 114 mm (a, b), 57 mm (c, d) and 27 mm (e, f)

Conclusions to STAGE A.

The in-cell facility was developed to study the hydrogen generation and fission products release from single fuel rods under the conditions typical for the VVER core flooding during the severe LOCA accident. The facility operation is based on the indirect resistive heating of the specimen.

The experiments with unirradiated VVER fuel rod simulators were performed under the reflooding conditions in the frame of the first stage of test. The facility allows the implementation of the following testing conditions: temperature of the preliminary oxidation in the steam-argon medium up to the generation of the prescribed oxide film thickness is of 1400 °C, flooding temperature - 1600 °C.

The hydrogen generation is measured both at the stage of preliminary oxidation of the simulator claddings and at the flooding stage. The thickness of oxide films was determined as well as ECR of the central part of claddings.

At present, the facility is being prepared for the experiments with simulators fabricated from spent VVER fuel rods at a burn up of 45-50 MW*day/kgU.

STAGE B. Fresh FA-QUENCH

The VVER bundle material has been finally delivered to FZK and the material will be used for bundle fabrication in the coming months. The following set of semi-manufactured parts made of Zr-Nb alloy was delivered:

- Etched and anodized cladding tubes 9.13x7.73 mm
- Shroud tube 88x79.5x1800 mm
- Flange tube 120x85x300 mm
- Holder rods, diameter 9 mm
- Corner rods, diameter 6 mm
- Corner tubes, diameter 5.8x4.75 mm
- Spacing grids 37 cells

STAGE C. FA Quench Model

Development of the requirements to models and codes

The requirements to the SVECHA code models (mainly concerning the material properties) were elaborated in order to be able to describe VVER reactor behavior under severe accident conditions.

Preparation and adaptation of models and codes

The adaptation of the models of high temperature oxidation and mechanical behavior of VVER cladding tubes with respect to:

- Comparison of the results obtained during examination of "fresh" and spent claddings;
- Development of physical model of time-dependent high temperature cladding oxidation based on the PWR Zry-4 cladding oxidation model developed in IBRAE;
- Theoretical processing of the results of Zr-1%Nb "fresh" and spent cladding mechanical properties examination at different temperatures depending on burn-up, ECR and hydrogen content;
- Further development of cladding mechanical behaviour model developed in IBRAE for PWR Zry-4 claddings and application of modified model to describe examined VVER fuel rods; including in the model a new data base on mechanical properties obtained in the experiments and irradiation impact on these properties;
- Simulation of hydrogen absorption during the cladding oxidation and description of accumulated hydrogen impact on the mechanical failure of fuel rods under accident conditions

was performed.

Processing, analysis and modelling of the experiments

The available experimental data on the oxidation of fresh and spent Zr-1%Nb cladding at different temperatures were analysed and systematized. The verification calculations matrix with respect to the following test parameters:

- oxidation temperature,
- degree of preoxidation (oxide thickness),
- irradiation degree

was compiled. In order to perform cross-comparison of the Zr-1%Nb cladding test results with the Zry-4 ones, the corrdesponding Zry-4 tests with similar parameters were taken.

The numerical processing (averaging, smoothing) and adaptation of a part of experimental data for the SVECHA code calculations were performed. The work on the making up of the SVECHA code input files matrix corresponding to the boundary conditions of the performed tests

- measured temperature of the oxidised surface (time dependent),
- heating conditions,
- geometry of the hydraulic channel,
- radiation heat exchange

was initiated.

Development of codes and their validation

The work on modification of SVECHA code (initially developed on the basis of PWR fuel rod behaviour models) for the description of VVER fuel rod materials was initiated. In particular, the organisation of the SVECHA code material properties database concerning oxidation and mechanical behaviour of fuel rod cladding was modified. The main aim of this modification was to enable performing of two test simulations with the identical boundary conditions but different cladding materials (Zr-1%Nb, Zry-4). Such calculations that allowed direct comparison of the two materials behaviour under severe accident conditions will be performed later, after Zr-1%Nb properties database completion, within the framework of the present project.

References

1. M. Steinbrück et. al, "Status of the QUENCH Program at FZK", Compilation of handouts, 7th International QUENCH Workshop, Germany, Karlsruhe, December 12-13, 2001

2. J. Stuckert, M. Steinbrück, U. Stegmaier, “Single rod quench tests with Zr-1%Nb cladding.Comparison with Zircaloy-4 cladding tests and modeling”, FZKA 6604, 2001