SIMULATION OF LOSS-OF-COOLANT ACCIDENTS IN THE CODEX INTEGRAL TEST FACILITY

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ABSTRACT

The behaviour of VVER cladding materials in different LOCA scenarios was investigated in the CODEX (COre Degradation EXperiment) facility. The experiments were performed with seven rod electrically heated bundles which consisted of a mixture of traditional and sponge based E110 cladding materials. The fuel rod simulators were filled with alumina pellets and pressurized to different values. The two tests simulating design basis LOCA scenario (200% large break LOCA) indicated that the representative pressure and temperature conditions would not result in cladding burst for this scenario. In the three tests simulating LOCA events with limited availability of emergency core cooling water, considerable difference was observed between the high temperature oxidation of traditional and sponge based E110 alloys. There was no significant difference in ballooning and burst between the two cladding materials, and from the test results cladding burst can be expected for most of the fuel rods in LOCA events with limited availability of cooling water.

1. Introduction

The high temperature conditions during a loss of coolant accident (LOCA) may result in significant changes in the fuel, first of all in the state of zirconium cladding. Due to the increase of temperature the mechanical properties change, the plastic deformation can lead to ballooning and burst of the cladding tubes. The interaction of zirconium with steam produce zirconium-oxide on the tube surface, considerable amount of oxygen can diffuse into the metallic phase of the cladding and part of the produced hydrogen can be absorbed by the metal. These changes of cladding microstructure can lead to the embrittlement of zirconium. The mechanical and thermal loads associated with LOCA conditions (e.g. reflooding the core) may lead to the loss of cladding integrity if the material is very brittle.

Typically, the design basis LOCA scenarios in a nuclear power plant reactor last rather short time and the oxidation phases are not long enough to cause brittle state of the fuel. However, the plastic deformation and burst can take place even with very short dry periods in the core. In case of beyond design basis or severe accident conditions, however, the oxidation times might be long enough to result in cladding embrittlement and failure.

The load bearing capabilities of nuclear fuels under accident conditions highly depend on the cladding geometry and alloy type. The VVER reactors use niobium containing E110 type zirconium alloys which have high corrosion resistance under normal operation of the reactor. The recent developments of the fuel supplier include the production of the E110 alloy based on sponge materials.

The first experimental investigations indicated that the new material can withstand much better the interaction with high temperature steam than the traditional alloy produced with an electrolytic process [1][2]. The small scale separate effect tests showed that the oxidation of sponge based E110 alloy in high temperature steam was not accompanied with the breakaway process, the formed oxide scales were compact and the amount of absorbed hydrogen was modest [3][4][5][6][7]. In order to investigate the integral behaviour of the new alloy under LOCA conditions a new experimental programme was launched in Hungary using the CODEX (COre Degradation EXperiment) facility.

2. CODEX-LOCA test facility

The accident conditions were simulated with seven electrically heated fuel rods in the CODEX facility. In the LOCA test series the bundle included both traditional and sponge based E110 type cladding tubes. The seven fuel rods were fixed by original VVER spacer grid in hexagonal geometry (Fig. 1.). The fuel rods could be pressurised, they were filled with alumina pellets and their lengths was 600 mm. The diameter and thickness of the cladding tubes were 9.1 mm and 0.69 mm respectively. The tungsten heater wires were placed into two holes in the ceramic pellets and electrical connections were needed only at the bottom of the rods. The tops of the cladding tubes were closed by welded Zr plugs. The test bundle was covered by a hexagonal Zr2.5%Nb shroud, insulation materials and a stainless steel tube.

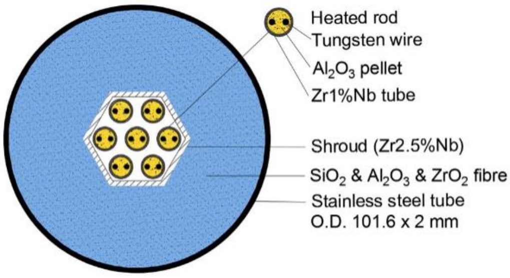

Fig. 1. Cross section of the CODEX-LOCA bundle

The inlet junction at the bottom of the test section was connected to the steam generator (Fig. 2.). Argon carrier gas can be also injected at this junction. Another connecting tube can be used for water injection to reflood the hot bundle from the bottom. The top of the bundle had a connection to the cooler section where the remaining steam could be condensed.

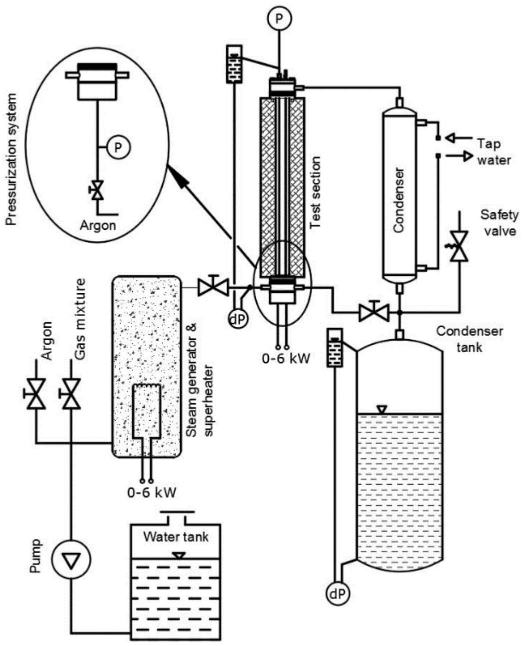

Fig. 2. Main components of the CODEX-LOCA facility

The measurement system recorded system and rod internal pressures, flowrates, values of input power, coolant inlet and outlet temperatures, water levels and rod temperatures. Several high temperature thermocouples were built into the fuel rods, shroud and insulation layers at different elevations. The temperature measurement uncertainty was ±0.4% for temperature values up to 1000 °C, while the pressure measurement uncertainty was ±1% for pressure values between 0 and 100 bar.

3. Simulated LOCA scenarios and test matrix

In the CODEX-LOCA test series it was intended to cover several different accident scenarios, for this reason five different tests were executed (Tab. 1.). The reference scenarios for all of the tests were based on the results of safety analyses performed for different LOCA events in a VVER-440 nuclear power plant. The reference scenarios were used to determine the maximum cladding temperatures, the durations of dry periods, the fuel rod internal pressures and the durations of final water quench.

In the CODEX facility there are several technical limitations compared to reactor case. In the facility large negative pressure difference between the fuel rod internal and external pressures cannot be produced. Furthermore, the temperatures cannot be changed as quickly as it takes place in the reactor. For these reasons:

- the temperatures histories were selected in such a way that the maximum temperatures were reached and the duration of the dry period covered the reference case.
- the fuel rod internal pressure was determined so that the maximum overpressure in the reference case (difference between fuel rod and coolant side pressures) was reached. Different pressure values were set in the different fuel rods in order to cover a wider range of this parameter.

There were two main objectives in the CODEX-LOCA test series:

1) Examination of cladding burst in scenarios close to design basis cases.
2) Investigation of cladding oxidation and hydrogen uptake in high temperature steam and their consequences on the embrittlement of Zr alloys.

The first reference scenario was representative for a large break (200% of primary circuit pipe cross section) LOCA event in a reactor at nominal power. The maximum cladding temperature reached 900 °C in the blow-down phase and 886 °C in the oxidation phase. The total duration of the dry period lasted for 150 s. The analyses of the primary coolant pressure history and the evaluation of the internal pressure in the fuel rod indicated that the maximum overpressure in the fuel rod was 15.6 bar and it was reached in a low burnup (18 MWd/kgU) fuel rod. This scenario was simulated in the CODEX-LOCA-200 and CODEX-LOCA-200B experiments with slightly different conditions.

Since the oxidation time in this first (design basis type) reference scenario was very short, other two scenarios were selected with limited availability of emergency core cooling water to investigate cladding behaviour with longer dry periods.

The reference scenario for the CODEX-LOCA-E4 test was taken from the safety analysis of a shut-down LOCA event. It was supposed that the large break took place about one day after shut-down and the average primary coolant temperatures were close to 150 °C. The heat-up of the fuel rods took place slowly after the initial event and the 1000 °C maximum cladding temperature was reached in 20 minutes. Fuel rods were in dry conditions above 600 °C for 750 s and were cooled-down by the injection of water from the low pressure emergency core cooling system.

Spent fuel pool LOCA event with limited availability of emergency cooling water was simulated in the CODEX-LOCA-SFP1 and CODEX-LOCA-SFP2 experiments. The initial event was the break of a pipe in the cooling circuit which led to the heat-up and boil-off of the spent fuel pool coolant. The maximum cladding temperature reached 900 °C. Due to the supposed very low flowrate of the emergency water injection the fuel rods were in dry conditions for almost three hours and this hypothetical scenario was terminated by slow injection of water to the bottom of the pool. The first test (CODEX-LOCA-SFP1) was performed with steam starvation conditions, while in the second test (CODEX-LOCA-SFP2) high steam flowrate was provided in order not to limit the oxidation of zirconium surfaces.

Test	**Simulated conditions**	**Date**
CODEX-LOCA-200	200% large break LOCA with conservative conditions	November 30, 2015
CODEX-LOCA-E4	Shutdown LOCA with limited availability of emergency cooling water	July 12, 2016
CODEX-LOCA-200B	200% large break LOCA	November 9, 2016
CODEX-LOCA-SFP1	Spent fuel pool LOCA with steam starvation and with limited availability of emergency cooling water	February 16, 2017
CODEX-LOCA-SFP2	Spent fuel pool LOCA with unlimited steam and with limited availability of emergency cooling water	July 3, 2017

Tab. 1: CODEX-LOCA test matrix

4. Execution of CODEX-LOCA experiments

The CODEX-LOCA integral tests were started with heat-up to 600 °C and then stabilisation of temperatures at 600 °C in argon atmosphere. The further heat-up in steam atmosphere was performed by using appropriate high powers for the electrical heaters to follow the requested temperature history. After the predetermined oxidation time at high temperature the bundle was cooled-down by water quench from the bottom of the bundle. The fuel rods were individually pressurised to different pressure values. An example of the planned main parameters is shown in Fig. 3.

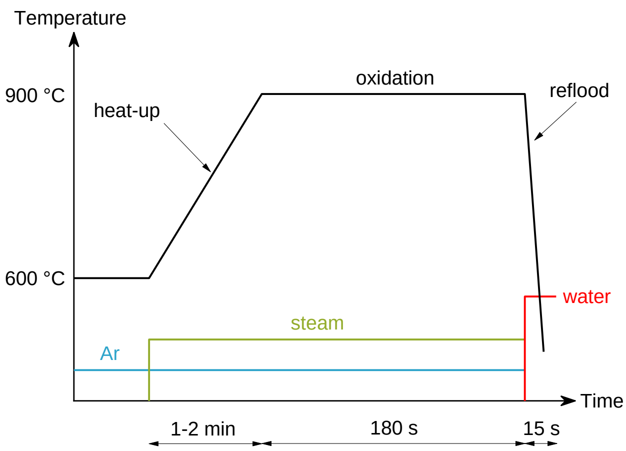

Fig. 3. Main phases of the CODEX-LOCA-200 test

The simulation of 200% large break LOCA was carried out in two experiments. Both covered the temperature and pressure conditions of the reference scenario, but in the CODEX-LOCA-200 more conservative conditions were applied: the maximum temperature was higher, the dry period was longer (Fig. 4.) and the fuel rod internal pressures were higher (Fig. 5.).

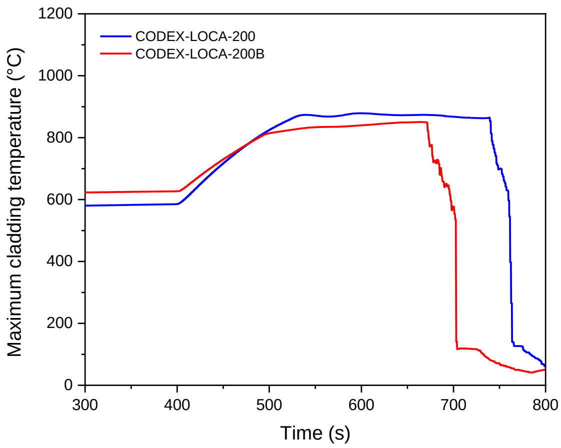

Fig. 4. Maximum cladding temperatures in the CODEX-LOCA-200 and CODEX-LOCA-200B tests

The slightly higher pressures in the CODEX-LOCA-200 test led to ballooning and burst of three fuel rods (Fig. 5.), while in the other test all fuel rods remained intact.

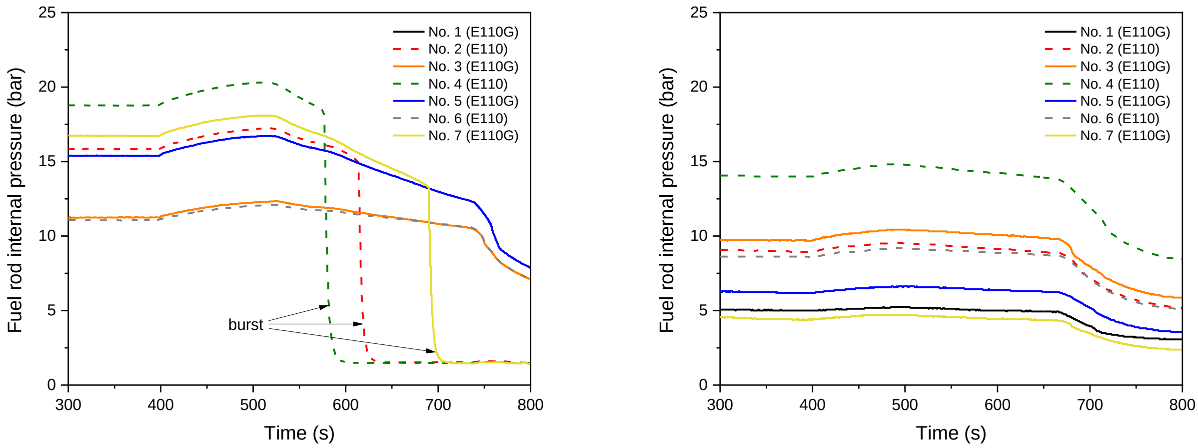

Fig. 5. Internal fuel rod pressure histories in the CODEX-LOCA-200 (left) and CODEX-LOCA-200B (right) tests

The simulation of shut-down LOCA scenario was performed in the CODEX-LOCA-E4 experiment. The high temperature dry period in this experiment lasted for more than 10 minutes and maximum temperature reached 1089 °C (Fig. 6.). All seven fuel rods failed due to burst under these conditions (Fig. 7.).

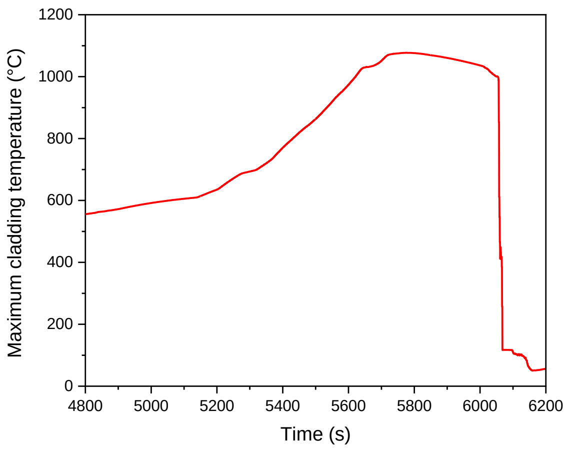

Fig. 6. Maximum cladding temperature in the CODEX-LOCA-E4 test

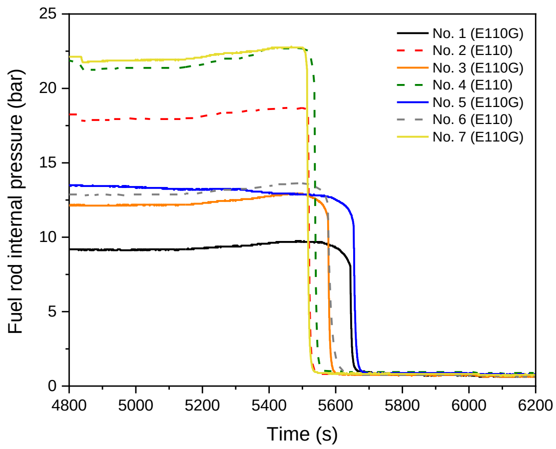

Fig. 7. Internal fuel rod pressure histories in the CODEX-LOCA-E4 test

The CODEX-LOCA-SFP1 and CODEX-LOCA-SFP2 tests simulated about 3 hours dry conditions in a spent fuel pool. At the beginning of the experiments the test section was filled up with water. The tests were started with boiling off the coolant and after that slow heat-up rate was applied. The maximum temperatures were 924 °C in the first and 896 °C in the second test (Fig. 8.). The high temperatures led to the ballooning and burst of claddings. The first test was carried out with steam starving conditions in order to simulate limited steam access to the zirconium surfaces.

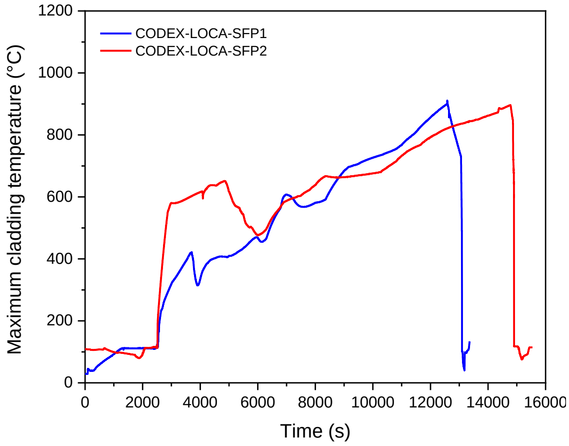

Fig. 8. Maximum cladding temperatures in the CODEX-LOCA-SFP1 and CODEX-LOCA-SFP2 tests

5. State of the fuel rods after the tests

The fuel rods in the tests with short oxidation times (CODEX-LOCA-200 and CODEX-LOCA-200B) suffered very limited oxidation (Fig. 9.). The comparison of traditional and sponge based E110 claddings did not show any differences. The burst pressures were also comparable for the claddings made of the two alloys.

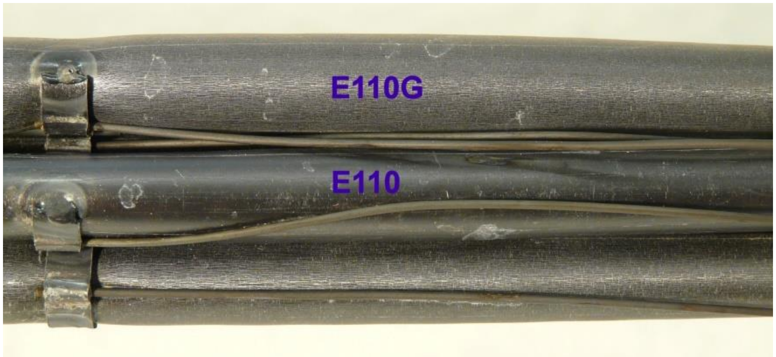

Fig. 9. View of the CODEX-LOCA-200 bundle after the test

The hydrogen distribution along the longitudinal axis of fuel cladding tubes was measured by position-sensitive prompt gamma-ray neutron activation imaging (PGAI) driven by neutron radiography (NR) for the CODEX-LOCA-200 bundle. The uncertainties of the measured H/Zr mass ratios were <5-10% for the elevated H-content positions (>150 ppm). In the cladding tubes (No. 1, 3, 5 and 6) with no visible deformation the hydrogen contents along the longitudinal axis fluctuate around 80 – 100 ppm and show no clear peaks (see Fig. 10.). For the cladding tubes (No. 2 and 4) which have a visible burst the hydrogen concentration values show a clear peak (1100 and 1500 ppm) around the opening. The shape of the H-profile, however, does not show the usual two-peaks shape [8]. In the cladding tube (No. 7) which has a visible burst with two smaller openings the hydrogen concentration values show three smaller clear peaks (250 ppm).

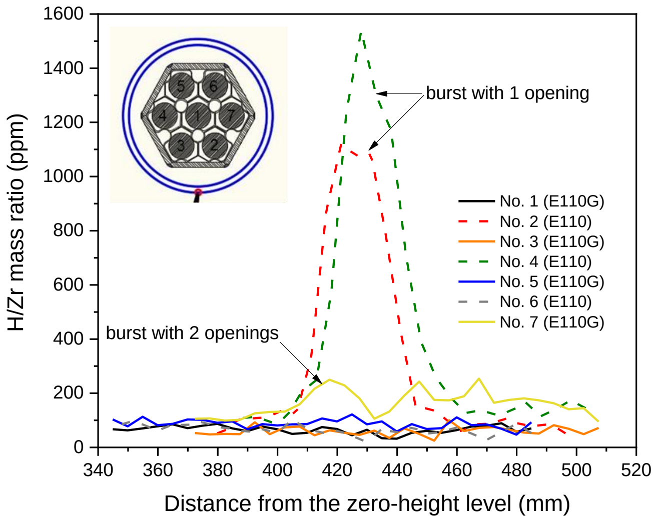

Fig. 10. The longitudinal profiles of the H/Zr mass ratios as a function of the distance from the zero-height level

The longer oxidation time in the CODEX-LOCA-E4 test resulted in considerable oxidation of traditional E110 tubes with spalling white oxide scale. The sponge based E110 cladding, however, had compact dark oxide layer (Fig. 11.).

Fig. 11. View of the CODEX-LOCA-E4 bundle after the test

In the CODEX-LOCA-SFP1 test the cladding suffered large deformations before burst (Fig. 12.). The cross section of coolant channels was significantly reduced by the ballooning of the cladding. Oxidation practically did not take place in this test due to the limited steam supply.

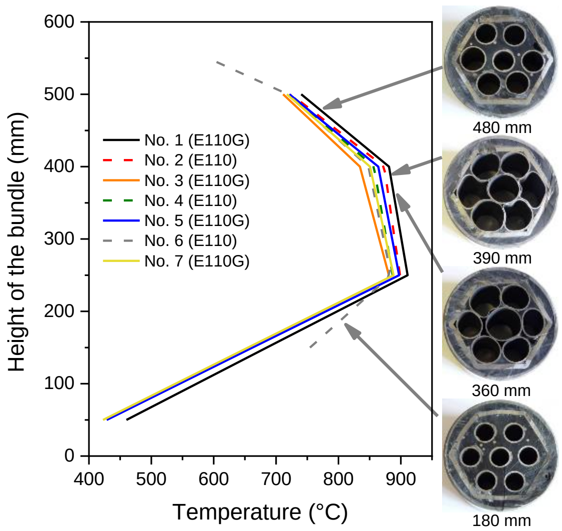

Fig. 12. Axial temperature distribution at 12600 s and cross sections of the CODEX-LOCA-SFP1 bundle

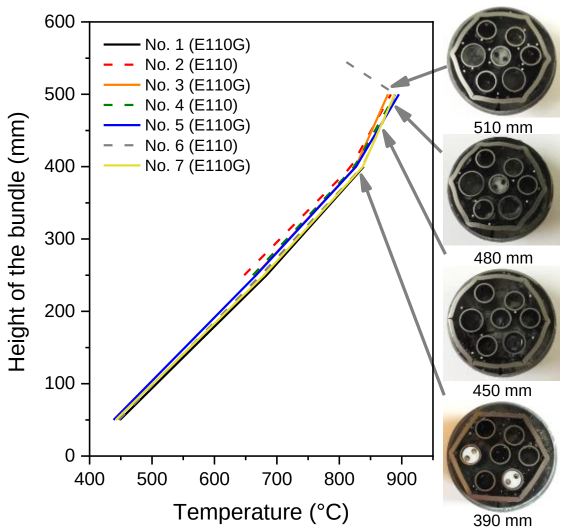

Fig. 13. Axial temperature distribution at 14612 s and cross sections of the CODEX-LOCA-SFP2 bundle

In the CODEX-LOCA-SFP2 test unlimited steam was available during the 3 hours oxidation phase of the experiment thus the cladding tubes suffered smaller deformations than in the CODEX-LOCA-SFP1 test (Fig. 13.). At the highest temperature zone of the bundle (between 390 and 540 mm) both the formed oxide and α layer thicknesses vary around 10 μm on the outer surfaces of all rods. The metallographic examinations proved that formed oxide layer is compact on the sponge based E110 cladding tubes but layered and spalling on the traditional E110 tubes.

6. Discussion

Several LOCA tests have been performed with irradiated and non-irradiated fuel in the past in different laboratories.

- The PARAMETER facility was used in Russia for testing the behaviour of a bundle of 19 rods electrically heated in high temperature conditions [9]. The typical maximum temperatures were above 1000 °C and the fuel rods were pressurised.
- 19 rod bundle and single rod VVER fuel were tested in the MIR reactor in Dimitrovgrad for LOCA conditions. The ballooning and burst of high pressure fuel rods took place in these experiments. The maximum temperatures reached 820 °C, 950 °C and 1070 °C in the executed three experiments [10][11].
- In the framework of the Halden Reactor Project two LOCA tests were performed with VVER single rods irradiated in the Loviisa NPP. 832 °C and 940 °C maximum temperatures were reached in the two tests, and burst took place in both high pressure fuel rods [12].

The main characteristics of the above listed experiments are summarised in Tab. 2. It must be noted that in all these tests the high temperature phase (above 700 °C) lasted only for a few minutes and these periods were not enough to produce significant oxidation and/or embrittlement of the cladding tubes. Furthermore, in most of the above tests the fuel rod internal pressures were higher than that pressure difference across the cladding which can be expected in a real design basis accident in a VVER-440 reactor. This conservative approach did not allow us to draw conclusions on the loss of integrity of VVER fuel in the design basis accident scenario.

The CODEX-LOCA-200 and CODEX-LOCA-200B tests could be compared to the above listed experiments, since the high temperature oxidation periods in these tests were short (that is not the case for the other three CODEX-LOCA tests which simulated LOCA accidents with limited availability of emergency core cooling water). The special feature of these two tests is that the fuel rod internal pressures were rather low compared to the experiments performed in the above facilities.

Facility	**PARAMETER**				**MIR**			**Halden**		**CODEX**	
Test	1.	2.	3.	4.	BT-2	BT-3	LOCA/72	IFA-650.6	IFA-650.11	LOCA-200	LOCA-200B
Bundle	19 rod	19 rod	19 rod	19 rod	19 rod (3 irrad.)	19 rod (3 irrad.)	1 rod (irrad.)	1 rod (irrad.)	1 rod (irrad.)	7 rod	7 rod
Max. temp. (°C)	1274	1100	1050	1180	950	820	1070	832	940	908	874
Burst pressure (bar)	31-38	30-37	28-37	32-34	58-77	65	66	65	57	13-18	-
Duration above 700 °C (s)	330	300	550	330	400	60	120	300	350	325	255

Tab. 2: LOCA tests with VVER fuel

The maximum cladding temperatures and burst pressures are summarized in Fig. 14. It can be seen that most of the tested fuel rods failed due to the high internal pressures. In case of CODEX-LOCA-200 test burst of cladding took place on three fuel rods, but in case of CODEX-LOCA-200B all seven rods could keep their integrity.

Taking into account that both CODEX-LOCA-200 and CODEX-LOCA-200B tests conservatively covered the reference VVER-440 LOCA scenario in both terms of pressure and temperature, it can be concluded that in the design basis LOCA event for this reactor type the fuel rods will keep their integrity.

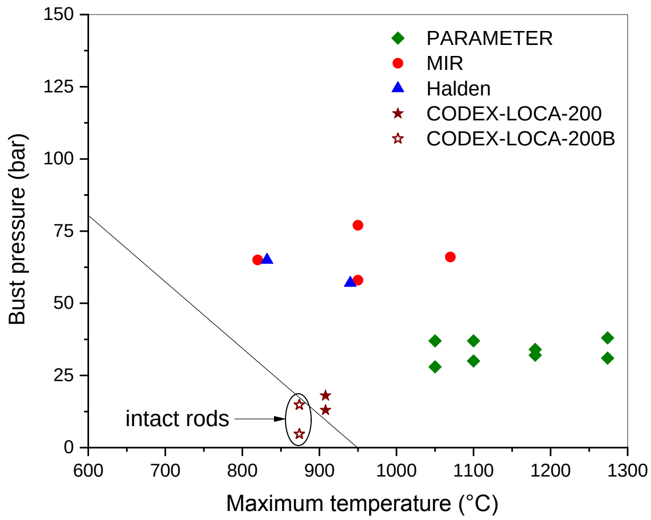

Fig. 14. Burst pressure vs. maximum temperature in VVER LOCA integral experiments

The high temperature oxidation in the CODEX-LOCA-E4 and CODEX-LOCA-SFP2 tests led to microstructural changes in the Zr tubes. On the traditional E110 tubes spalling oxide scales could be observed, while in case of sponge based E110 tubes the oxide scale was dark and compact. Similar conclusions were drawn from small scale oxidation tests in different laboratories [2][6][7][13][14]. The present results confirmed that such difference takes place under integral conditions, too, since the CODEX bundle contained both cladding types in the same experiments.

7. Summary

Integral LOCA experiments have been performed in the CODEX-LOCA facility with electrically heated, non-irradiated VVER type fuel bundles.

Two tests simulated the design basis LOCA scenario for a VVER-440 reactor. The results indicated that the representative pressure and temperature conditions would not result in cladding burst for this scenario.

Three tests simulated LOCA events with limited availability of emergency core cooling water injection in the shut-down reactor and in the spent fuel pool. The long oxidation times at high temperatures resulted in the formation of oxide scale on the zirconium surfaces. The observed significant difference between the traditional and sponge based E110 alloys were in good agreement with the results from small scale separate effect tests.

8. Acknowledgements

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