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Experimental Simulation of the Paks-2 Cleaning Tank Incident Through Separate Effect and Integral Tests

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ABSTRACT

Following the ex-core cleaning of VVER type fuel assemblies, a severe fuel damage took place at the Paks NPP. Assemblies with high decay-heat remained without cooling for seven hours. As a common result of high temperature oxidation and final water quenching the assemblies were broken and the fuel rods fragmented.

In order to improve the understanding of the phenomena that took place during the Paks-2 incident, several series of separate effect and integral tests have been carried out. The separate effect tests investigated the phenomena related to the upward shift of fuel assemblies, to the role of the spacer grid and the spring in the loss of cladding integrity, and to the importance of high hydrogen content in the vessel's atmosphere on the embrittlement of zirconium. Integral tests were carried out in the CODEX facility to simulate the whole scenario of the incident using electrically heated fuel rods.

1. Introduction

Ex-core chemical technology was applied at the Paks NPP in order to clean fuel assemblies with heavy crud depositions (Bajsz and Gadó, 2004). The cleaning of the fuel assemblies was performed in a cleaning tank which was placed in the bottom of a service pit next to the spent fuel storage pool. After the completion of chemical cleaning, circulation of spent fuel pool water was established in an open loop at low flow rate. During this operation mode some by-pass flows came off between the inlet and outlet junctions. Since both junctions were positioned in the bottom part of the tank, the circulation in the upper part was stopped. The coolant reached saturation conditions, a steam volume was formed and the heat removal from fuel rods was lost. The cleaning tank was opened only several hours later. According to water level measurements, the fuel rods were in dry conditions for seven hours. Some activity release was detected during the dry phase – obviously due to clad ballooning and burst – and large activity release took place when the lid of the tank was opened.

The examination of the cleaning tank after the incident indicated that most of the fuel assemblies were heavily damaged. Fuel rod fragments and shroud pieces accumulated on the lower plate between the assemblies. There were no signs of melting. The white surfaces of the assemblies and the fuel rods showed that heavy oxidation took place on the zirconium surfaces. Beyond the typical forms of fuel degradation some specific phenomena were also observed:

- The examination of the lid of the tank revealed that there were mechanical interactions between some fuel assemblies and the lid. The assemblies had to move up from their normal position to reach the lid.

- There were some assemblies with full cross section breaks. The position where all fuel assemblies were broken was typically at the location of the spacer grids.
- Near the upper end of some fuel rods external spiral shape was shown up at the elevation of internal springs.

The Paks-2 cleaning tank incident took place under specific conditions, which are usually not considered for reactor accidents: the oxidation time was very long, the assembly powers were relatively low (two weeks after shutdown), and oxidation took place in hydrogen rich steam atmosphere in a stagnant volume.

After the incident detailed numerical analyses were performed using thermal hydraulic, fuel behaviour and severe accidents codes (Hózer et al. 2009a). The calculations successfully reproduced the main events of the incident, estimated the ranges of most important parameters and revealed the causes of the incident.

However, many interesting details of the event could not be covered by the available models, and the comparison between calculated and real values was limited, for only very few parameters were measured in the cleaning tank. For these reasons special experimental programmes were carried out to determine more precisely the conditions and mechanisms of fuel failure and to explain some interesting details of the incident.

The integral behaviour of the fuel rods was simulated in the CODEX (Core Degradation EXperiment) facility (Hózer et al., 2009b; Steinbrück et al., 2009). The oxidation and embrittlement of E110 type cladding were investigated in high temperature hydrogen rich steam atmosphere (Perez-Feró et al., 2007). Separate effect tests have been performed with small cladding pieces and short fuel rod samples to examine the possibility of upward shift of the assemblies, to investigate the interactions between the spacer grid and the cladding, furthermore between the spring

and cladding at high temperature. The main results of separate effect and integral tests will be summarized in this paper and it will be discussed how the different tests contributed to the understanding of phenomena which took place during the Paks-2 cleaning tank incident.

2. Separate effect tests

2.1. Upward shift of the fuel assemblies

During the visual examination of the Paks-2 cleaning tank lid, several scratches were observed on the internal surface. These were obviously the signs of interaction between the fuel assembly headers and the internal surface of the lid. The cleaning tank had a lower plate and an upper spacer plate to prevent horizontal shift of the assemblies, but the assemblies were not fixed at the top. The normal operation of pumps with high flow rate (170t/h) during chemical cleaning did not change the position of the assemblies, since several batches of fuel assemblies were treated in the cleaning tank before the incident and in those cases interactions between the assemblies and the lid were not observed. It is very probable that the operation of a low flow rate (21 t/h) pump could not move the 215 kg assemblies even during the seven hours dry phase and so the mechanical contact with the lid took place at the opening of the cleaning tank (Fig. 1).

The potential mechanisms for the upward shift of assemblies were investigated in a high temperature facility. A hexagonal seven rod fuel bundle was constructed and covered by a shroud. The bottom and top sections of the bundle were collected from

standard fuel rods, while in the central part larger diameter tubes were used to simulate blockage formation in the bundle. Inductive heating was applied in inert atmosphere and the bundle was heated up to 1050 °C. Quenching was simulated by injecting water from a tank above the furnace into the bottom of the fuel bundle. The short period (1-2 seconds) of position change was recorded by a video camera (Fig. 2). The total vertical shift of the 0.59 kg bundle was 9 cm. The bundle removed the lid from the top of the test section and also some water was released as a result of intense boiling of the injected water.

The experimental results confirmed that the upward shift of the fuel assemblies took place presumably during the quenching phase of the incident. The main reason for the change of the vertical position was the penetration of cold water into the fuel assemblies from the bottom and its fast evaporation. The internal blockage caused by ballooning enhanced the effect of pressure increase on the vertical acceleration of assemblies. The produced steam could not leave the assembly in horizontal direction, for the VVER-440 assemblies are covered by shrouds. The cross section in the upper direction was partially closed by clad ballooning, so the produced steam had to flow out at the bottom and the assembly moved up as a consequence of this rocket force type effect.

Simple numerical analysis of the process was carried out supposing balance in the upper position of the assembly between the gravity force and the difference of pressures inside and outside of the fuel assembly multiplied by flow cross section. Using typical heat exchange coefficients for reflood conditions and considering the geometry and the stored heat in the assembly the steam production was estimated.

The calculations showed that 2-3 bar overpressure in the bottom of the real VVER-440 fuel assemblies could easily result in a 0.2-0.3 m position change and that was enough in the geometry of the cleaning tank to reach the lid. The necessary steam mass for such a pressure was only a few times ten grams, which could be easily and quickly produced on the hot surface of the fuel rods.

2.2. Role of the spacer grid in assembly fracture

The fragmentation of heavily oxidized fuel assemblies in the cleaning tank covered a wide range from very small fragments to long cladding and shroud pieces. The fracture of fuel elements and in some cases that of full assemblies happened typically at the position of spacer grids. The reason for these phenomena (e.g. fragmentation at the location of the spacer grid) was not well understood after the incident. Several mechanisms could have been taken into account. One idea was that during the ballooning of the fuel rods the local deformation was limited to the vicinity of the spacer grids and local stresses between the spacer and the cladding could create some cracks in the Zr tube material.

Ballooning of Zr cladding was investigated in several experimental programmes in the past (Markiewicz et al., 1988; Réocreux et al., 1990; Hózer et al., 2005; Kim et al., 2006). The main objective of those tests was the investigation of the conditions of fuel failure due to ballooning and burst, the estimation of clad deformation and its effect on the coolability of fuel assemblies. Since maximum ballooning can be expected away from the spacer grids, the effect of spacers on ballooning process was not addressed in the previous tests. In order to reproduce the conditions of the Paks-2

event, a new experimental programme was initiated for the investigation of the role of spacer grid on the failure of fuel rod during high temperature ballooning of Zr cladding.

VVER cladding samples were tested in high temperature furnaces at isothermal conditions and with linear pressure increase. Single rod samples and seven rod bundles have been prepared with closing plugs in one end and with connecting tube for pressurization at the other end. Spacer grids were fixed on the samples at different positions. The typical temperature of the experiments was about 1000 °C. The atmosphere of tests was steam or argon. Tests with argon were conducted until the burst failure of the samples and the role and mechanism of initial interaction (without oxidation) were investigated between the spacer grid and the cladding. Tests with steam characterized the local oxidation of cladding in the vicinity of spacer grids and the final state of ballooned fuel after long term oxidation in high temperature steam. In case of seven rod bundles each rod was individually pressurized. After the tests post-test examinations were carried out. Axial (Fig. 3) and lateral cross sections were prepared and metallography, SEM and mechanical testing were applied.

The main results of the single rod tests can be summarized as follows:

- If the ballooning took place at the spacer grid, then the burst of cladding would happen later i.e. at higher pressure compared to burst at the cylindrical part of the cladding tube.
- In some cases the spacer grid could prevent the burst of the cladding and thus initiated a secondary ballooning in another position along the fuel rod (see Fig. 4).

- Oxidation of the cladding under the spacer grid was limited and so embrittlement of the Zr cladding locally was less than on the other parts of the fuel rod surface. However, during the Paks-2 incident the very long term oxidation could lead to significant embrittlement and fragmentation even at this location.
- Local cracks in the vicinity of spacer grid could not be detected in the examined cross sections.

Mechanical testing of a seven rod bundle was carried out after oxidation in steam. Radial mechanical load was applied at the elevation of the spacer grid on the bundle. The total energy of the knock was ≈ 260 mJ. After 6000 s of oxidation at 1000 °C the bundle was so brittle that even this small load was enough to break the full bundle (Fig. 5) into small pieces. This test indicated that the failure of the fuel rods at the spacer grid took place as a result of radial mechanical load transfer through the spacer. During the opening of the cleaning tank in the Paks-2 incident about 4 tonnes of cold water penetrated into the vessel. Since the lid was opened only on one side, the injection of water took place in a complex 3D manner, it created asymmetrical radial loads on the fuel assemblies. The fuel rods are connected to each other through the spacer grids, so the mechanical load from one fuel rod to the other could be transferred only through the spacers. Such load transfer could take place during the quenching phase of the Paks-2 incident and this effect caused the failure and break of many fuel rods.

2.3. Interaction between the spring and cladding

During visual examination of the damaged fuel after the incident an external spiral shaped deformation was observed on some fuel rods at the elevation of the springs. It was suspected that the external spiral could have been produced by mechanical interaction between the spring and the cladding, and/or by formation of Fe/Zr eutectics. Eutectic interaction between steel and zirconium becomes significant above 1100 °C (Maróti, 1997; Hofmann, 1999) and the temperature in the cleaning tank could have reached this value.

High temperature experiments were carried out between 1000-1200 °C in order to identify the possible mechanisms leading to such a structure and for the estimation of the potential role of steel spring in the failure of fuel rods under high temperature accidents. Different geometrical arrangements have been tested in order to produce contacts with initial forces between the cladding and the steel spring. The spring was produced from steel with less than 1% Mn and Si content. The original spring of the fuel rod is characterized by two segments of different diameters. The small diameter segments allows to follow the expansion of the fuel stack, while the large diameter segment is in tight contact with the cladding and fixes the structure during assembling of fuel rod. These features were taken into account in the design of specimens. Schematic view of a typical sample is shown in Fig. 6. Some of the high temperature treatments were carried out in steam and some others in inert atmosphere. The oxidation time was several hours long in order to produce such conditions which are comparable to those of the cleaning tank incident.

The contact between the steel spring and the zirconium cladding was examined in details by scanning electron microscopy (Fig. 7). The BEI (Backscattered Electron

Image) view of an oxidised sample showed significant oxidation of the spring and formation of cracks in the 400-500 μm thick iron oxide scale (Fig. 8). The thickness of the zirconium oxide layer was between 30-100 μm on the surface of the cladding. Considering the seven hour dry phase of the incident and the possible temperature range, the above oxide layer thicknesses could be similar to the real values in the cleaning tank. The crack formation was probably the result of thermal stresses during the cool-down of the samples.

The first series of experiments was carried out in inert atmosphere. Twelve samples were tested at 1000-1200 $^{\circ}\text{C}$ for 2-5 hours. The samples did not show any measurable deformation on the outer surface of the cladding tubes after the high temperature treatment. There were signs of interaction between spring and cladding on the inner surface of the tube (Fig. 7). On the basis of these experiments it was concluded that neither the plastic deformation of cladding at the position of the spring, nor the formation of Fe/Zr eutectics between the steel and zirconium surface could produce alone the external spiral shape.

The second series of experiments was performed in high temperature steam. Four samples were oxidized in steam at 1000 $^{\circ}\text{C}$ for 4-6 hours. Three samples were oxidized after the high temperature treatment in argon and one sample without pre-treatment in argon. This last sample showed the typical picture of oxidized Zr cladding without any indication of interaction between spring and cladding. The three other samples were oxidized up to 25-38% ECR (Equivalent Cladding Reacted). The very high degree of oxidation produced spalling oxide scale and an uneven surface on

the cladding. The external spiral, however, could be observed on the sample which was oxidized only up to 25% ECR.

The phenomena (Fig. 9) observed at the Paks NPP could be reproduced only if the following conditions were met:

- There was tight contact between the spring and the fuel rod cladding in cold state before the test.
- Eutectic formation took place during the high temperature phase of the test.
- The sample was oxidized for long time in steam atmosphere.

It was an unexpected observation that the bulge of the external spiral was located not at the location of the spring wires, but between the wires. The bulge formation was obviously the result of the oxidation process which is normally accompanied with diameter increase, but in the present tests this size increase was limited by the eutectic contact with spring wires. The experimental results underlined that the steel spring played only negligible role in the behaviour and the failure of the fuel rods during the Paks-2 incident.

2.4. Zirconium oxidation in hydrogen rich steam

The hydrogen produced during zirconium oxidation accumulated in the cleaning tank and the chemical reaction between steam and zirconium took place mainly in hydrogen rich steam. Before the Paks-2 incident there were no published experimental data on the oxidation of E110 type alloy in high temperature hydrogen rich steam, for

most of the related tests were performed with Zircaloy-4 cladding (Chung, 1982; Moalem, 1991 and Steinbrück, 2004) and sponge Zr (Kim, 1997).

Since new experimental correlations (e.g. on E110 oxidation in hydrogen rich steam) were necessary for numerical modelling of the Paks-2 incident, a series of small scale experiments with 2-8 mm long E110 cladding tube rings and 100 mm long plugged tubes were carried out. The COHYRA (Cladding Oxidation in HYdrogen Rich steam Atmosphere) programme aimed at providing such information on the oxidation kinetics of E110 in hydrogen rich steam and on the change of mechanical properties due to oxidation and hydrogen uptake that could support the understanding and the numerical simulation of the Paks-2 event (Perez-Feró et al., 2006 and Perez-Feró et al., 2007).

Oxidation tests were performed at temperatures from 900 to 1100 °C in a high temperature furnace with special steam and hydrogen supply system. The oxidized samples were characterized by their oxygen content.

At each temperature several VVER cladding specimens were treated during different tracts of time between 100 s and 15000 s in order to achieve different oxidation ratios. The extent of the oxidation was measured through the weight gain of the specimens and was compared to that in pure steam. Tests were carried out in hydrogen-steam mixtures with hydrogen content between 5 vol.% and 65 vol.%.

Oxidation tests in pure steam produced larger mass gains than any test in hydrogen-steam mixture. Surprisingly, the oxidation mass gain rates measured in high vol. % H-

steam mixture had no significant difference as compared to the results in low vol. % H-steam mixture. The difference between 5 vol.% and 65% vol.% concentrations was less than between pure steam and 5 vol.% H-steam mixture. The comparison of oxidation rate constants measured in pure steam and in hydrogen-rich steam atmosphere indicates that the hydrogen content in the steam is likely to decelerate the cladding oxidation (Fig. 10).

After oxidation of the samples, mechanical testing (ring compression, ring tensile and burst tests) was carried out and the hydrogen content of the broken pieces was determined by means of hot extraction method. The measured data indicated that the hydrogen absorption by the Zr alloy was much more intense in hydrogen rich steam atmosphere than in pure steam.

Ring compression and ring tensile tests were performed in standard tensile test machine at room temperature. The results of ring tensile and compression tests showed that the effects of slower oxidation and high hydrogen uptake compensated each other, and the mechanical load bearing capabilities of samples oxidized in steam and in hydrogen-steam mixture at the same temperature, for the same oxidation time, proved to be very similar.

High temperature furnace with argon atmosphere was applied for ballooning tests, which were performed under isothermal conditions in the temperature range of 900 – 1000 °C with increasing internal pressure. The samples were closed with end-plugs. The pressurization was performed through a pipe attached to one end of the specimen.

The 100 mm long Zr1%Nb tube specimens were pre-oxidized under isothermal conditions in constant steam-hydrogen flow, the maximum oxidation ratio was 5 %.

The ballooning tests showed that the burst pressure of the pre-oxidized samples was higher than that of the as-received specimen. At low oxidation ratio the strength of the cladding increased and the cladding deformation was lower. The effect of hydrogen uptake was not obvious. The measurements of the hydrogen content of the specimens carried out after the burst tests have indicated that most of the hydrogen absorbed in the pre-oxidized specimens was released during the high temperature burst tests.

The new experimental data on E110 cladding have been compiled in order to support model development and code validation purposes. The database is available in the OECD NEA Databank as part of the International Fuel Performance Experiments Database (Perez-Feró, 2008).

3. Integral tests

Integral tests were carried out in the CODEX facility which was originally built for severe accident studies. The behaviour of fuel rods in high temperature steam, the quenching at high temperature, the role of control rods (Hózer, 2006) and the phenomena related to air ingress scenarios (Hózer, 2003) were addressed in the earlier tests. Integral severe accidents tests with electrically heated fuel bundles have been carried out in the CORA (Schanz et al., 1992; Hofmann et al., 1997), QUENCH (Hofmann et al., 1998; Miassoedov et al., 2008; Steinbrück et al., 2006; Stuckert et al., 2009) and PARAMETER (Steinbrück et al., 2009) tests facilities and in some of these tests the high temperature bundles were quenched by cold water after intense

oxidation. Similarly to the previous CODEX tests, the CORA, the QUENCH and the PARAMETER experiments simulated relatively fast heat-up of fuel rods and none of the tests was performed in hydrogen rich steam.

In order to simulate the very long (7 hours) heat-up phase and establish high hydrogen concentration in the test section, the original arrangements of the CODEX facility had to be significantly changed for the CODEX-CT (Cleaning Tank) test series. There were no internal heaters applied inside of the fuel rods, but external heaters were used to produce the necessary temperature for the hexagonal seven-rod bundle. The 1 m long fuel rods were filled with alumina pellets and pressurized inside. The bundles were surrounded by hexagonal shrouds made of Zr2.5%Nb alloy (Fig. 11). The test section with the bundle was connected to another vessel that simulated the water volume of the spent fuel storage pool. In the test section several perforations were applied on the inner cylinder and on the shroud to allow the by-pass flow between the inlet and outlet junctions without cooling of the fuel rods. In this configuration the full scenario of the Paks-2 incident could be simulated. In the design of the facility the ratio of Zr surface to the total volume of the coolant was kept as a main parameter providing the similarity for fuel oxidation process in the cleaning tank. The facility was thoroughly instrumented for the measurement of temperatures, flowrates, pressures, power, hydrogen concentration and hydrogen release. Detailed description of test facility, test conditions and post-test examinations have been published elsewhere (Hózer et al., 2009b), in the present paper it is intended to summarize only those findings from the CODEX-CT tests which contribute to the interpretation of results of separate effect tests described in Chapter 2.

The experiments were performed according to the following scenario:

- The tests started from cold state and the test section was filled with water. The decrease of coolant flowrate led to heat up of the water and formation of steam volume as a result of by-pass flow.
- The low water level was kept for seven hours with constant coolant flow and electric power. The temperature monotonously increased and high temperature oxidation of Zr took place in H-rich steam.
- The final cool-down of the fuel rods was performed by a combined water quenching from the bottom and from the top. The bottom injection simulated the operation of pumps while the upper one represented the opening of the lid.

Three tests were carried out with the main conditions of the cleaning tank incident.

First a preliminary test was carried out with empty cladding tubes and sheets of assembly shroud. The CODEX-CT-1 and CODEX-CT-2 tests were performed with 1 m long seven-rod bundles.

The original purpose of the preliminary test was the testing of different components and data acquisition system of the facility. In order to have information on the kinetics of the zirconium oxidation and on the dynamical behaviour of the system with hydrogen production, pieces of fuel rod cladding and plates of zirconium shroud were placed in the test section. The total amount of zirconium alloy was equal to the mass of the zirconium in the 7-rod bundle that was used in the later tests. The cladding tubes were heavily fragmented during the test: the fuel rods were broken into several pieces and during the handling of the tubes further fragmentation took place (Fig. 12).

The shroud plates were mainly intact, but so brittle that the 2 mm thick plates could be broken by hands.

In the CODEX-CT-1 test the fuel rods were pressurized in the beginning of the test to different values. The rods with high pressure lost their integrity due to burst at 800-900 °C. Long ballooned sections were observed in the post-test examinations. The hottest part of the rods was in the central-upper section at about 700 mm elevation. The bottom part of the rods (about 50 mm) was cooled by water and the temperatures remained low in that section. The fuel rods and bundles suffered severe damage during the tests. The final state was characterized by fragmentation, formation of cracks and brittle failure of the Zr components. The bottom part of the fuel bundle that was cooled by water remained intact. The experience of handling of fuel rods after the test showed that the material was very brittle: even a small mechanical load lead to further fragmentation of the cladding and the shroud. Cross section of the CODEX-CT-1 bundle is shown in Fig. 13. Large ballooning of the tubes can be noticed in both cross sections. In the lower cross section the accumulation of fuel rod fragments can be seen which were fallen down from higher elevations. In the preliminary test and CODEX-CT-1 test the produced hydrogen was released from the test section meanwhile the internal pressure of the cleaning tank model was kept constant. During those two tests 200-300 dm³ of H₂ was released, the atmosphere contained 60-80 vol.% hydrogen and the average degree of oxidation was above 20% ECR. The maximum temperature during the oxidation phase reached 1250 °C in the upper part of the bundle (Fig. 14).

In the CODEX-CT-2 test hydrogen was not released from the tank model during the dry phase. The oxidation was much less before quenching, for the produced hydrogen could not escape and it filled up the volume of the cleaning tank. Large amount of the produced hydrogen was taken up by the zirconium components of the bundle. The final quenching led to significant temperature increase in some positions. Fig. 15 shows that the maximum temperature reached during the oxidation phase was 1250 °C, but during quenching the peak value was 1380 °C. In the CODEX-CT-1 test there was no temperature increase during quench, since the rods were highly oxidized before this phase. In the CODEX-CT-2 test the oxidation was much less and the high temperature surfaces reacted with the cold water. The bundle was even more brittle than in the previous test. The fuel rods were broken into pieces inside of the assembly and the shroud was also severely damaged.

4. Discussion of results

The CODEX-CT integral tests simulated the main events of the Paks-2 incident, but the investigation of some special phenomena needed special separate effect tests. The sequence of fuel behaviour related events could be deduced considering both integral and separate effect tests. Fig. 16 shows the temperature history curve of CODEX-CT-1 test with the indication of the temperature ranges for several events and processes.

The cleaning tank incident started with water circulation using a low flow rate pump. The low flow rate and the by-pass flow led to stratification of water in the tank. Quick steam volume formation took place after reaching saturation of water. The coolant circulated through the by-pass between the inlet and outlet junctions in the bottom of

the tank and the upper part of the fuel rods were in dry conditions until the opening of the vessel. This dry period lasted for seven hours. The high decay heat (241 kW) and the insufficient heat removal from the fuel resulted in monotone temperature increase.

Start of Zr oxidation was detected above 600 °C in the test facility. The produced hydrogen was accumulated in the steam volume and the high temperature oxidation took place in hydrogen rich steam. Part of the produced hydrogen was absorbed by the cladding and the shroud.

Plastic deformation of fuel rods with high internal pressure started above 800 °C.

Ballooning and burst took place between 800 °C and 1000 °C. Ballooning was limited at the position of spacer grids. Inner side oxidation of cladding started after loss of fuel integrity.

The interaction between spring and cladding and formation of Fe/Zr eutectic on the inner surface of cladding tubes could take place in those positions where temperature reached 1100 °C.

Due to long term oxidation and hydrogen uptake, the Zr components lost ductility and their embrittlement continuously increased. In the hottest part of the fuel the load-bearing capability of cladding was very low.

After the opening of the cleaning tank the water injected by the pump could penetrate into the hot section of the assemblies. The quick steam production resulted in high

pressure in the bottom part of the assemblies and this could lead to the upward shift of some assemblies. Those assemblies could touch the cover of the tank.

The fast quenching of the fuel assemblies by cold water created thermal and mechanical loads on the fuel. Some very brittle fuel cladding and shroud could fragment because of thermal stresses. The penetration of water from the top of the tank took place from one side and this created some radial flows inside of the tank. The large mass water produced high mechanical loads on the fuel assemblies. The radial loads between the fuel rods could be transferred through the spacer grid and many fuel rods were broken at the location of spacers.

Finally, the tank was fully quenched and the heat removal was stabilized by circulation of water from the surrounding spent fuel storage pool.

5. Conclusions

The small scale separate effect and large scale integral tests made possible the understanding of several phenomena that took place in the Paks-2 cleaning tank incident. The experiments provided new measured data on the behaviour of fuel assemblies under high temperature conditions. The conclusions of the performed experiments may improve the prediction of the consequences of such fuel accidents (e.g. ex-core fuel damage) that were not covered by earlier experimental programmes.

High temperature tests with small fuel bundles confirmed the possibility of upward shifts of fuel assemblies due to a rocket force type effect during reflood. The intense

production of steam inside of the bundle can lift up the assembly if it is covered by shroud and is not fixed. Such situation can potentially take place in spent fuel storage pools with VVER or BWR assemblies.

Investigation of the interactions between the cladding and the spacer grid during ballooning of fuel rods indicated that the local stresses did not create cracks in the vicinity of the contact and the cladding did not become weaker in this region. The mechanical testing of ballooned and oxidized bundles showed that the radial load could be easily transferred by the spacer grid and this fact explained the reason for breaking of many fuel rods at the position of the spacer grid during the Paks-2 incident.

According to high temperature tests with short fuel rod samples, interactions between the steel spring and the zirconium cladding did not lead to failure of the cladding in the investigated range of parameters (up to 1200 °C). The external spiral shape observed on some fuel rods of the Paks-2 incident was explained by a combined effect of mechanical and chemical interactions between the cladding and the spring in steam atmosphere.

The COHYRA experiments provided detailed information and new numerical correlations on the oxidation, hydrogen uptake and embrittlement of the E110 type cladding in high temperature hydrogen rich steam. The collected experimental data are available in the OECD NEA Databank.

The test conditions in the integral CODEX experiments were selected in such a way that several unknown parameters of the incident were covered. The final state of the fuel rods showed many similarities with that observed after the incident at the Paks NPP and for this reason it is presumable that the thermal conditions and the chemical reactions in the tests were also similar to those during the incident. The post-test examination of the CODEX bundles indicated that the high degree of embrittlement was a common result of oxidation and hydrogen uptake by the zirconium components.

References

Bajsz, J., Gadó, J., 2004. Ex-core Fuel Damage Event at Paks - Causes, Consequences and Lessons Learned, Proc. Int. Conf. Nuclear Energy for New Europe 2004, Portorož , Paper 901

Chung, H. M., Thomas, G. R., 1982. High-Temperature Oxidation of Zircaloy in Hydrogen-Steam Mixtures; 6th International Symposium on Zirconium in the Nuclear Industry, ASTM 04-824000-35.

Hofmann, P., Hagen, S.J.L., Noack, V., Schanz, G., Sepold, L.K., 1997. Chemical-Physical Behaviour of Light Water Reactor Core Components Tested under Severe Reactor Accident Conditions in the CORA Facility, Nucl. Technol., 118, 200-224.

Hofmann, P., Hering, W., Homann, C., Leining, W., Miassoedov, A., Piel, D., Schmidt, L., Sepold, L., Steinbrück, M., 1998. QUENCH-01 Experimental and Computational Results, FZKA 6100, Forschungszentrum Karlsruhe.

Hofmann, P., 1999. Current knowledge on core degradation phenomena, a review, J. Nucl. Mat. 270 194-211

Hózer, Z., Windberg, P., Nagy, I., Maróti, L., Matus, L., Horváth, M., Pintér, A., Balaskó, M., Czitrovszky, A., Jani P., 2003. Interaction of failed fuel rods under

air ingress conditions, Nucl. Technology, 141, 244-256

Hózer, Z., Győri, Cs., Horváth, M., Nagy, I., Maróti, L., Matus, L., Windberg, P.,
Frecska, J., 2005. Ballooning Experiments with VVER Cladding, Nucl.
Technology, 152, pp. 273-285

Hózer, Z., Maróti, L., Windberg, P., Matus, L., Nagy, I., Gyenes, Gy., Horváth, M.,
Pintér, A., Balaskó, M., Czitrovsky, A., Jani, P., Nagy, A., Prokopiev, O., Tóth,
B., 2006. Behaviour of VVER fuel rods tested under severe accident conditions
in the CODEX facility, Nucl. Technology, 154, 302-317.

Hózer, Z., Aszódi, A., Barnak, M., Boros, I., Fogel, M., Guillard, V., Győri, Cs.,
Hegyí, Gy., Horváth, G.L., Nagy, I., Junninen, P., Kobzar, V., Légrádi, G.,
Molnár, A., Pietarinen, K., Pernecky, L., Makihara, Y., Matejovic, P., Perez-
Feró, E., Slonszki, E., Tóth, I., Trambauer, K., Tricot, N., Trosztel, I.,
Verpoorten, J., Vitanza, C., Voltchek, A., Wagner, K.C., Zvonarev, Y., 2009a.
Numerical analyses of an ex-core fuel incident: Results of the OECD-IAEA
Paks Fuel Project, Nucl. Eng. Des., doi:10.1016/j.nucengdes.2009.09.031

Hózer, Z., Balaskó, M., Horváth, M., Kunstár, M., Matus, L., Nagy, I., Novotny, T.,
Perez-Feró, E., Pintér, A., Vér, N., Vimi, A., Windberg, P., 2009b. Quenching
of high temperature VVER fuel after long term oxidation in hydrogen rich
steam, Ann. Nucl. Energy, doi:10.1016/j.anucene.2009.09.014

Kim, Y.S, Wang, W.E., Lim, S., Olander, D.R., Yagnik, S.K., 1997. High Pressure
Oxidation of Sponge-Zr in Steam/Hydrogen Mixtures, J. Nucl. Mat., 245, 152-

- Kim, J.H., Choi, B.K, Baek, J.H., Jeong, Y.H., 2006. Effects of oxide and hydrogen on the behavior of Zircaloy-4 cladding during the loss of the coolant accident (LOCA), Nucl. Eng. Des. 236, 2386–2393
- Markiewicz, E.M., Erbacher, F.J, 1988. Experiments on Ballooning in Pressurised and Transiently Heated Zircaloy-4 Tubes, Kernforschungszentrum Karlsruhe, KfK-Bericht 4343.
- Maróti, L., 1997, Chemical interaction between VVER core components under accidental condition, Nucl. Eng. Des. 172, 73-81.
- Miassoedov, A., Alsmeyer, H., Meyer, L., Steinbrück, M., Groudev, P., Ivanov, I., Sdouz, G., 2008. Results of the QUENCH-L2, DISCO-L2, and COMET-L2 experiments performed within the LACOMERA project at the Forschungszentrum Karlsruhe, Nucl. Eng. Des., 238, 2017-2026.
- Moalem, M., Olander, D. R., 1991. Oxidation of Zircaloy by Steam, J. Nucl. Mat. 182, 170-194.
- Perez-Feró, E., Windberg, P., Hózer, Z., Horváth, M., Nagy, I., Pintér-Csordás, A., Szabó, E., Kulacsy, K., 2006. Experimental Database of E110 Cladding Oxidised in Hydrogen Rich Steam, Transactions of TOPFUEL 2006, 605-609

- Perez-Feró, E., Hózer, Z., Windberg, P., Nagy, I., Vimi, A., Vér, N., Matus, L.,
Kunstár, M., Novotny, T., Horváth, M., Gyóri, Cs., 2007. Behavior of Zr1%Nb
Fuel Cladding under Accident Conditions, Proc. Int. LWR Fuel Performance
Meeting, San Francisco, Paper 1018
- Perez-Feró, E., Gyóri, Cs., Matus, L., Vasáros, L., Hózer, Z., Windberg, P., Maróti,
L., Horváth, M., Nagy, I., Pintér-Csordás, A., Novotny, T., 2008. Experimental
Database of E110 Claddings under Accident Conditions, NEA-1799
IFPE/AEKI-EDB-E110
- Réocreux, M., Scott de Martinville, E.F., 1990. A study of fuel behavior in PWR
design basis accident: an analysis of results from the PHEBUS and EDGAR
experiments, Nucl. Eng. Des. 124, 363-378.
- Schanz, G., Hagen, S., Hofmann, P., Schumacher, G., Sepold, L., 1992. Information
on the evolution of severe LWR fuel element damage obtained in the CORA
program, J. Nucl. Mat. 188, 131-145.
- Steinbrück, M., 2004. Hydrogen absorption by zirconium alloys at high temperatures,
J. Nucl. Mat., 334, 58-64
- Steinbrück, M., Miassoedov, A., Schanz, G., Sepold, L., Stegmaier, U., Stuckert, J.,
2006. Experiments on air ingress during severe accidents in LWRS, Nucl. Eng.
Des., 236, 1709-1719.

Steinbrück, M., Birchley, J., Bodyrev, A.V., Goryachev, A.V., Grosse, M., Haste, T.J., Hózer, Z., Kisselev, A.E., Nalivaev, V.I., Semishkin, V.P., Sepold, L., Stuckert, J., Vér, N., Veschunov, M.S. 2009. High temperature oxidation and quench behaviour of Zircaloy-4 and E110 cladding alloys, Prog. Nucl. Energy, doi:10.1016/j.pnucene.2009.07.012

Stuckert, J., Birchley, J., Große, M., Haste, T., Sepold, L., Steinbrück, M., 2009. Experimental and post-test calculation results of the integral reflood test QUENCH-12 with a VVER-type bundle, Ann. Nucl. Energy, 36, 183-192

Figure captions

Fig. 1. Cleaning tank with fuel assemblies touching the lid during the opening of the tank

Fig. 2. Snapshots illustrating the change of bundle position during injection of cold water from the bottom

Fig. 3. Cross section of ballooned tube

Fig. 4. View of sample with secondary ballooning away from the position of the spacer grid

Fig. 5. View of seven rod bundle after oxidation and ballooning in steam (left) and followed by radial mechanical testing (right)

Fig. 6. Schematic view of a cladding sample with spring

Fig. 7. Signs of interaction on the internal surface of cladding (left) and on the surface of the spring (right) after test without oxidation

Fig. 8. BEI view of the interface between steel spring and zirconium cladding after oxidation

Fig. 9. Cladding sample showing the external spiral shaped deformation

Fig. 10. Oxidation rate constants for E110 as functions of temperature in steam and steam-hydrogen mixture

Fig. 11. Horizontal cross section of the bundle and the heaters

Fig. 12. View of Zr cladding and shroud after seven hours of high temperature oxidation and final quenching by cold water in the preliminary test (left picture: reconstructed vertical state of plates and tubes, right picture: close view of the tubes)

Fig. 13. Cross sections of the CODEX-CT-1 bundle at 360 mm (left) and mm 560 mm (right) elevations

Fig. 14. Temperature histories in CODEX-CT-1 test

Fig. 15. Temperature histories in CODEX-CT-2 test

Fig. 16. Probable sequence of events in the Paks-2 incident

Hózer, Fig. 1.

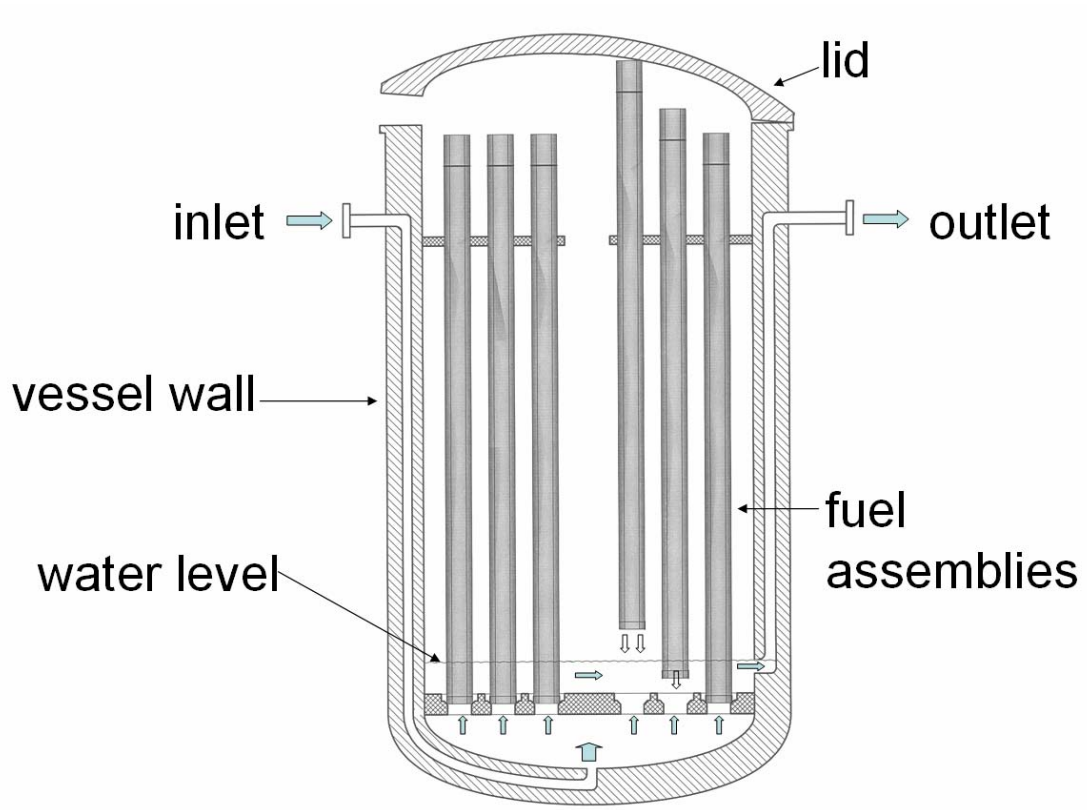


Fig. 1. Cleaning tank with fuel assemblies touching the lid during the opening of the tank

Hózer, Fig. 2.

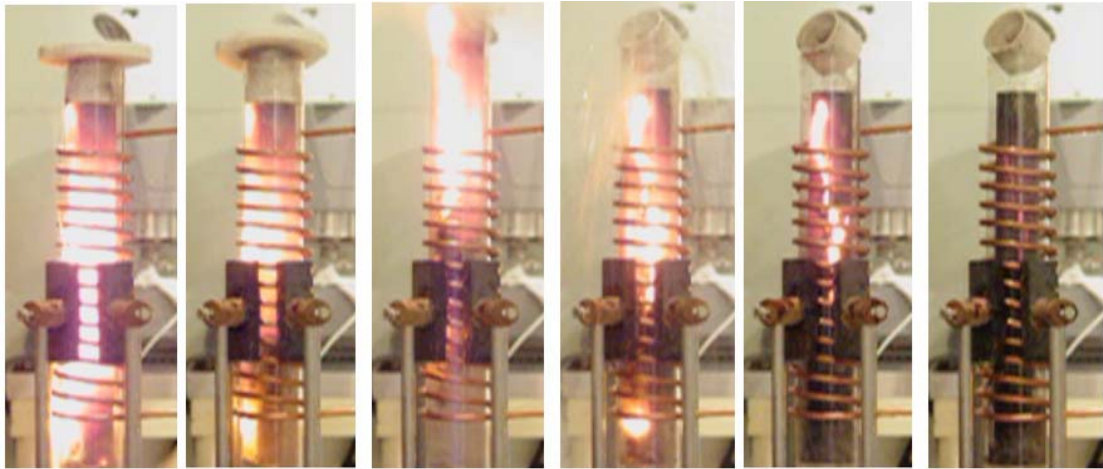


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Hózer, Fig. 3.



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Hózer, Fig. 4.



Fig. 4. View of sample with secondary ballooning away from the position of the spacer grid

Hózer, Fig. 5.

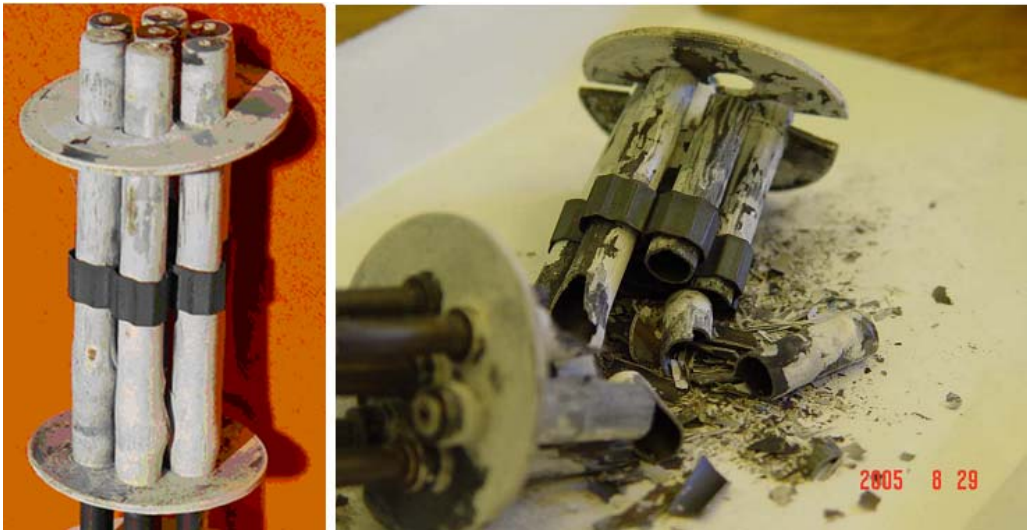


Fig. 5. View of seven rod bundle after oxidation and ballooning in steam (left) and followed by radial mechanical testing (right)

Hózer, Fig. 6.

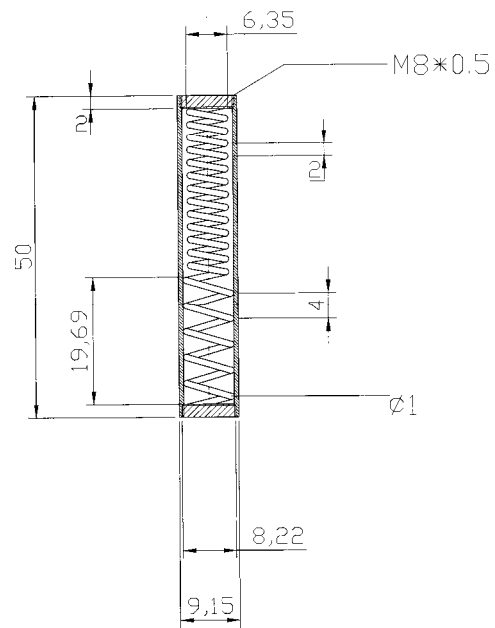


Fig. 6. Schematic view of a cladding sample with spring

Hózer, Fig. 7.

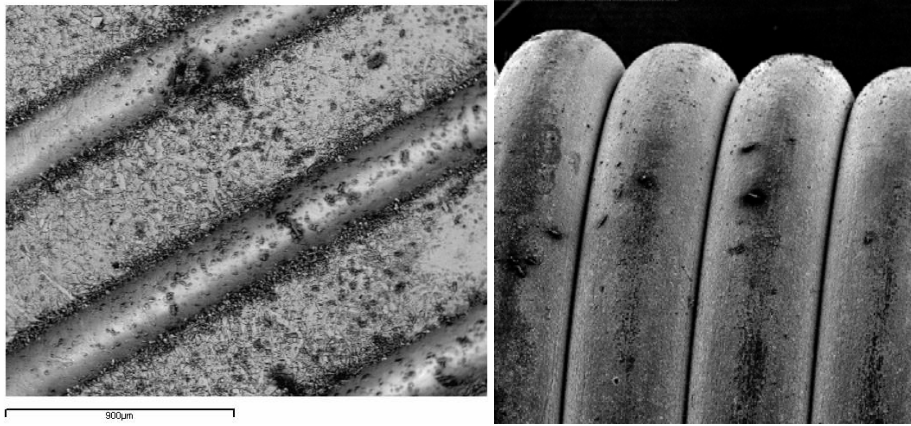


Fig. 7. Signs of interaction on the internal surface of cladding (left) and on the surface of the spring (right) after test without oxidation

Hózer, Fig. 8.

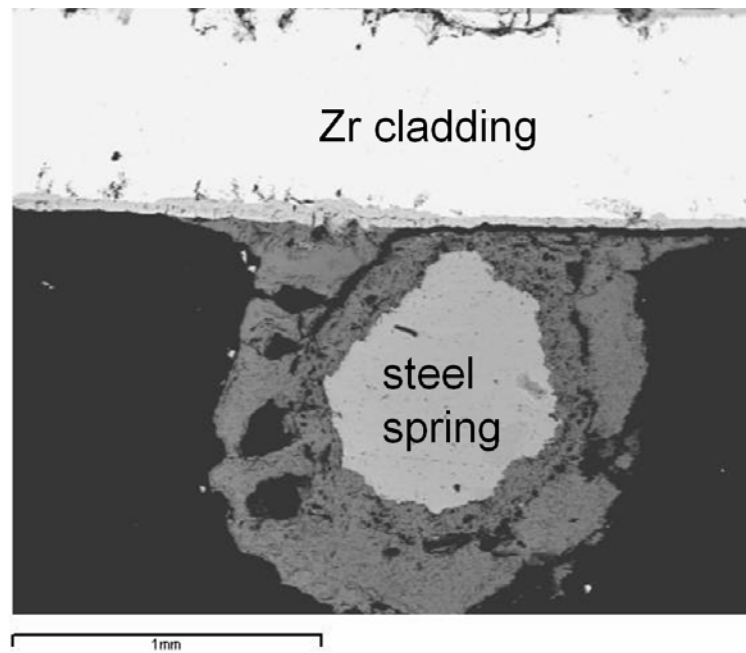


Fig. 8. BEI view of the interface between steel spring and zirconium cladding after oxidation

Hózer, Fig. 9.

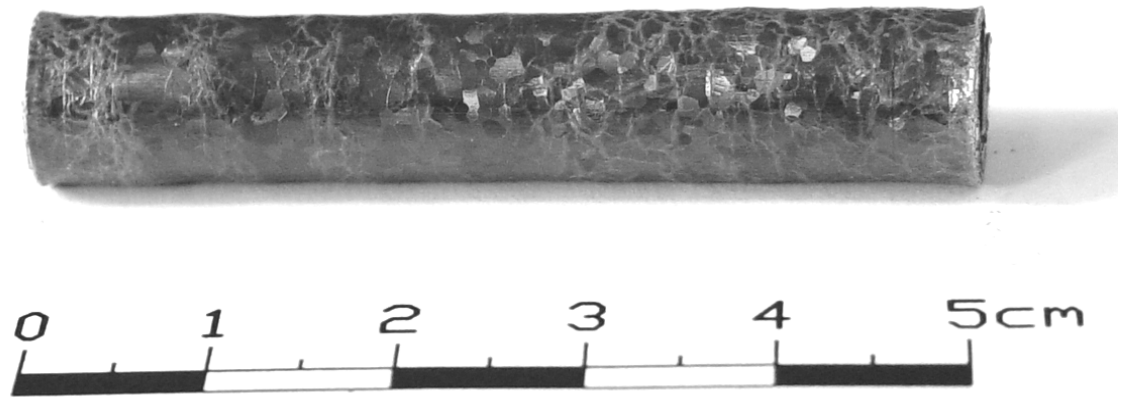


Fig. 9. Cladding sample showing the external spiral shaped deformation

Hózer, Fig. 10.

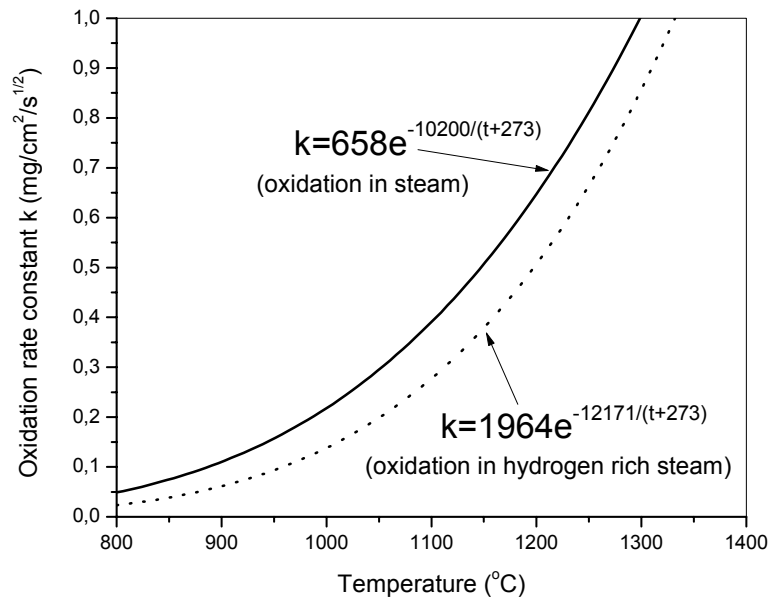


Fig. 10. Oxidation rate constants for E110 as functions of temperature in steam and steam-hydrogen mixture

Hózer, Fig. 11.

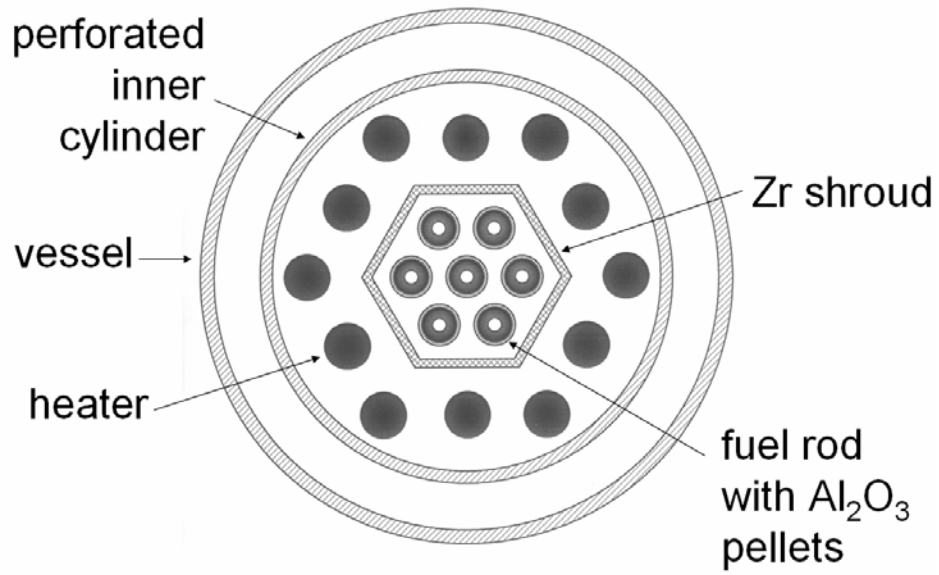


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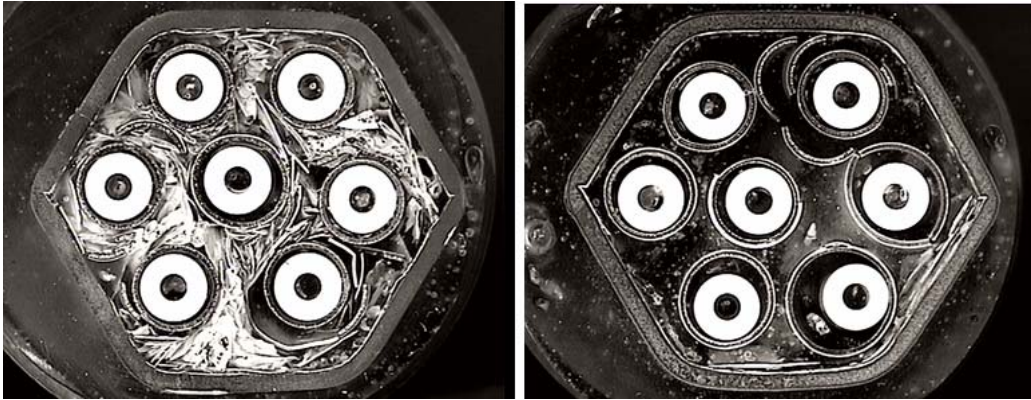


Fig. 13. Cross sections of the CODEX-CT-1 bundle at 360 mm (left) and mm 560 mm (right) elevations

Hózer, Fig. 14.

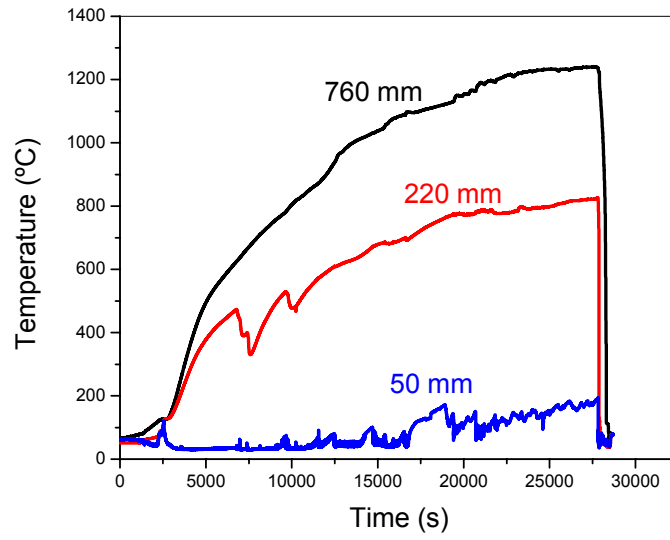


Fig. 14. Temperature histories in CODEX-CT-1 test

Hózer, Fig. 15.

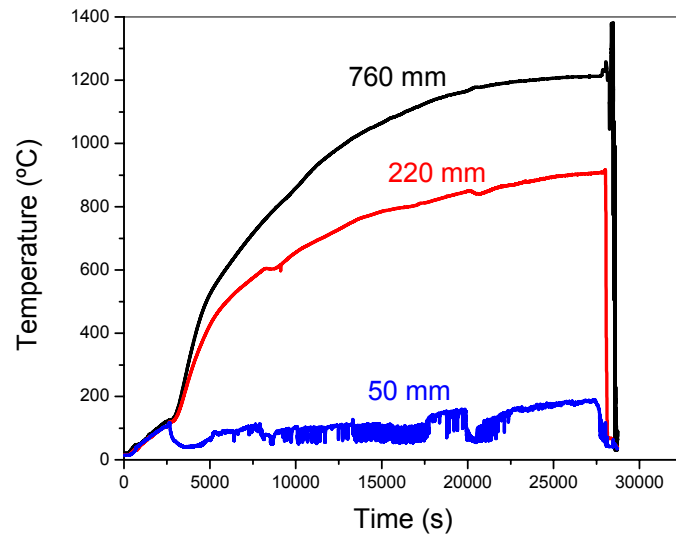


Fig. 15. Temperature histories in CODEX-CT-2 test

Hózer, Fig. 16.

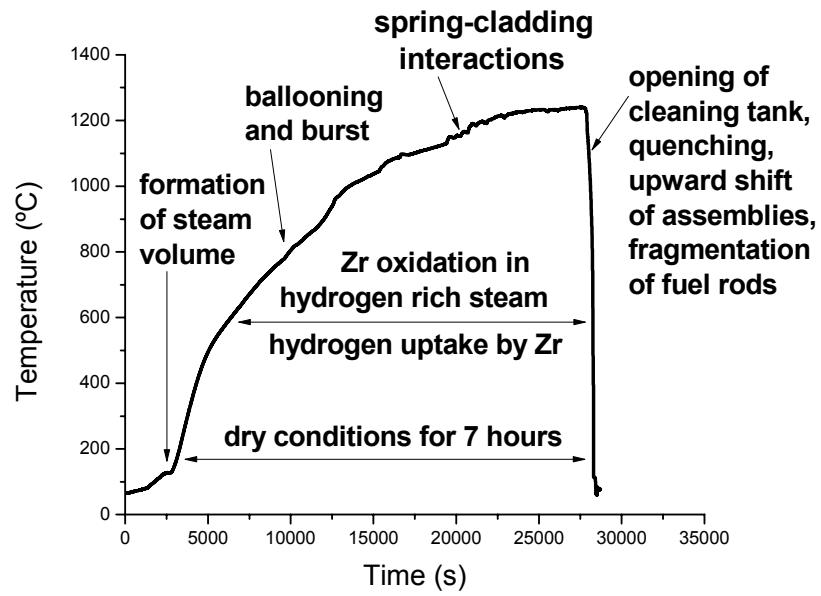


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