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CODEX-CT-1 AND CT-2 INTEGRAL TESTS: TWO POSSIBLE SCENARIOS OF THE PAKS-2 INCIDENT

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ABSTRACT

In April 2003 chemical cleaning of VVER fuel took place at the Paks Nuclear Power Plant in order to remove crud from the assemblies. Due to design problems the cooling of the fuel was insufficient and the decay heat resulted in the heat-up, oxidation and embrittlement of the zirconium components. The opening of the cleaning tank and the water inflow from the spent fuel storage pool led to the fragmentation of fuel assemblies and to the release of radioactive fission products. The conditions of the incident were characterised by large uncertainties because of poor instrumentation. The Paks-2 cleaning tank incident was simulated with an electrically heated 7-rod fuel bundle in the CODEX facility. The tests conditions covered the main phases of the incident.

There was no exact information on the role and operation of air let-down valve in the Paks-2 incident. The CODEX-CT-1 and CT-2 tests confirmed that both fully open and closed status of the valve could result in the embrittlement of fuel assemblies after seven hours of high temperature treatment.

The CODEX-CT-1 and CT-2 tests were carried out with slightly different power, system pressure and fuel rod internal pressures. Both tests were performed in hydrogen rich steam atmosphere. The most significant difference between the two tests was that in case of CT-1 experiment the produced hydrogen was continuously released from the tank through an air letdown valve, while during the CT-2 test this valve was closed. The accumulation of hydrogen in the second test resulted in much lower degree of oxidation then in the first test. The zirconium components picked up large amount of hydrogen in both tests. The final reflood led to full cross section break of the CT-1 bundle and fragmentation of CT-2 bundle.

1 INTRODUCTION

During the Paks-2 incident very few measurements were taken. The coolant outlet temperature and flow rate were recorded from measurements in the connecting tubes. The temperature was decreasing during the intermediate cooling mode and it indicated that the heat removal from the tank decreased at least by ~30%. The decrease of outlet temperature stopped after the water level change in the pressurizer. This fact indicated that after the formation of steam volume a special flow path was established, which cooled only a limited (bottom) part of the fuel. The pressurizer level was recorded continuously. The water level increased at ≈2,5 hours after the initiation of intermediate cooling mode and returned to the original level after the opening of the cleaning tank. This measurement showed that the steam volume formation took ≈15 minutes only. The time between the level changes was about 7 hours, so part of the fuel rods were in dry conditions for this long period.

After the incident detailed visual examination was carried out with the help of video cameras. The examination indicated that most of the fuel assemblies suffered damage. Brittle failure and fragmentation of fuel assemblies was observed. Many assemblies were broken and fragmented below the upper plate, too. Some assemblies were fractured in their entirety. Fuel rod fragments and shroud pieces accumulated on the lower plate between the assemblies. Some fuel pellets were fallen out of fuel rods, their form remained mainly intact. Heavy oxidation of the zirconium components was identified. Less oxidation was found in the periphery than in the centre. The bottom part of the fuel remained intact. There were no signs of melting or formation of zirconium-steel eutectics on the surface of stainless steel components. This fact indicated that the maximum temperature during the incident remained below ≈1400 ^{o}C. There was a ^{85}Kr activity measurement in the air letdown line. Significant increase of this value indicated the loss of some fuel rod integrity at about 5 hours after the initiation of intermediate cooling mode in the tank. That time the fuel were already in dry conditions for about 2,5 hours.

Thermal hydraulic calculations pointed out that the main reason for the insufficient cooling in the cleaning tank was a design problem: both inlet and outlet junctions were located in the lower part of the tank and a by-pass flow could be formed between them [2]. Due to the low flow rate of the bundle, the by-pass flow through the perforations in the assembly shroud and at the bottom of the imperfectly seated assemblies became much more significant, than it was during the cleaning operation with high flow rate The numerical analysis showed that the heating-up of the water lead to saturation state in the top of the tank. The production of 4m^3 steam could take place rather fast, considering the decay heat of the assemblies, and the formation of water level in the cleaning tank took only some minutes after saturation was reached. The fuel behaviour calculations proved that the loss of fuel integrity in 5 hours after the initiation of intermediate cooling mode was a result of fuel rod ballooning and burst . The fuel rods could heat up above 800 ^{o}C by that time and the internal pressure in some rods resulted in plastic deformation and burst.

2 CLEANING TANK DESIGN

The chemical cleaning of the fuel assemblies was performed in cleaning tank that was placed in the bottom of a special pit under 13 m water. The tank had double walls and vacuum between them to reduce heat losses. In the cleaning tank was place for 30 fuel assemblies. The assemblies had verticon, they were rested on the bottom plate and were fixed by the upper plate . The distance between the assemblies was much larger than in the reactor core. Acidic solution was applied for the chemical removal of magnetite containing crud, this operation was performed at high liquid flow (170 t/h) in a closed circulation loop. After the completion of crud removal the solution was changed for clean water of the spent fuel storage pool and the circulation was established in an open loop at low flow rate (21 t/h). The flow path of the coolant started from the lower plenum of the tank and entered the assemblies from the bottom. The upper plate of the tank had large holes and it made possible the down flow of the coolant between the fuel assemblies. The outlet tube was connected to the bottom part the tank just above the bottom plate. There was an air letdown valve on the top of the tank to release gases if necessary.

3 THE CODEX-CT EXPERIMENTS

While the small scale tests investigated some important but specific aspects of the Paks-2 incident, it was necessary to carry out integral tests simulating the whole scenario of the incident. Two integral experiments were carried out with fuel rod bundles in the CODEX facility and a preliminary test with empty cladding tubes and shroud plates. The CODEX-CT-1 and CT-2 tests were performed with 1 m long seven-rod bundles. The rods were filled with alumina pellets and pressurised inside. The bundles were covered by hexagonal shrouds made of Zr2.5%Nb alloy. The bundle was surrounded by electrical heaters. The tests section was connected to another vessel that simulated the water volume of the spent fuel storage pool.

Main phases of CODEX-CT tests scenarios were the followings:

- Formation of water level and steam volume in the tank
- Seven hours oxidation in high temperature steam,
- Final reflood of brittle fuel assemblies.

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 temperatures monotonely increased and the maximum temperature reached 1200-1300 ^{o}C. The fuel rods were pressurised in the beginning of the tests to different values. The rods with high pressure lost their integrity due to burst at 800-900 ^{o}C. The pressure increase reached a maximum during the tests and before burst their value slightly decreased. (Fig. 7). The tests were finalised by water reflood simulating the opening of the cover of cleaning tank. The fuel rods and bundles suffered severe damage during the tests. The final state was characterised by fragmentation, formation of cracks and brittle failure of the Zr components. The bottom part of the fuel that was cooled by water remained intact. This fact allowed us to draw conclusions on the similarities between measured test parameters and the unknown parameters of the incident.

The next tables and figures (Table 1, Fig. 2, Fig. 3,) show the genuine construction of cleaning tank used during the Paks-2 incident and its model applied in CODEX-CT facility integral tests.

Table 1. Main parameters of the Paks cleaning tank and the CODEX-CT facility

	Paks-2 cleaning tank	CODEX-CT facility
Number of fuel rods	3870	7
Total flow rate	21 t/h	106 l/h
Total volume	6 m^3	9,2 l
Volume of steam	4 m^3	6 l
Total surface of Zr	300 m^2	0,44 m^2
Ratio of total Zr surface/total volume	50 m^{-1}	48 m^{-1}
Total power	241 kW	2,3 kW

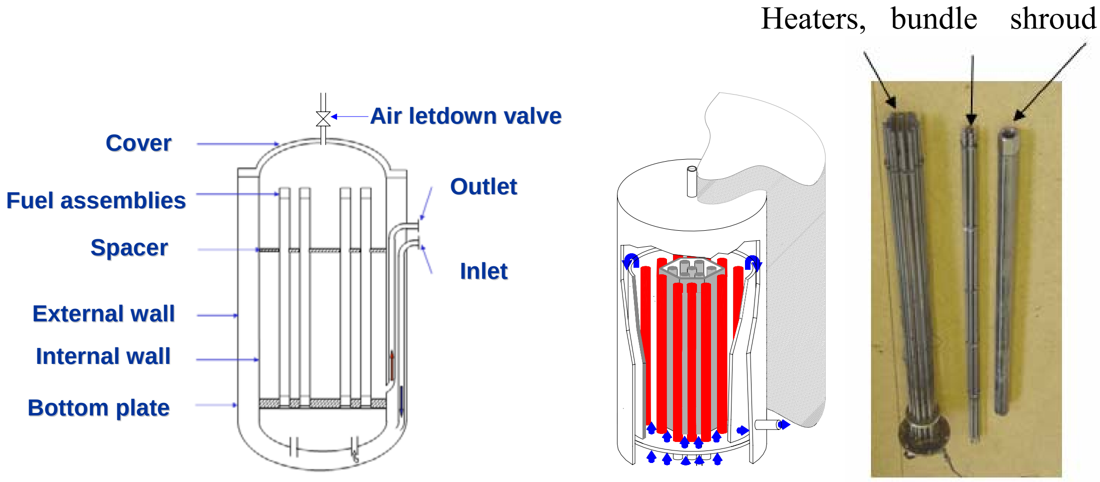


Fig. 2. Design of the cleaning tank, scheme of the CODEX-CT test section and picture of the bundle

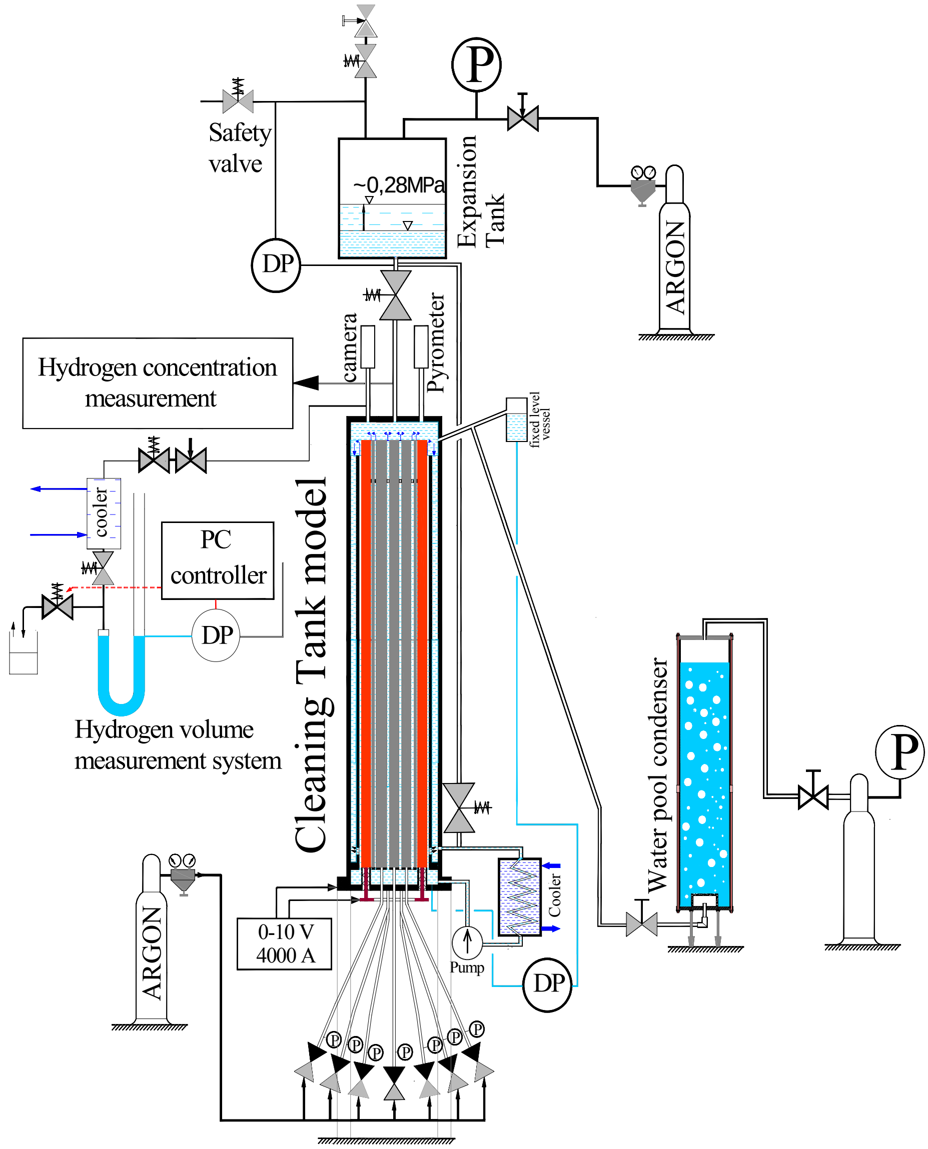


Fig. 3 Main components of the CODEX-CT facility

4 RECONSTRUCTION OF THE INCIDENT

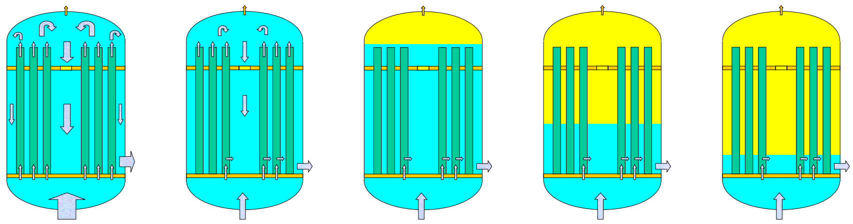
As there were no measurements inside of the cleaning tank the reconstruction of the event included may uncertainties. The following scenario was put together from the mosaics of numerical analysis, high temperature experimental work and observations of the fuel state. The Paks-2 incident contained three main phases:

4.1 Formation of steam volume

After the initiation of intermediate cooling mode part of the coolant could bypass the fuel assemblies and did not take part in the removal of decay heat. Two paths were identified for the bypass flow:

- The working type VVER-440 fuel assemblies have perforation holes in the shroud.
- The perfect seating of the assemblies was not controlled and some gap could exist.

The flow through the assemblies was not enough to remove the decay heat and the temperature in the upper part started to increase. When the saturation temperature was reached the formation of a steam volume took place in short time. This period lasted about 2,5 hours



a *b* *c* *d* *e*

Fig.4. [1] Flow path of coolant in the cleaning tank during normal cleaning operation (a), at the beginning of intermediate cooling mode (b) and the steps of steam volume formation (c,d,e)

4.2 Plastic deformation of cladding and high temperature oxidation

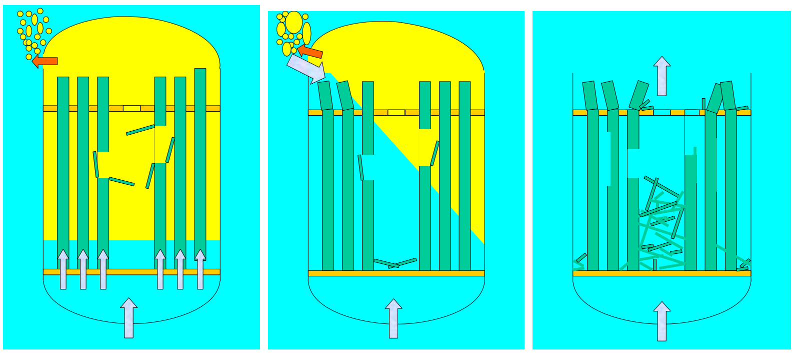
Continuous temperature increase started in the tank, when the upper part of the fuel rods was not cooled by water. The heat removal from the tank to the surrounding water was very low, because the vessel was isolated by the double wall system. The temperature increase led to the increase of pressure inside of the fuel rods. At 800-900 oC the internal pressure could reach 30-40 bars. In this range of pressure and temperature plastic deformation of the cladding can take place and the ballooning can lead to burst and activity release from the fuel. It is very probable that this type of fuel failure was responsible for the activity release measured by the 85Kr detectors. (Very long ballooned areas were found in the later visual inspection of the fuel.) The further increase of temperature accelerated the oxidation of zirconium components. The maximum cladding temperature reached 1200-1300 oC. The oxidation produced high hydrogen content in the stagnant steam volume. Most of the hydrogen could escape through the air letdown valve, but the high hydrogen concentration resulted in significant hydrogen uptake by the cladding and shroud. This period lasted for 7 hours. The bottom part was cooled by water and suffered no significant changes.

4.3 Reflood

The possible reflood scenario included the following steps:

1. The opening of the hydraulic locks created a small gap between the cover and the vessel.
2. Some gas was released through the gap from tank into the spent fuel storage pool and the pressure in the tank decreased (Fig.5.f).
3. Water injection through the inlet line could reach higher elevations than before the opening of the cover due to low pressure.
4. Intense steam production took place when the cold water evaporated on the hot surface of the fuel. Probably this process resulted in vertical upward movements of the assemblies, that were recognised by the signs of interactions between the inner surface of the cover and the assembly headers. These signs were found after the removal of the cover.
5. The pressure increase in the tank lead to the rising of the cover and increase of the gap between cover and vessel.
6. The large gap size facilitated water penetration from the surrounding pool and so large amount of water flooded the fuel assemblies from the pit (Fig. 5.g).
7. Finally the tank was filled up by water and stable circulation of coolant was established with the pump (Fig. 5.h).

The thermal and mechanical loads resulted in the fragmentation of many fuel rods. This final event of Paks-2 cleaning tank incident was modelled in all three CODEX CT experiments with a short time water inject from above and reflood from the bottom.



f *g* *h*

Fig. 5 **[2]** The main phases of reflood

5 MAIN RESULTS OF CODEX-CT INTEGRAL TESTS

Fig.6 shows the temperature histories. In the CODEX-CT integral tests the maximum temperatures were nearly 1200-1250 ^{o}C. The final reflood of the bundle led to significant temperature increase in some positions. In test CT-2 the maximum temperature reached during the oxidation phase was 1250 ^{o}C, but during quench the peak value was 1380 ^{o}C.

The state of fuel rods treated in the CODEX-CT facility was very brittle after the experiments. The X-ray view of CT-1 and CT-2 bundles, some cross section of the bundles and pictures of the cladding tubes and shroud plates used in the preliminary test are shown in the figures of Table 2.

CODEX-CT-2

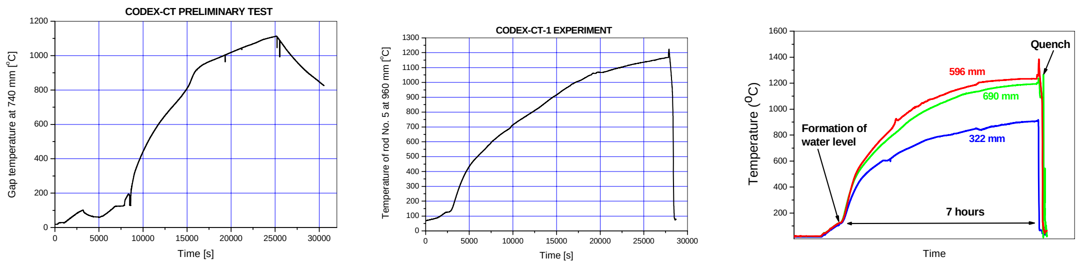
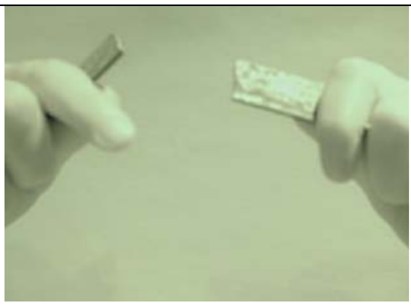
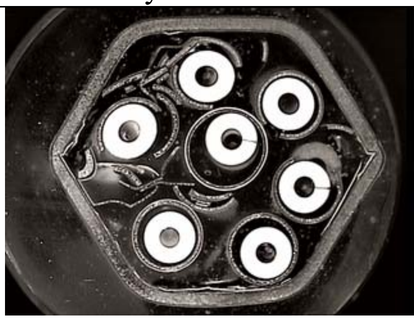
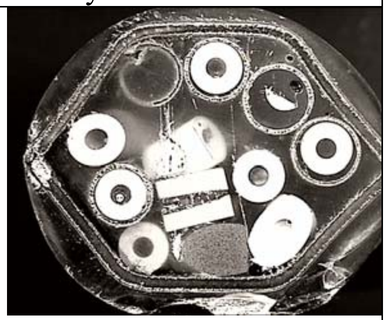


Fig.6. Temperature histories in the preliminary, CODEX-CT-1 and CT-2 tests

Table 2. State of fuel bundles, cladding tubes and shroud plates after the CODEX-CT tests

CODEX CT preliminary test	CODEX CT-1	CODEX CT-2
 View after the treatment	 X-ray view of the bundle	 X-ray view of the bundle
 An brittle and oxidized shroud plate element	 Cross section of CT-1 bundles at 760mm	 Cross section of CT-2-at 760mm

The Fig.7 shows the pressure histories in rods. In booth CODEX CT-1 and CT-2 tests the story happened similarly. The rods with high pressure lost their integrity due to burst at 800-900 °C. The pressure increase reached a maximum during the tests and before burst their value slightly decreased (Fig. 7). It was a result of plastic deformation that increased the internal gas volume and had larger effect on the pressure change, than the temperature increase. Long ballooned sections were observed in the post-test examinations.

During the preliminary and CODEX-CT-1 tests the produced hydrogen was released through the air letdown valve. In CODEX-CT-2 test this valve was closed and hydrogen release from the cleaning tank was allowed only during the final quench. Summary on hydrogen measurements are given in Table 3.

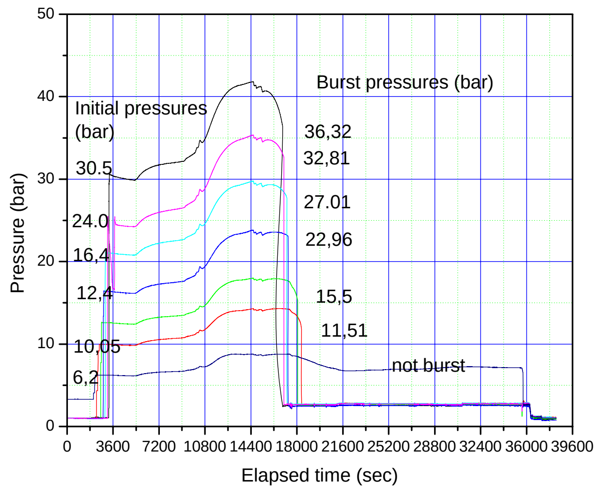


Fig.7. Fuel rod pressures in CODEX-CT-1 test

Table 3. Hydrogen release from the cleaning tank and hydrogen content of the Zr components

	CODEX Pre-test	CODEX-CT-1	CODEX-CT-2
Released through the air let-down valve (l)/(g)	196/ 16	277/ 22.6	80/* 6.53
Absorbed in metallic Zr (l)/(g)	113.2/ 9.24	127/ 10.37	82.9/ 6.77
Total hydrogen production (l)/(g)	309.2/25.2	404/32.97	162.9/13.3

*This hydrogen went out not through the air let down valve but through the water pool condenser during the reflood and remained in the vessel after the condensation of steam.

6 CONCLUSIONS

The CODEX-CT experiments carried out with different scenarios resulted in similar final state of fuel assemblies. The final state of the fuel rods showed many similarities with the conditions observed after the incident at the NPP and for this reason it is very probable that the thermal conditions and chemical reactions were also similar in the tests and in the incident. The post-test examination of CODEX bundles indicated that the high degree of embrittlement was a common result of oxidation and hydrogen uptake by the Zr components.

7 REFERENCES

[1] Experimental Simulation of the Paks-2 Cleaning Tank Incident
Zoltán Hózer, Péter Windberg, Imre Nagy, András Vimi, Nóra Vér, Lajos Matus and Mihály Kunstár.Hungarian Academy of Sciences KFKI Atomic Energy Research Institute, Budapest, Hungary

[2] Fuel Failures During the Paks-2 Incident

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