# Results of the QUENCH-12 reflood experiment with a VVER-type bundle

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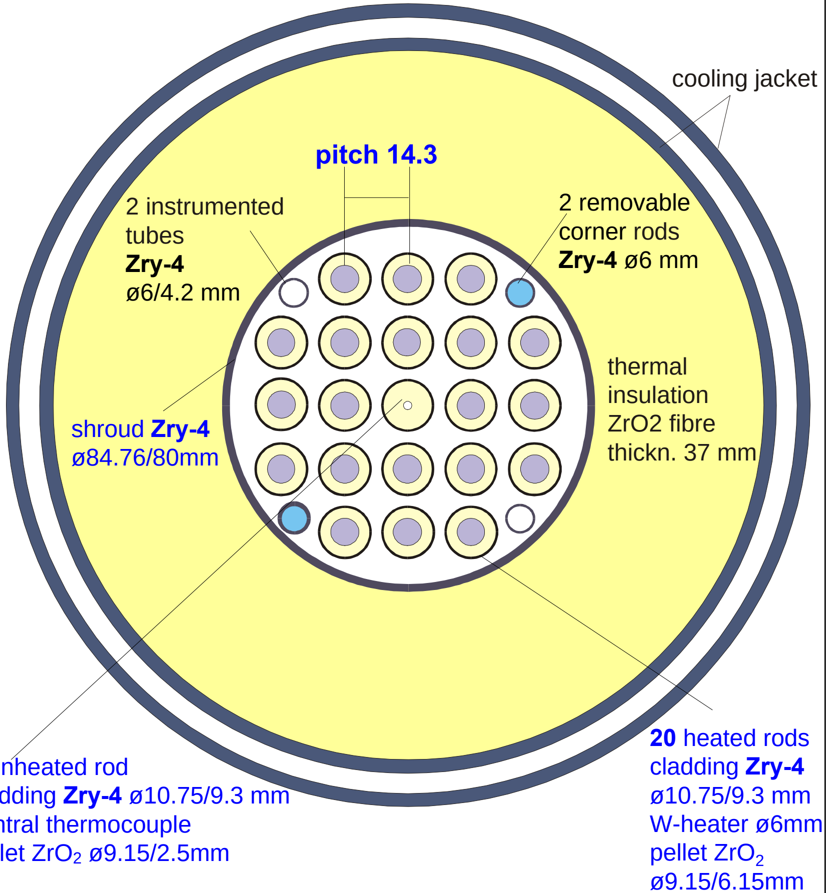
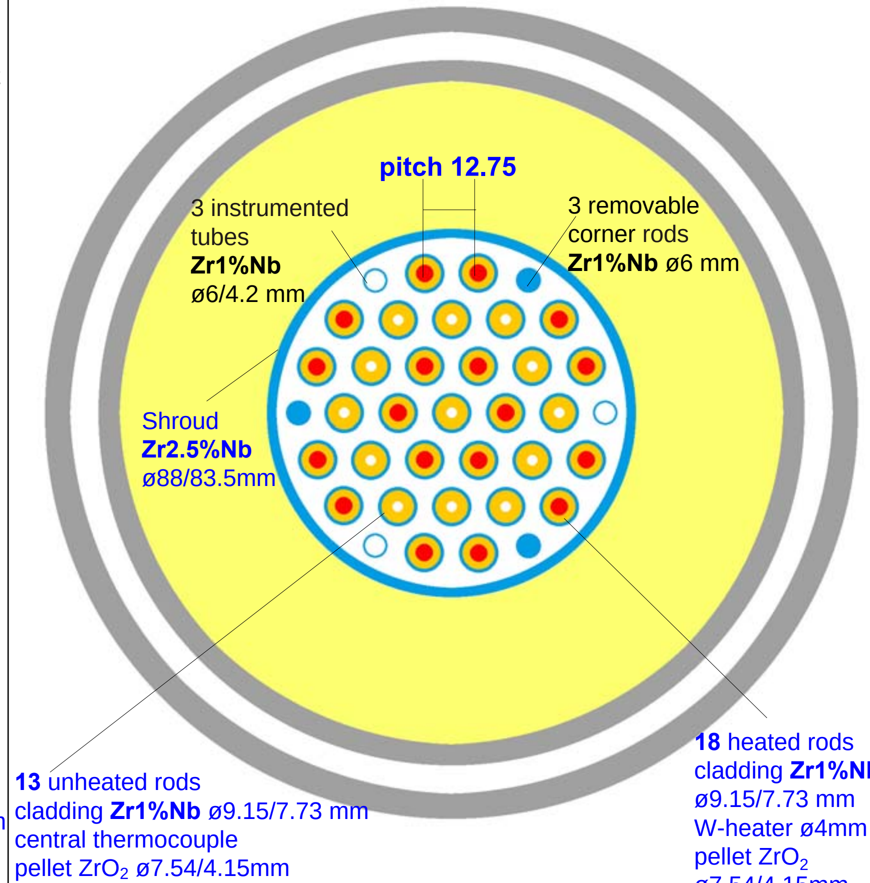
# Objectives of the QUENCH-12 test

- **investigation of the effects of VVER materials and bundle geometry on core reflood**
- **comparison with the PWR bundle on the base of repeat of the test QUENCH-06 (ISP-45) scenario**




| Cross section of the PWR test column | Cross section of the VVER test column (QUENCH-12) |
|---|---|

## Comparison of PWR and VVER test columns

## Comparison of geometrical parameters of the QUENCH-12 (VVER) bundle with the QUENCH-06 (PWR) bundle:

1) **metallic surface relationship Q12/Q06 = 1.22** ⇒ ***higher chemical energy production for the VVER bundle due to exothermic steam-metal reaction*****;**

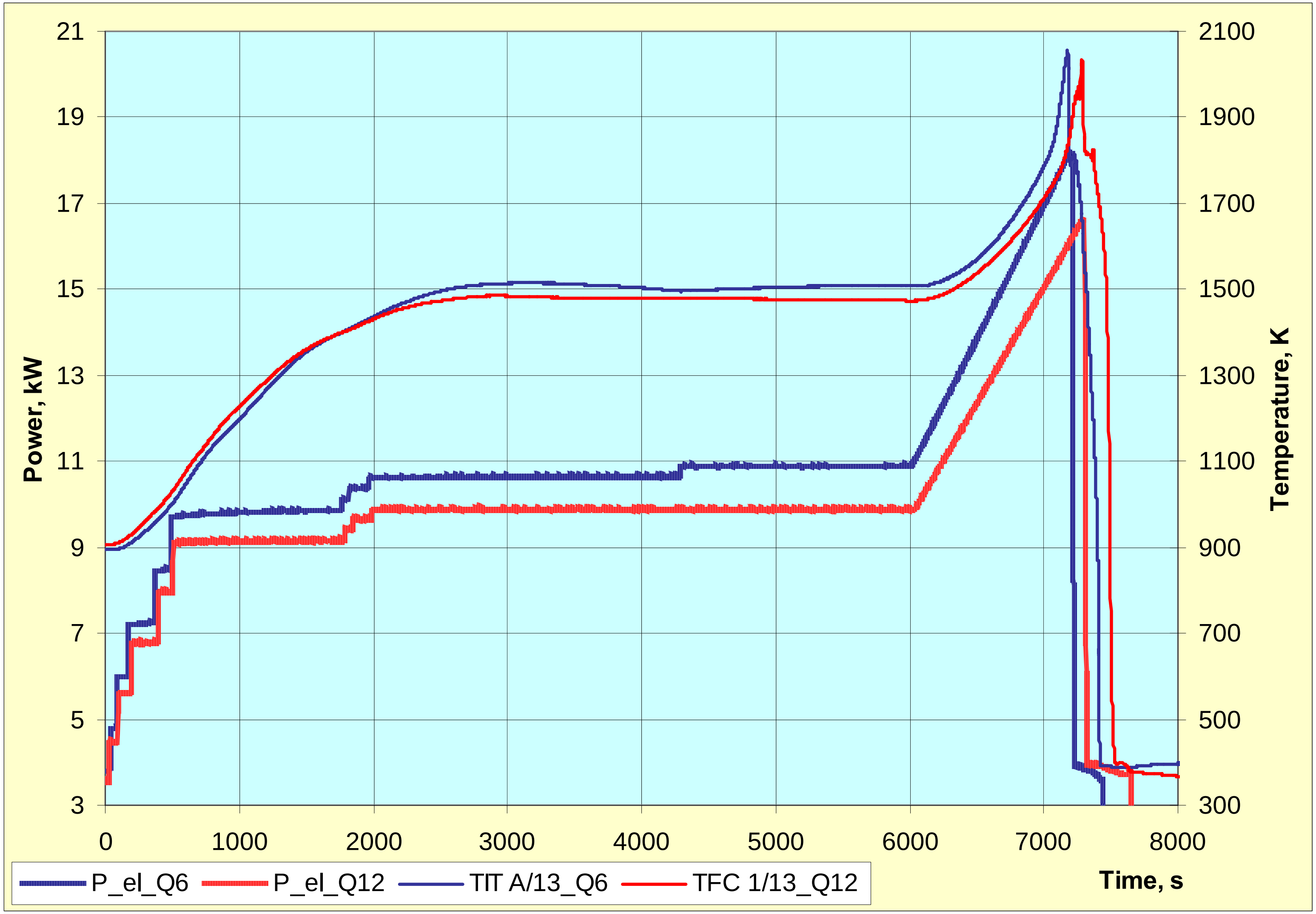
2) **bundle material mass relationship Q12/Q06 ~0.97** ⇒ ***the electrical power for the VVER bundle should be lower than for the Q06 bundle*****.**

# Pretest modelling support:

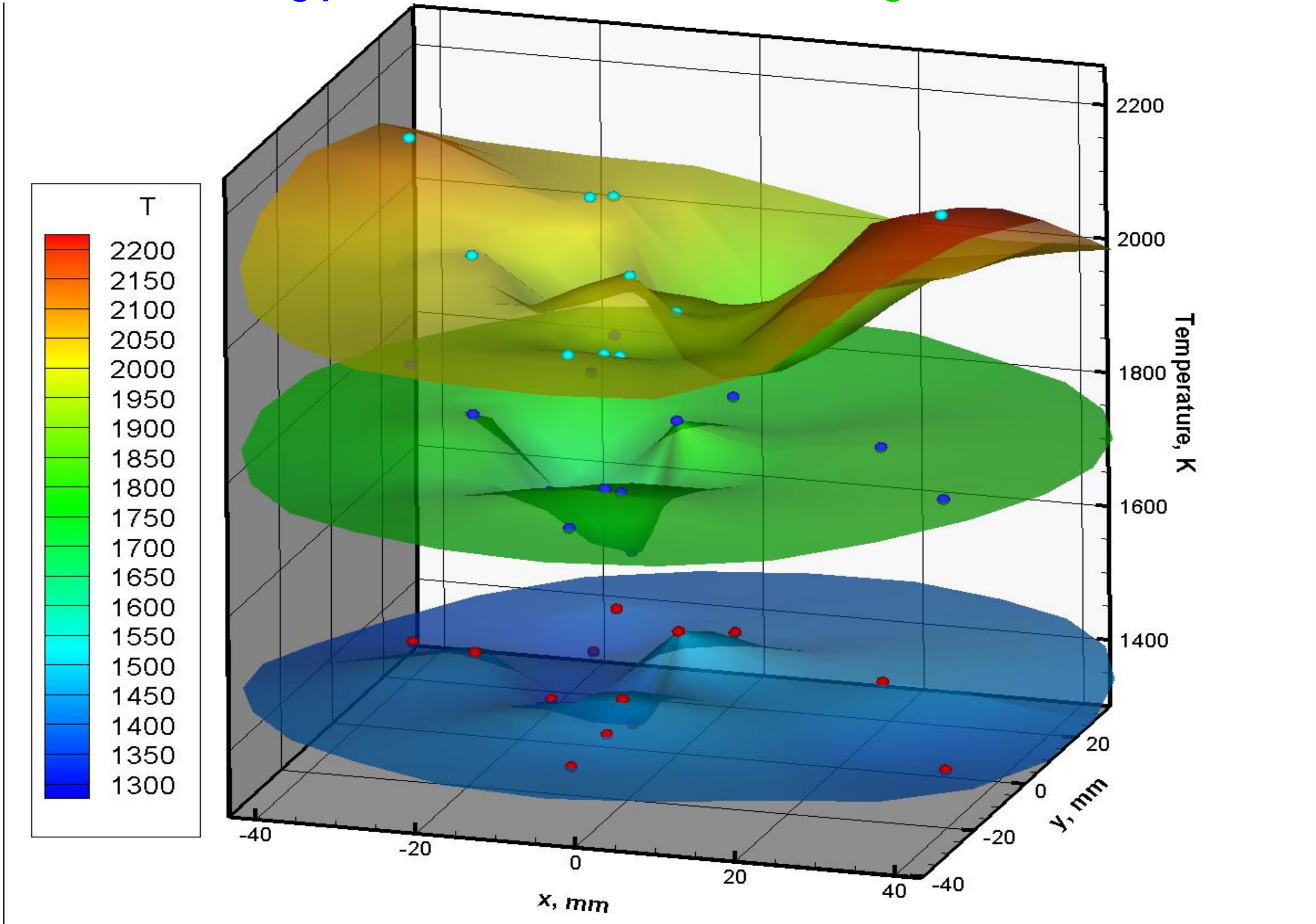
**1. SCDAP/SIM simulations:** *Paul Scherer Institute, Switzerland*.

**2. ICARE/CATHARE simulations:** *Kurchatov Institute, Mosccow, with support from IRSN Cadarache*.

# Comparison of power and temperature profiles for QUENCH-12 and QUECH-06

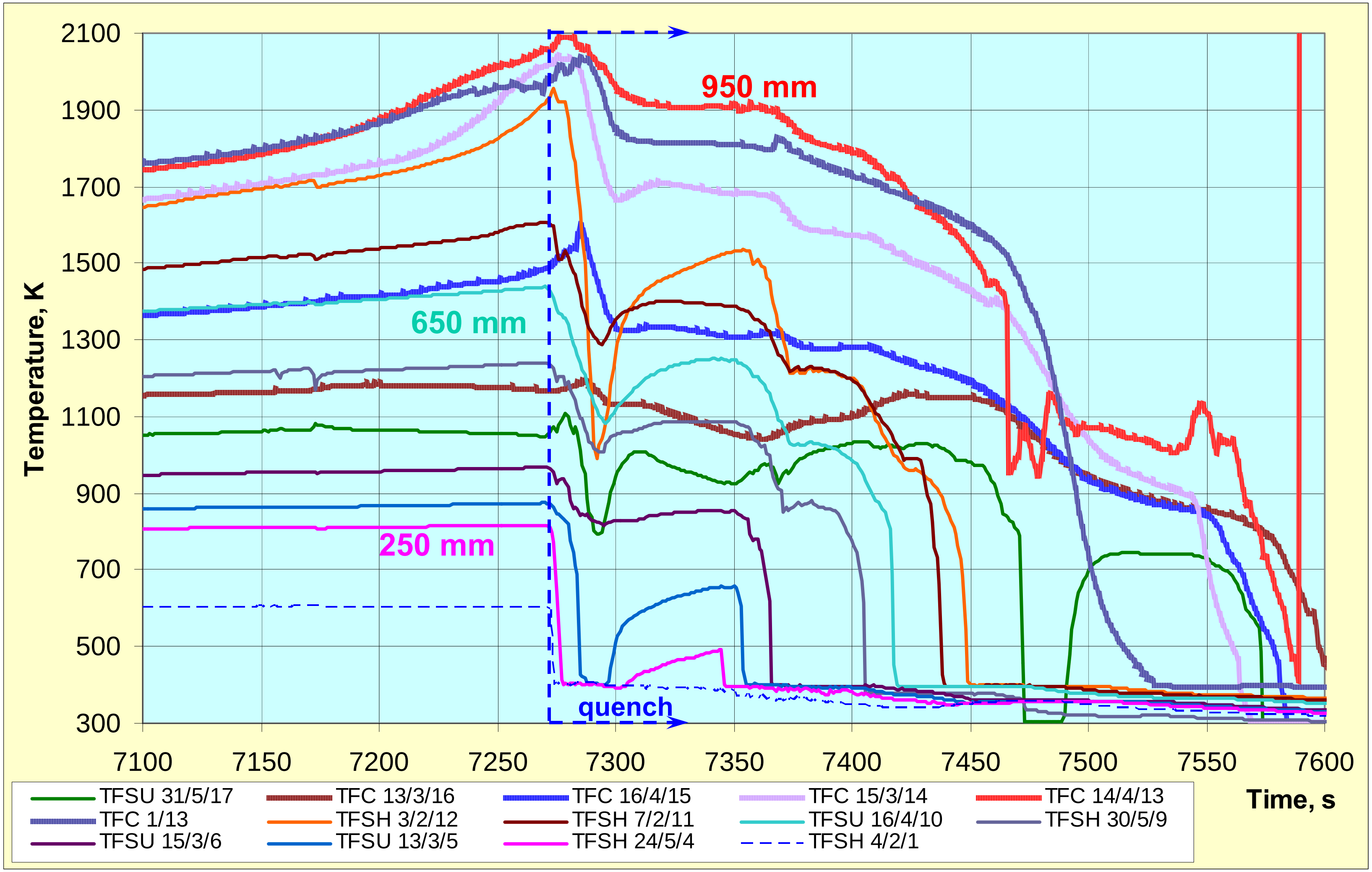


# Temperature distribution across the bundle at hottest bundle elevation (950 mm): 1. during preoxidation, 2. after transient begin, 3. before reflood

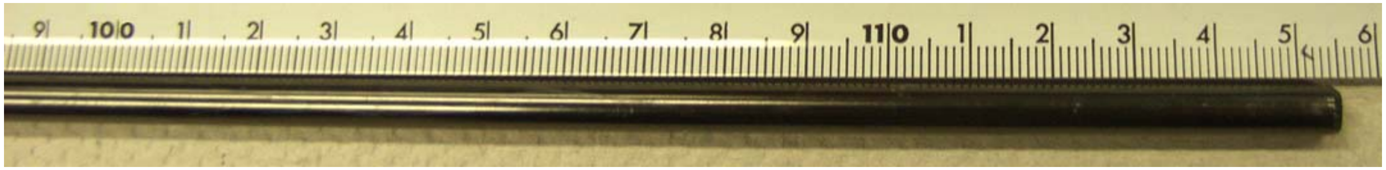


# QUENCH-12, quench phase: selected reading of the bundle thermocouples. Quench front propagation.

## Cooling of the bundle during ~350 s



## QUENCH-12: withdrawn corner rods



**corner rod B after pre-test (800 °C, oxide layer thickness less of 5 μm)**


**corner rods withdrawn during the test: spalling of the outer skin of oxide layer.**
**D – withdrawn after pre-oxidation,**
**F – withdrawn before reflood,**
**B – withdrawn after test.**

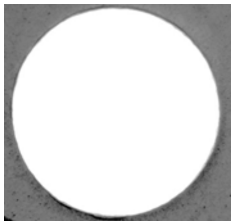
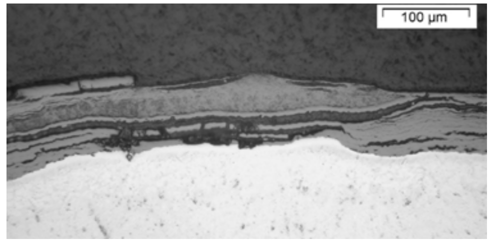
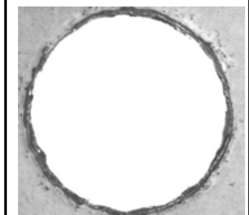
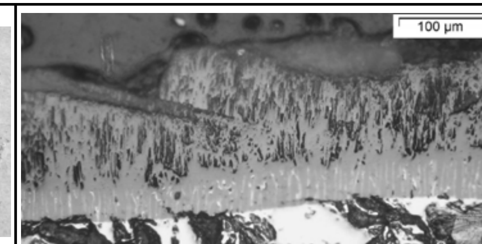
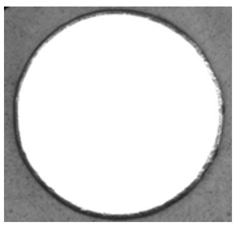
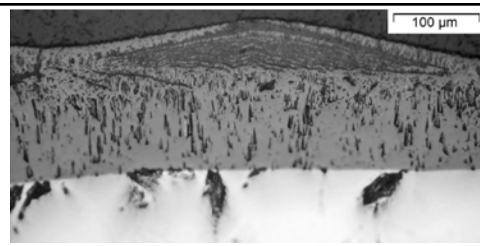
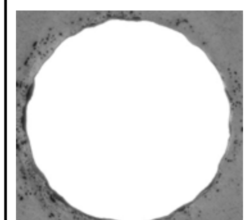
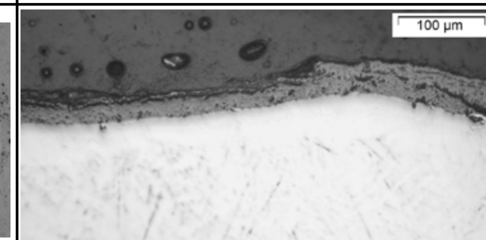
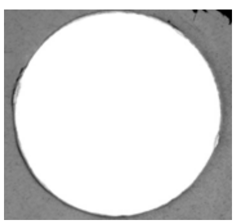
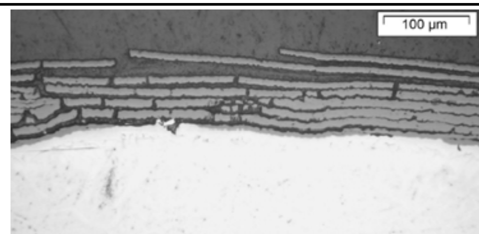
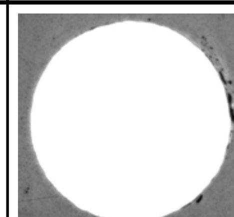
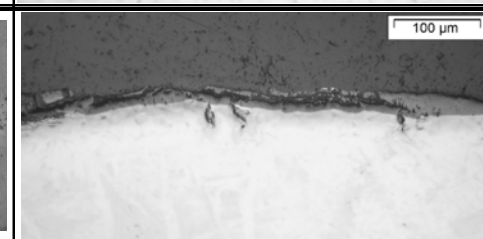
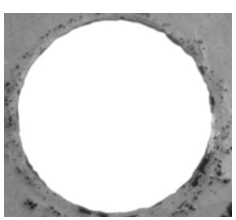
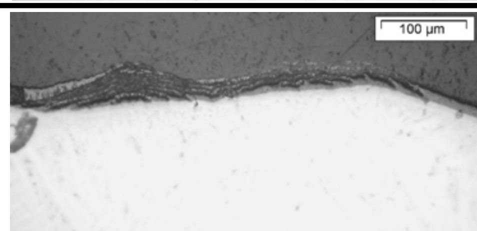
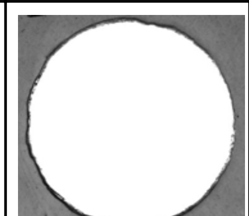
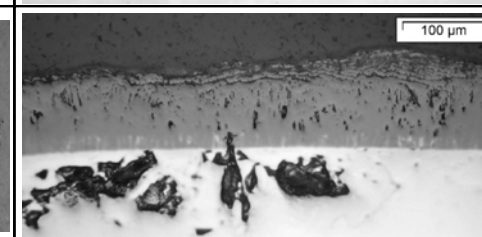
## QUENCH-12: axial sections of different $ZrO_2$ spalling intensity on corner rods withdrawn during the test


B after test | F before reflood | D after preoxidation


F | D

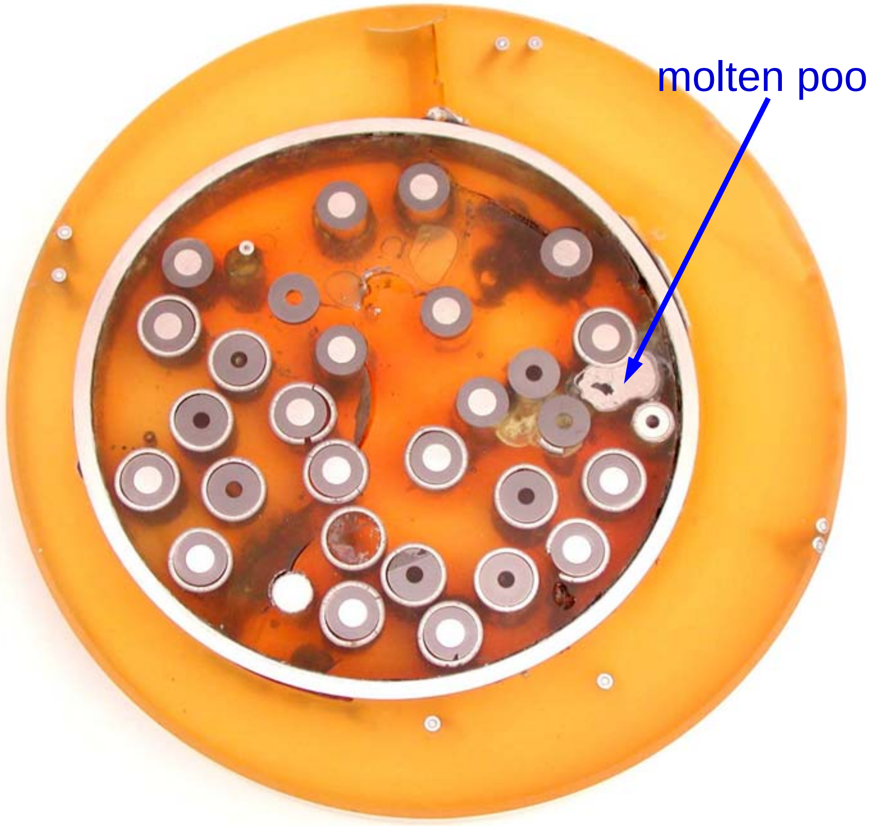

F | D

# QUENCH-12: Structure of the residual oxide layer on the surface of three withdrawn corner rods at different bundle elevations.

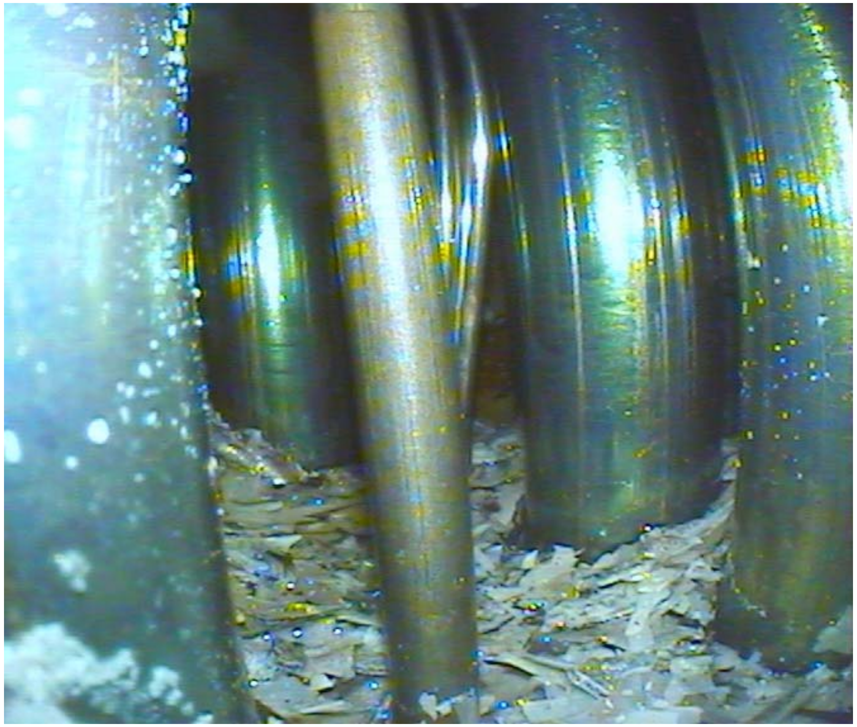
| | | | | | |
|---|---|---|---|---|---|
| **1st rod 700 mm** |  |   | **2nd rod 940 mm** |  |   |
| **1st rod 940 mm** |  |   | **2nd rod 1120 mm** |  |   |
| **1st rod 1120 mm** |  |   | **3rd rod 700 mm** |  |   |
| **2nd rod 700 mm** |  |   | **3rd rod 820 mm** |  |   |

**Breakaway structure was formed generally during pre-oxidation by temperatures about:**
**850°C (@700 mm), 1100°C (@940 mm), 900°C (@1120 mm)**

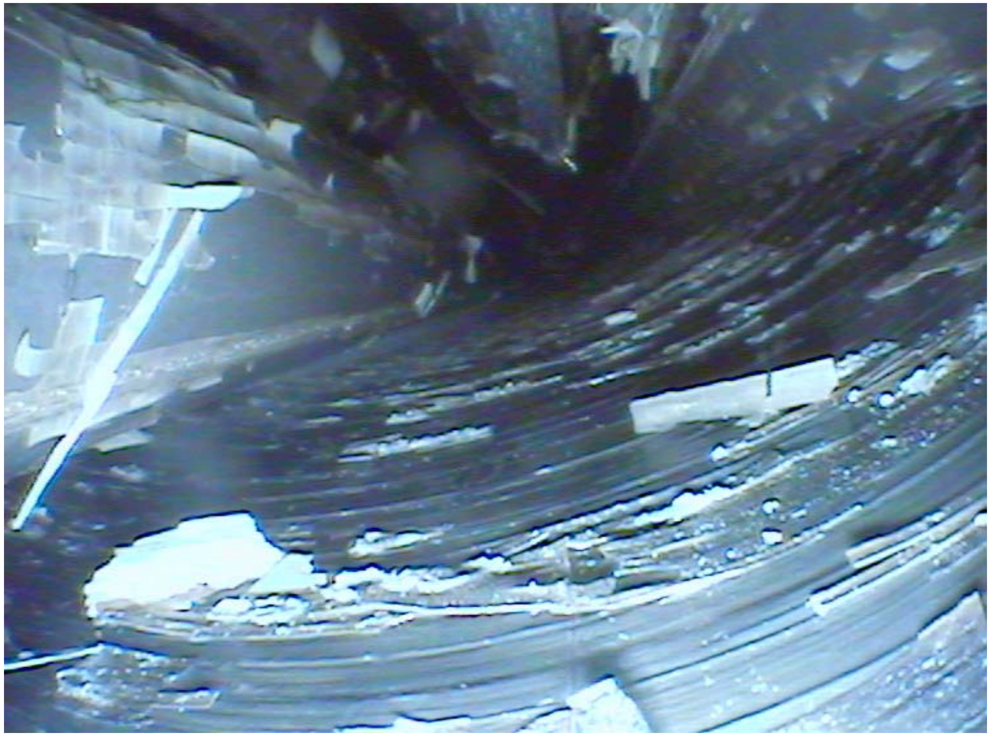
## QUENCH-12: cross-sections of the bundle (top view)

|  |  |
|---|---|
| Elevation 550 mm: debris bed on spacer grid | Elevation 854 mm: loss of bundle geometry and melt formation |

# QUENCH-12, videoscope analysis: intensive oxide scale spalling inside of bundle

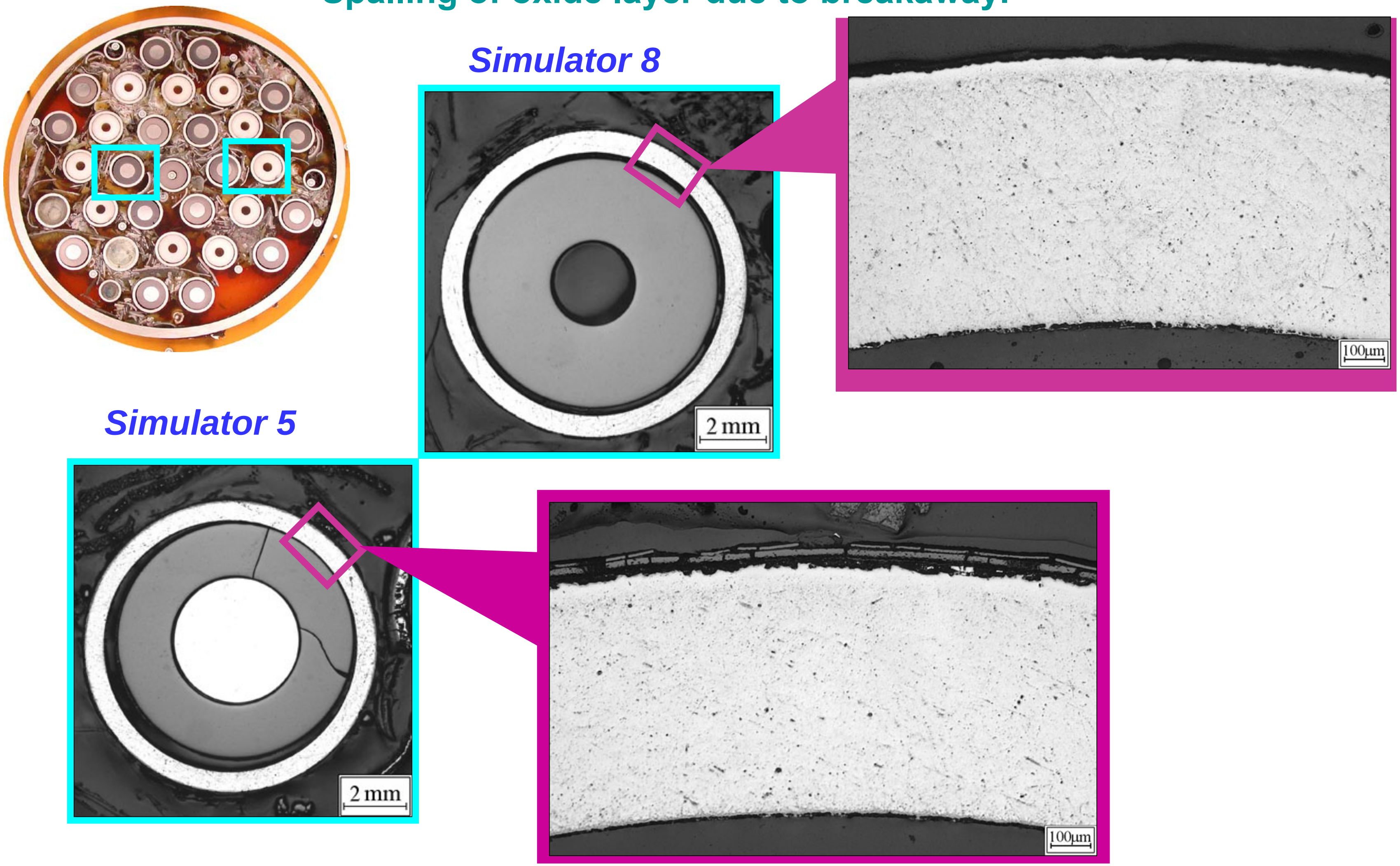


**debris at the bundle bottom**

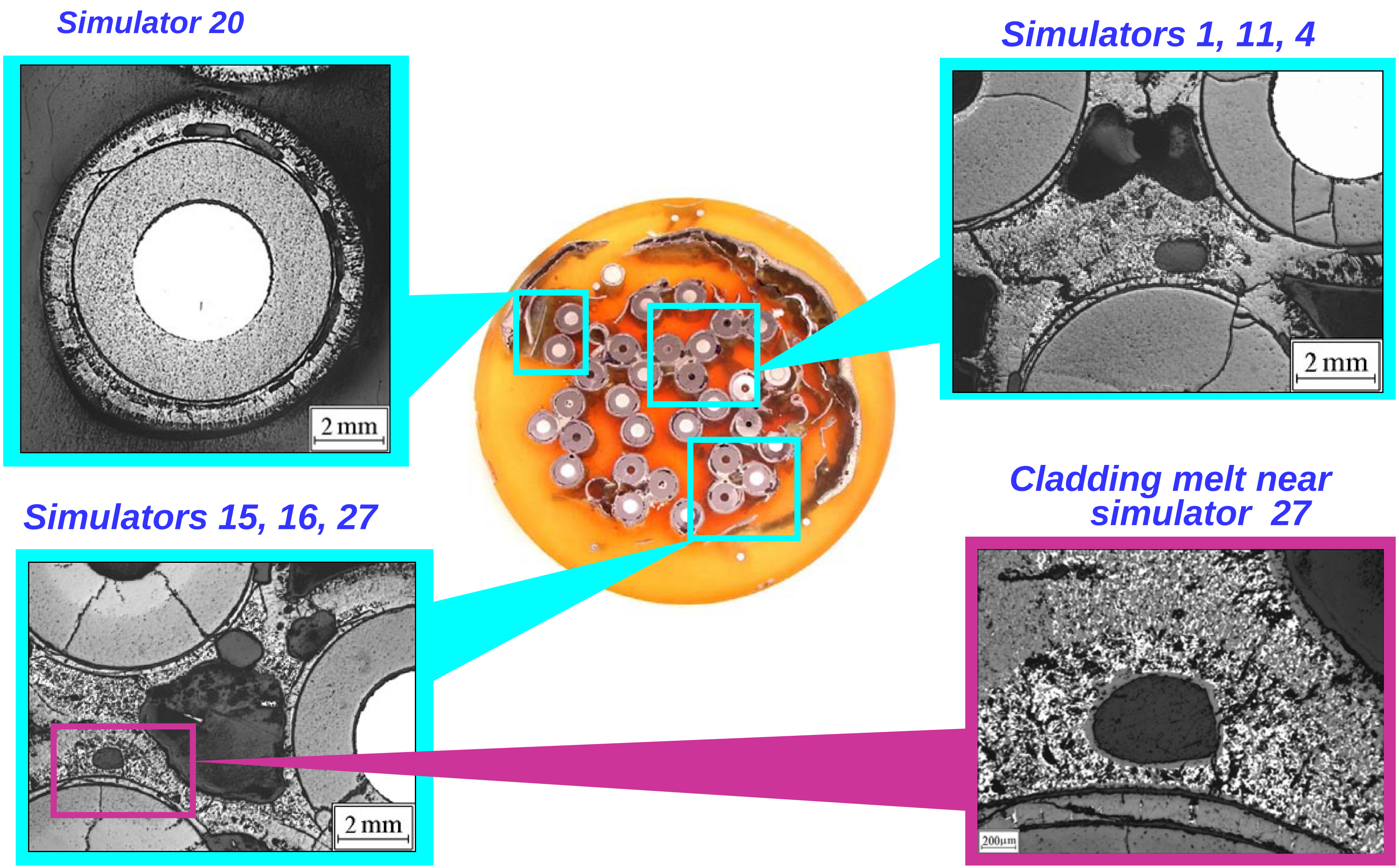


**bundle elevation 650 mm:**
**spalled oxide scales at shroud and cladding**

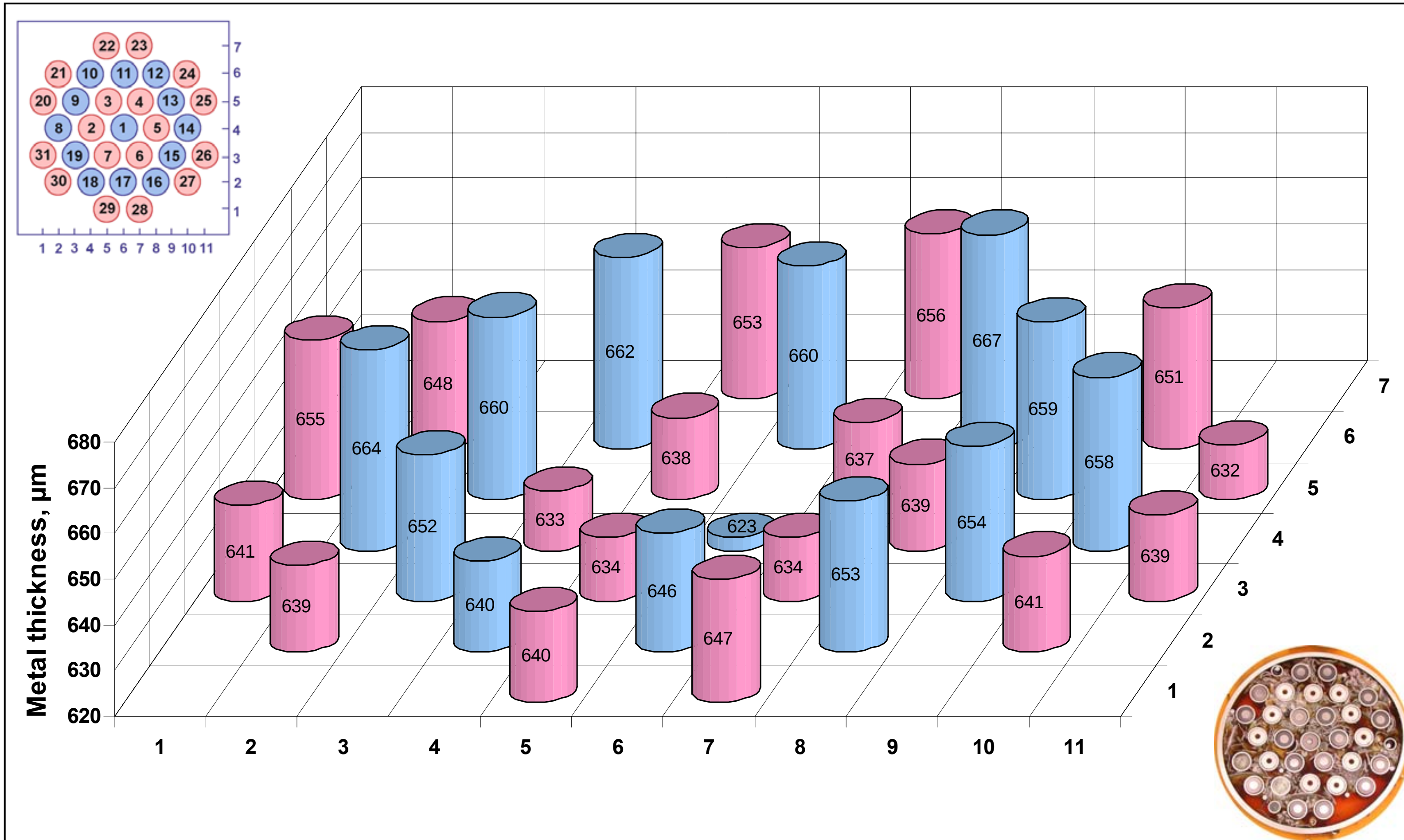
# QUENCH-12 post-test by RIAR: cladding structure at 554 mm elevation (950 - 1050 °C). Spalling of oxide layer due to breakaway.



## QUENCH-12 post-test by RIAR: melt structure at 954 mm elevation

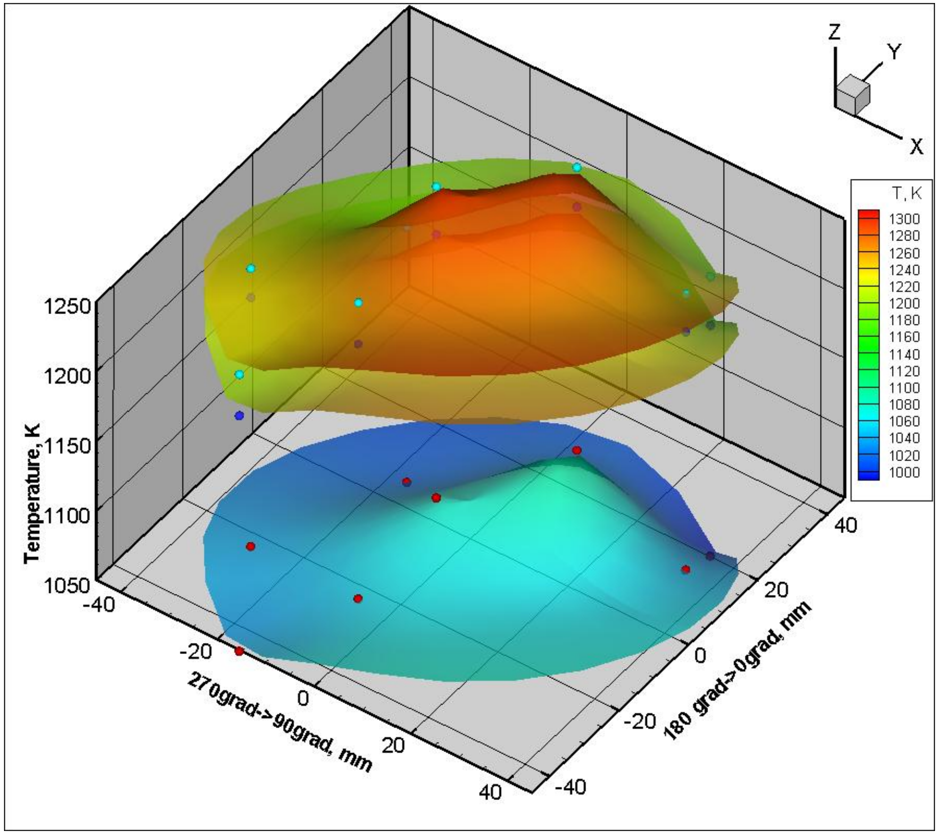


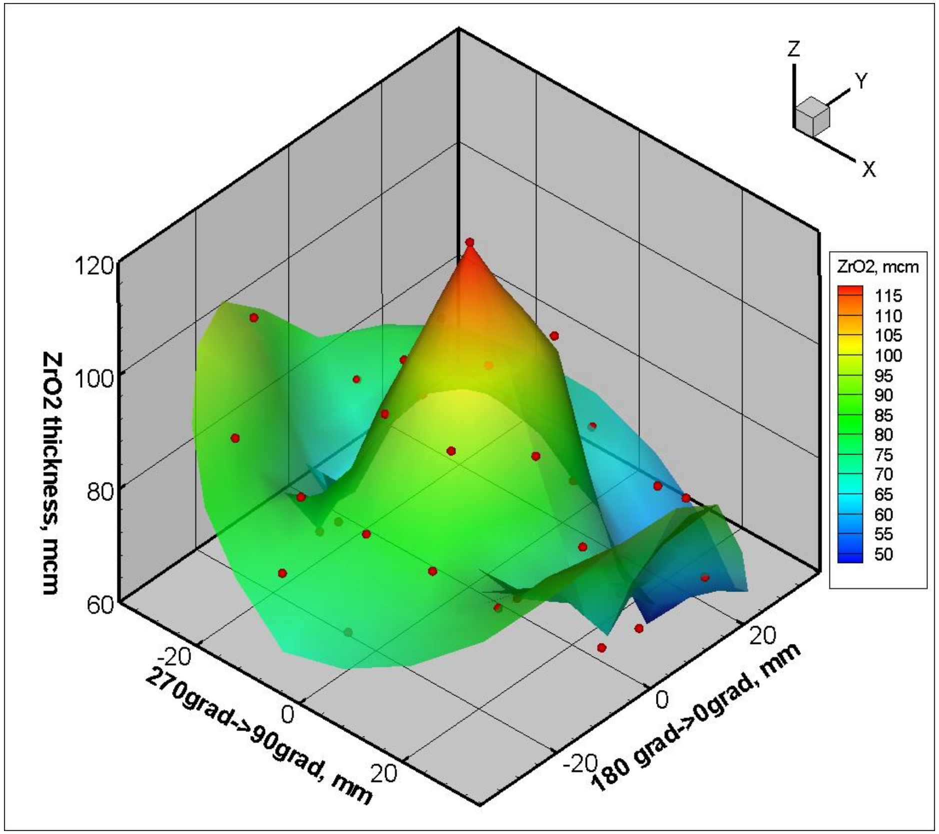
# QUENCH-12: metallographical examination of residual cladding metal thickness were performed at RIAR and FZK for 5 bundle elevations




**example of RIAR measurements at cross-section 554 mm:**
**average value and median deviation: 654 ± 8 µm for unheated rods,**
**642 ± 6 µm for heated rods.**

## QUENCH-12 bundle cross-section at elevation 550 mm: temperature distribution and corresponding $ZrO_2$ thickness distribution

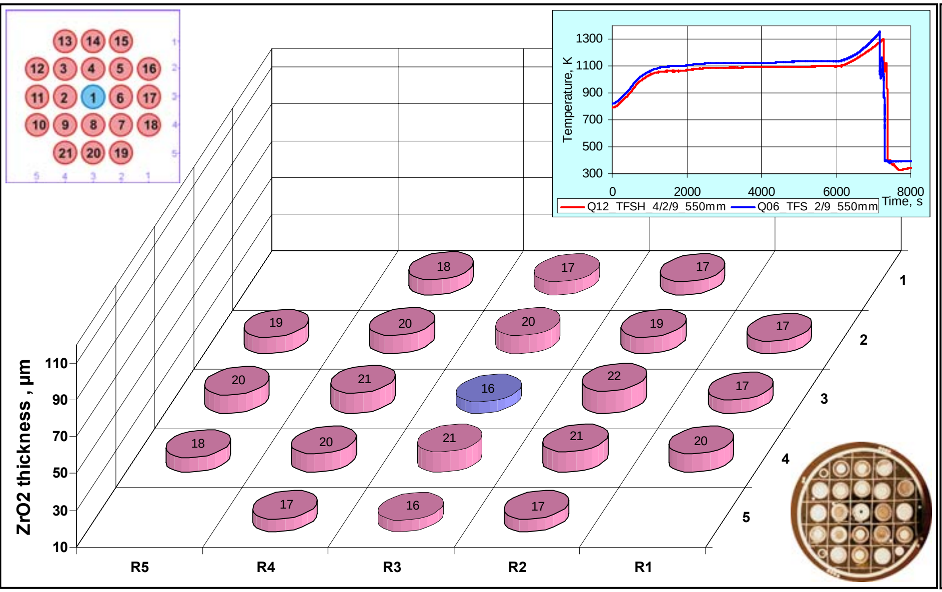


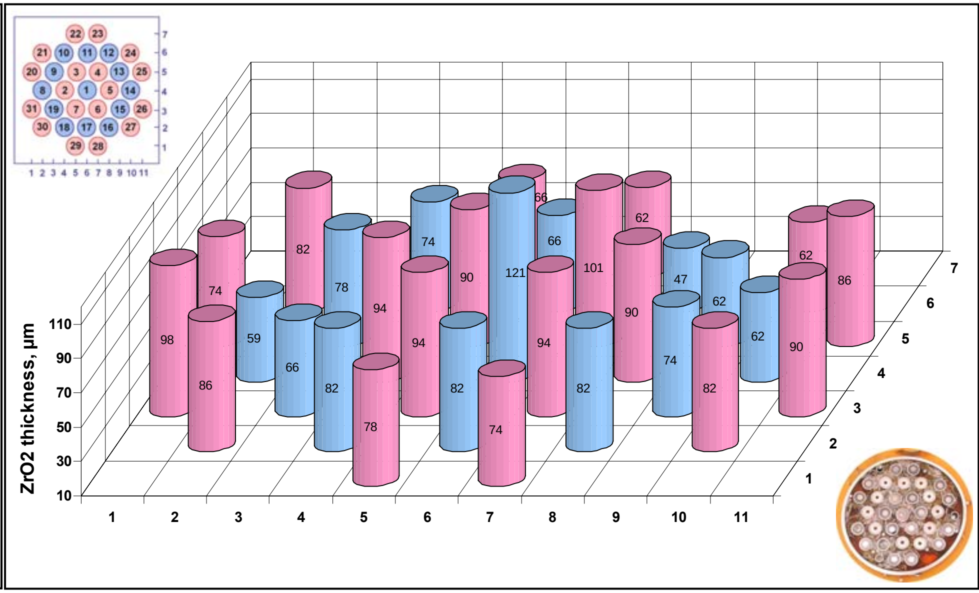




**temperature distributions for three time points (from bottom to top):**
**1) 5960 s (end of pre-oxidation),**
**2) 7150 s (middle of transient),**
**3) 7265 s (before reflood).**

**distribution of cladding oxide layer thicknesses after test completion calculated _on the basis of residual metallic layers_**

## QUENCH-12<-> QUENCH-06:
## comparison of oxide layer thicknesses at bundle elevation 550 mm

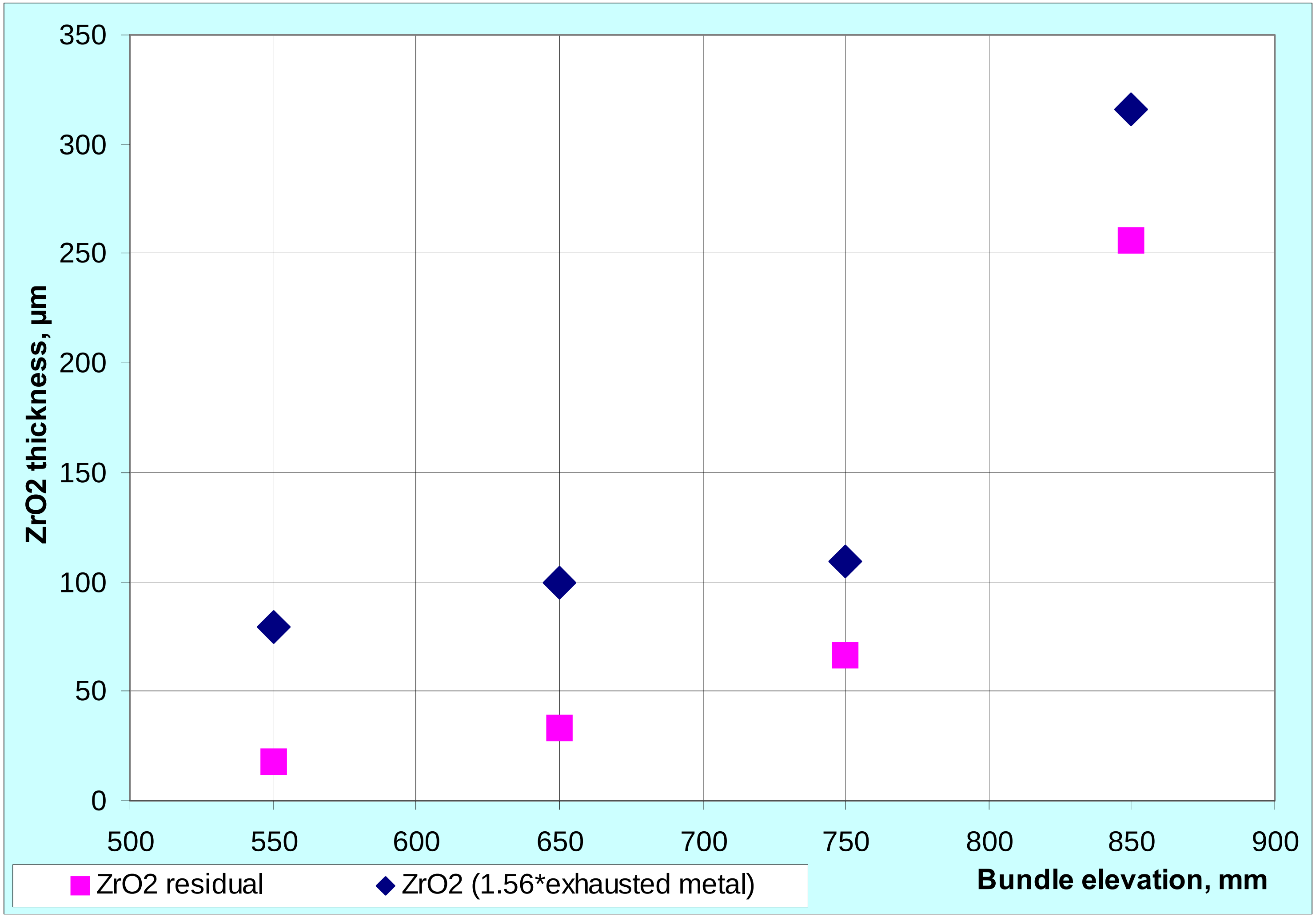


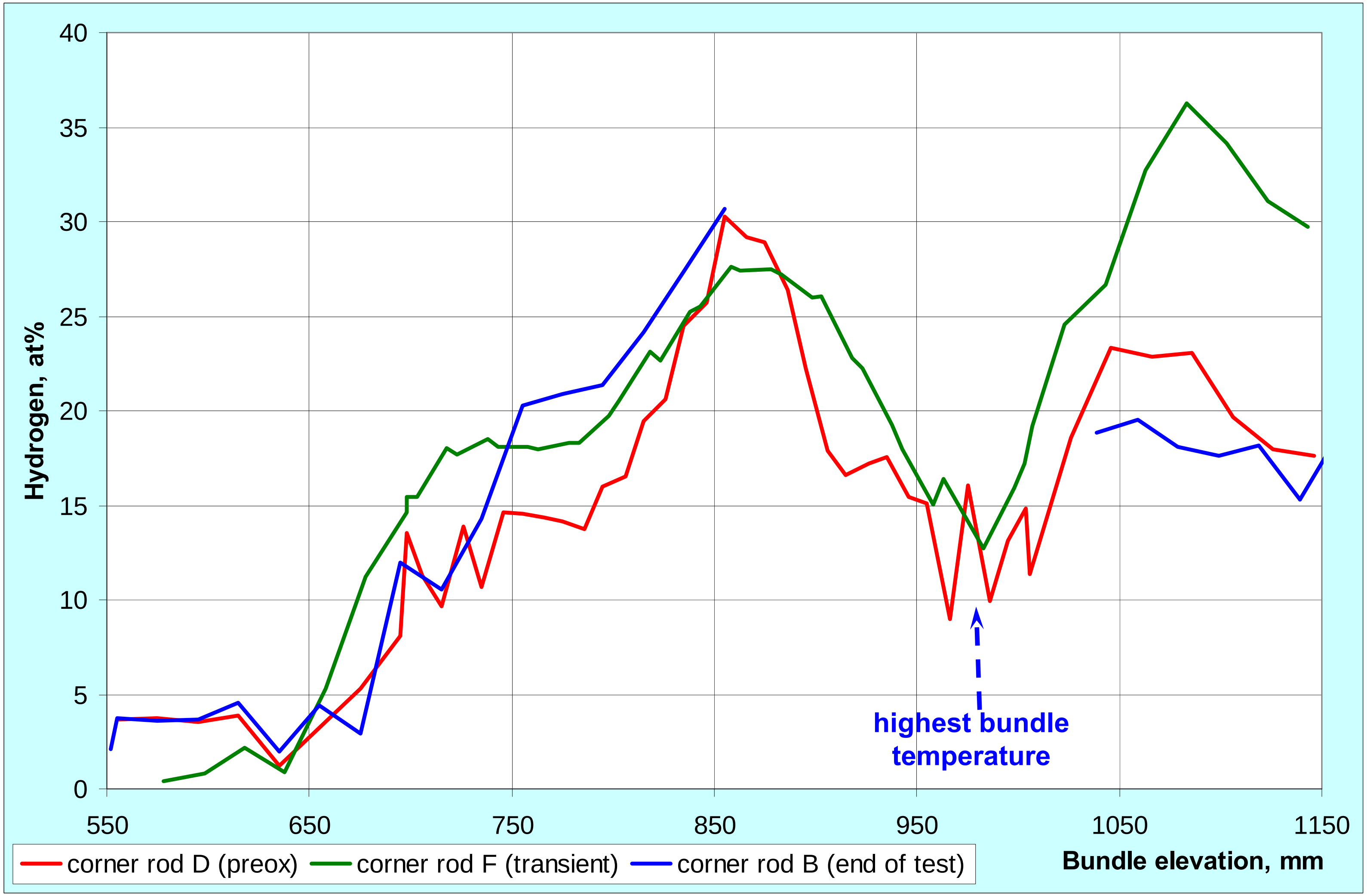

**QUENCH-06**
**measured average oxide layer thickness: 19 µm**

**QUENCH-12**
**estimated oxide layer thickness : 79 µm**

## QUENCH-12, post-test analysis:
## axial distribution of the oxide layer on the surface of cladding tubes.
## Measured residual oxide and oxide calculated on the base of residual metal.

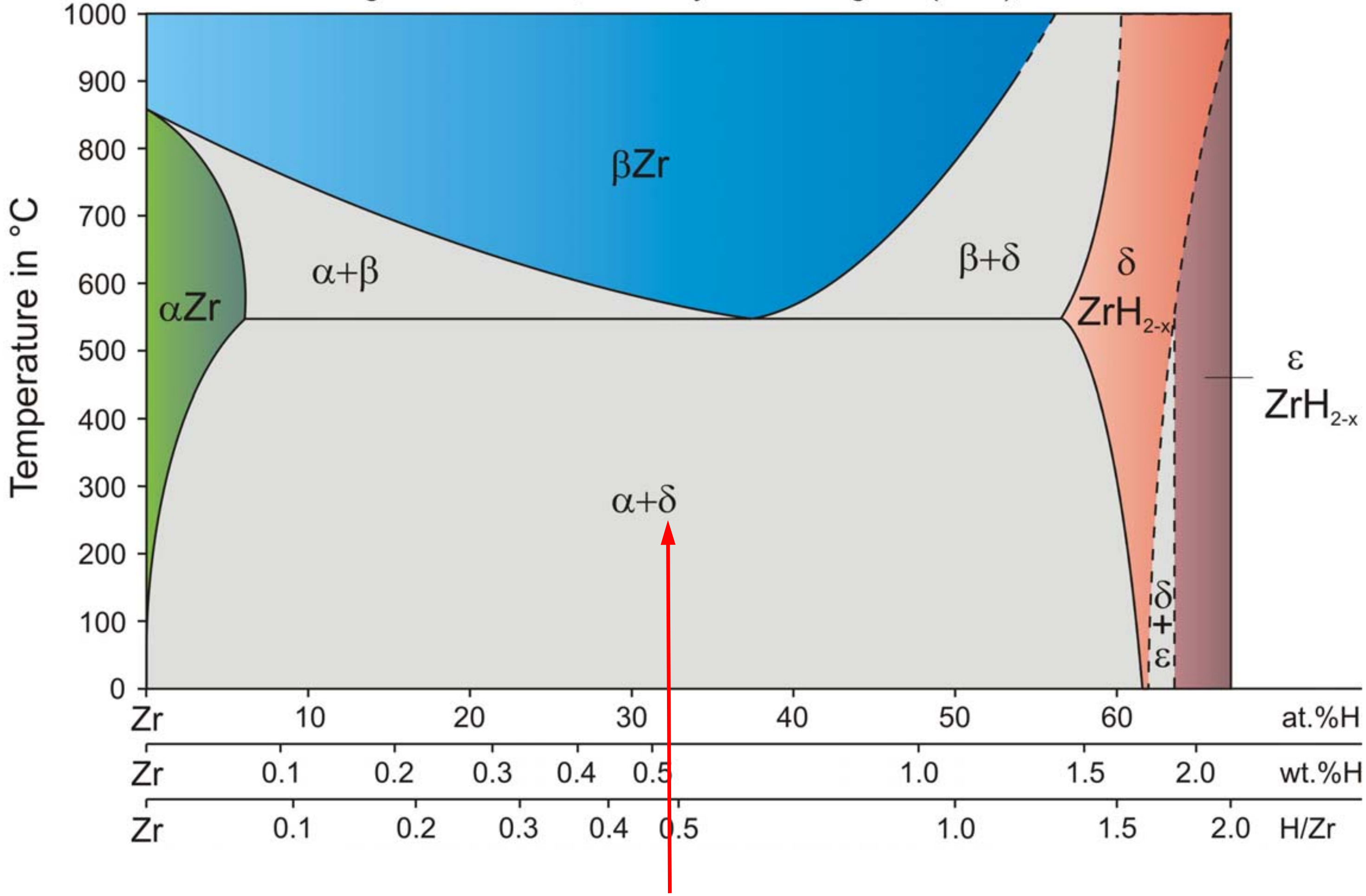


## QUENCH-12: hydrogen uptake by corner rods
## /results of neutron radiography by PSI (M. Große)/



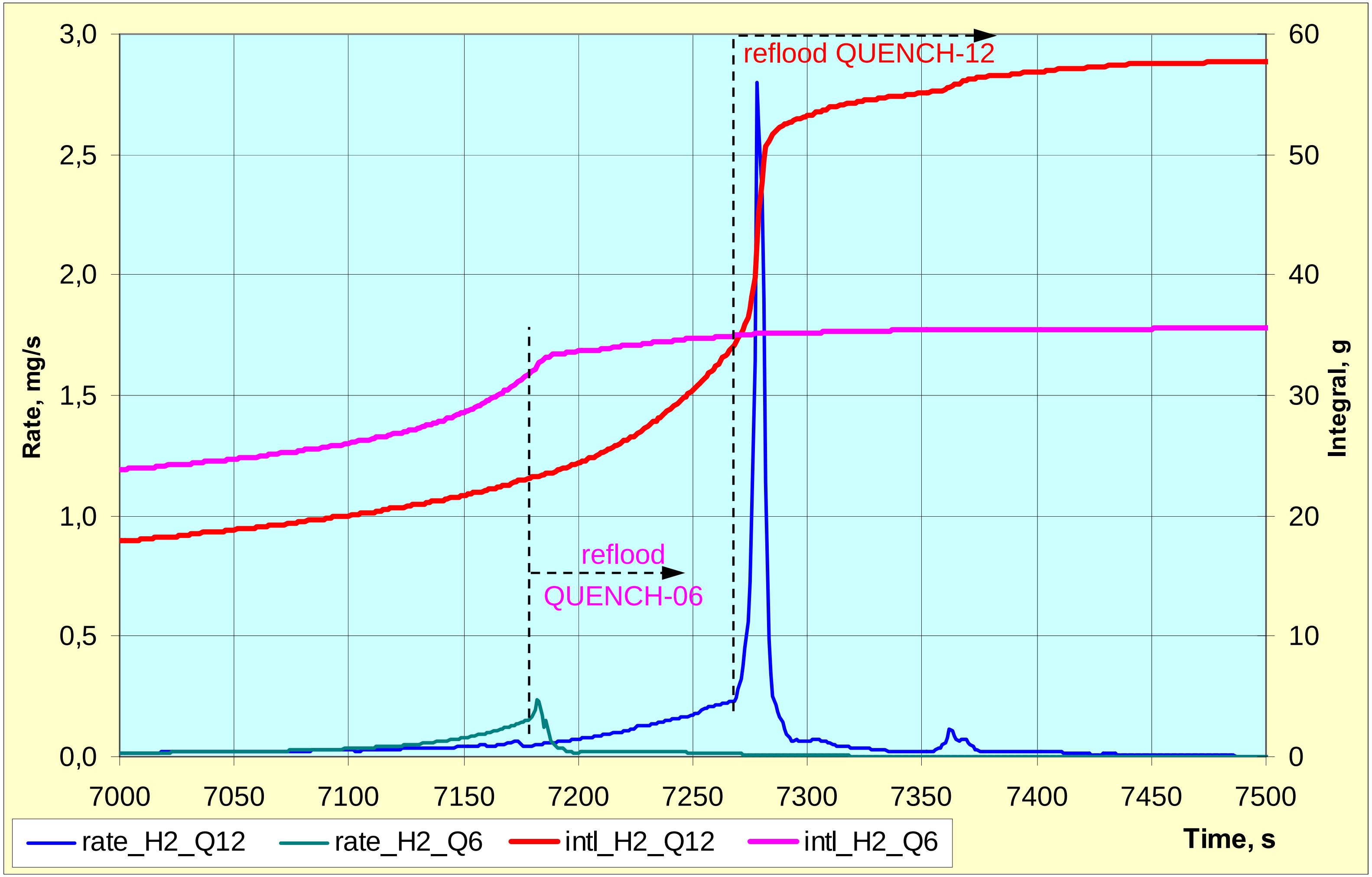
# Zirconium-Hydrogen Phase Diagram

According to Zuzek et al., Bull Alloy Phase Diagr. 11 (1990), 385




**Hydrides formation at temperatures <550°C**

## Comparison of hydrogen release during QUENCH-12 and QUECH-06.

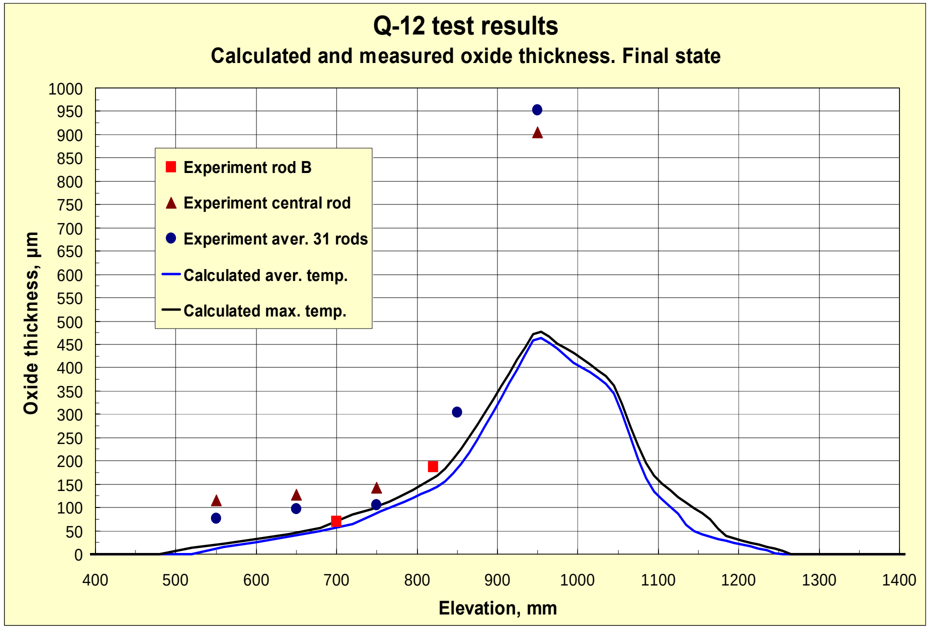



**QUENCH-06: $H_2$ production before reflood 32 g, during reflood 4 g**

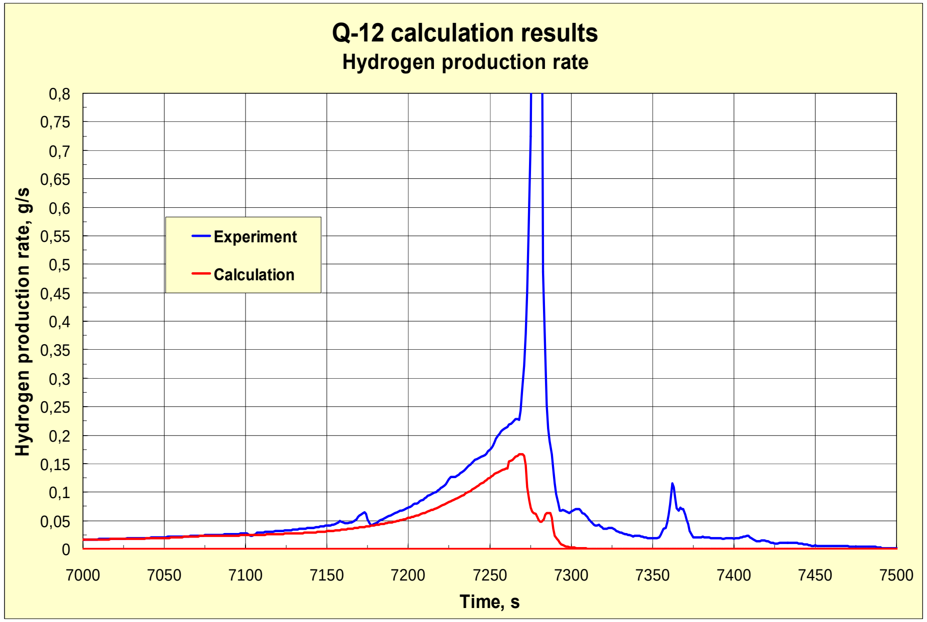
**QUENCH-12: $H_2$ production before reflood 34 g, during reflood 24 g**

# QUENCH-12: results of the SVECHA simulation (by A. Palagin)

In the SVECHA/QUENCH code the thermal boundary conditions for the central rod are predetermined by specifying the temperatures of the "**effective channel**" inner wall on the basis of experimentally measured temperatures. The inner surface of the effective channel represents the surfaces of the heated rods surrounding the central rod.




Measured oxide layer thickness profiles, compared to the calculated oxide layer thickness profile of the central rod (final state).




Experimentally measured and calculated hydrogen production rate. Transient and quenching phases of the test.

Amount of hydrogen released during quenching: 24 g (exp); 9.9 g (calc.)

# SUMMARY (1)

- The QUENCH-12 experiment investigated the effects of VVER materials and bundle geometry on core reflood, in comparison with test QUENCH-06 (ISP-45) with Western PWR geometry.

- The electrical power changing during the test corresponds completely to calculated values up to reflood phase. The temperatures at all bundle elevations during preoxidation are about 30 - 40 K lower than during corresponding phase of QUENCH-06.

- The surfaces of the rod simulator and shroud evident influence of the breakaway oxidation. Many oxide scales with were spalled and collected at the spacer grid.

## SUMMARY (2)

- Post-test bundle examinations performed at RIAR and FZK showed significantly more oxidised cladding surfaces in comparison to QUENCH-06. Also the radial oxidation inhomogeneity is much higher for QUENCH-12 bundle.

- The hydrogen content in the corner rods reached a value more than 30 at% at the bundle elevations of 850 and 1100 mm.

- The total hydrogen production was 58 g (for QUENCH-06: 36 g), during the reflood was released 24 g hydrogen (for QUENCH-06: 4 g). This may be attributed partly to the longer excursion time in QUENCH-12. Other reasons for the increased hydrogen production may be extensive damaging of the cladding surfaces due to the breakaway oxidation and local melt formation with subsequent melt oxidation.

## SUMMARY (3)

- SVECHA/QUENCH code was applied to the simulation of the QUENCH -12 bundle test. The calculations adequately reproduce temperature evolution of the central rod at different elevations during the whole test duration including quenching phase.

- The calculated oxide thickness at the end of the test was significantly underestimated, especially at 950 mm. This fact may be explained by more intensive oxidation during transient and quenching phases through friable cracked oxide structure formed due to break-away oxidation previously.

- Calculations underestimate hydrogen production rate at the end of transient and quenching phase of the test.