# Experimental and Post-Test Calculation Results of the Integral Reflood Test QUENCH-12 with a VVER-type Bundle

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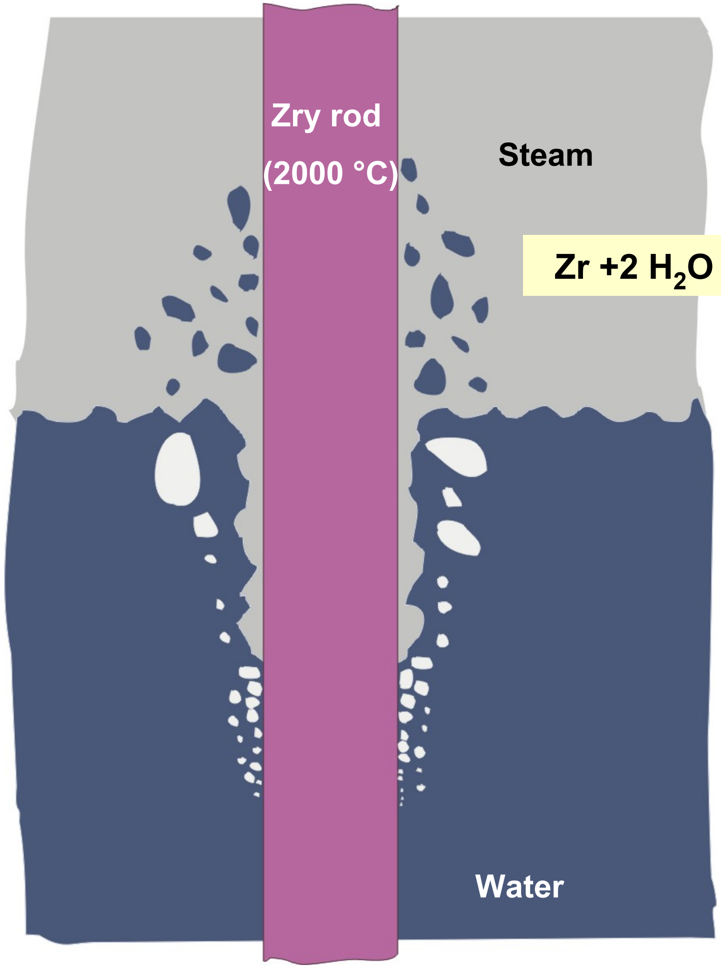
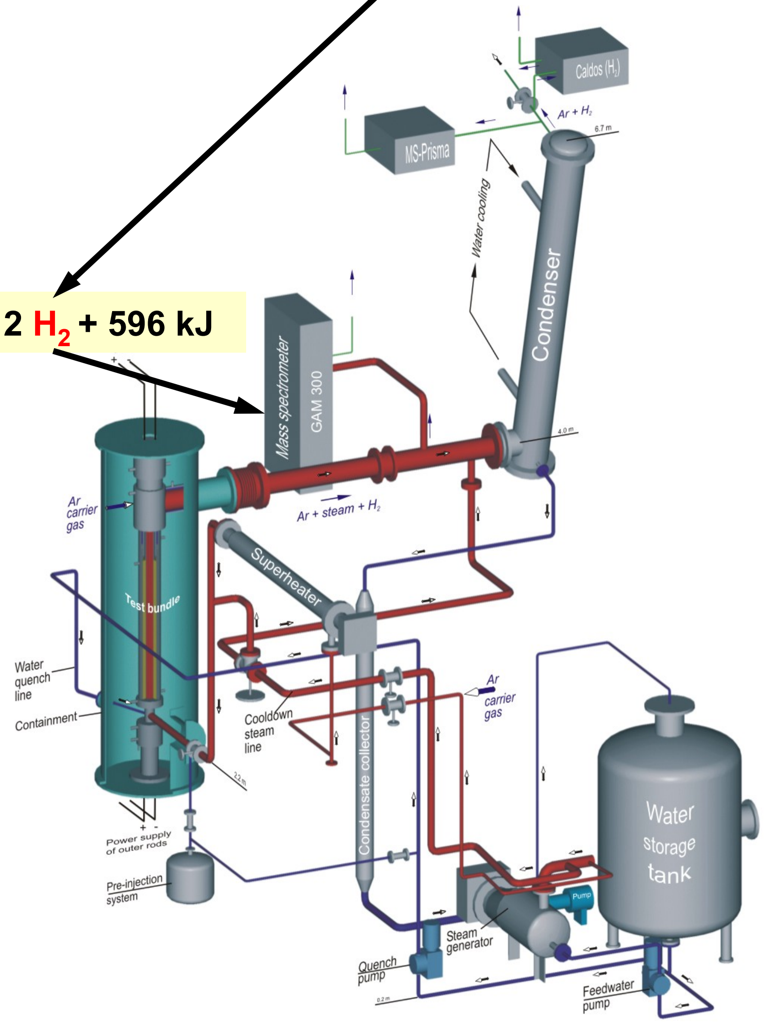
*Forschungszentrum Karlsruhe*

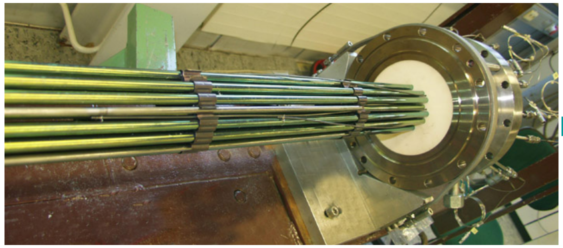
# High-Temperature Materials Behavior and Flooding of an Overheated LWR Core and Hydrogen Source Term



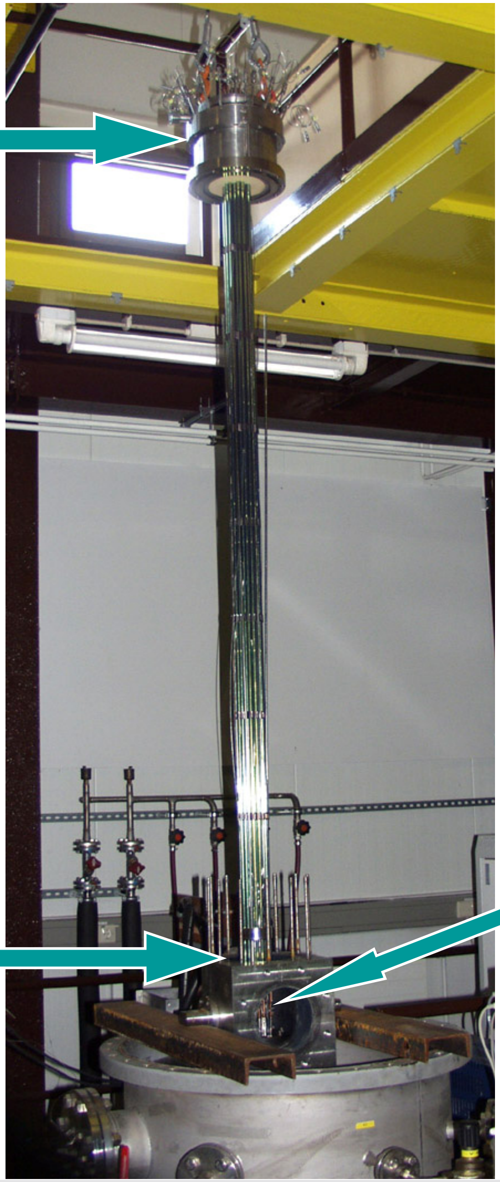

$Zr + 2\ H_2O \rightarrow ZrO_2 + 2\ H_2 + 596\ kJ$

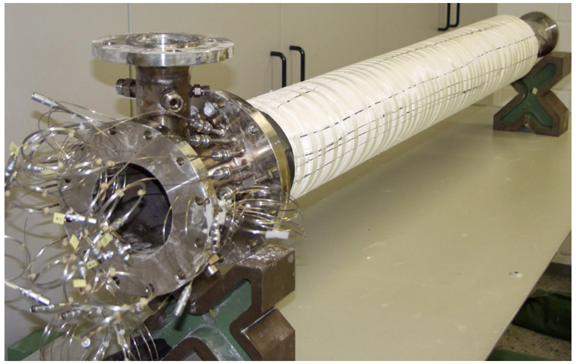


# QUENCH-12Test bundle assembling

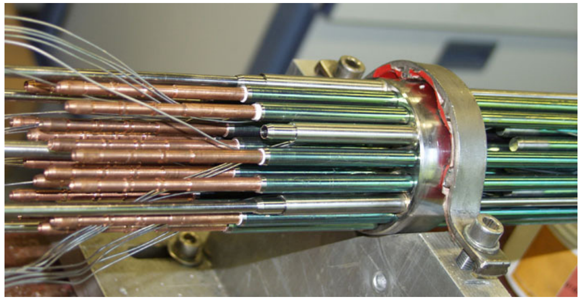


bundle top





shroud with heat insulation



bundle bottom

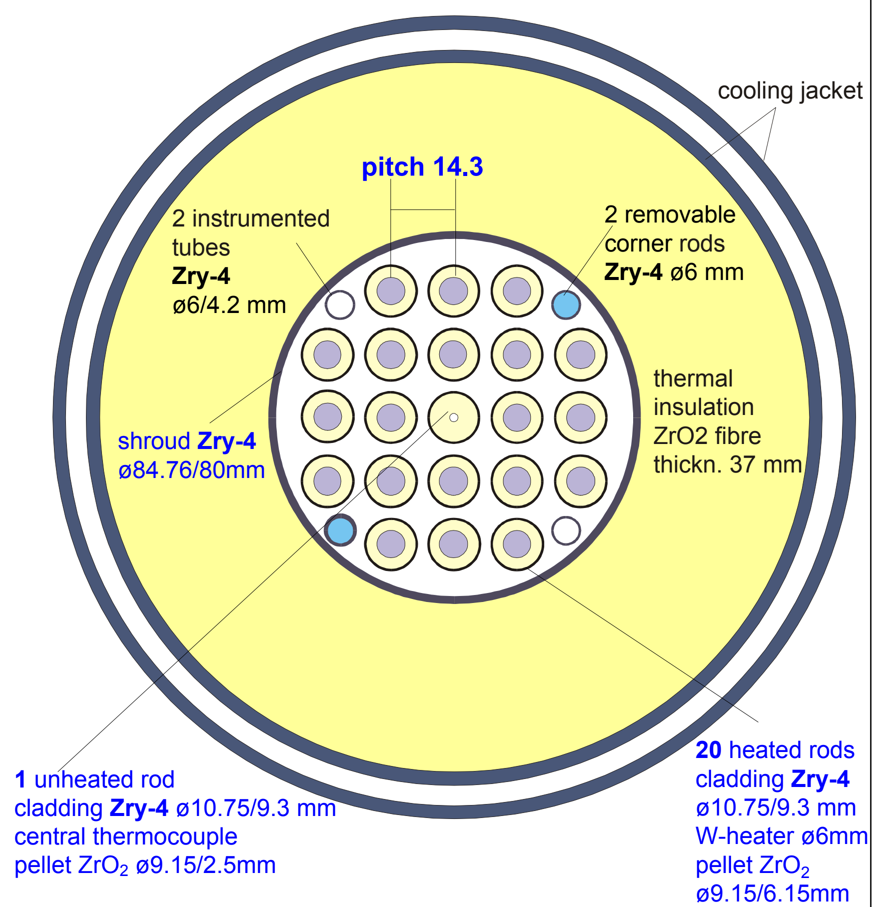
# Test Matrix (1998-2008)

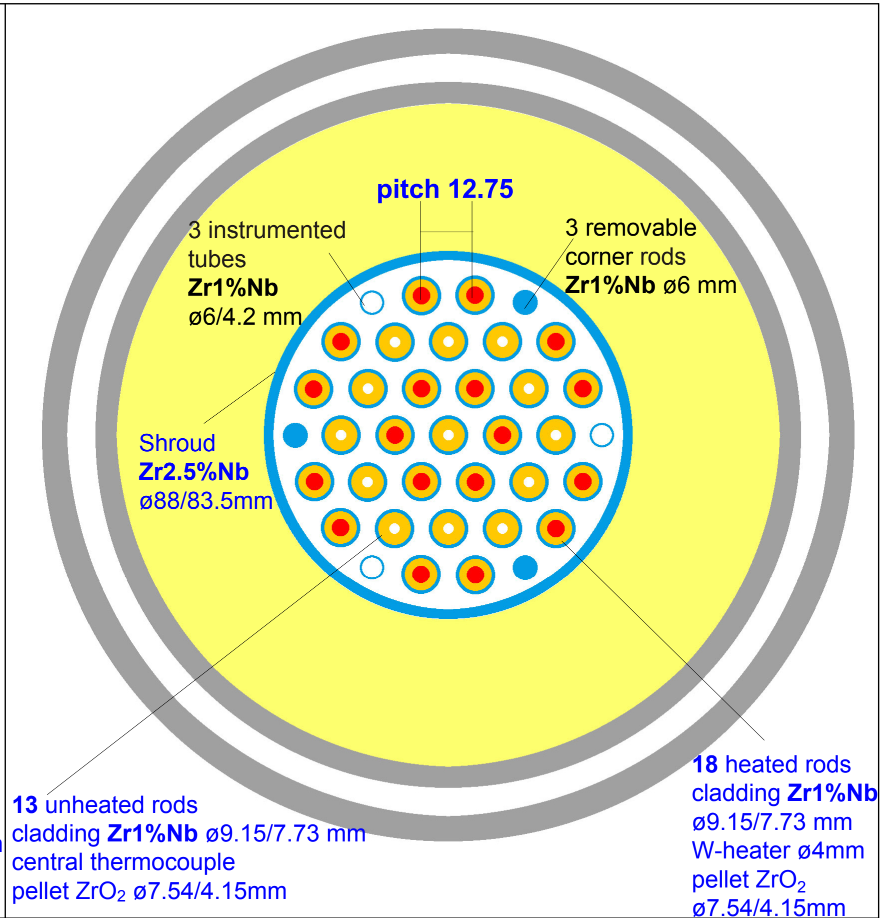
| Test | Test date | Quench medium | Flooding rate, g/s | Remarks |
|---|---|---|---|---|
| **QUENCH-01** | Feb 26, 1998 | Water | 52 | **EC COBE** |
| **QUENCH-02** | July 07, 1998 | Water | 47 | **EC COBE** |
| **QUENCH-03** | Jan 20, 1999 | Water | 40 | As Q-02 but flooding delayed |
| **QUENCH-04** | Juni 30, 1999 | Steam | 50 | Steam, reference |
| **QUENCH-05** | March 29, 00 | Steam | 48 | As Q-04 but with pre-oxidation |
| **QUENCH-06** | Dec 13, 2000 | Water | 42 | **OECD ISP-45**; As Q-05 but with water flooding |
| **QUENCH-07** | July 25, 2001 | Steam | 15 | **EC COLOSS**; $B_4C$ absorber |
| **QUENCH-08** | July 24, 2003 | Steam | 15 | As Q-07 but without $B_4C$ absorber |
| **QUENCH-09** | July 03, 2002 | Steam | 49 | **EC COLOSS**; As Q-07 but under steam starvation |
| **QUENCH-10** | July 21, 2004 | Water | 50 | **EC LACOMERA-1**; Air ingress |
| **QUENCH-11** | Dec 8, 2005 | Water | 15 | **EC LACOMERA-2**; Boil-off, **SARNET-Benchmark** |
| **QUENCH-12** | Sept 27, 2006 | Water | 48 | **ISTC 1648.2**; **VVER** |
| **QUENCH-13** | Nov 7, 2007 | Water | 52 | AgInCd absorber, **SARNET-Aerosol** |
| **QUENCH-14** | July 2, 2008 | Water | 41 | ACM series: **M5 ® cladding** |

# 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**

# Comparison of PWR and VVER test columns



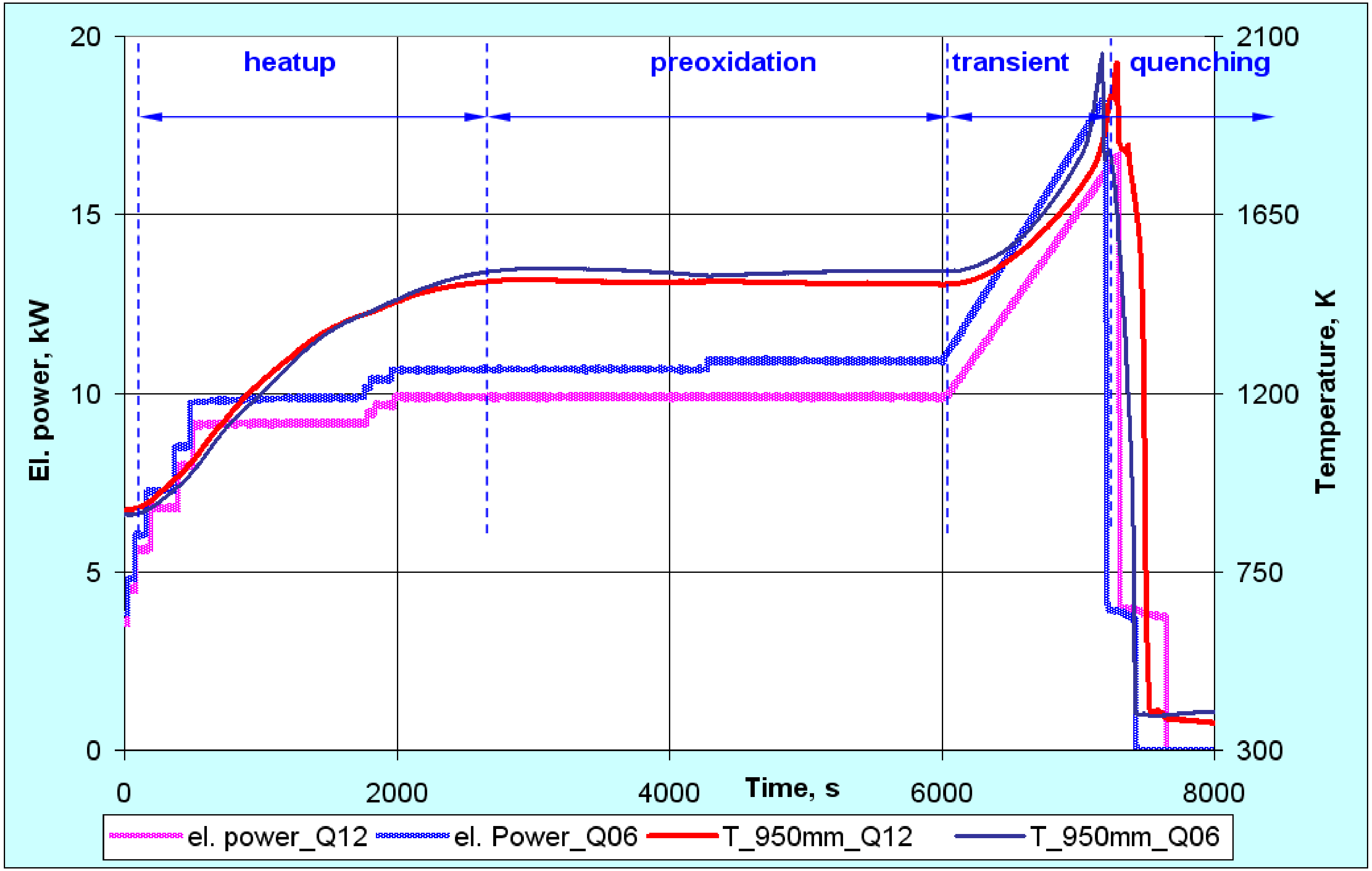

| Cross section of the PWR test column | Cross section of the VVER test column |
|---|---|
| **Cladding material: Zry-4 (or M5)** | **Cladding material: E110 (Zr1%Nb)** |

# Pretest modelling support:

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

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

# Test performance: el. power profile in accordance to the pre-test calculations provided good reproduction of temperature history in comparison with the reference test QUENCH-06



# Comparison of transient and reflood phases for QUENCH-14 (M5), QUENCH-12 (E110), QUENCH-06 (zry-4): similar escalation before reflood

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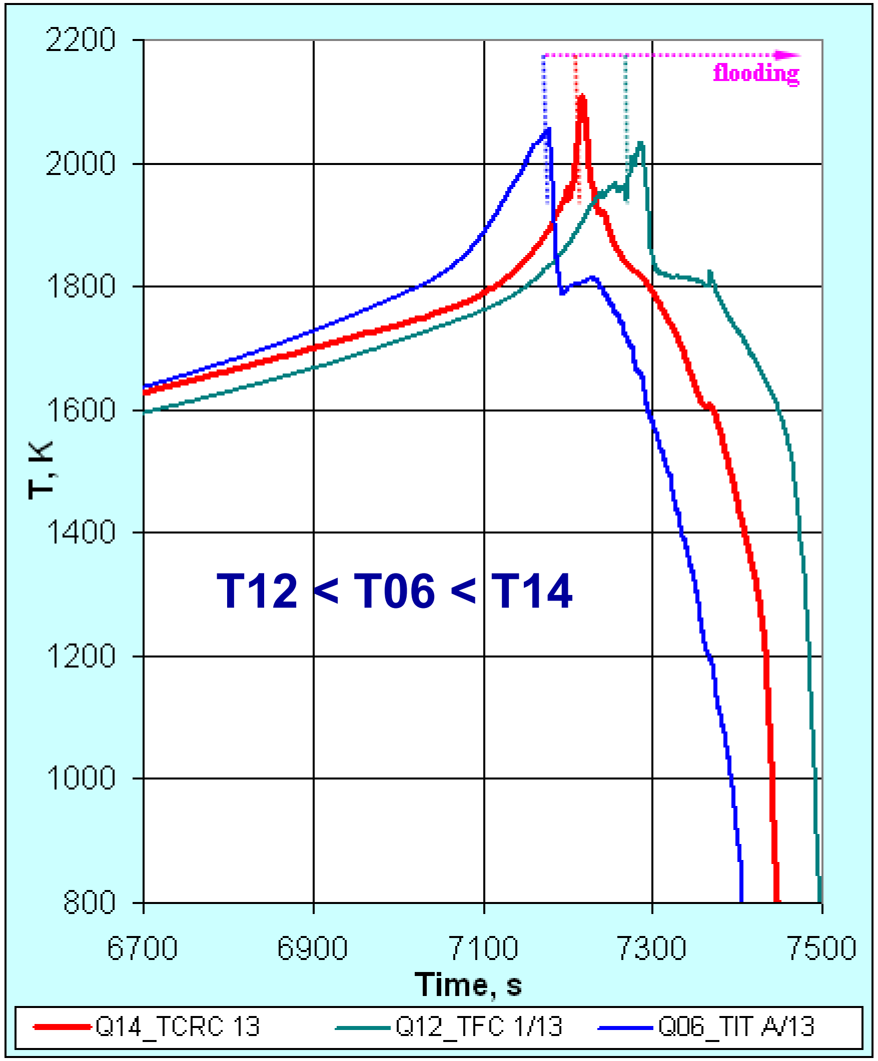
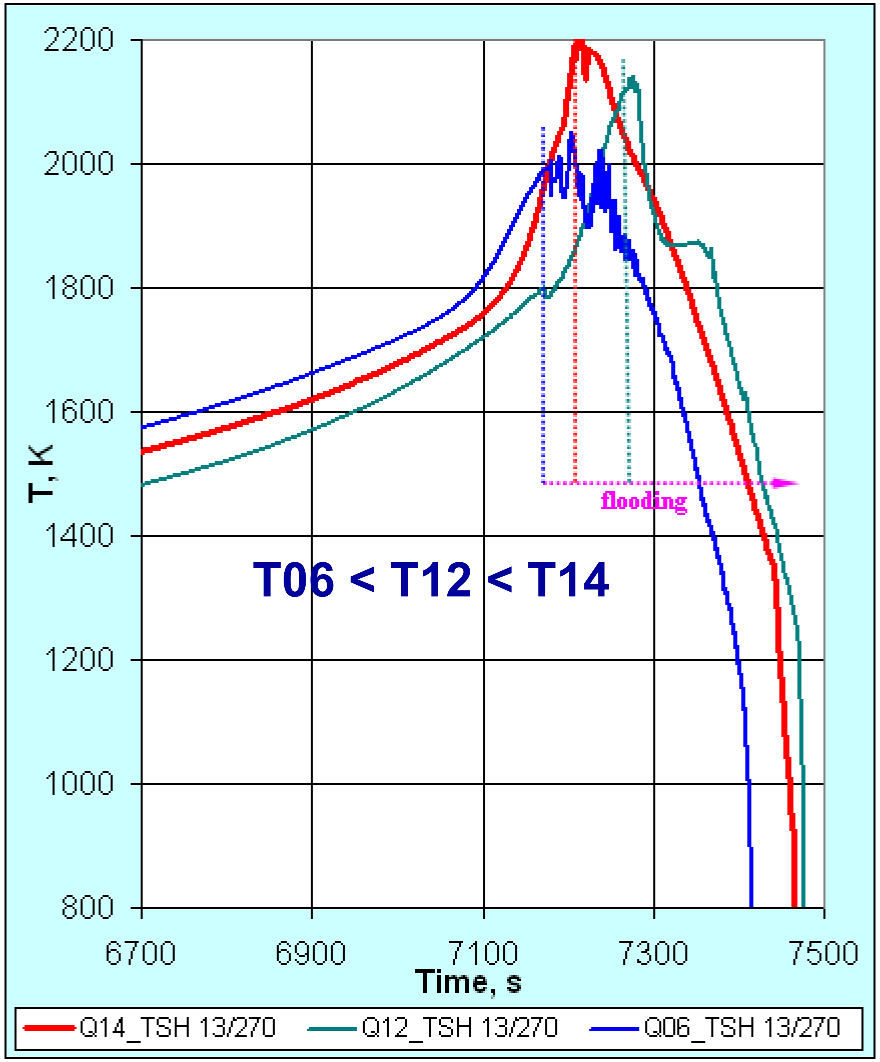
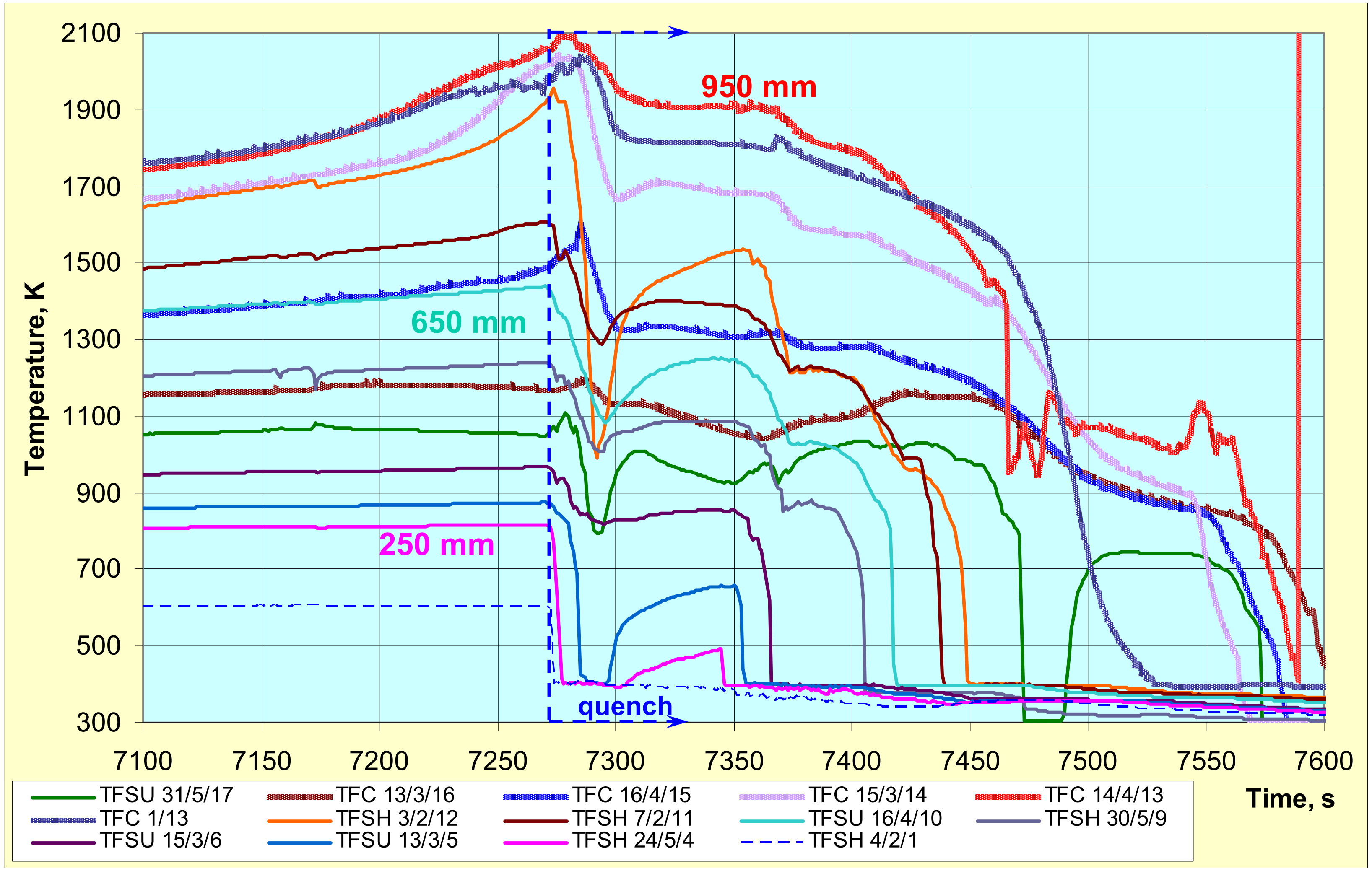



**bundle temperature at hot elevation of 950 mm**

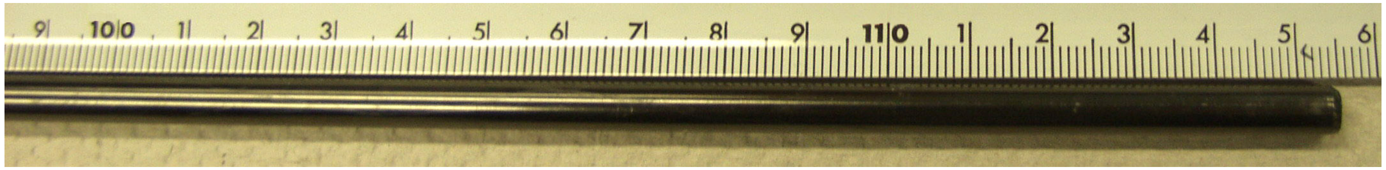



**shroud temperature at hot elevation of 950 mm**

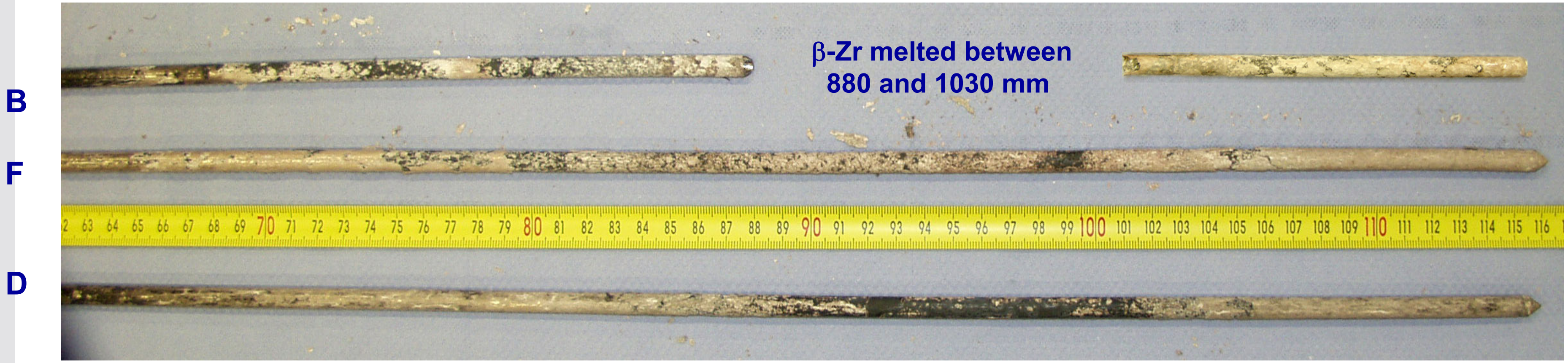
## QUENCH-12, quench phase: selected reading of the bundle thermocouples. Quench front propagation.
## Cooling of the bundle during ~350 s (similar to Q-06 and Q-14)



# QUENCH-12: withdrawn Zr1%Nb 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 due to breakaway oxidation.**

**D – withdrawn after pre-oxidation,**
**F – withdrawn before reflood,**
**B – withdrawn after test.**

# Axial bundle temperature profiles for QUENCH-06 and QUENCH-12 on beginning and end of transient phase

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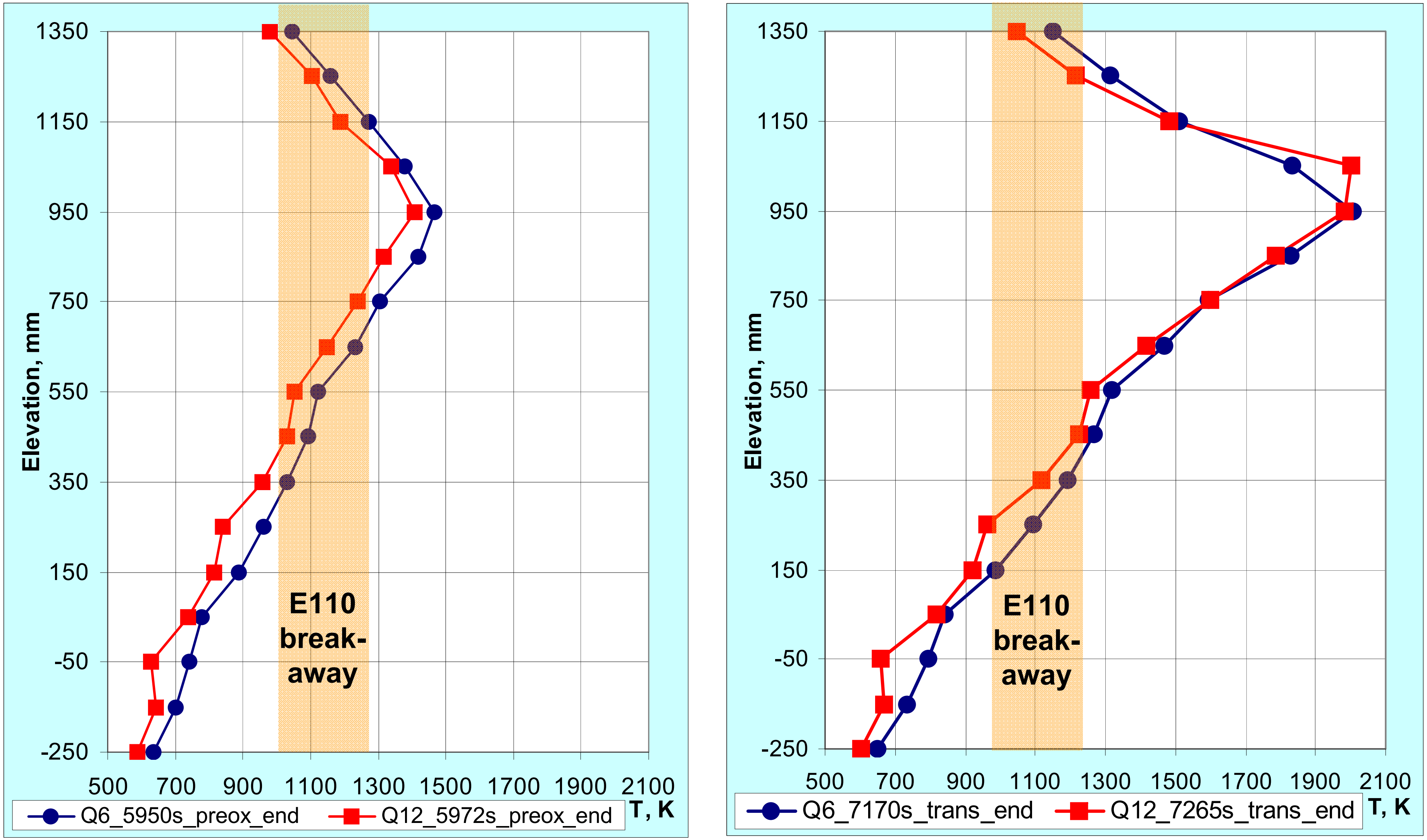


**beginning of transient** **end of transient**

# QUENCH-12: post-test videoscope observations of breakaway oxidation at different elevations of the bundle

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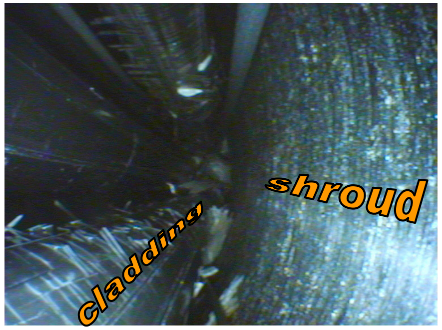
Tmax

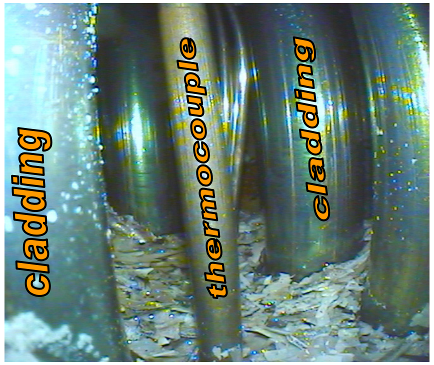

900 mm:
circumferential
and longitudinal cracks
at the cladding;
nodular breakaway
corrosion
at the shroud


650 mm:
spalled oxide scales
at shroud and cladding




400 mm:
circumferential spalling
of the oxide layer
on the surface
of fuel rod simulator cladding

Tmin




-400mm:
spalled oxide scales
as debris
at the bundle bottom

# Comparison cross-sections of QUENCH-06 and QUENCH-12 at elevation 550 mm with $ZrO_2$ thickness ~40 µm

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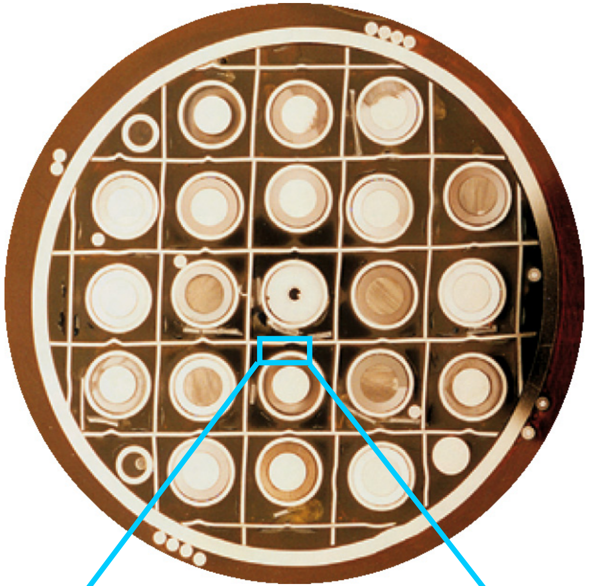
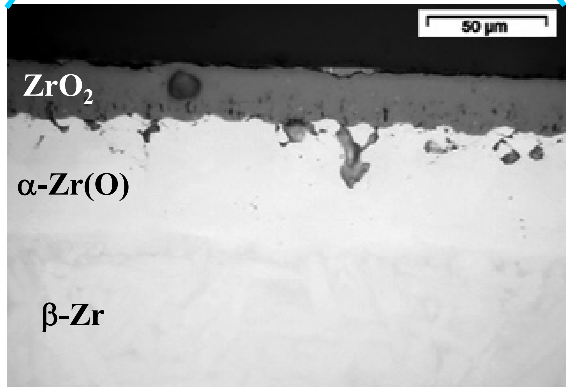
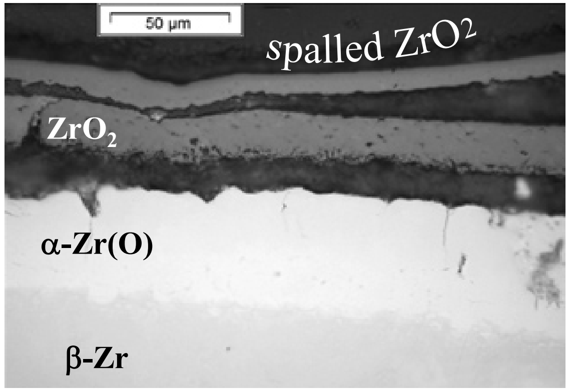


Q06 cross-section




Q06 oxidized cladding

Q12: rubble on spacer grid consists of spalled cladding scales and fragments of partially oxidized cladding




Q12 cladding: spalling of oxide scales due to breakaway effect

# Comparison cross-sections of QUENCH-06 and QUENCH-12 at elevation 750 mm with $ZrO_2$ thickness ~80 µm

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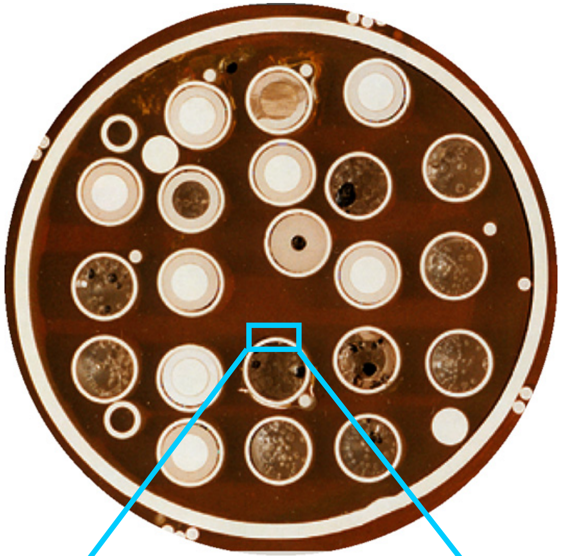
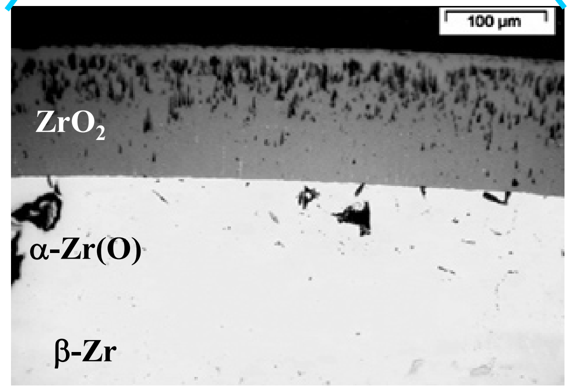
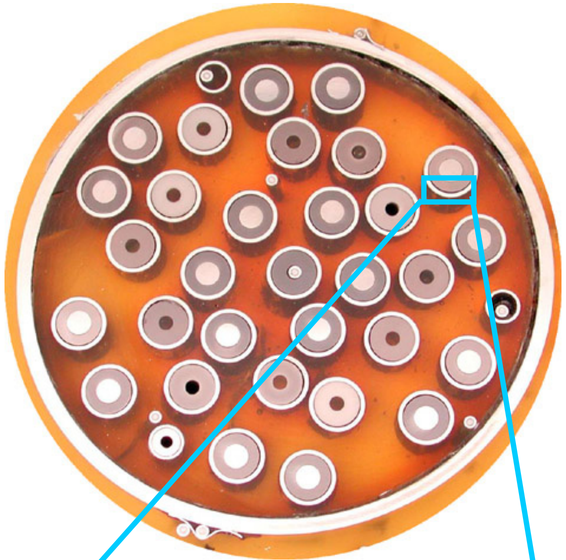


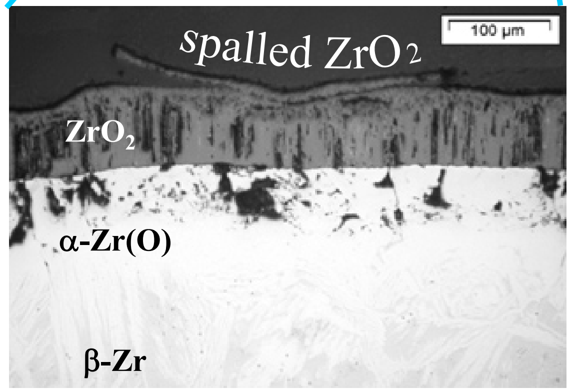
**Q06 cross-section;**
**few bundle deformation**




**Q06 oxidized cladding**

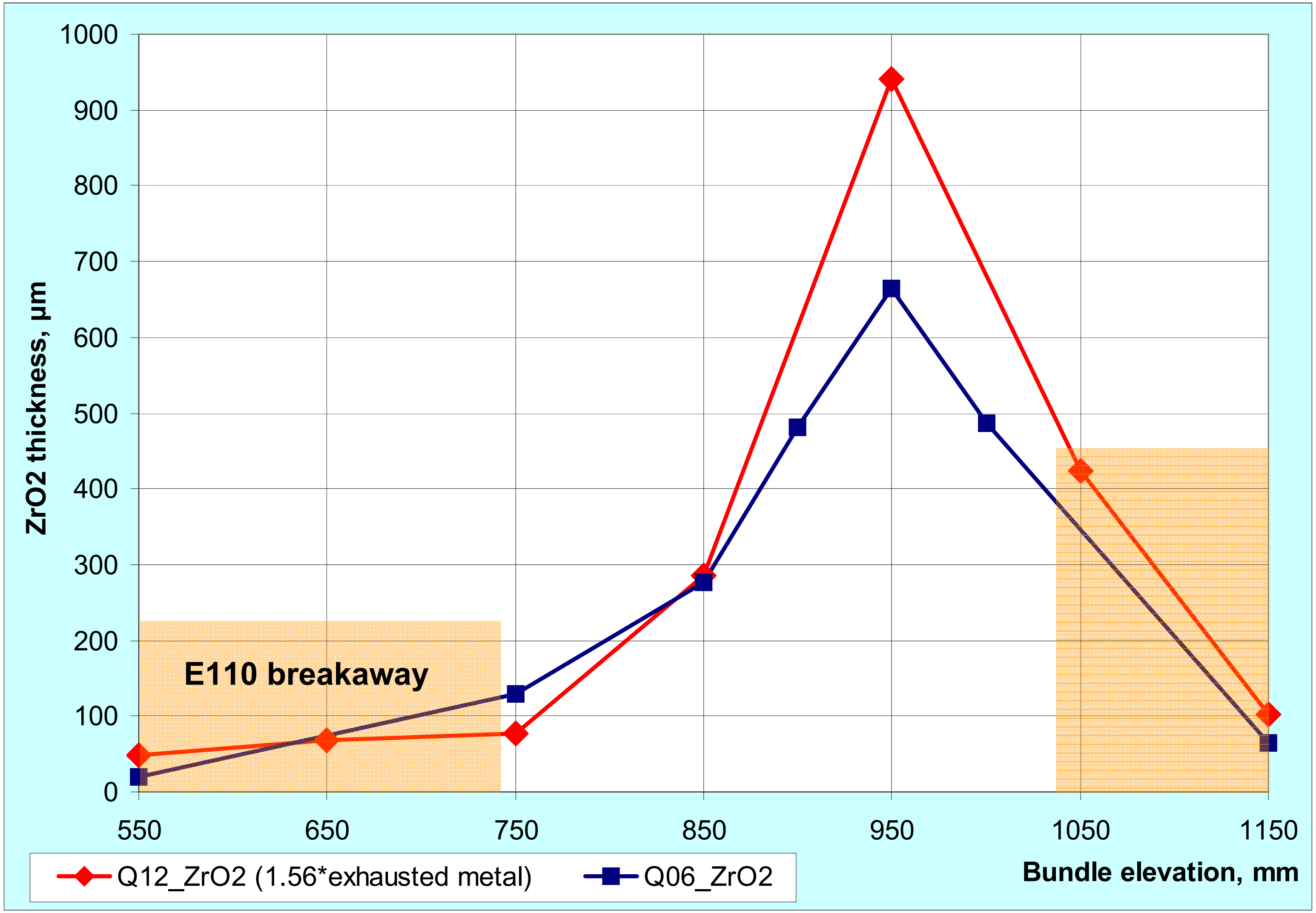


**Q12 cross-section;**
**moderate bundle deformation**



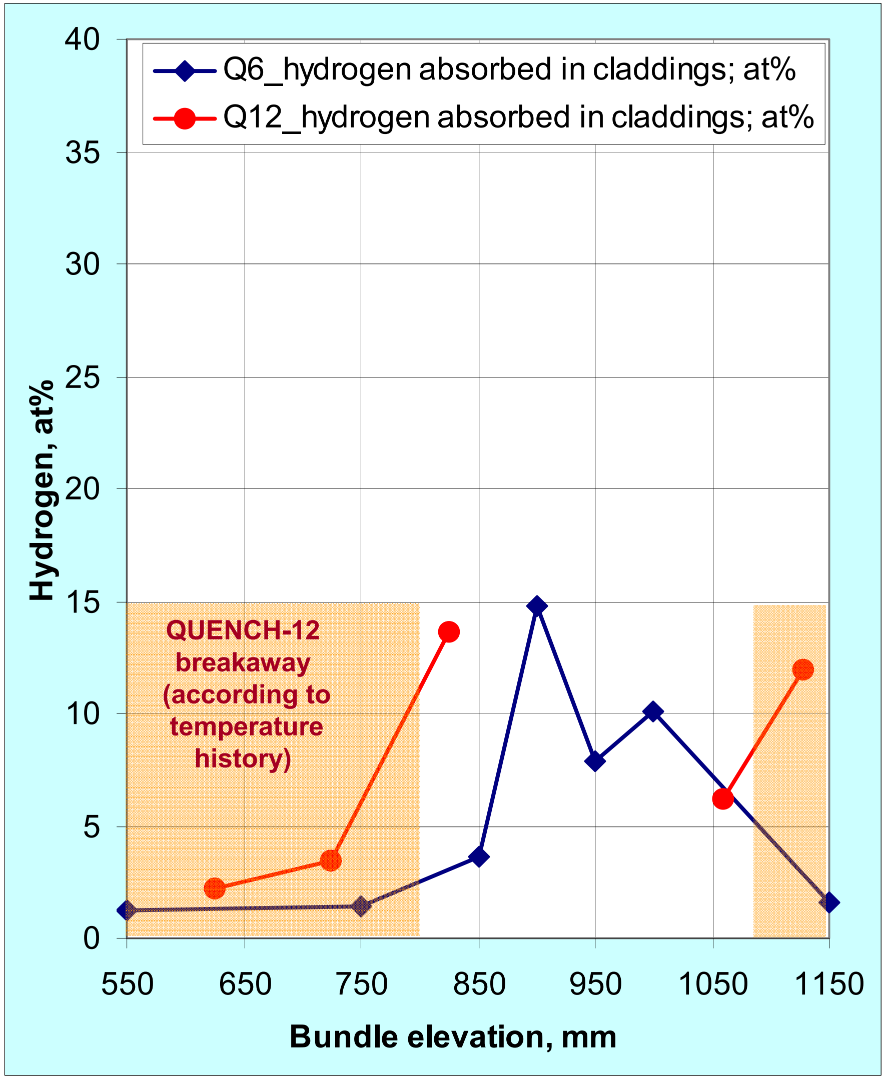

**Q12 cladding: spalling of oxide scales due to breakaway effect**

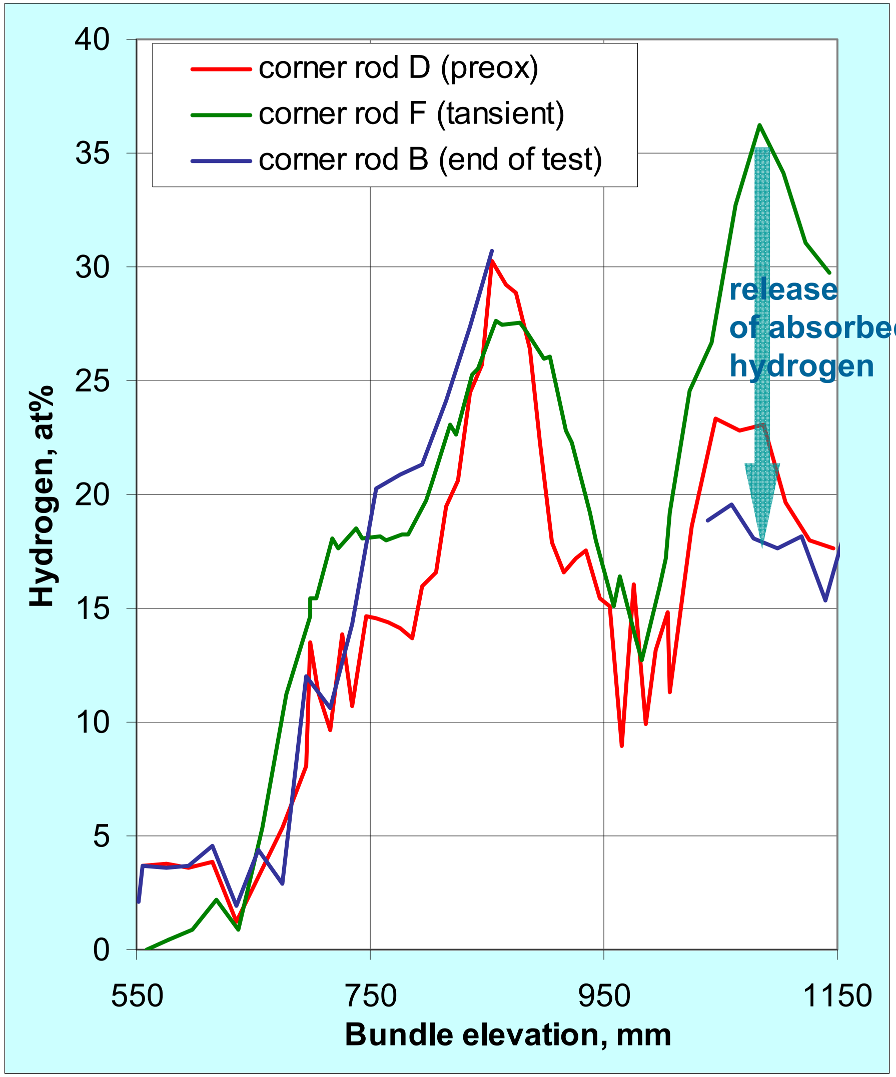
# Comparison of averaging oxide cladding thicknesses for QUENCH-06 and QUENCH-12 at all elevations




**Degree of cladding oxidation is mostly lower for QUENCH-06 (Zry-4) in comparison to QUENCH-12 (E110)**

# Comparison of hydrogen uptake by bundle during QUENCH-06 and QUENCH-12



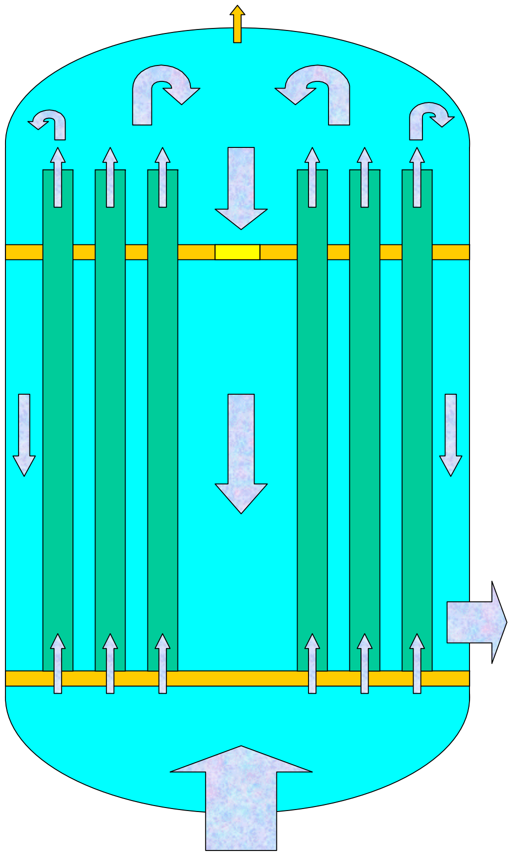




**Q-06<->Q12: $H_2$ uptake in cladding measured by hot extraction**

**Q-12: $H_2$ uptake in corner rods measured by neutron radiography**

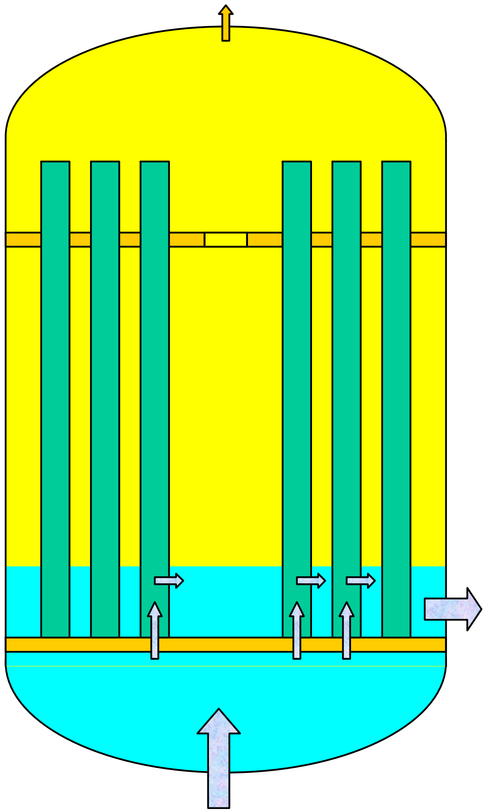
# Paks/Ungary cleaning tank incident in April 2003 with destroying of 30 VVER fuel assemblies

***Cooling during normal cleaning:***
- high flow rate
- closed loop

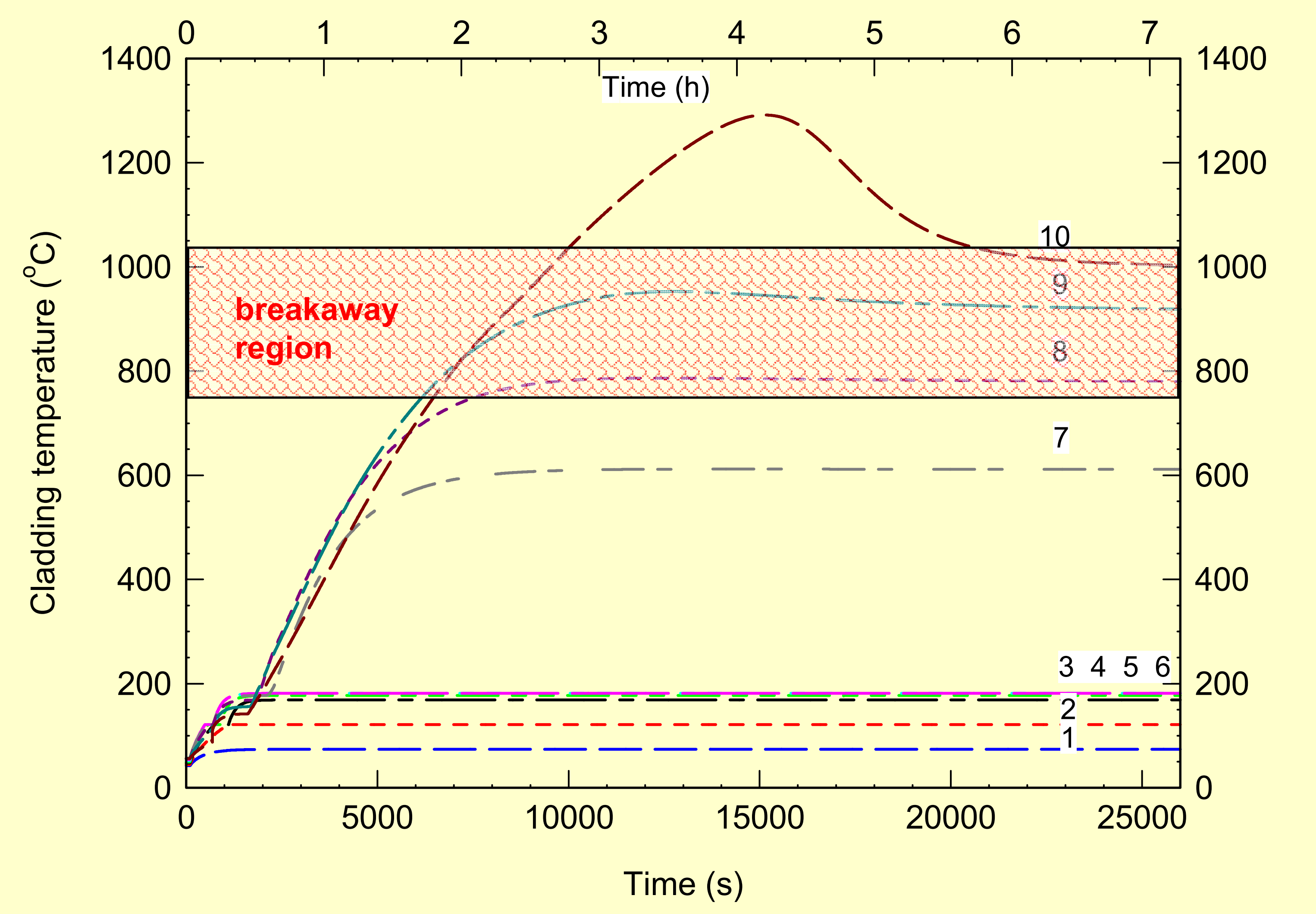


***Cooling after cleaning***
- low flow rate
- open loop with connection to spent fuel pool
- possibility of by-pass by bundle low head

decay heat for 30 bundle: 241 kW

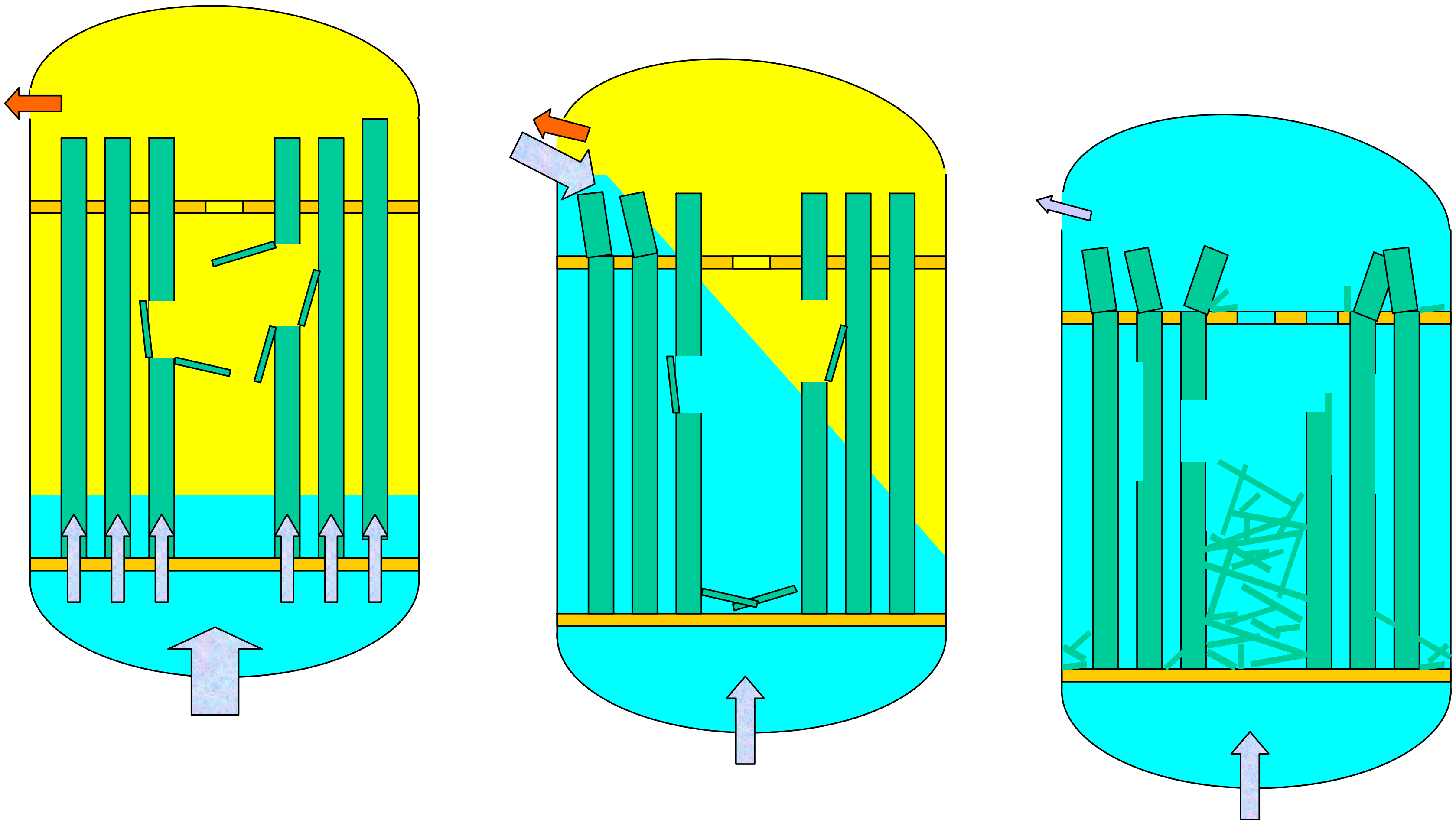


## Breakaway long-term oxidation during the Paks cleaning tank incident (destroying of 30 VVER fuel assemblies)

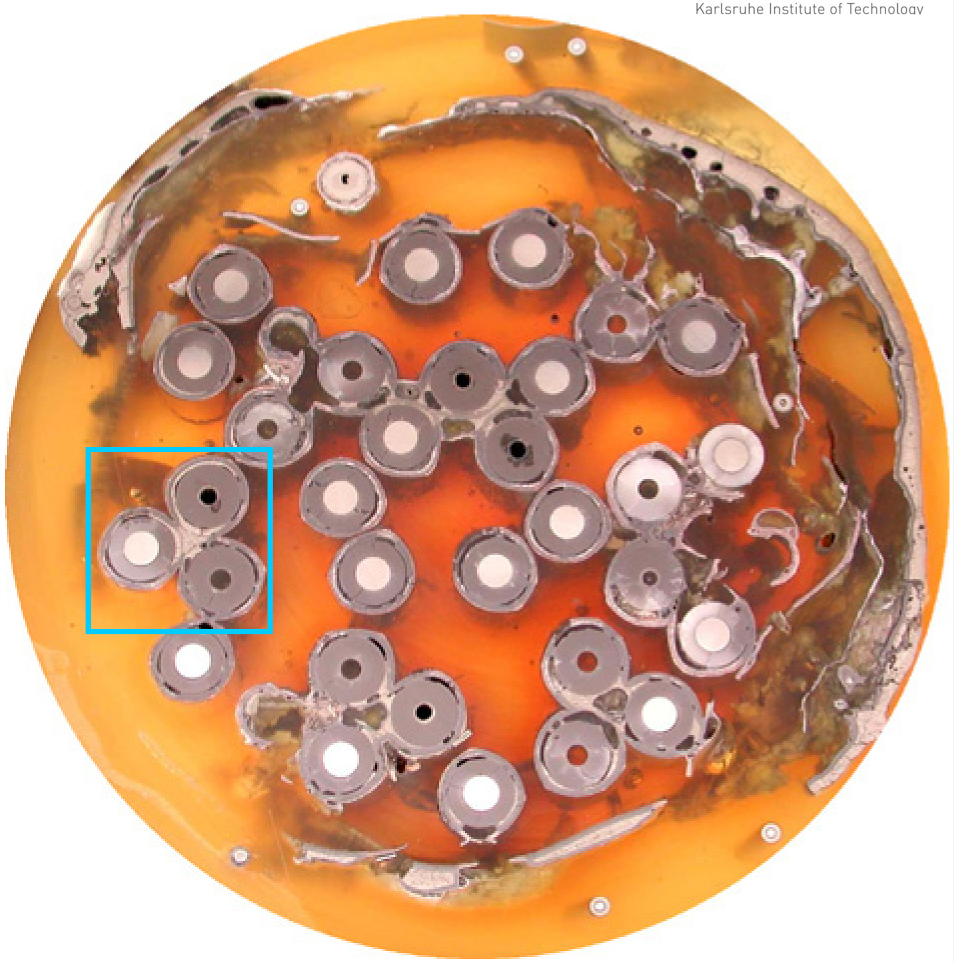



**Results of modeling (FRAP-T6 code)**

# Collapse of VVER-bundles, strong hydrogenated under breakaway conditions



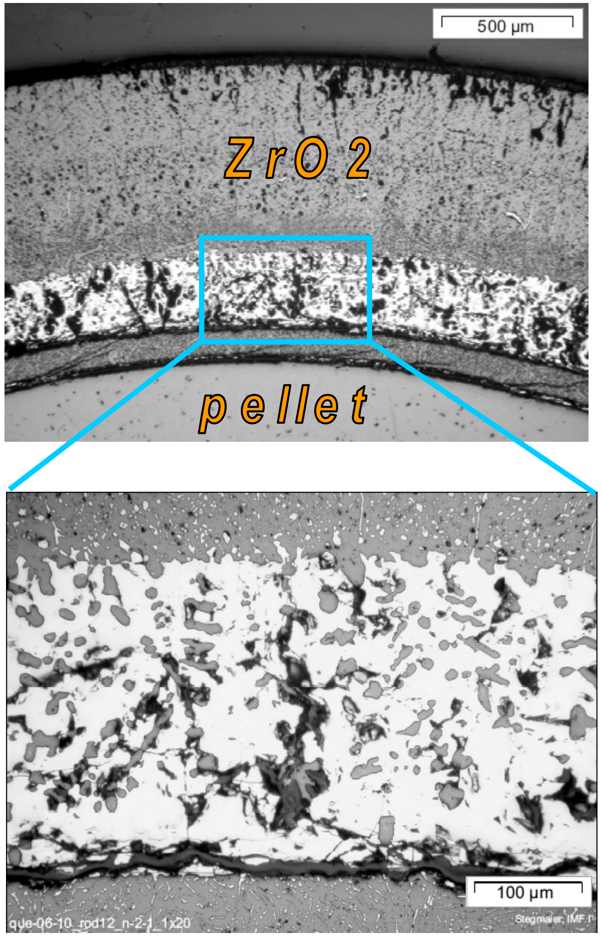
# Other important phenomenon: melt formation and oxidation by QUENCH-06 and QUENCH-12 at elevation 950 mm



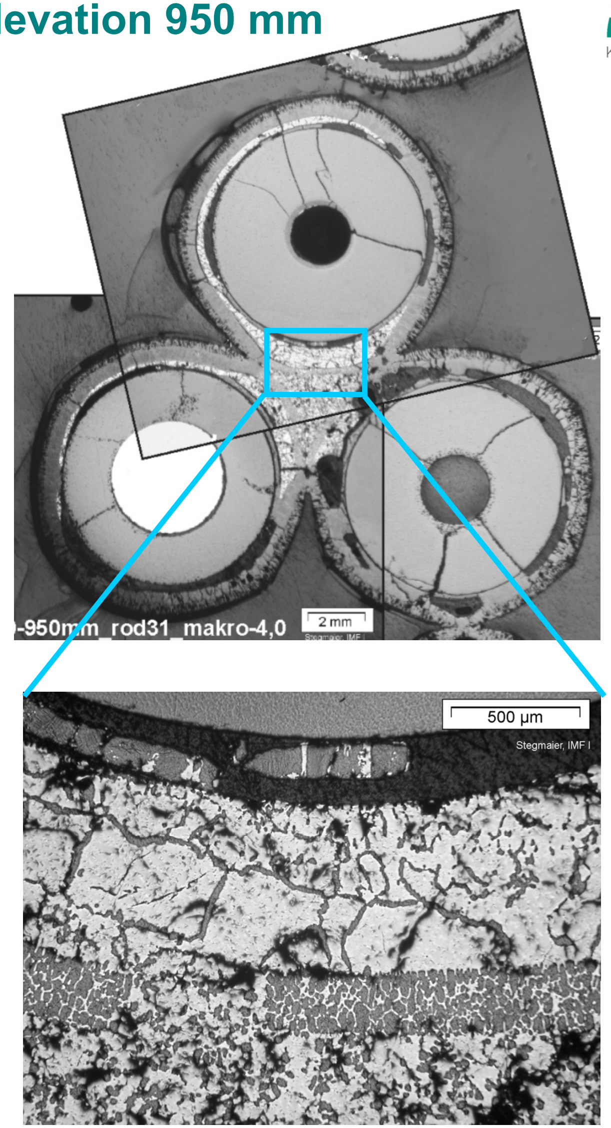
**Q06 - bundle geometry intact-> good coolability; melt localized between pellet and $ZrO_2$ layer**

**Q12 – bundle geometry destroyed-> declined coolability; molten pools formation inside rod clusters**

# Melt formation and oxidation by QUENCH-06 and QUENCH-12 at elevation 950 mm

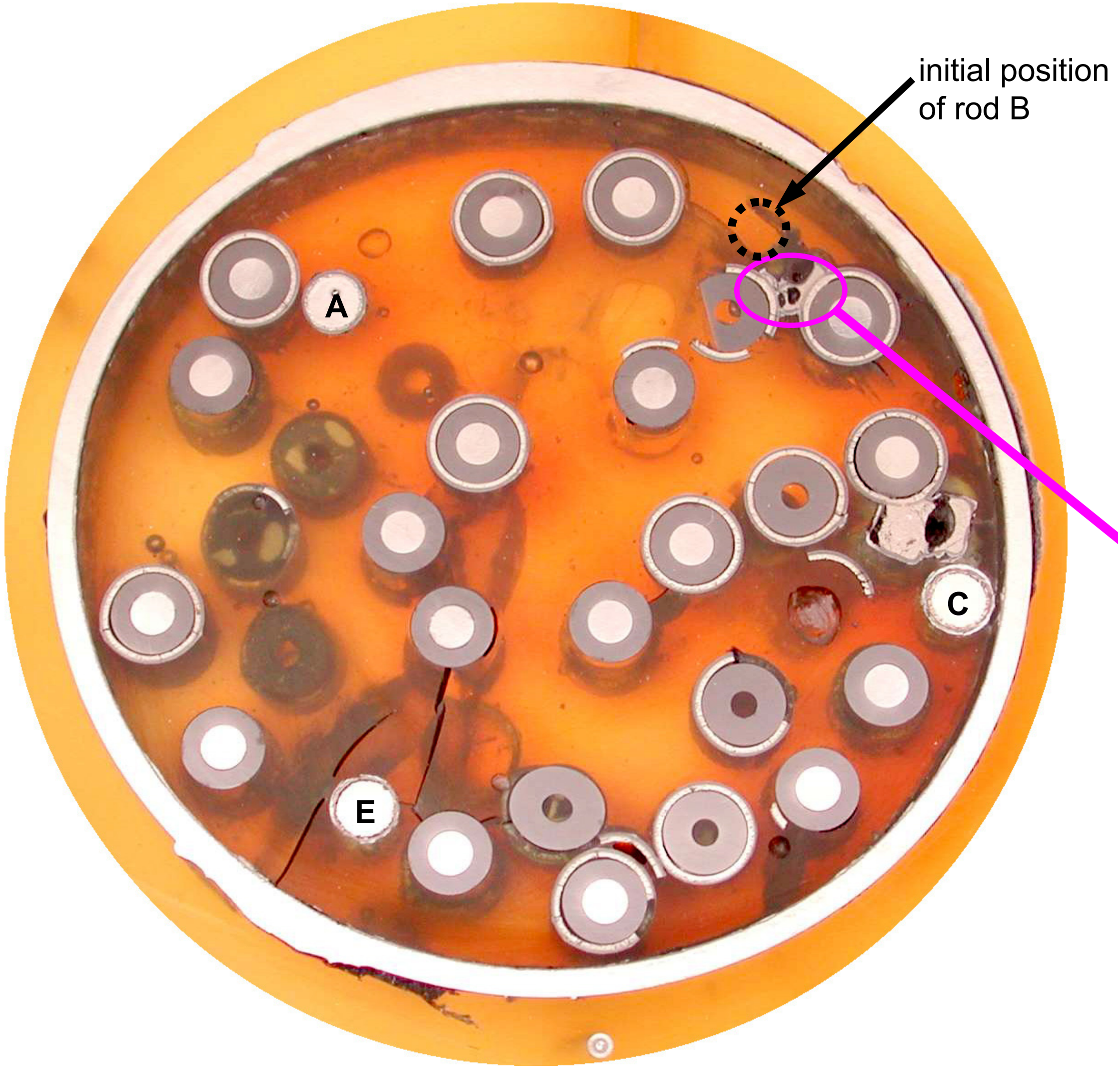


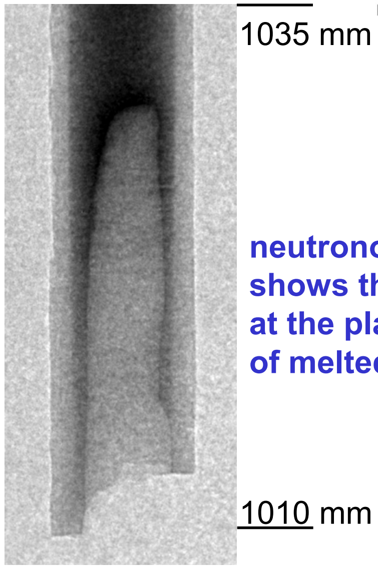

**Q06: melting of cladding metal layer, precipitates formation on cooldown**



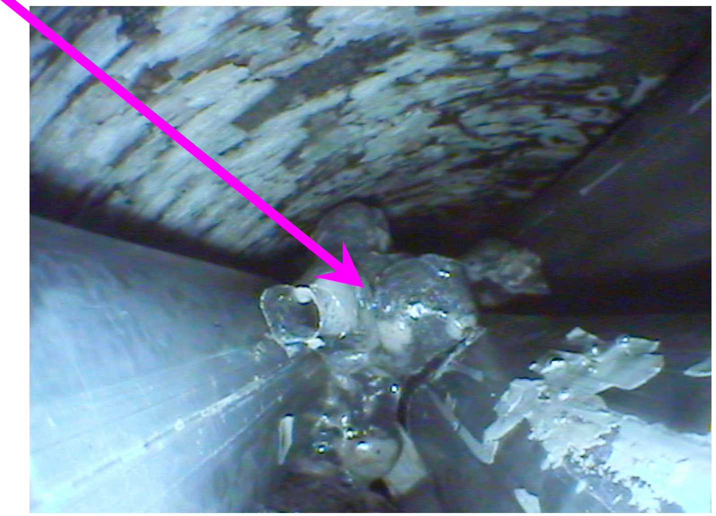

**Q12: molten pool between rods, precipitates formation due to melt oxidation in steam**

# QUENCH-12: melting of corner rod B



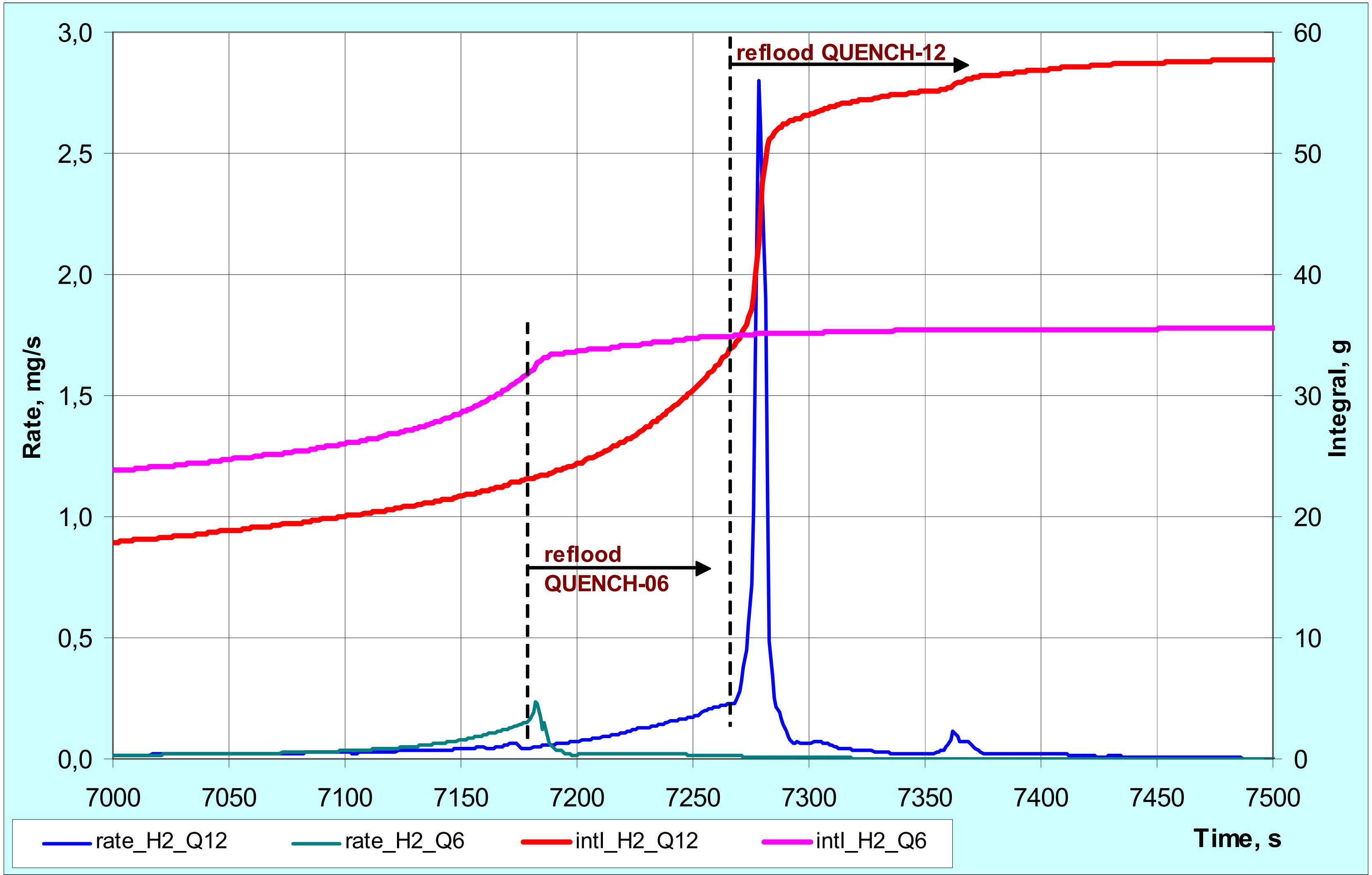




**neutronography shows the deep hole at the place of melted out β-Zr**

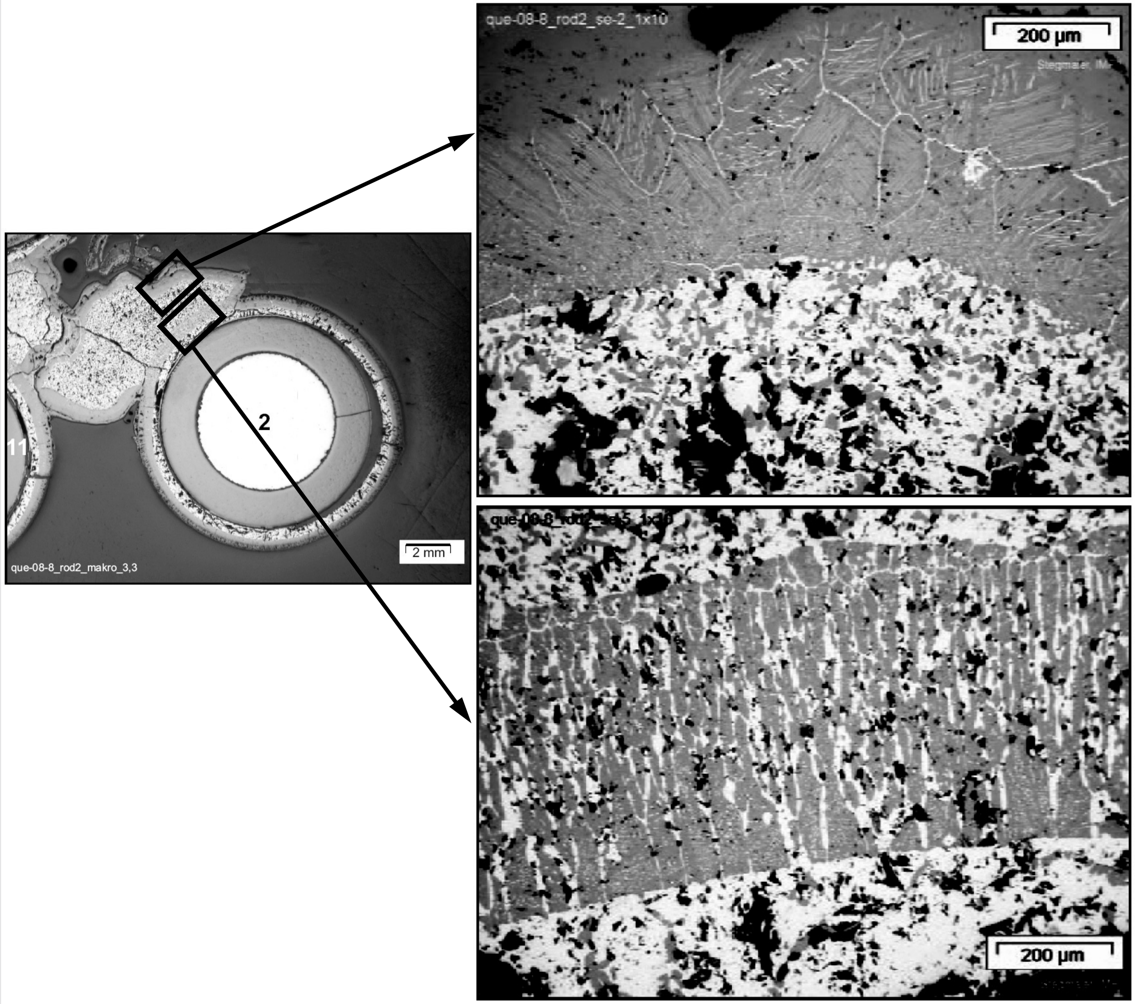


**850 - 900 mm: melt formation in bundle at the position of melted corner rod B**

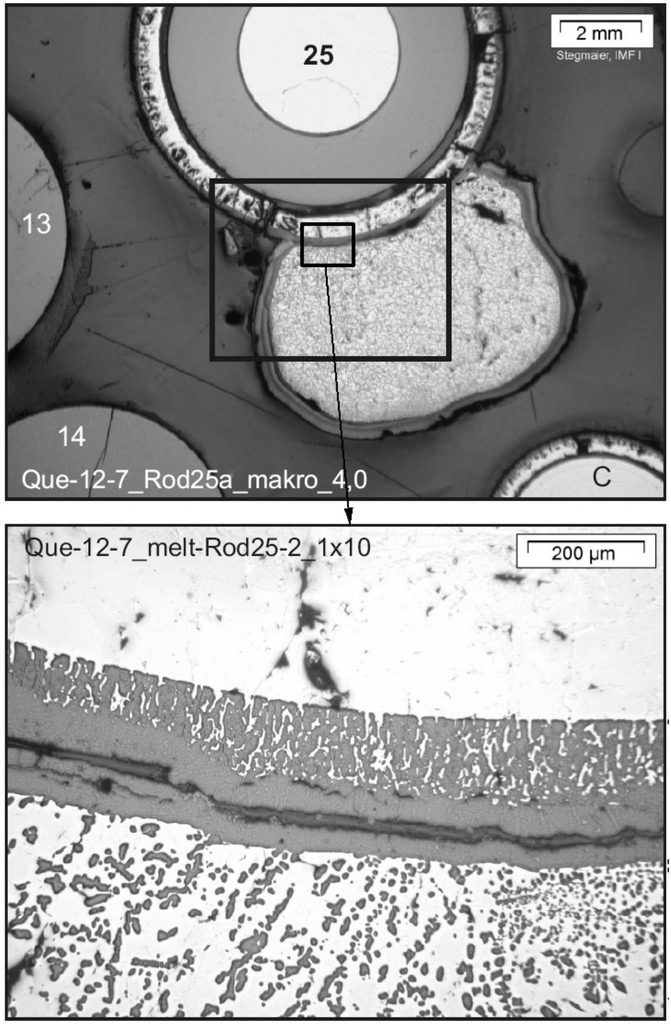
## Comparison of hydrogen release during QUENCH-12 and QUENCH-06



## Comparison of post-test cladding and melt structures for Q-08 and Q-12




**Q-08, 860 mm**




**Q-12, 850 mm**

# Comparison of hydrogen release during reflood for Q-08 test (oxidation before transient 270 µm; *significant melt oxidation*) and Q-12 test (oxidation before transient 160 µm; *minor melt oxidation*)

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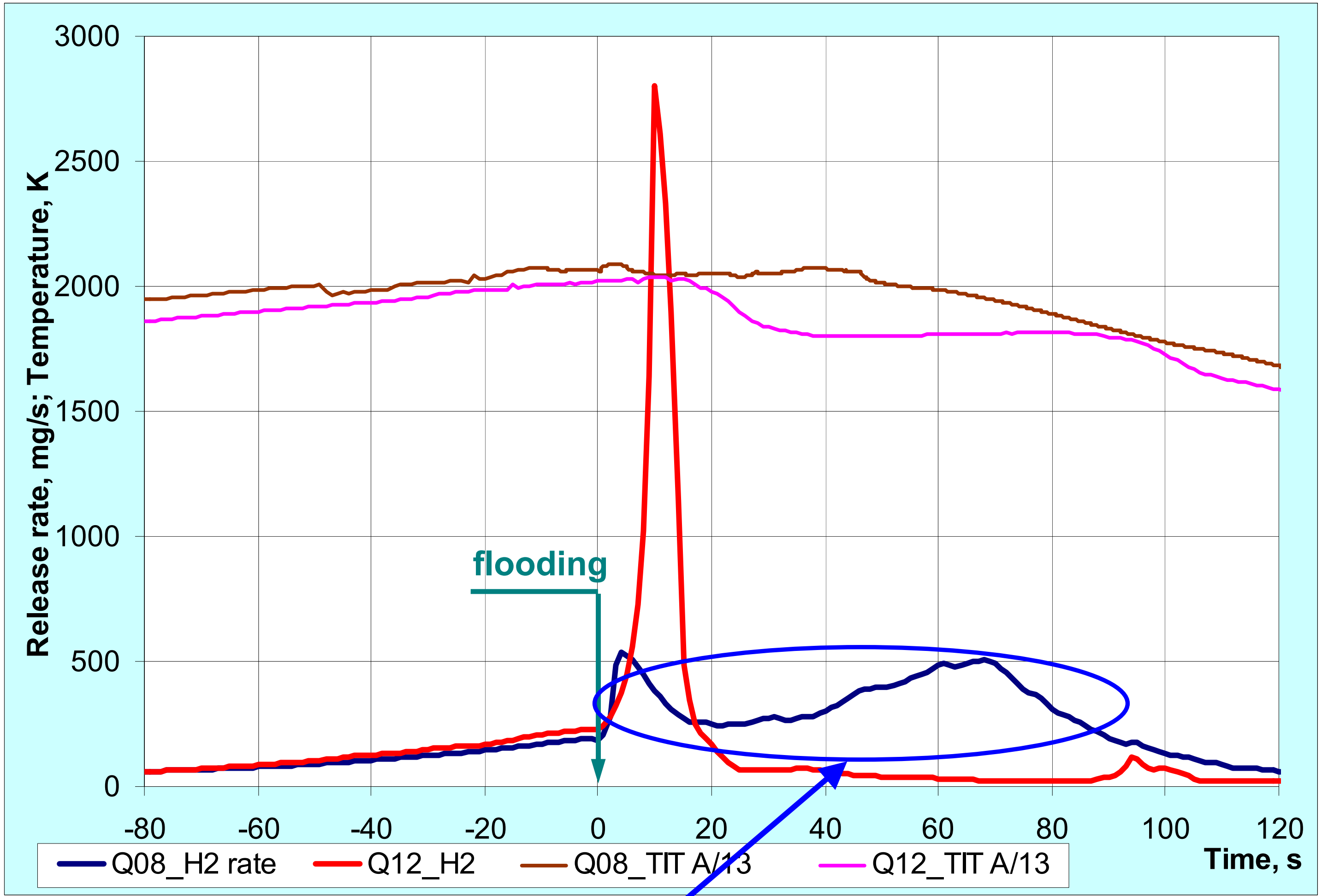
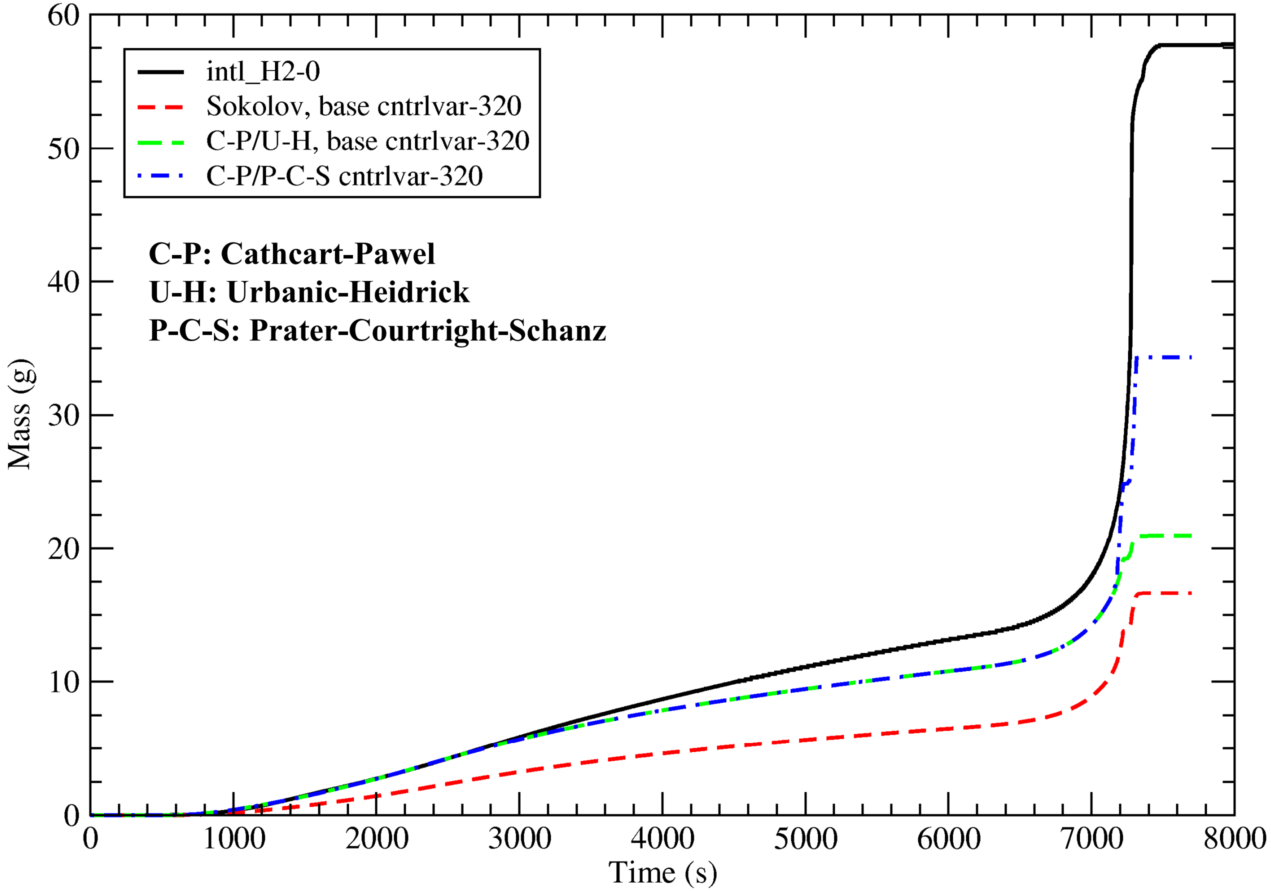



**Long duration of hydrogen production during the quench phase in case of significant melt oxidation (Q-08)**

# QUENCH-12: calculated and measured hydrogen generation /J. Birchley, PSI/




**Despite the similar thermal response through almost the entire sequence, all of the calculations underestimated the oxidation.**

## CONCLUSIONS

• The QUENCH-12 experiment was carried out to investigate the effects of VVER materials and bundle geometry on core reflood, in comparison with the test QUENCH-06 (Zry-4-cladding) with western PWR geometry.

• During the pre-oxidation and transient phases the E110 cladding alloy is susceptible to breakaway oxidation within relative broad temperature range (1050 – 1300 K). Oxide scale of layered type showed spalling into sub-layers and loss of fragments, which were collected at spacer grids and bundle bottom.

• The breakaway oxidation was accompanied by hydriding of claddings and shroud with the result of material embrittlement, which can lead to a severe degradation of the bundle during quenching as was demonstrated in the Paks accident.

## CONCLUSIONS (cont.)

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- Melting point of claddings and shroud metal layer was reached at the peak temperature elevations of 950 – 1050 mm. Contrary to QUENCH-06, where melt was confined between pellets and the outer cladding oxide layer, the melt in QUENCH-12 has in places dissolved the surrounding oxide layer. As a result, non-coherent melt relocation, melt pool formation, and minor melt oxidation were observed.

- The total hydrogen production was 58 g (QUENCH-06: 36 g), 24 g of which were released during reflood (QUENCH-06: 4 g). Three possible sources of increased hydrogen production during reflood: 1) interaction of steam with new metal surfaces developed by spalling of oxide scales damaged during pre-oxidation phase because breakaway effect; 2) release of hydrogen absorbed in metal by breakaway during pre-oxidation and transient phases; 3) moderate melt oxidation released into space between rods.

- The S/R5 code adequately reproduced the QUENCH-12 thermal transient. Both the Cathcart-Pawel and Sokolov correlations underestimated the oxidation kinetics, but preliminary analysis indicates that the comparison with QUENCH-06 is consistent with the change in the bundle configuration and cladding material; in particular breakaway effect may have enhanced the oxidation.