

# Final report on the stage B of the ISTC project # 1648.2.

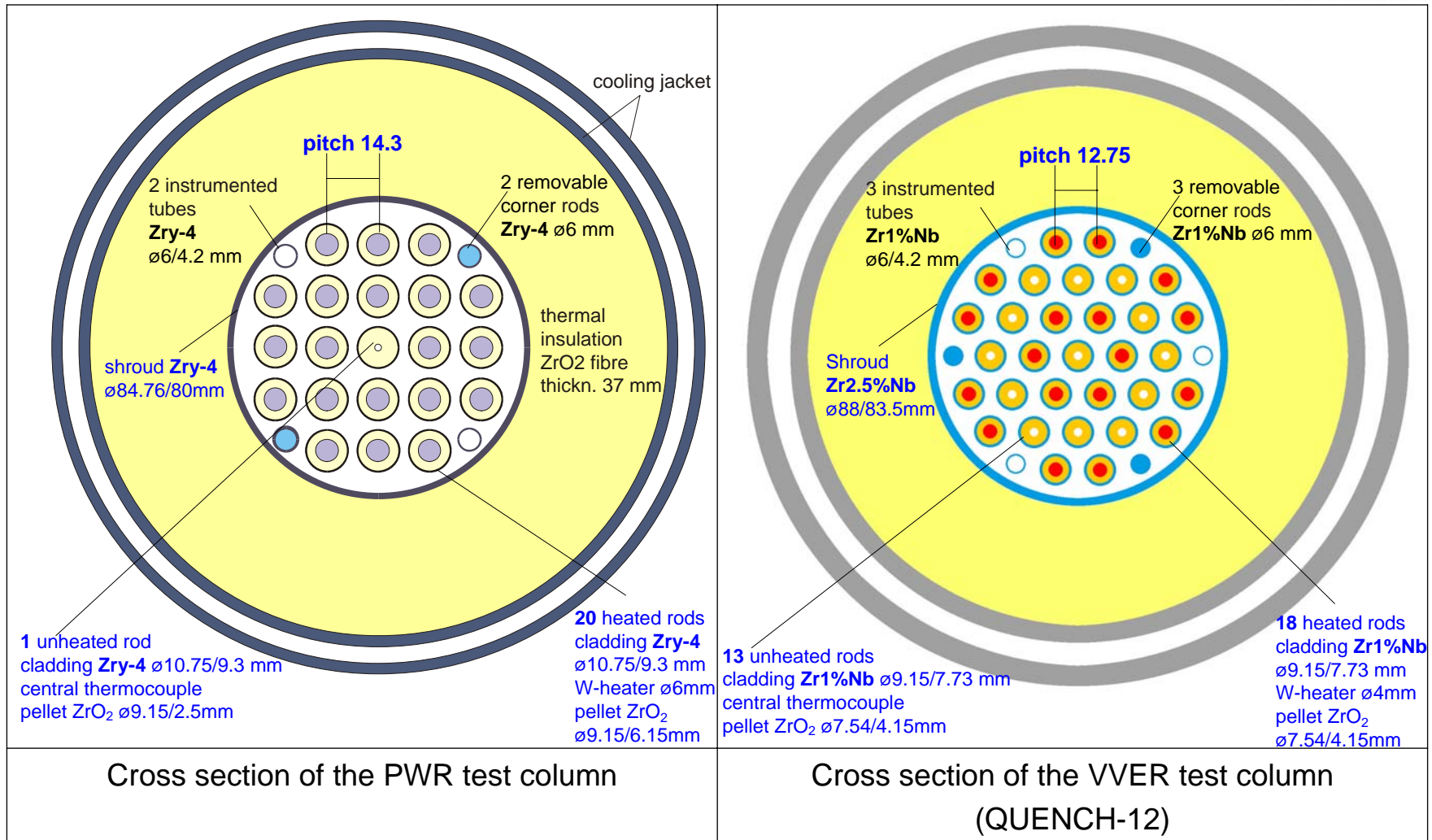
## Results of the integral reflood test QUENCH-12 with a VVER bundle

*presented by J. Stuckert,  
Forschungszentrum Karlsruhe*

## 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



- bundle metallic surface relationship  $Q_{12}/Q_{06} = 1.22$
- bundle material mass relationship  $Q_{12}/Q_{06} \sim 0.97$

# Time schedule of Project performance

July 1999	1 <sup>st</sup> Proposal from RIAR and ELECTROSTAL on a VVER bundle test in the QUENCH facility
2001	ISTC development grant for Project 1648
October 2002	Recommendation of 2 <sup>nd</sup> CEG-CM (Karlsruhe) for 1648.2 with highly priority
March 2003	Approval of Project 1648.2 by the ISTC Governing Board
June 2004	Start of Project 1648.2
March 2005	Contract between RIAR and FZK on delivery of the VVER bundle components
October 2005	Delivery of bundle components to FZK: 1) etched and anodized Zr1%Nb cladding tubes, 2) Zr2.5%Nb shroud tube, 3) Zr2.5%Nb flange tube, 4) Zr1%Nb holder rods, 5) Zr1%Nb corner rods, 6) Zr1%Nb corner tubes, 7) Zr1%Nb spacing grids.
27 September 2006	<u>Conducting of the QUENCH/VVER test (QUENCH-12) by FZK</u>
2006 - 2008	Evaluation of the test data; metallographic examination of bundle by RIAR and FZK
December 2007	Report FZKA-7353 on the post-test modelling with the SVECHA code (IBRAE-FZK-ITU)
March 2008	Report FZKA-7307 on results of the QUENCH-12 test



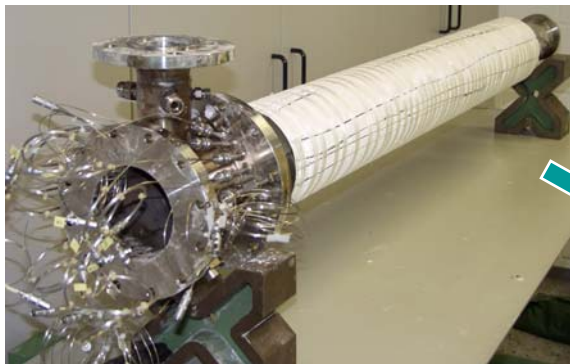
# Test bundle preparation



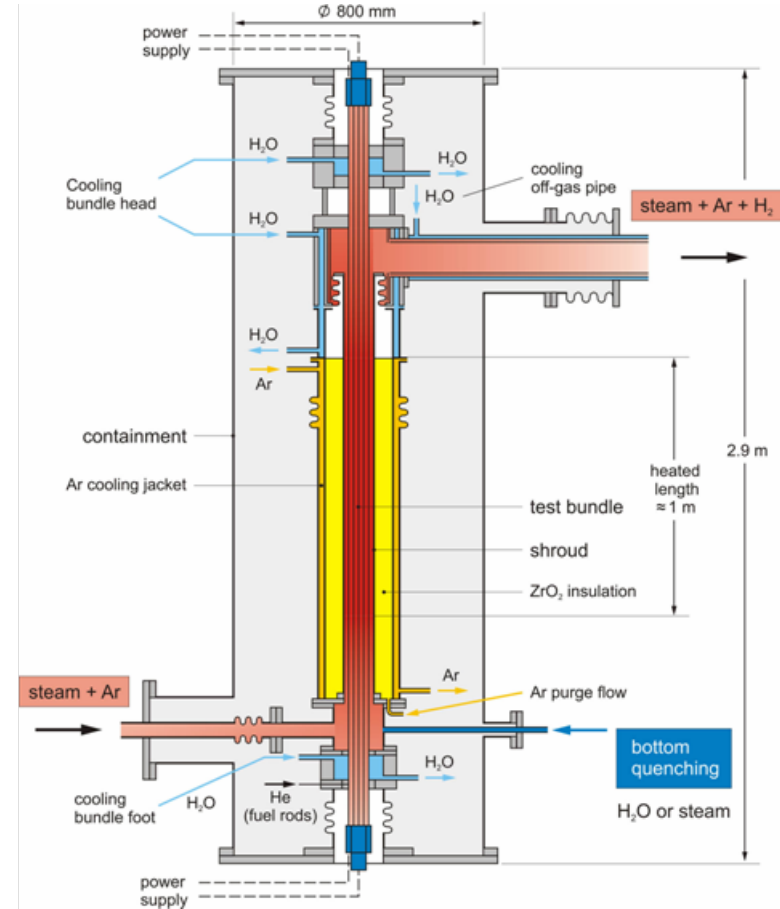
bundle bottom



bundle top



shroud with heat insulation



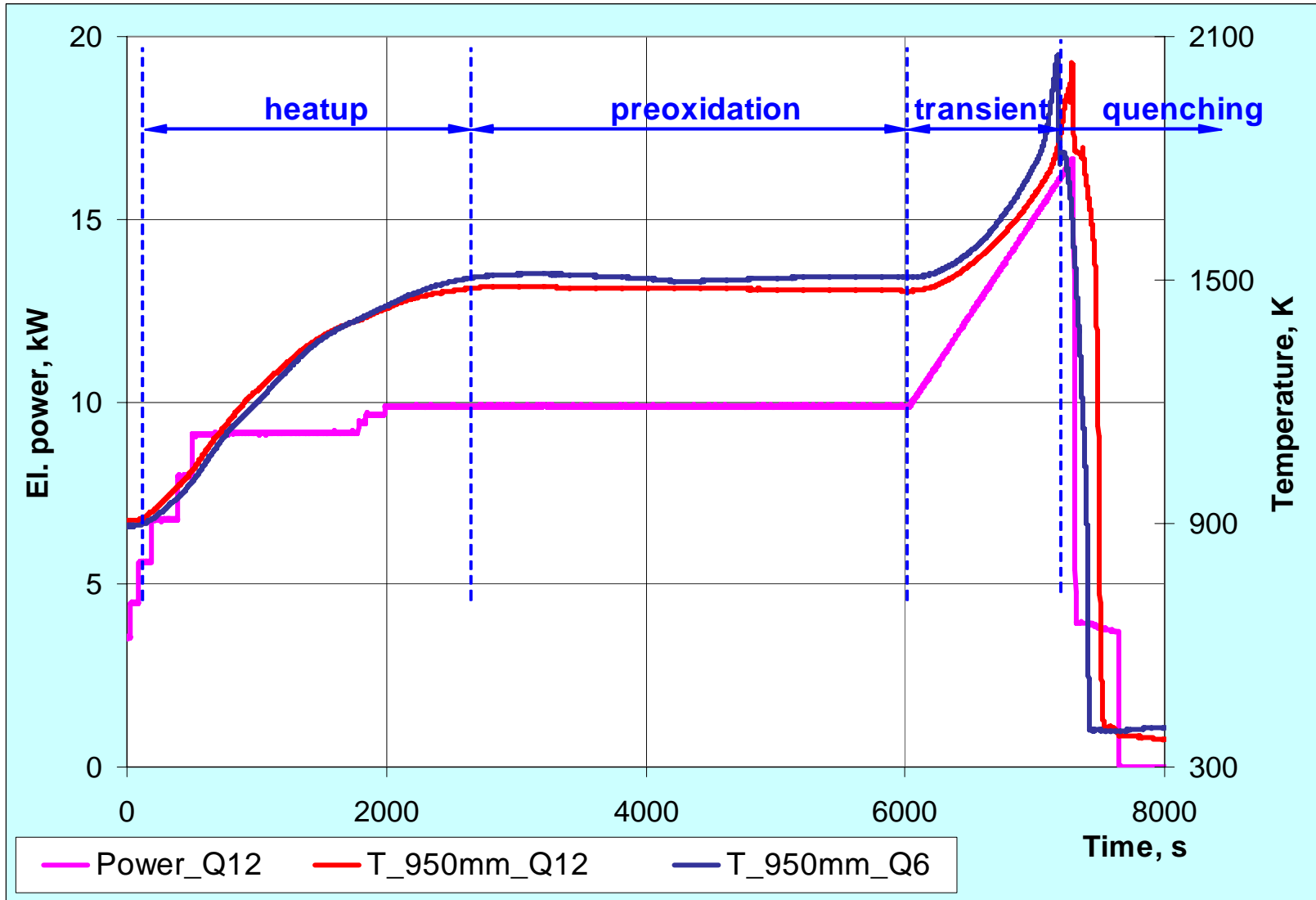
test containment with instrumented bundle

## Pretest modelling support:

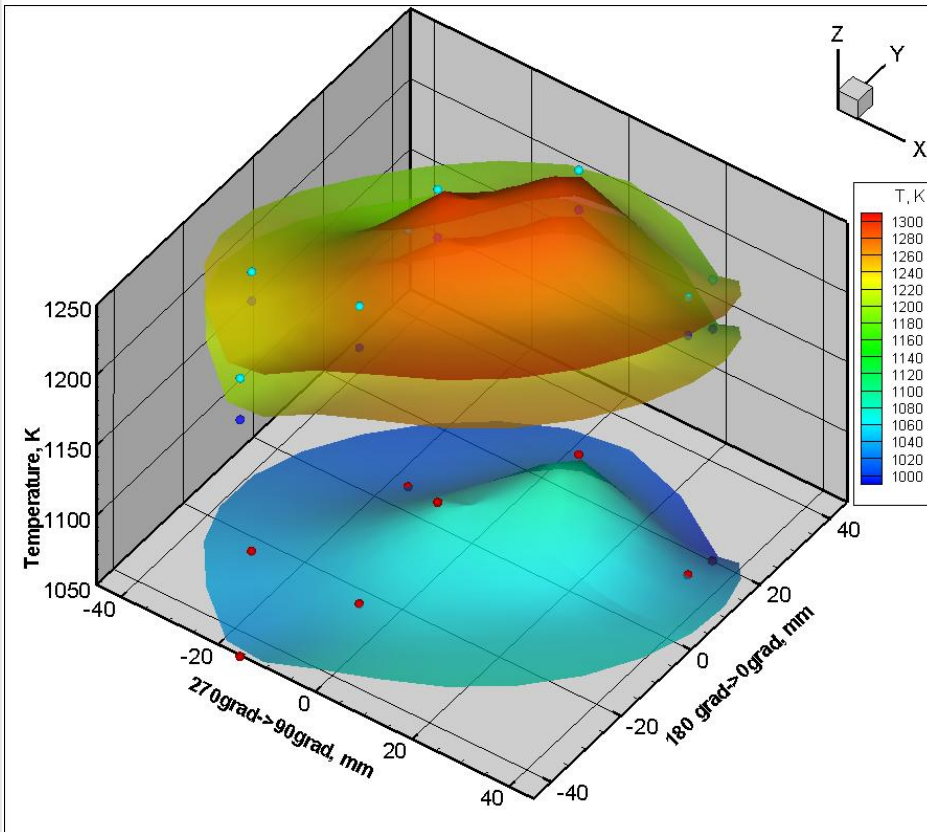
**1. SCDAP/SIM simulations:** *Paul Scherer Institute, Switzerland.*

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

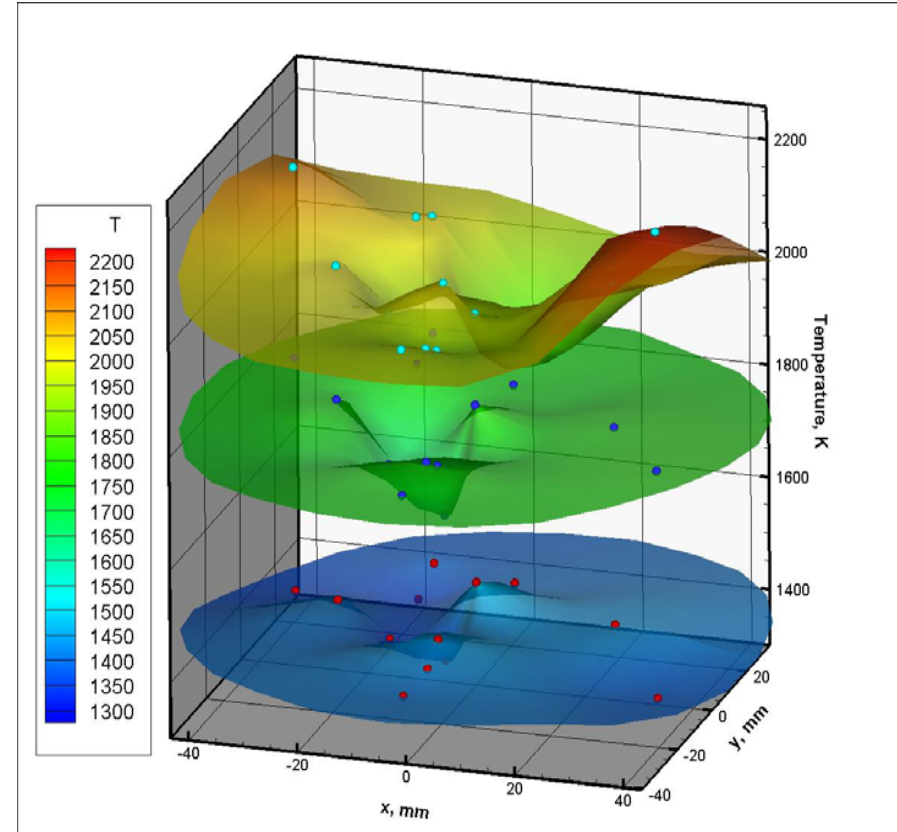
Test performance: el. power profile in accordance to the pre-test calculations provided good reproduction of temperature history in comparison with the reference test QUENCH-06



# QUENCH-12: inhomogeneous radial temperature distribution



550 mm



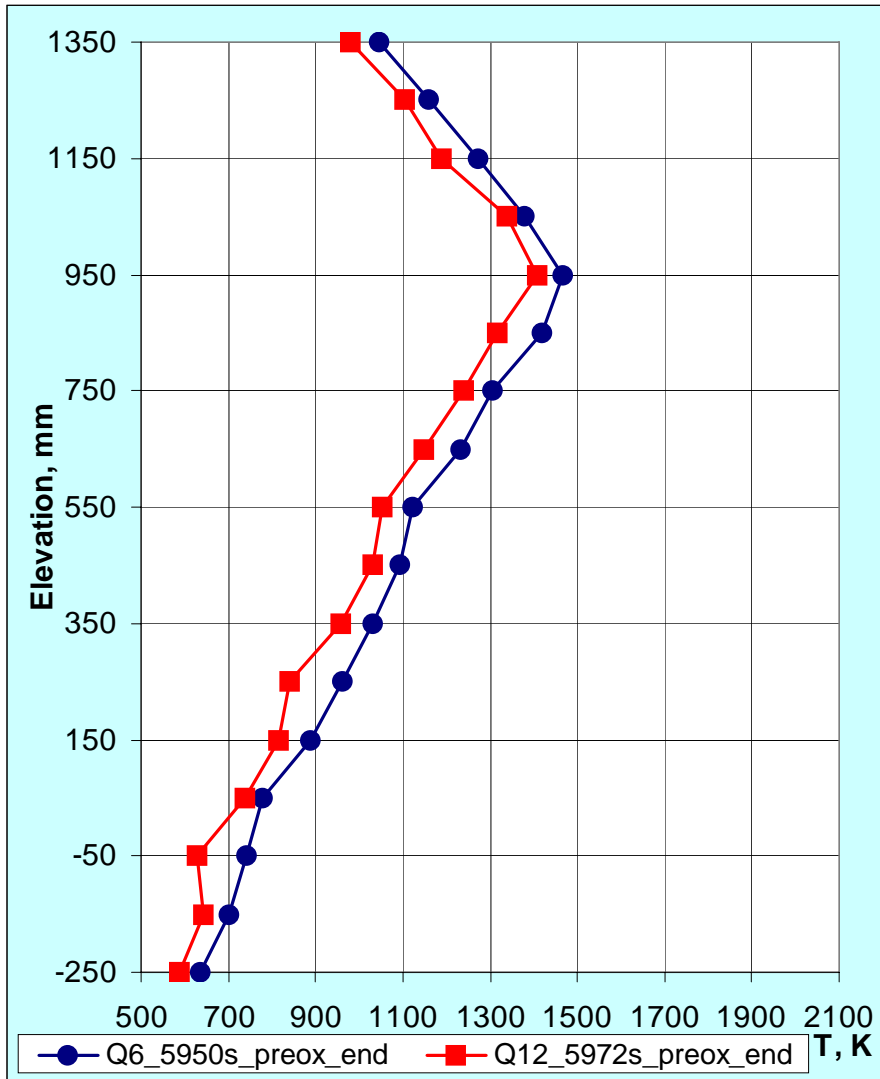
950 mm

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).

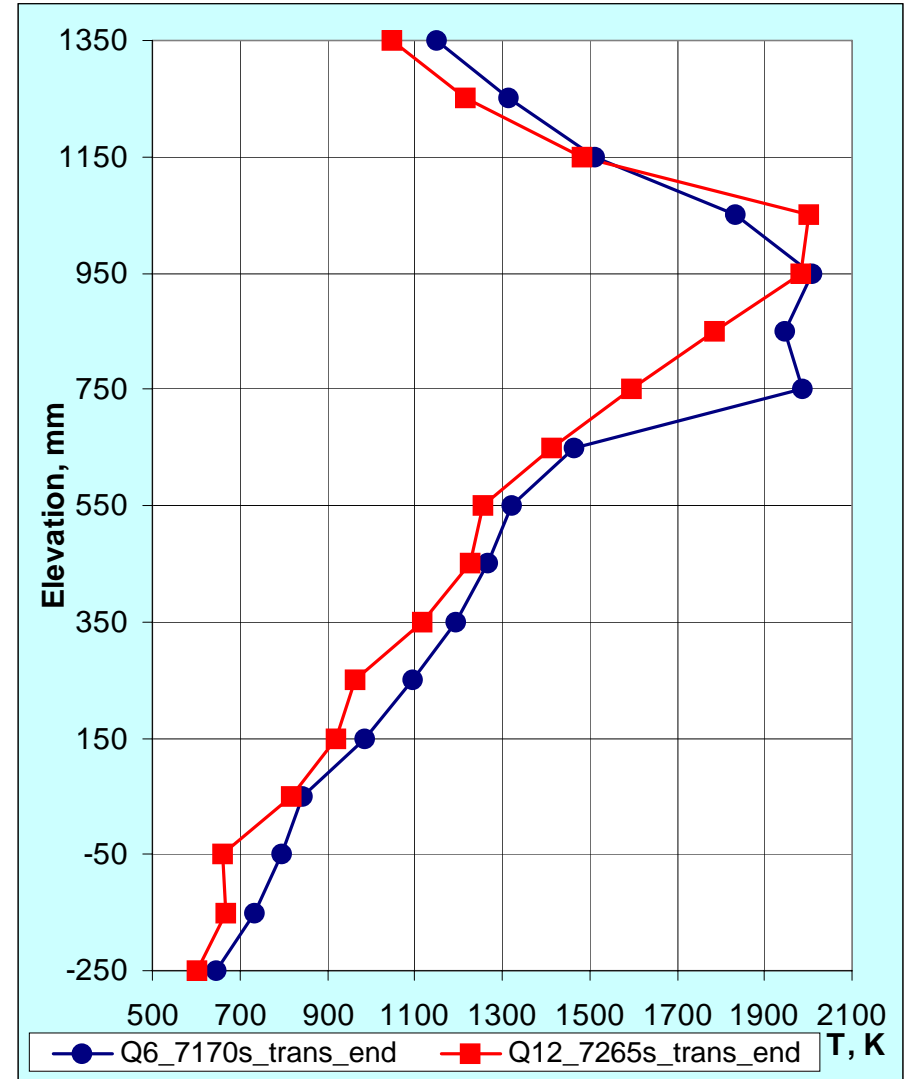




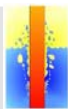
# Axial bundle temperature profiles for QUENCH-06 and QUENCH-12 on beginning and end of transient phase



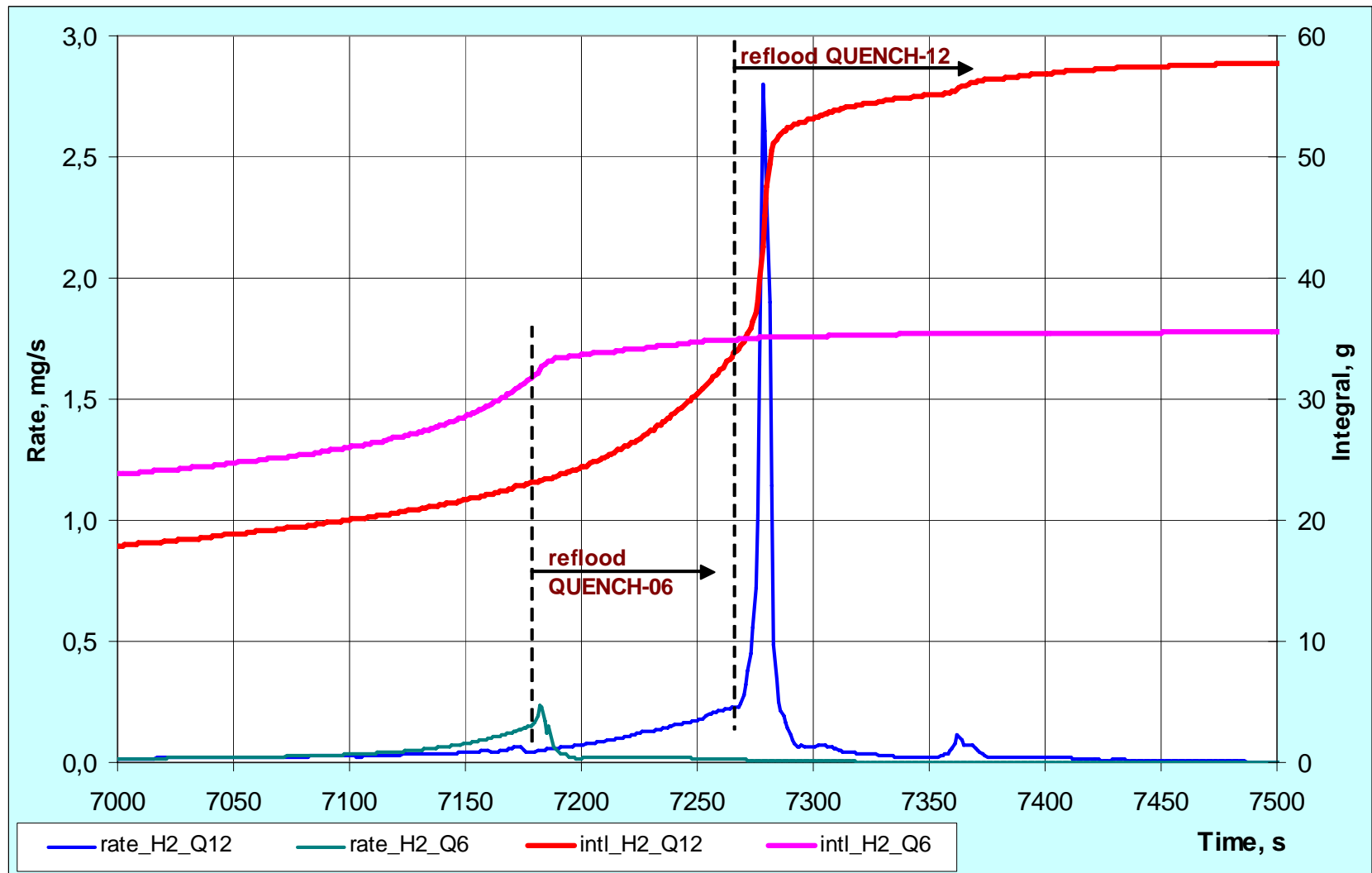
beginning of transient



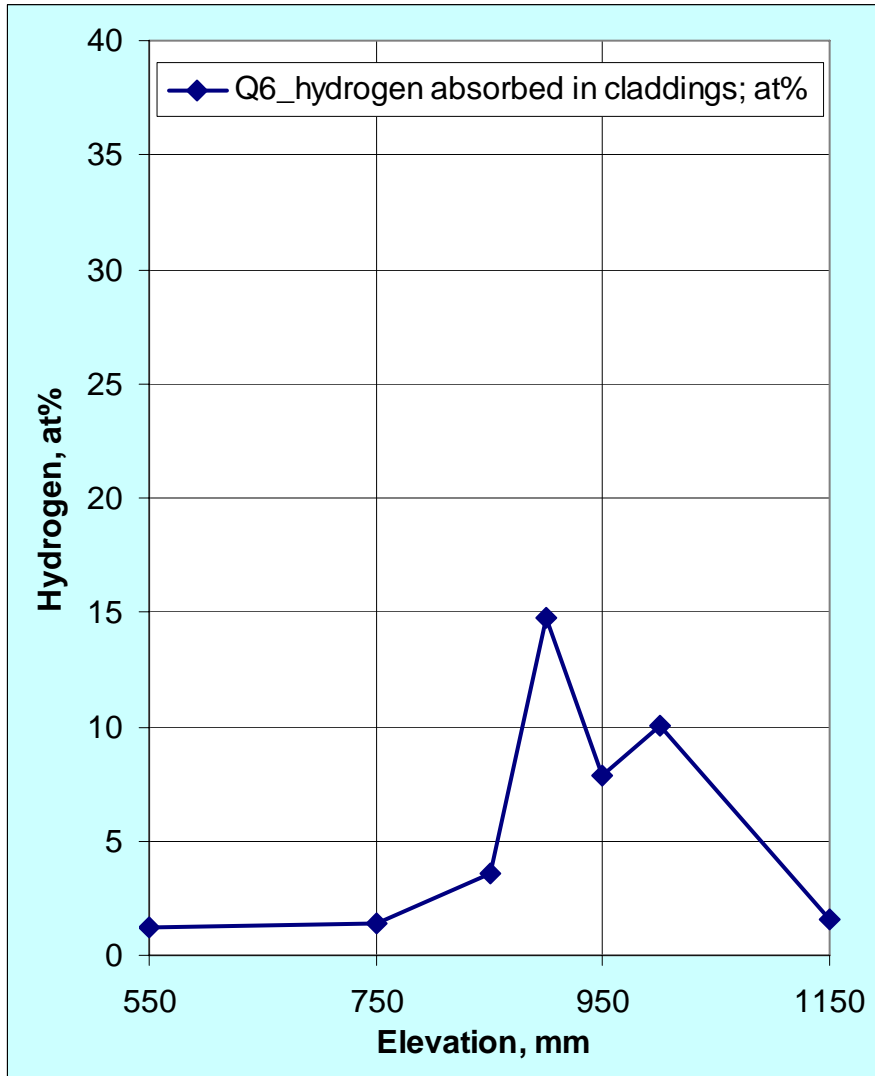
end of transient



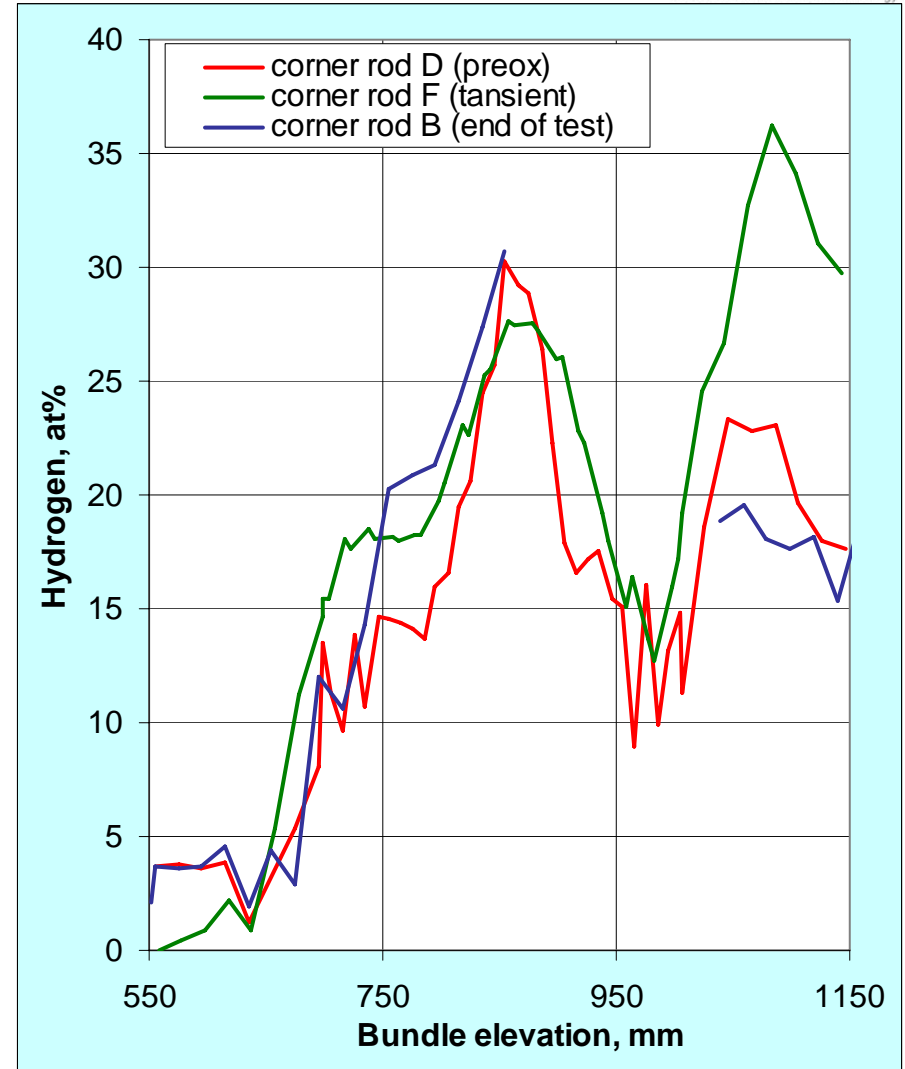
## Comparison of hydrogen release during **QUENCH-12** and **QUENCH-06**



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

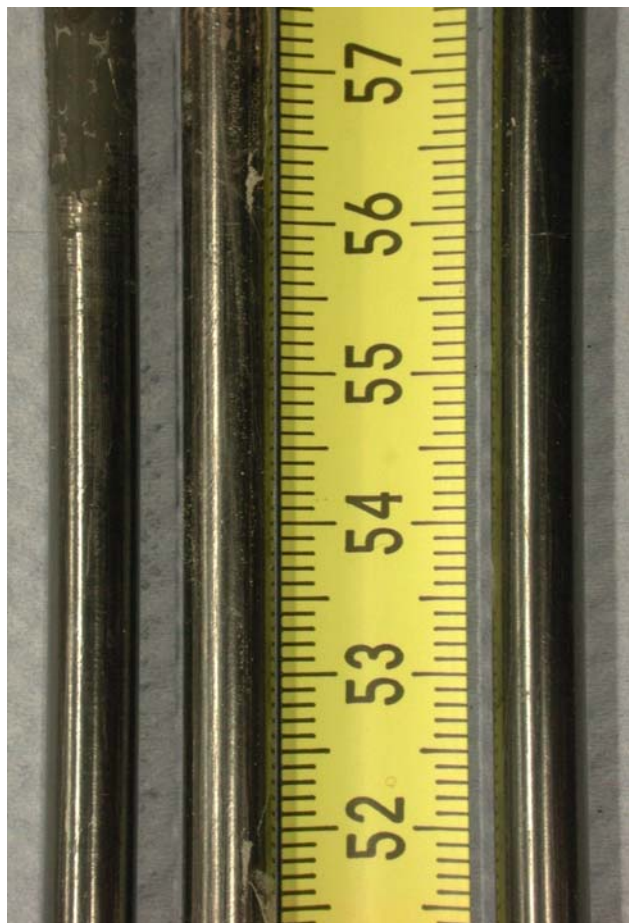


**Q-06: H<sub>2</sub> uptake in cladding measured by hot extraction**



**Q-12: H<sub>2</sub> uptake in corner rods measured by neutron radiography**

## QUENCH-12: axial sections of different ZrO<sub>2</sub> spalling intensity on corner rods withdrawn during the test



**B** after test  
**F** before reflow  
**D** after preoxidation



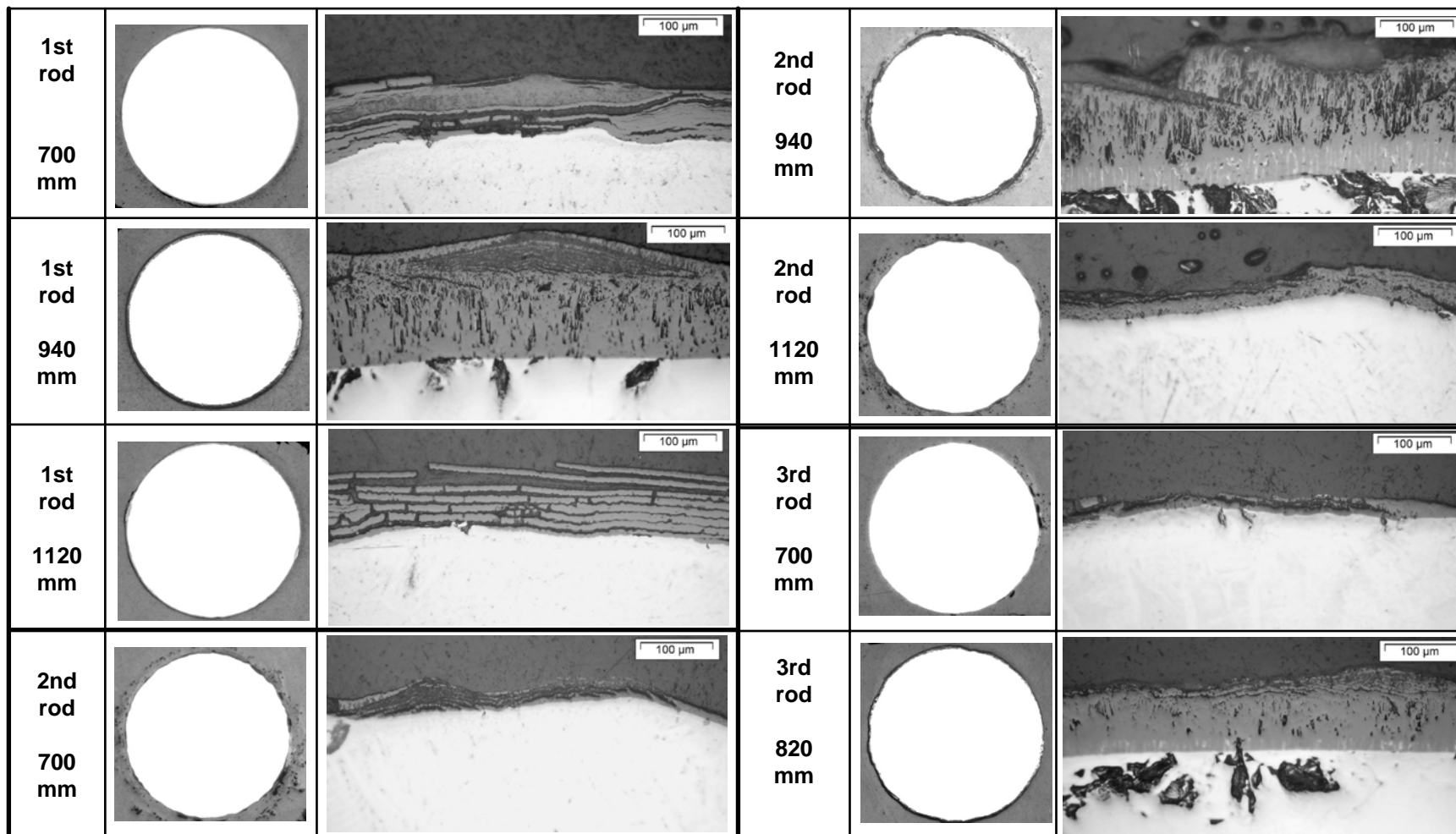
**F** **D**



**F** **D**

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

1<sup>st</sup> rod – after preoxid. phase, 2<sup>nd</sup> rod – before quench; 3<sup>rd</sup> rod – after test

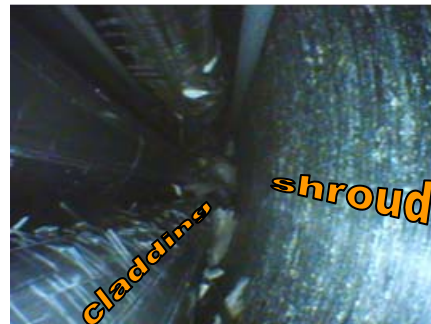


**Breakaway structure was formed generally during pre-oxidation by temperatures about:  
850°C (@700 mm), 900°C (@1120 mm)**

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



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



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

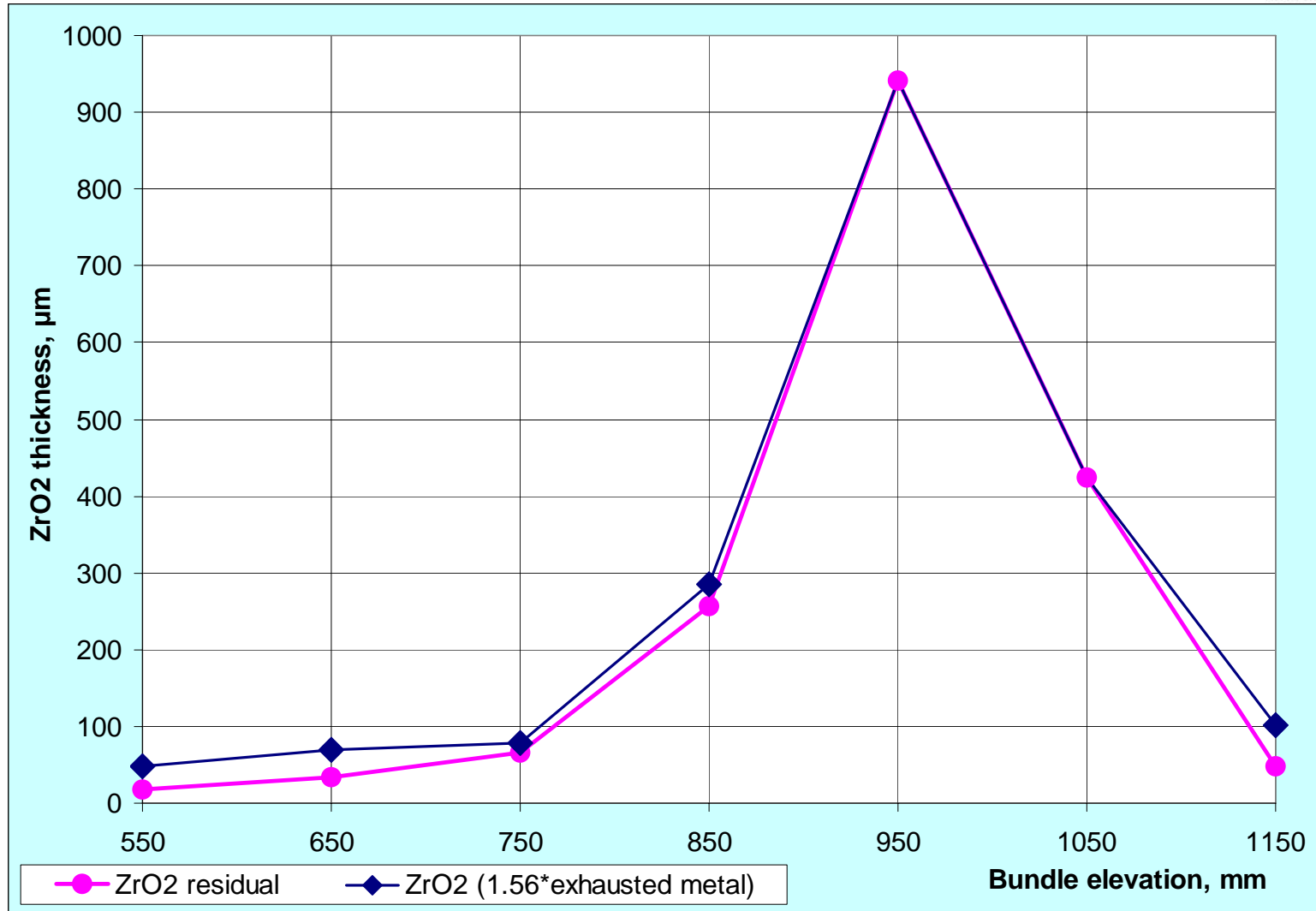


**650 mm:**  
spalled oxide scales  
at shroud and cladding



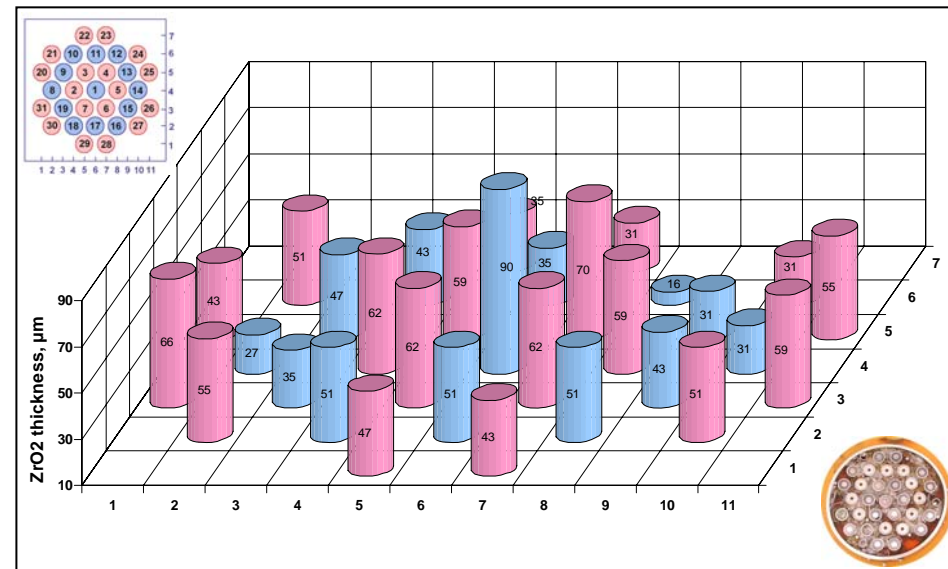
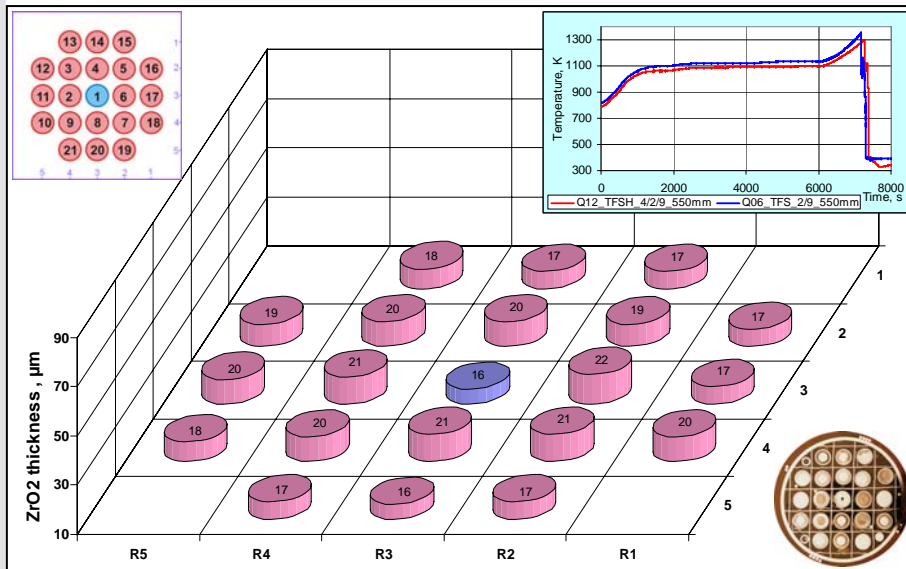
**900 mm:**  
circumferential  
and longitudinal cracks  
at the cladding;  
nodular breakaway  
corrosion  
at the shroud

# QUENCH-12 : axial distribution of oxide layer



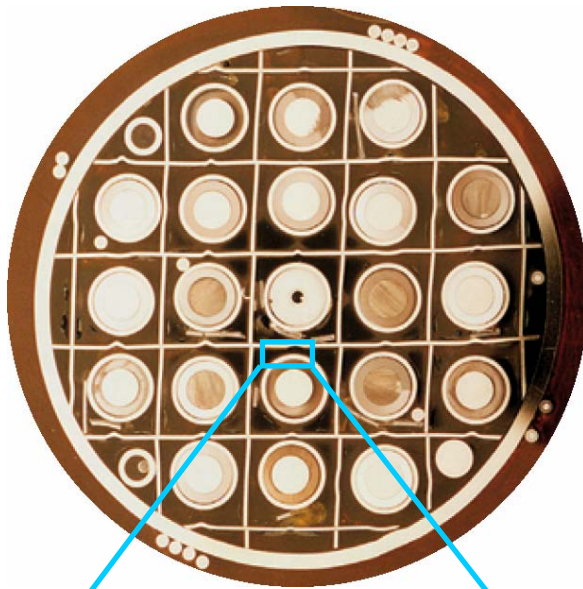
**Cladding oxidation: measured thickness of residual oxide and oxide thickness calculated on the base of residual metal**

## Comparison of oxide cladding thicknesses for QUENCH-06 and QUENCH-12 at elevation 550 mm

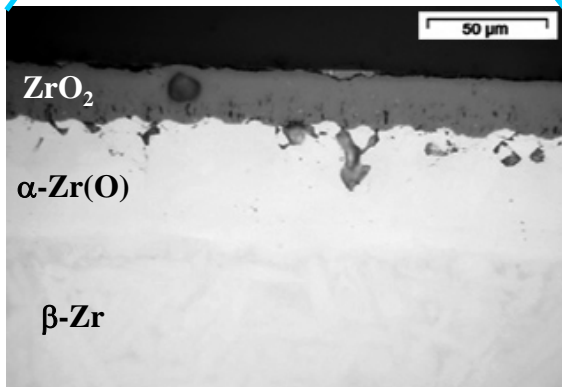




# Comparison cross-sections of QUENCH-06 and QUENCH-12 at elevation 550 mm



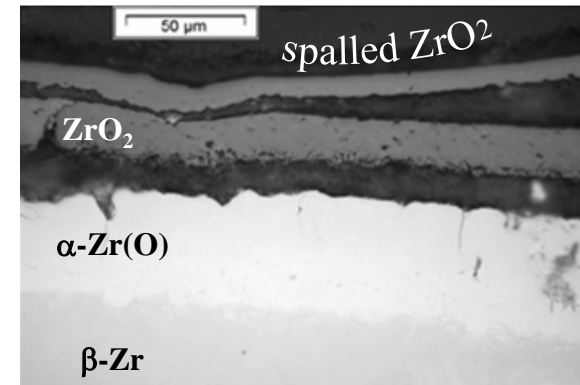
**Q06 cross-section**



**Q06 oxidized cladding**

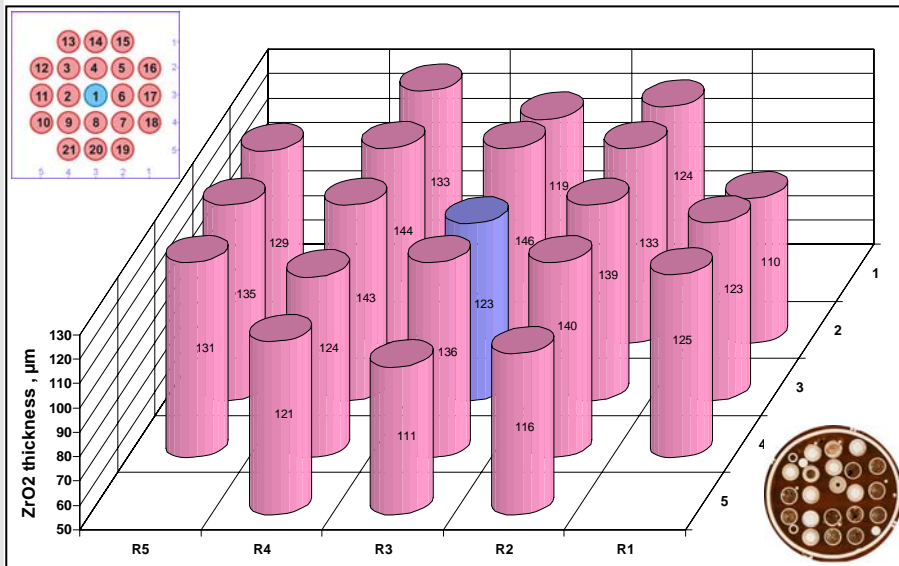


**Q12: rubble on spacer grid  
consists of spalled cladding scales  
and fragments of partially oxidized cladding**

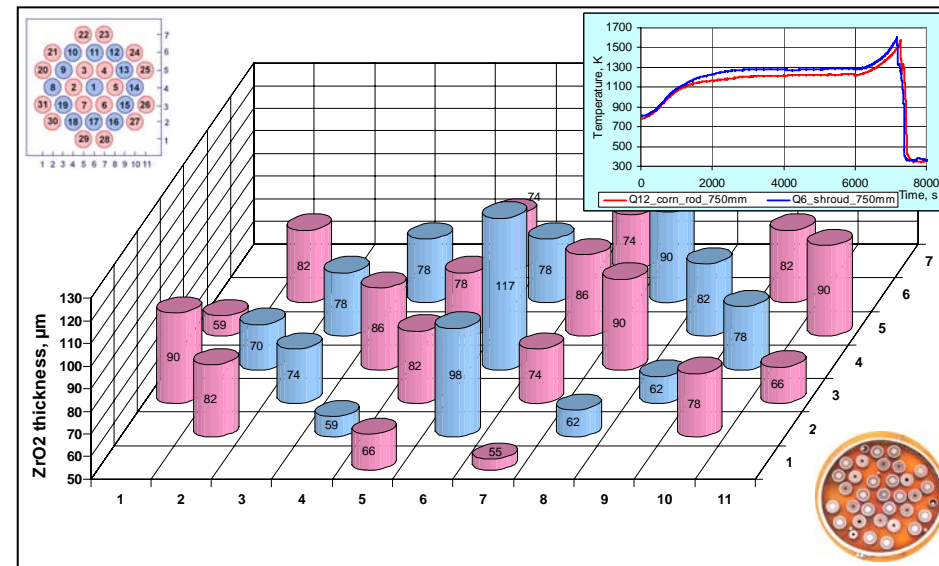


**Q12 cladding: spalling of oxide scales  
due to breakaway effect**

## Comparison of oxide cladding thicknesses for QUENCH-06 and QUENCH-12 at elevation 750 mm

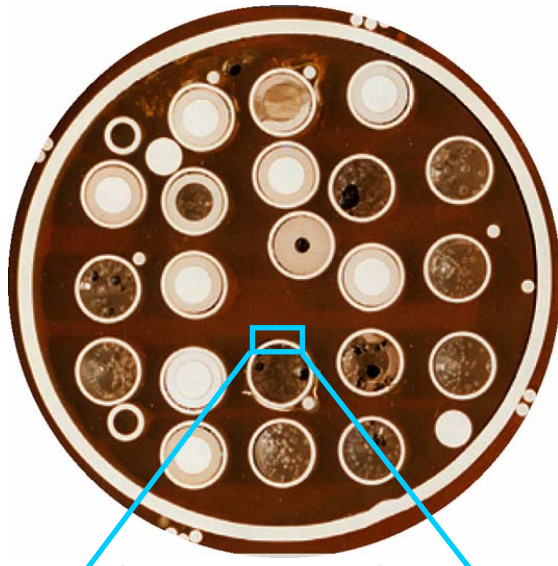


**QUENCH-06 (measured):**  
 average value and median deviation:  
 $129 \pm 9 \mu\text{m}$  for all rods,  
 $138 \pm 5 \mu\text{m}$  for inner heated rods,  
 $123 \pm 6 \mu\text{m}$  for outer heated rods

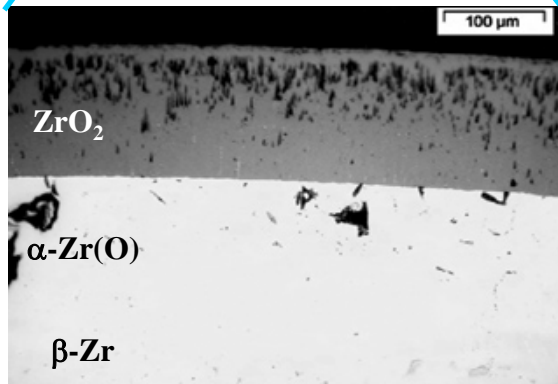


**QUENCH-12 (calculated from residual metal):**  
 average value and median deviation:  
 $79 \pm 11 \mu\text{m}$  for unheated rods,  
 $77 \pm 8 \mu\text{m}$  for heated rods

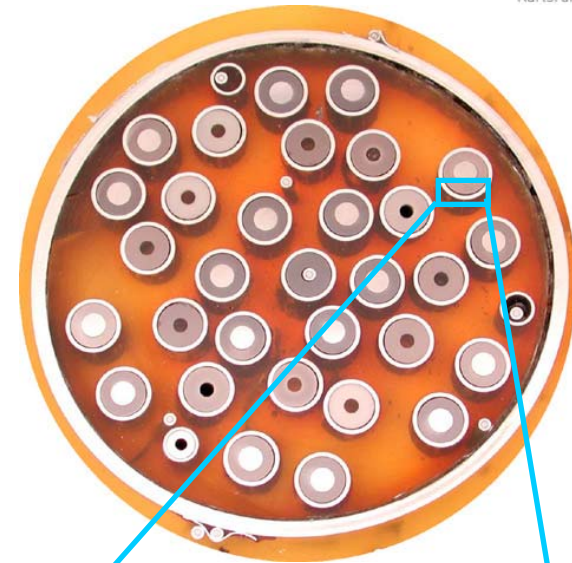
# Comparison cross-sections of QUENCH-06 and QUENCH-12 at elevation 750 mm



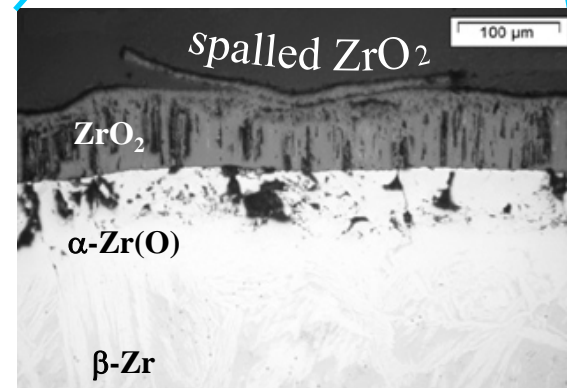
**Q06 cross-section;  
few bundle deformation**



**Q06 oxidized cladding**

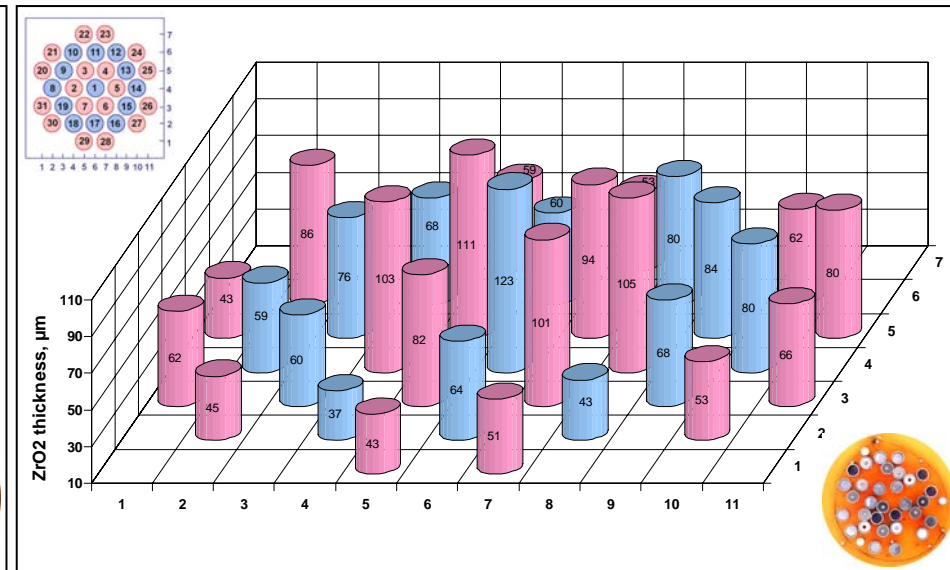
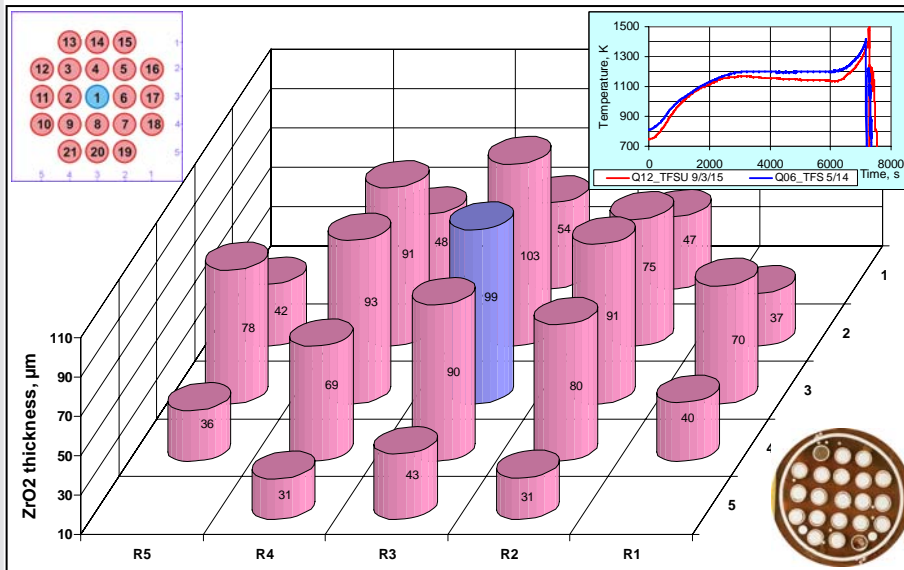


**Q12 cross-section;  
moderate bundle deformation**



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

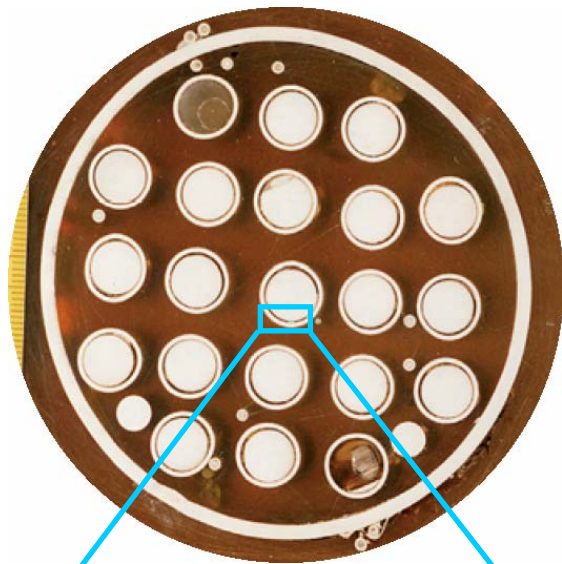
## Comparison of oxide cladding thicknesses for QUENCH-06 and QUENCH-12 at elevation 1150 mm



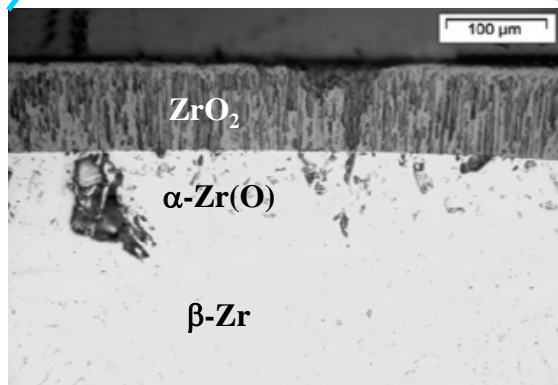
**QUENCH-06 (calculated):**  
 average value and median deviation:  
 $64 \pm 22 \mu\text{m}$  for all rods,  
 $86 \pm 9 \mu\text{m}$  for inner heated rods,  
 $46 \pm 11 \mu\text{m}$  for outer heated rods

**QUENCH-12 (calculated from residual metal):**  
 average value and median deviation:  
 $69 \pm 15 \mu\text{m}$  for unheated rods,  
 $72 \pm 21 \mu\text{m}$  for heated rods

# Comparison cross-sections of QUENCH-06 and QUENCH-12 at elevation 1150 mm



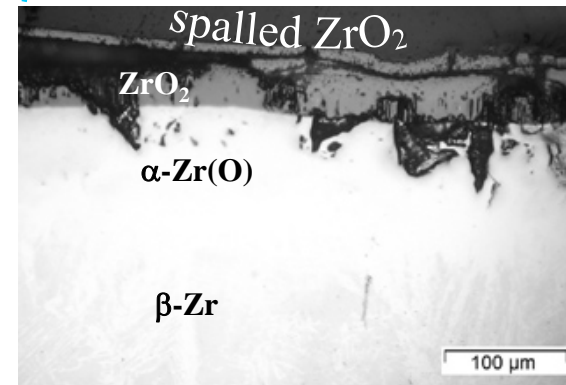
Q06 cross-section



Q06 oxidized cladding

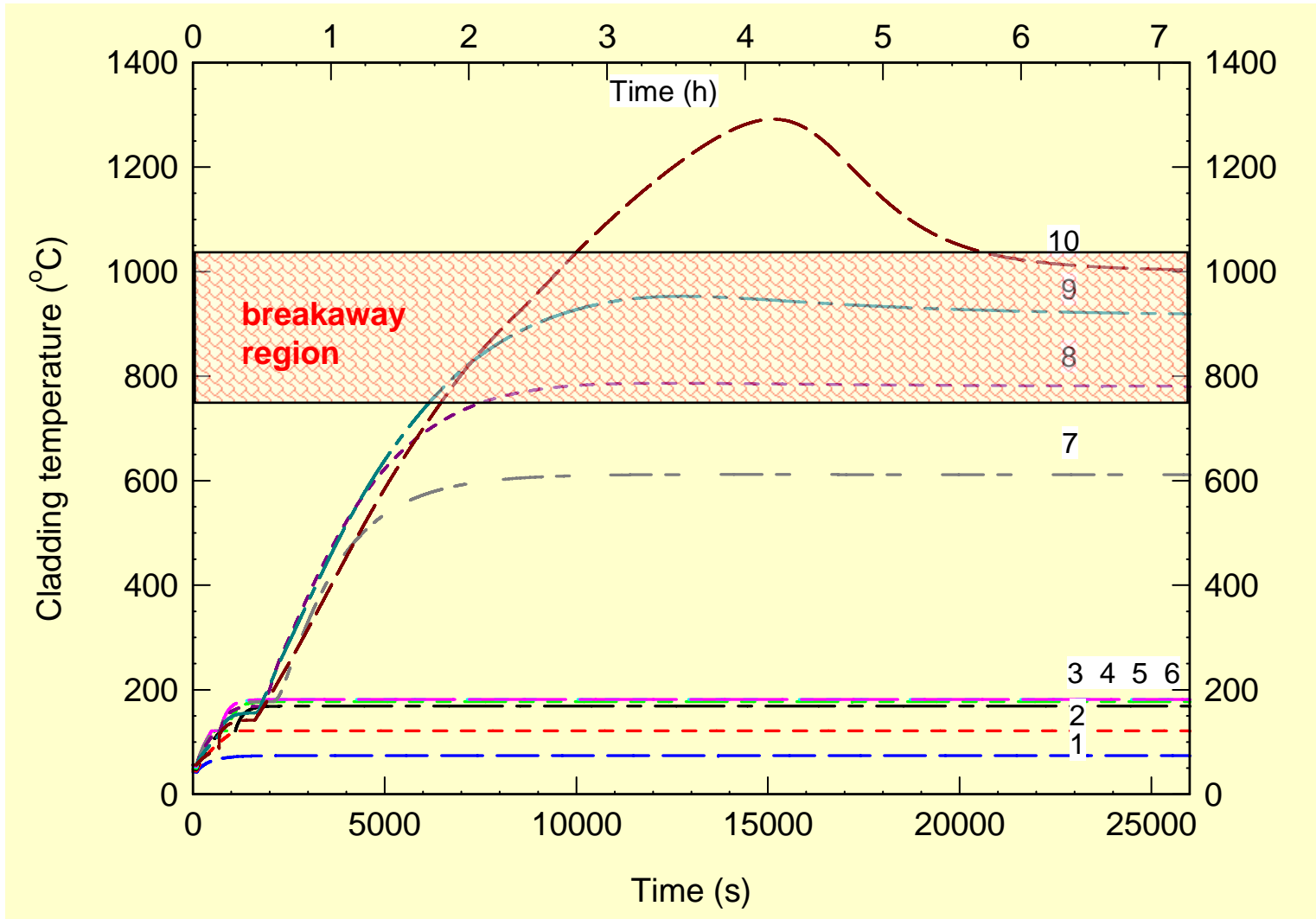


Q12 cross-section



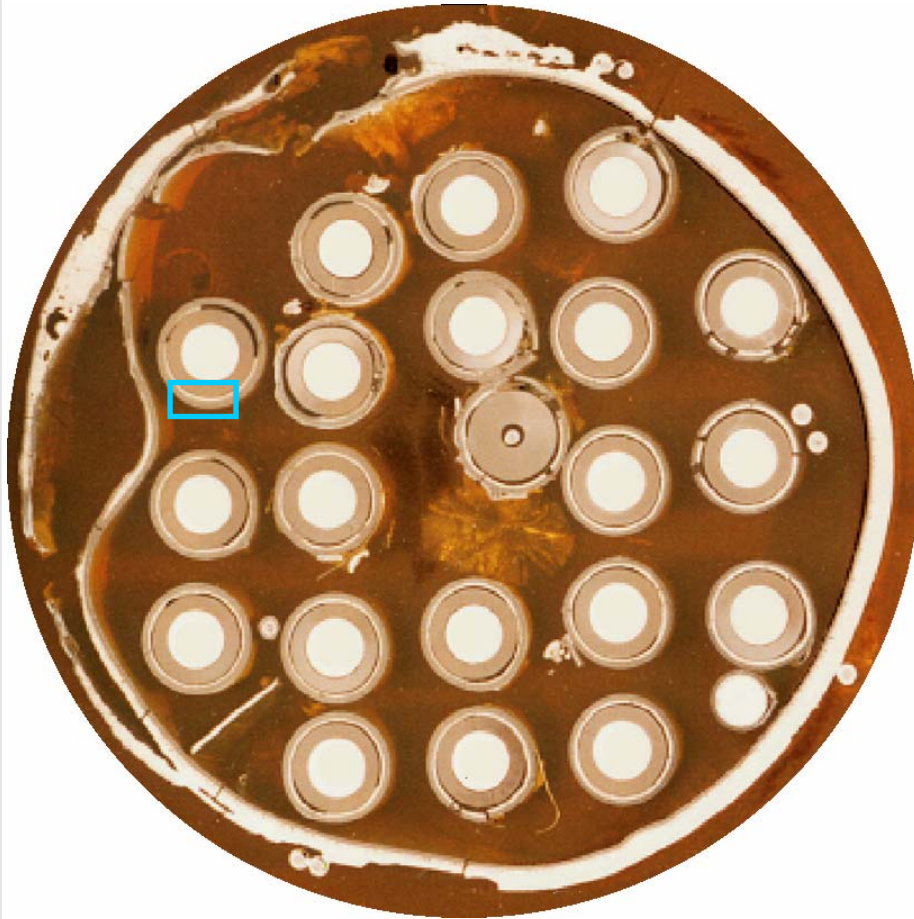
Q12 cladding: spalling of oxide scales  
due to breakaway effect

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

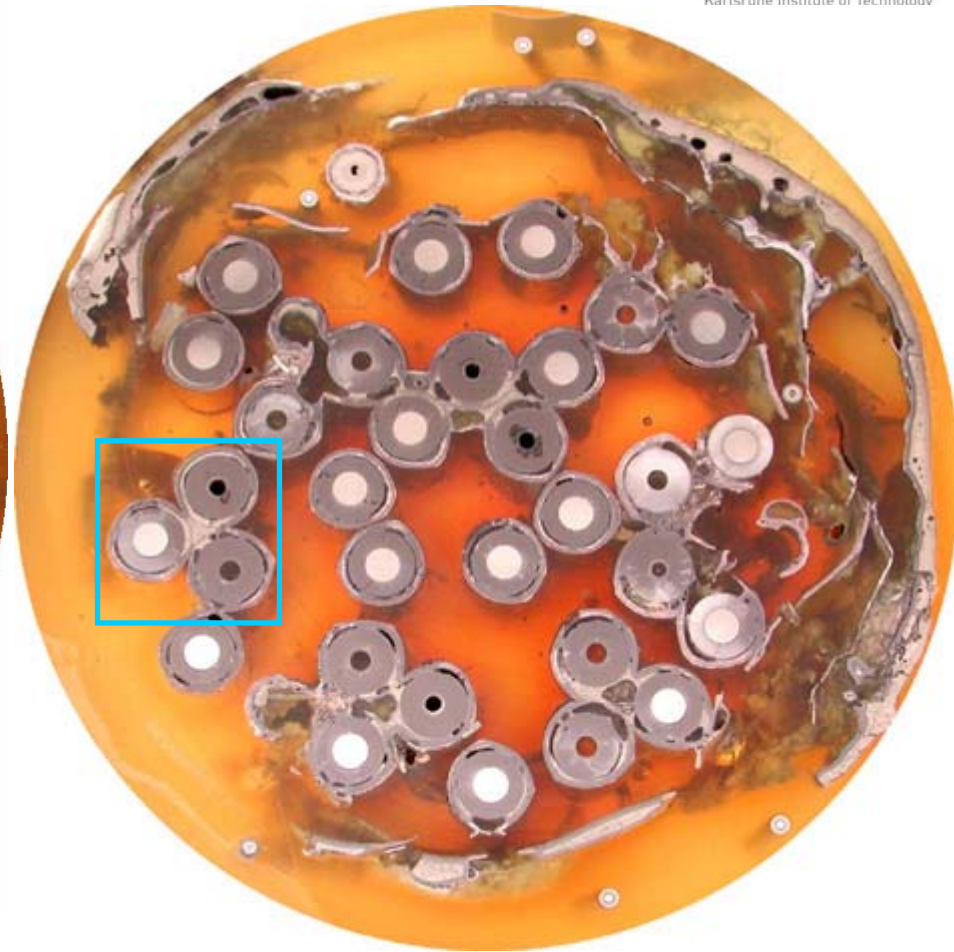


Results of modeling (FRAP-T6 code)

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

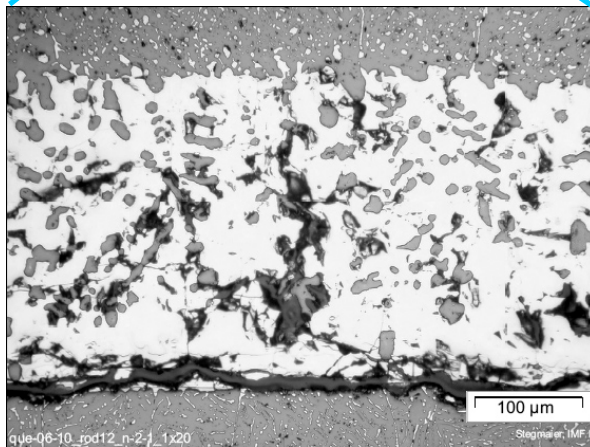
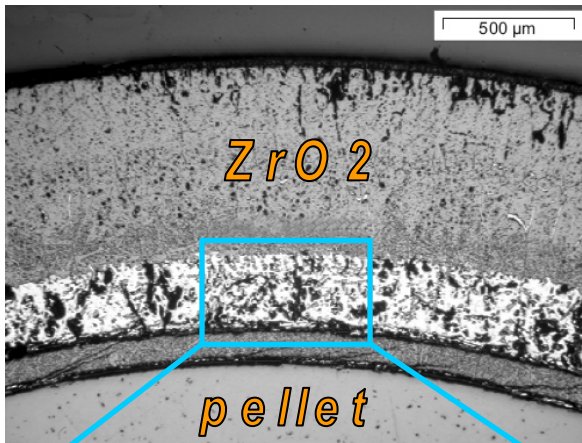


**Q06: melting of cladding internal metal layer  
and shroud external metal layer**

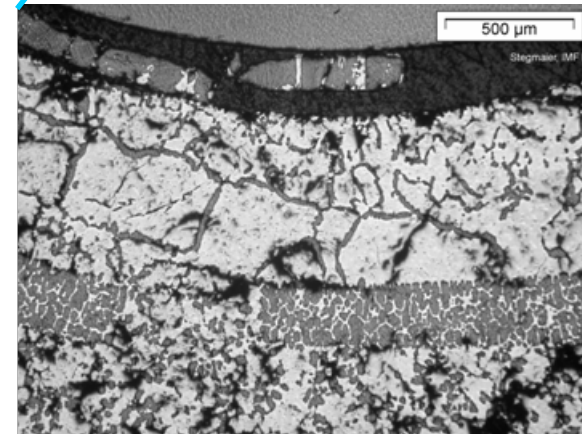
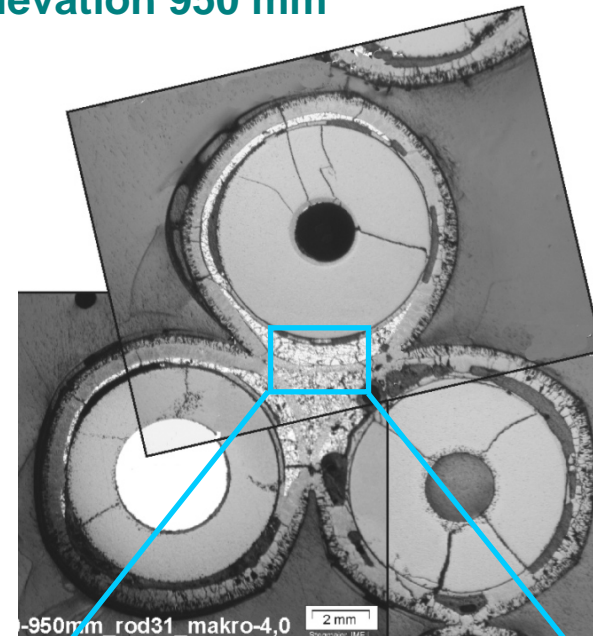


**Q12: melting of cladding internal player;  
oxide layer failure;  
molten pools formation between rods;  
shroud external metal layer melting**

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



**Q06: melting of cladding metal layer**

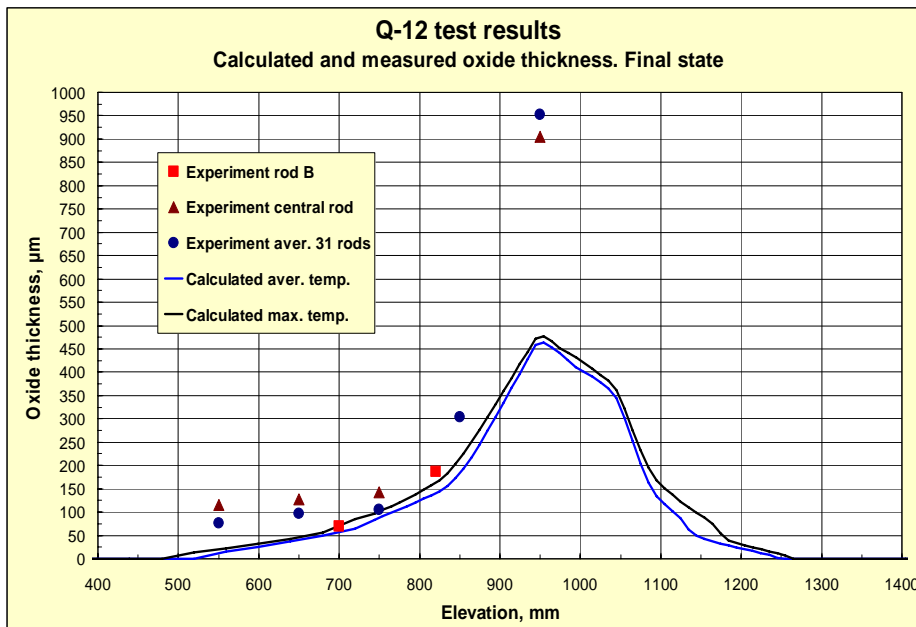


**Q12: molten pool between rods**

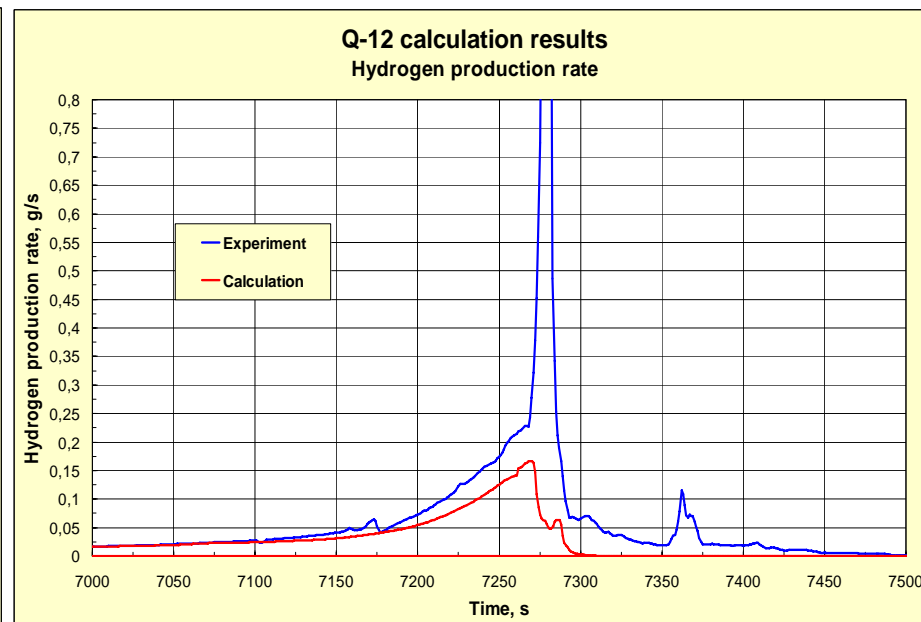


## QUENCH-12: results of the SVECHA simulation (IBRAE with support from ITU)

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 of the rod B (withdrawn from the bundle at the end of the test), central rod, averaged for 31 rods, all at final state, compared to the calculated oxide layer thickness profile of the central rod (final state).



Experimentally measured and calculated hydrogen production rate.  
Quenching phase of the test.

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



## SUMMARY to task 2 of ISTC 1648.2

- The QUENCH-12 experiment investigated the effects of VVER materials and bundle geometry on core reflood, in comparison with the QUENCH-06 test (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.
- Two corner rods were withdrawn at the end of preoxidation and transient phases correspondingly. The third corner rod was withdrawn after the test. The surface of the rods shows intensive traces of the break-away effect influence. Many oxide scales with thickness about 100  $\mu\text{m}$  were spalled during withdrawn. The reported findings on breakaway oxidation of the VVER-type cladding material strictly refer to long-term oxidation at temperatures between 850 °C and 1000 °C (not typical for reactor accident conditions).
- The surfaces of the rod simulator and shroud evident also influence of the breakaway oxidation. However the  $\text{ZrO}_2$  scales spalling is fewer intensive than by corner rods. Possible reasons can be 1) different mechanical properties of tube and massive rod; 2) other surface preparation of cladding and rods.



## SUMMARY (2)

- Following reflood initiation, a moderate temperature excursion of ca. 50 K was observed, over a longer period than in QUENCH-06. The temperatures at elevations between 850 mm and 1050 mm exceeded the melting temperature of  $\beta$ -Zr.
- 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 (IBRAE) 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.
- The details of the experimentally measured time dependence of the hydrogen production rate are well reproduced by the calculations at the preoxidation and transient phases. Calculations underestimate hydrogen production rate at the end of transient and quenching phase of the test.

**Many thanks to all participants  
of this fruitful international collaboration!**