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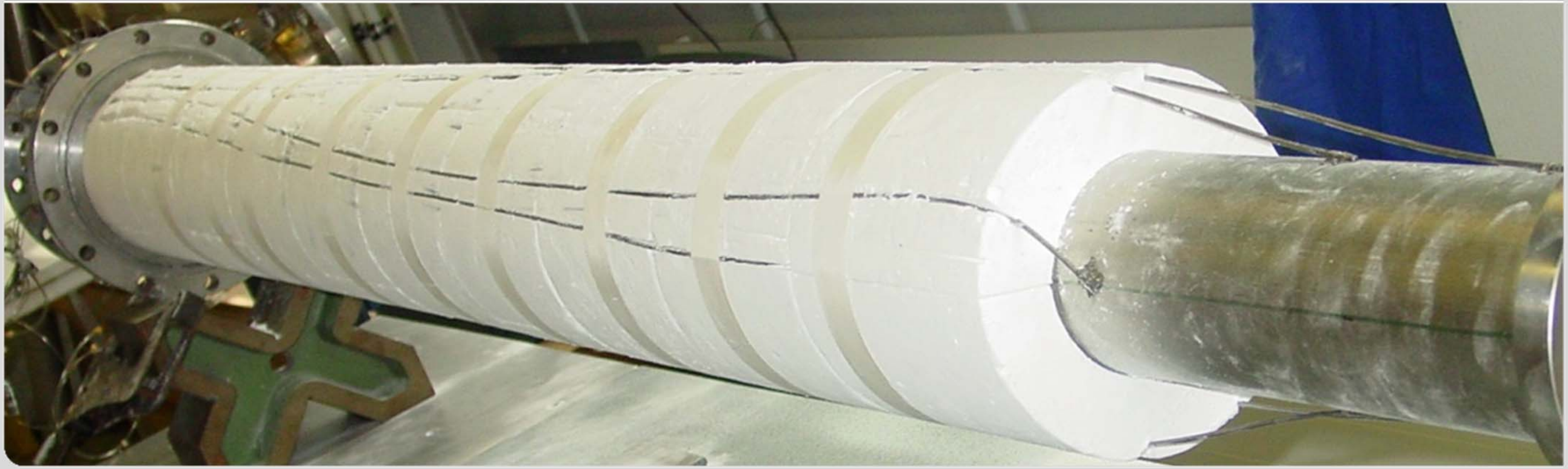
Bundle reflood tests QUENCH-14 and QUENCH-15 with advanced cladding materials: comparable overview

J. Stuckert, M. Große, M. Steinbrück

Institute for Materials Research

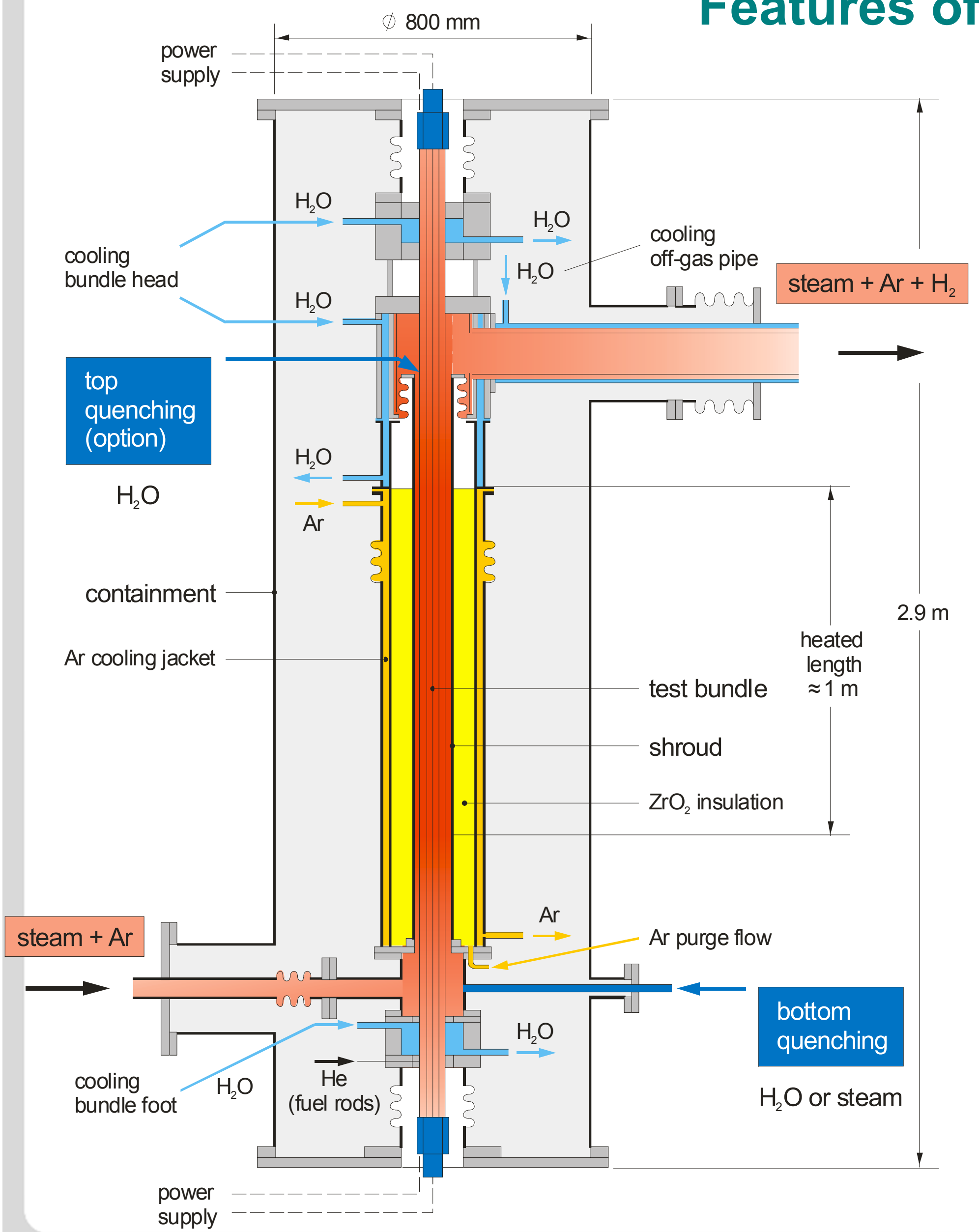


Objective

Investigation of influence of different cladding materials on bundle oxidation and core reflood for following bundles:

- **QUENCH-14 with niobium-bearing M5® cladding**
- **QUENCH-15 with tin-niobium-bearing ZIRLO™ cladding**
- **QUENCH-06 with Zircaloy-4 cladding (reference test)**
- **QUENCH-12 with niobium-bearing E110 cladding**

Features of QUENCH-facility



Scaling

Height: 1:3 … 1:2

Volume: 1:5000 … 1:3000

Bundle

- PWR (21 rods M5 or 24 rods ZIRLO)
- VVER (31 Stäbe, E110)

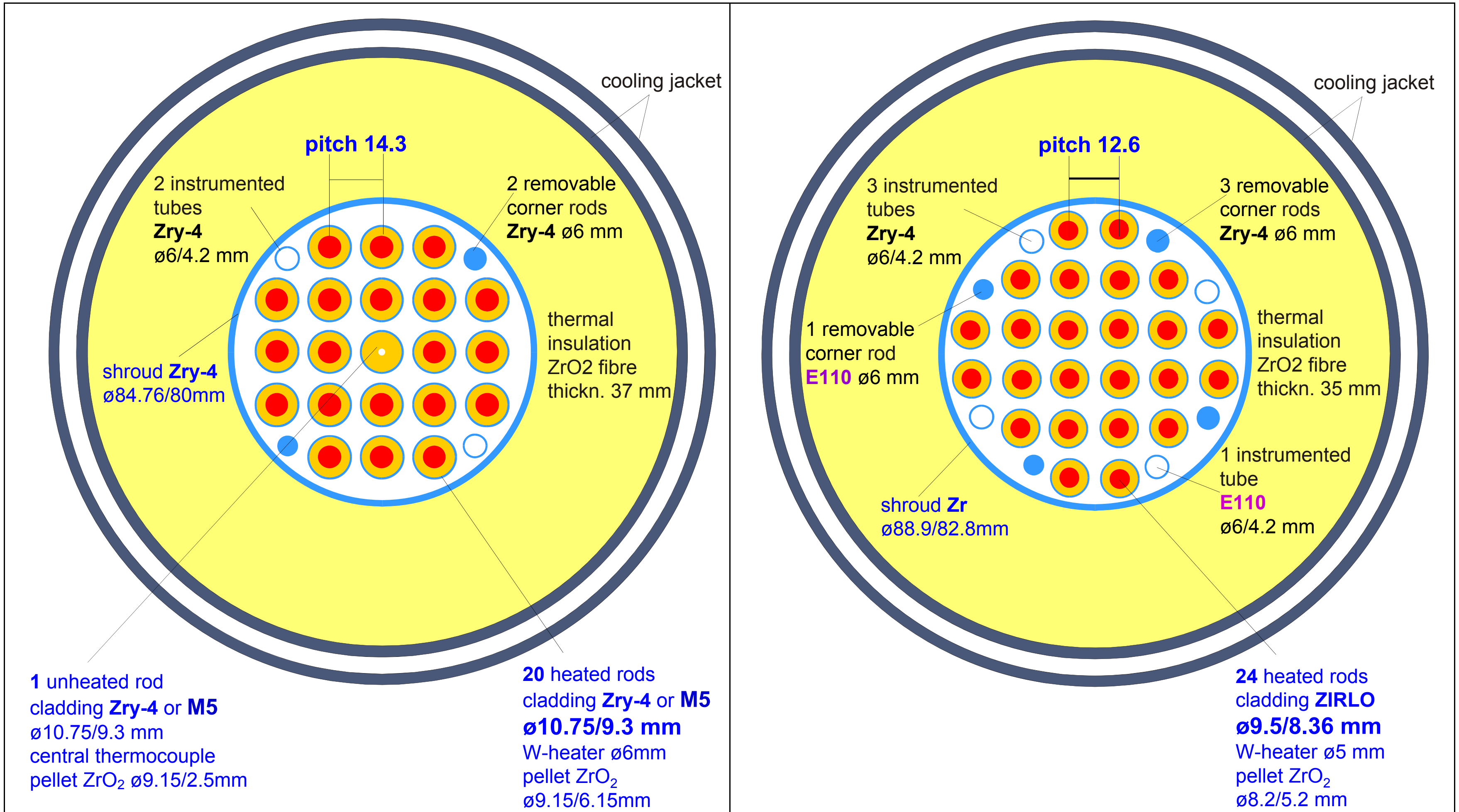
Heating

- electric 70 kW (~1 m W-heaters inside fuel rod simulators)

Instrumentation

- ~80 TCs at 17 axial levels
- Mass spectrometer (incl. steam)
- Quench water level (Δp)
- Corner rods for “online” check of oxide scale

Different bundle compositions



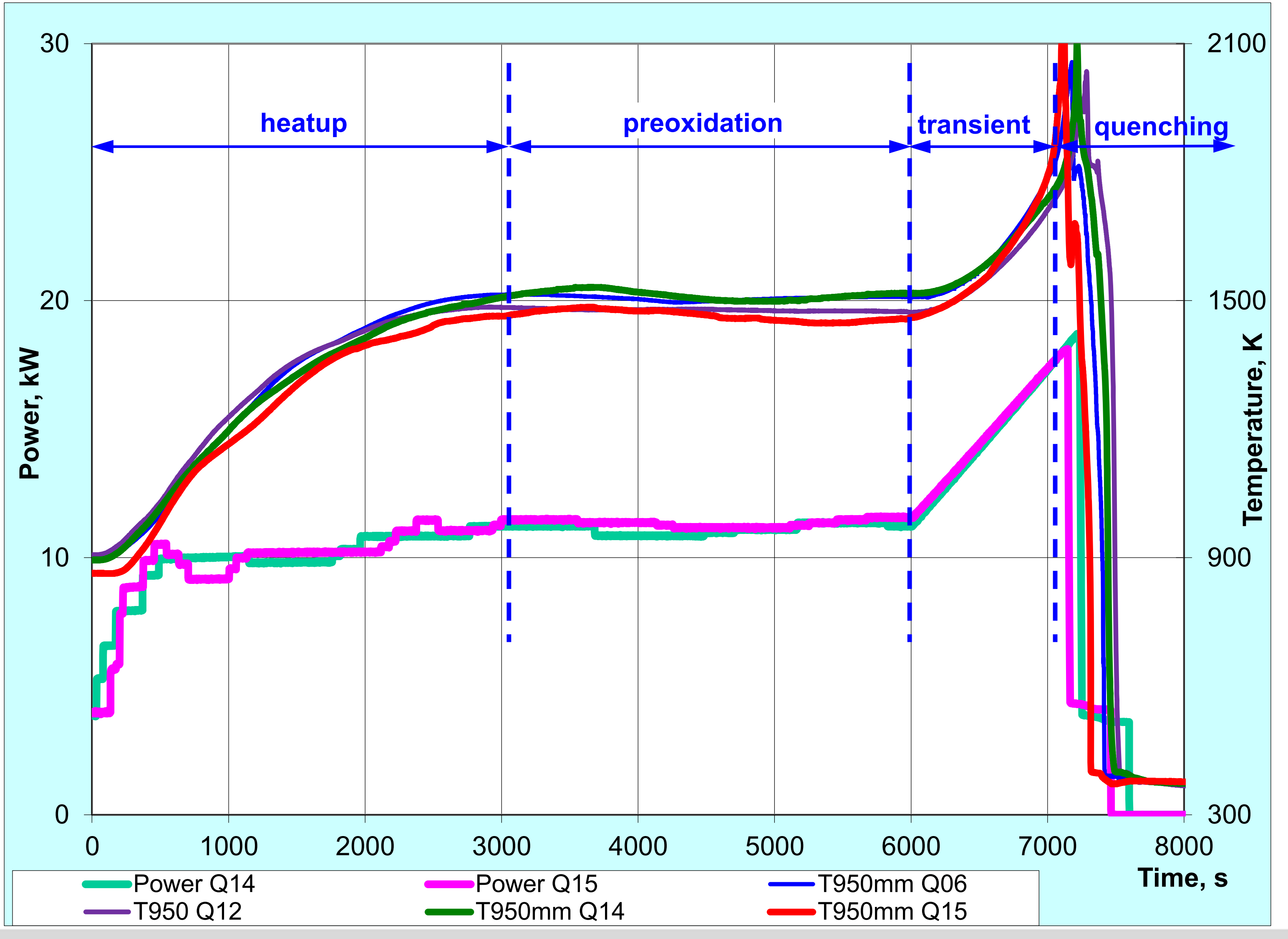
Q-14 bundle with 21 rod simulators **M5® cladding with thickness 750 µm**	**Q-15 bundle with 24 rod simulators** **ZIRLO™ cladding with thickness 570 µm**

Comparison of geometrical parameters of the QUENCH-15 bundle with the QUENCH-14 bundle:

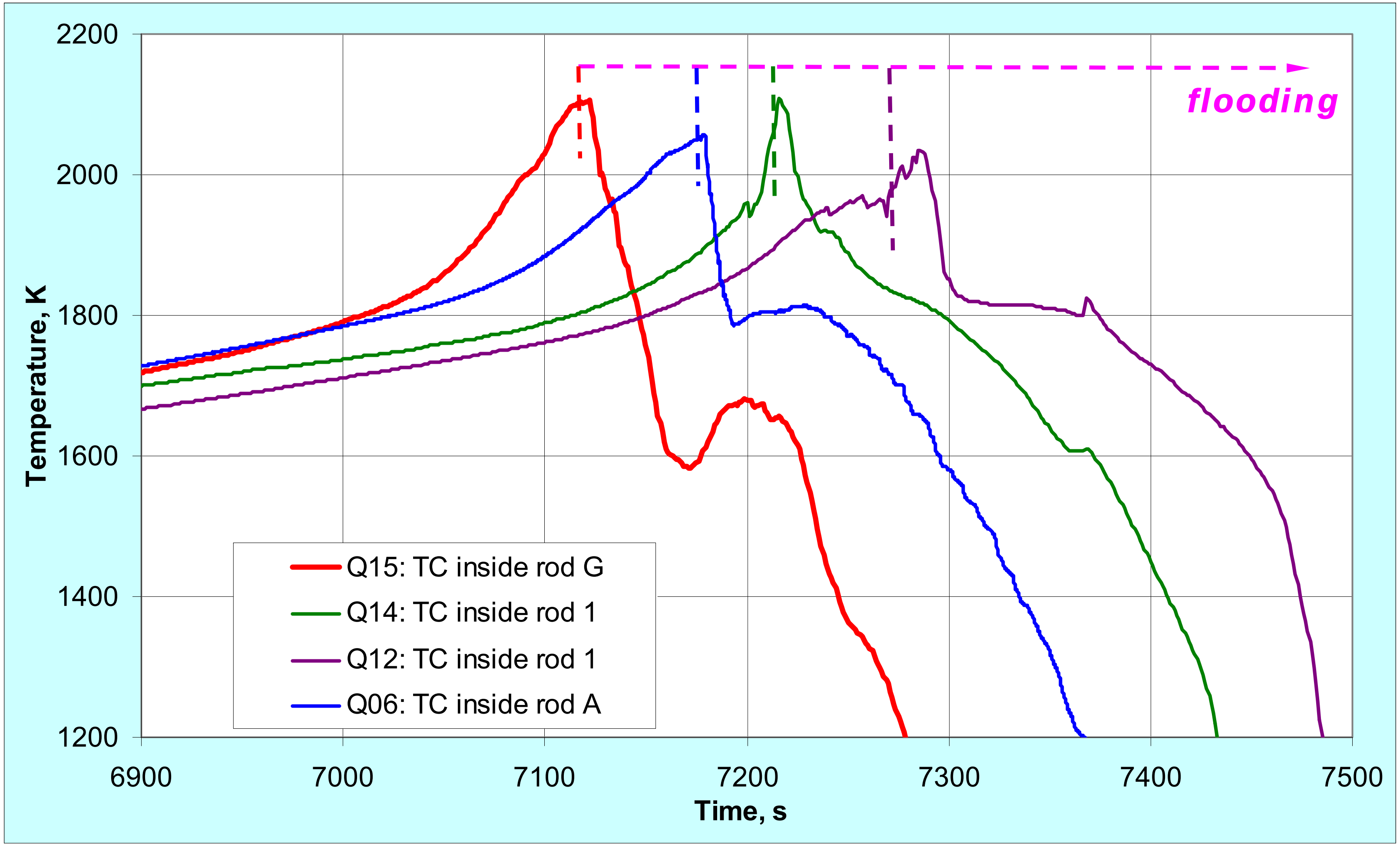
1) **coolant channel area relationship Q15/Q14 = 1.16 $\Rightarrow$ *the fluid flow rate should be 16% higher for the Q15 bundle than for the Q14 bundle to provide the same flow velocity***

2) **metallic surface relationship Q15/Q14 = 1.09 $\Rightarrow$ *increased chemical energy production for the Q15 bundle due to exothermic steam-metal reaction***

Performance of tests QUENCH-06, QUENCH-12, QUENCH-14 and QUNCH-15 under identical scenario

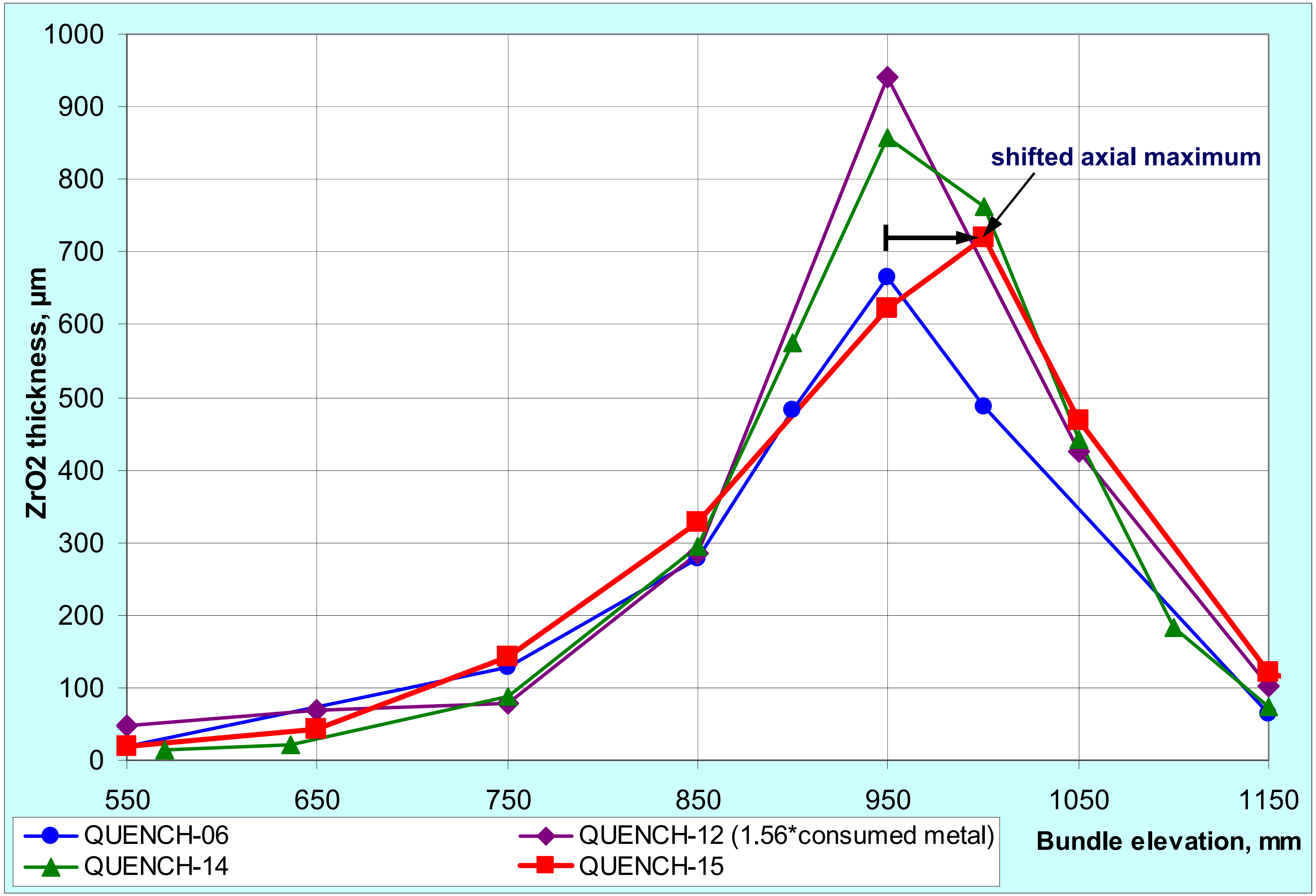


Comparison of bundle peak temperature evolution for QUENCH-06 (Zry-4), QUENCH-12 (E110), QUENCH-14 (M5) and QUENCH-15 (ZIRLO)

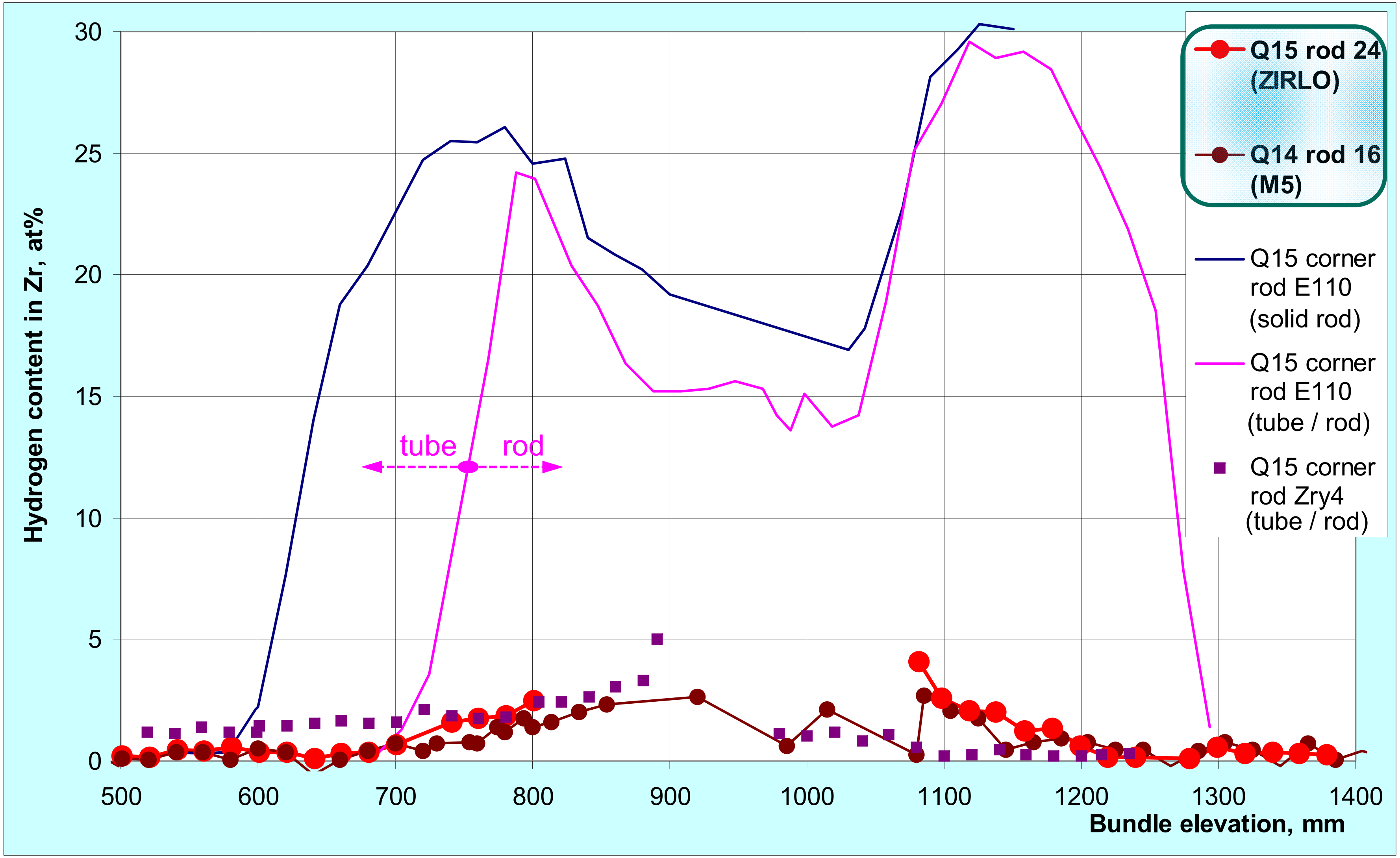


common characteristics: similar temperature escalation at the end of transient and similar cooling duration after reflood initiation

Axial distribution of cladding outer oxide thicknesses for the bundles QUENCH-06 (Zry4), QUENCH-12 (E110), QUENCH-14 (M5) and QUENCH-15 (ZIRLO)



Hydrogen uptake by ZIRLO cladding and different corner rods of QUENCH-15 bundle in comparison to M5 cladding of QUENCH-14 /corner rods were withdrawn from the bundle after the test/



Hydrogen production
according to mass-spectrometer measurements

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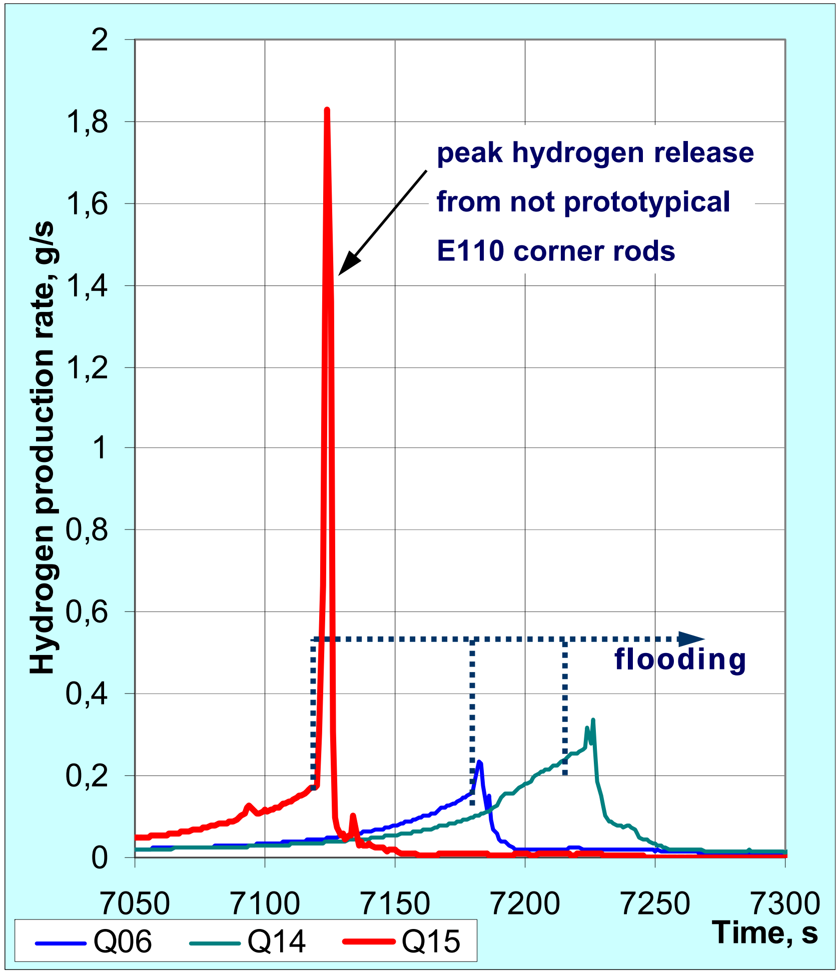
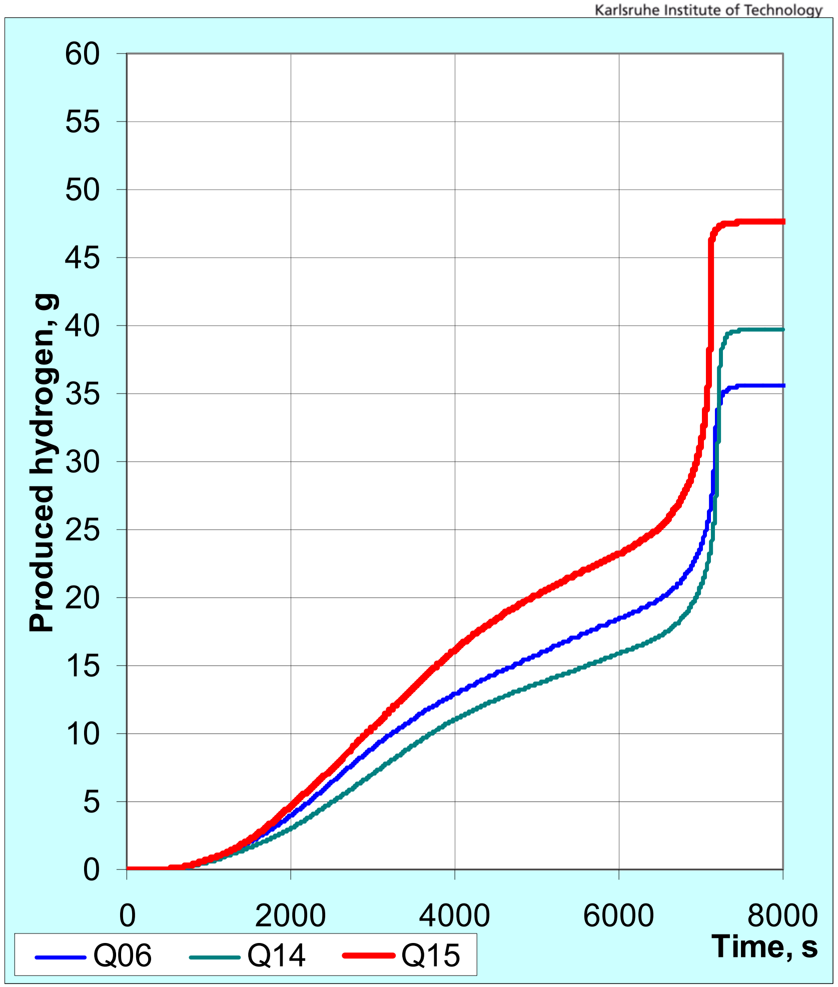




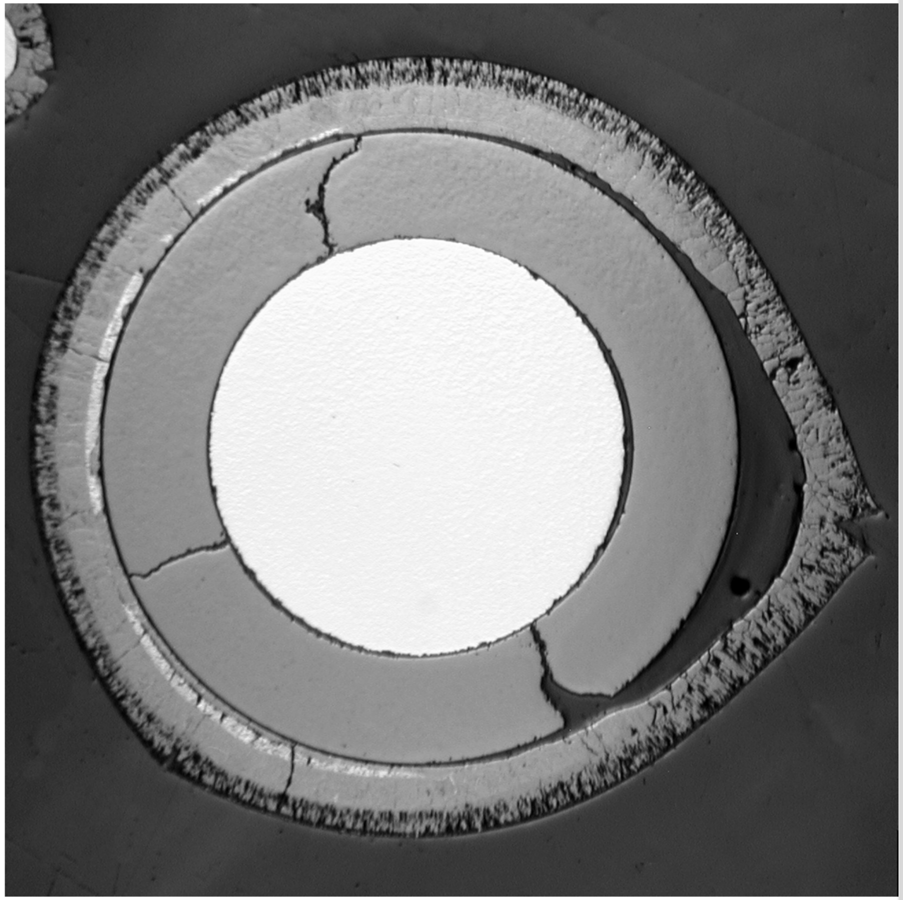
	Q-06 (Zry-4)	Q-14 (M5)	Q-15 (ZIRLO)
H_2 production before reflood (g):	32	34	41
H_2 production during reflood (g):	4	6	7

increased H_2 production due to:

- *increased Q15 metallic surface*
- *use of not prototypical corner rods*

QUENCH-14 bundle at elevations between 900 and 1000 mm (hottest zone): molten cladding metal between outer and inner oxide layers

rod #20 at elevation 900 mm



rod #11 at elevation 1000 mm

QUENCH-06 and QUENCH-14 at elevation 900 mm: cladding structure with partial oxidised metal melt, frozen between two oxide layers

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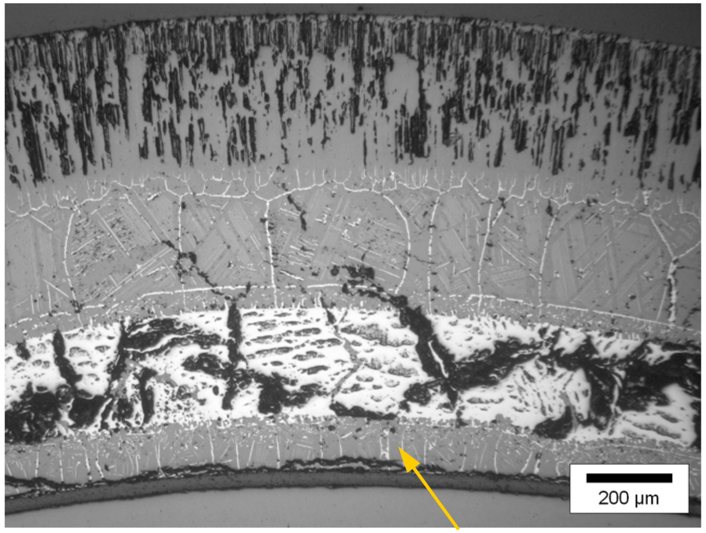
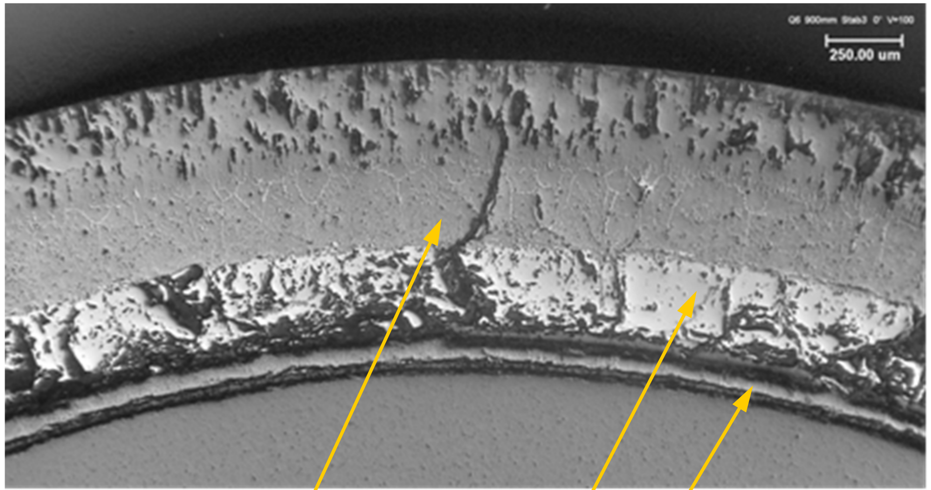
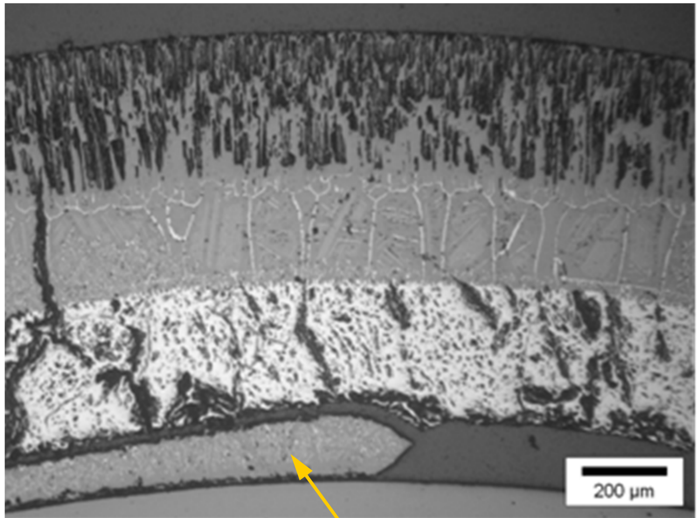


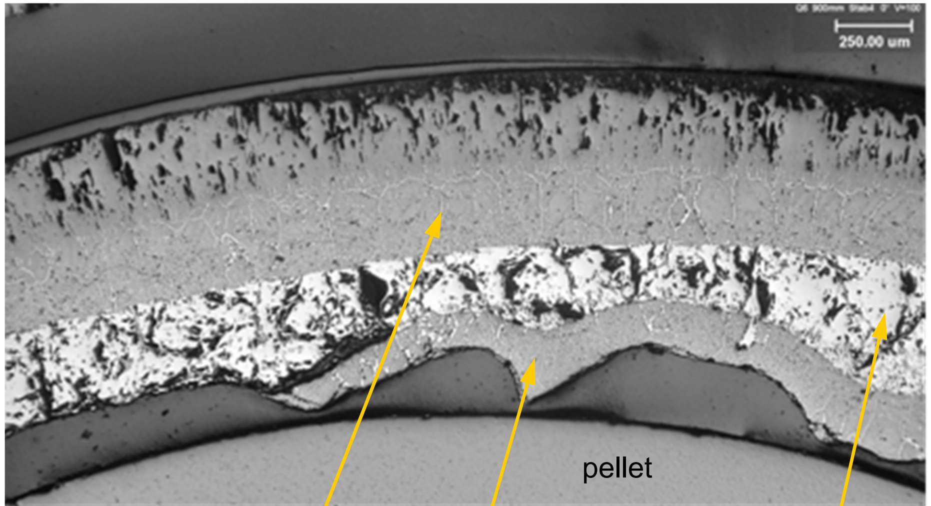
Q14, rod 20, 0°: homogeneous inner oxide layer



Q06, rod 3, 0°: outer oxide, oxidised Zr-melt, epoxy resin

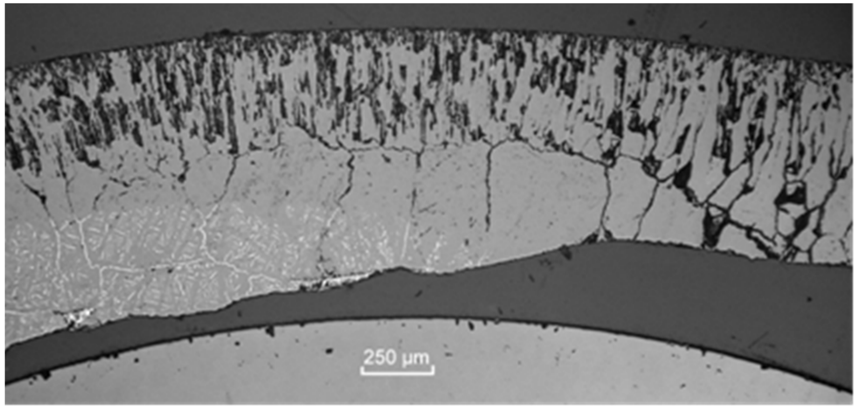


Q14, rod 20, 90°: interrupt of inner oxide layer development

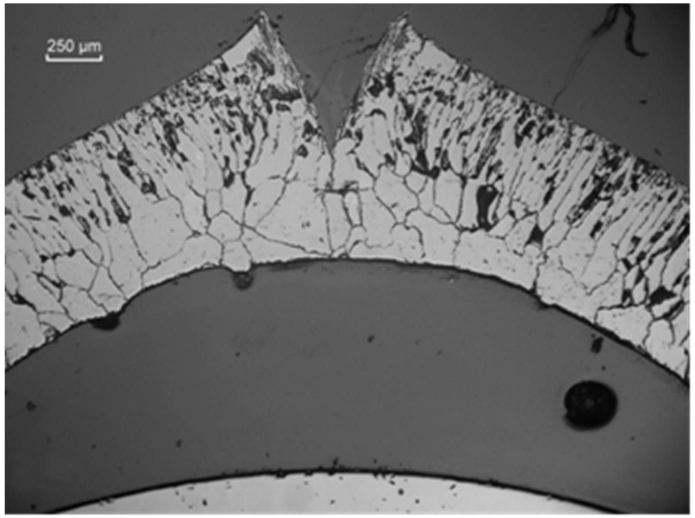


Q06, rod 4, 0°: outer and inner oxides; oxidised Zr-melt

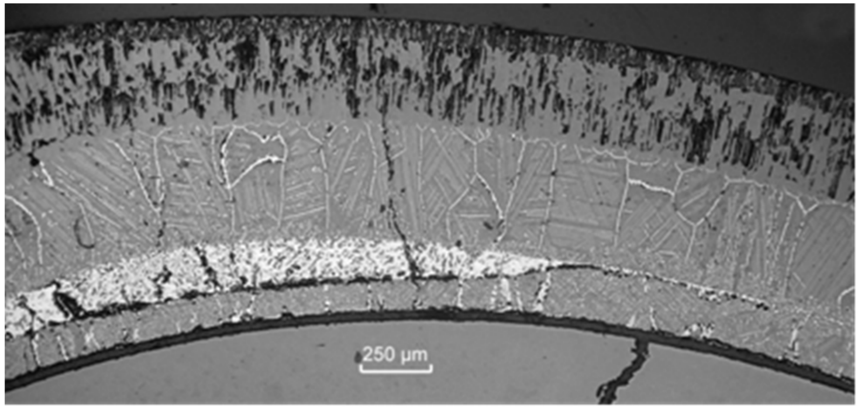
QUENCH-14, elevation 1000 mm: structure of oxidised cladding of rod #11 with frozen and lost melt of metal layer



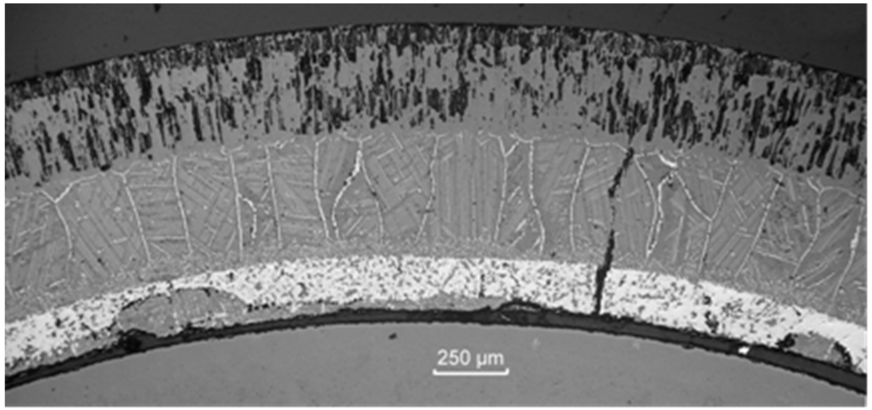
45°: transition from two oxide sub-layers to 1-phase oxide layer



90°: absence of cubic ZrO_2-x phase in oxide layer; melt relocated downwards

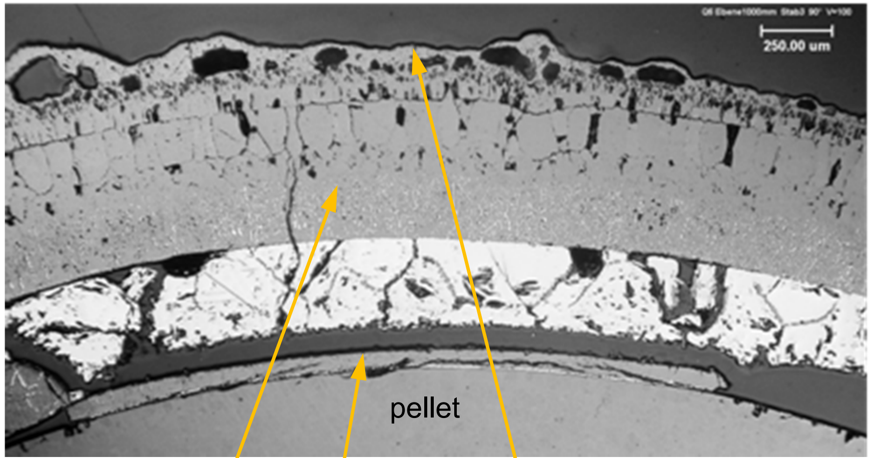


225°: transition from melt to completely oxidised cladding

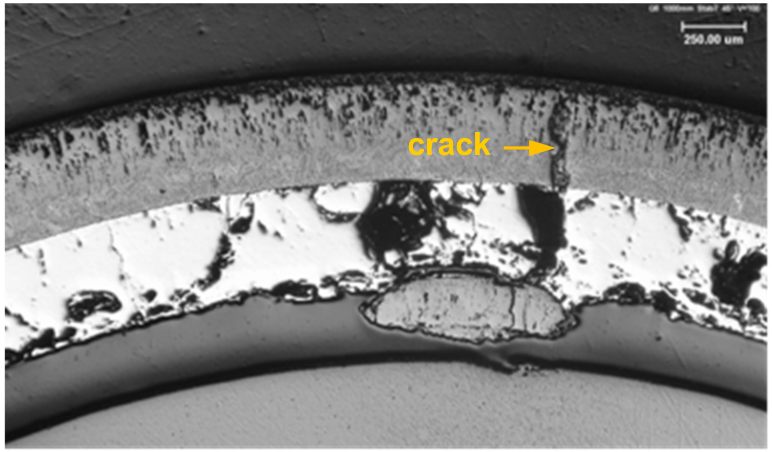


270°: non homogeneous internal oxide layer

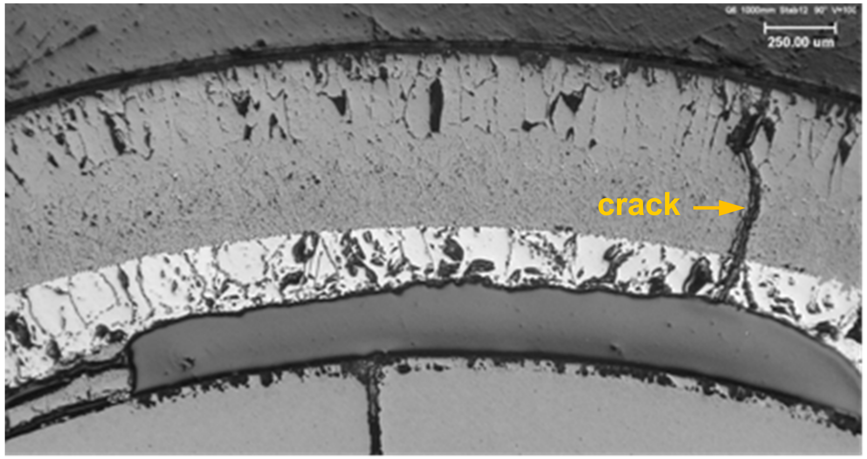
QUENCH-06: some fragments of cladding structures at elevation 1000 mm



rod 3, 90°: outer and inner oxides; foamy Ta_2O_5-containing external layer from failed thermocouple



rod 7, 45°: outer oxide, local inner oxide from relocated melt



rod12, 90°: void from downwards relocated melt

QUENCH-06 and QUENCH-15 at elevation 1000 mm: cladding structure with partial oxidised metal melt, frozen between two oxide layers

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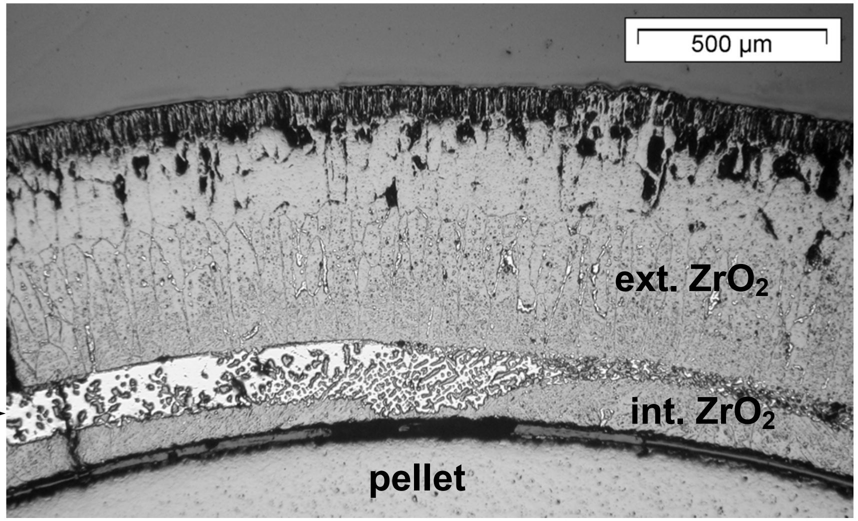
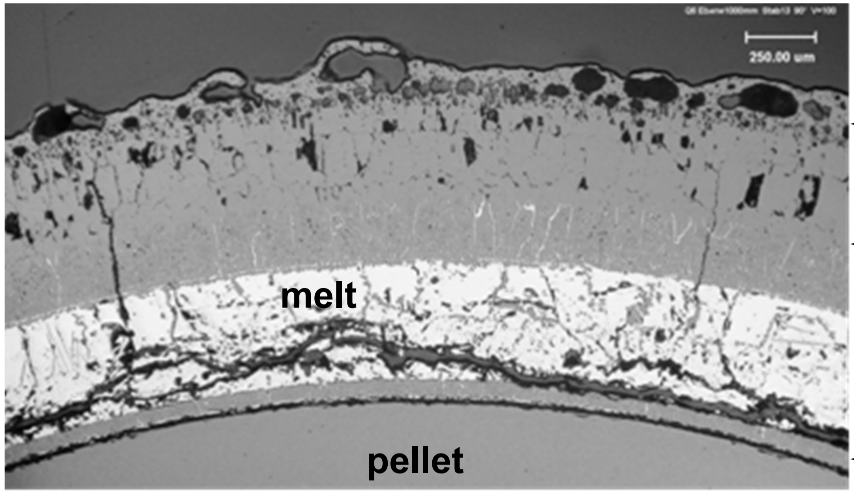


QUENCH-15, rod #17



QUENCH-06, rod #13, 90°

QUENCH-14, elevations 950 and 1100 mm: no interaction between cladding metal and ZrO_2 pellet

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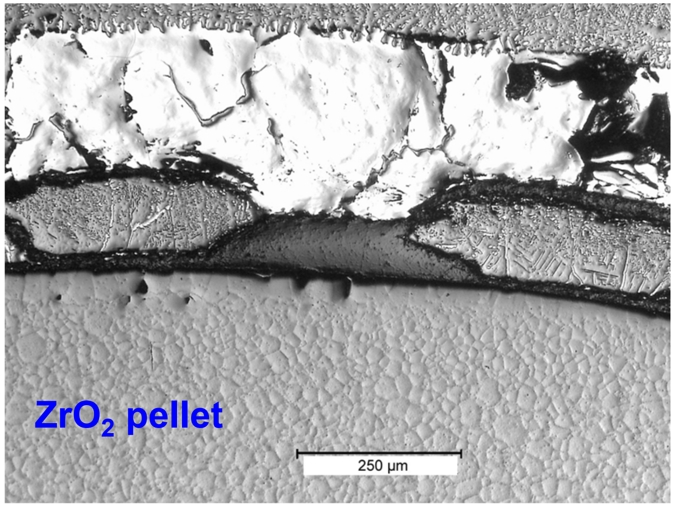
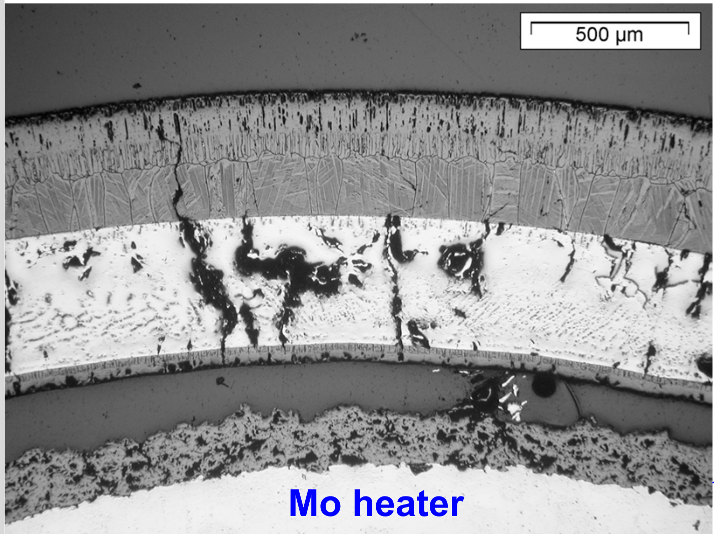
no indications of oxygen diffusion outside pellet (no contact with cladding, absence of α-Zr(O) precipitates at pellet grain boundaries)



rod #13 at elevation 950 mm

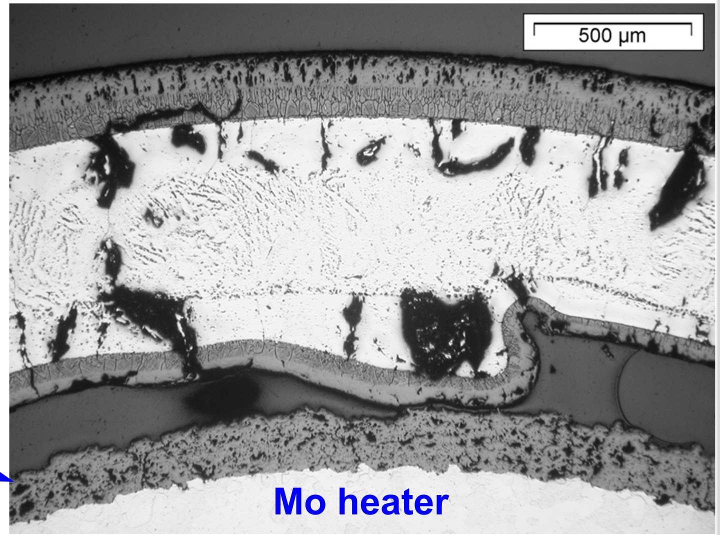
Reason of inner oxide layer development is penetration of steam under cladding through the cladding ruptures at different elevations.

Mostly it is not the interaction between cladding and pellet.



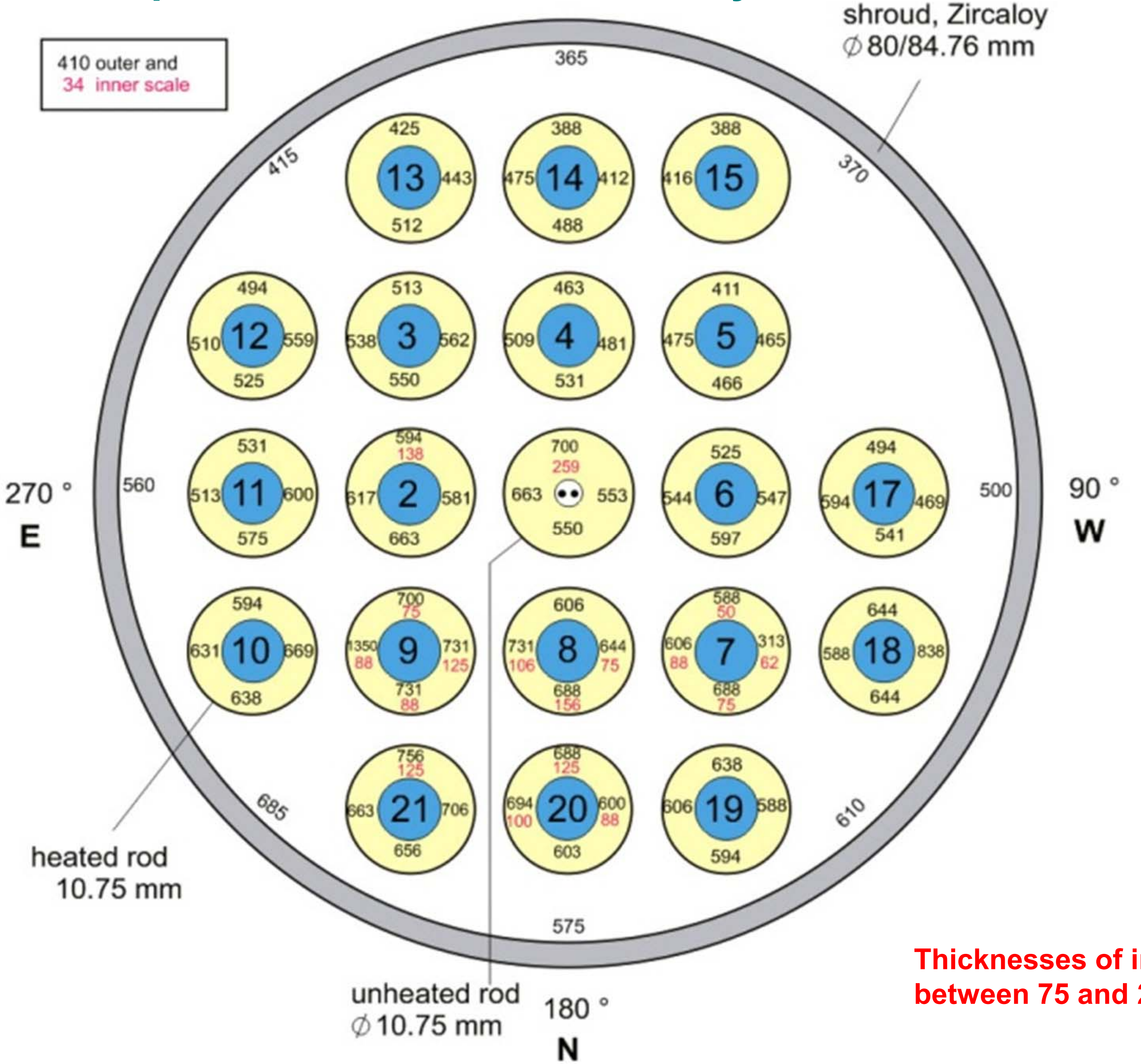
rod #3 at elevation 1100 mm: solid cladding position

ZrO_2 coating intact



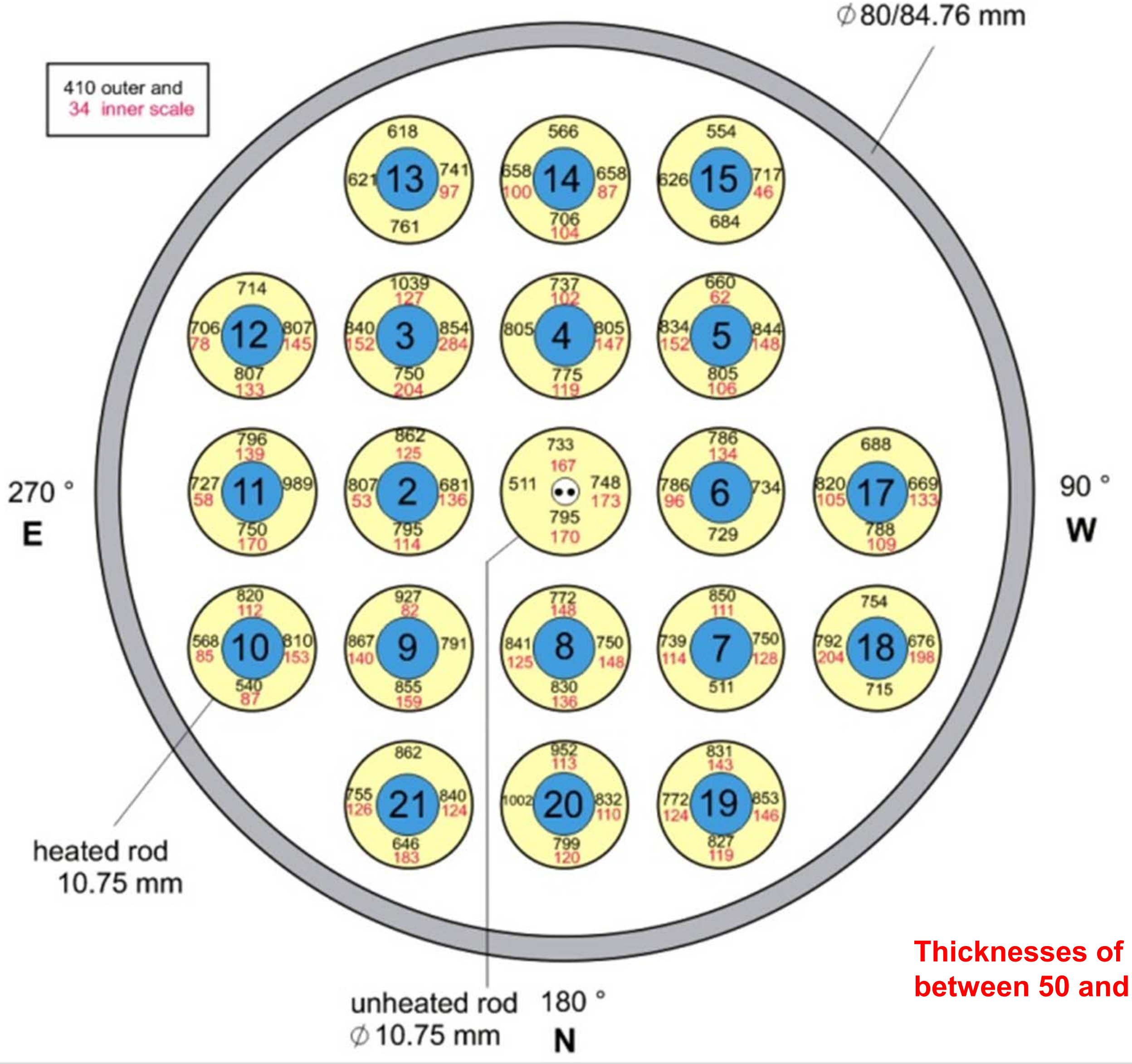
rod #3 at elevation 1100 mm: partial molten cladding position

QUENCH-14 at 900 mm:
map of outer and inner oxide layer thicknesses



Thicknesses of inner oxide layer between 75 and 260 µm

QUENCH-14 at 1000 mm:
map of outer and inner oxide layer thicknesses



Thicknesses of inner oxide layer between 50 and 200 µm

SUMMARY

- The QUENCH-14 (M5) and QUENCH-15 (ZIRLO) experiments investigated the influence of different cladding materials and bundle geometry on bundle oxidation and core reflood, in comparison with test QUENCH-06 (Zircaloy-4).

- After pre-oxidation phase, which lasted ~3000 s, the electric power was ramped during ~1150 s to reach desired maximum bundle temperature of ~1800°C. Following fast water injection the reflood with ~1.3 g/s/(eff.rod) water was initiated, and the electrical power was reduced to decay heat level. The cooling duration of 300 s was measured for all three bundles.

- Two Zircaloy-4 corner rods withdrawn during the tests showed the following peak ZrO_2 thickness for **QUENCH-14 / -15**: **180 / 150 µm** on the end of the pre-oxidation phase, **360 / 380 µm** before reflood. The E110 corner rods extracted after the tests evident intensive breakaway effect.

- Average post-test oxide layer thickness at elevation 950 mm for **QUENCH-14 / -15**: **840 / 630 µm**. These values correspond to **74 / 70% metal converted to ZrO_2**.

SUMMARY (Cont.)

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- Measured hydrogen production during the **QUENCH-14 /-15** tests were **34 / 41 g** in the pre-oxidation and transient phases and **6 / 7 g** in the quench phase (in QUENCH-06: 32 g and 4 g, respectively). Reasons of higher hydrogen production for QUENCH-15 were increased bundle surface and usage of not prototypical corner rods.

- Post-test investigations of bundles QUENCH-06, -14 and -15 reveals significant cladding <u>inner oxide layers</u> with thickness up to 20% of outer oxide layers. This inner oxide layers were developed mostly due to <u>penetration of steam</u> through cladding cracks and are noticeable factor for hydrogen generation.

- The partially oxidised cladding melt was catch between outer and inner oxide layers for all three tests QUENCH-06, -14 and -15.

- Bundle tests QUENCH-06, -14 and -15 showed comparable behaviour of Zircaloy-4, M5® and ZIRLO™ materials during reflood.

Thanks

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Thank you for your attention

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