Experimental Results of the QUENCH-16 Bundle Test on Air Ingress

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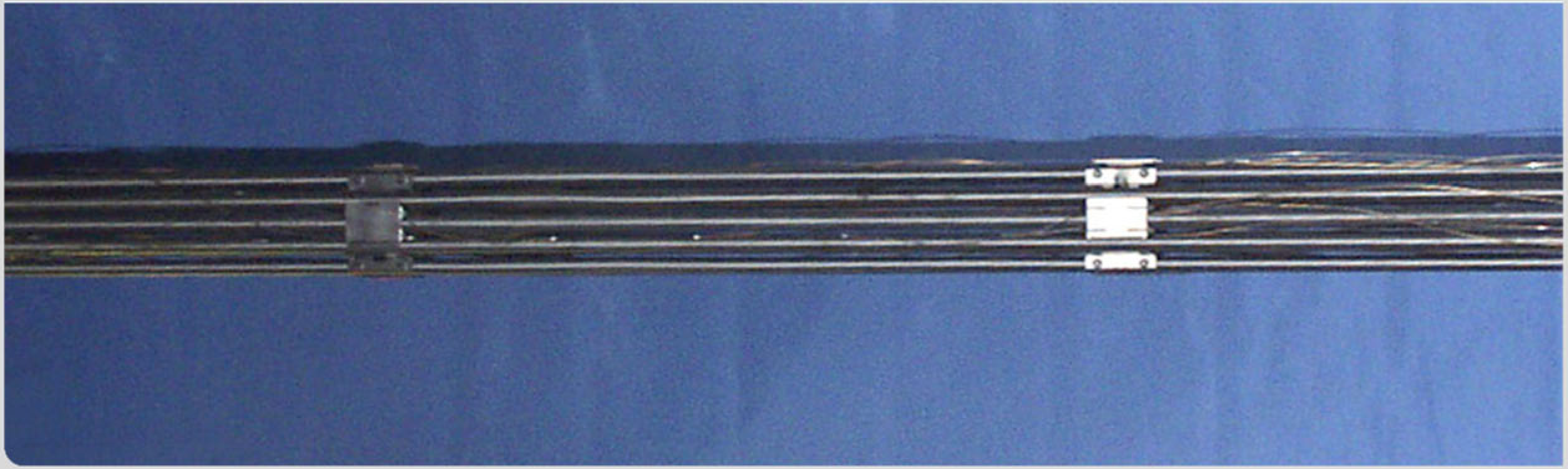
Institute for Applied Materials, IAM-WPT; Program NUKLEAR

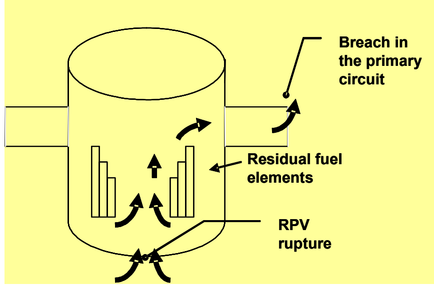


Oxidation in atmospheres containing nitrogen

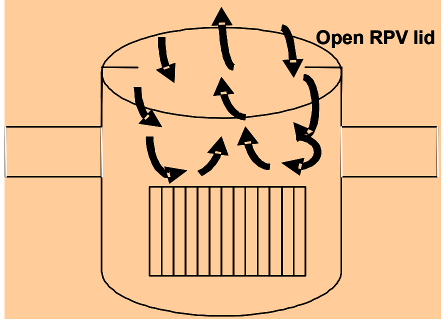
- air ingress reactor core, spent fuel pond, or transportation cask
- nitrogen in BWR containments (inertization) and ECCS pressurizers
- prototypically following steam oxidation and mixed with steam

- Consequences:
  - <u>significantt heat release</u> causing temperature runaway from lower temperatures than in steam
  - <u>strong degradation of cladding</u> causing early loss of barrier effect
  - <u>high oxygen activity</u> influencing FP chemistry and transport

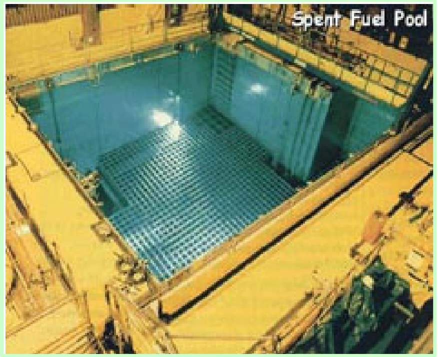
Late phase after RPV failure



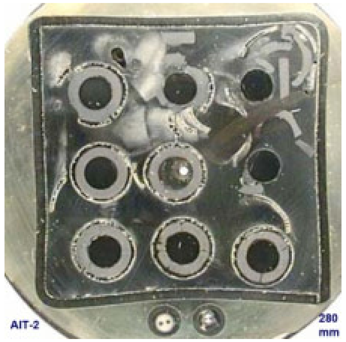
Mid loop operation



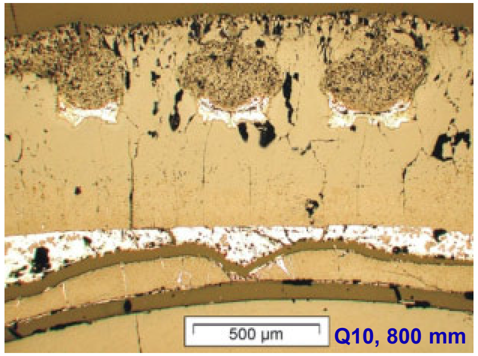
Spent fuel storage pool accident



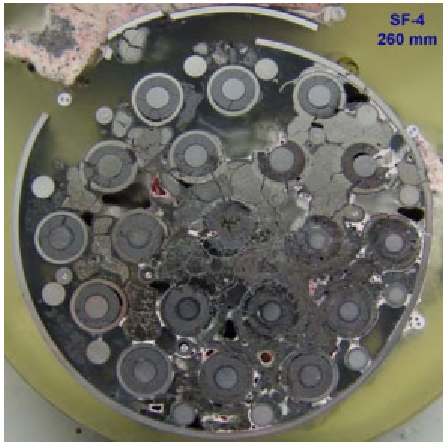
Previous bundle air ingress experiments



- **CODEX AIT-1, AIT-2 (Zry-4) performed 1999 at AEKI/Budapest: *small bundles with 9 rods***



- **QUENCH-10 (Zry-4 claddings) performed 2004 at KIT/Karlsruhe: *strong pre-oxidised bundle***



- **PARAMETER-SF4 (E110 claddings) performed 2009 at LUCH/Podolsk*: very high temperatures on reflood initiation with following escalation (bundle melting)***

Objectives of the QUENCH-16 test

- air oxidation after rather moderate pre-oxidation in steam;

- slow oxidation and nitriding of zirconium in high temperature air and transition to rapid oxidation and temperature excursion;

- role of nitrogen under oxygen-starved conditions,

- formation of oxide and nitride layers on the surface of Zr;

- release of hydrogen from oxidised zirconium during air ingress scenario;

- reflooding of oxidised and nitrided bundle by water initiated at temperatures well below the melting point of the cladding, release of nitrogen.

QUENCH facility

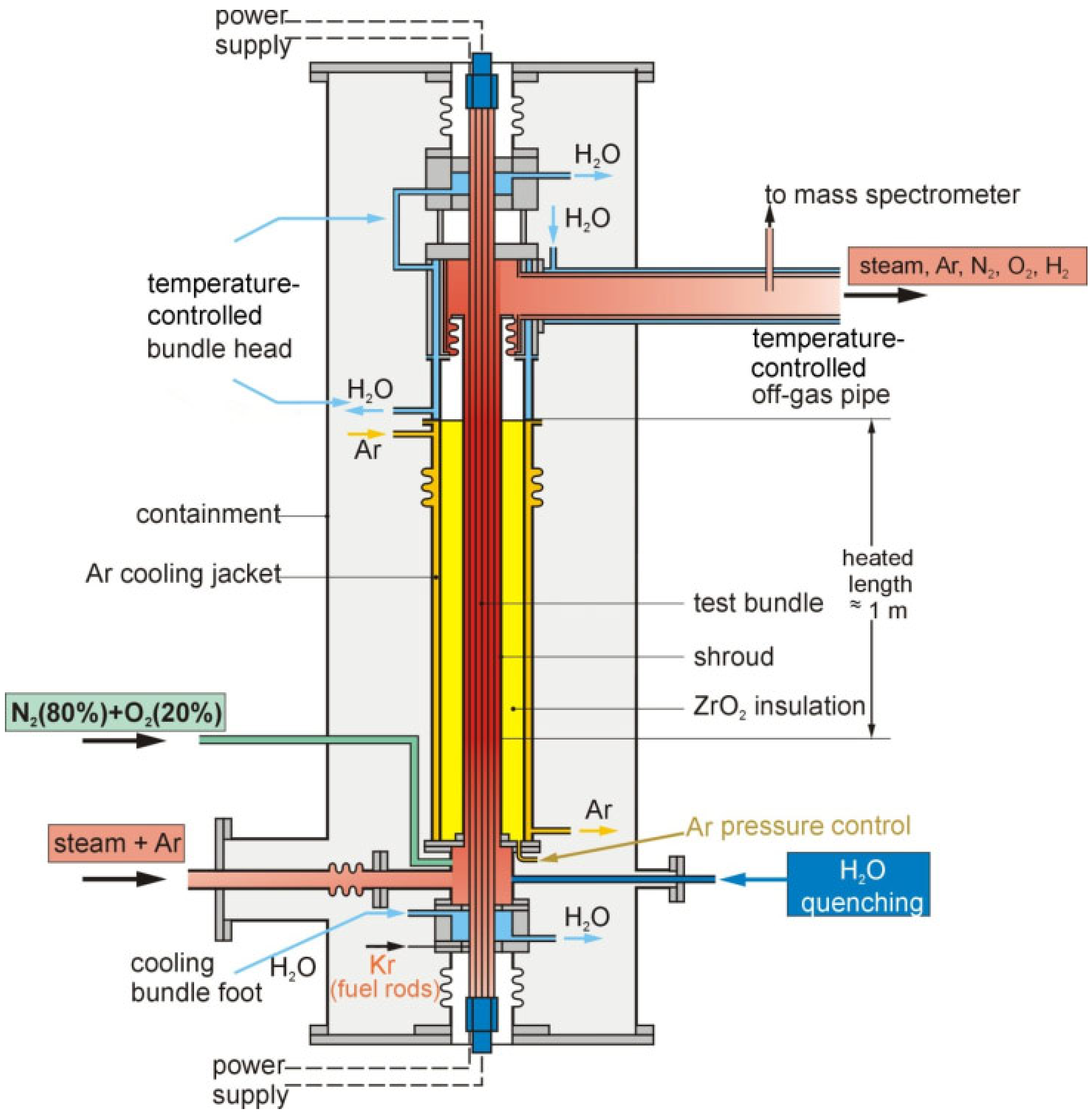
QUENCH-16 facility features:

1) controllable synthetic air input;

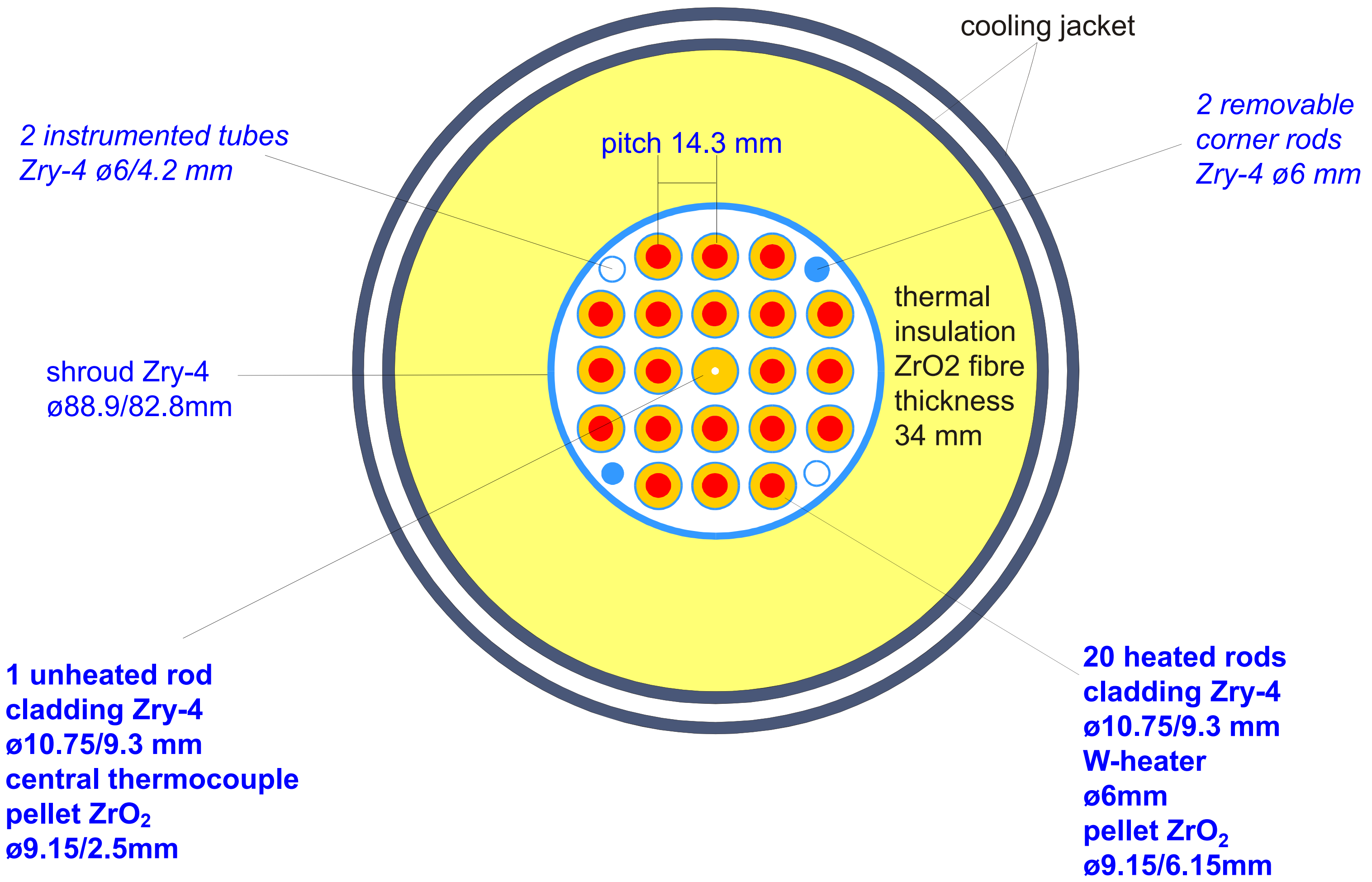
2) Krypton filling of rods;

3) temperature control for off-gas pipe (to avoid the steam condensation)

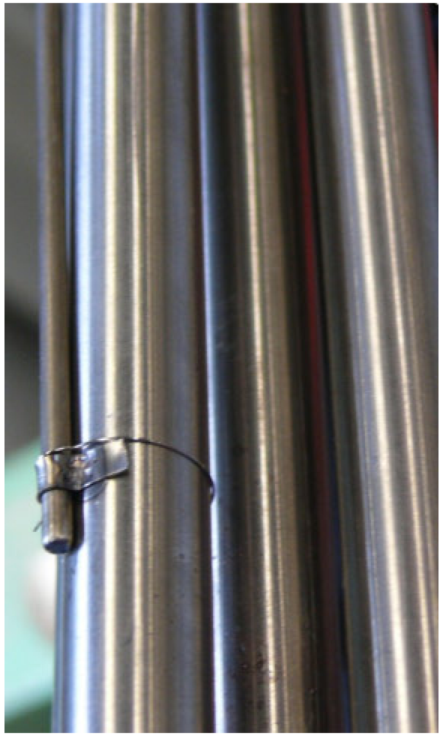
4) control of pressure in space between shroud and jacket



Cross section of the PWR test column

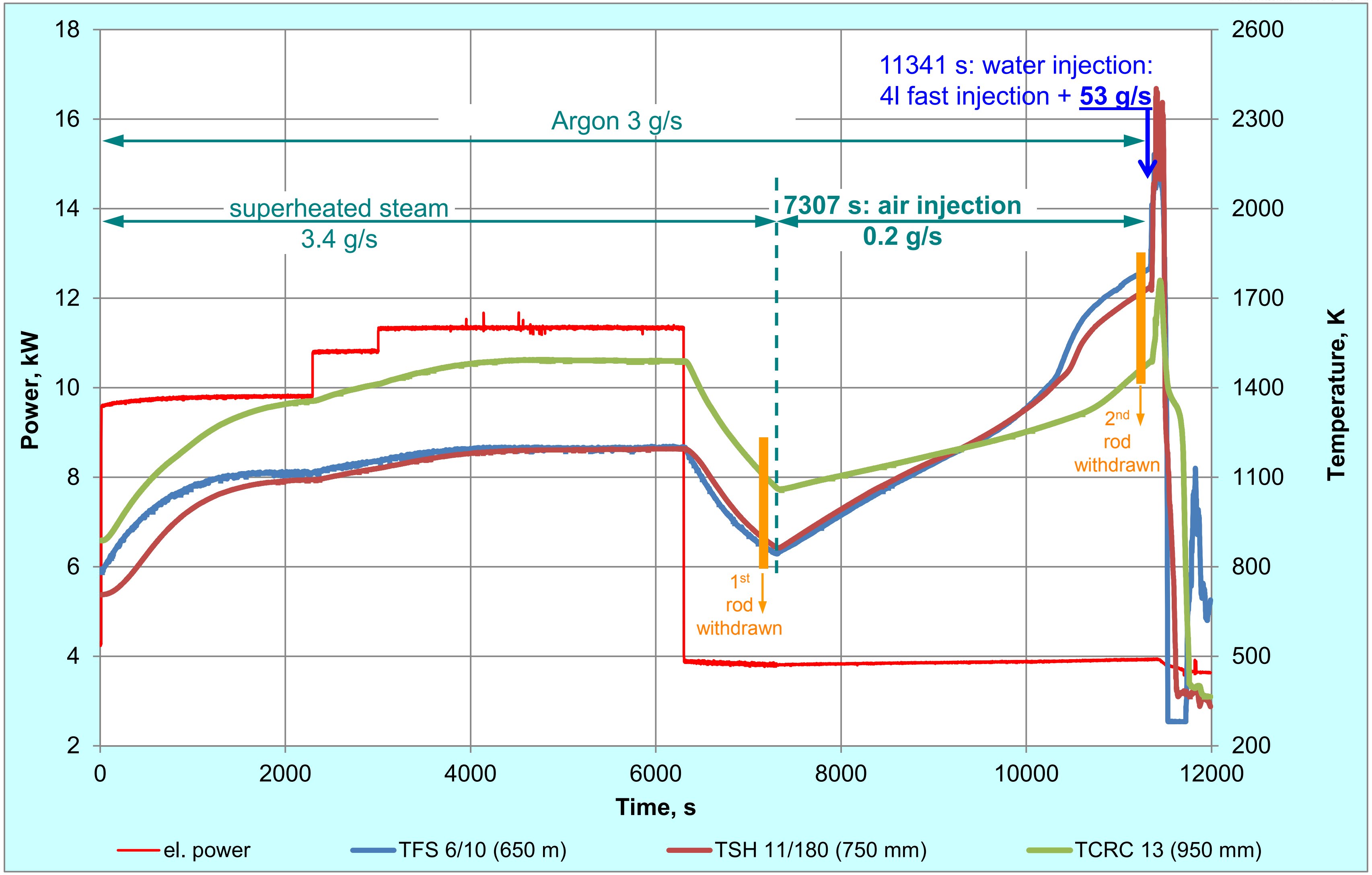


Mounting of high temperature thermocouples

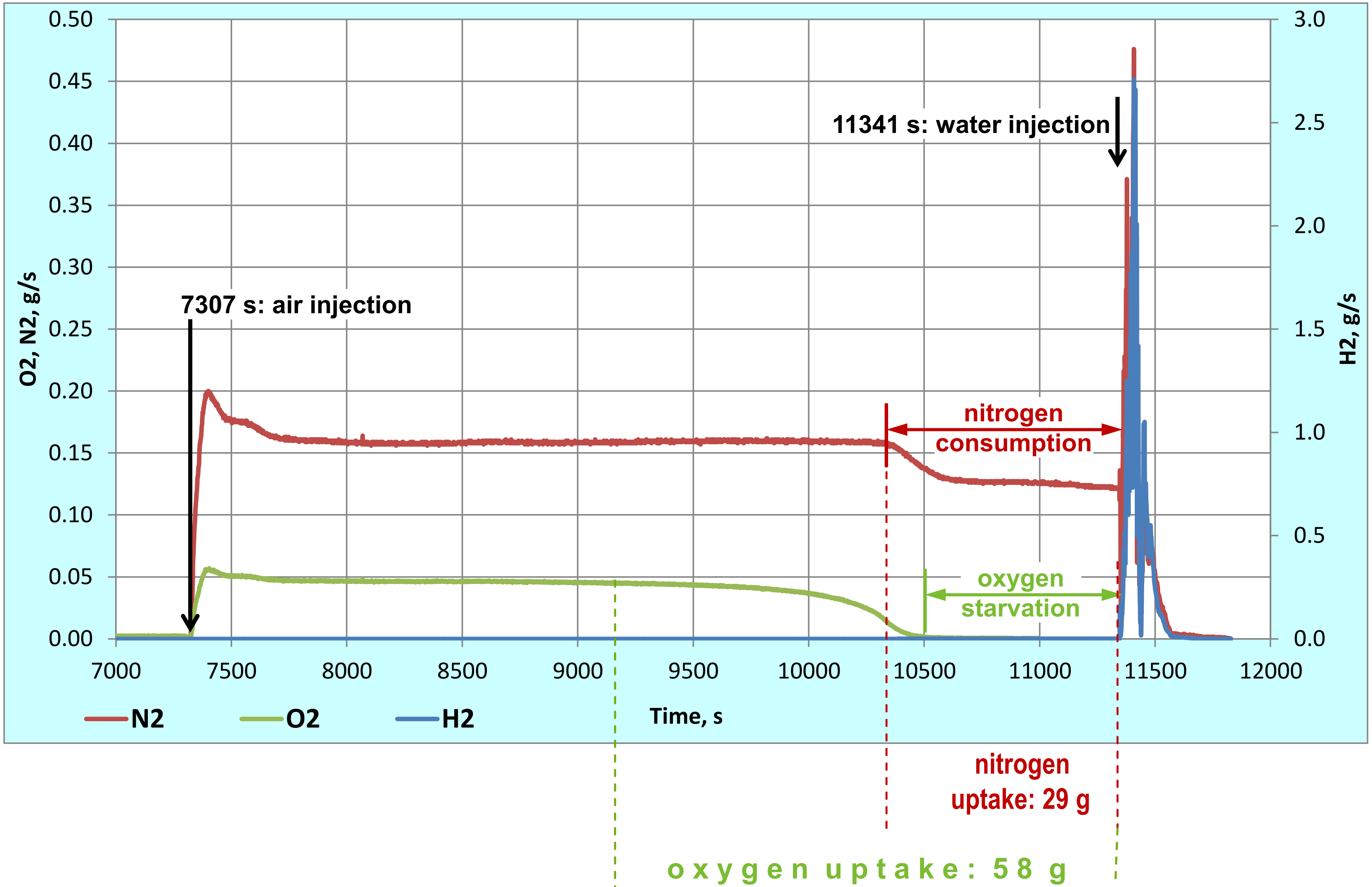
			
TC inserted from bundle bottom up to 850 mm	TC inserted from bundle top above 850 mm	TC inserted from bundle top under GS4 (1150 mm)	TC installed at shroud
Cladding surface thermocouples TFS			Shroud thermocouples TSH

QUENCH-16 test progression

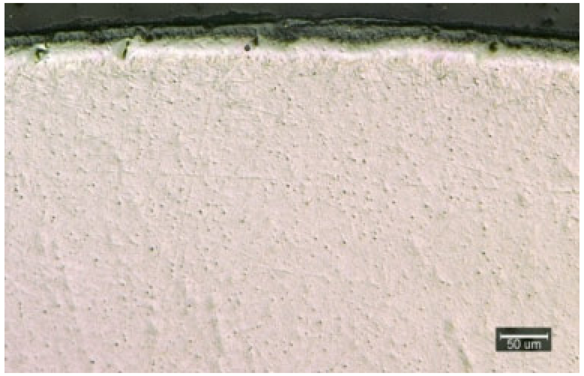
test performed on 27.07.2011 at KIT/IAM
according to pre-test calculations from PSI, GRS, EdF



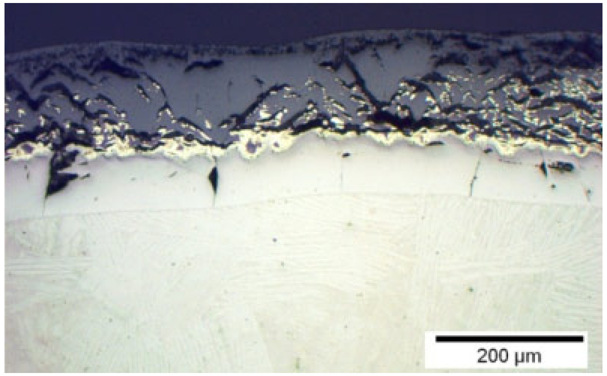
Consumption of nitrogen and oxygen during air ingress phase:
data of mass spectrometer



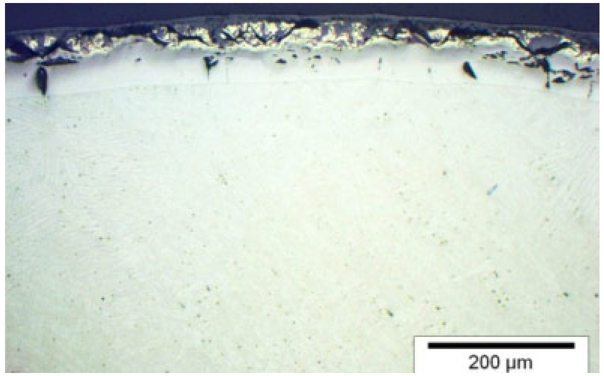
Corner rod D withdrawn from the bundle on the end of the air ingress phase: nitride formation between 300 and 900 mm



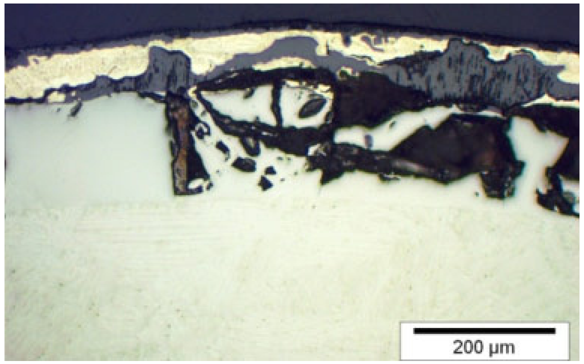
250 mm (1070°C): no nitrides



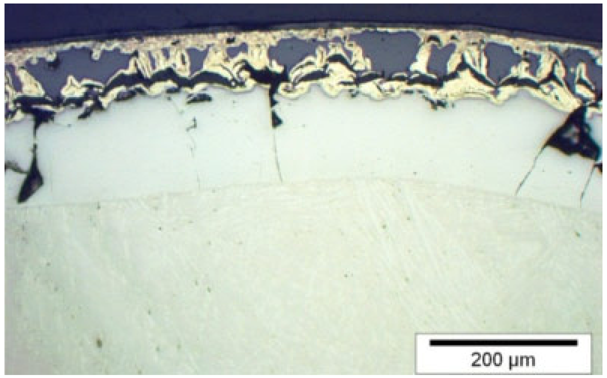
450 mm (1530°C): strong corrosion; nitrides



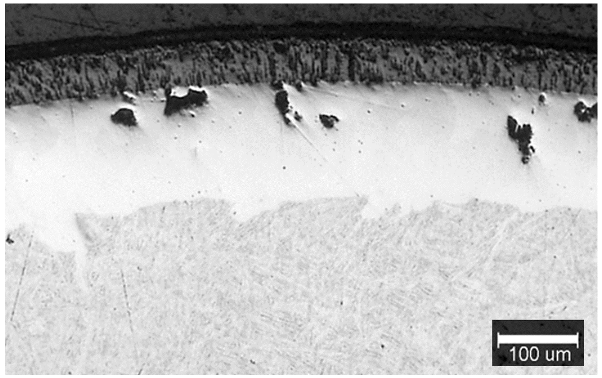
650 mm (1400°C): moderate corrosion; nitrides



750 mm (1460°C): strong corrosion; nitrides

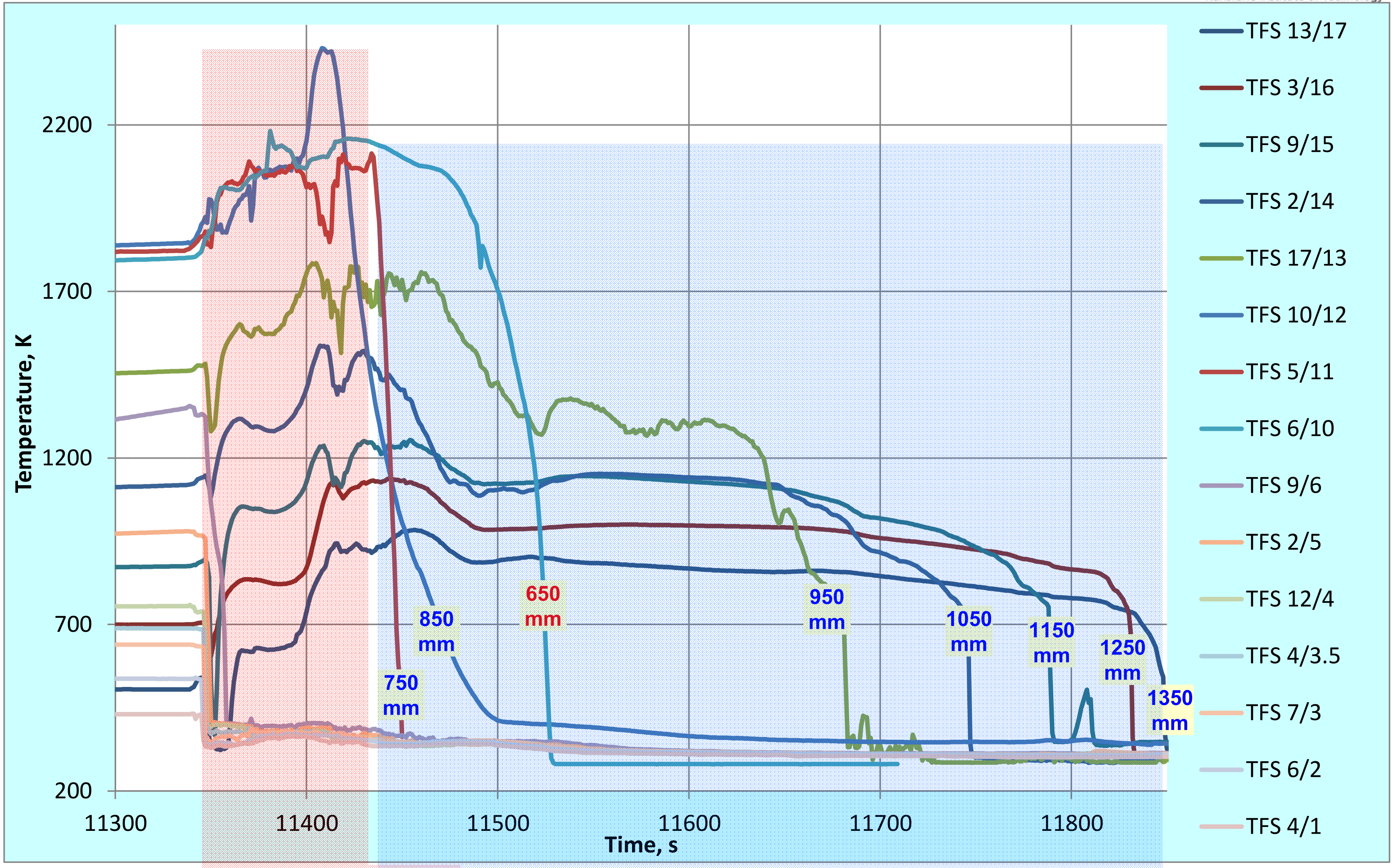


850 mm (1570°C): strong corrosion; nitrides



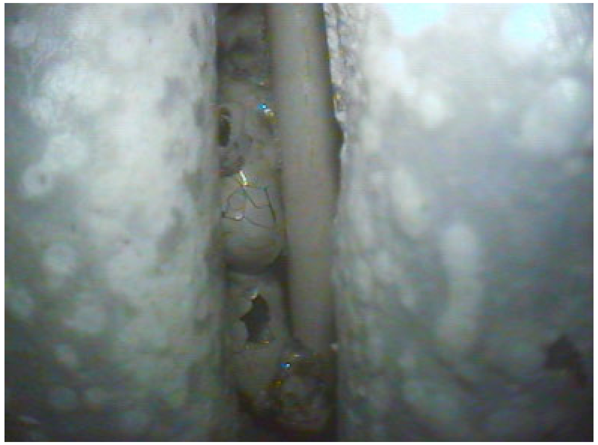
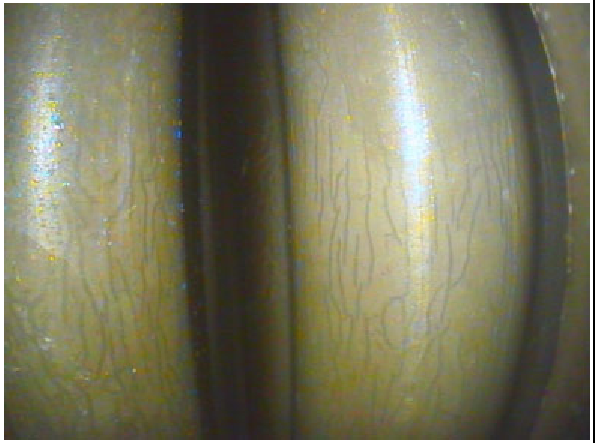
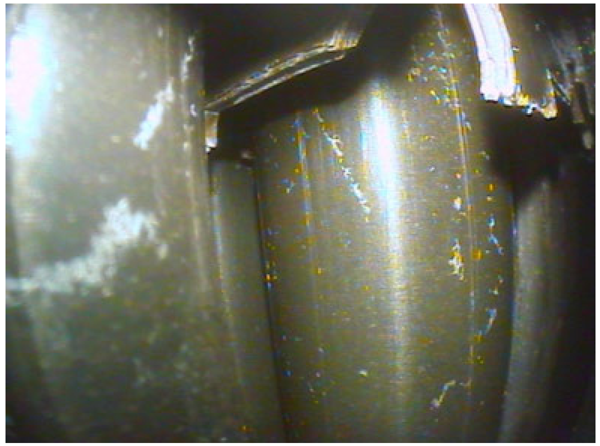
950 mm: no nitrides

Temperature escalation (above Zr melting point) and cooldown during reflood



Durations: escalation 100 s cooldown 400 s

Post-test visual investigations by endoscope introduced at the position of the corner rod B: side view

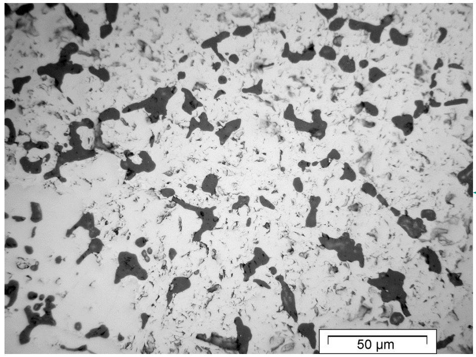
		
350 mm: frozen metallic melt relocated from upper elevations	420 mm: oxide shells of melt droplets and rivulets	600 mm: intensive cladding damaging
		
835 mm: spalling of outer scale of oxide layer	880 mm: not damaged outer scale of oxide layer	1050 mm: dark oxide of claddings, intact Grid Spacer #4

Bundle cross sections: melt formation and relocation

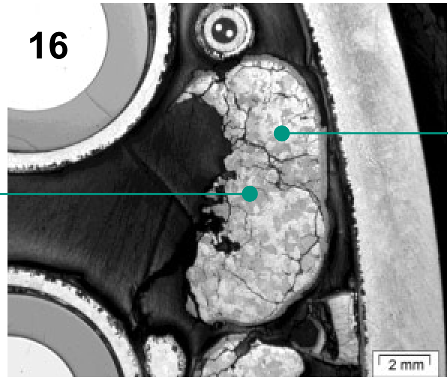
		
350 mm: metallic and oxidised **melt pools**	450 mm: mostly oxidised **melt pools**	550 mm: downwards **relocated cladding metal**
		
650 mm: downwards **relocated cladding metal**	750 mm: downwards **relocated cladding metal**	850 mm: outer oxide layer not failed

Frozen melt at elevation 350 mm: not oxidised and oxidised melt

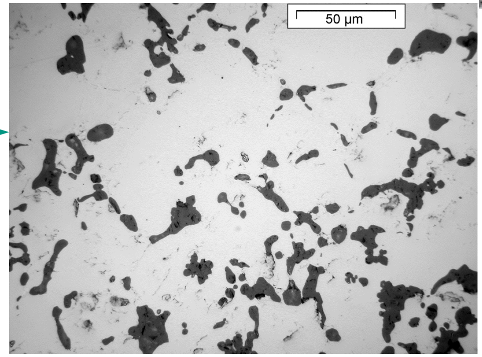
Karlsruhe Institute of Technology



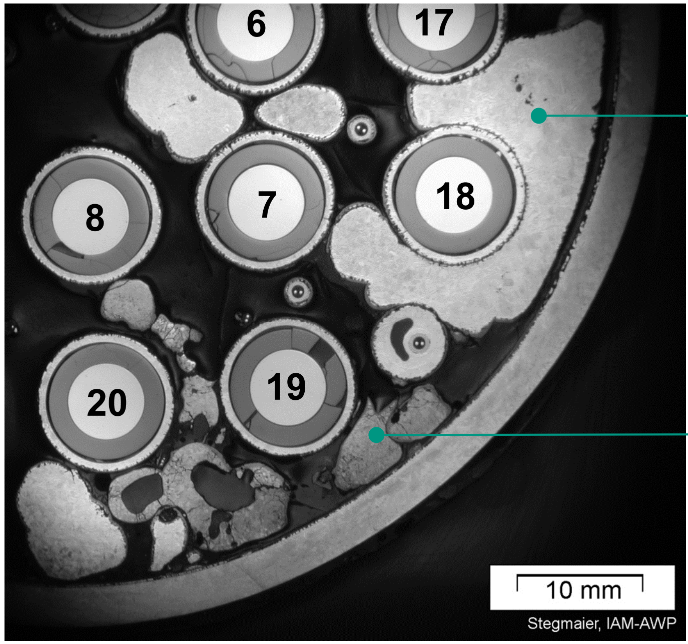
grey porous region;
precipitates 10%

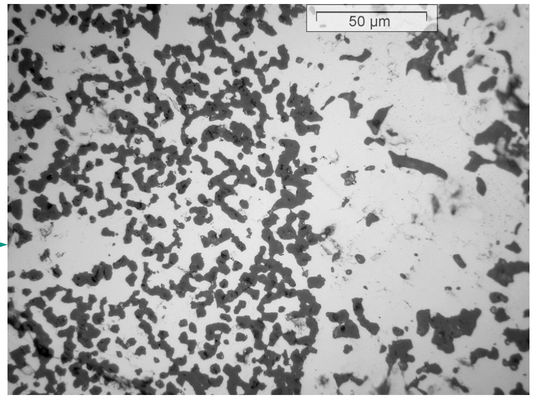


grey and light melt regions

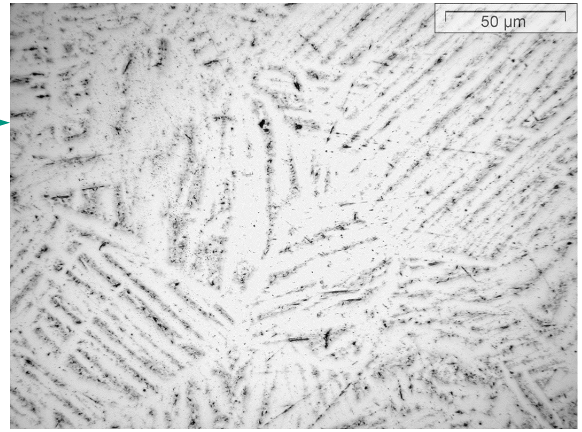


light non porous region;
precipitates 10%



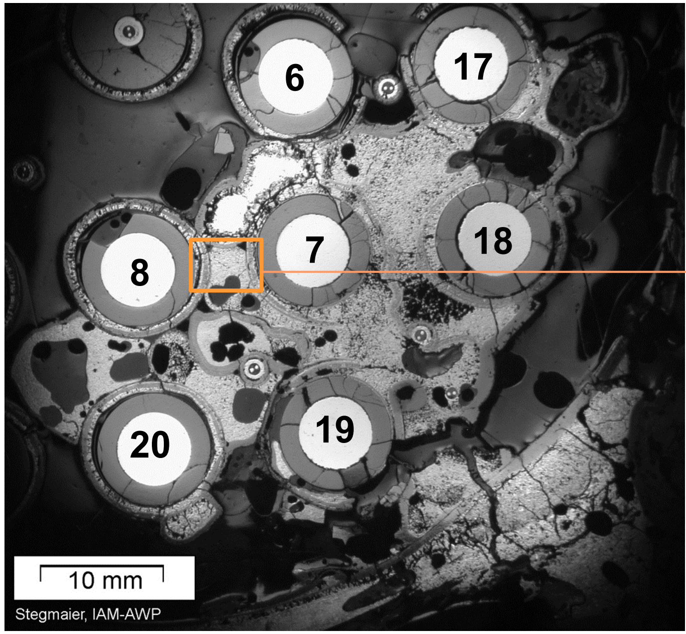


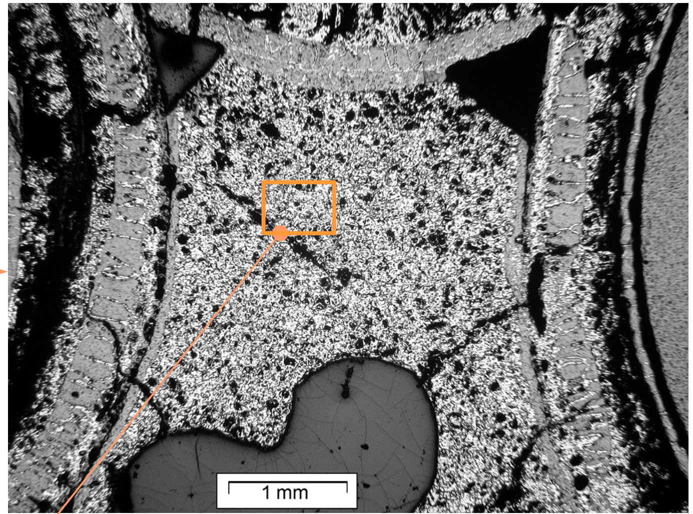
precipitates part 20%



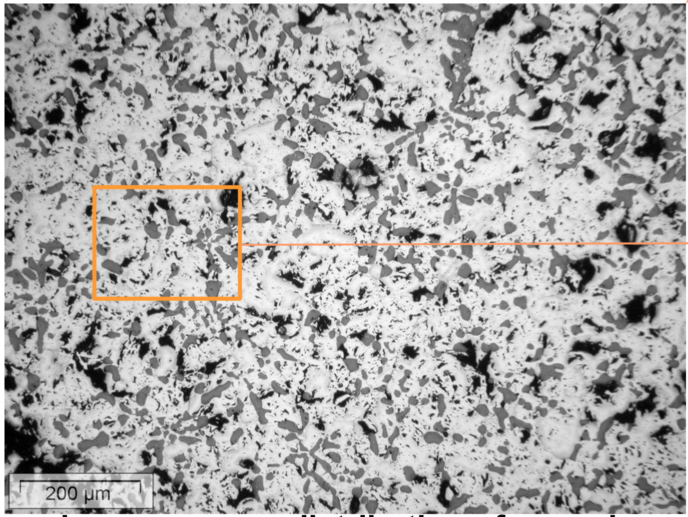
Widmanstätten pattern of frozen metallic melt

Frozen melt at elevation 450 mm: mostly oxidised melt

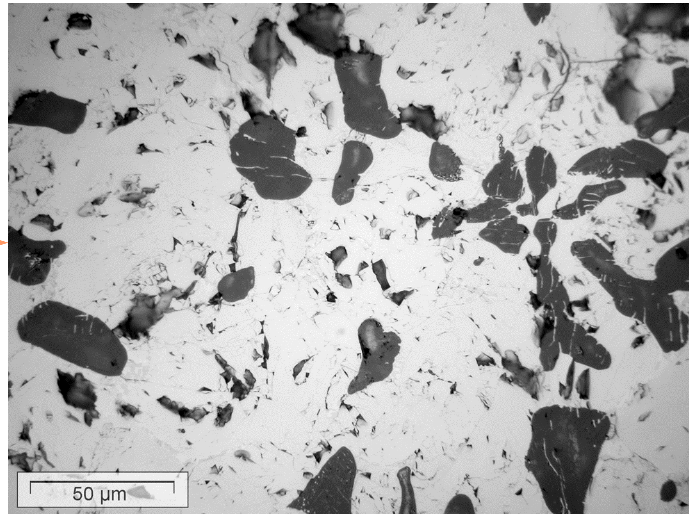




molten pool between two rods: oxidation at melt periphery and ceramic precipitates inside melt



homogeneous distribution of ceramic precipitates in the melt



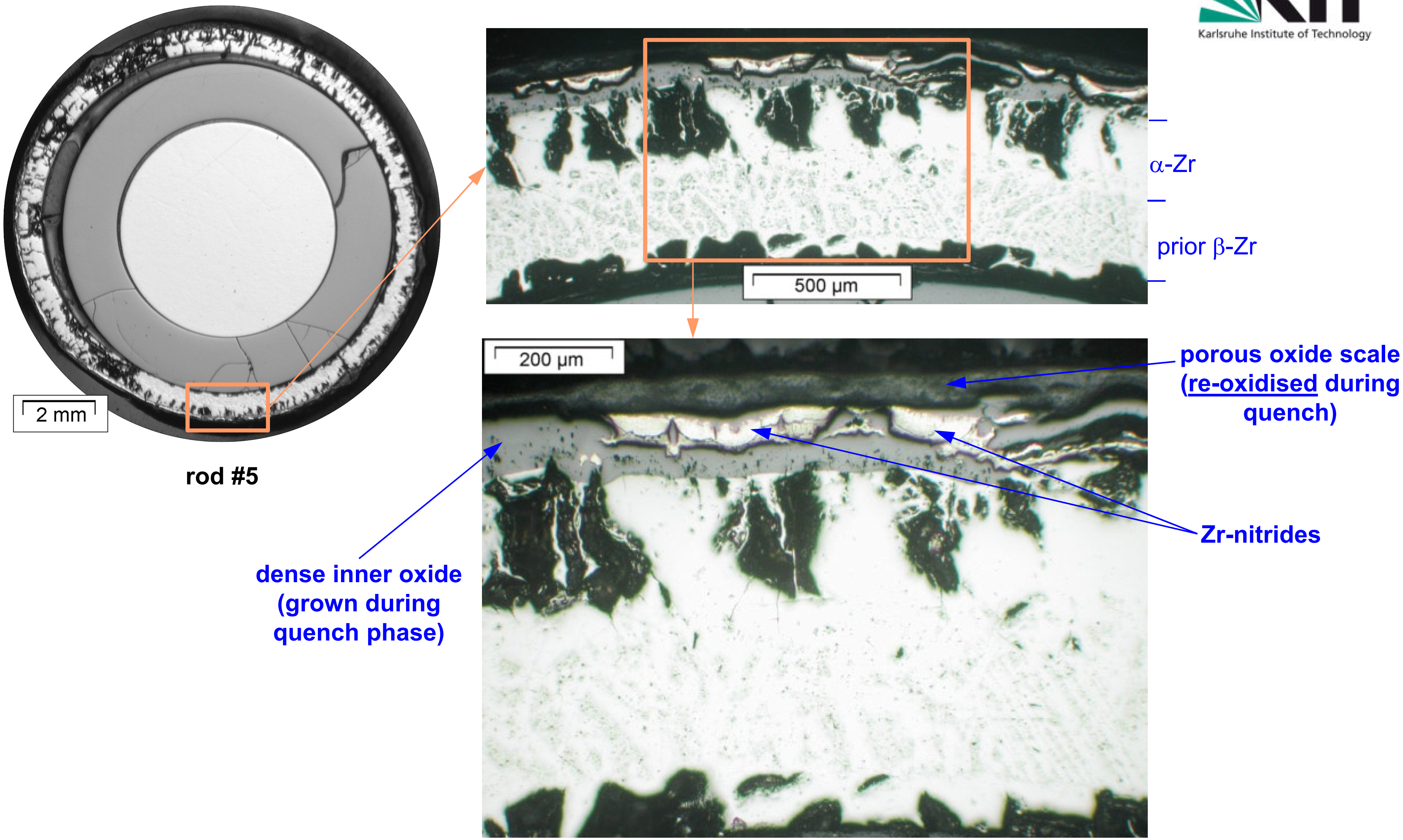
precipitates part 28%

Release of hydrogen and nitrogen during quench phase:
data of mass spectrometer

hydrogen release: 128 g. 3 main sources: 1) re-oxidation of Zr-nitrides; 2) secondary oxidation of cladding; 3) melt oxidation

nitrogen release: 24 g from consumed 29 g -> severe nitrides leftover and should be observed

Nitride re-oxidation during quench at elevation 350 mm



Nitride re-oxidation and secondary cladding oxidation during quench at elevation 450 mm

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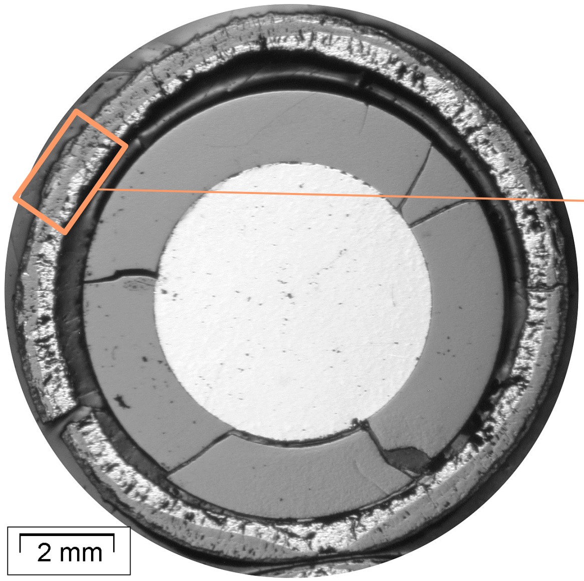
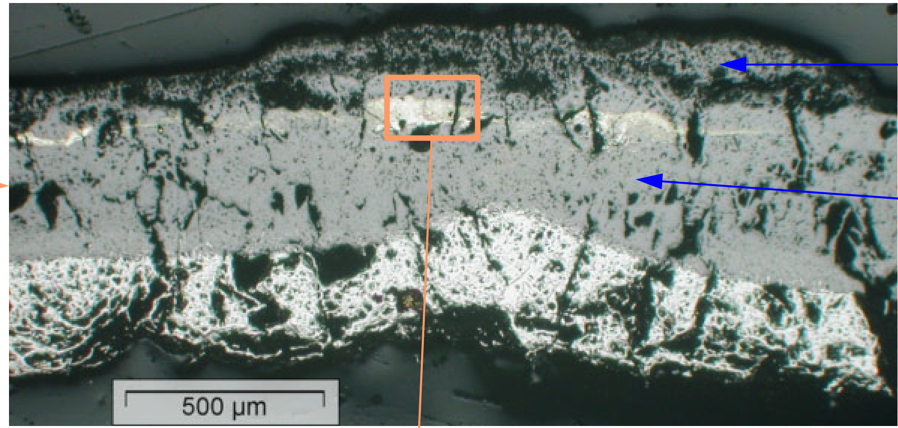


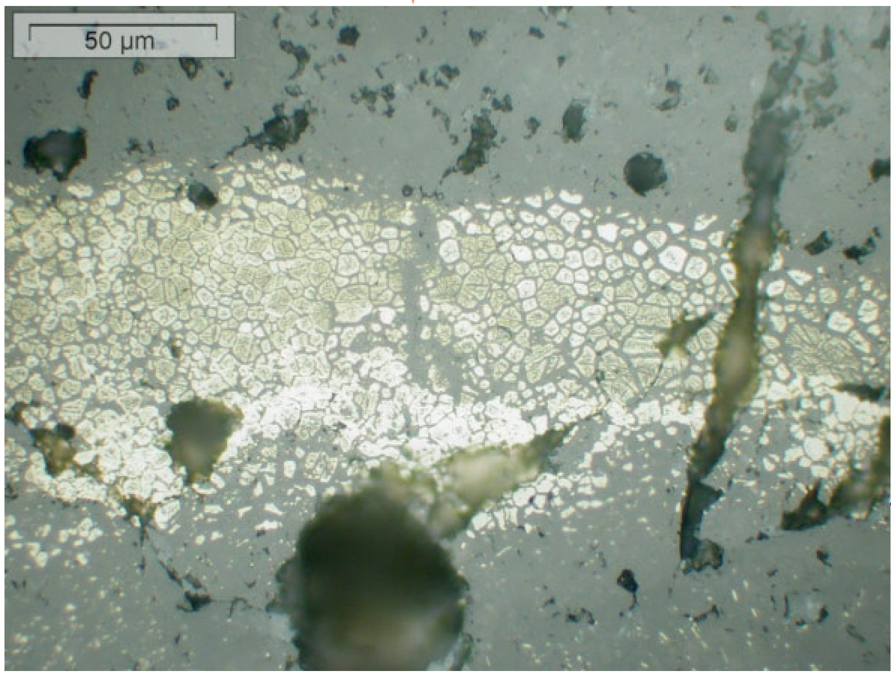
rod #4



porous oxide scale (re-oxidised during quench)

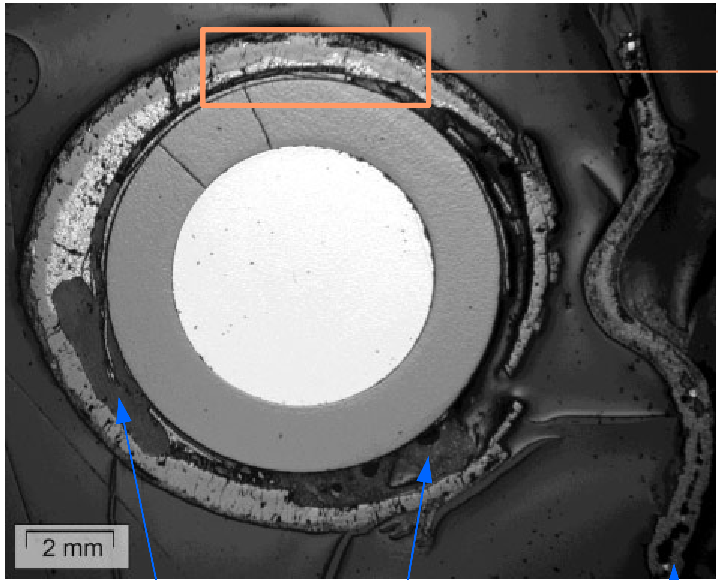
secondary dense inner oxide (grown during quench phase)

α-Zr(O)



Zr-nitrides

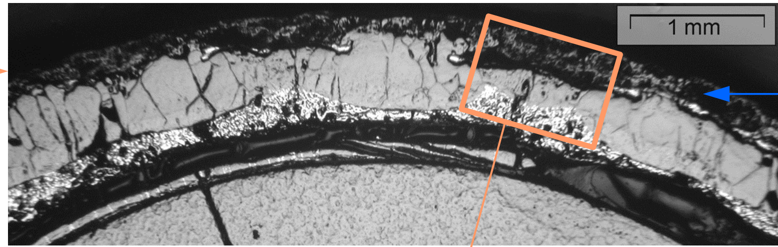
Nitrides and melting at elevation 550 mm



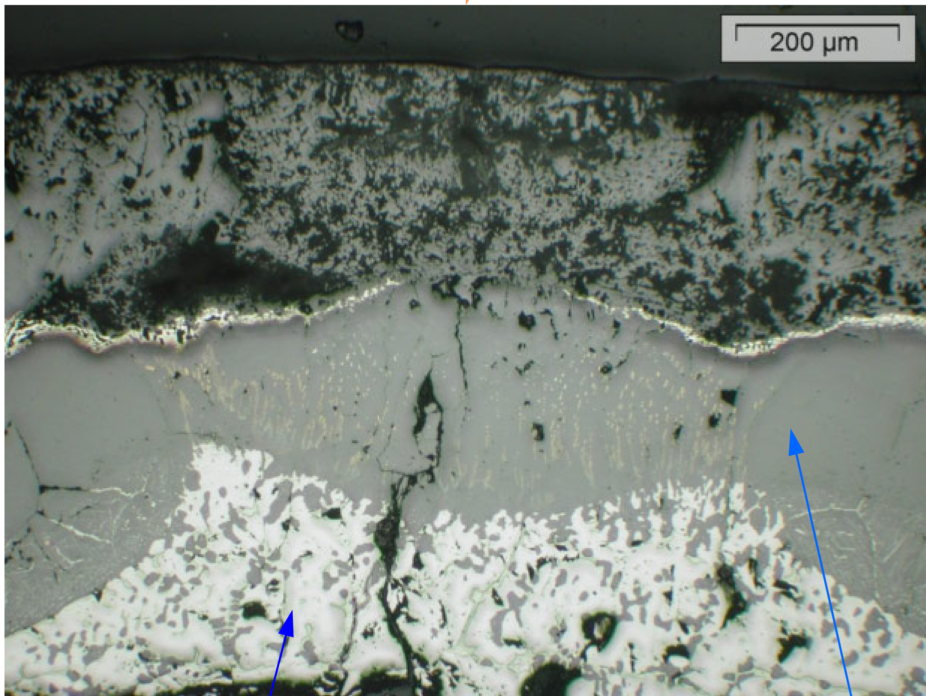
rod #9

voids from downwards relocated melt

completely oxidised Zry grid spacer



porous outer oxide scale

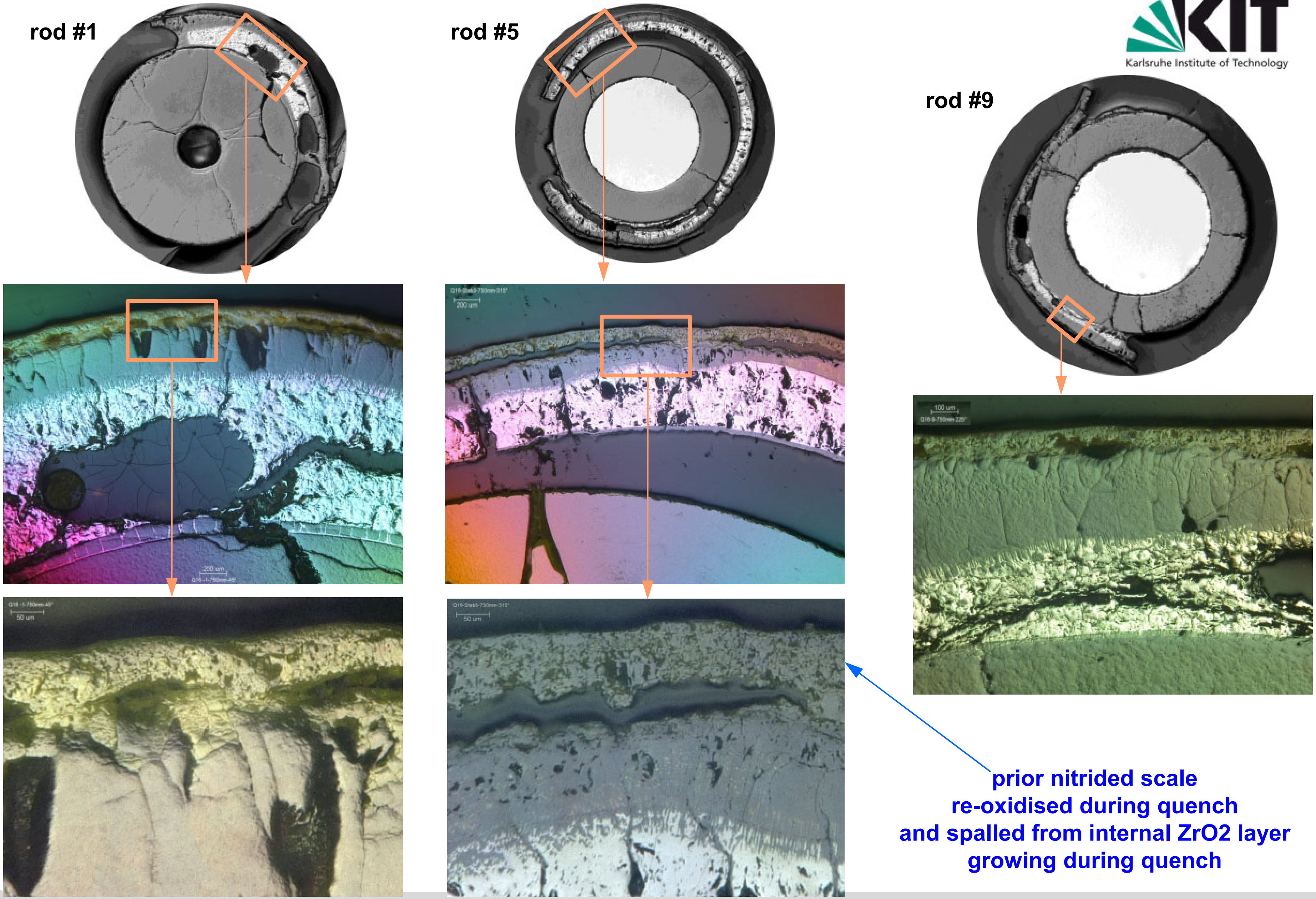


Zr-nitrides

frozen partially oxidised melt

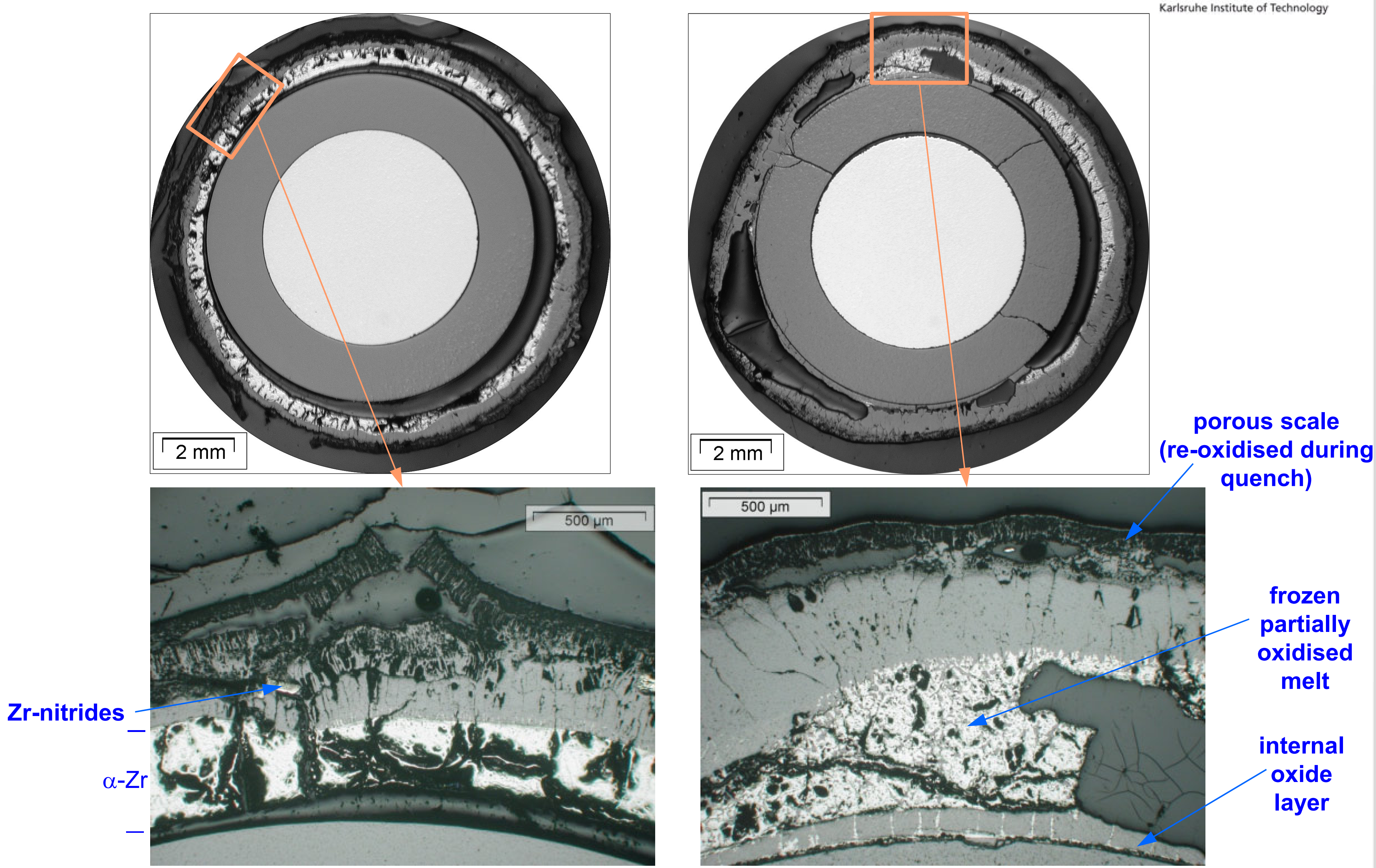
secondary dense inner oxide (grown during quench phase)

Spalling of re-oxidised scales at elevation 750 mm



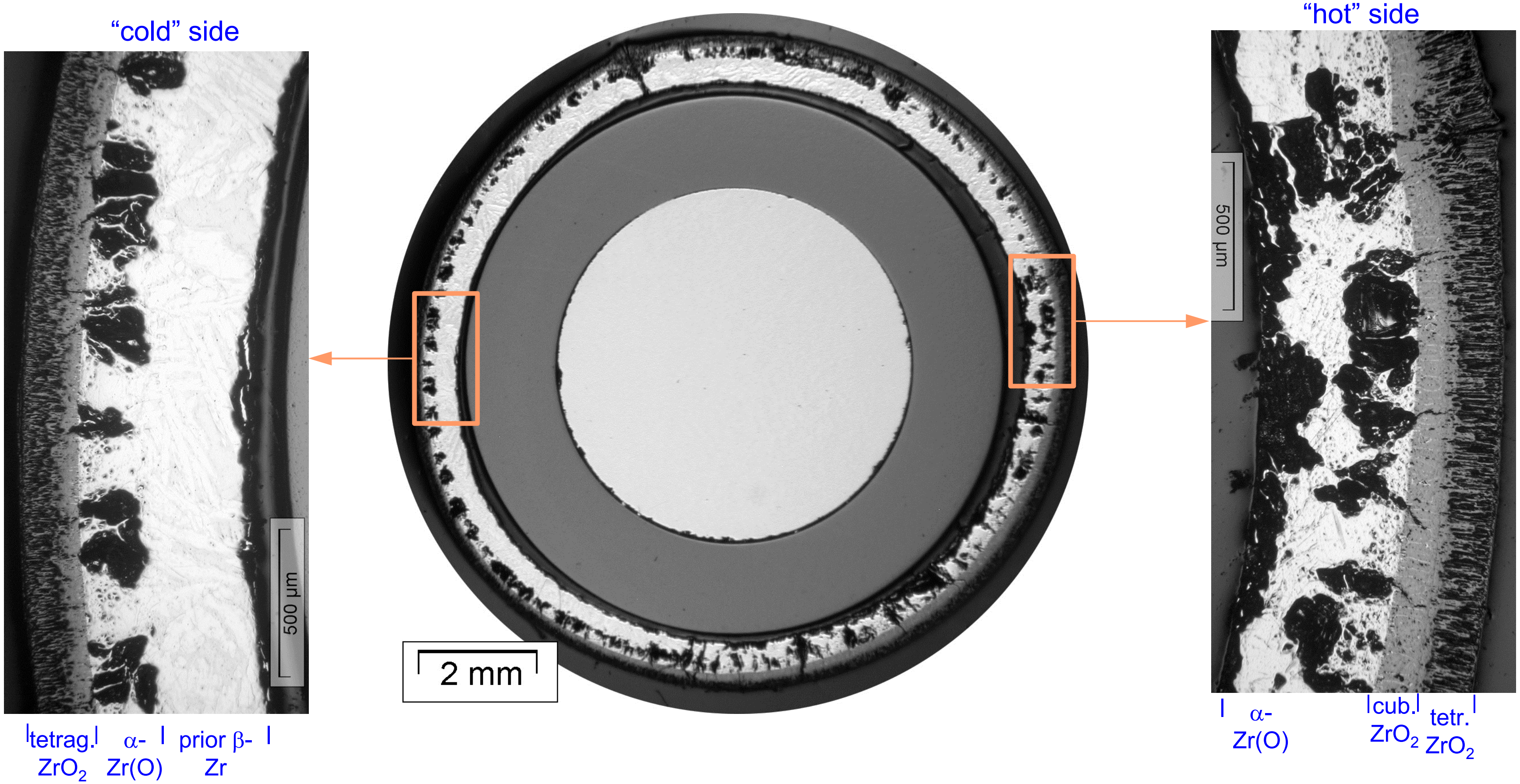
Re-oxidation of nitrided scales and metal melting at elevation 850 mm

rod #6 | rod #18



Elevation 950 mm: no nitrides, no melt formation

rod #8



SUMMARY

• Three typical features of QUENCH-16: moderate pre-oxidation to 135 µm of oxide layer (instead 500 µm for QUENCH-10), a long period of oxygen starvation during the air ingress phase (800 s instead 80 s for QUENCH-10), and reflood initiation at temperatures significantly below the melting point of the cladding (1700 K instead of 2200 K for QUENCH-10).

• A partial consumption of nitrogen during the oxygen starvation, accompanied by acceleration of the temperature increase at mid bundle elevations, caused the formation of porous zirconium nitrides inside the oxide layer at bundle elevations between 350 and 850 mm.

• Immediate temperature escalations to 2420 K after reflood initiation were caused by massive steam penetration through the porous oxide/nitride scales and intensive reaction with nitrides and especially with metallic cladding. The cooling phase to the final quench lasted ca. 500 s after achievement of peak temperature.

• 24 g nitrogen from 29 g, consumed during oxygen starvation period, were released during the quench phase. This quantity of released nitrogen corresponds to 7 g hydrogen developed during re-oxidation of nitrides.

• Image analysis of frozen Zr-O melt regions, formed during reflood, allows estimating the hydrogen release due to melt oxidation to 25 g.

• The main part of hydrogen production during reflood (96 g) was released due to secondary cladding oxidation by steam penetrated through the porous re-oxidized nitrides.

• The total hydrogen production during QUENCH-16 was higher compared to QUENCH-10, i.e., 144 g (QUENCH-10: 53 g), 128 g of which were released during reflood (QUENCH-10: 5 g).

Acknowledgement

The QUENCH-16 test was performed in framework of the LACOMECO program at KIT with financial support from the HGF Program NUKLEAR and the European Commission

Thank you for your attention

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