Karlsruhe Institute of Technology

Institute for Applied Materials

Experimental results of the QUENCH-16 bundle tests on air ingress, performed within the framework of the LACOMECO project

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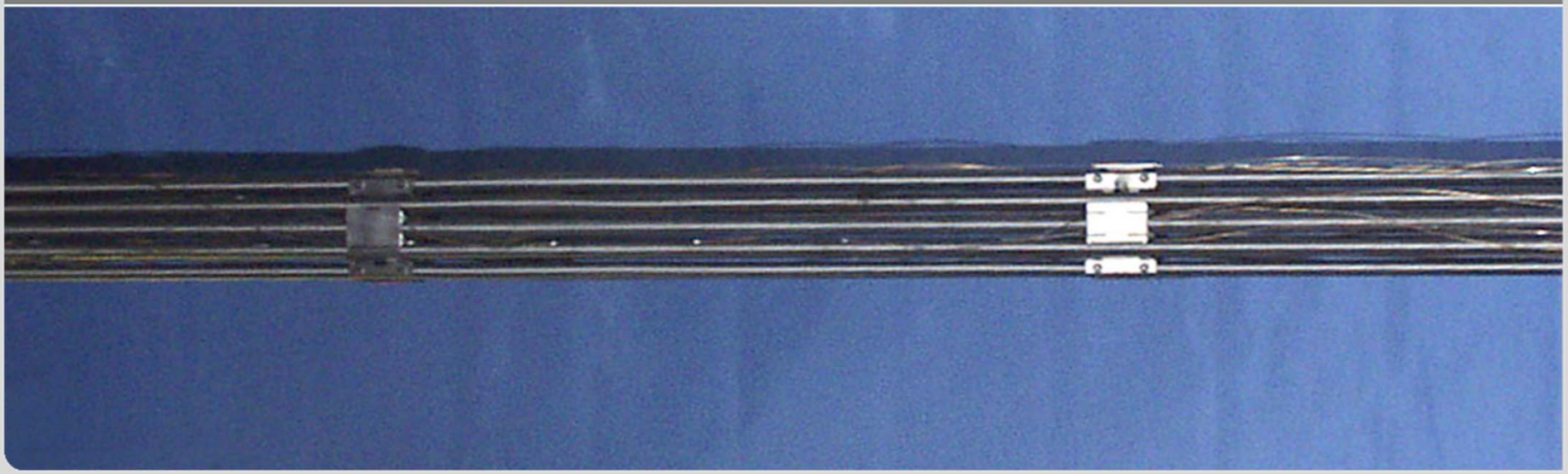
17th QUENCH Workshop, Karlsruhe

Institute for Applied Materials, IAM-WPT; Program NUKLEAR



Consequences of possible air ingress into overheated fuel assembly:

- **acceleration in the cladding oxidation;**
- **fuel rod degradation;**
- **the release of some fission products, most notable ruthenium.**

Previous integral air ingress experiments:

- **AIT-1, AIT-2 performed 2003 at AEKI: *small bundles*;**
- **QUENCH-10 performed 2004 at KIT: *strong pre-oxidised bundle*;**
- **PARAMETER SF4 performed 2009 at LUCH/Podolsk*: very high temperatures on reflood initiation*.**

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;
- reflooding of oxidised and nitrided bundle by water initiated at temperatures well below the melting point of the cladding; release of nitrogen;
- release of hydrogen during reflood of oxidised and nitrited bundle.

QUENCH facility

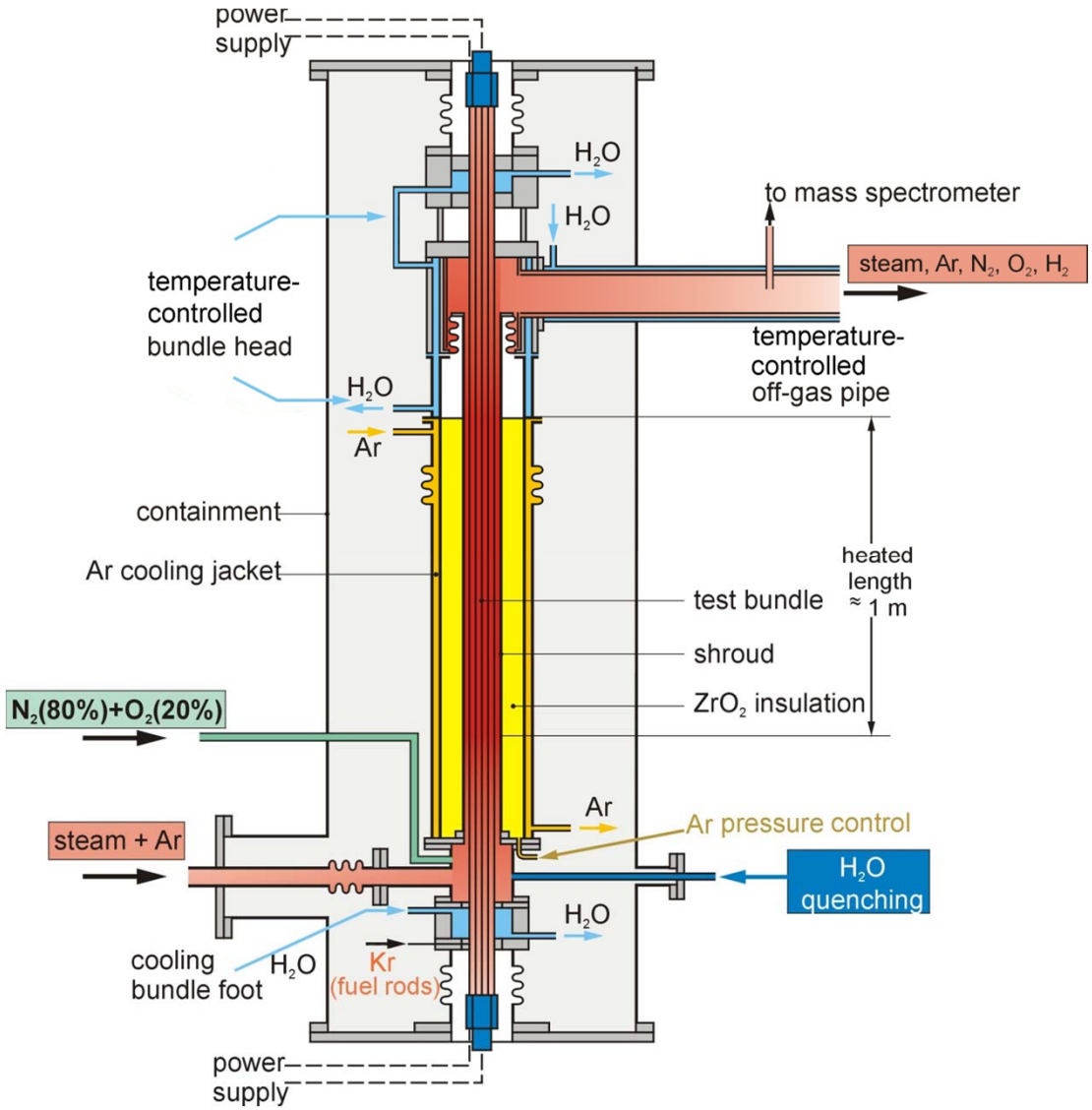
QUENCH-16 facility features:

1) controllable synthetic air input;

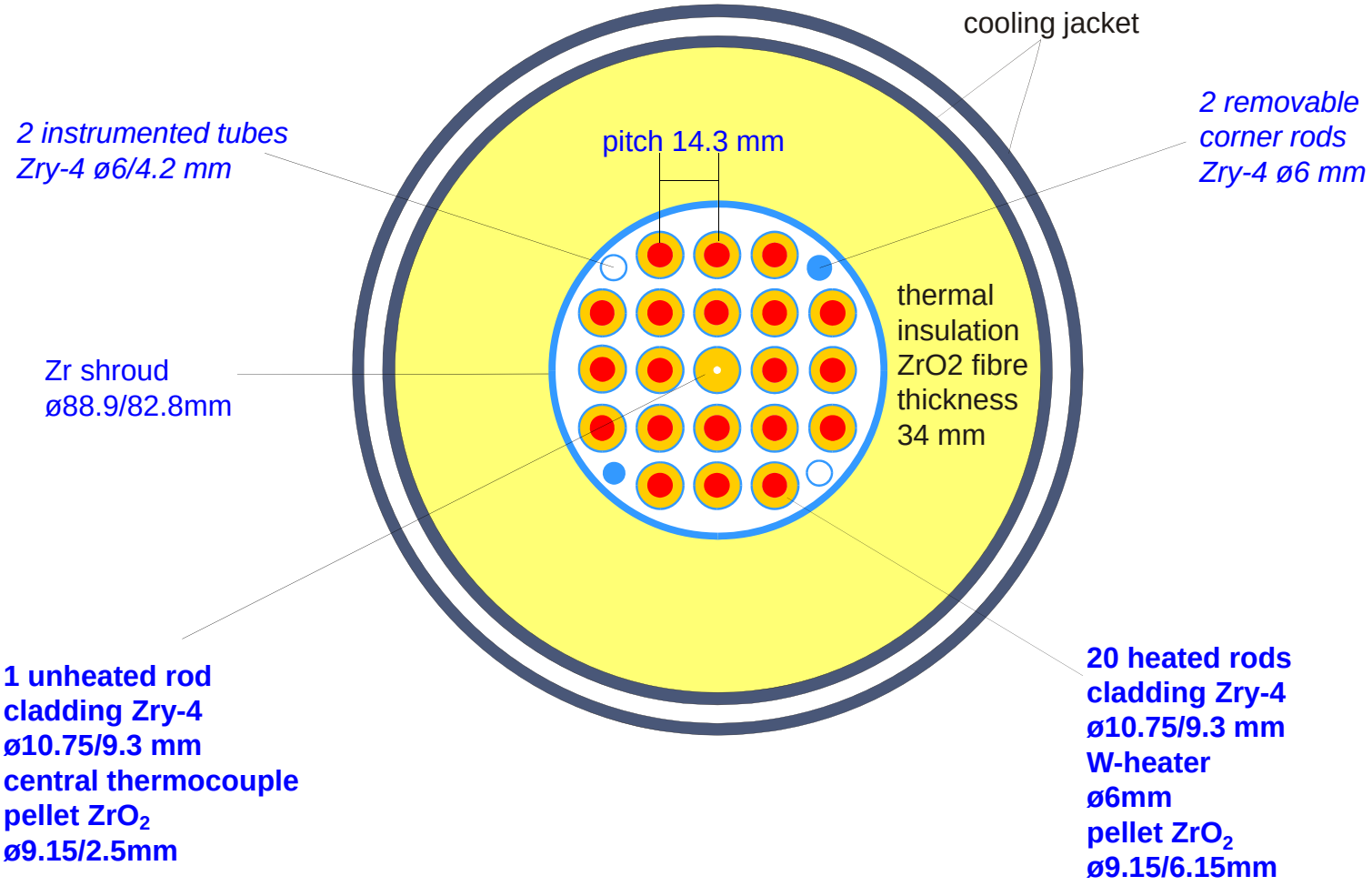
2) Krypton filling of rods;

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

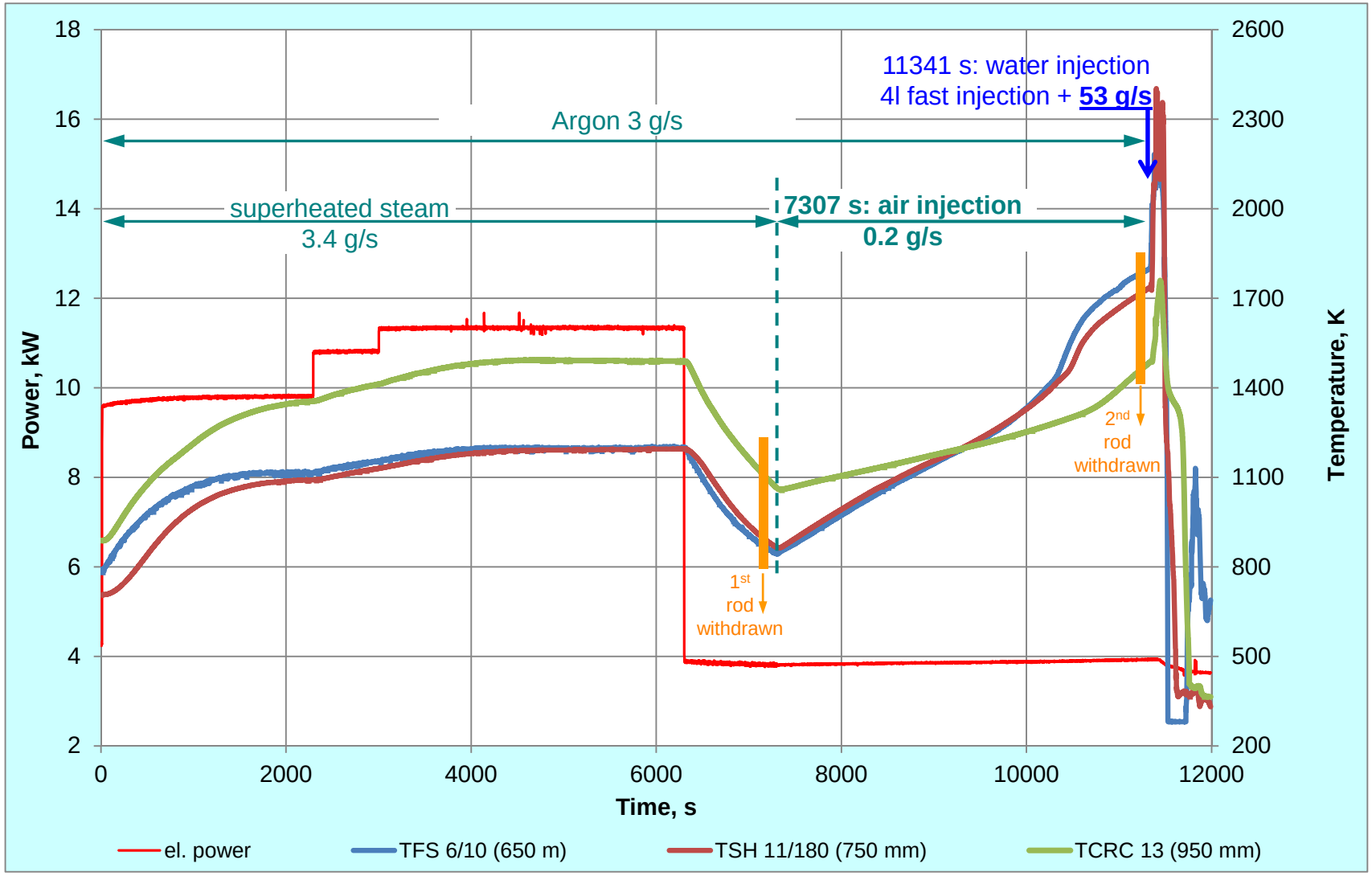


Mounting of high temperature thermocouples

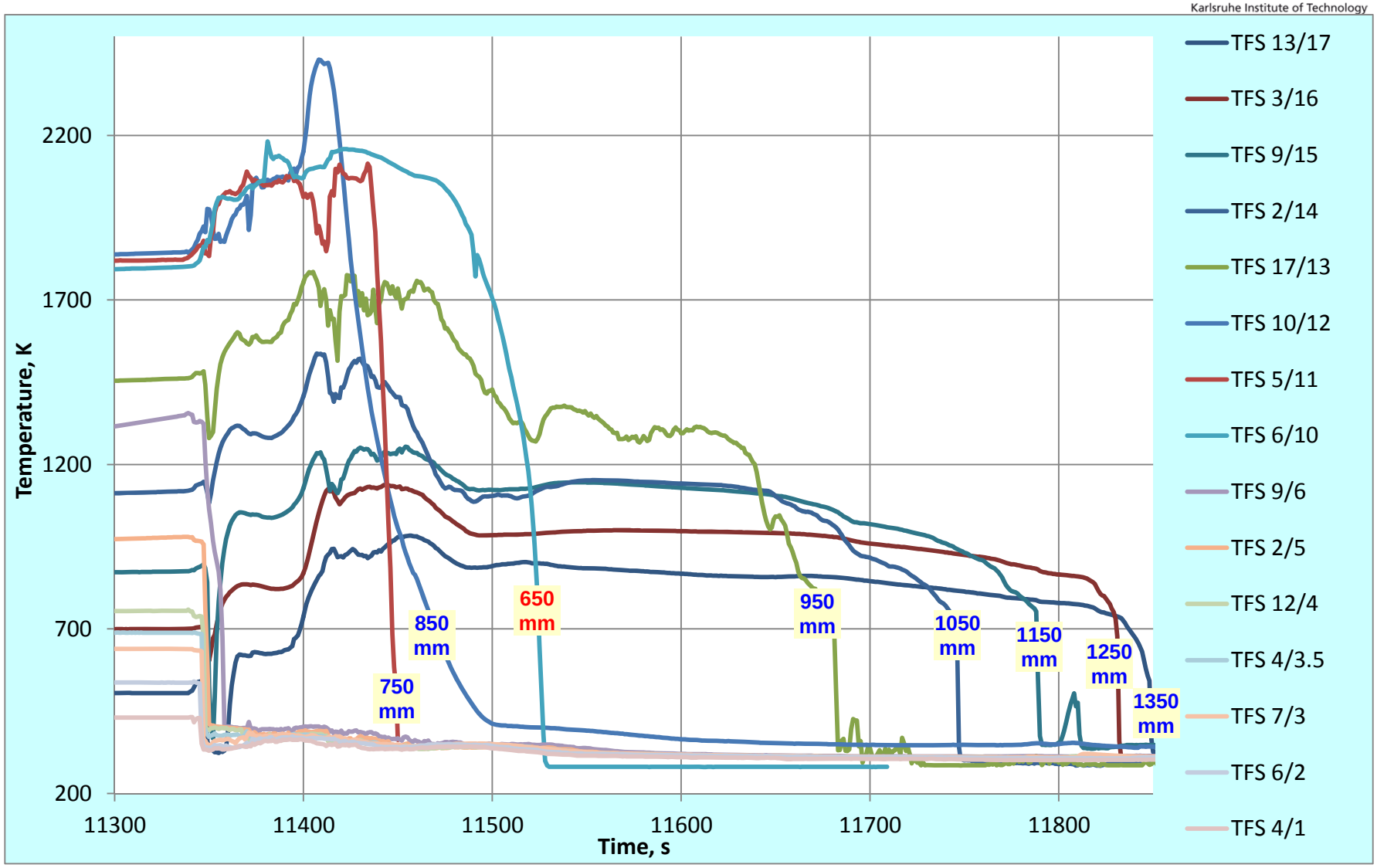
			
TC inserted from bundle bottom up to 850 mm	**TC inserted from bundle top above 850 mm**	**TC inserted from bundle top under GS4 (1150 mm)**	**TC installed at shroud**
Cladding surface thermocouples TFS			**Shroud thermocouples TSH**

QUENCH-16 test progression

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

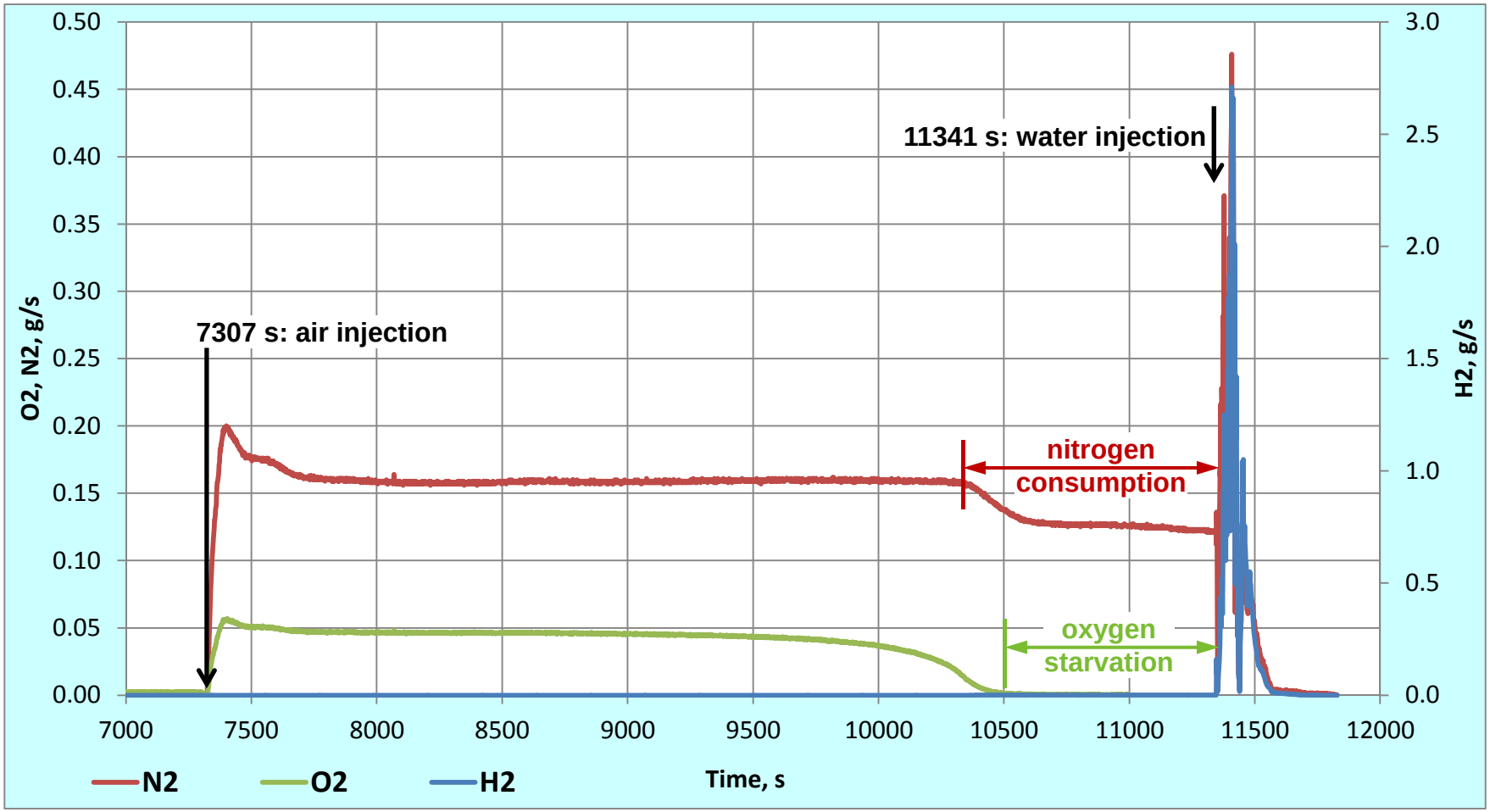


Temperature escalation and cooldown during reflood



Durations: escalation 100 s cooldown 400 s

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



oxygen uptake: 58 g

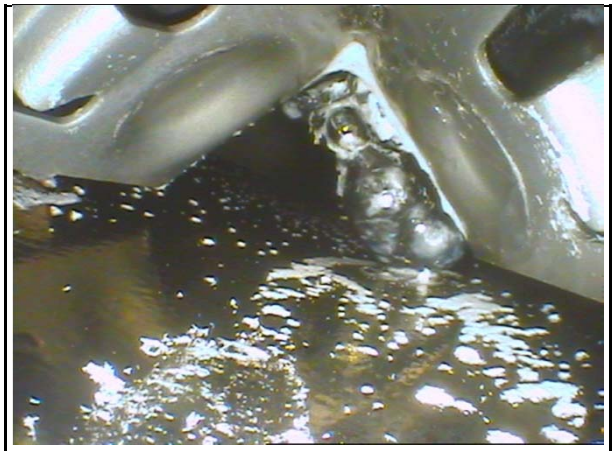
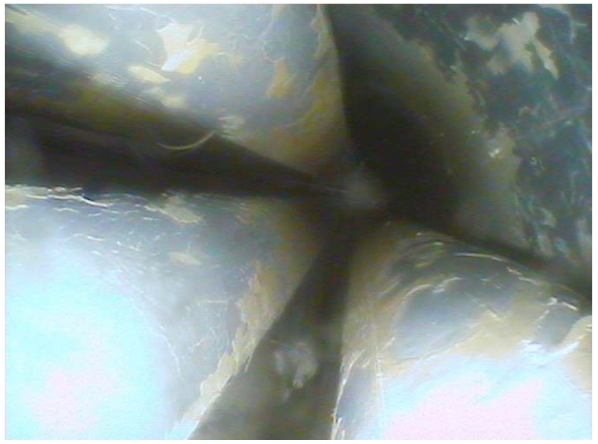
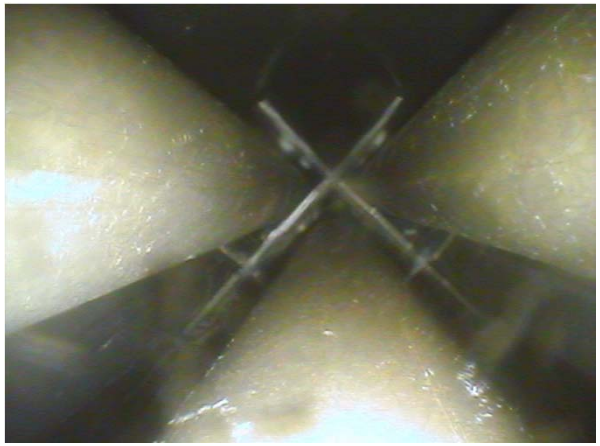
nitrogen uptake: 29 g

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

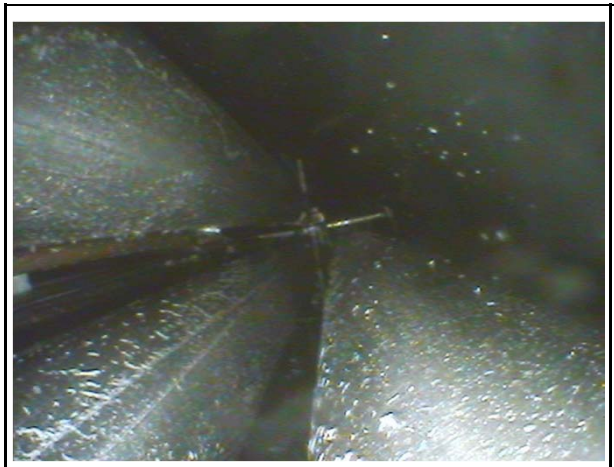
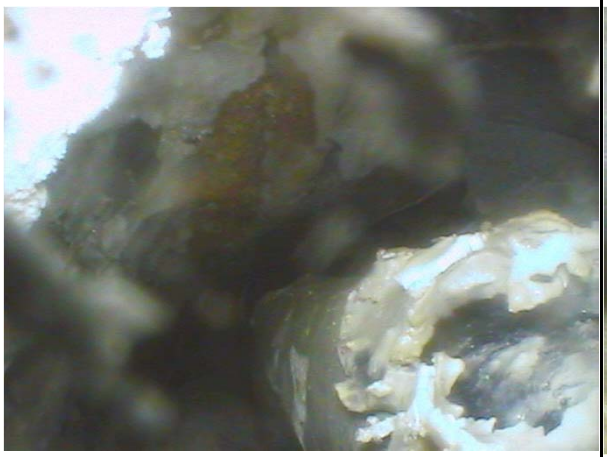
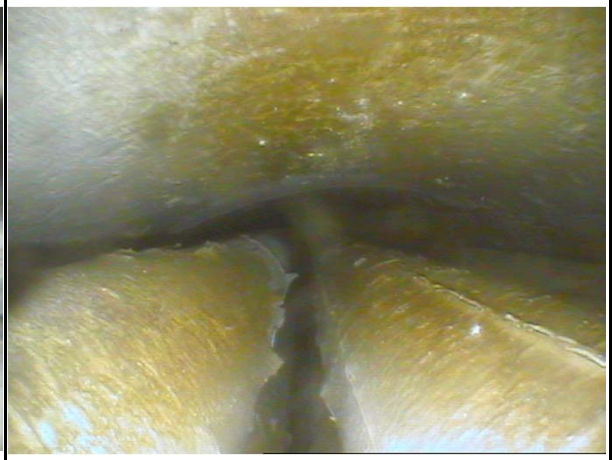
hydrogen release: 128 g. Two main sources: 1) melt oxidation; 2) re-oxidation of Zr-nitrides

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

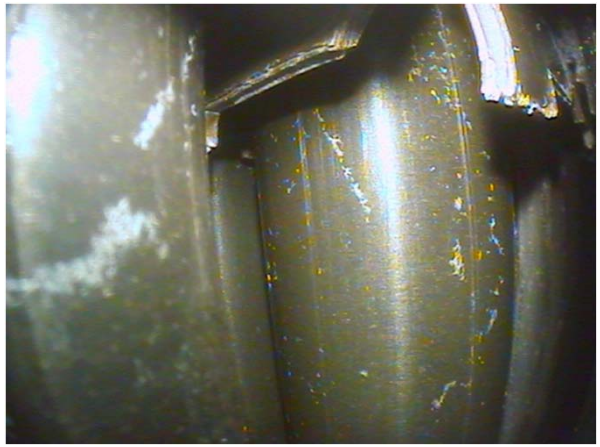
Post-test visual investigations by endoscope introduced at the position of the corner rod B: front view

		
Grid spacer #1 at -60 mm: frozen melt relocated from upper elevations	350 mm: oxide cracks; between rods – melt relocated from upper elevations	650 mm: absence of upper spalled oxide scales
		
950 mm: spalling of coloured (yellow) surface layer of claddings	1050 mm: coloured (yellow) surface layer of claddings	1150 mm: intact dark oxidised surface of claddings

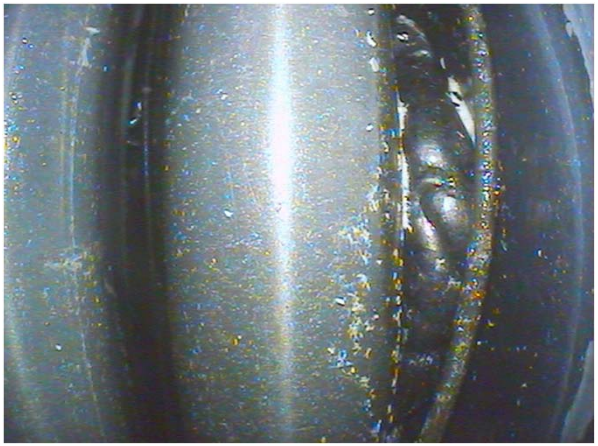
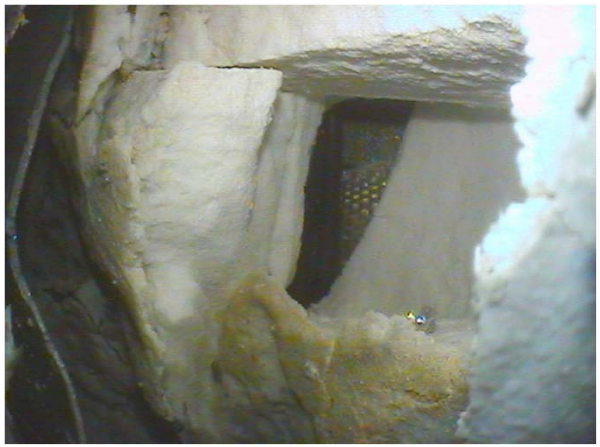
Post-test visual investigations by endoscope introduced at the position of the corner rod D: front view

		
0 mm: relocated small oxidised debris adhered to surface of lightly oxidised claddings	400 mm: breakup of cladding pieces	450 mm: cracks going through the oxidised cladding; piece of relocated oxidised GS#3
		
600 mm: cladding melted through	700 mm: spalling of yellowed ZrO2 scales from oxide layer	1000 mm: spalling of yellowed ZrO2 scales from oxide layer

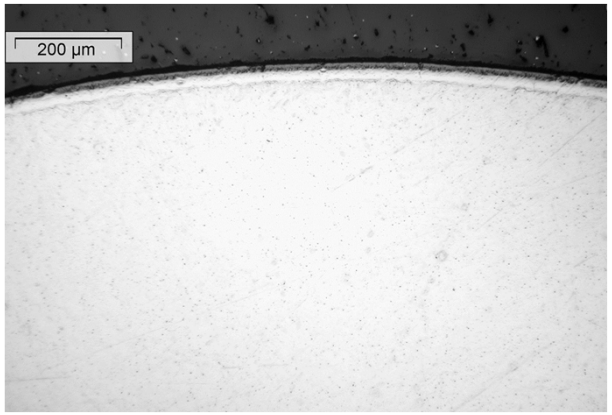
Post-test visual investigations by endoscope introduced at the position of the corner rod B: side view

		
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

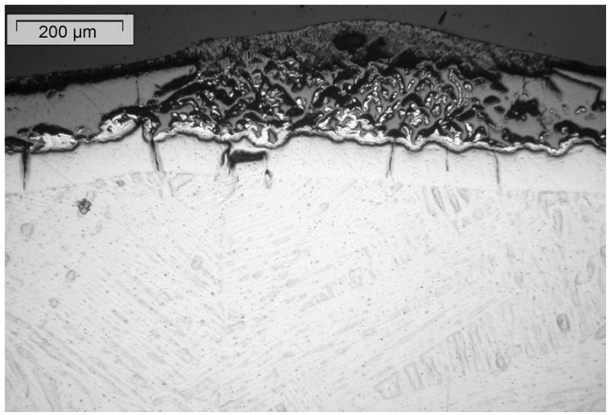
Post-test visual investigations by endoscope introduced at the position of the corner rod D: side view

		
215 mm: frozen melt relocated from upper elevations	400 mm: frozen melt between rods	550 mm: ZrO2 insulation damage under failed shroud
		
600 mm: damaging of cladding due to influence of melt	775 mm: spalling of outer oxide scales	1050 mm: dark oxide of claddings, intact Grid Spacer #4

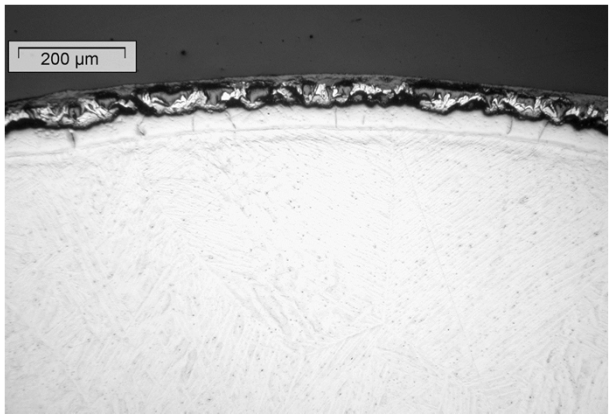
Corner rod D withdrawn from the bundle on the end of the air ingress phase: nitride formation between 300 and 900 mm



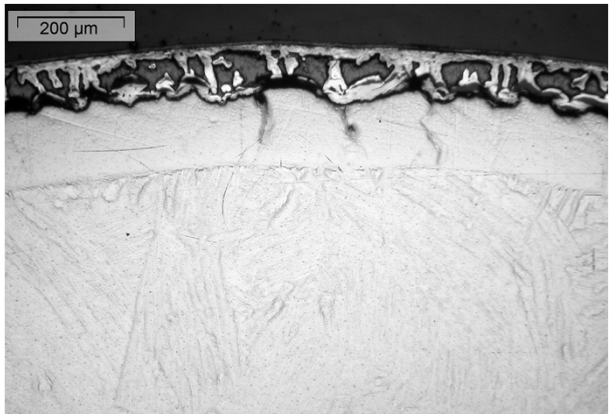
250 mm: several nitrides



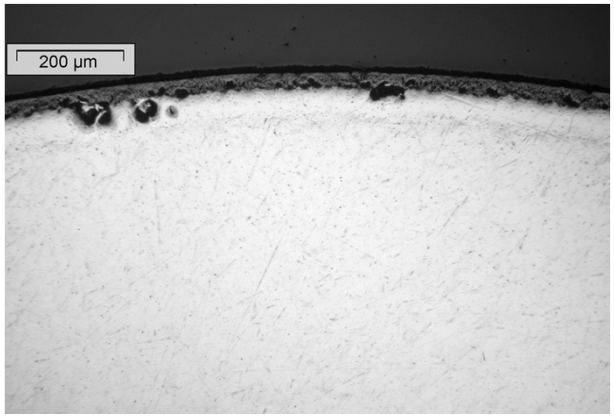
450 mm: nitrides



650 mm: nitrides

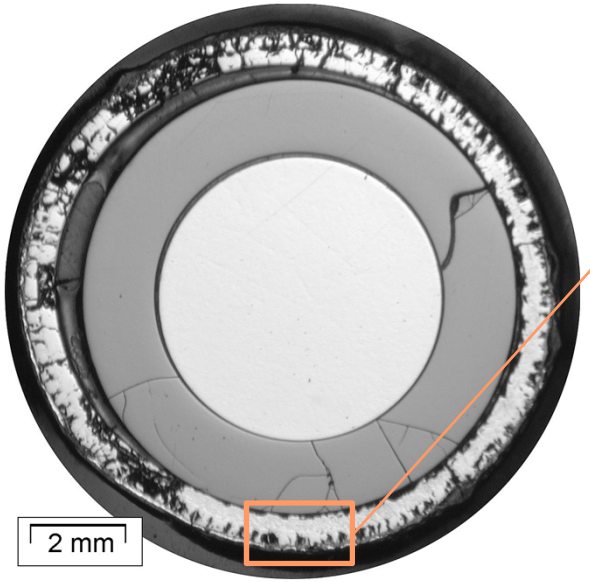


850 mm: nitrides

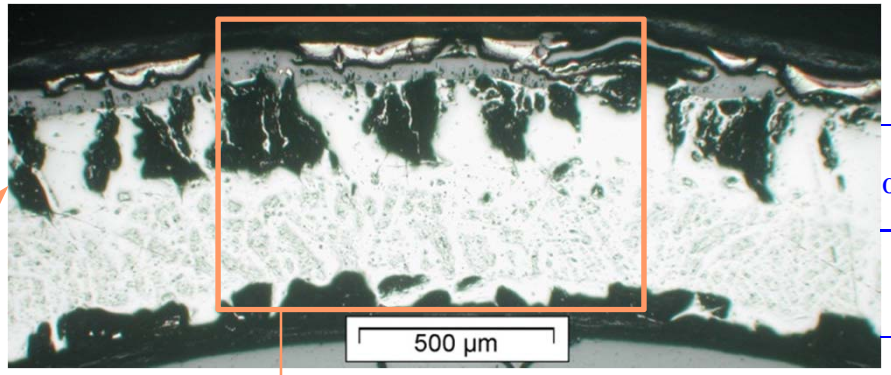


1050 mm: no nitrides

Formation of nitrides at elevation 350 mm

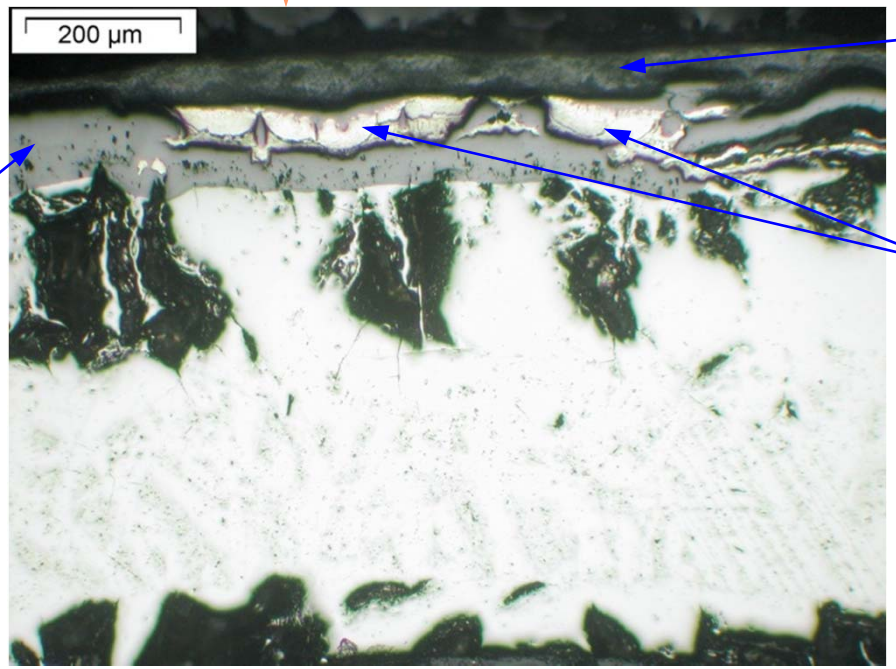


rod #5



α-Zr

prior β-Zr

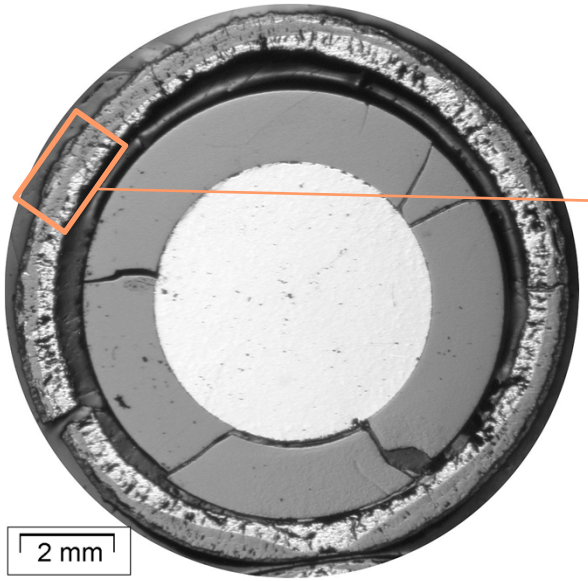


porous oxide scale (re-oxidised during quench)

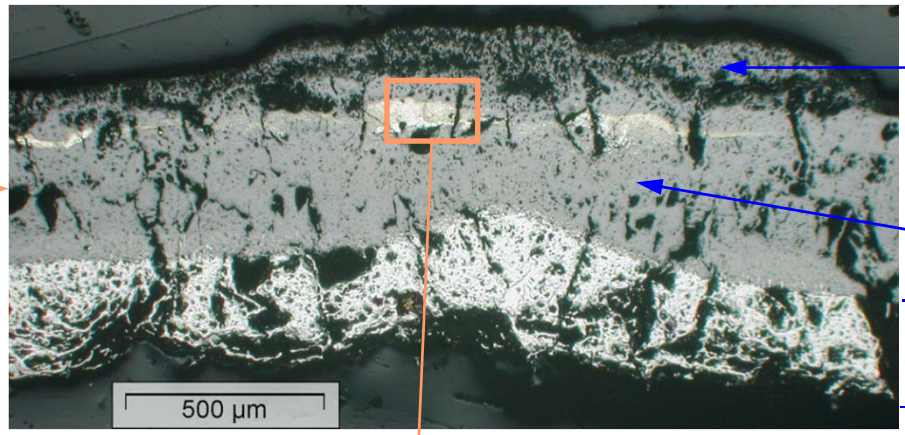
Zr-nitrides

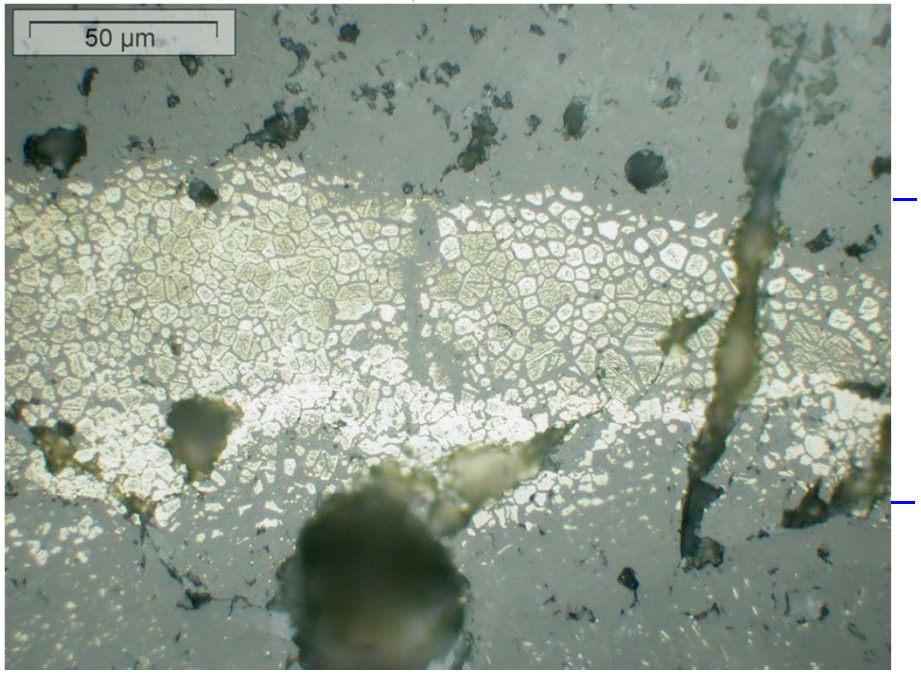
dense inner oxide (grown during quench phase)

Formation of nitrides at elevation 450 mm



rod #4





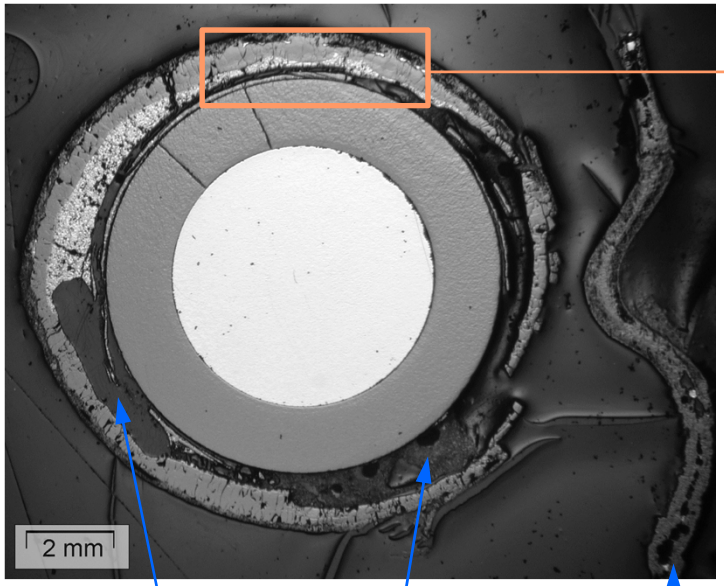
porous oxide scale (re-oxidised during quench)

dense inner oxide (grown during quench phase)

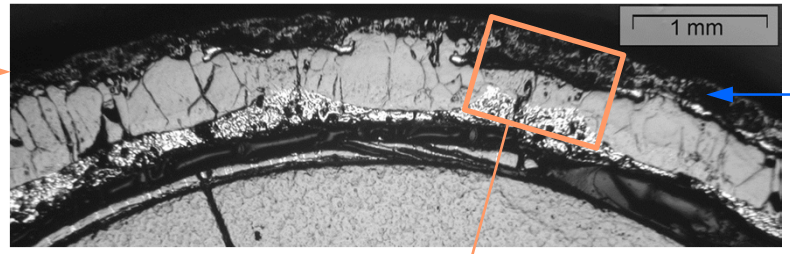
α-Zr(O)

Zr-nitrides

Nitrides and melting at elevation 550 mm

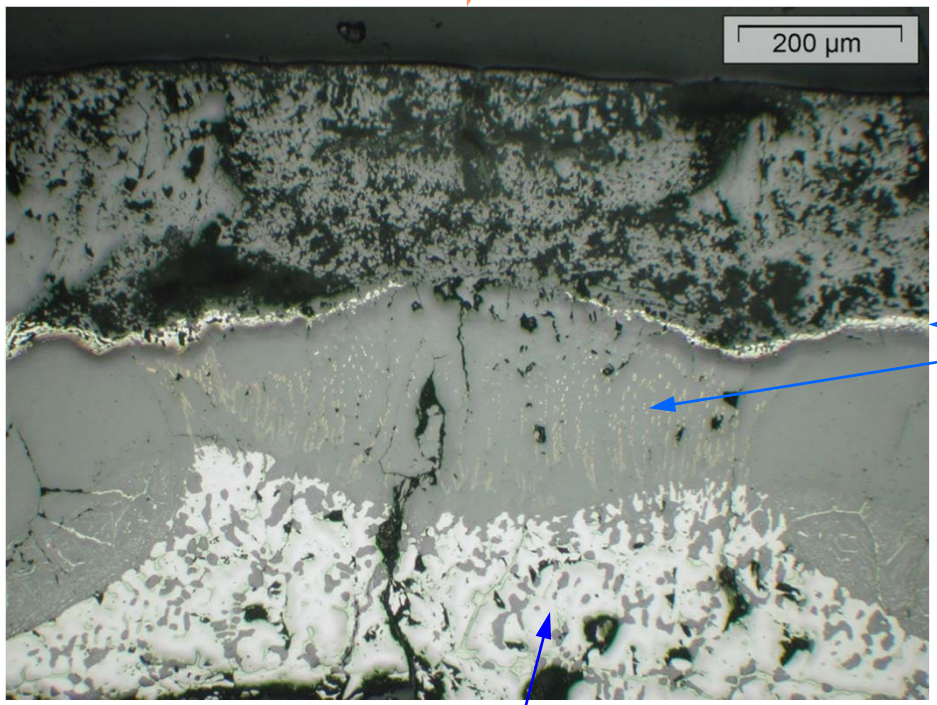


rod #9



porous outer oxide scale

completely oxidised Zry grid spacer

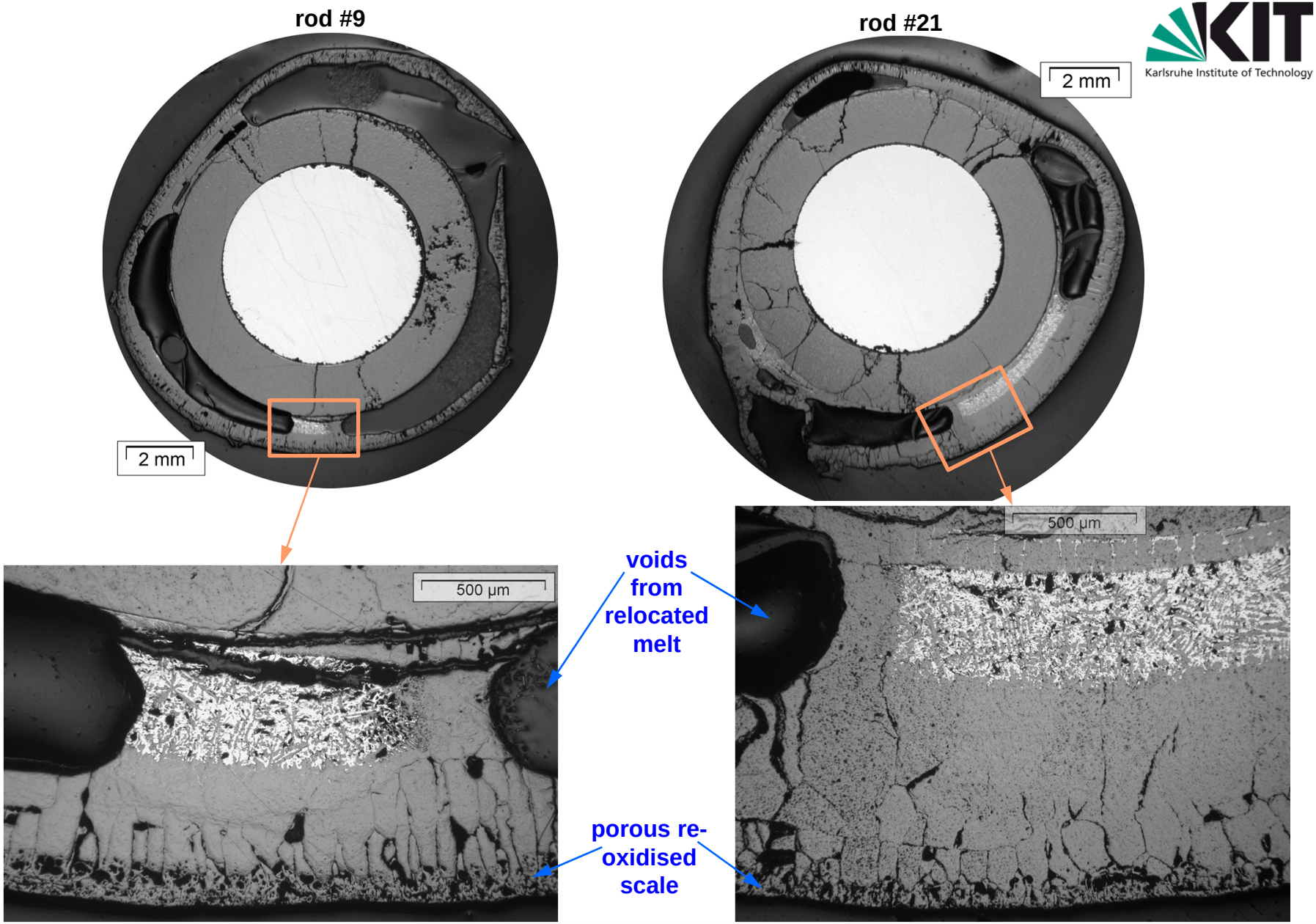


Zr-nitrides

voids from downwards relocated melt

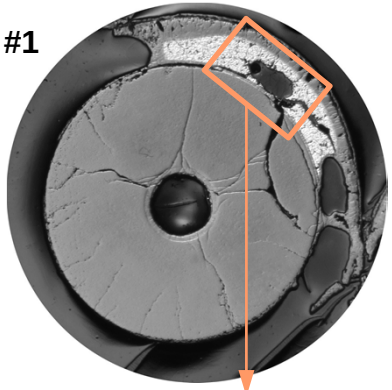
frozen partially oxidised melt

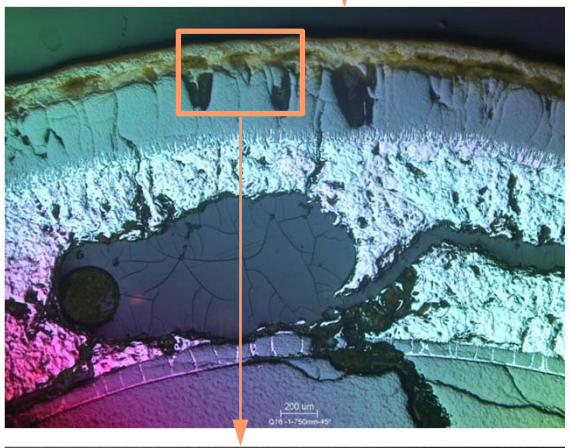
Thin re-oxidised outer scale and intensive metal melting at elevation 650 mm

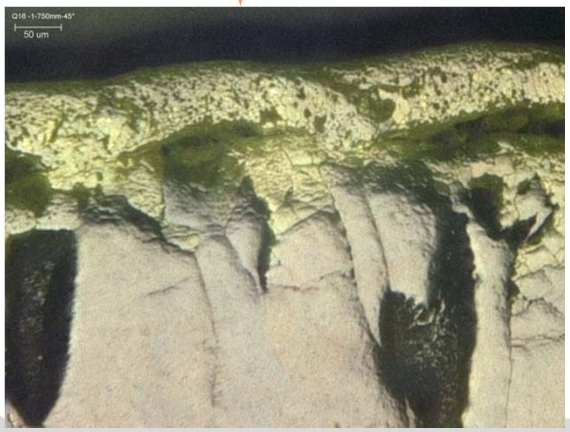


Spalling of re-oxidised scales at elevation 750 mm

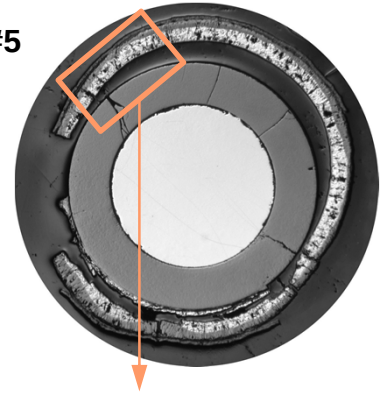
rod #1

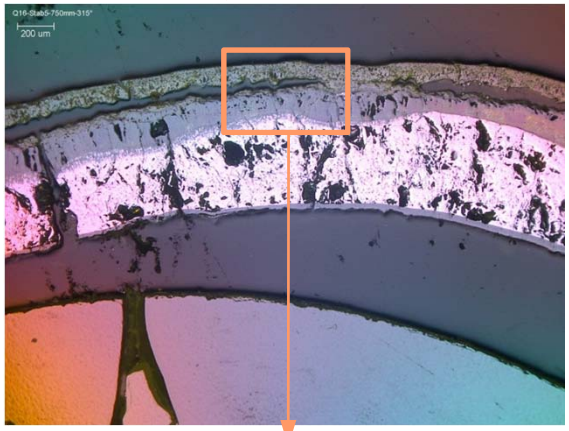




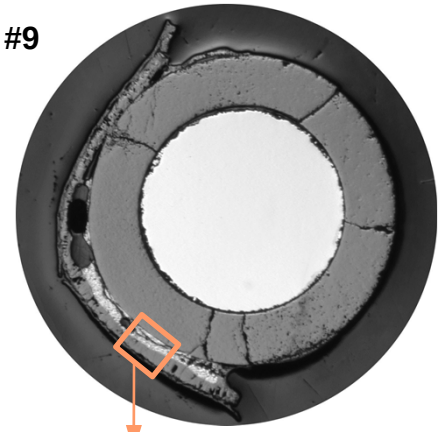


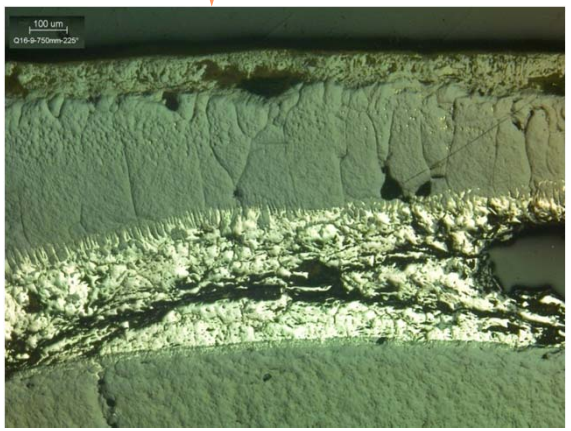
rod #5





rod #9



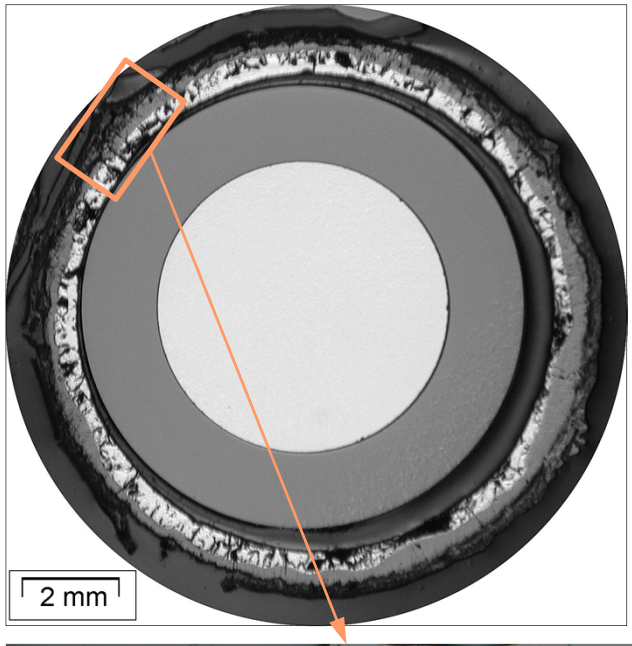


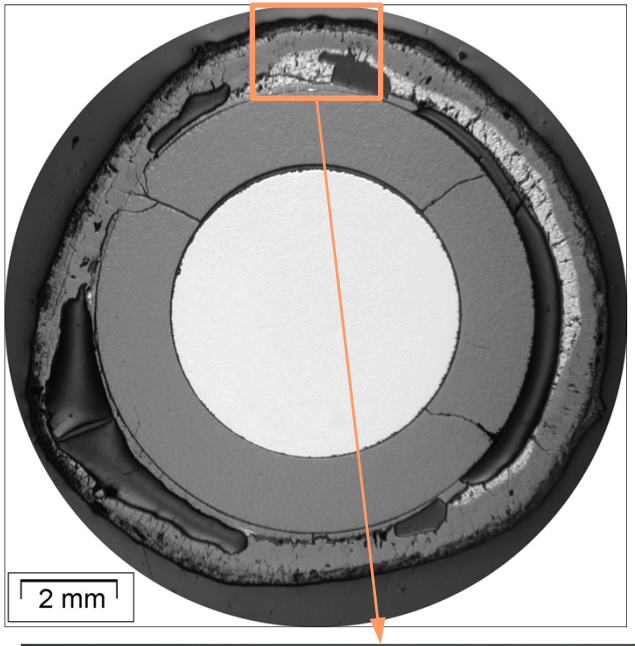
prior nitrided scale
re-oxidised during quench
and spalled from internal ZrO2 layer
growing during quench

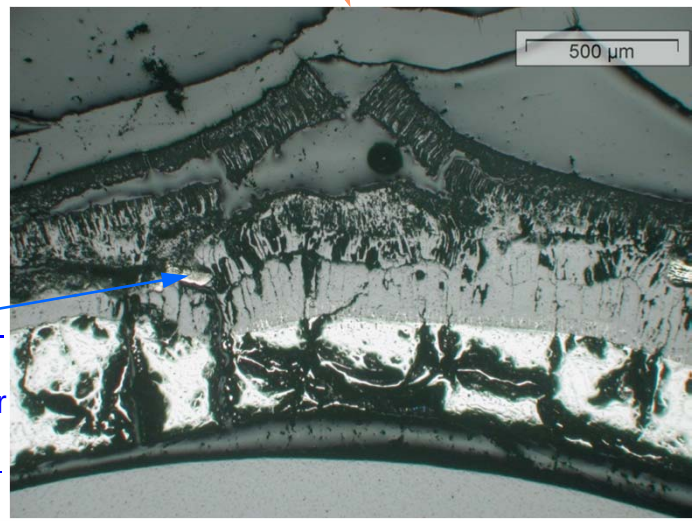
Re-oxidation of nitrided scales and metal melting at elevation 850 mm

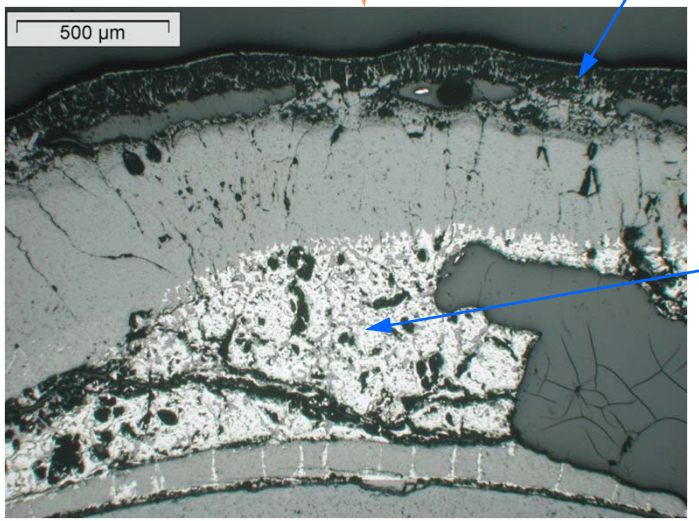
rod #6

rod #18









porous scale (re-oxidised during quench)

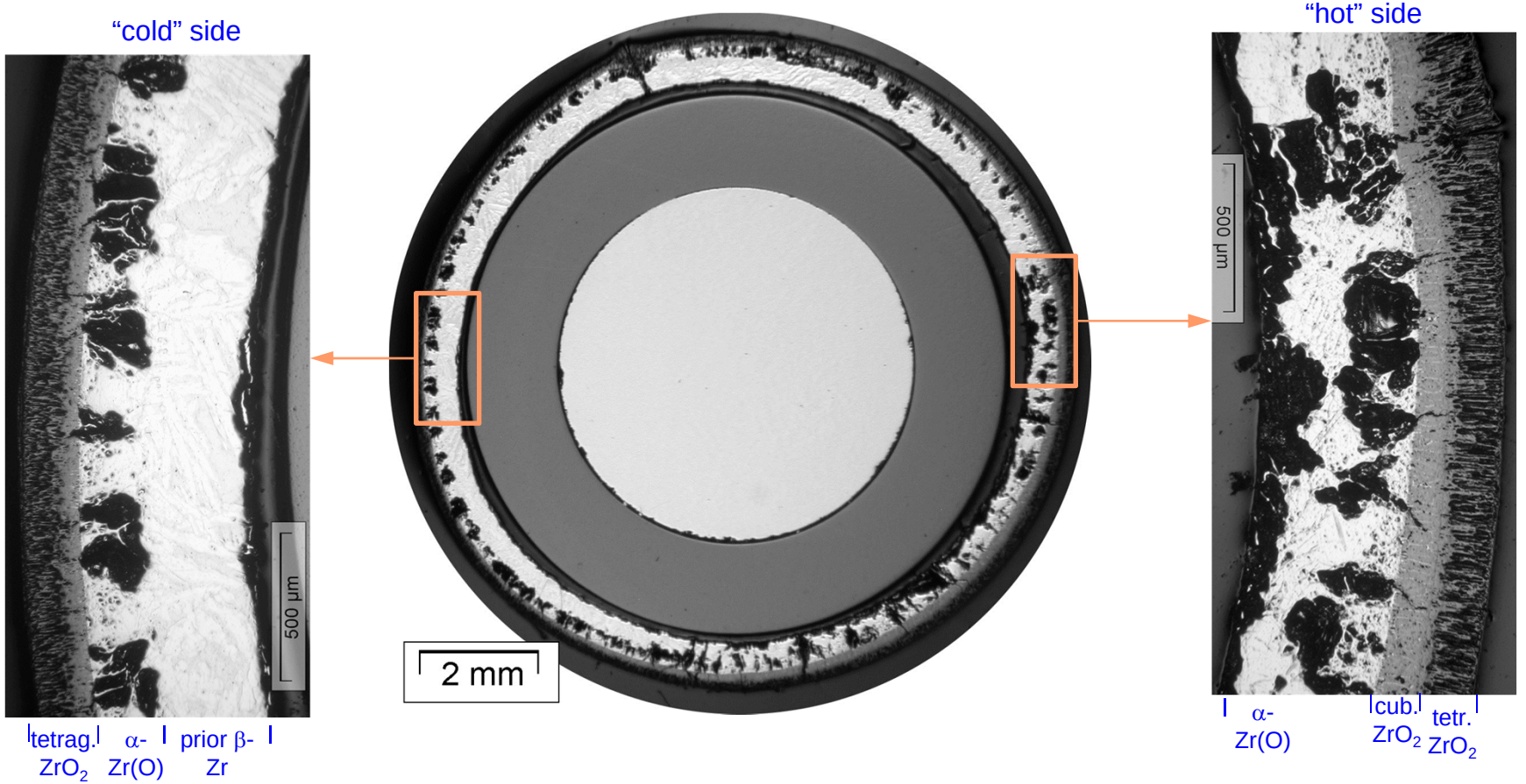
Zr-nitrides

α-Zr

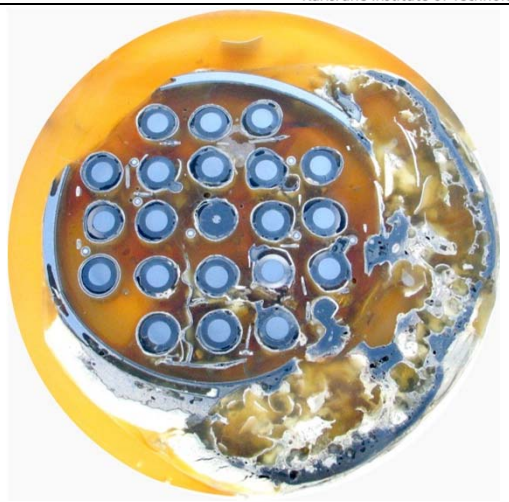
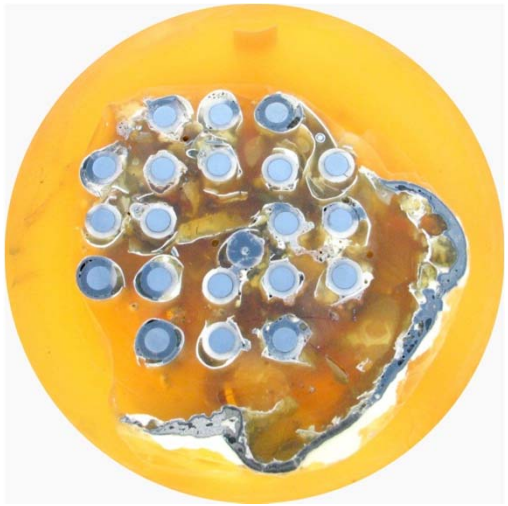
frozen partially oxidised melt

Elevation 950 mm: no nitrides, no melt formation

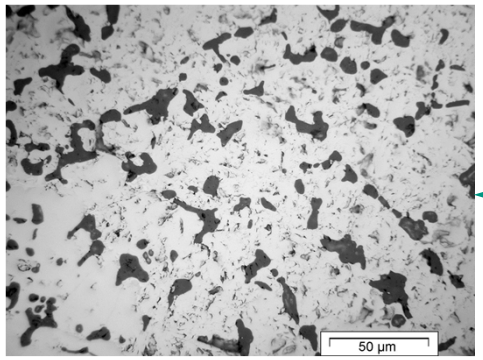
rod #8



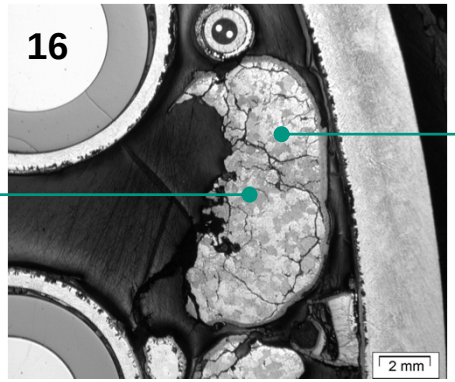
Bundle cross sections

		
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

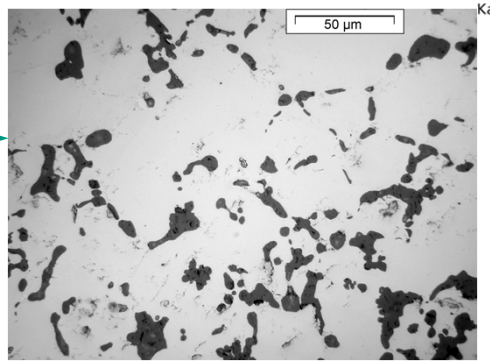
Frozen melt at elevation 350 mm: not oxidised and oxidised melt



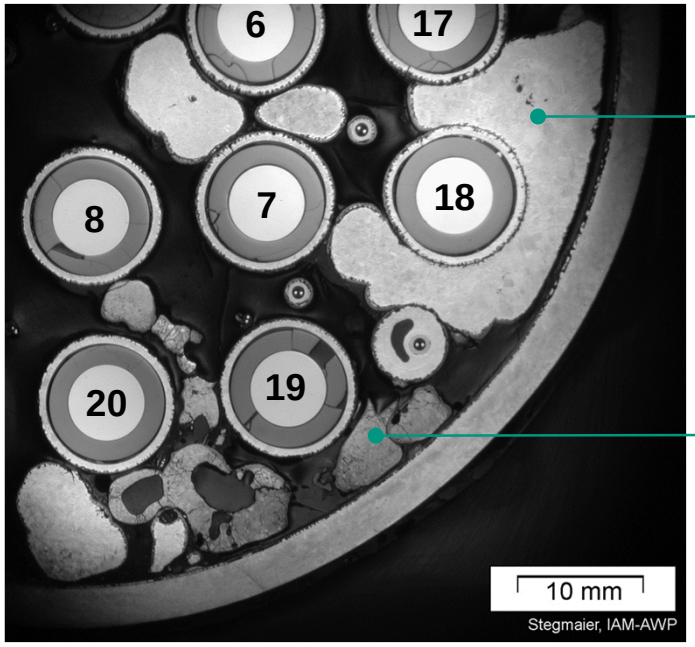
grey porous region; **precipitates 10% -> 8 wt% oxygen**

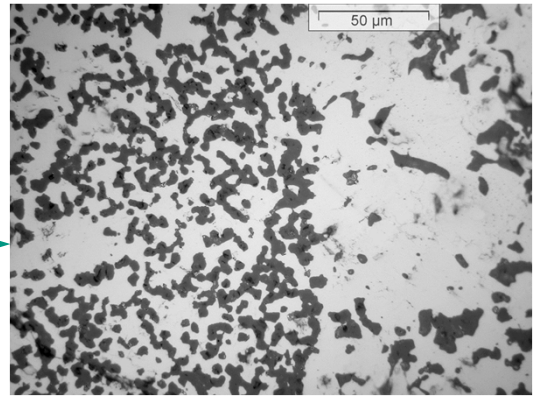


grey and light melt regions

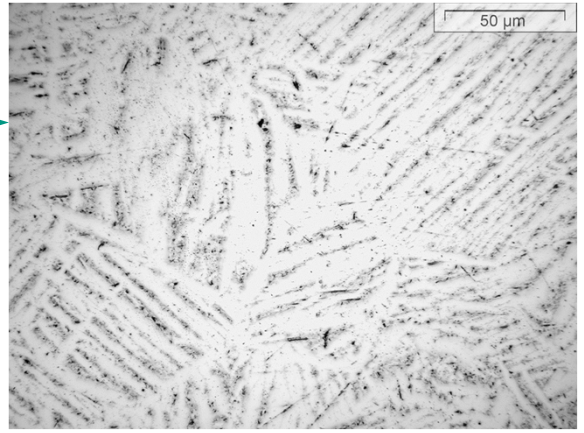


light non porous region; **precipitates 10% -> 8 wt% oxygen**



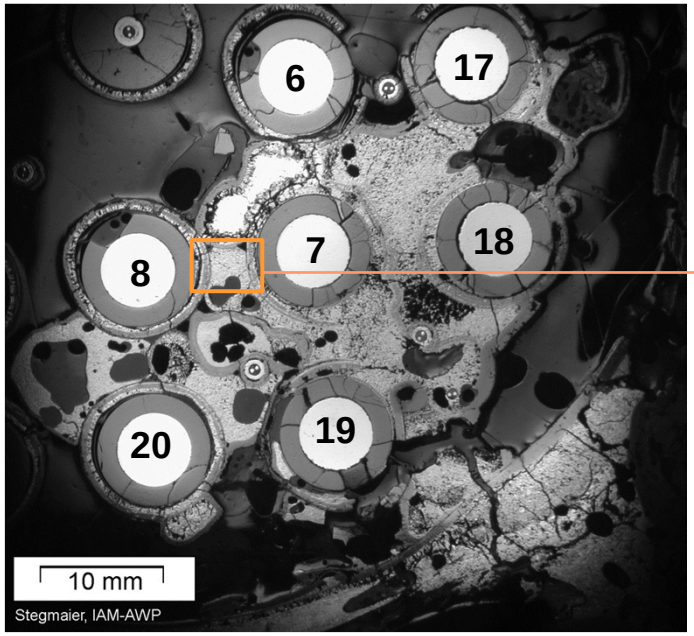


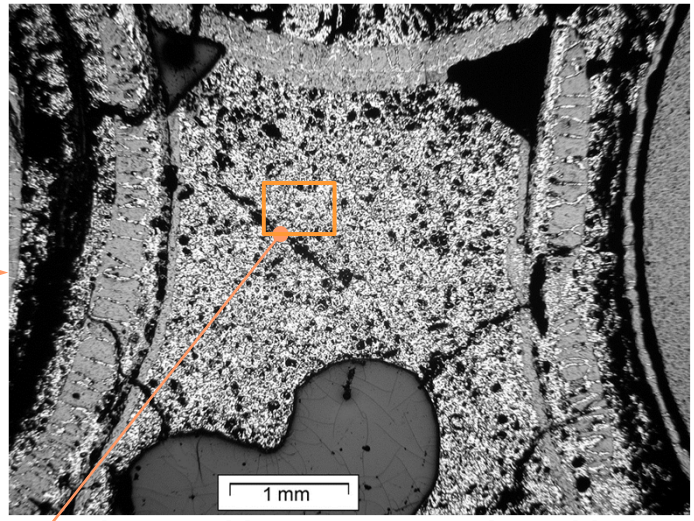
precipitates part 20% -> 10 wt% oxygen



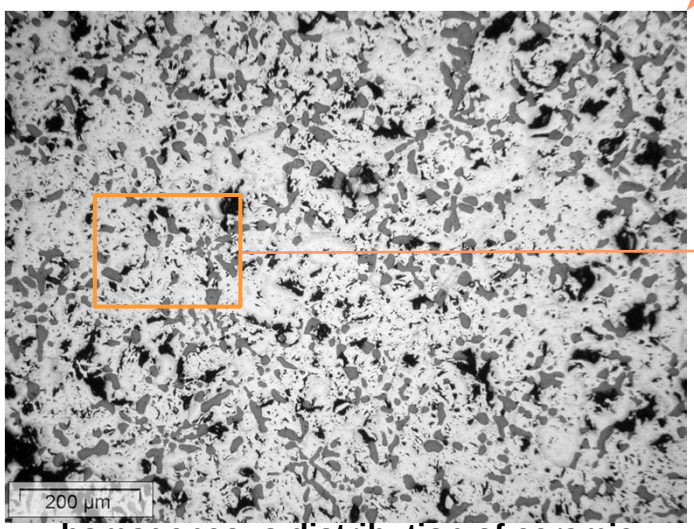
Widmanstätten pattern of frozen metallic melt

Frozen melt at elevation 450 mm: mostly oxidised melt

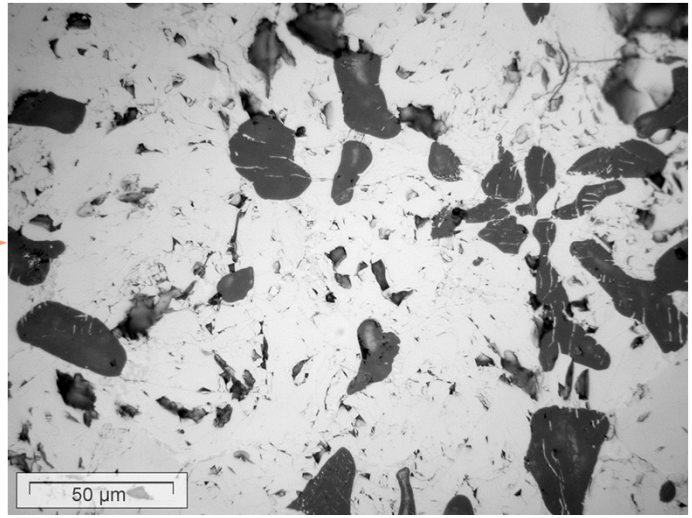




molten pool between two rods: oxidation at melt periphery and ceramic precipitates inside melt



homogeneous distribution of ceramic precipitates in the melt



precipitates part 28% -> 11.5 wt% oxygen

SUMMARY

• The QUENCH-16 bundle test with Zry-4 cladding was performed in six stages: 1. Stabilisation at 600°C, 2. Transient to 1300 K during 2300 s, 3. Pre-oxidation at T_{PCT}=1300-1430 K during 4000 s, 4. Cooling to 1000 K during 1000 s (to increase duration of air ingress phase), 5. Air ingress with transient heat-up during 4040 s, 6. Quench.

• Maximal oxide thickness before air ingress 130 µm (measured on withdrawn corner rod).

• The last 835 s of air ingress phase correspond oxygen starvation and partially consumption of nitrogen and accompanied by acceleration of the temperature increase at mid bundle elevations.

• Immediate temperature escalation on reflood initiation, leading to maximum measured temperatures of about 2420 K. 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

• Significant quantity of hydrogen was generated during the reflood (128 g).

• Metallographic investigation of cross sections between 300 and 500 mm showed frozen partially oxidised melt, relocated from upper elevations 500 – 800 mm. The melt oxidation could have been the main source of hydrogen during reflood.

• Very high concentration of residual nitrides was observed at elevations 350 – 550 mm. Spalled oxide scales with a re-oxidised porous structure were observed at elevations between 350 and 850 mm.

Acknowledgements

Ms. Peters for photography and microscopy

Ms. J. Laier for processing the test data

Thank you for your attention

http://www.iam.kit.edu/wpt/english/471.php/
http://quench.forschung.kit.edu/