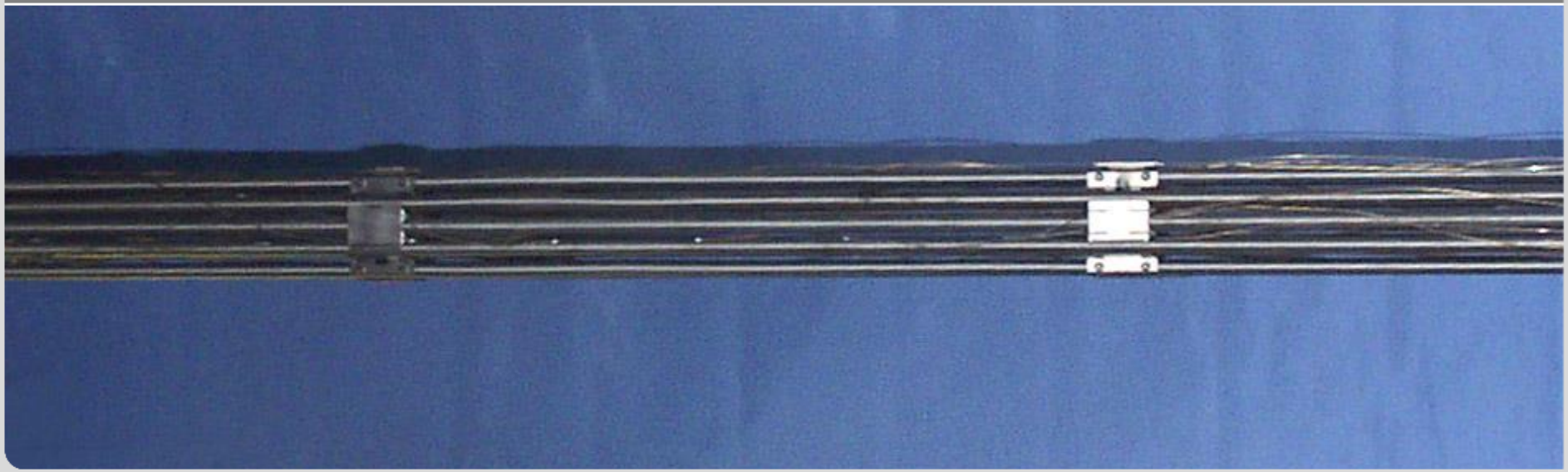
Karlsruhe Institute of Technology

Institute for Applied Materials

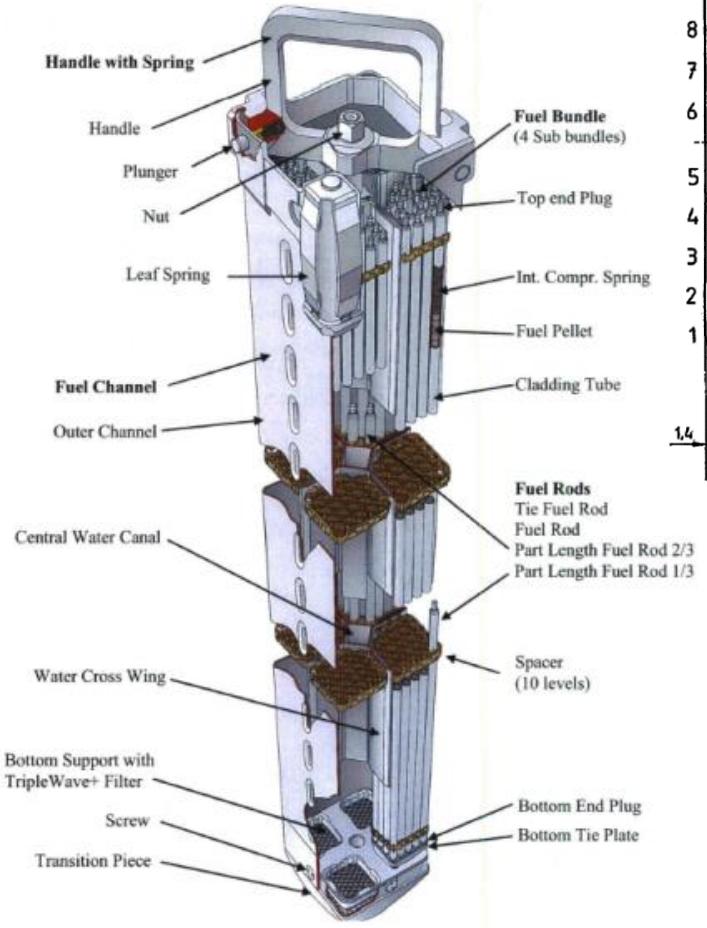
Results of metallographic analysis of the QUENCH-20 bundle with B_4C absorber

J. Stuckert, U. Peters, U. Stegmaier, M. Steinbrück

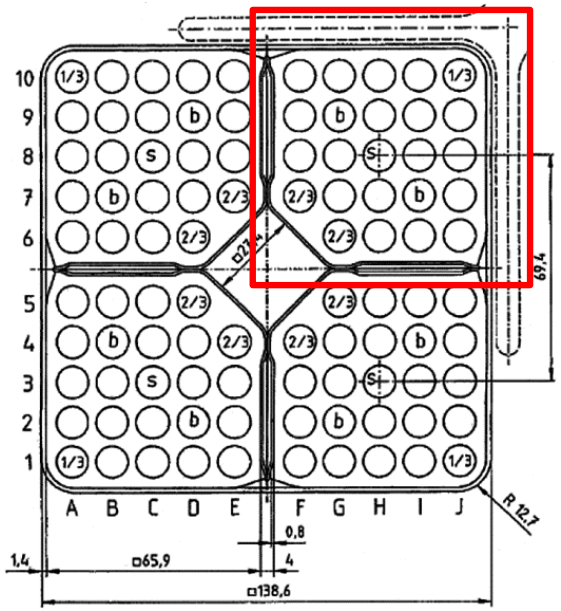
Institute for Applied Materials; Program NUSAFE



QUENCH-20 (SAFEST): Choice of BWR elements, which should be simulated during QUENCH-SAFEST

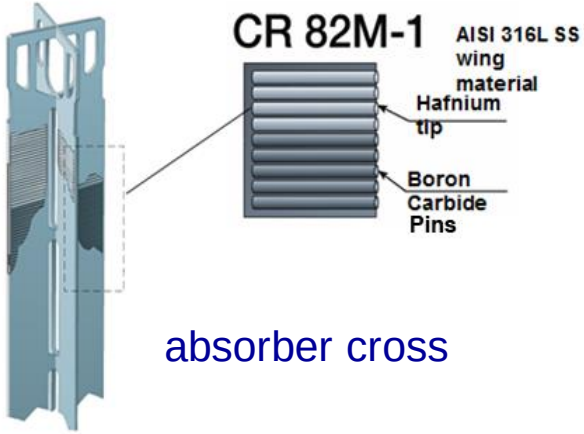


assembly SVEA-96 Optima



assembly cross section

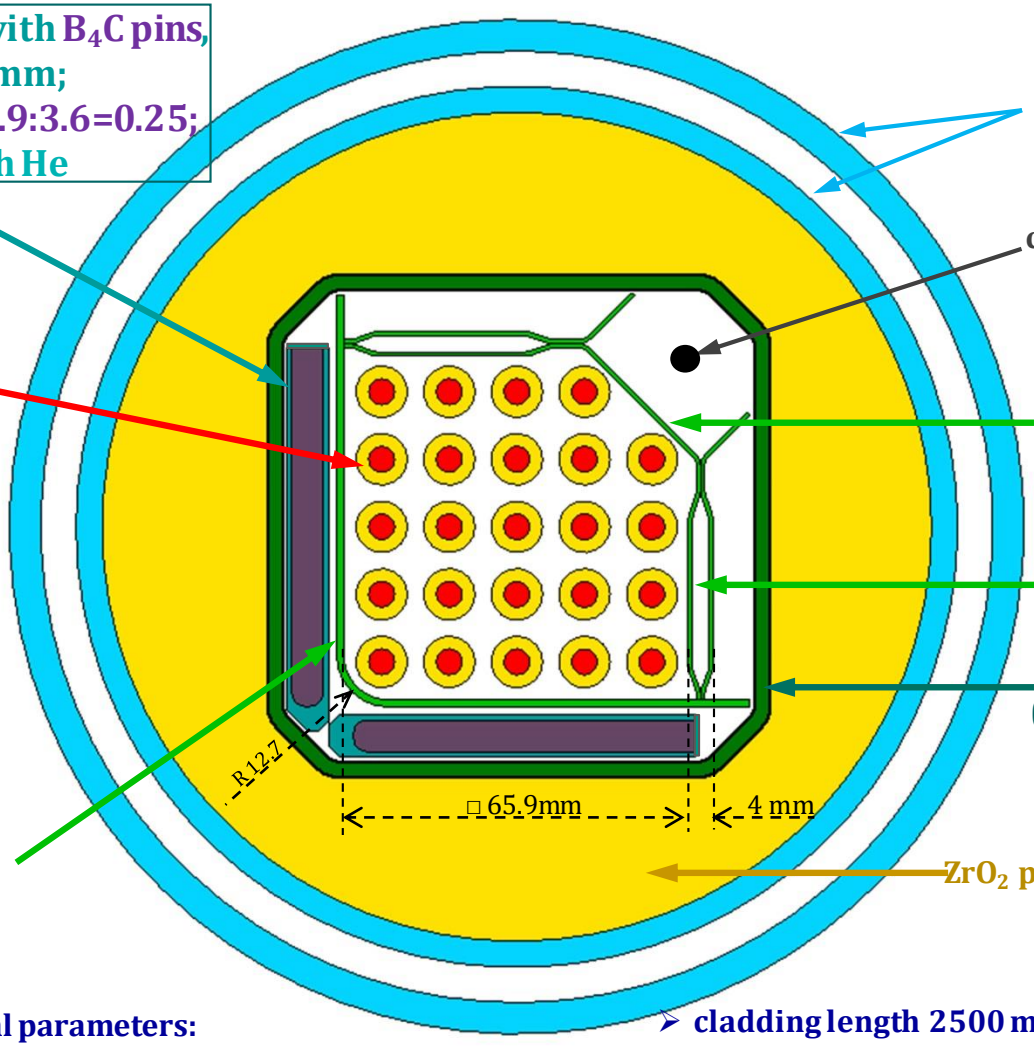
***SSM/Sweden proposal for SAFEST*: study of high temperature degradation of BWR assembly mock-up in QUENCH facility: 1) melt formation due to eutectic material interaction inside absorber cross, 2) melting of claddings.**



absorber cross

horizontal holes for B_4C pins

QUENCH-20: suggested test bundle composition (¼ SVEA-96 OPTIMA2 assembly)



absorber steel blades with B_4C pins, side length 67 mm; mass ratio B_4C:steel=0.9:3.6=0.25; holes filled with He

pressurized (5.5 bar Kr) heated rods (24):

cladding Zy-2 with inner ZrSn-liner (10% of clad),

ZrO_2 pellet OD 8.48±0.05 ID 5.45±0.1 mm, length 11 mm,

W heater OD 5.25±0.025 mm

advanced low tin ZIRLO fuel channel box, wall thickness 1.4 mm

Inconel cooling jacket, inner tube ID=158.3 mm

corner rod (Zry-4, OD 6 mm)

water channel box (ZIRLO), side length 27.4 mm

water cross wing (ZIRLO), wall thickness 0.8 mm

Zr shroud 90 mm x 114 mm (inner clearance dimensions), wall thickness 3 mm

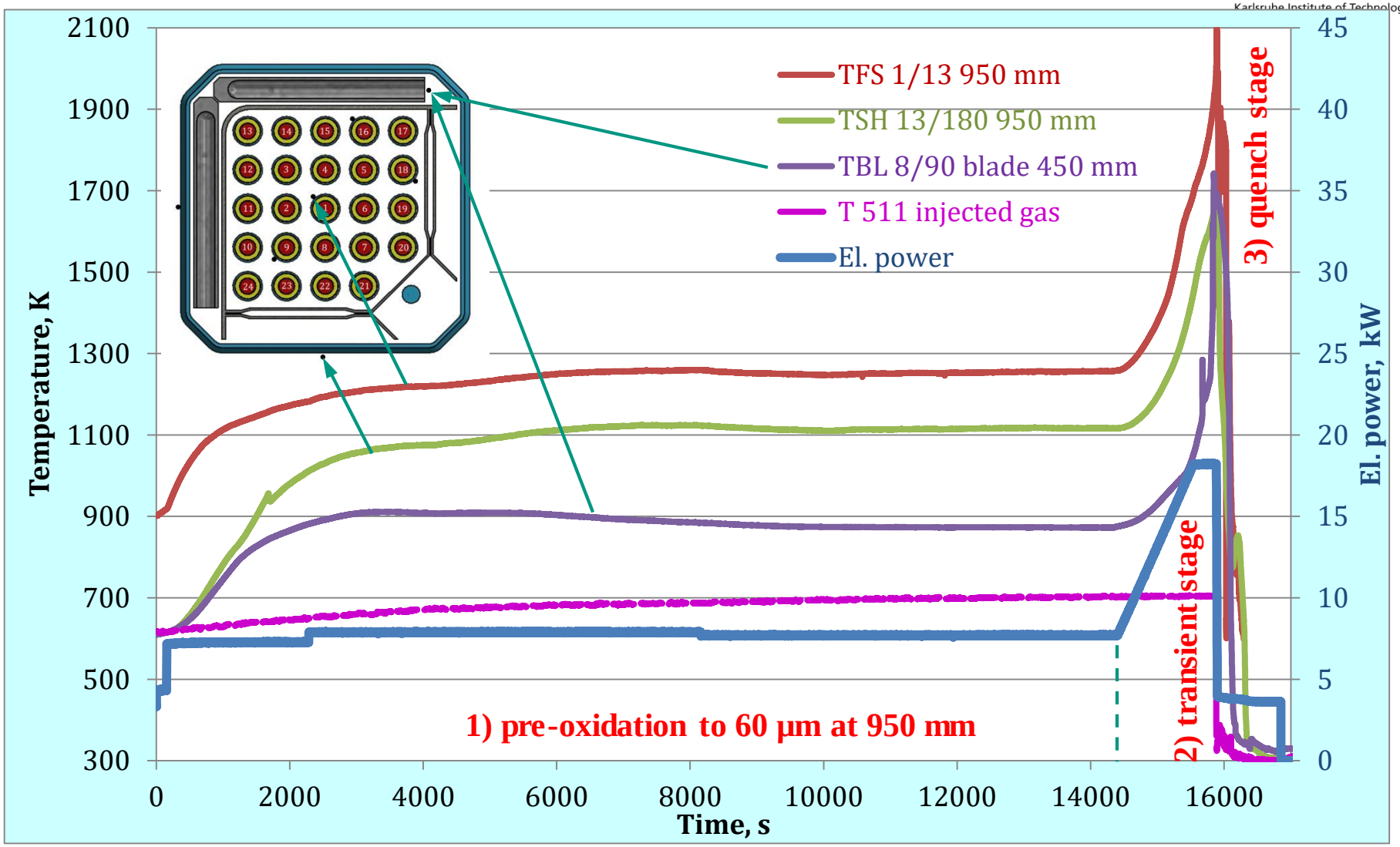
ZrO_2 porous thermal insulation

Geometrical parameters:

- bundle pitch 12.898 mm;
- outer diameter of claddings 9.84 mm;
- thickness of claddings 0.605 mm;
- absorber blades: thickness 8.05 mm

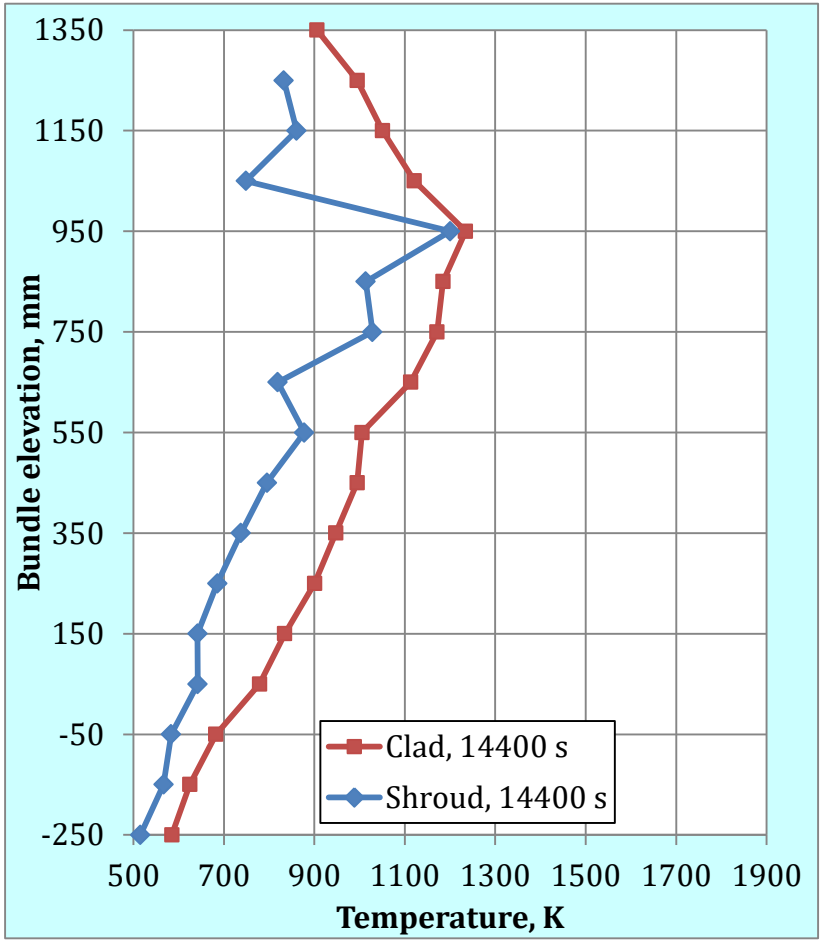
- cladding length 2500 mm
- absorber and cannel box lengths 1600 mm
- water gap between channel box and absorber blade 2.5 mm (nominal inter-assembly gap in BWR-PROTEUS core is 13.8 mm -> water gap 2.875 mm)

QUENCH-20: test progress

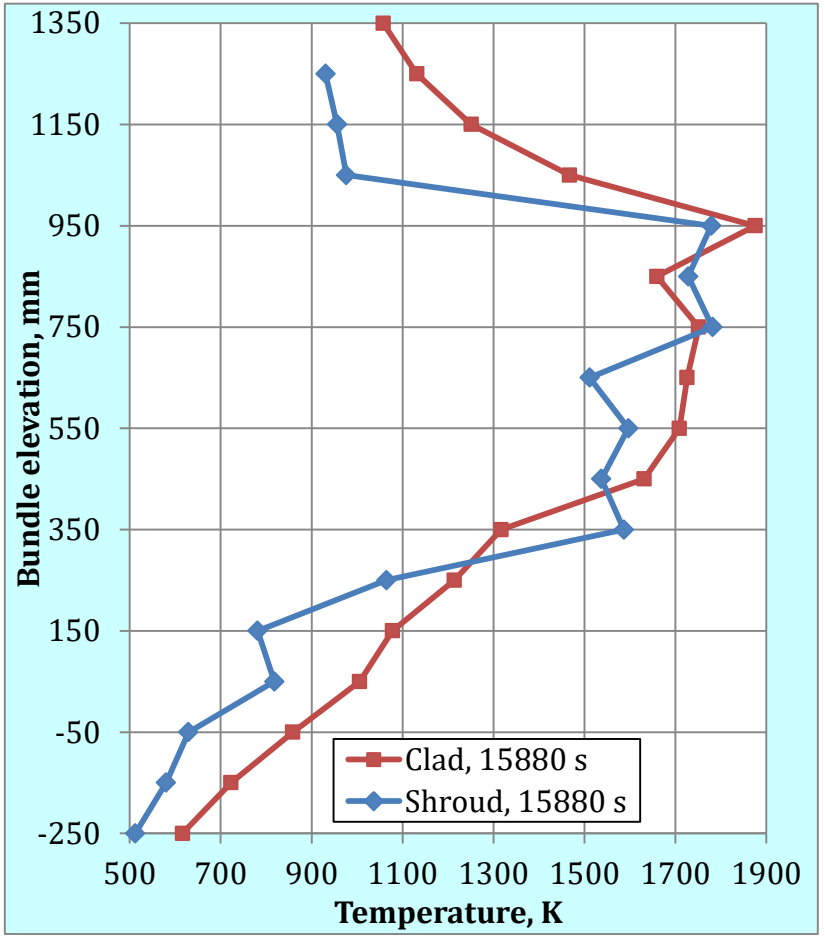


gas injection: Ar 3g/s during the whole test; superheated steam 3 g/s until the quench initiation

QUENCH-20: axial temperature profiles of outer cladding surfaces and outer shroud surface (TC readings averaged through the cross-section for each elevation)

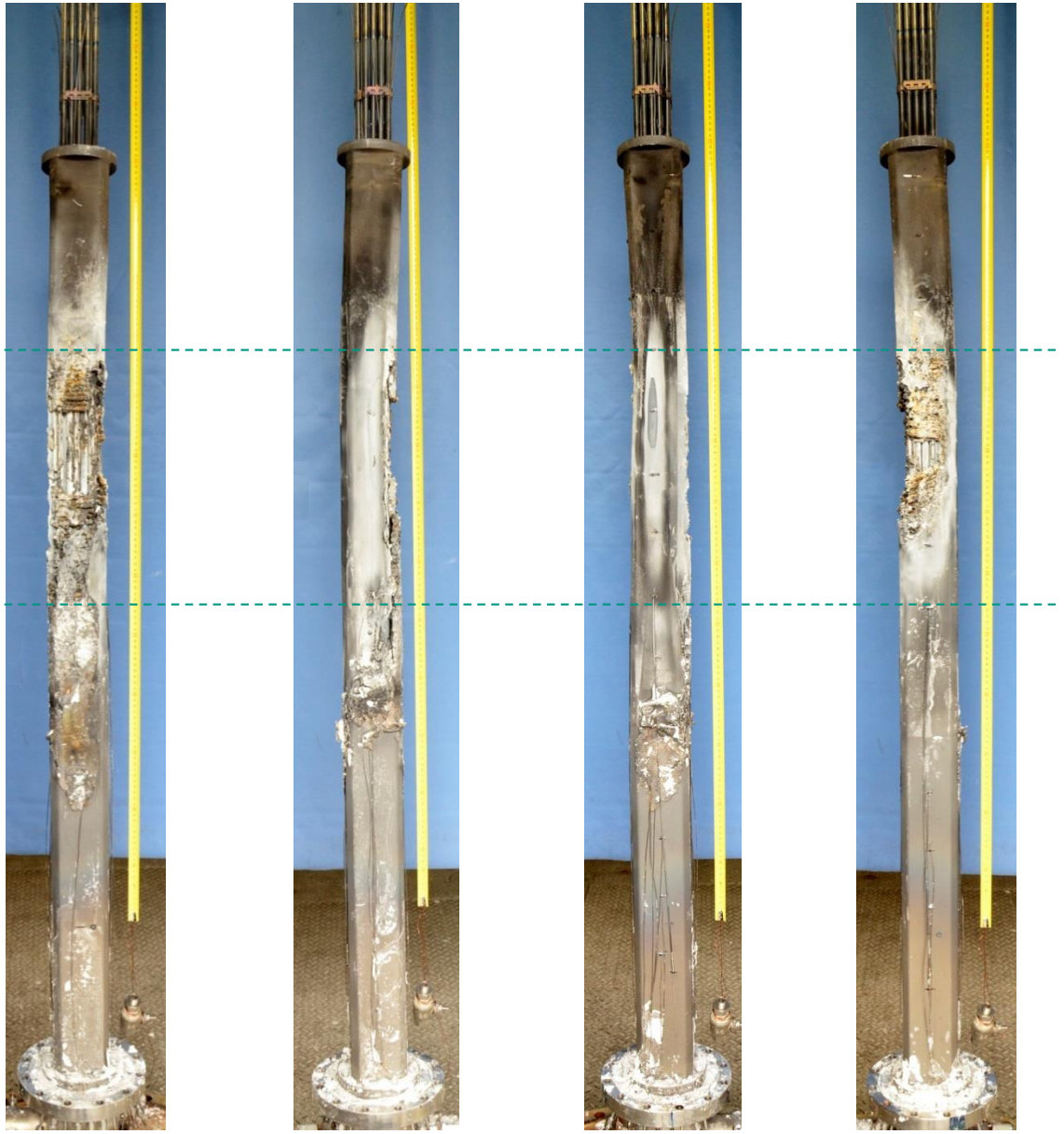


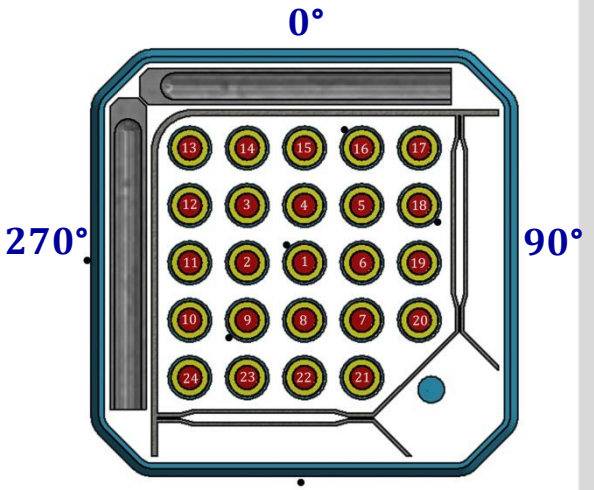
on the end of pre-oxidation (14400 s)



on the end of transient (15880 s)

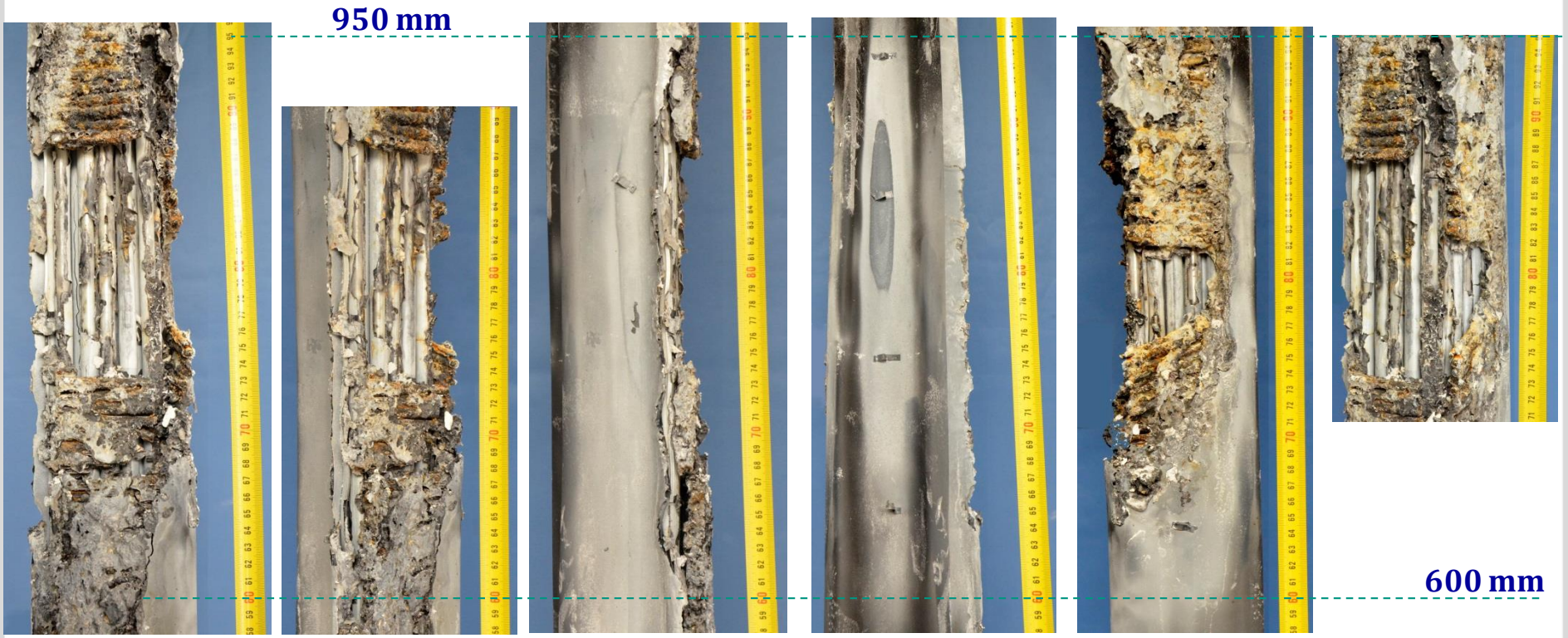
QUENCH-20 bundle surrounded by shroud: post-test view

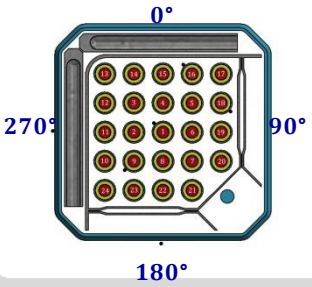




bundle cross-section, top view

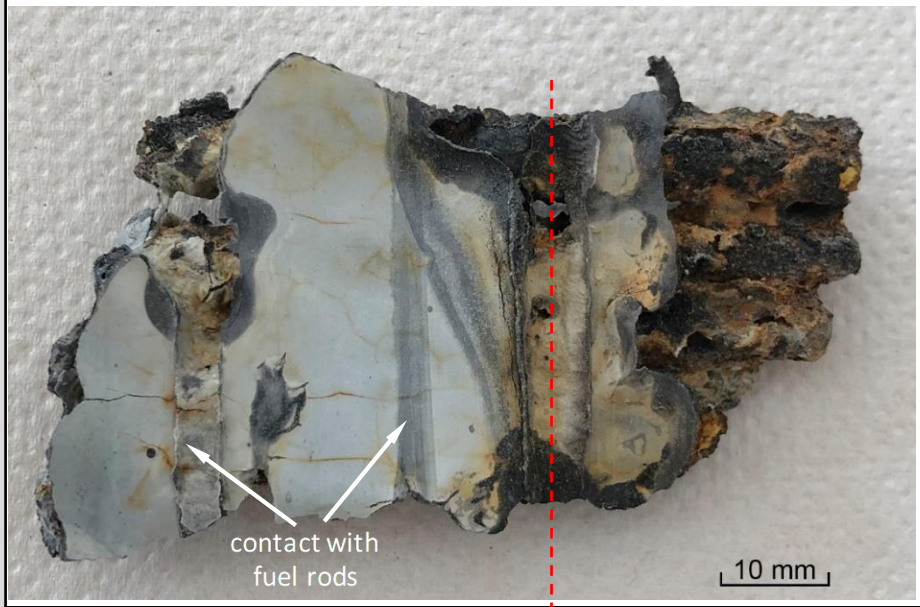
QUENCH-20 bundle surrounded by shroud: post-test view





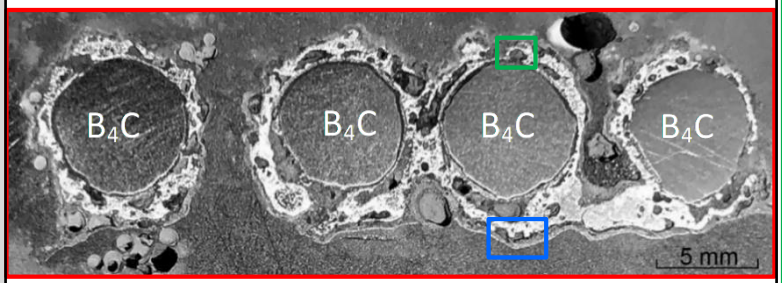
Strong degradation of absorber blades, channel box and shroud between elevations 650 and 950 mm at angle positions 0° and 270°

Piece of absorber blade broken away between 750 and 800 mm, 0°: eutectic interaction of B_4C pins with SS blade

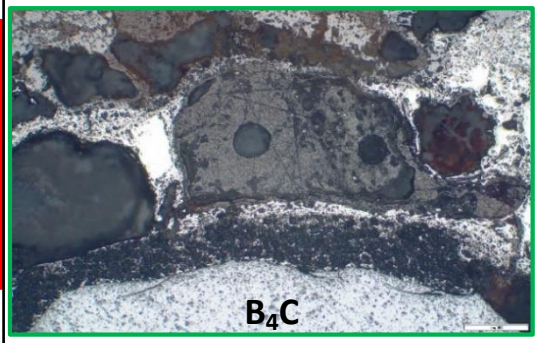


back side view: absorber blade covered by **oxidized channel box**

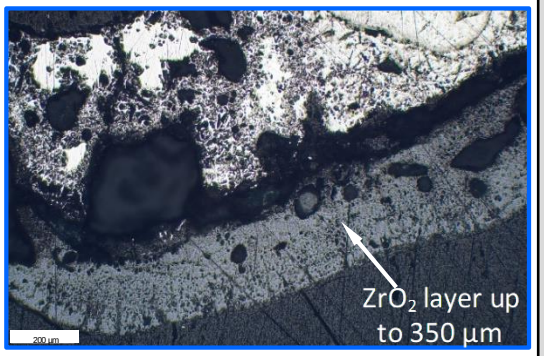
front side view: oxidized eutectic SS blade – B_4C absorber pins



cross section of four B_4C pins interacted with steel blade



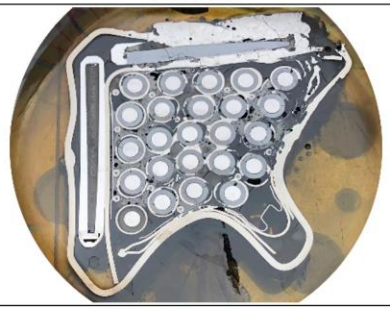
interaction B_4C - stainless steel



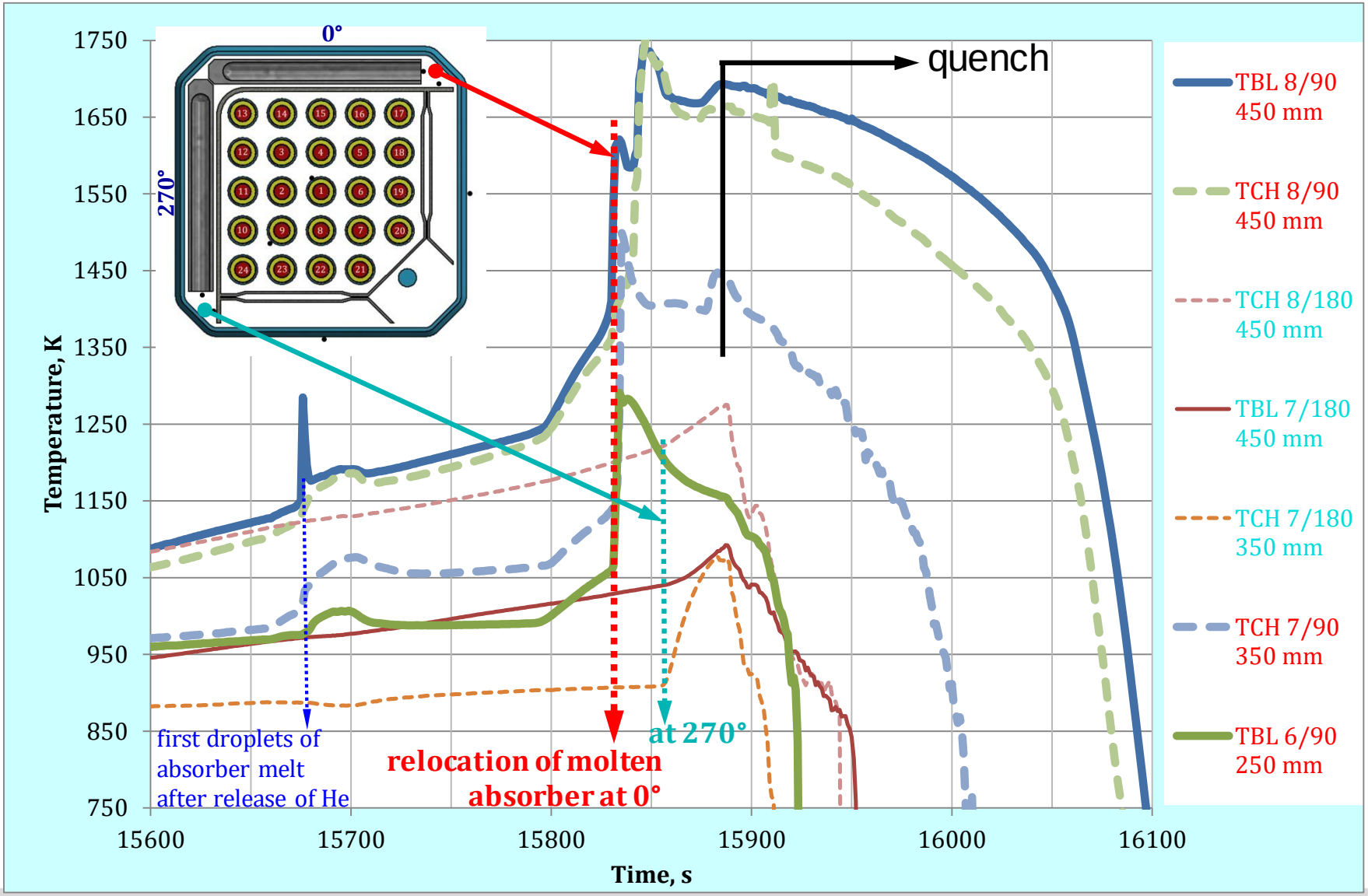
interaction B_4C - stainless steel - ZIRLO

Overview of polished cross sections:
formation of eutectic absorber melt at elevations 450…950 mm;

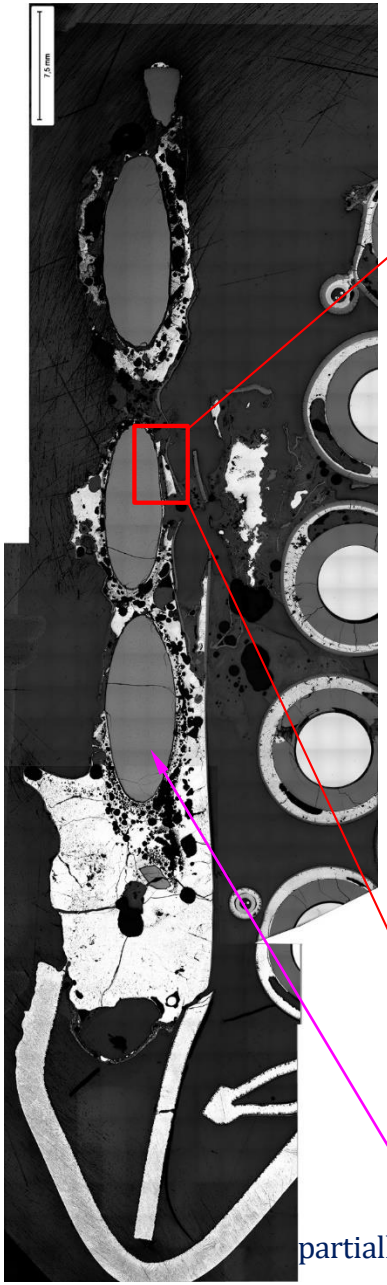
deformation of Zr shroud and ZIRLO channel box at ≈900 °C due to outer overpressure of 1 bar

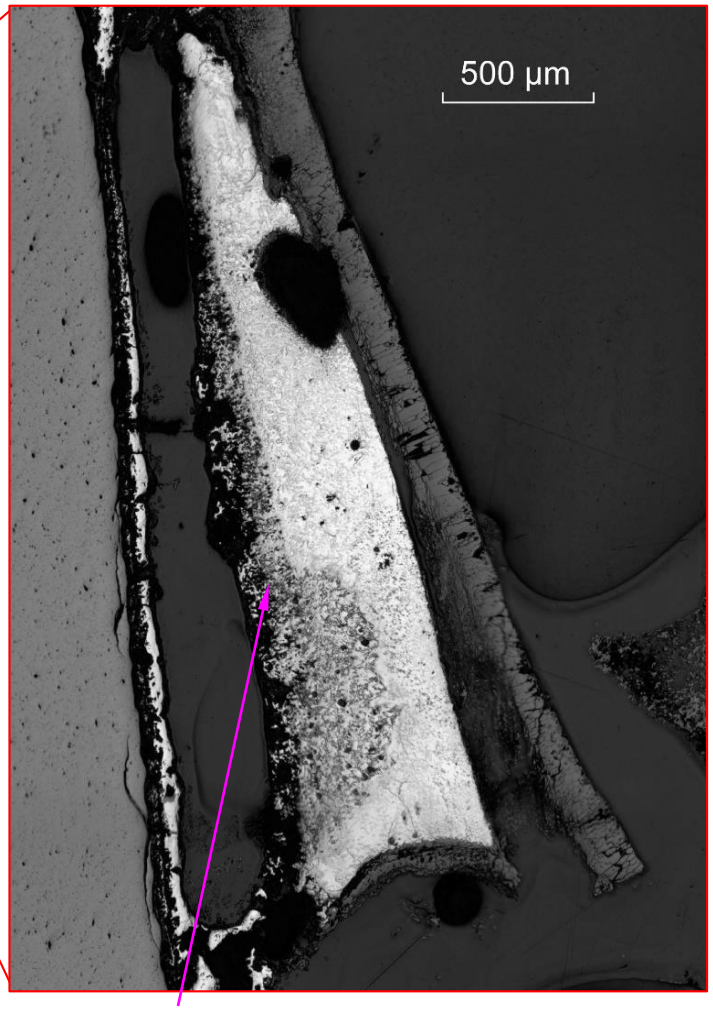
			
1150 mm	1050 mm, bottom of 4th spacer	950 mm	850 mm
			
750 mm	650 mm	555 mm, middle of 3rd spacer	450 mm
			
350 mm	250 mm	50 mm, bottom of 2nd spacer	

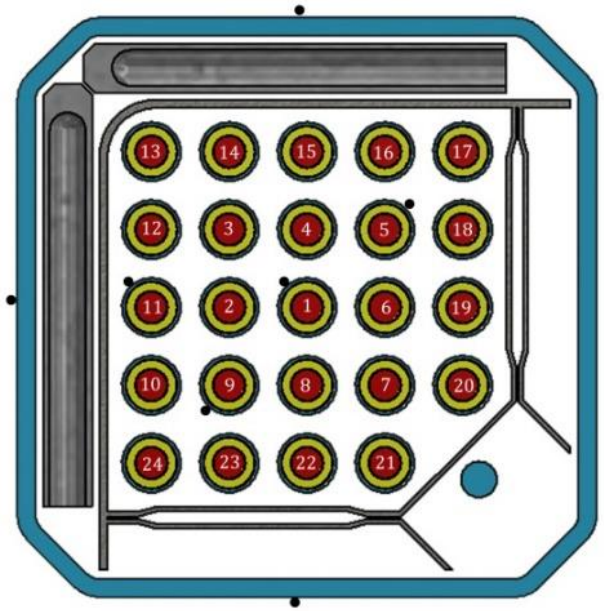
QUENCH-20: absorber melt relocation from hottest bundle elevations to elevations 250-450 mm (indication by TCs)

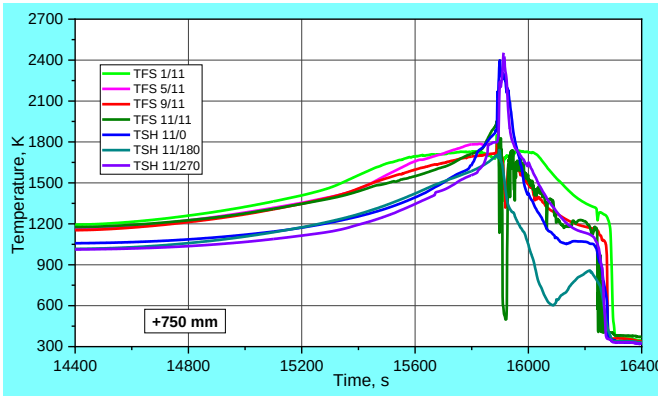


750 mm: interaction of stainless steel blade with B_4C and ZIRLO channel box





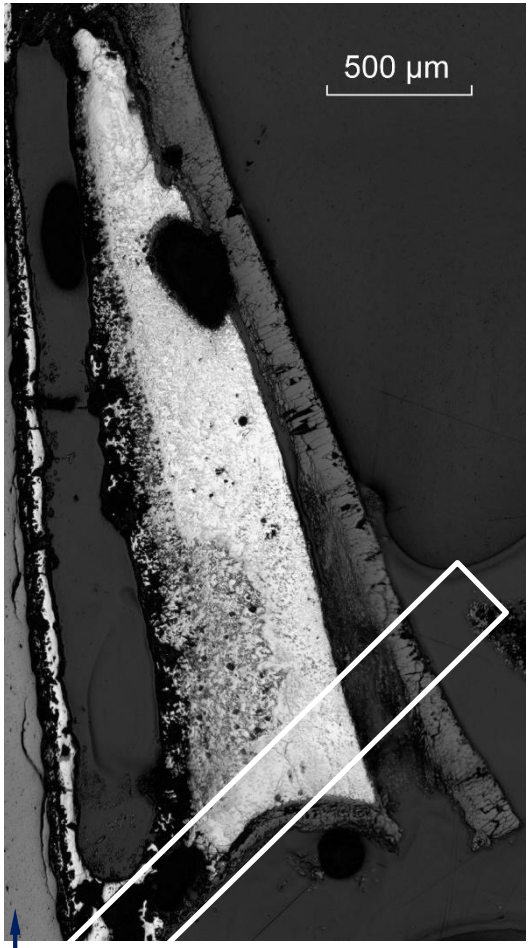




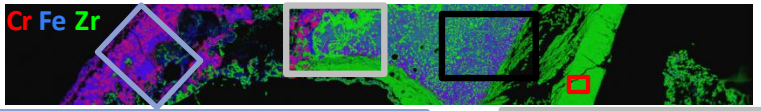
eutectic interaction B_4C pin ↔ SS blade at T>1500 K;

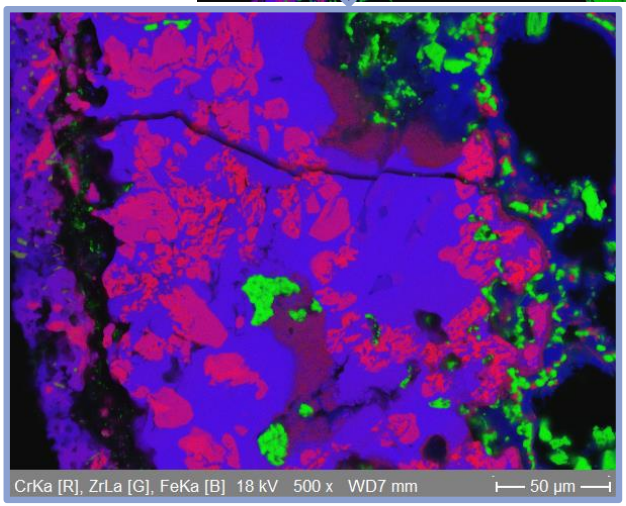
partially dissolved B_4C pin

750 mm: SEM/EDX investigation of interaction of B_4C with steel blade and ZIRLO channel box

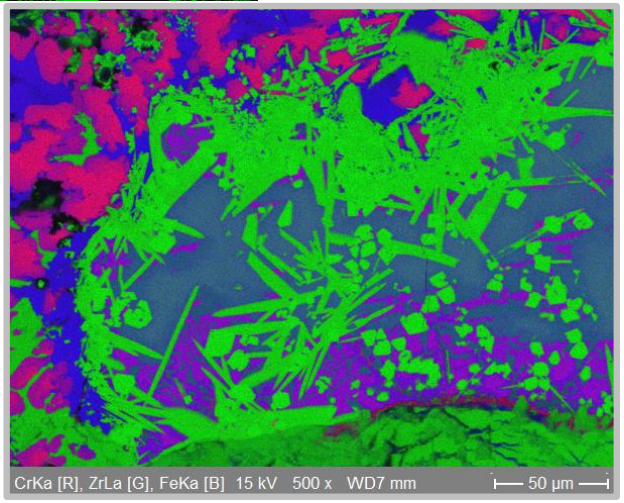


B_4C pin

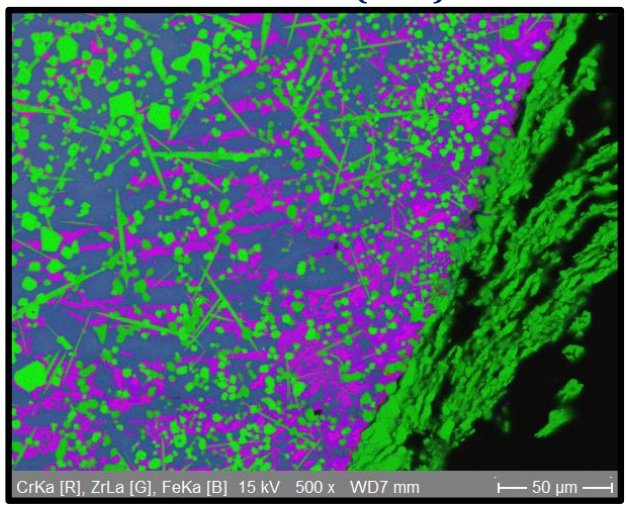




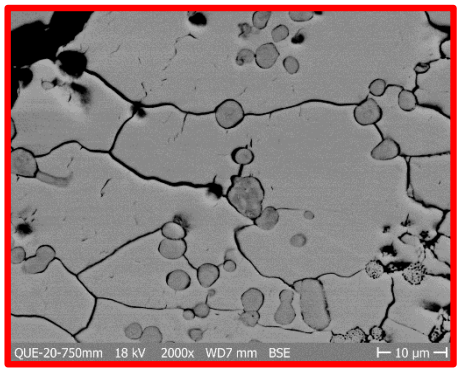
stainless steel blade: (Fe, Cr) boride (red) in steel melt (blue)



ZrB_2 needle precipitates in Zr-steel eutectic melt

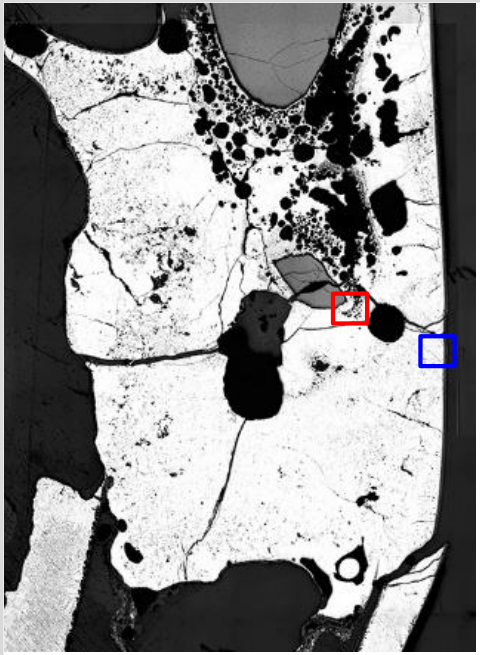


ZrB_2 needle precipitates in Zr-steel eutectic melt



ZrO_2 layer of ZIRLO channel box

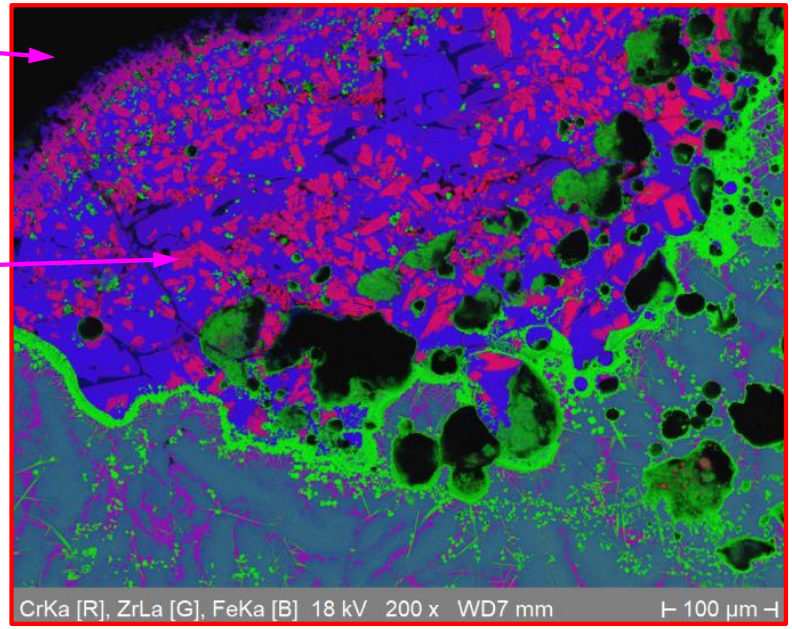
750 mm: SEM/EDX investigation of interaction of B_4C with steel blade and ZIRLO channel box



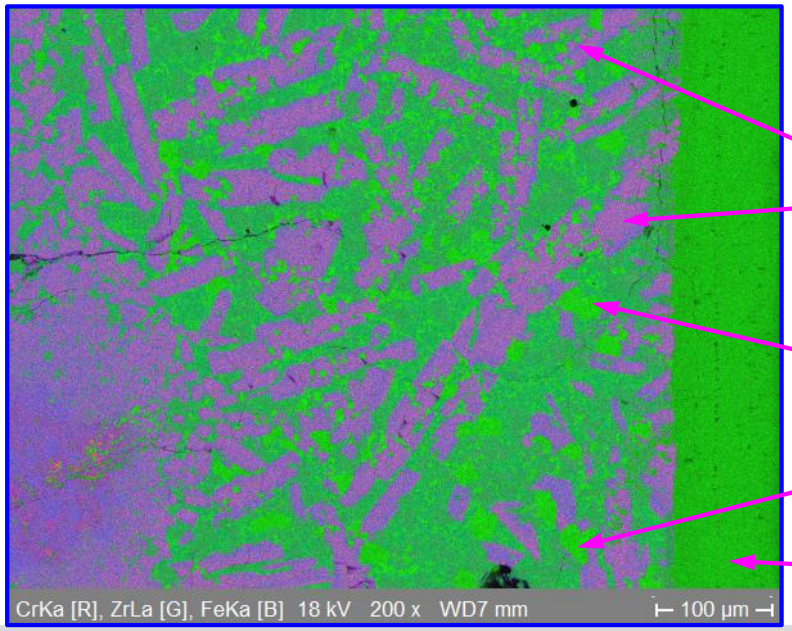
contact steel blade with ZIRLO channel box

B_4C

(Fe, Cr) precipitates
(partially borides)
in Fe melt



contact B_4C with steel blade

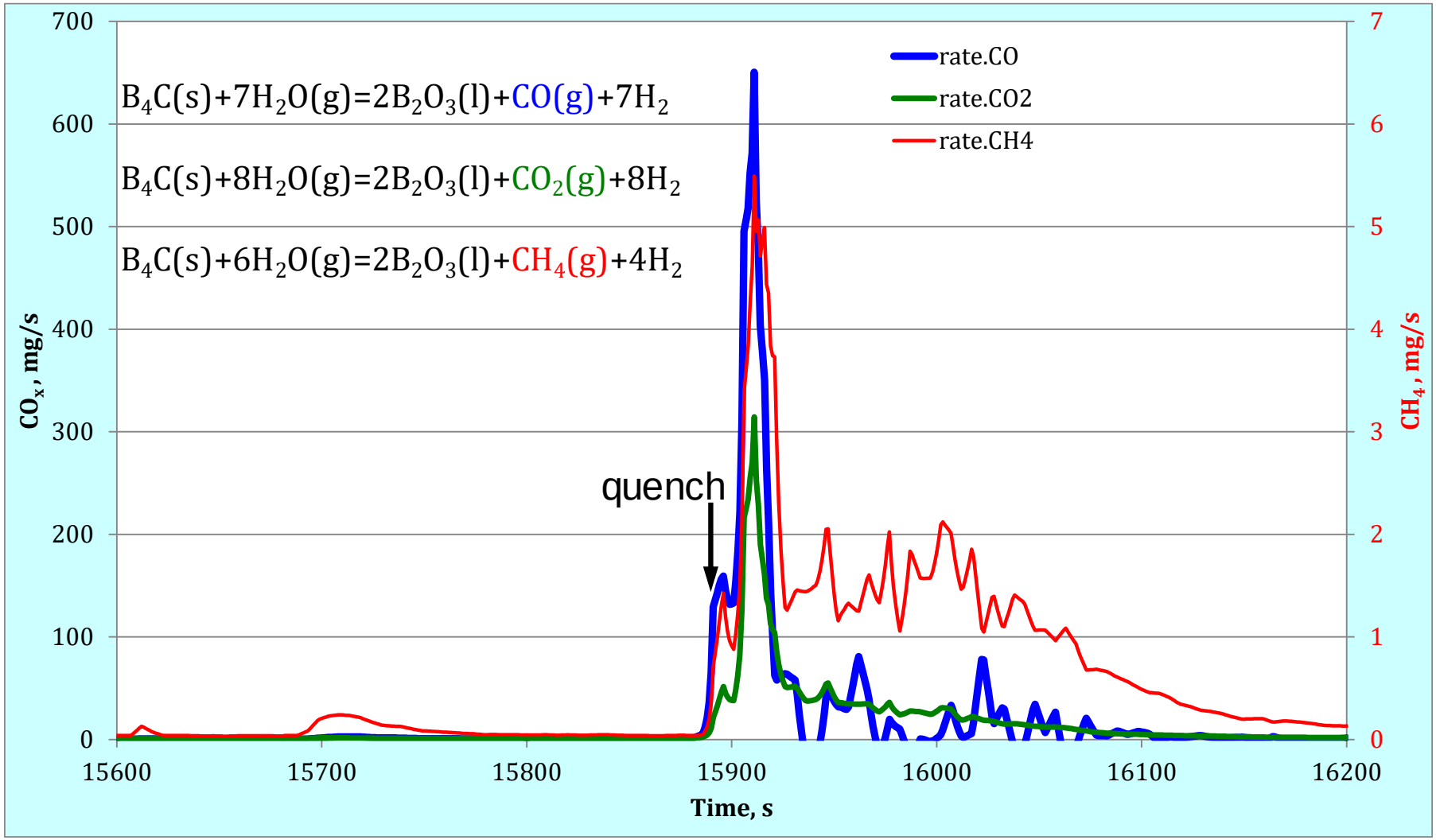


(Fe, Cr) precipitates
in (Ni, Fe, Zr) melt

ZrB_2 precipitates in
(Ni, Fe, Zr) melt

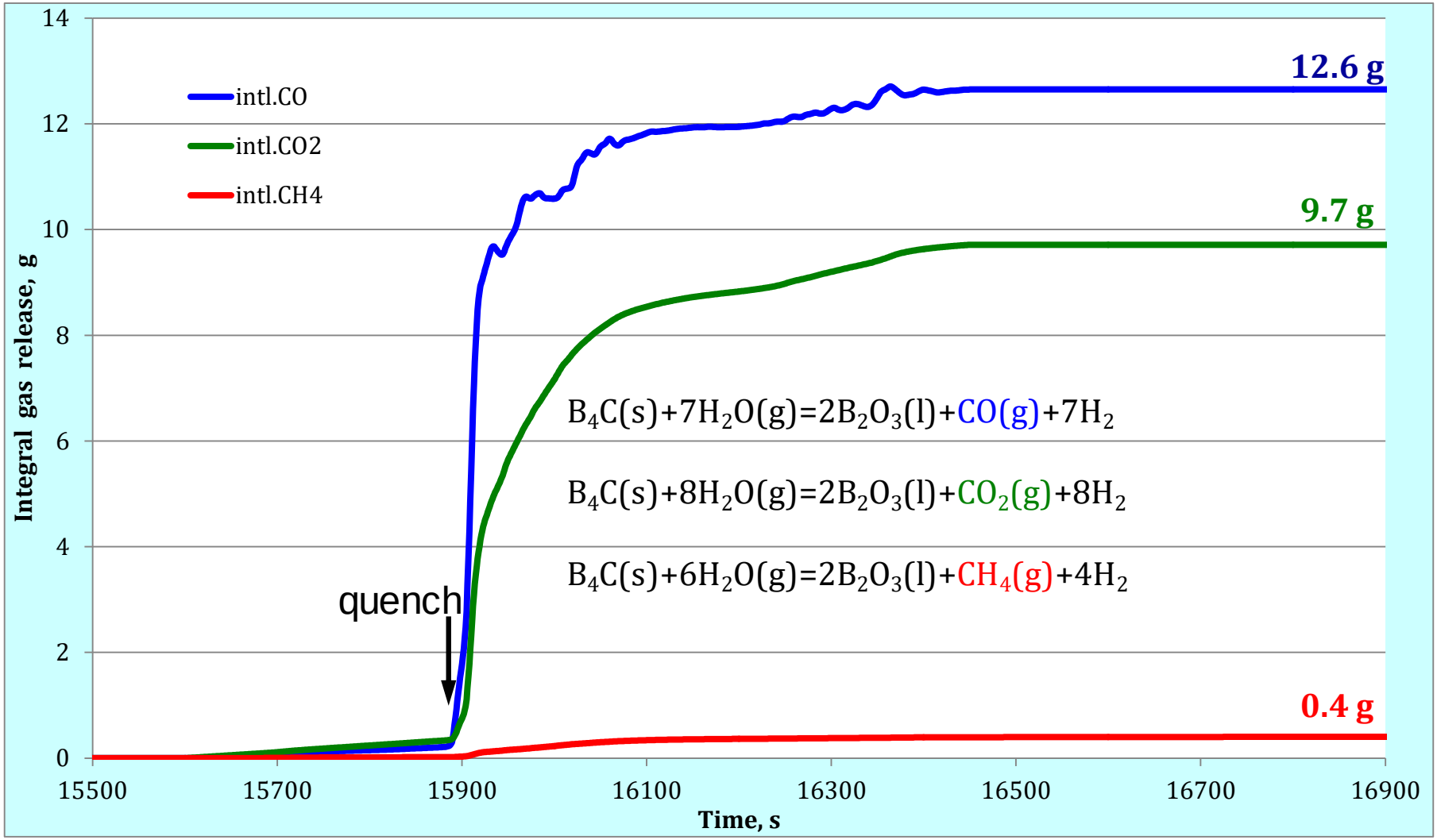
ZrO_2

QUENCH-20: reaction of B_4C with steam



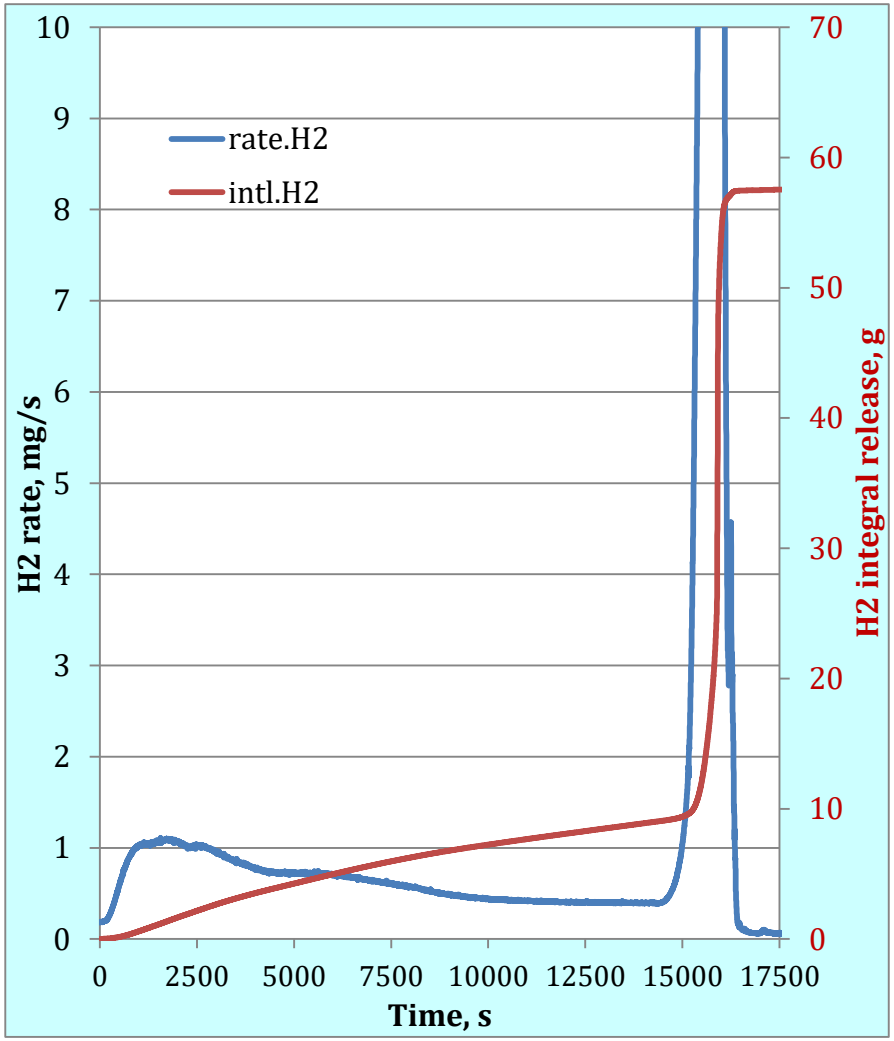
only small release of CH_4 before quench; CO and CO_2 formation firstly in the quench stage

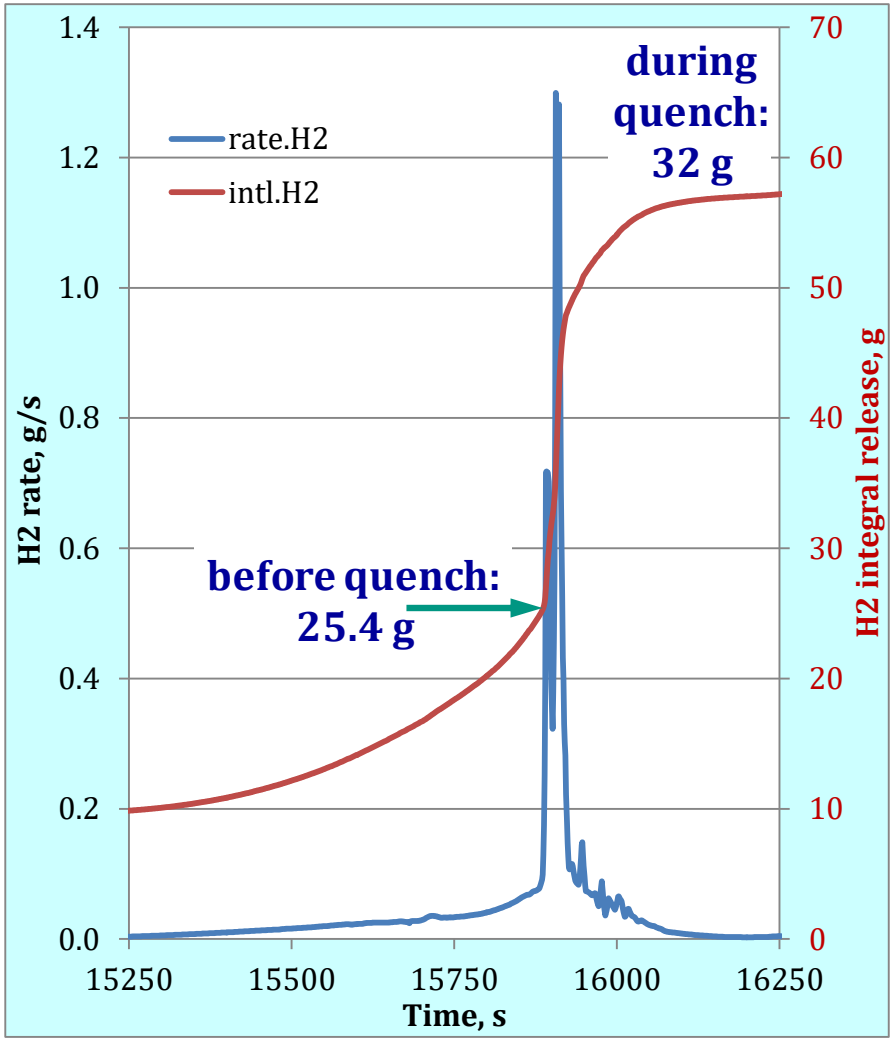
QUENCH-20: reaction of B_4C with steam, integral gas release



According to CO_x and CH_4 release: corresponding mass of B_2O_3 is 96.8 g; H_2 is 10.0 g; reacted B_4C 41 g, i.e. 4.6% of total B_4C mass (900 g)

QUENCH-20: hydrogen release

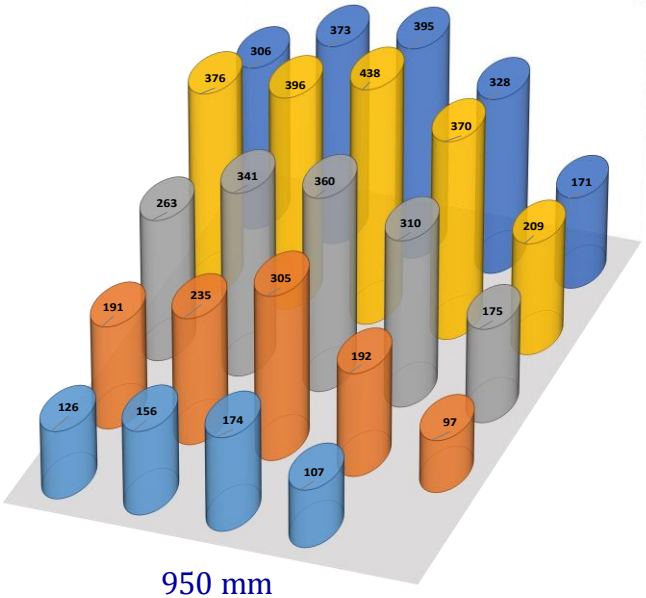




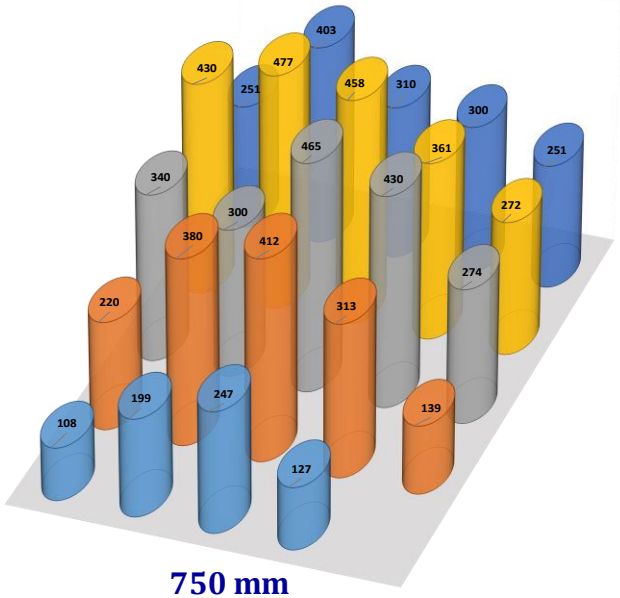
H_2 release during the whole test: 57.4 g;
before quench – interaction of steam with Zry,
during quench – steam interaction with Zry and absorber

H_2 release during quench:
22 g (from Zry and molten steel) +
+ 10 g (from B_4C)

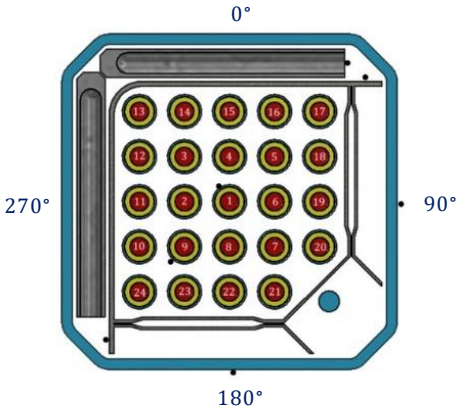
Average thicknesses of outer ZrO_2 for each cladding at the bundle elevations 450…950 mm; *not symmetrical distribution of oxidation degree across the bundle due to influence of absorber blades*

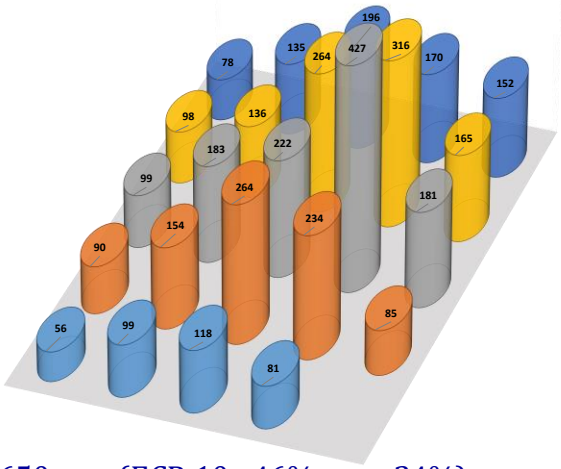


950 mm
(*ECR 17…47%; avg. 31%)*

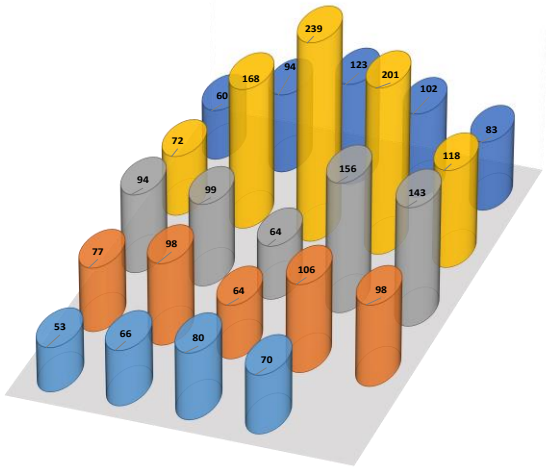


750 mm
(ECR 18…49%; avg. 33%)

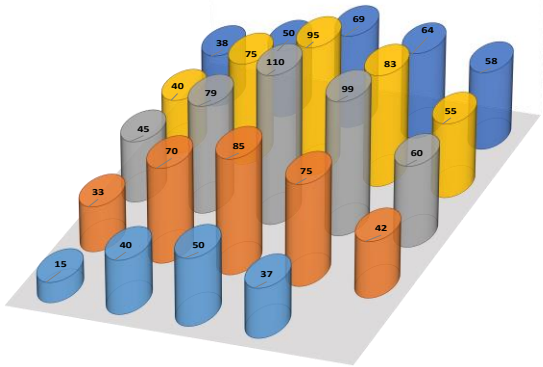




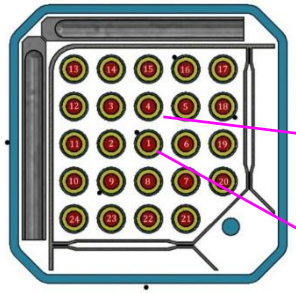
650 mm (ECR 10…46%; avg. 24%)



555 mm (grid spacer) (*ECR 6…22%; avg. 15%*)



450 mm (*ECR 7…19%; avg. 14%*)

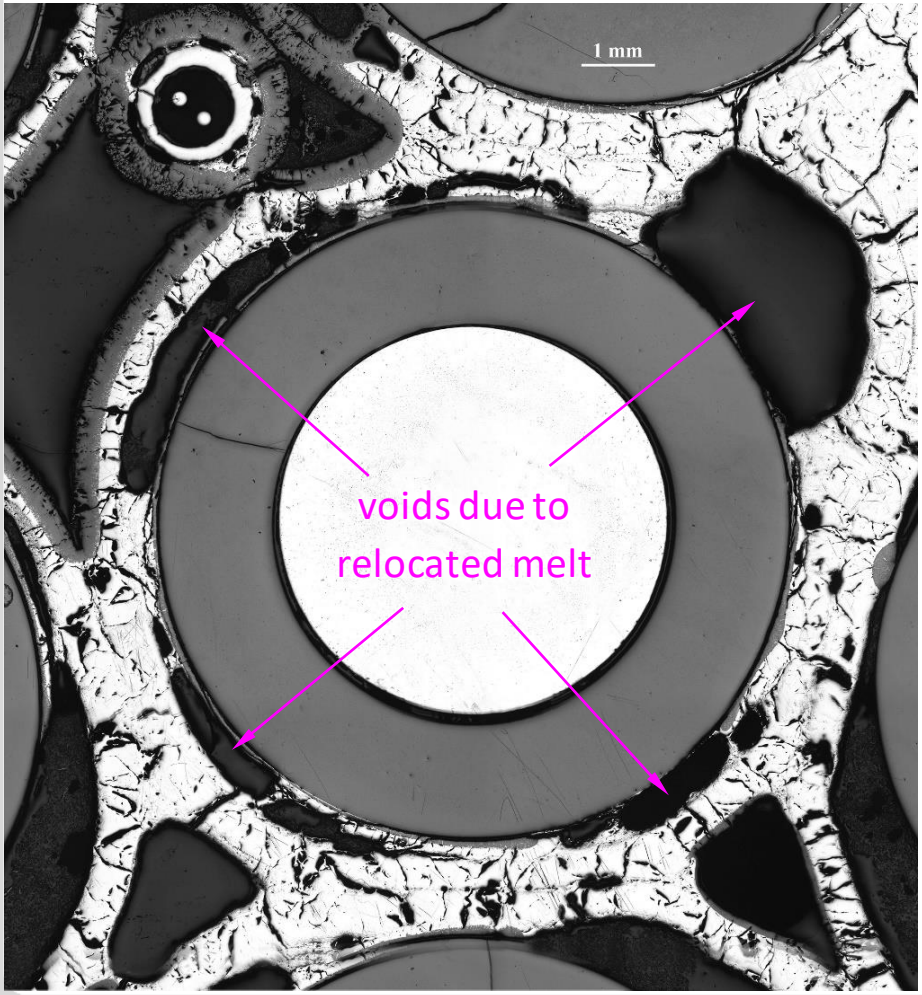


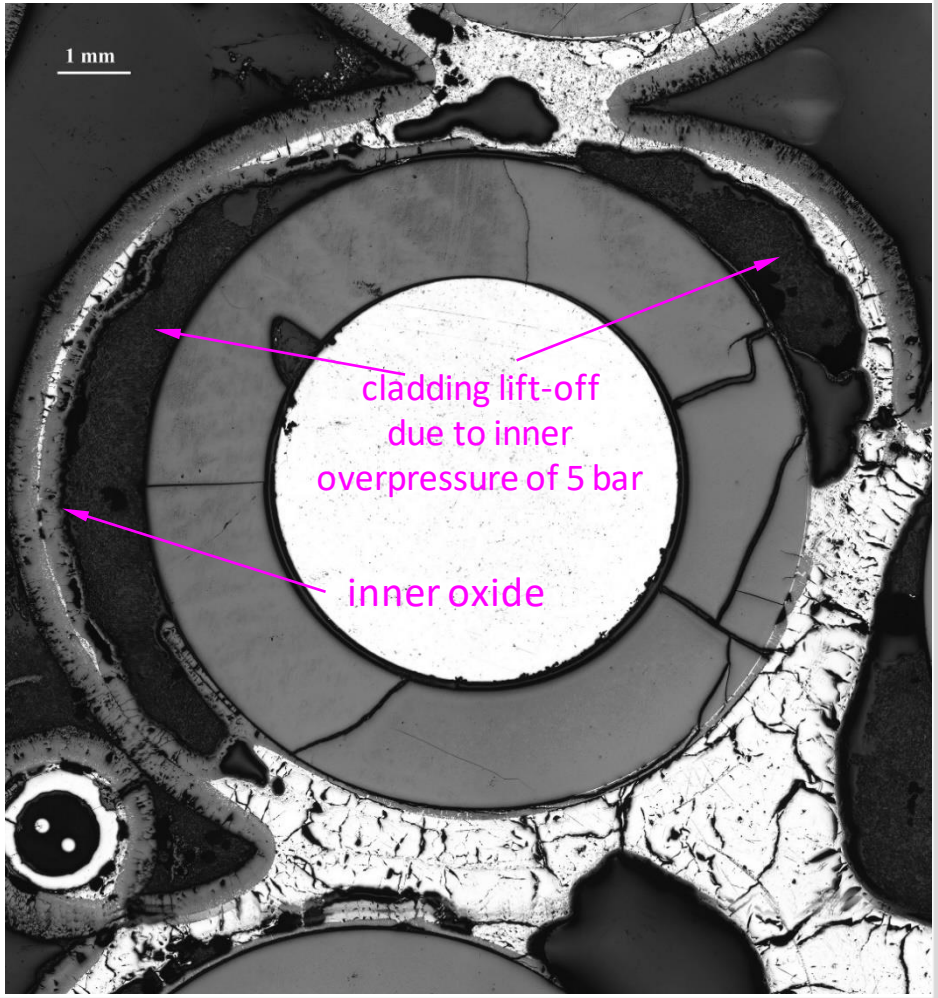
Cladding behavior of relatively hot inner rods at 950 mm

Karlsruhe Institute of Technology

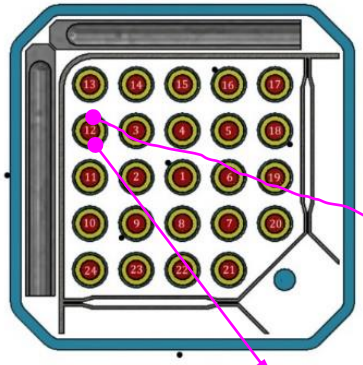
central rod (#1)

inner rod (#4)

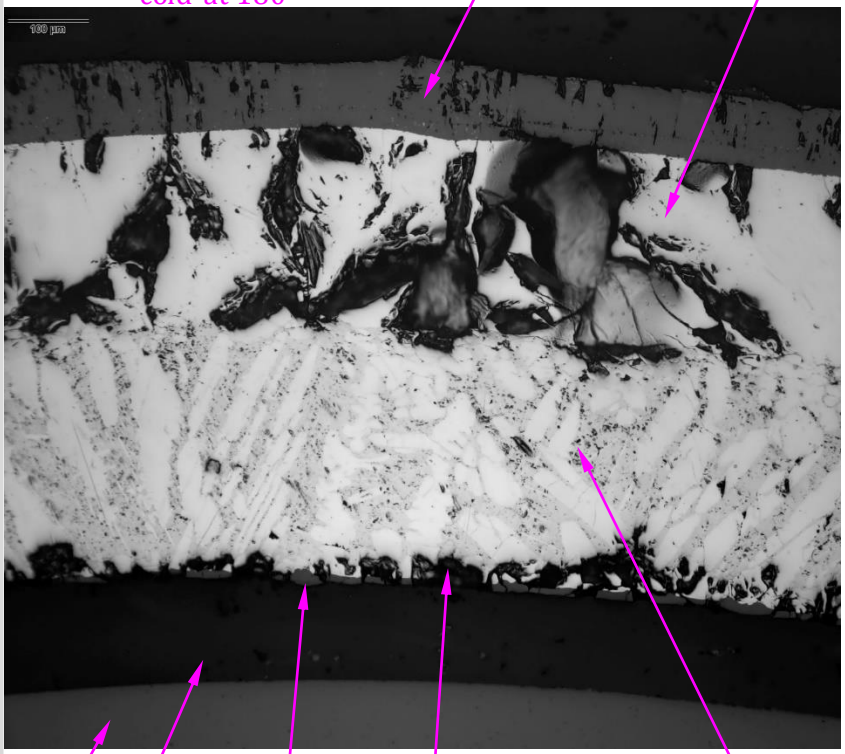




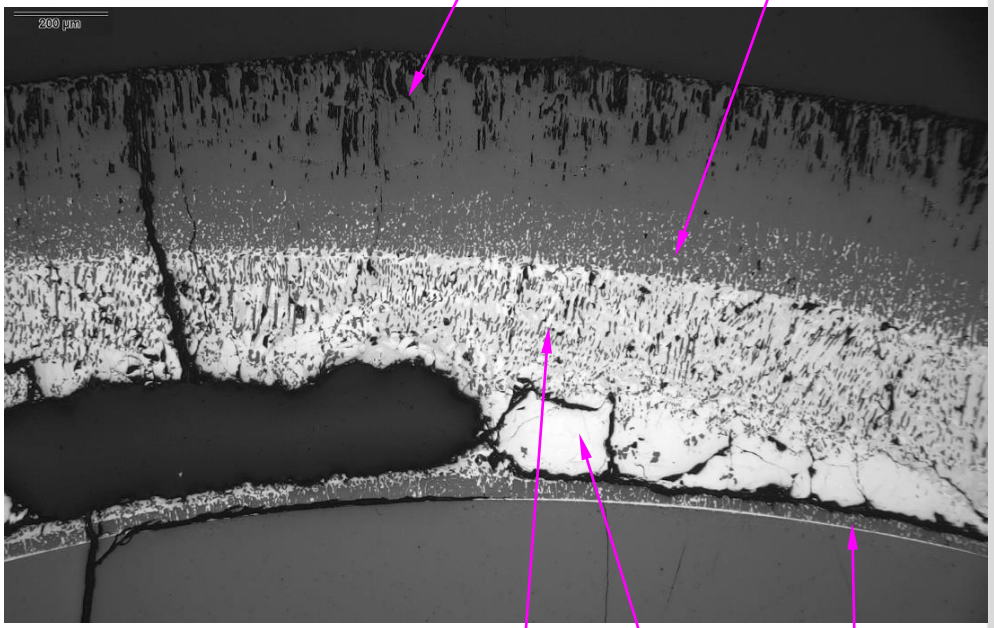
Layer composition for peripheral road #12 at 950 mm: *not melted and melted β-Zr depend on the angle position*



"cold" at 180°



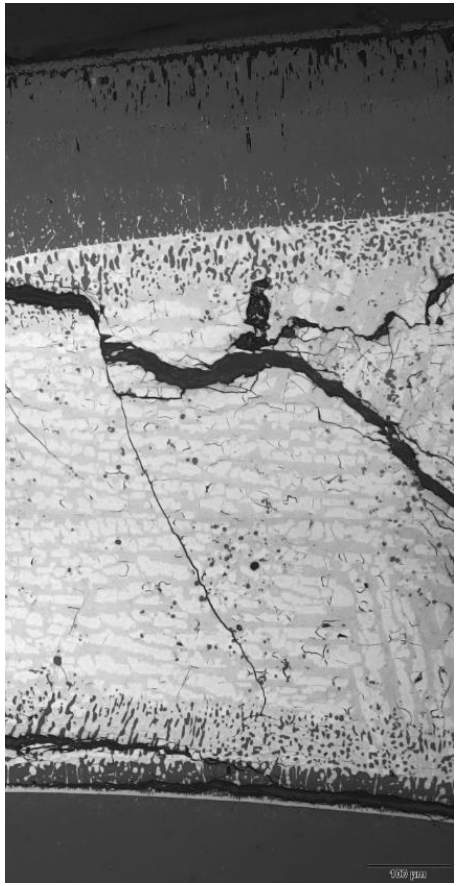
"hot" at 0°



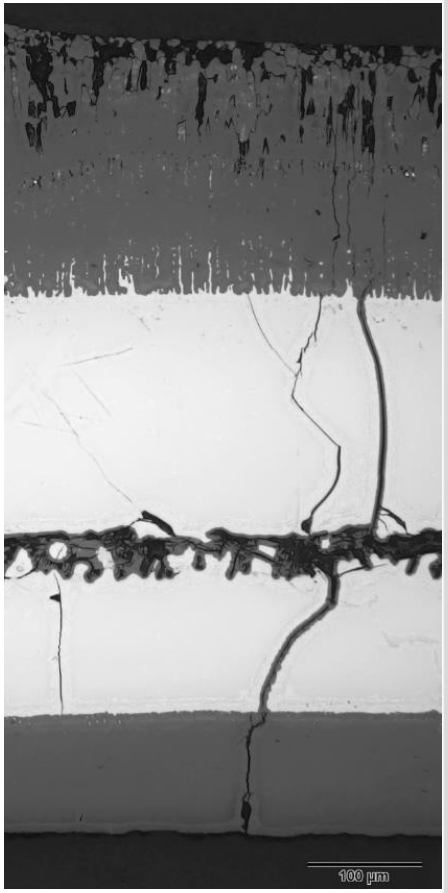
750 mm: micro structure of claddings

internal rod #2 at 315°: melted and frozen β-Zr between outer α-Zr(O) and inner ZrO_{2-x}

peripheral rod #12 at 0°: partially oxidized metal melt between outer and inner ZrO_2

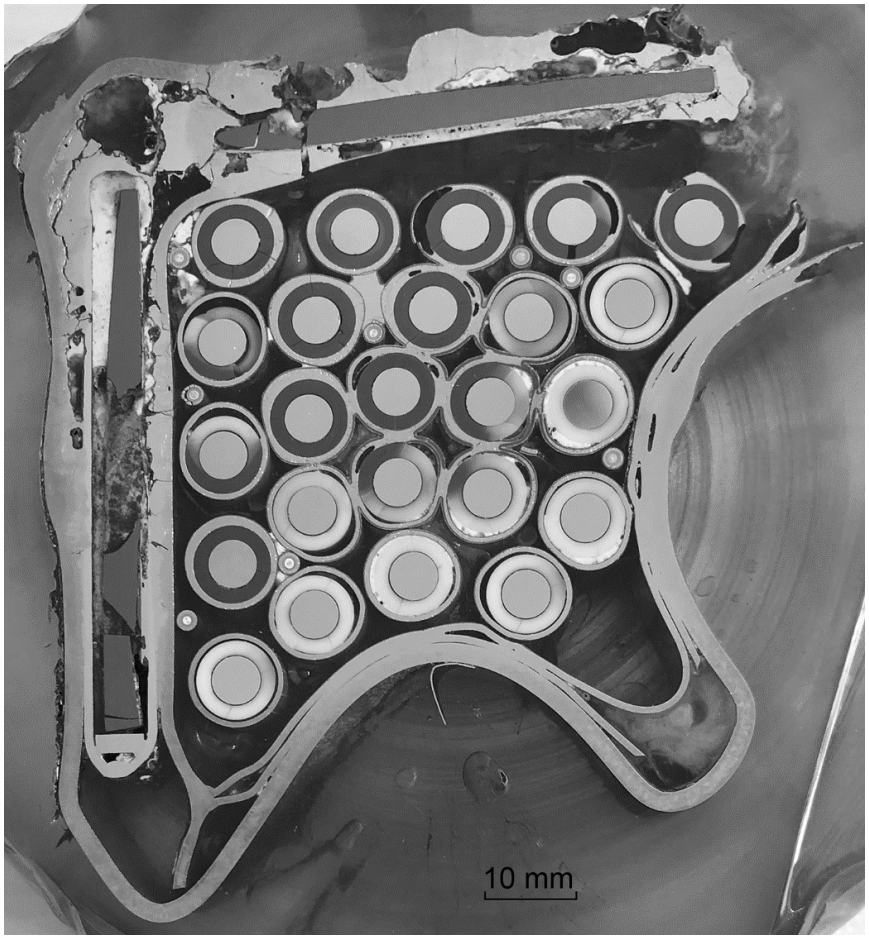


peripheral rod #17 at 45°: partially oxidized metal melt between outer and inner ZrO_2

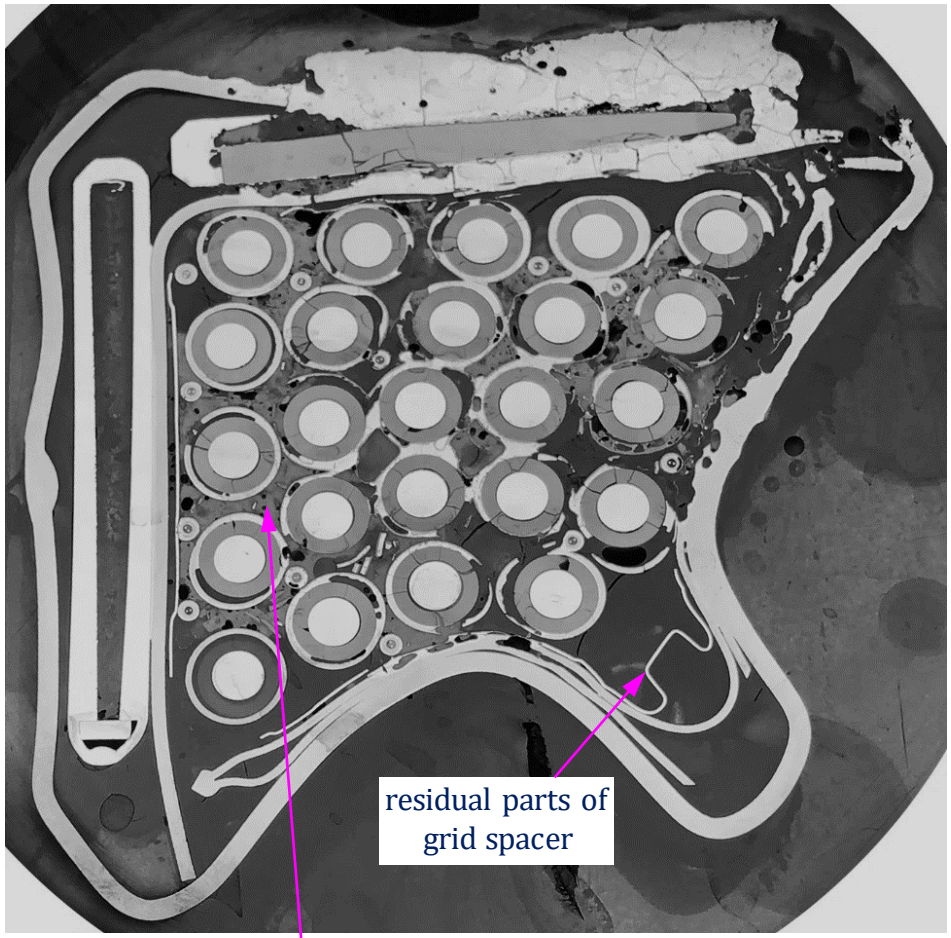


peripheral rod #21 at 315°: not melted metal, oxidation of cracks

Elevations without and with grid spacer

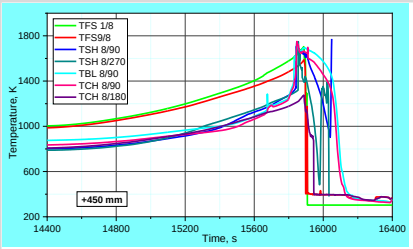


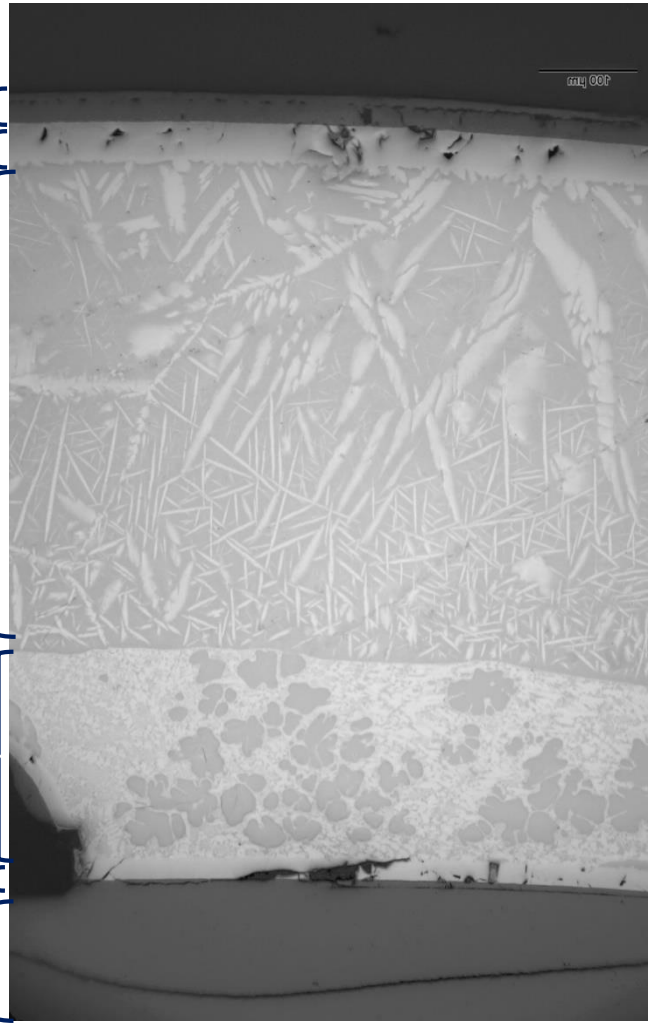
650 mm:
1) local blockages between several rods,
2) dark pellets contacted with inner melt: oxygen transport to melt
(white pellets had no contact with melt)



550 mm:
strong bundle blockage by melt collected inside
partially *molten* grid spacer

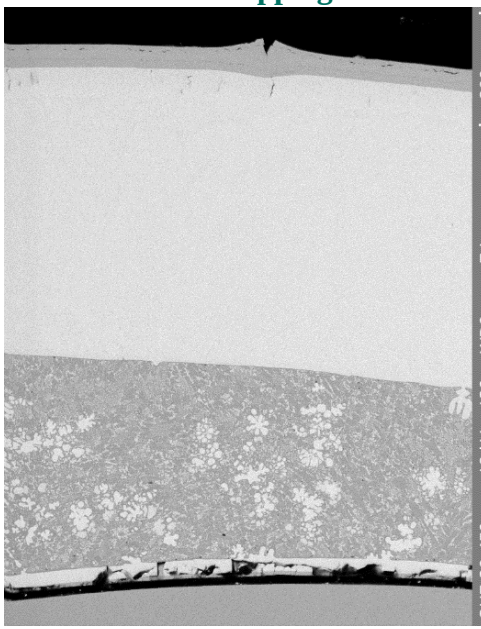
450 mm: eutectic (*Inconel* spacer/ZIRLO clad) melt relocated inside the rod from 550 elevation



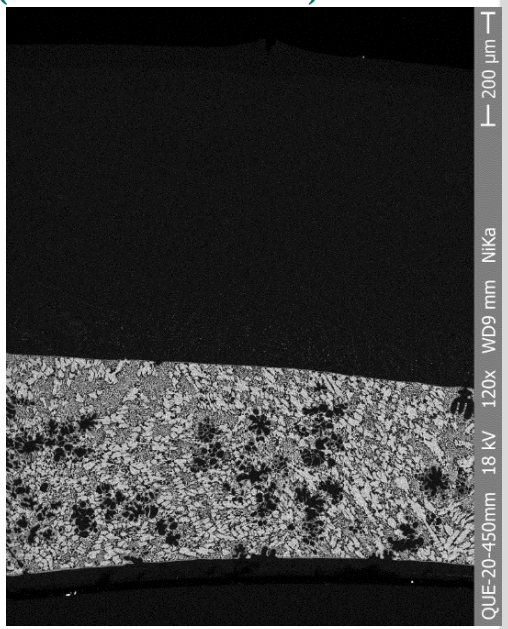


optical observation of cladding at 450 mm

SEM/EDX mapping at 450 mm (main element is white)

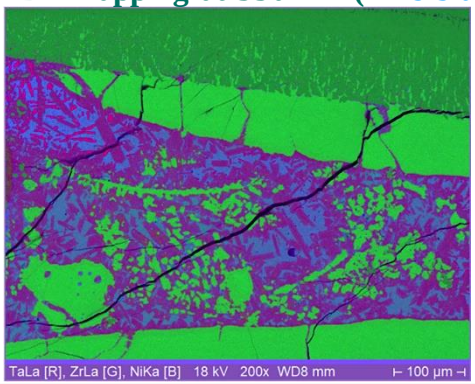


Zr map



Ni map: Ni as main component of molten INCONEL spacer was relocated down in the gap between cladding and pellet

SEM/EDX mapping at 550 mm (Ni is blue)



Summary and conclusions

- The QUENCH-20 test bundle mock-up represented one quarter of a BWR fuel assembly with 24 electrically heated fuel rod simulators and B_4C control blade. The pre-oxidation stage to ZrO_2 thickness >55 µm lasted 4 hours at the peak cladding temperature of 1250 K.
- During the transient stage, the bundle was heated to a maximal temperature of **2000 K**. The eutectic interaction of B_4C with steel blade and ZIRLO channel box was observed at elevations 650…950 mm with formation of eutectic melt. The typical components of this melt are (Fe, Cr) borides and ZrB_2 precipitated in steel or in Zr-steel eutectic melt.
- *Massive absorber melt relocation was observed 50 s before the end of transient stage and was localized between shroud and channel box*.
- The test was terminated with the quench water injected with a flow rate of 50 g/s from the bundle bottom. Fast *temperature escalation* from 2000 to **2300 K** during 20 s was observed. The mass spectrometer measured *release of CO (12.6 g), CO_2 (9.7 g) and CH_4 (0.4 g) during the reflood as products of absorber oxidation; corresponding* ***B_4C mass reacted*** *with steam was 41 g or* ***4.6% of total B_4C***.
- Cladding melt was formed at elevations 650…1000 mm and relocated to lower bundle elevations *inside* and outside rods to elevations 450…550 mm, where was mixed with molten Inconel grid spacer. Residual parts of claddings were oxidized with the highest oxidation degree ECR 33% at the elevation 750 mm.
- Hydrogen production during the reflood amounted to **32 g** (57.4 g during the whole test) including ***10 g from B_4C oxidation***.

Acknowledgment

The QUENCH-20 experiment was performed in the framework of the SAFEST project in cooperation with Swedish Radiation Safety Authority (SSM), Westinghouse Sweden, GRS and KTH and supported by the KIT program NUSAFE. Personal thanks to Mr. Isaksson (SSM), Mr. Bechta (KTH), Mr. Hollands (GRS), Ms. Korske (Westinghouse) for their help and fruitful cooperation. The bundle materials and absorbers were provided by Westinghouse Sweden.

The authors would like to thank all colleagues involved in the post-test investigations.

Thank you for your attention

http://www.iam.kit.edu/awp/163.php

http://quench.forschung.kit.edu/