First Results of the QUENCH-ALISA Bundle Test

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ABSTRACT

The bundle experiment QUENCH-18 on air ingress and aerosol release was successfully conducted at KIT in the frame of the EC supported ALISA program. The primary aims were to examine the oxidation of M5® claddings in air/steam mixture following a limited pre-oxidation in steam, and to achieve a long period of oxygen and steam starvations to promote interaction with the nitrogen. Additionally, the QUENCH-18 experiment investigated the effects of the presence of two Ag-In-Cd control rods, and two pressured unheated rod simulators (60 bar, He). The low-pressurized heater rods (2.3 bar, similar to the system pressure) were Kr-filled. In a first transient, the bundle was heated in an atmosphere of flowing argon and superheated steam by electrical power increase to the peak cladding temperature of 1400 K. During this heat-up, claddings of the two pressurized rods were burst at temperature of 1045 K. The attainment of 1400 K marked the start of the pre-oxidation phase to achieve a maximum cladding oxide layer thickness of about 100 µm. In the air ingress phase, the steam and argon flows were reduced, and air was injected. The first Ag-In-Cd aerosol release was registered at 1350 K and was dominated by Cd bearing aerosols. Later in the transient, a significant release of Ag was observed. A strong temperature escalation started in the middle of the air ingress phase. Later a period of oxygen starvation occurred and was followed by almost complete steam consumption and partial consumption of the nitrogen. Following this, the temperatures continued to increase and stabilized at melting temperature of Zr bearing materials until water injection. Almost immediately after the start of reflood there was a temperature excursion, leading to maximum measured temperatures of about 2450 K. Final quench was achieved after about 800 s. A significant quantity of hydrogen was generated during the reflood (238 g). Nitrogen release (>54 g) due to re-oxidation of nitrides was also registered.

First results of the QUENCH-ALISA bundle test

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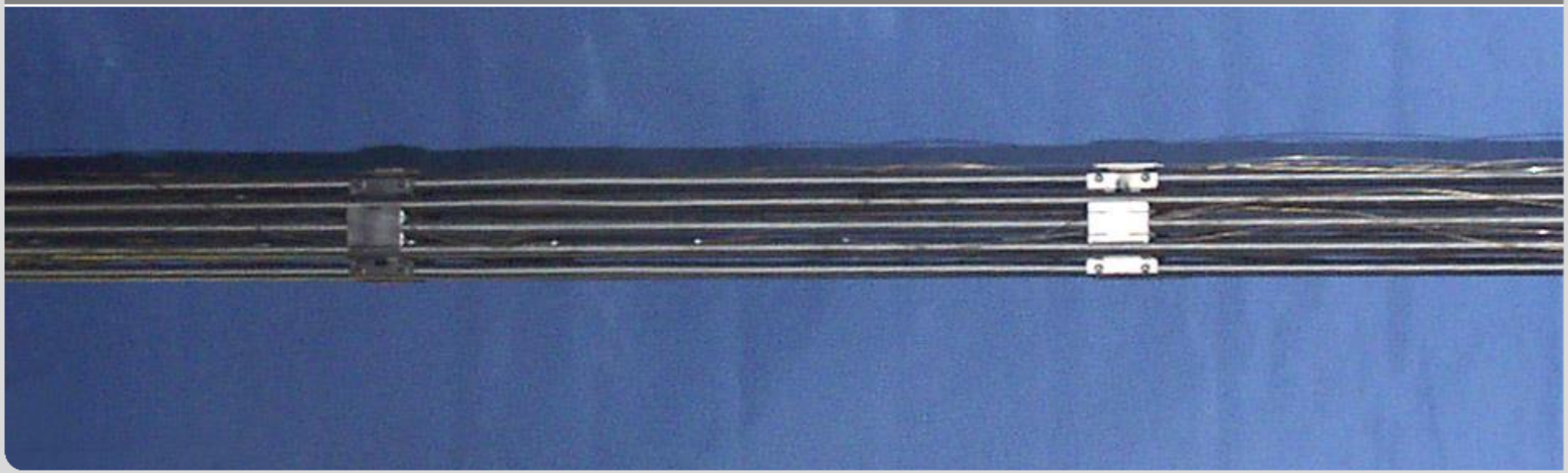
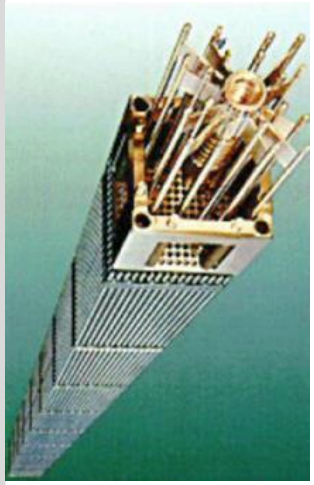
KIT, Institute for Applied Materials; Program NUSAFE



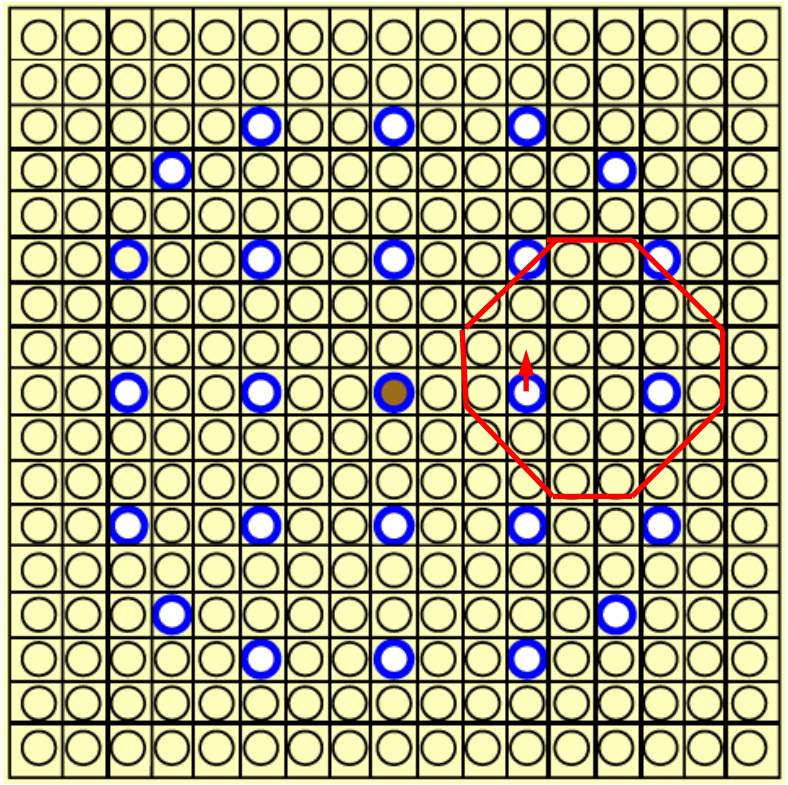
Features of the QUENCH-ALISA (QUENCH-18) bundle test:

- 20 EPR claddings M5® with OD=9.50 mm and wall thickness 0.57 mm, AREVA grid spacers AH 32715 with pitch of 12.6 mm (*investigation of EPR cladding behavior under severe accident conditions*);
- 2 rods pressurized to 60 bar (*LOCA conditions*);
- 2 Ag-In-Cd absorber rods surrounded by stainless steel cladding and M5® guide tube (*investigation of aerosol release*);
- *air + steam ingress after pre-oxidation in steam.*

Composition of test bundle



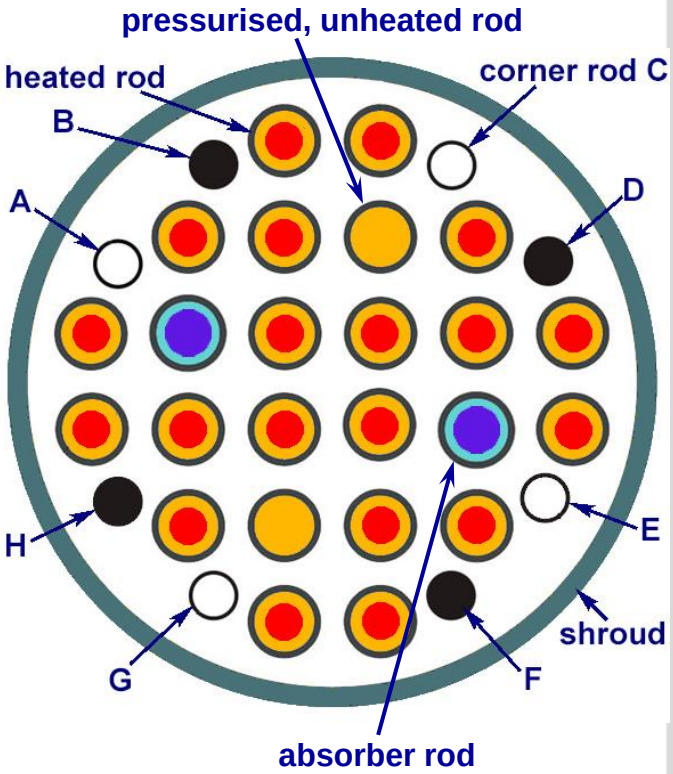
fuel assembly **17x17**



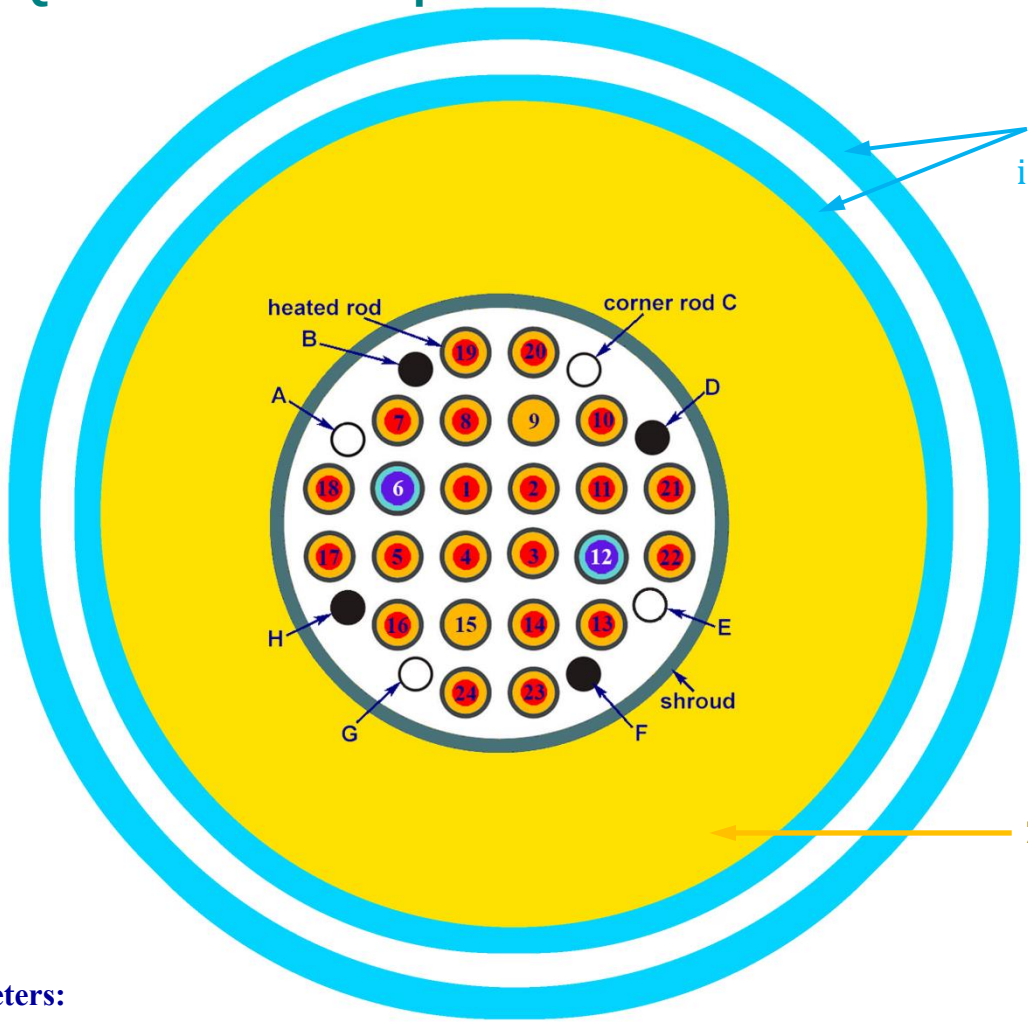
- fuel rod (264)
- guide tube for AgInCd control rod (24)
- instrument thimble

10:1

proposed QUENCH test bundle



QUENCH-ALISA: parameters of test section



Inconel cooling jacket, inner tube ID=158.3 mm

ZrO_2 porous thermal insulation

Bundle geometrical parameters:

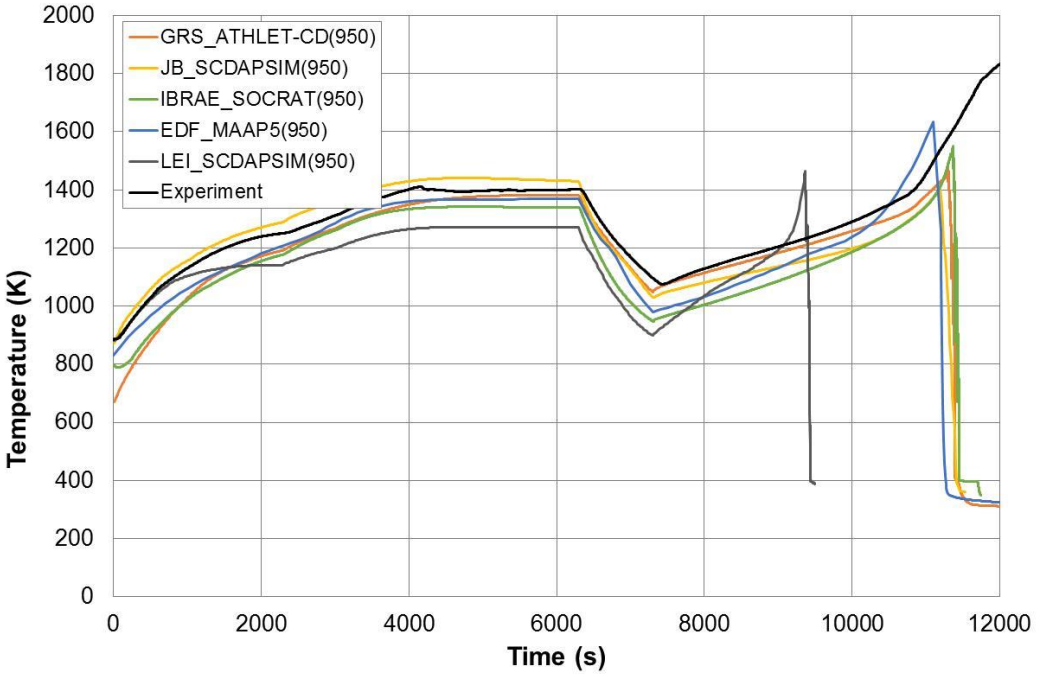
- **heated** rods (20): cladding M5® 2200 mm, OD=9.50 mm, ID=8.36 mm; ZrO_2 pellet 10 mm, OD=8.2 mm, ID 5.2 mm; W heater OD=5 mm;
- **pressurized** /to 60 bar/ *unheated* rods (2): M5®cladding; ZrO_2 pellet with OD 8.2 mm;
- **absorber** rods (2): Ag/In/Cd absorber bar with OD = 7.65 mm; stainless steel cladding with OD = 9.68 mm and ID = 7.72 mm; guide tube M5® OD = 12.45 mm, ID = 11.25 mm;
- **corner** rods (8): Zry-4; OD = 6 mm.

Absorber rod features

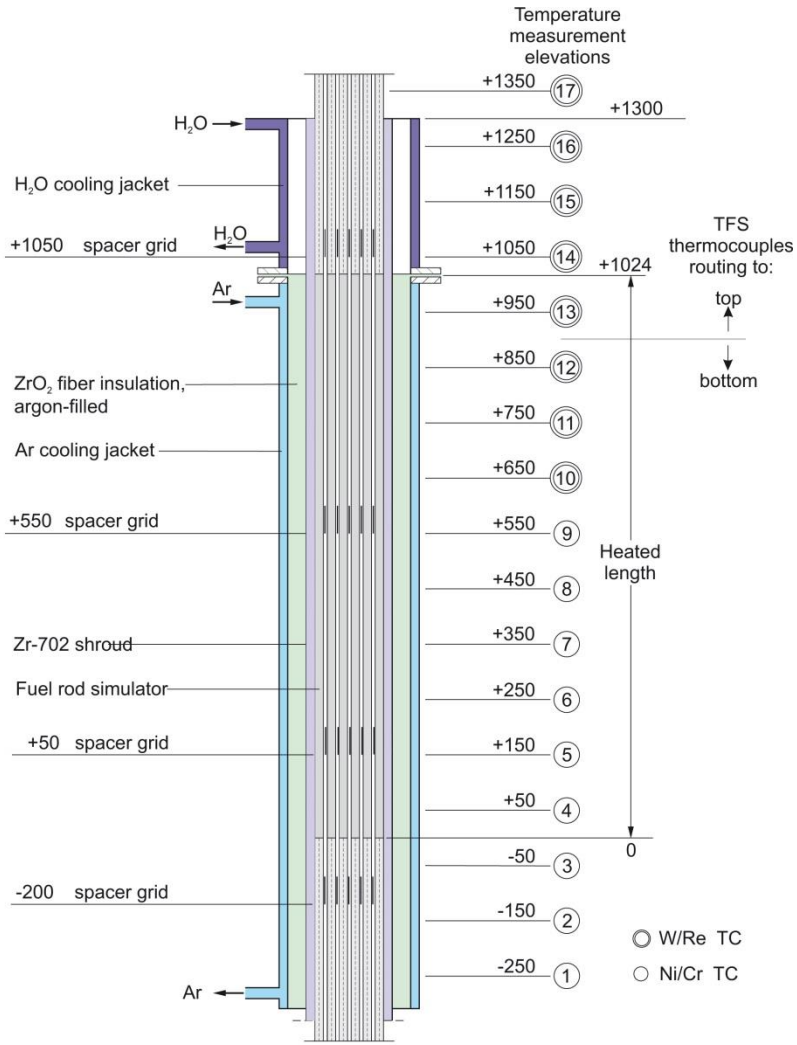
Absorber rod	**material**	**80 Ag, 15 In, 5 Cd (wt-%)**
	dimensions	∅ 8.60 mm, L=1068 mm (Elev. -15 to 1053 mm), ***M ≈ 633 g***
Cladding of absorber rod		**SS**, ∅ 9.70 / 8.75 mm L = 1083 mm (Elev. -20 to 1063 mm)
Guide tube of absorber rod		**M5®** , ∅ 12.45 / 11.25 mm L = 1187 mm (Elev. -42 to 1145 mm) Holes for coolant penetration (2x4): ∅4 mm (Elev. -34 and +1137 mm)
Internal rod pressure of absorber rod		0.12 MPa abs. (**He**)

Results of pre-test simulations

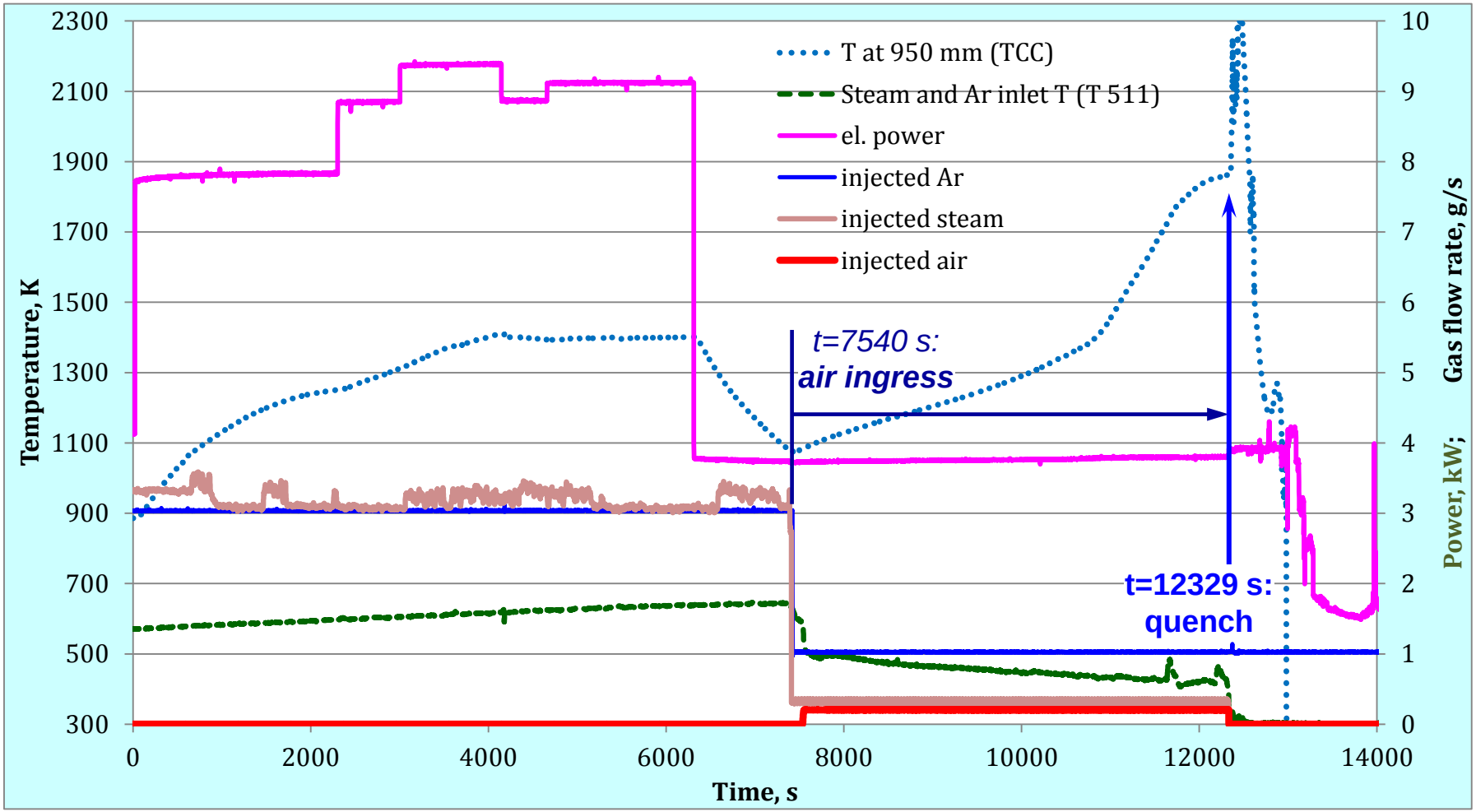
Temperatures at 950 mm



Bundle thermocouples

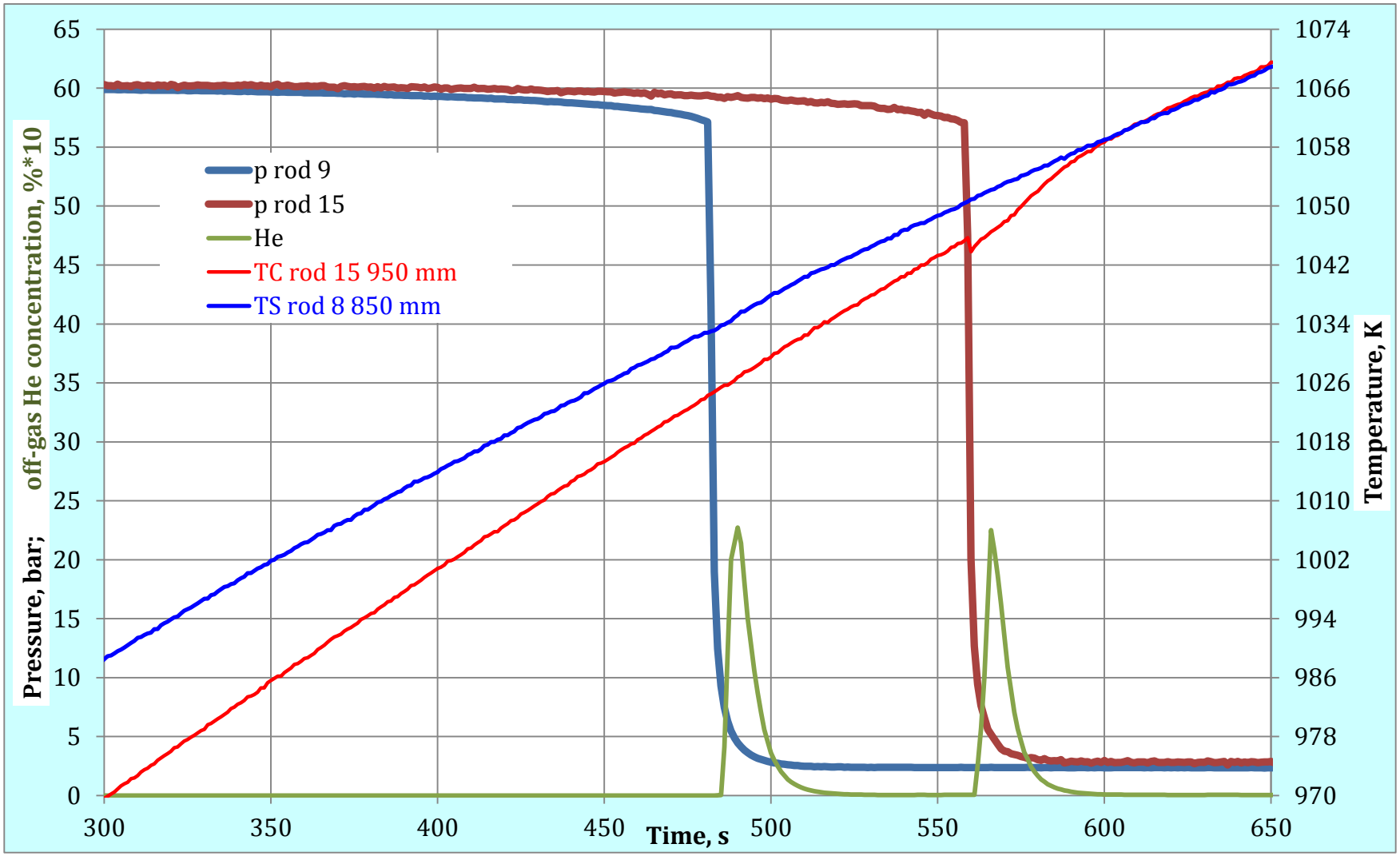


Input parameters of the QUENCH-ALISA (QUENCH-18) test



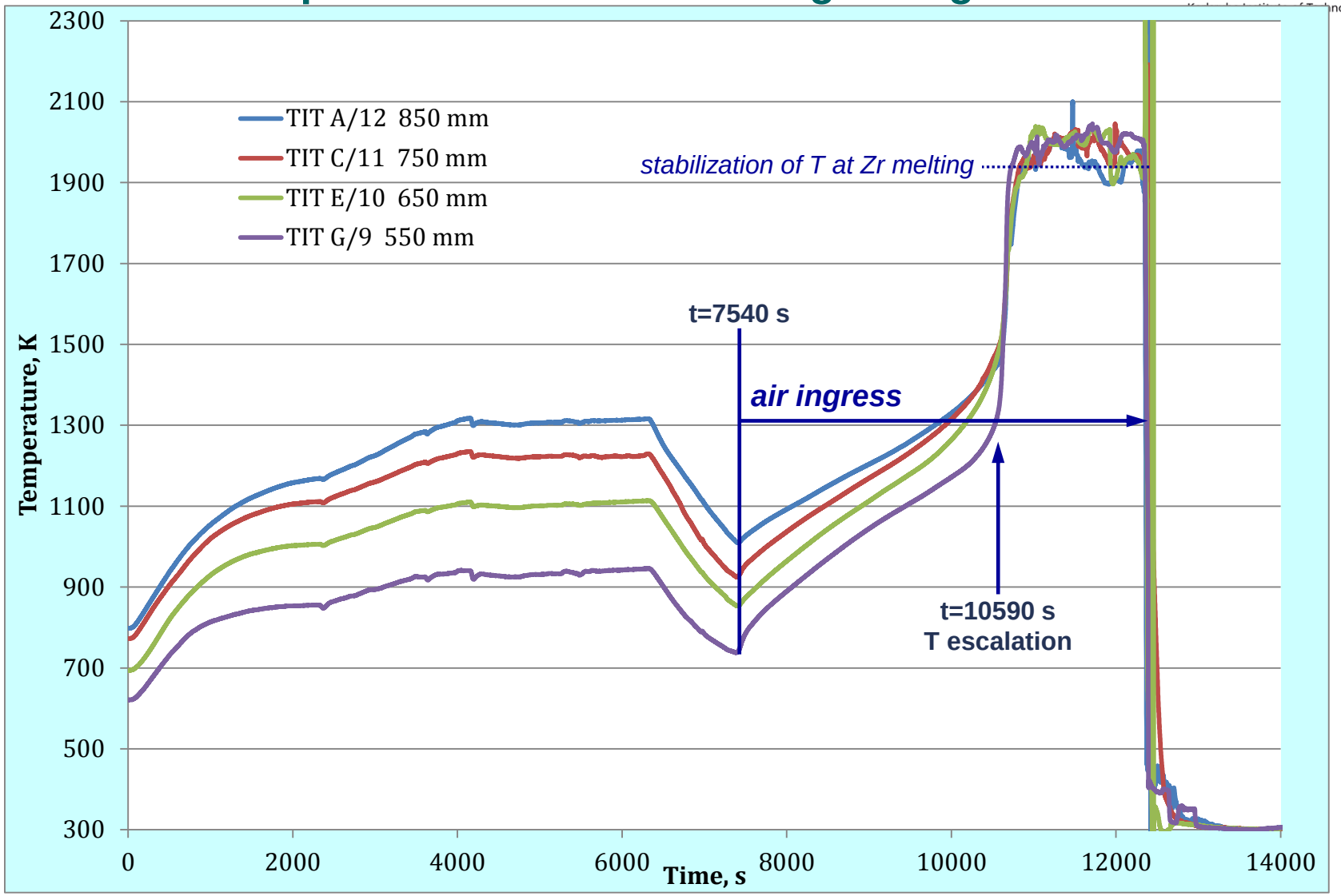
Important feature of QUENCH-18: steam flow during air ingress

Q18: burst of pressurised rods #9 (at 850 mm?) and #15 (at 950 mm)

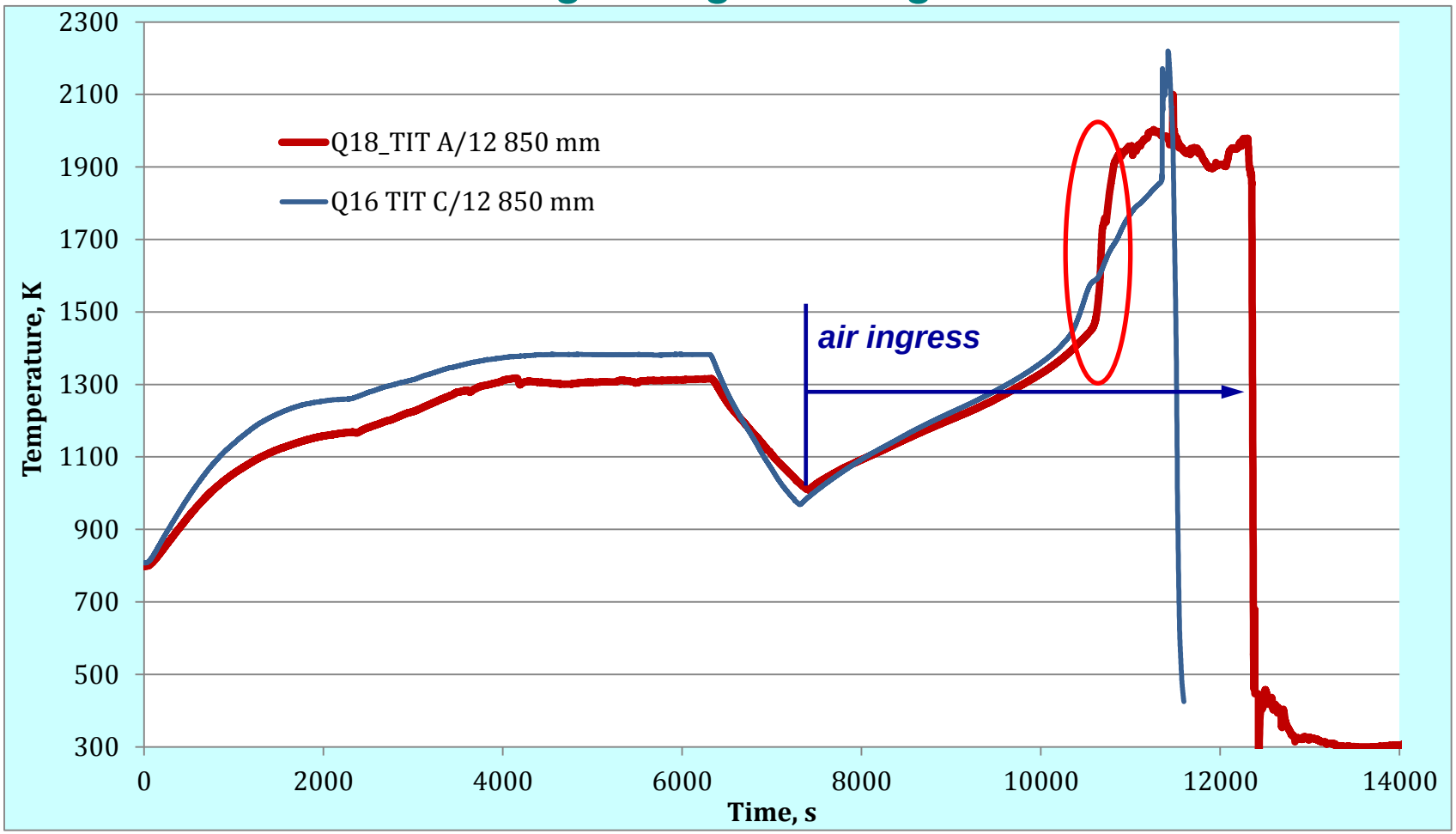


Burst temperature: 1045 K (rod #15) **at heat-up rate 0.3 K/s**

Q18: readings of sheathed thermocouples (corner rods): temperature escalation during air ingress

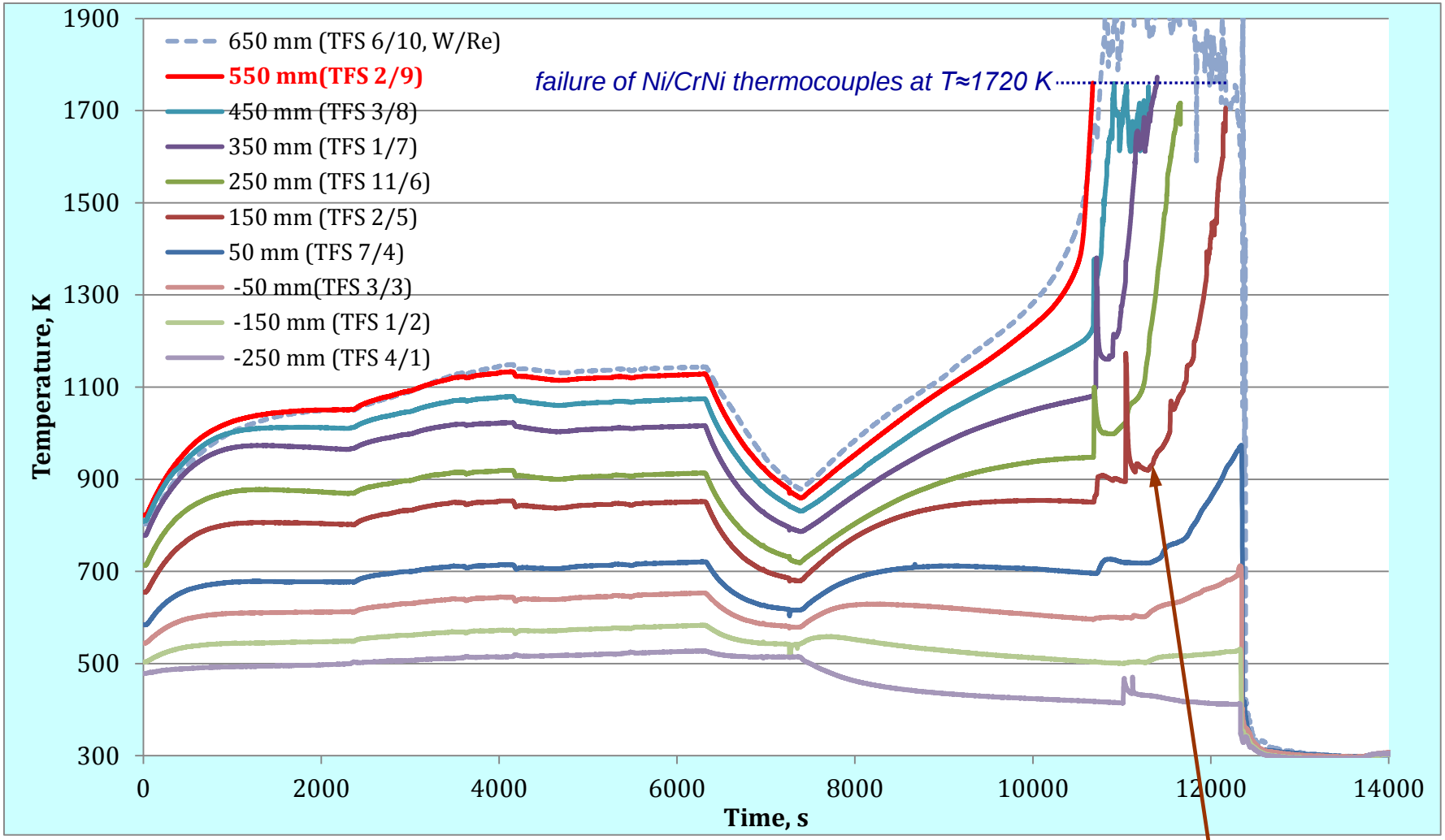


QUENCH-18 (air + steam) vs. QUENCH-16 (only air): accelerated temperature escalation during air ingress stage



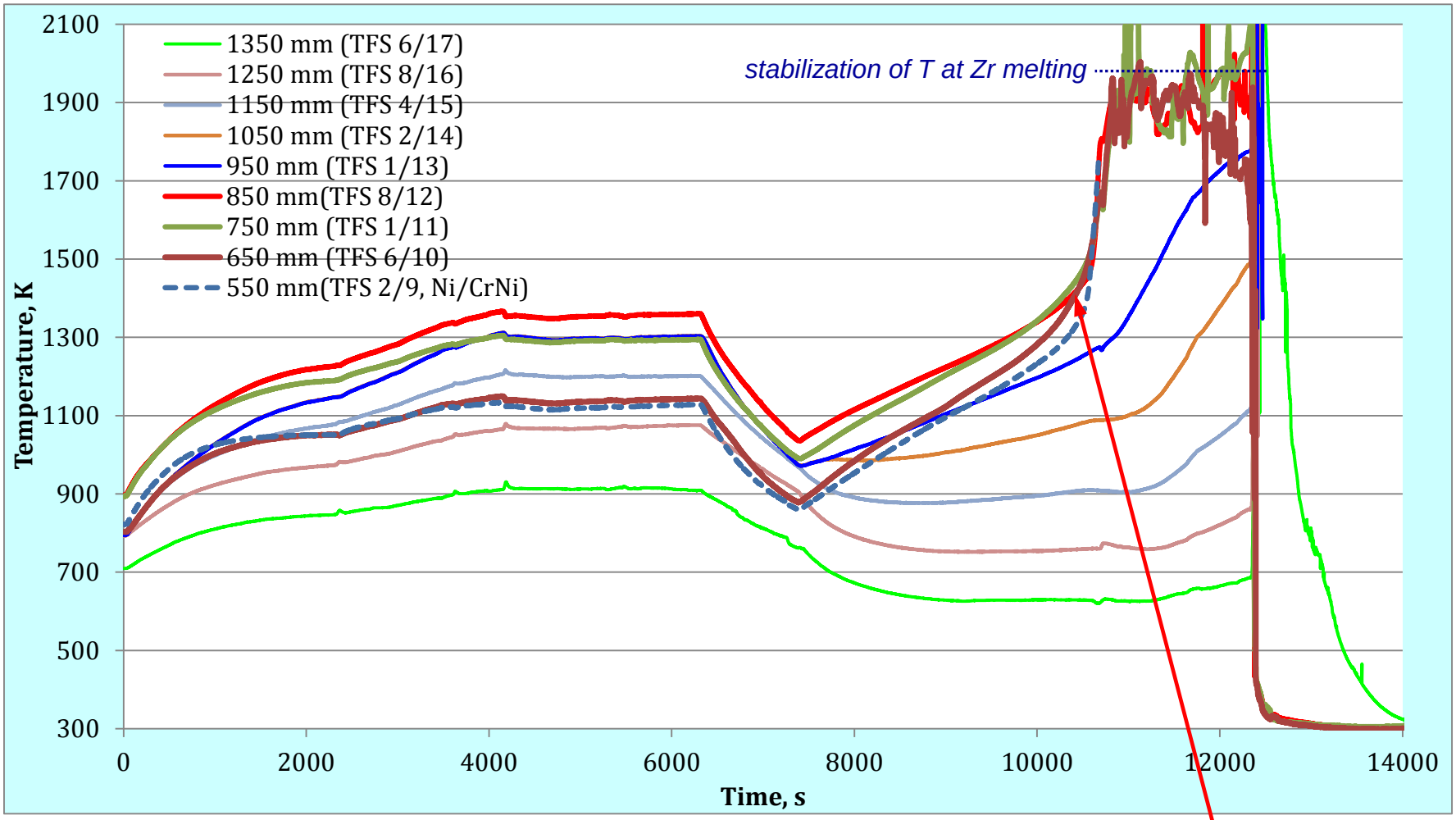
Additional chemical power (≈ 4 kW) due to cladding oxidation in steam during air ingress

Readings of clad surface thermocouples (Ni/CrNi) at lower elevations



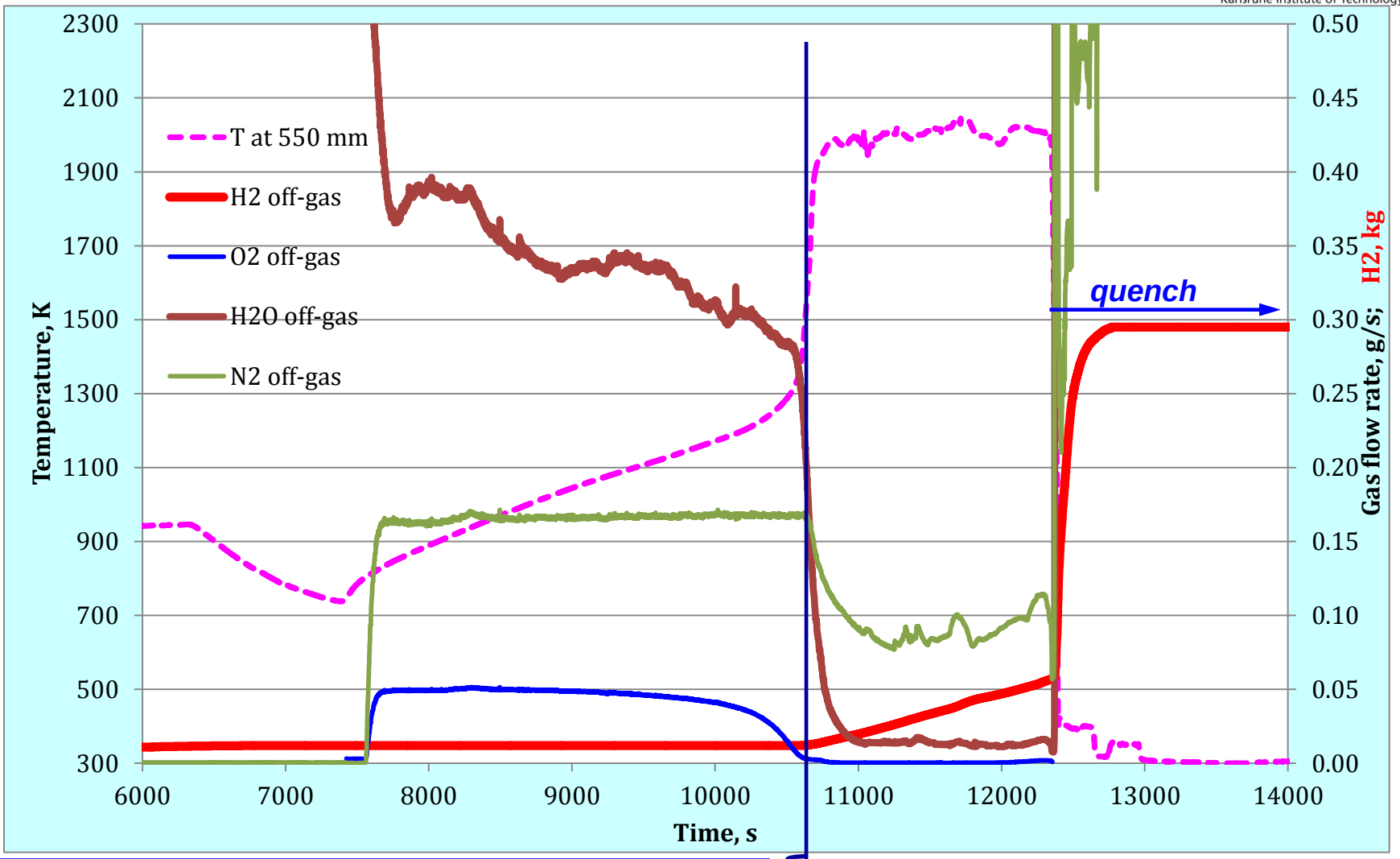
Lowest elevation with strong temperature escalation during air ingress: 150 mm

Readings of clad surface thermocouples (W/Re) at upper elevations



Highest elevation with strong temperature escalation during air ingress: 850 mm

Outlet gas behaviour during air ingress: starvation phenomena



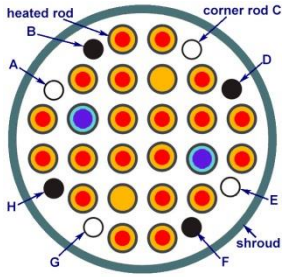
consumed oxygen: 100 g; consumed nitrogen: 120 g;
consumed steam: 450 g; released hydrogen: 45 g

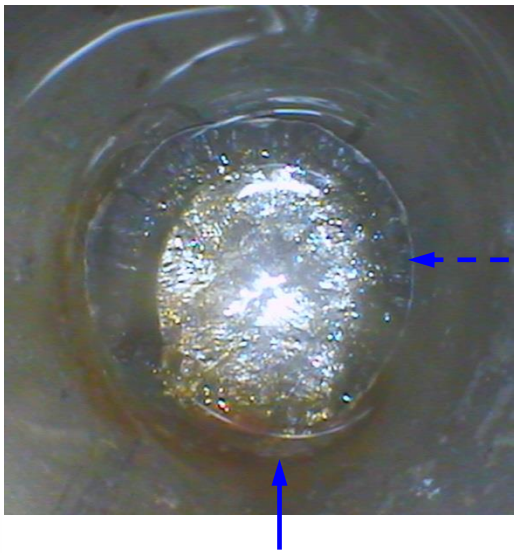
t≈10600 s: oxygen starvation, H_2 increase
steam and nitrogen consumption

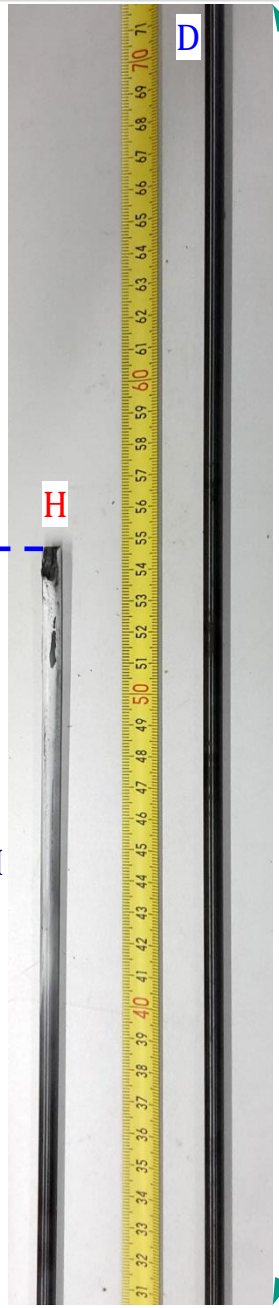
Withdrawn corner rods:

rod D before air ingress,

rod H on cessation of T escalation at 300 mm

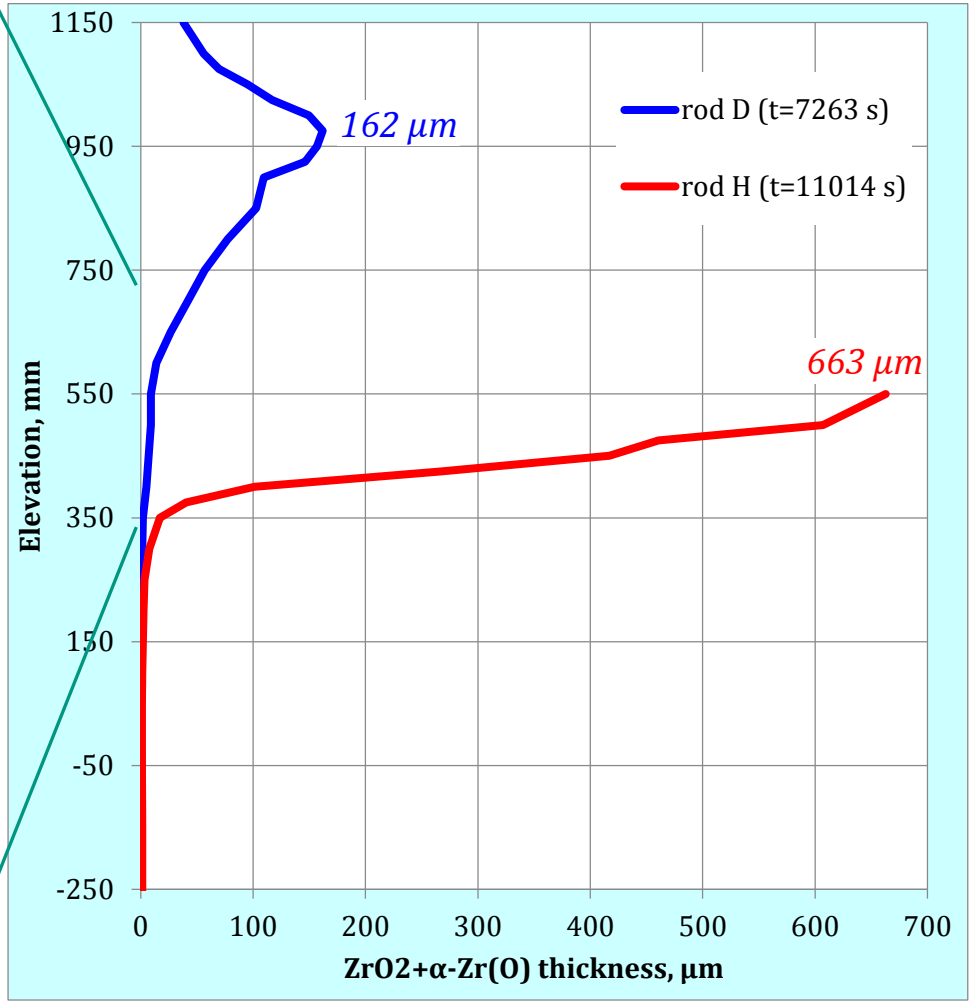






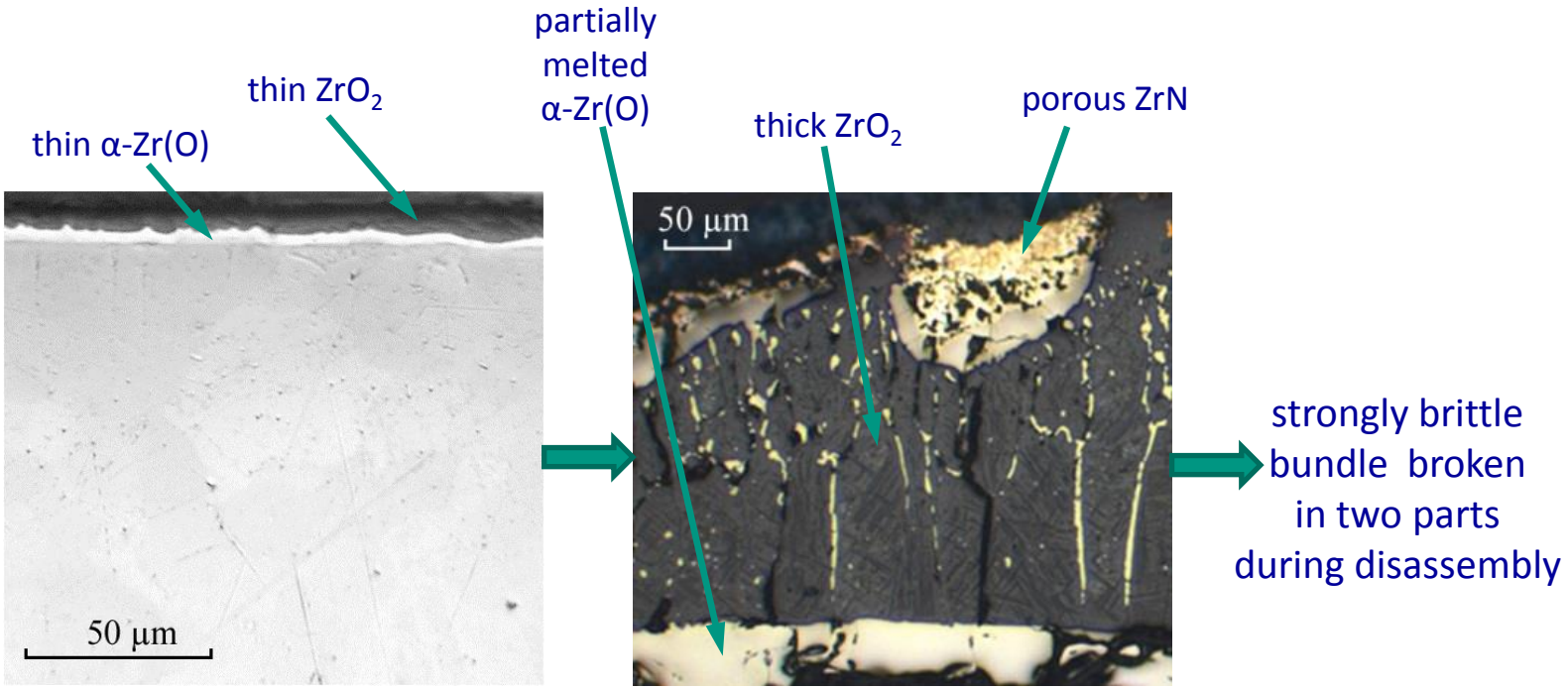
rupture position of corner rod H (550 mm)
relocated to -475 mm during the rod withdrawn

(videoscope observation through the guide tube of the corner rod H)



increased oxidation above 250 mm

Zry-4 corner rods withdrawn before air ingress (rod D) and after temperature escalation (rod H)

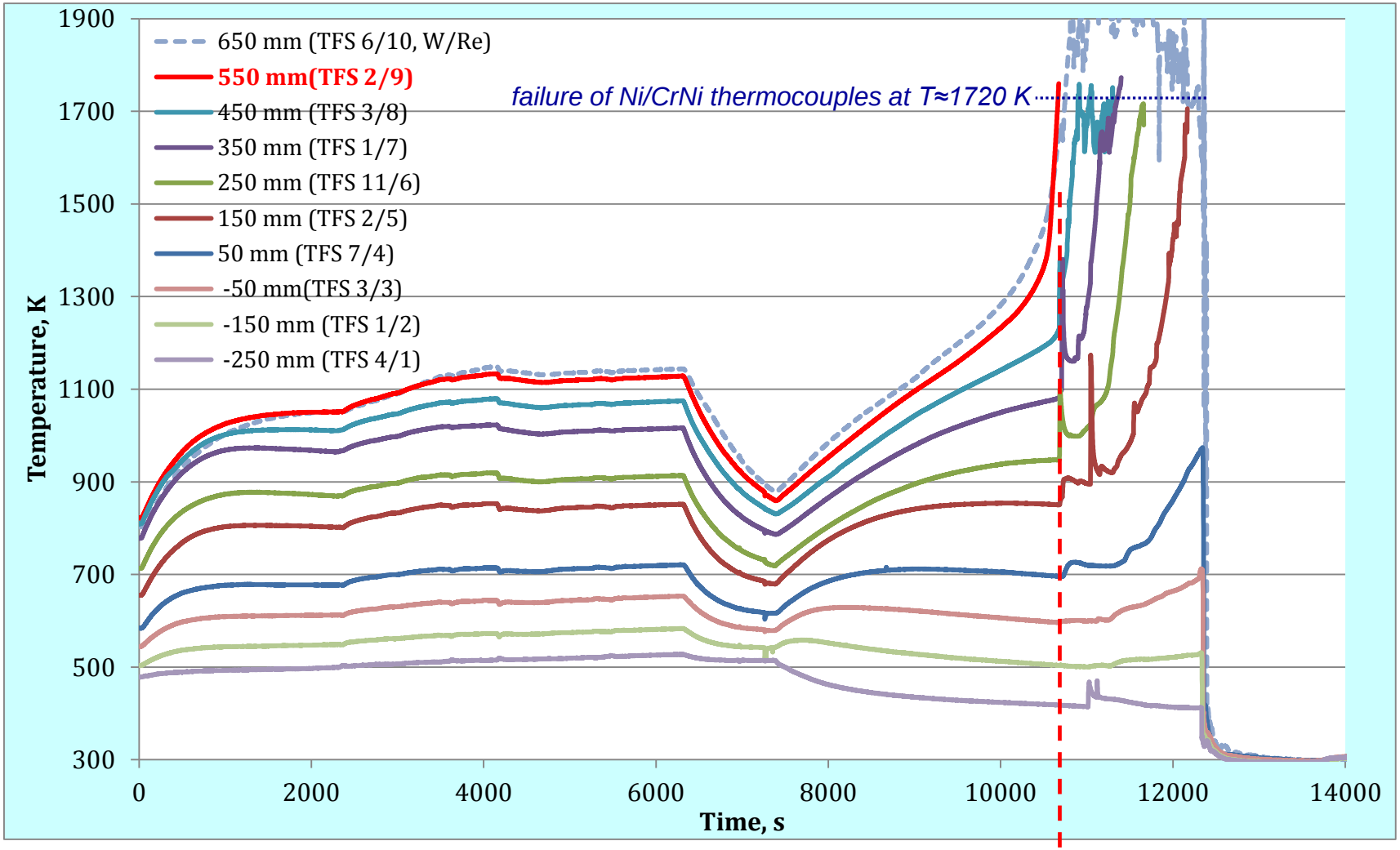


strongly brittle bundle broken in two parts during disassembly

rod D (550 mm): pre-oxidation of Zry cladding in steam at 900 °C to ZrO_2 and α-Zr(O) thicknesses of 5 µm

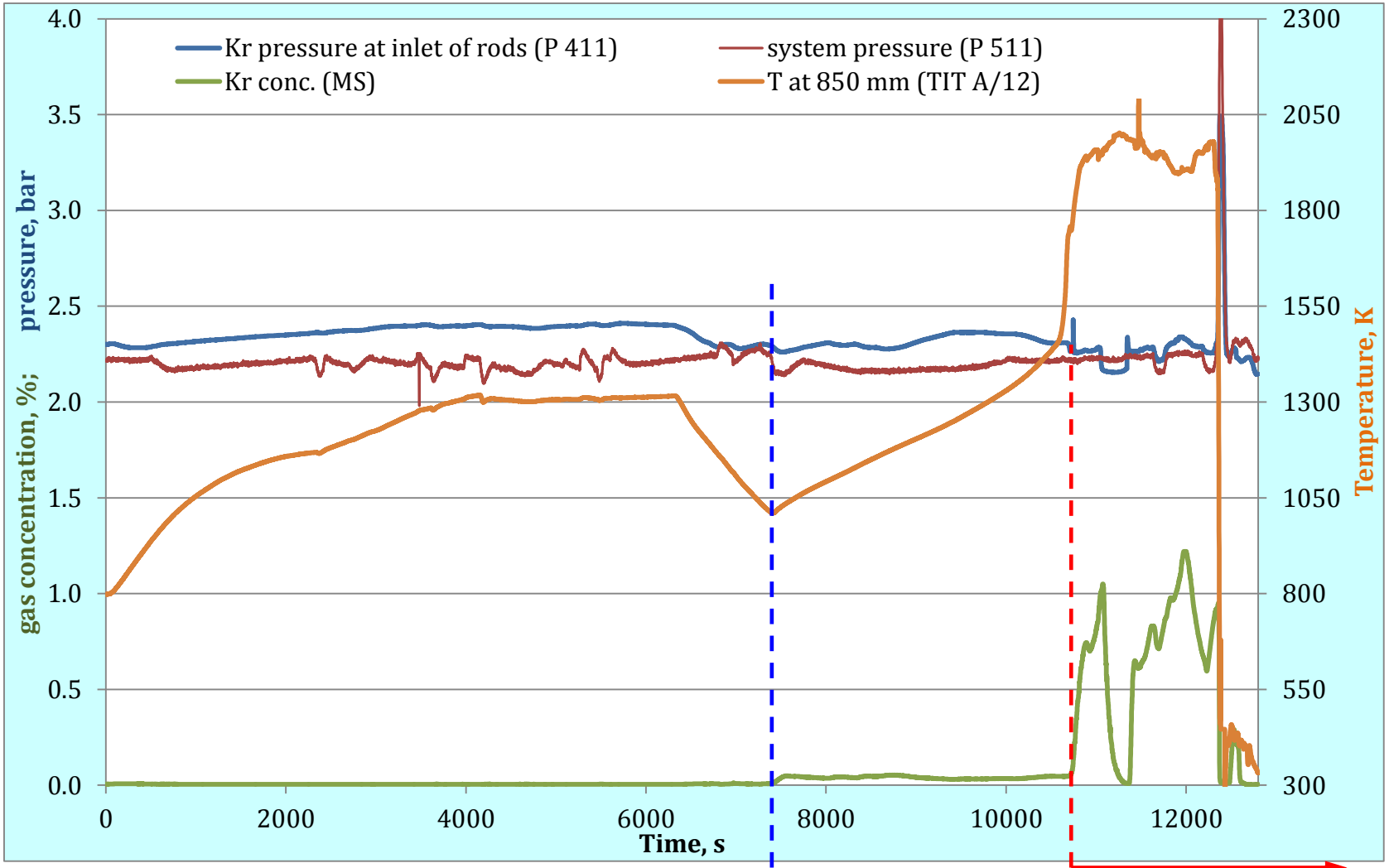
rod H (520 mm): following oxidation under transient 900…1900 °C in steam + air caused formation of ZrN inside growing ZrO_2

Readings of thermocouples at bundle elevations from -250 mm (bundle bottom) to +550 mm (strongest T escalation)

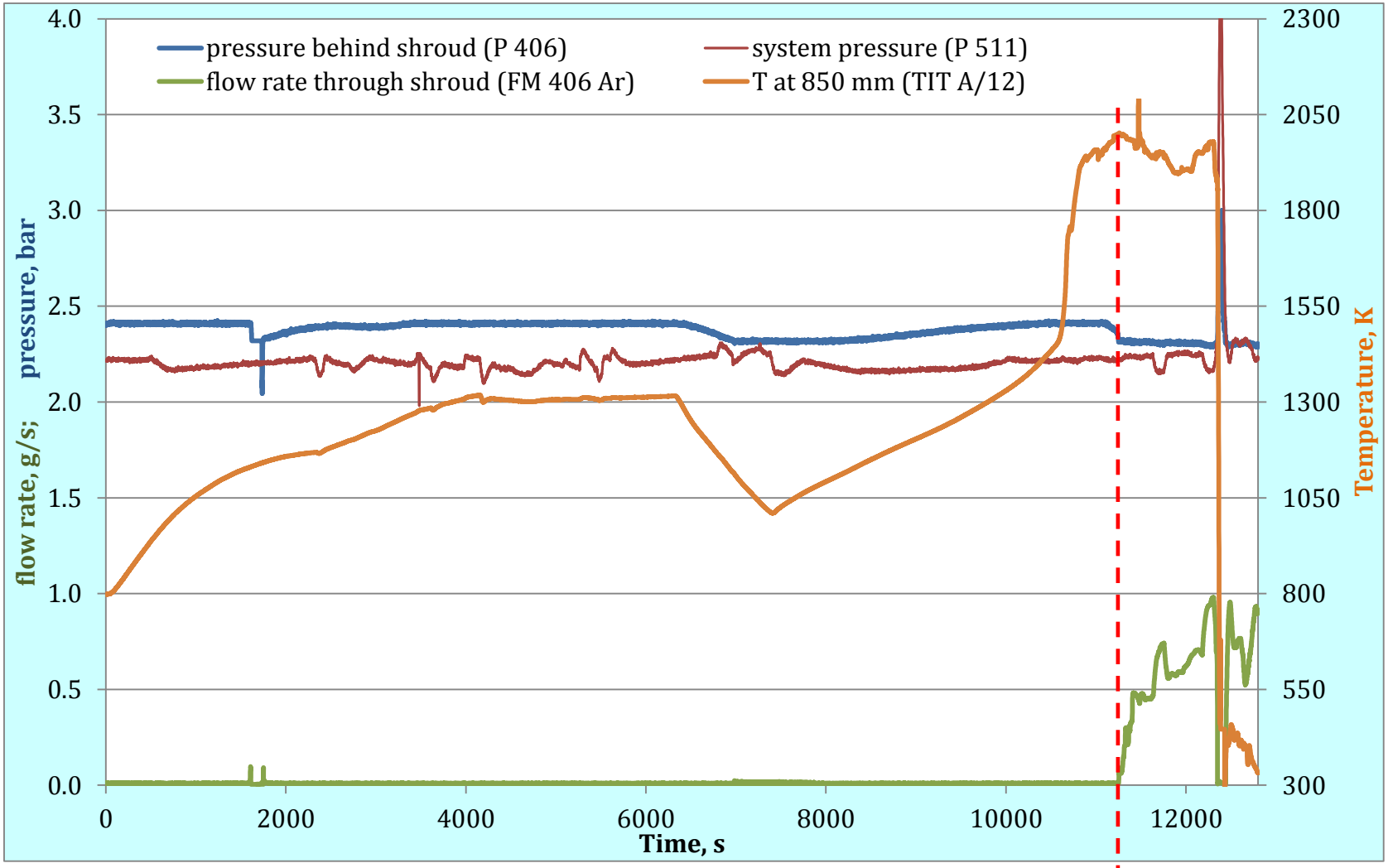


t=10680 s: absorber melt relocation from ≈ +550 mm to lower elevations

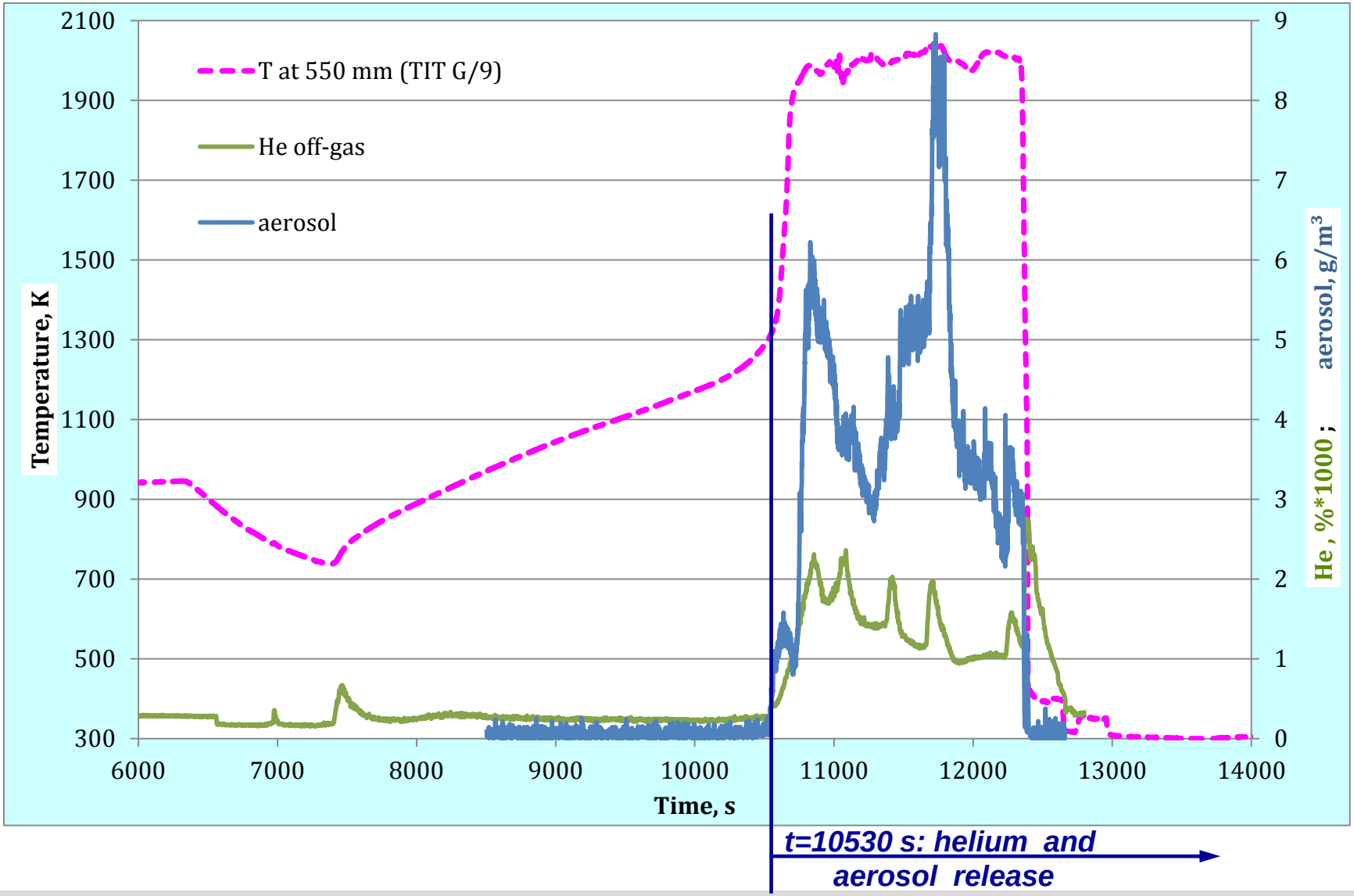
Failure of claddings (Kr release)



Failure of shroud (Ar flow through shroud breach)



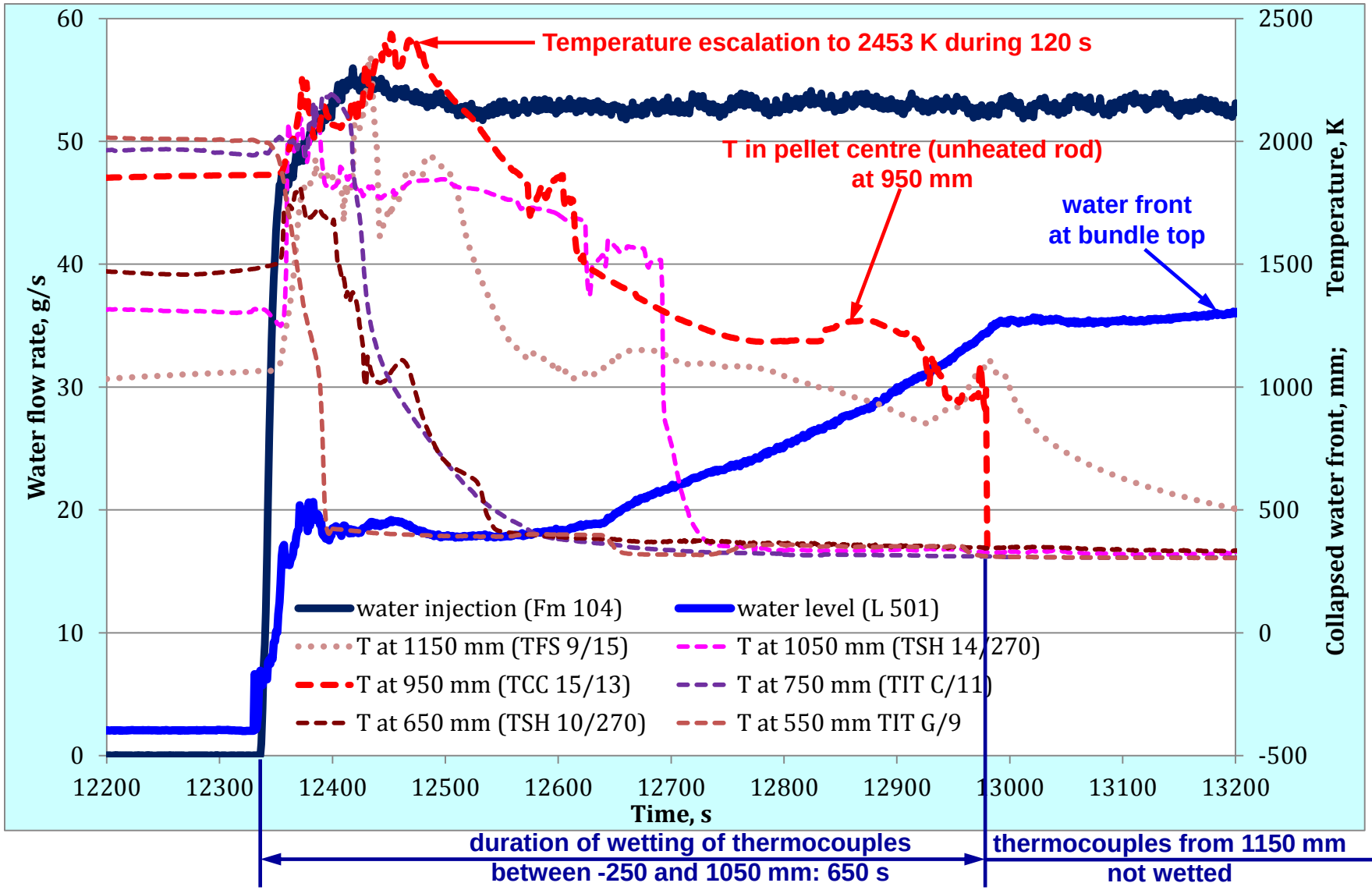
Failure of absorber rods and aerosol release



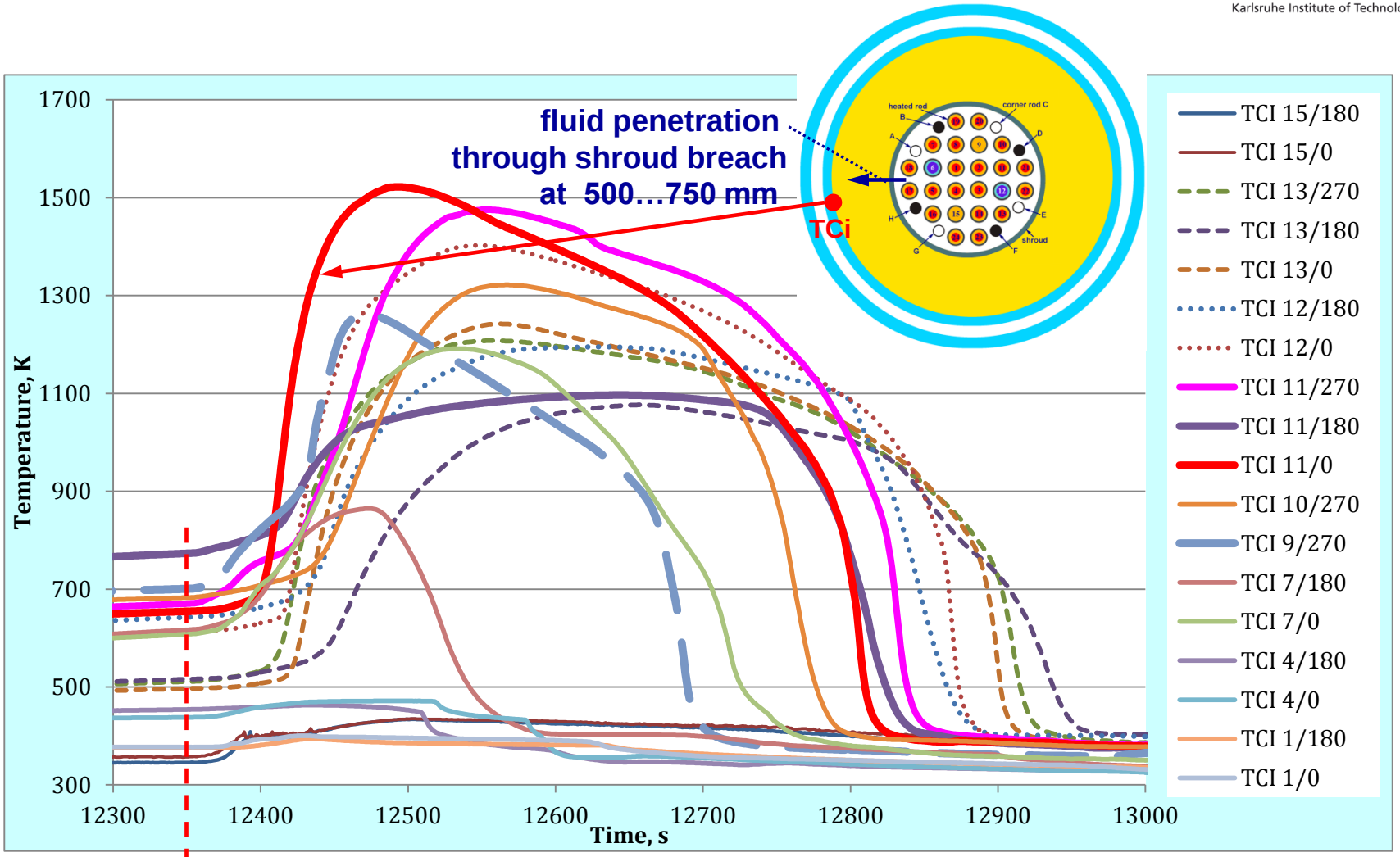
QUENCH-ALISA: release of Cd, In, Ag

Element	Released, g	fraction from total, %
Cadmium	**7.5**	**12**
Indium	0.7	0.4
Silver	6.9	0.7
Total	*15.1*	*1.2*

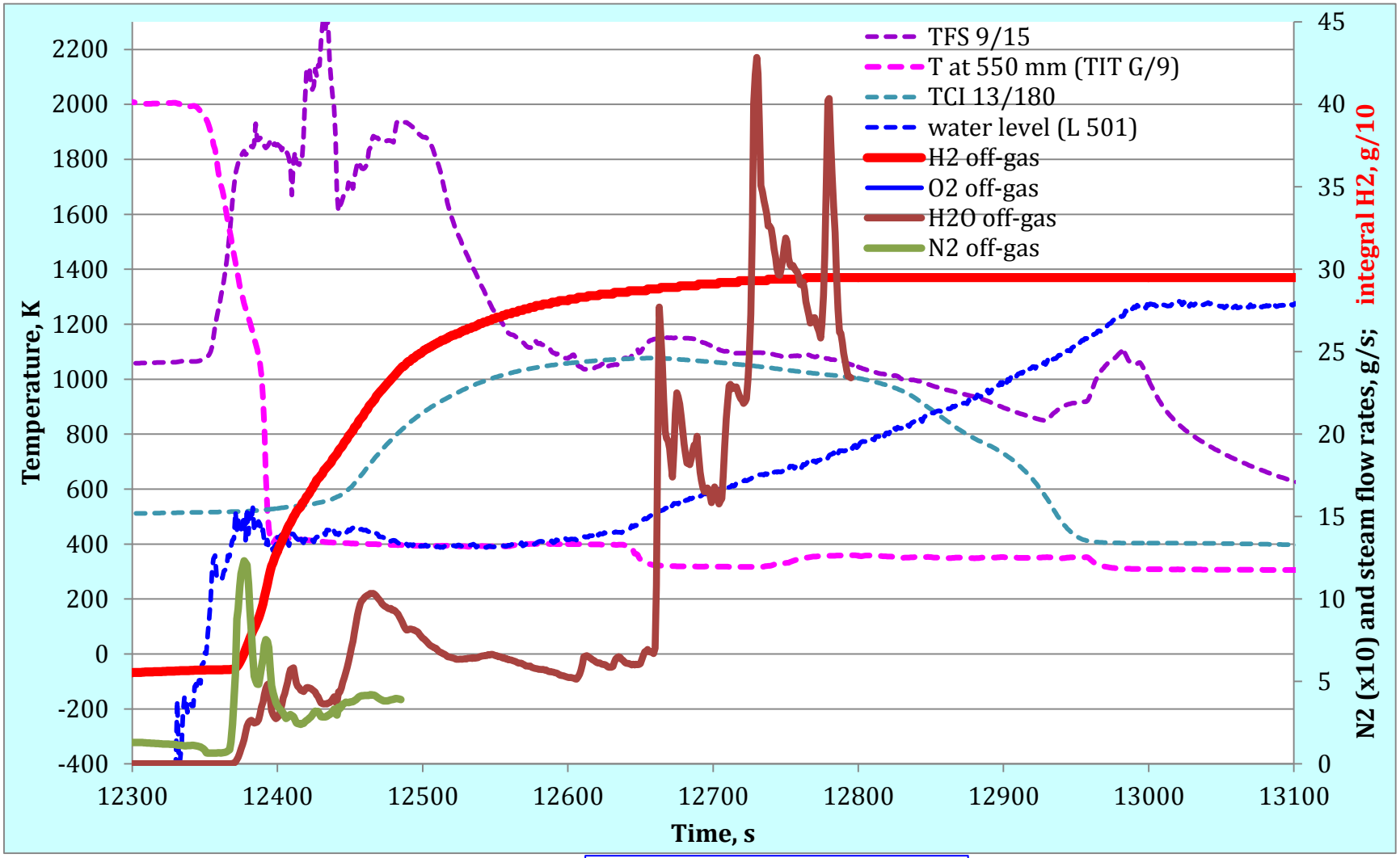
Water and temperatures during the quench stage



Readings of thermocouples at inner surface of cooling jacket after quench initiation

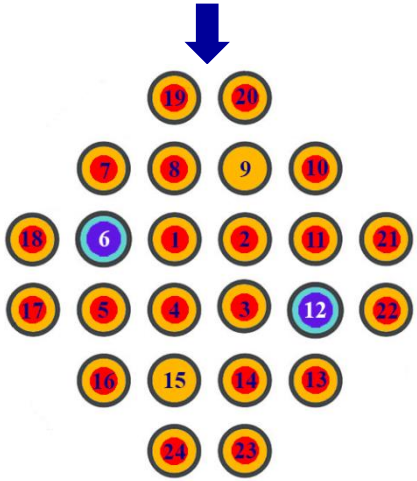


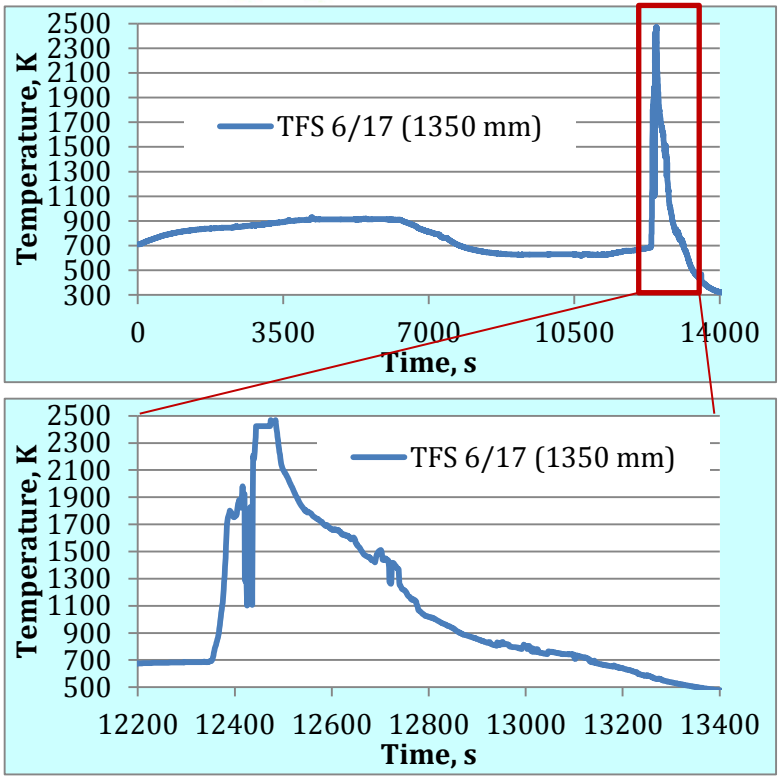
Gas release during the quench stage

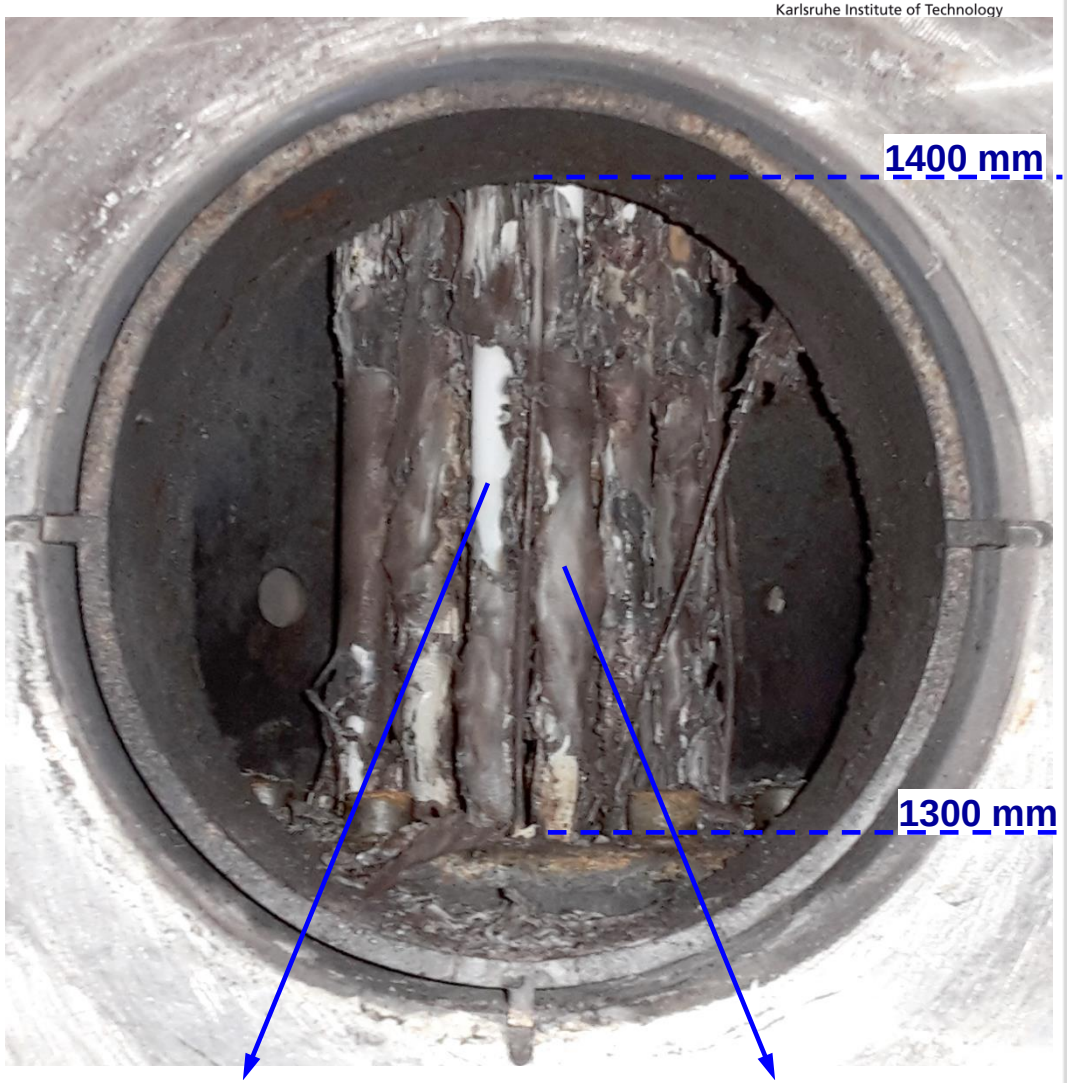


released hydrogen: 238 g
released nitrogen: >54 g

Overview of the bundle at bundle top



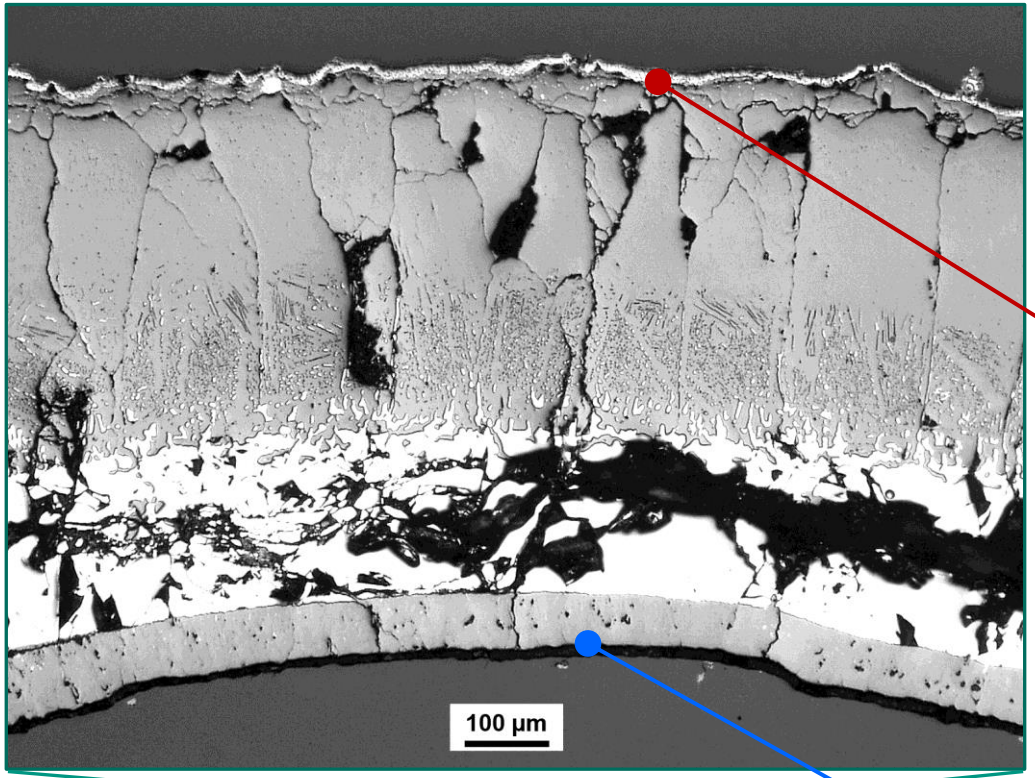


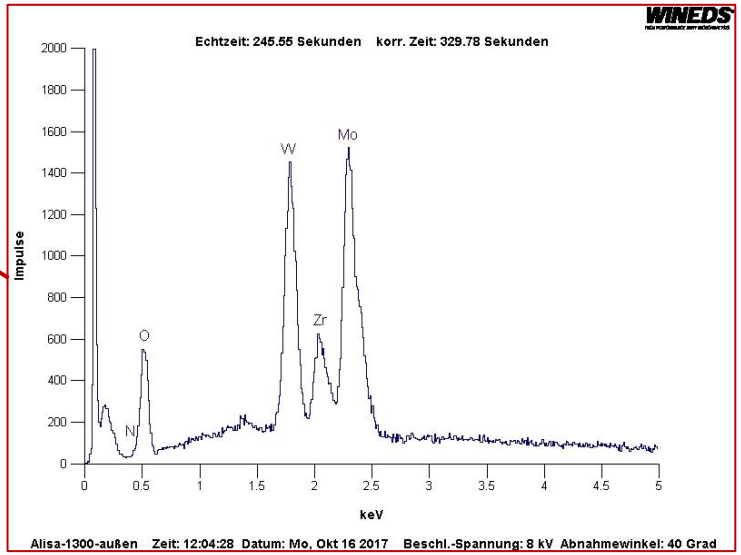


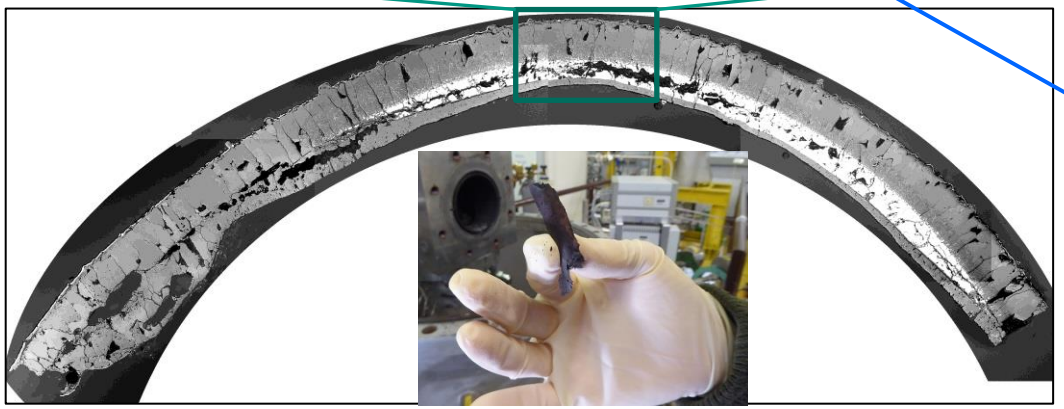
ZrO_2 coating of Mo heater
(rod 20)

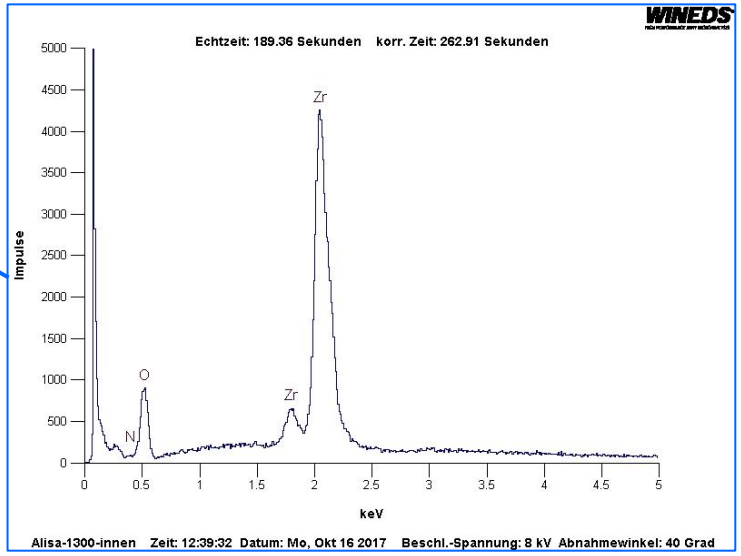
oxidised cladding
(rod 19)

Analysis of cladding segment spalled at 1350 mm from rod #20



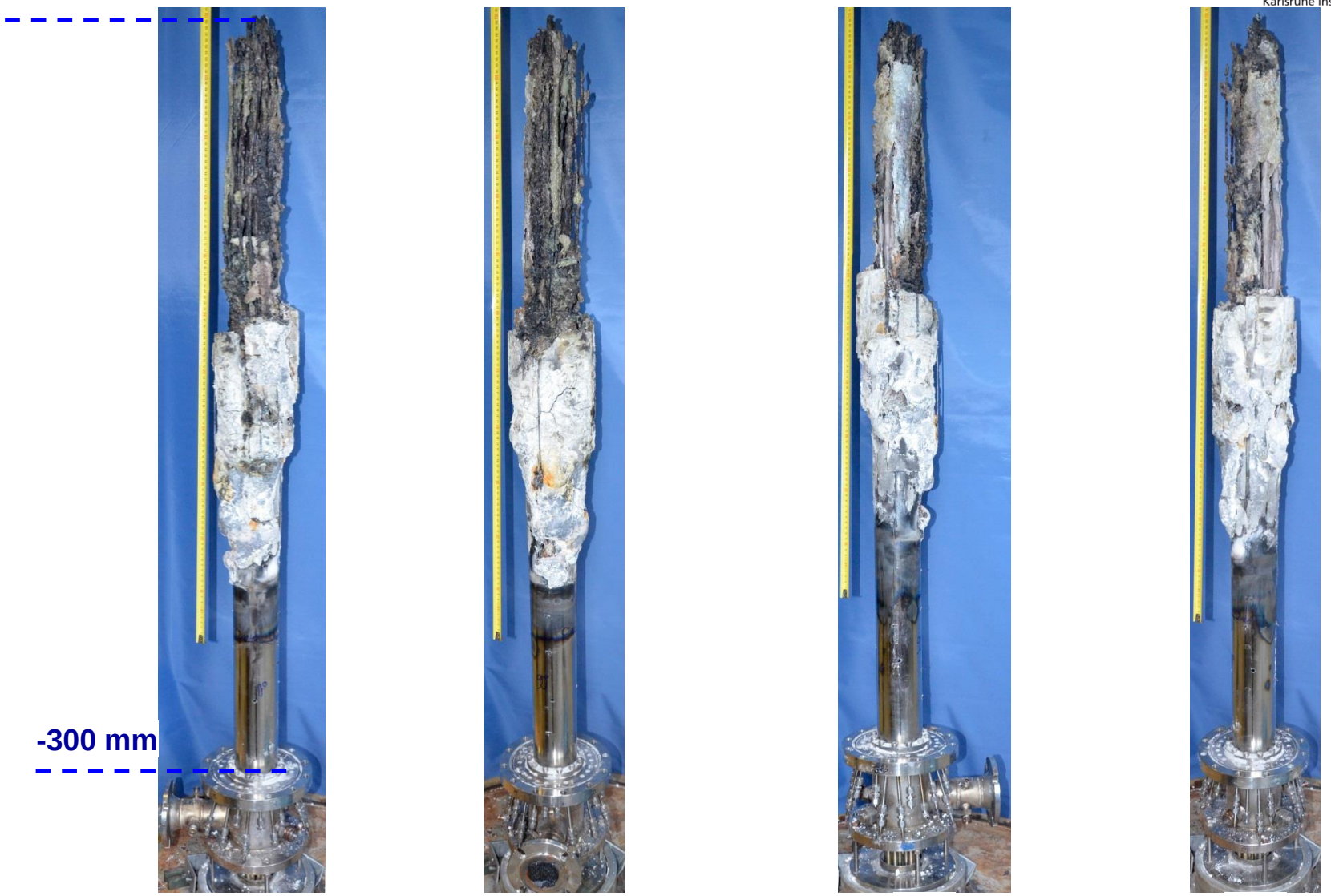






Post-test upper bundle part between 1100 and 1500 mm

Post-test bundle overview between -300 and 1100 mm



Post-test bundle overview between 600 and 1100 mm

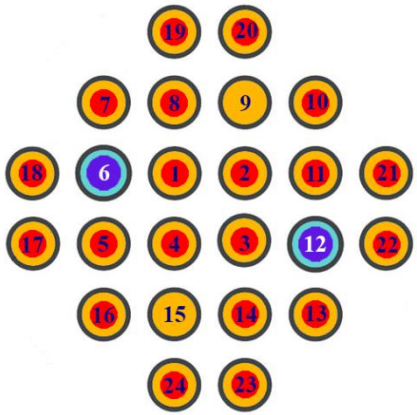
0°

90°

180°

270°

Post-test bundle cross-sections at upper elevations with coated Mo heaters



bundle composition at upper elevations

1480 mm: intact rods, slightly oxidized clads

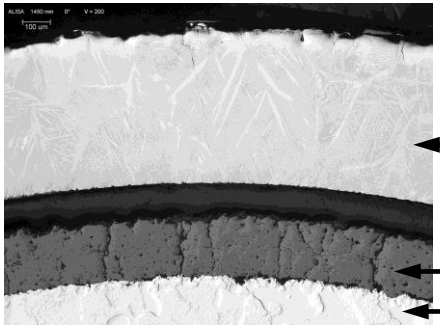
1430 mm (upper spacer grid): loss of clads

1350 mm: remainders of strong oxidized clads

1250 mm: remainders of strong oxidized clads

1150 mm: remainders of strong oxidized clads

Upper part of rod #3 between 1100 and 1500 mm

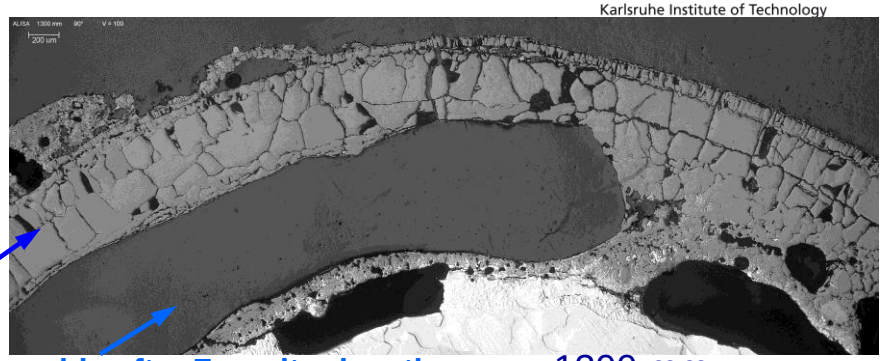


metallic part of cladding (≈550 µm)

ZrO_2 coating

Mo

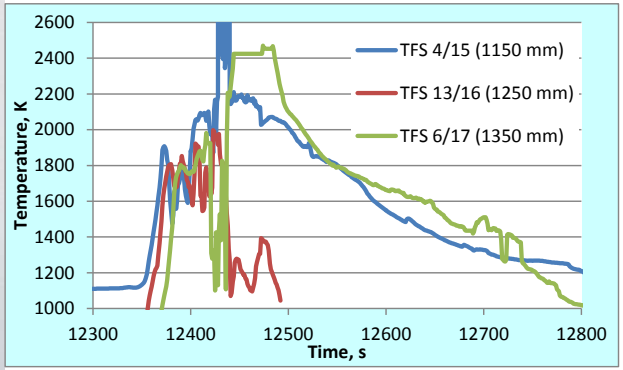
1450 mm

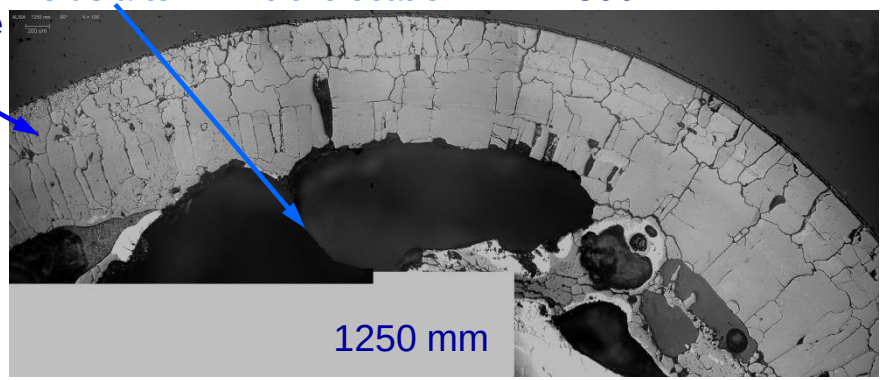


oxidised cladding with partially dissolved oxide

voids after Zr melt relocation

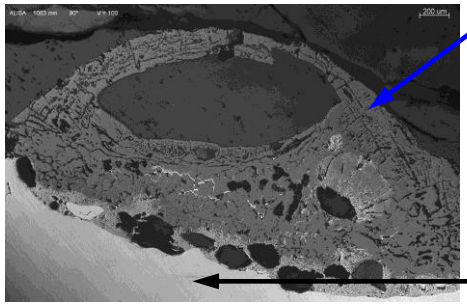
1300 mm



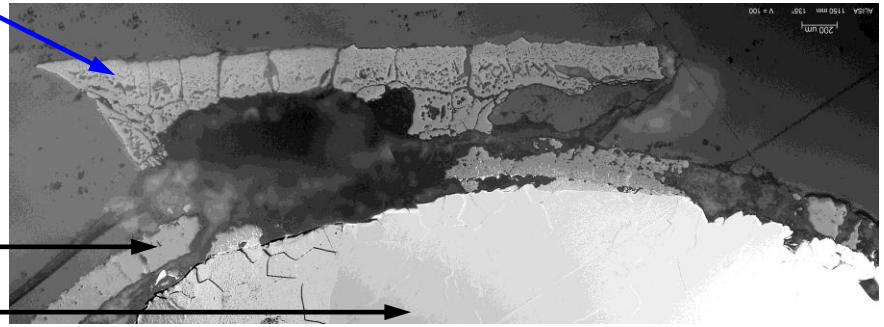


1250 mm

remnants of cladding oxide



1083 mm



ZrO_2 coating

Mo

1150 mm

Summary

- The QUENCH-18 test with bundle containing 20 heated and 2 unheated rods with M5® cladding as well as 2 Ag-In-Cd absorber rods was performed at KIT on September 27, 2017 in the framework of the ALISA project.
- Three typical features of QUENCH-18: moderate pre-oxidation to ≈80 µm of oxide layer (less than in QUENCH-16), a long period of oxygen starvation during the air+steam ingress phase (1770 s instead 800 s for QUENCH-16 without steam injection during air ingress), and reflood initiation at the melting point of the cladding (≈ 2000 K instead of 1700 K for QUENCH-16).
- The claddings of unheated rods burst at 1045 K at heat-up rate 0.3 K/s. It is lower in comparison to burst temperatures for the bundle test QUENCH-L2 (Tpct = 1138 ± 34 K) due to lower heat-up rate and thinner cladding wall.
- The temperature escalation during the air ingress between elevations 150 and 850 mm was significantly stronger than for QUENCH-16 due to additional exothermal cladding oxidation in steam (corresponding additional chemical energy of ≈4 kW was even slightly higher than electrical power).

Summary (cont.)

- Releases of aerosols and helium were registered on the beginning of temperature escalation (failure of absorber rods). Simultaneously, the readings of cladding surface thermocouples below elevation of 550 mm indicated the relocation of absorber melt.
- During the starvation period about *100 and 450 g oxygen and steam* were consumed. During the steam consumption period about *45 g hydrogen* were released. In the same period the partial consume of *nitrogen (about 120 g)* was registered.
- Initiation of reflood with 50 g/s water caused strong temperature escalation to about 2450 K at elevations between 750 and 1150 mm. As result, about *238 g hydrogen* were released (128 g for QUENCH-16). During re-oxidation of zirconium nitrides more than *54 g nitrogen* were released.
- First observations of bundle at elevations between 1300 and 1400 mm showed spalling of strongly oxidized cladding segments from rods. No remaining nitrides or nitrides re-oxidized during reflood were indicated at these upper elevations. Probably, they were dissolved by relocated melt.

Thank you for your attention

http://www.iam.kit.edu/awp/666.php
http://quench.forschung.kit.edu/

https://www.psi.ch/sacre/

http://en.xjtu.edu.cn/