First results of the QUENCH-ALISA bundle test

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Experiment QUENCH-18 on air ingress and aerosol release was successfully conducted at KIT on 27 September 2017. This test was performed in the frame of the EC supported ALISA programme. It was proposed by XJTU Xi'an (China) and supported by PSI (Switzerland) and GRS (Germany). The determination of the test protocol was based on planning calculations by participants of the QUESA project: EDF (MAAP5), GRS (ATHLET-CD), IBRAE (SOCRAT), Jon Birchley (SCDAP-SIM) and LEI (RELAP/SCDAPSIM).

The test objectives were agreed following discussions between XJTU, EDF and KIT. The primary aims were to examine the oxidation of M5® claddings (OD=9.5 mm, wall thickness 570 μm) 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. QUENCH-18 was thus a companion test to the earlier air ingress experiments, QUENCH-10 and QUENCH-16 (in contrast to QUENCH-18, these two bundle tests were performed without steam flow during the air ingress stage). Additionally, the QUENCH-18 experiment investigated the effects of the presence of two Ag/In/Cd control rods on early-phase bundle degradation (companion test to the QUENCH-13 experiment), and two pressured unheated rod simulators (60 bar, He). The low pressurised heater rods (2.3 bar, similar to the system pressure) were Kr-filled.

In common with the previous QUENCH experiments, the bundle was heated by a series of stepwise increases of electrical power from room temperature to a maximum of ≈900 K in an atmosphere of flowing argon (3 g/s) and superheated steam (3.3 g/s). The bundle was stabilised at this temperature, the electrical power being ≈4.1 kW.

In a first transient, the bundle was heated by power increase to the peak cladding temperature of $T_{pct} \approx 1400$ K, reached at 4000 s (with the heat-up rate 0.3 K/s). During this heat-up, claddings of the two pressurised rods were burst at temperature of 1045 K. The attainment of $T_{pct} \approx 1400$ K marked the start of the pre-oxidation phase to achieve a maximum cladding oxide layer thickness of up to 150 μm. The power was controlled via small variations between 8.8 kW to 9.4 kW, to maintain more or less constant temperatures. In line with pre-test planning calculations about 11.5 g of hydrogen were produced in this phase which lasted until 6310 s. At this point the power was reduced to 3.8 kW which effected a cooling of the bundle to $T_{pct} \approx 1080$ K, as a preparation for the air ingress phase. This phase lasted about 1100 s, until 7400 s. Towards the end of this phase, one of the corner rods was extracted from the test bundle for determination of the oxide thickness axial distribution. Preliminary measurement showed an oxide layer thickness of less than 160 μm (at bundle elevation of 950 mm) indicating maximum oxidation in the bundle was within the target band.

In the subsequent air ingress phase, the steam flow was reduced to 0.3 g/s (7411 s), the argon flow was reduced to 1 g/s (7424 s), and air was injected at 7540 s with the flow rate of 0.2 g/s. The power was maintained at 3.8 kW. The change in flow conditions had the immediate effect of reducing the heat transfer so that the temperatures began to rise again.

After some time measurements demonstrated a gradual increasing consumption of oxygen, starting at about 9000 s. The first Ag/In/Cd aerosol release was registered at 10530 s with corresponding T_{pct} = 1350 K (at 950 mm) and T_{550mm} = 1300 K. The first aerosol release was dominated by Cd bearing aerosols. Later in the transient, a significant release of Ag was observed along with continued Cd release, as well as a small amount of In. High aerosol concentration of several g/Nm^3 was measured until the isolation of the aerosol measurement system at the time of the quench initiation. The sharp increase of the steam consumption with simultaneous hydrogen release was registered at 10550 s. In contrast to the QUENCH-16 test (performed with the air ingress stage without steam flow), oxidation of bundle parts in steam caused release of additional chemical energy (power about 4 kW) and consequently acceleration of bundle heat-up. A strong temperature escalation started at about 10590 s at the bundle elevation of 550 mm and propagated to the upper and lower elevations between 150 and 850 mm. A period of oxygen starvation started at about 10700 s and was followed (about 300 s later) by almost complete steam consumption. Shortly before that time (10640 s), partial consumption of the nitrogen was first observed, indicating the possibility of local oxygen and steam starvation which promoted the onset of nitriding of claddings, shroud, corner rods and absorber guide tubes. Following this the temperatures continued to increase and stabilised at melting temperature of Zr bearing materials until water injection was initiated at 12330 s. Thus there was a period of 1630 s of strong steam and complete oxygen consumptions and hence starvation in at least part of the bundle. The total uptakes of oxygen, steam and nitrogen were 100±3, 450±10 and 120±3 g, respectively. During this starvation period a noticeable production (about 25 mg/s, totally 45±1 g) of hydrogen was measured. Significant release of Kr beginning at 10730 s and continued until quench initiation indicated failures of fuel rod simulators, probably mostly due to melting of claddings.

Toward the achievement of the cladding melting point, a lower part of the second corner rod (below elevation 550 mm) was removed (11014 s). Some local spalling of the oxide scale was observed from preliminary examination at the top of the withdrawn rod segment. The shroud failure with penetration of additional argon flow into the bundle was registered at 11253 s.

The reflood was initiated simultaneously with turning off the air and steam flows, switching the argon injection to the top of the bundle, followed by rapidly filling the lower plenum of the test section with 4 kg of water, and continuing by injecting 50 g/s of water. The power remained at 3.8 kW during the reflood.

Almost immediately after the start of reflood there was a temperature excursion in the mid to upper regions of the bundle (750 to 1150 mm), leading to maximum measured temperatures of about 2450 K. Cooling was established at the middle bundle elevation (550 mm) ca. 70 s after the start of injection, but was delayed further at upper elevations. Reflood progressed rather slowly, perhaps due to the high temperatures and partial bundle melting, and final quench was achieved after about 800 s. A significant quantity of hydrogen was generated during the reflood (238±2 g). Nitrogen release (>54 g) due to re-oxidation of nitrides was also registered.

The facility is now being dismantled prior to post-test examinations. The first videoscope inspection at the position of withdrawn corner rods shows absorber melt relocation to the bundle bottom. The overview of the bundle top shows strong cladding oxidation. In parallel, the recorded test data as well as the results of the aerosol measurements are being processed for further analyses by participants within the ALISA and QUESA projects.

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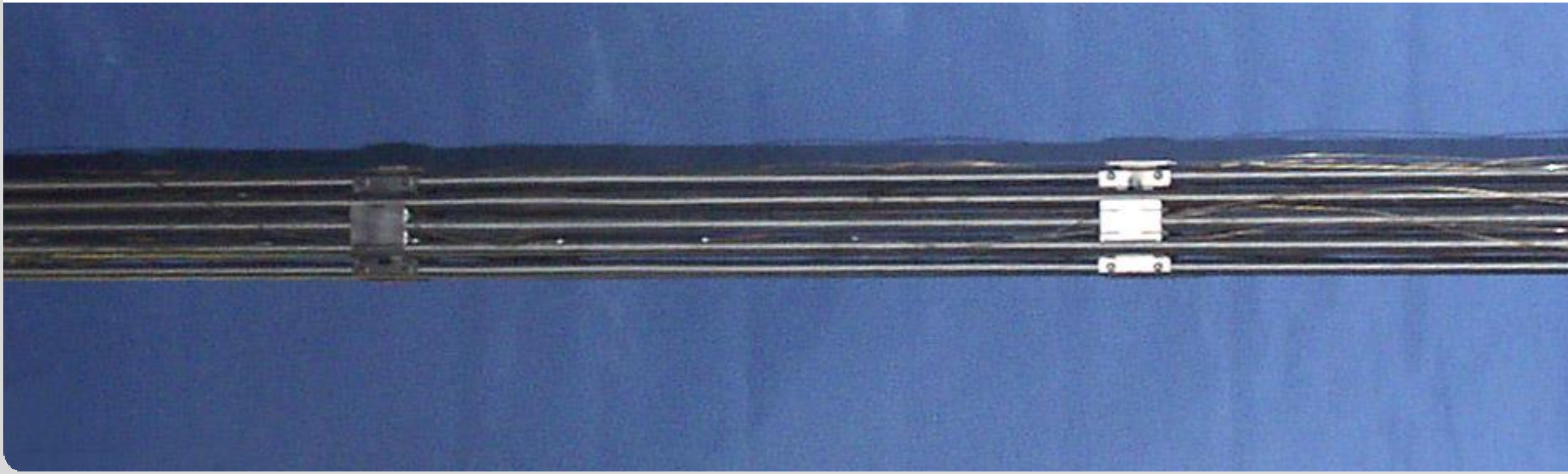
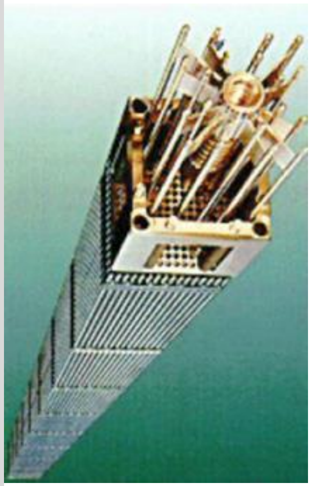
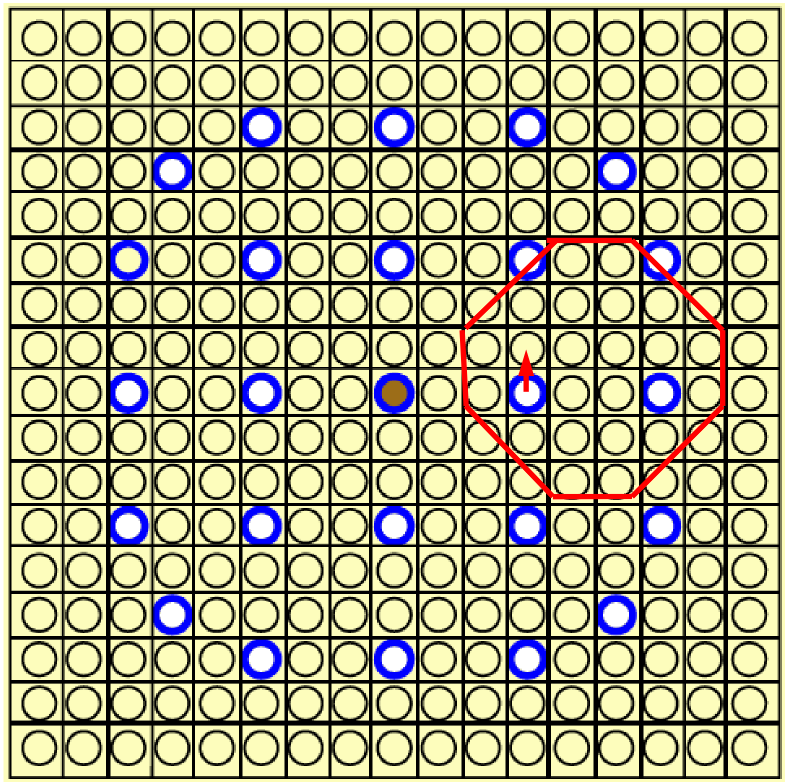
Institute for Applied Materials; Program NUKLEAR



Composition of test bundle

fuel assembly **17x17**

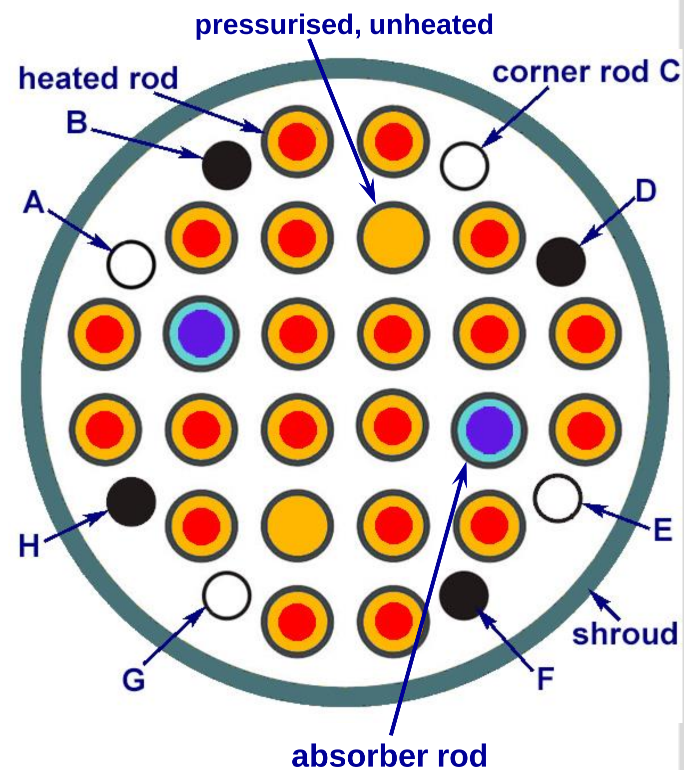




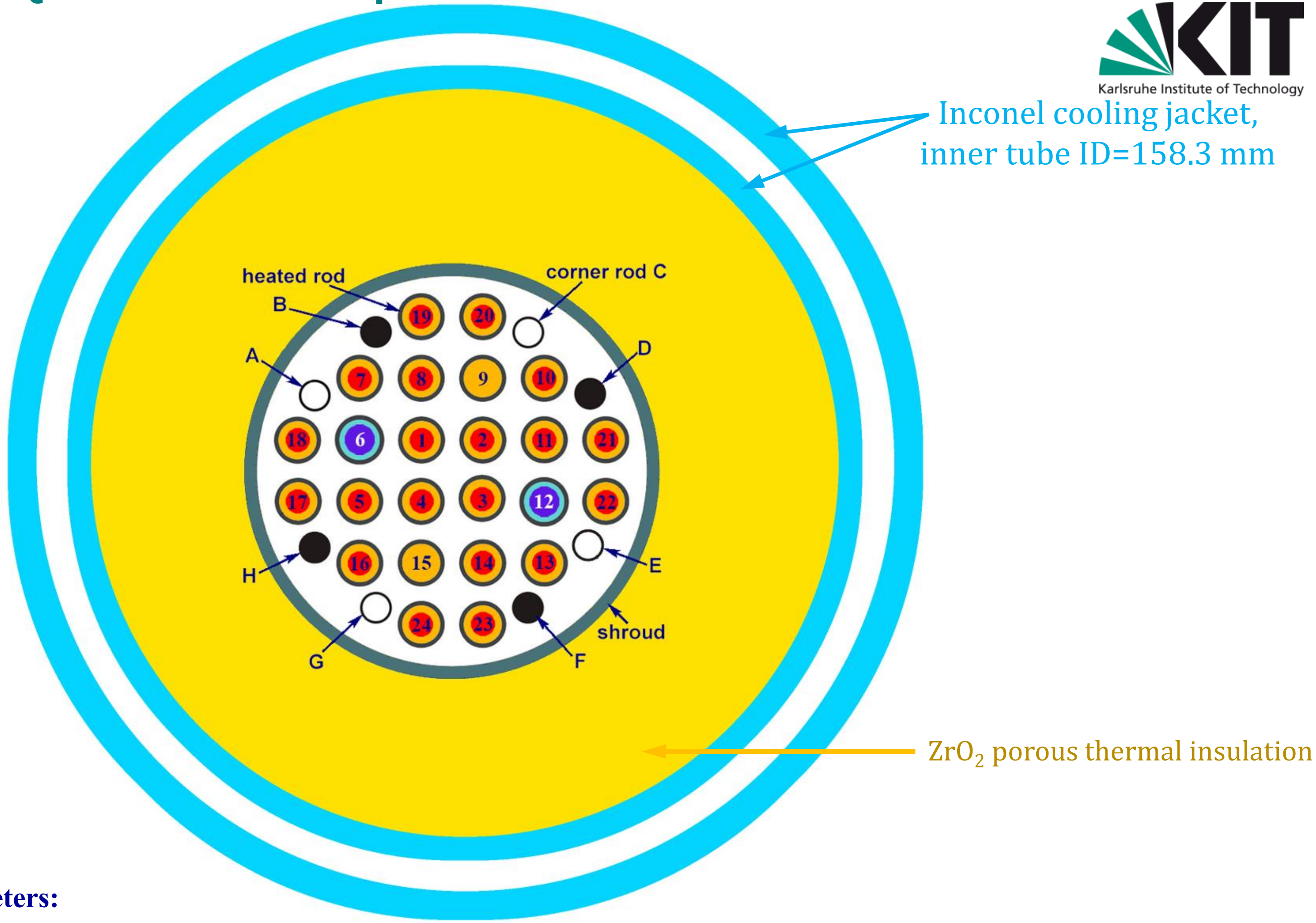
- fuel rod (264)
- guide tube for AgInCd control rod (24)
- instrument thimble

10:1 (fuel rod : guide tube)

proposed QUENCH test bundle



QUENCH-ALISA: parameters of test section



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

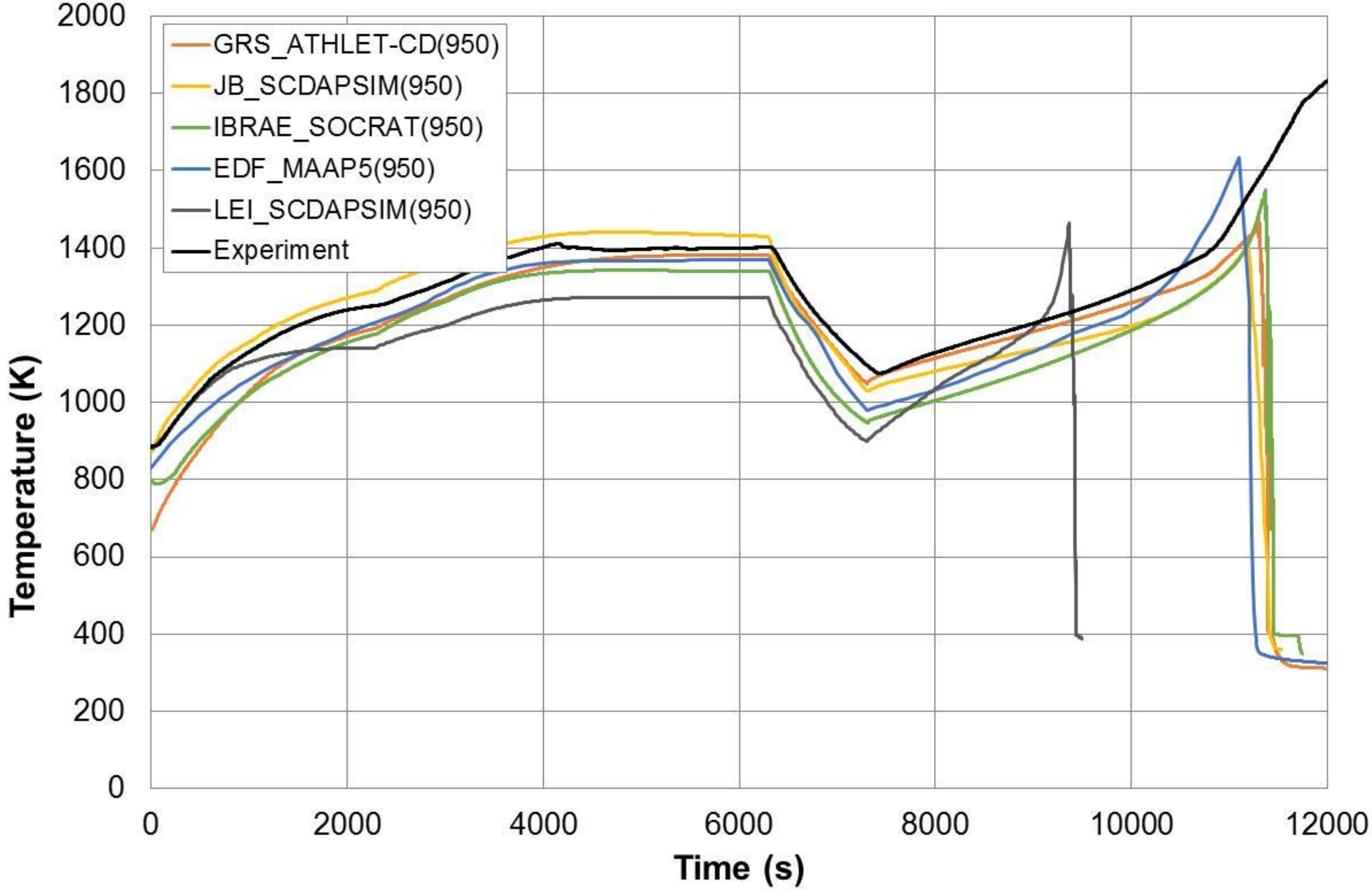
guide tube bottom

guide tube top

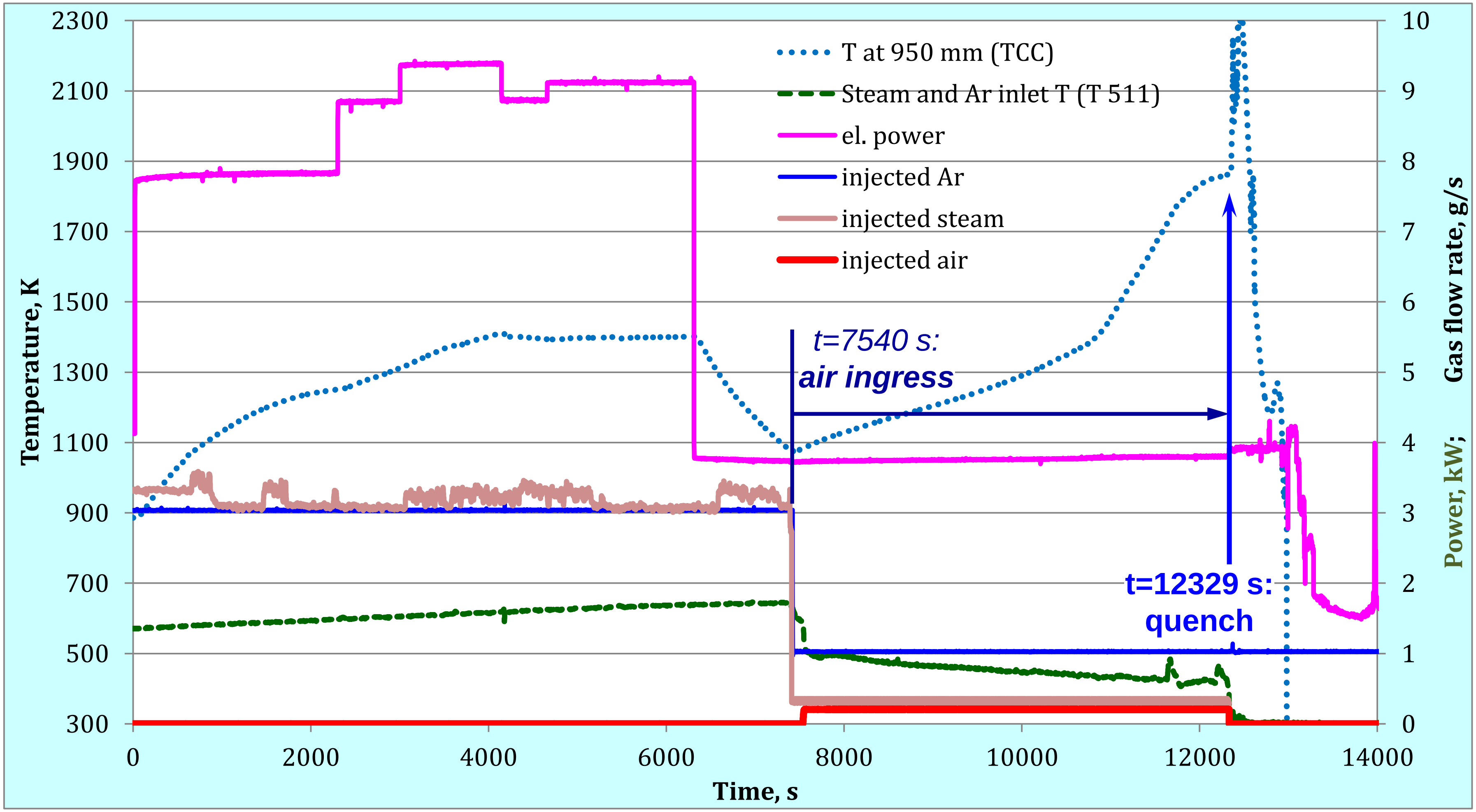
Absorber rod	**material**	**80 Ag, 15 In, 5 Cd (wt-%)**
	dimensions	∅ 7.65 mm, L=1068 mm (Elev. -15 to 1053 mm), ***M ≈ 488 g***
Cladding of absorber rod		**SS**, ∅ 9.68 / 7.72 mm L = 1083 mm (Elev. -20 to 1063 mm)
Guide tube of absorber rod		**M5®** , ∅ 12.45 / 11.25 mm L = 1187 mm (Elev. -42 to 1145 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

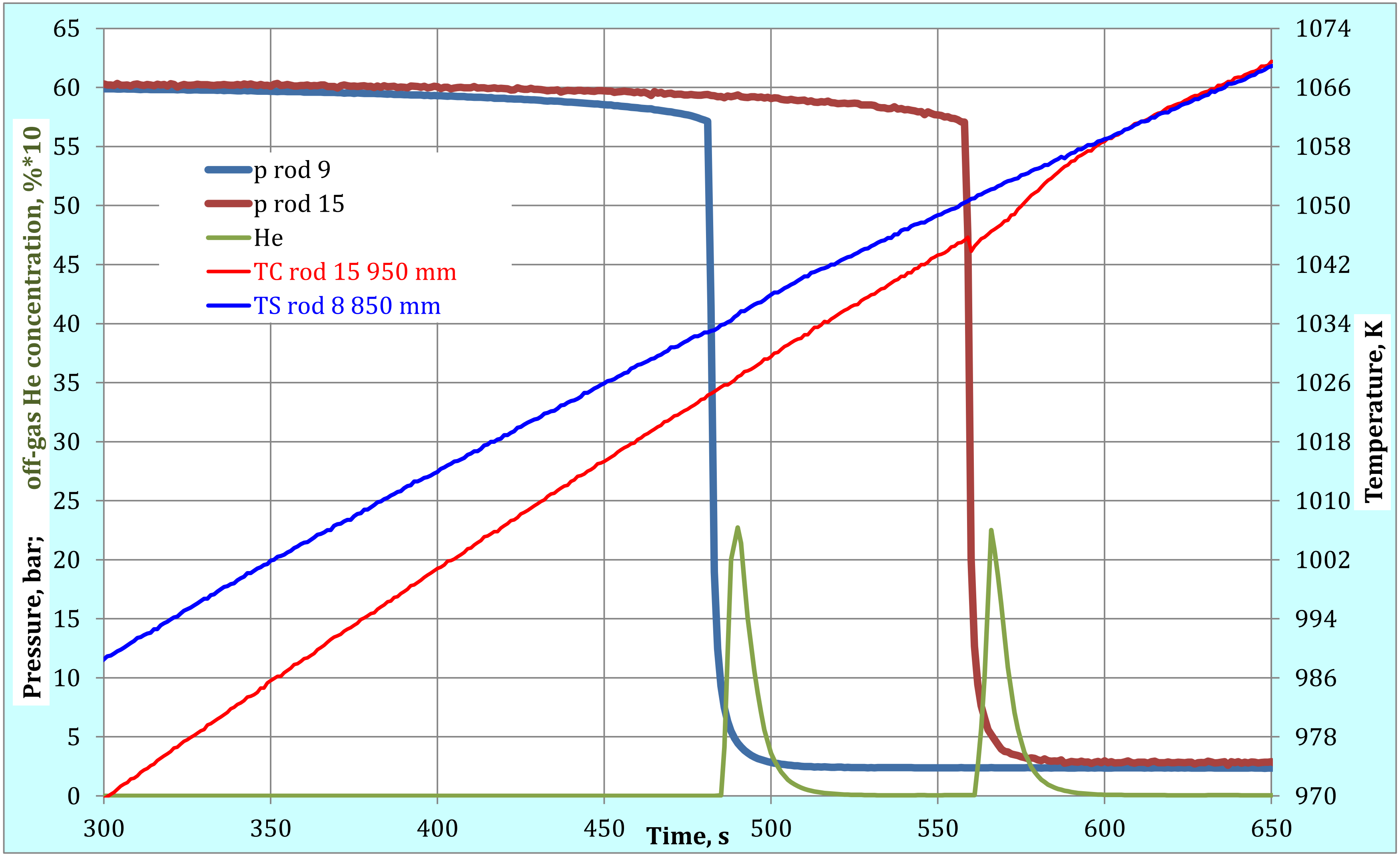


Input parameters of the QUENCH-ALISA (QUENCH-18) test



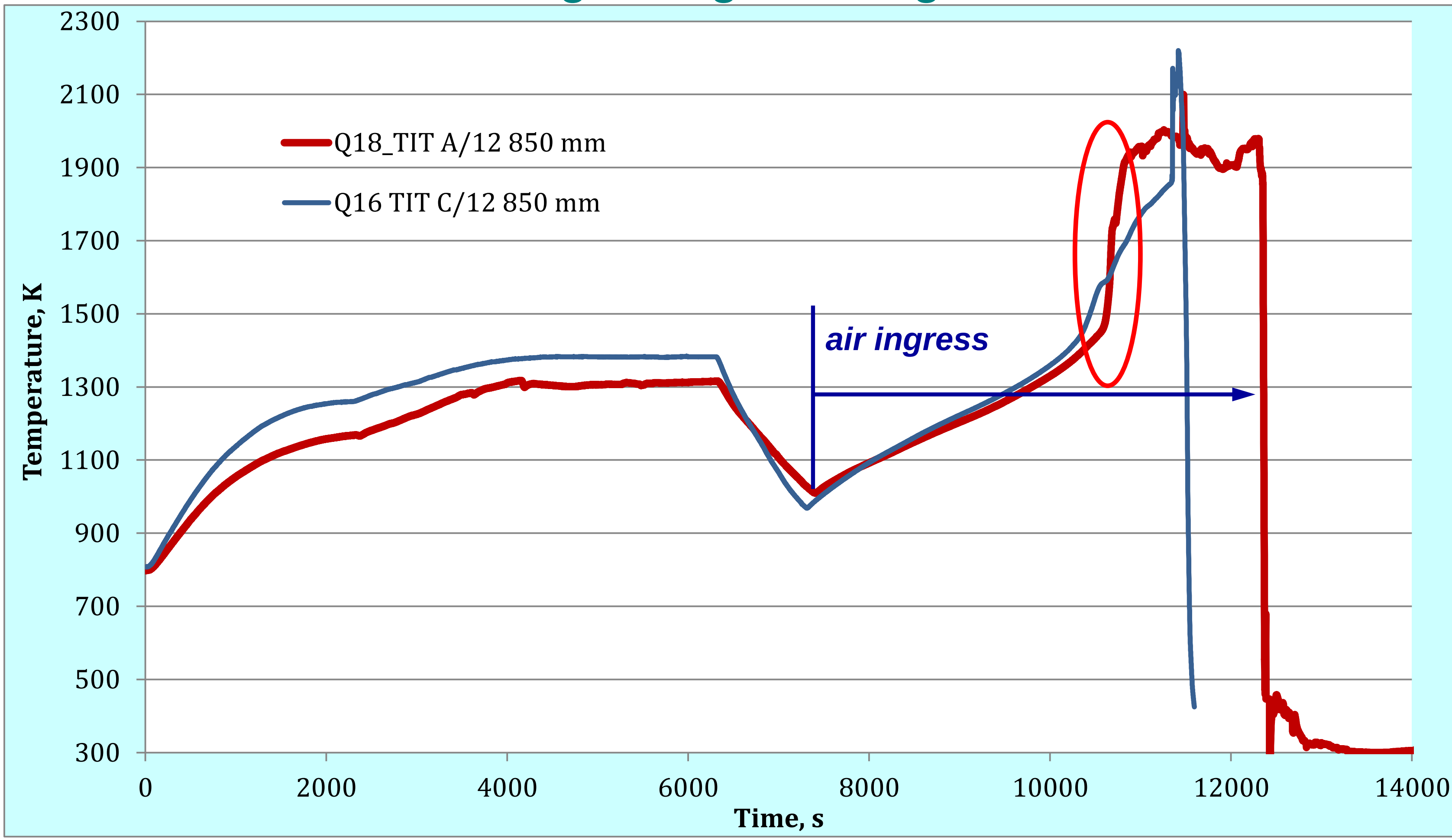
Important feature of QUENCH-18: steam flow during air ingress

Burst of pressurised rods #9 (at 850 mm?) and #15 (at 950 mm)



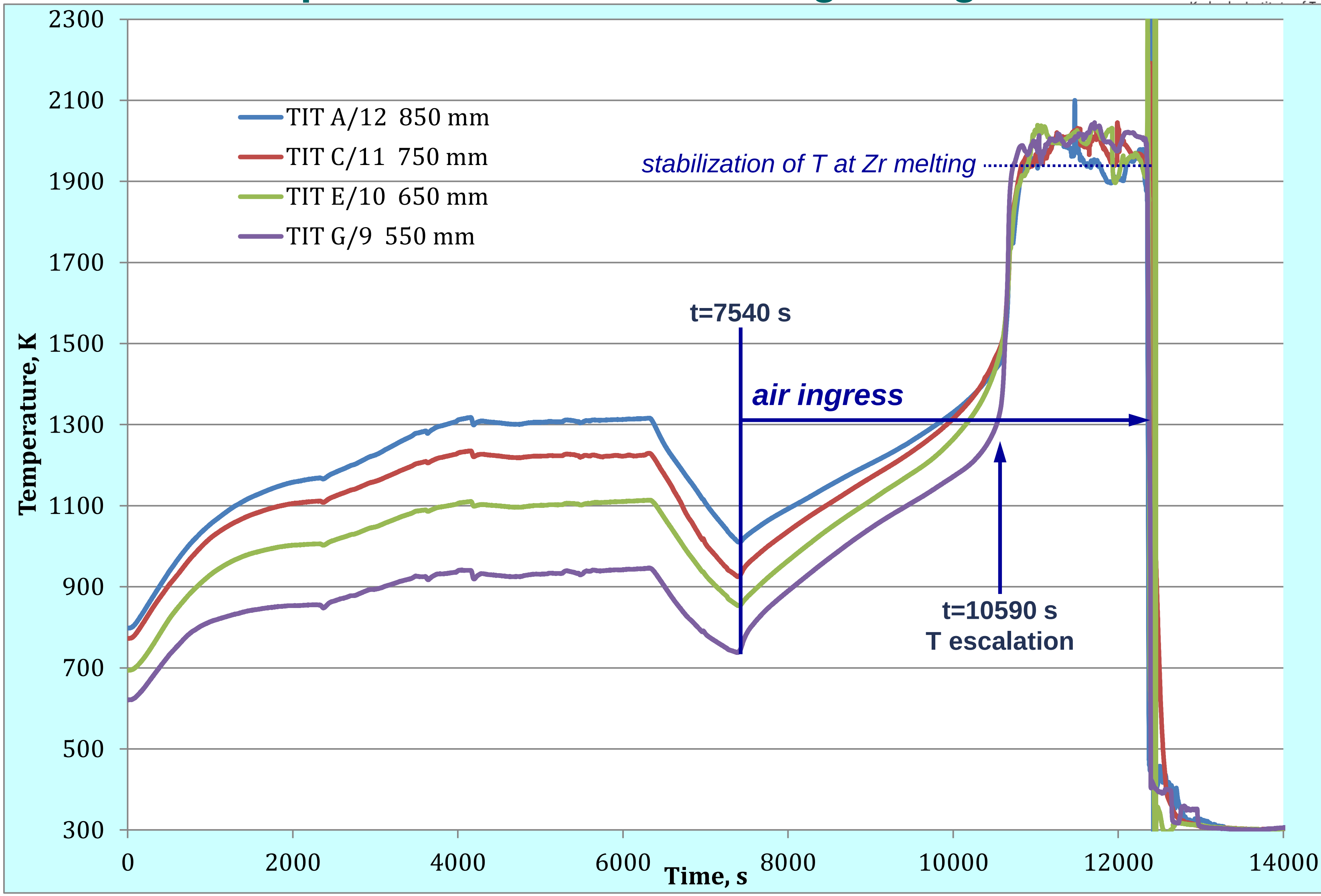
Burst temperature: 1045 K (rod #15) **at heat-up rate 0.3 K/s**

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

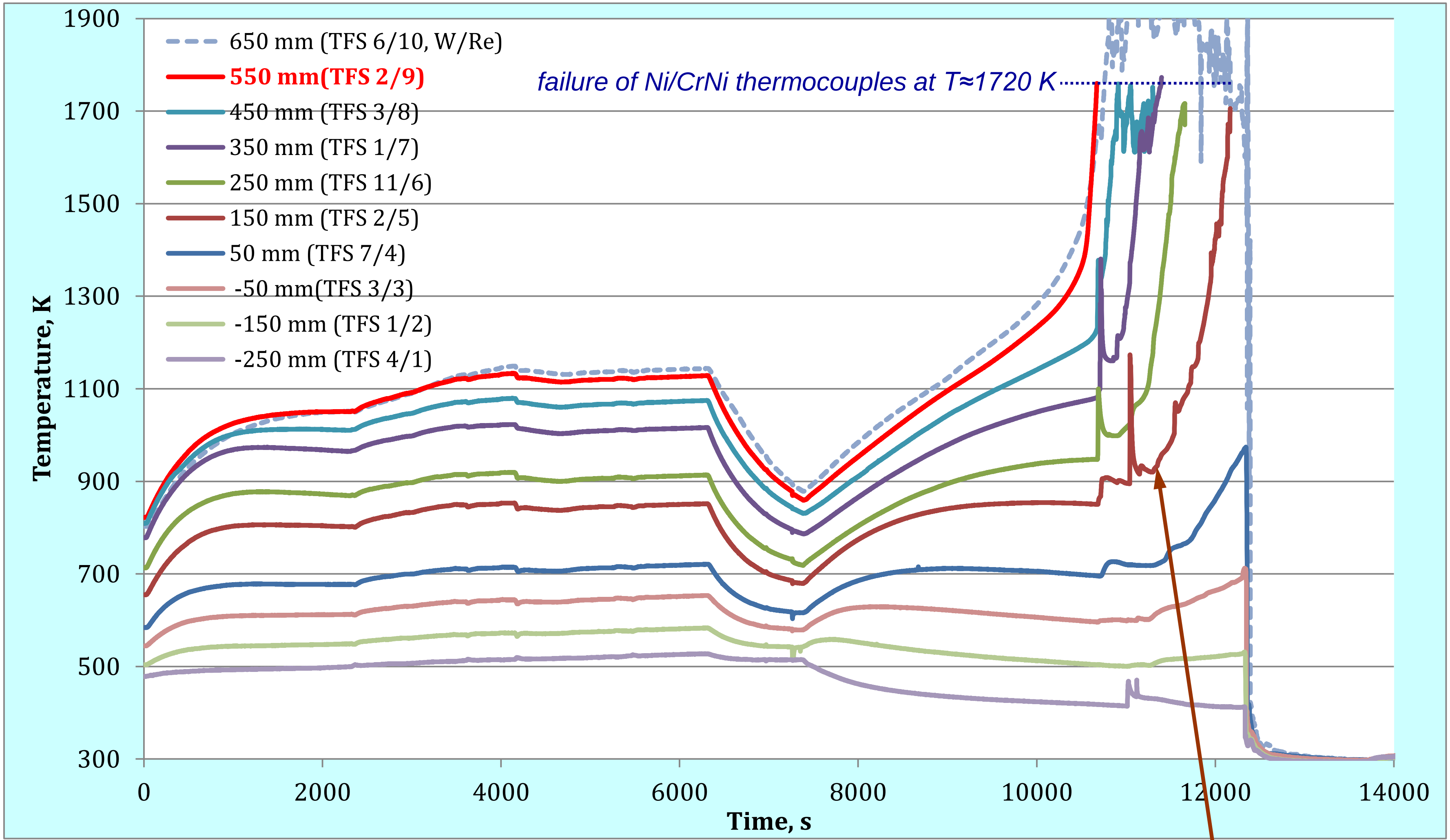


Additional chemical power (≈ 4 kW) due to cladding oxidation in steam during air ingress

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



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

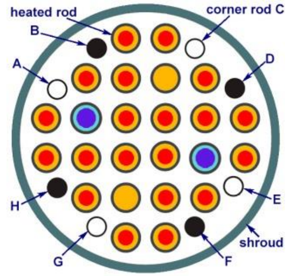


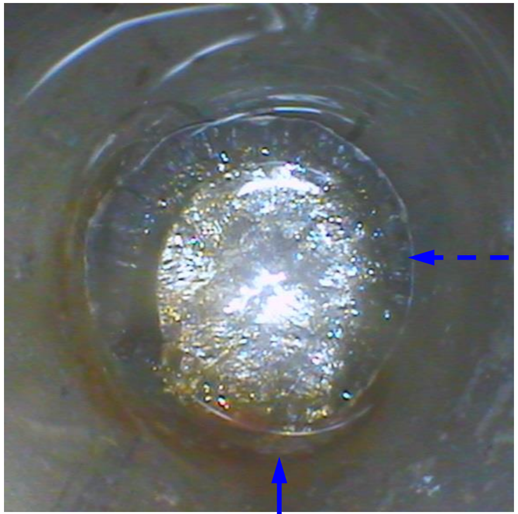
Lowest elevation with strong temperature escalation during air ingress: 150 mm

Withdrawn corner rods:

rod D before air ingress,

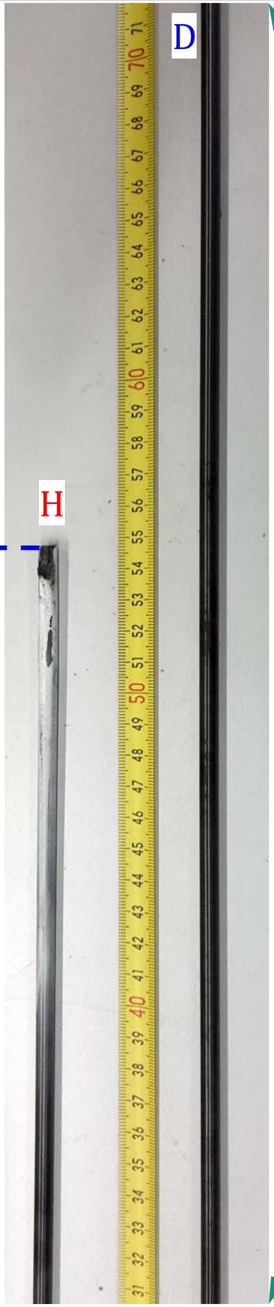
rod H on cessation of T escalation at 300 mm

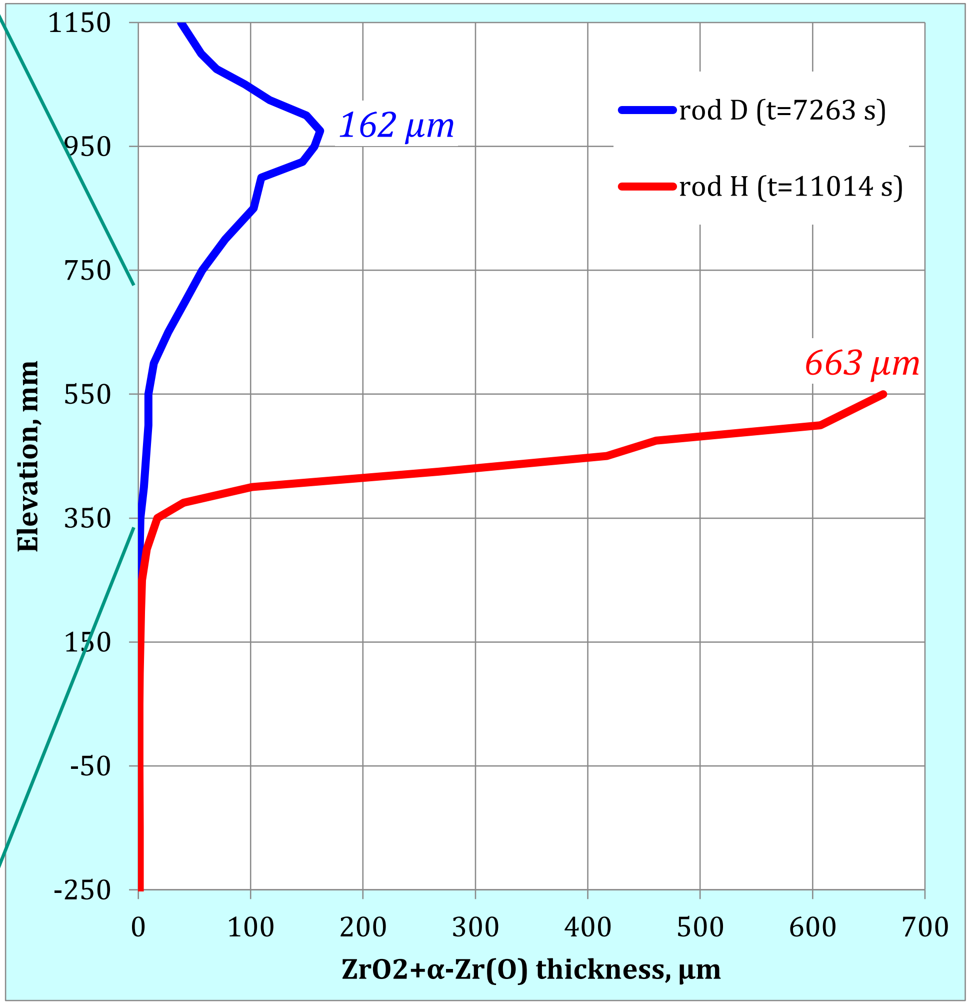




rupture position of corner rod H (550 mm) relocated to -475 mm during the rod withdrawn

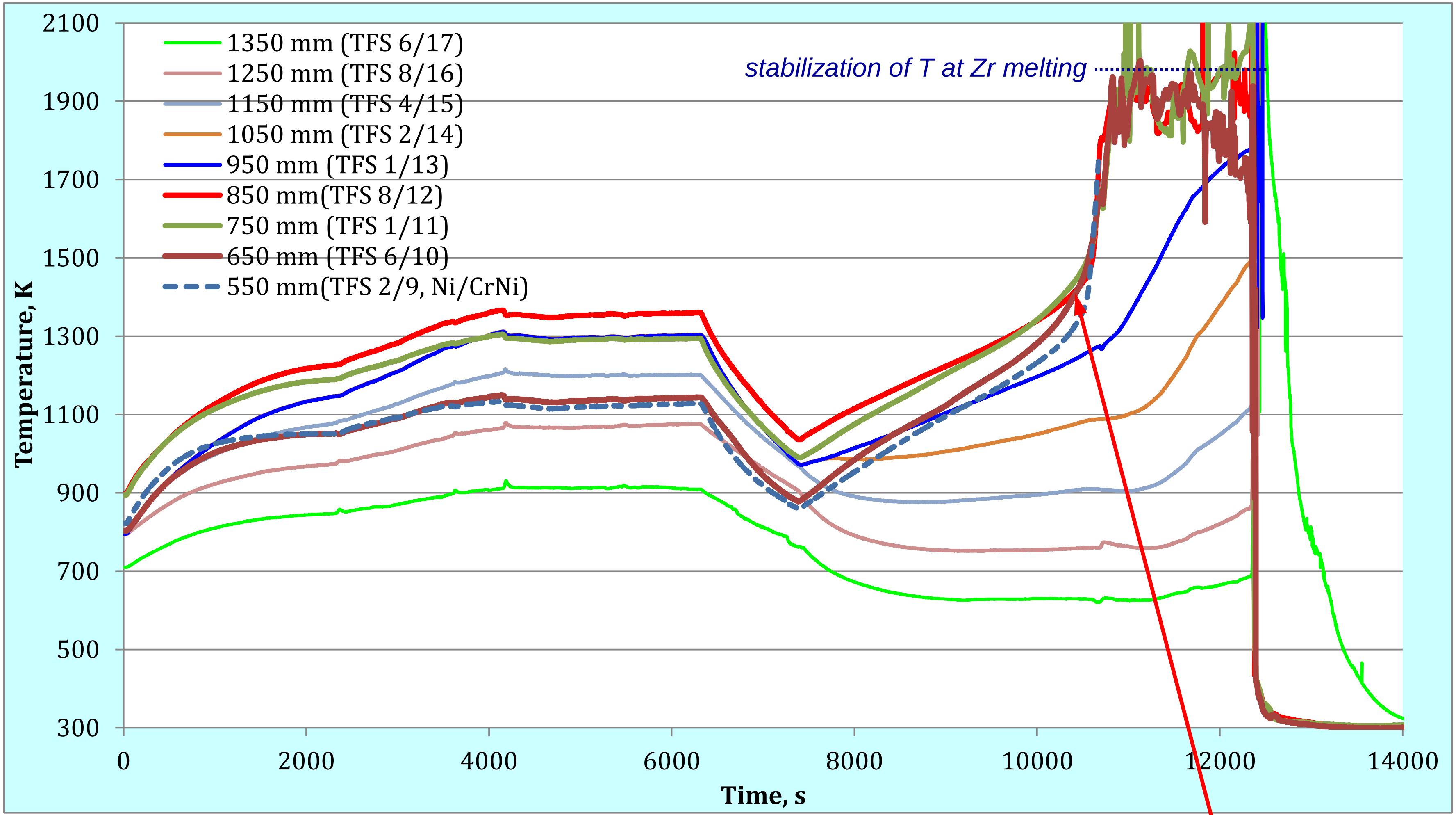
(videoscope observation through the guide tube of the corner rod H)





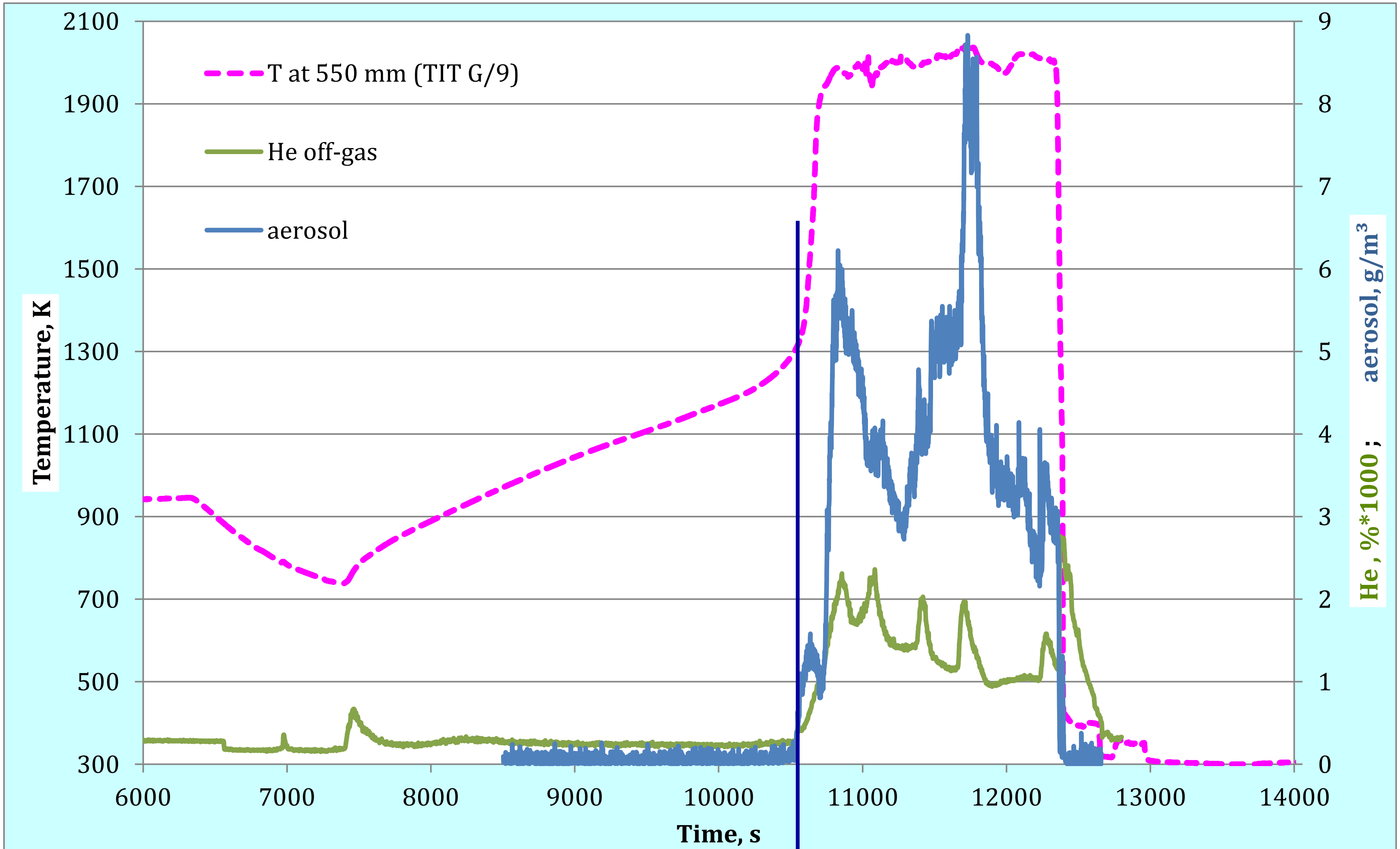
increased oxidation above 250 mm

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



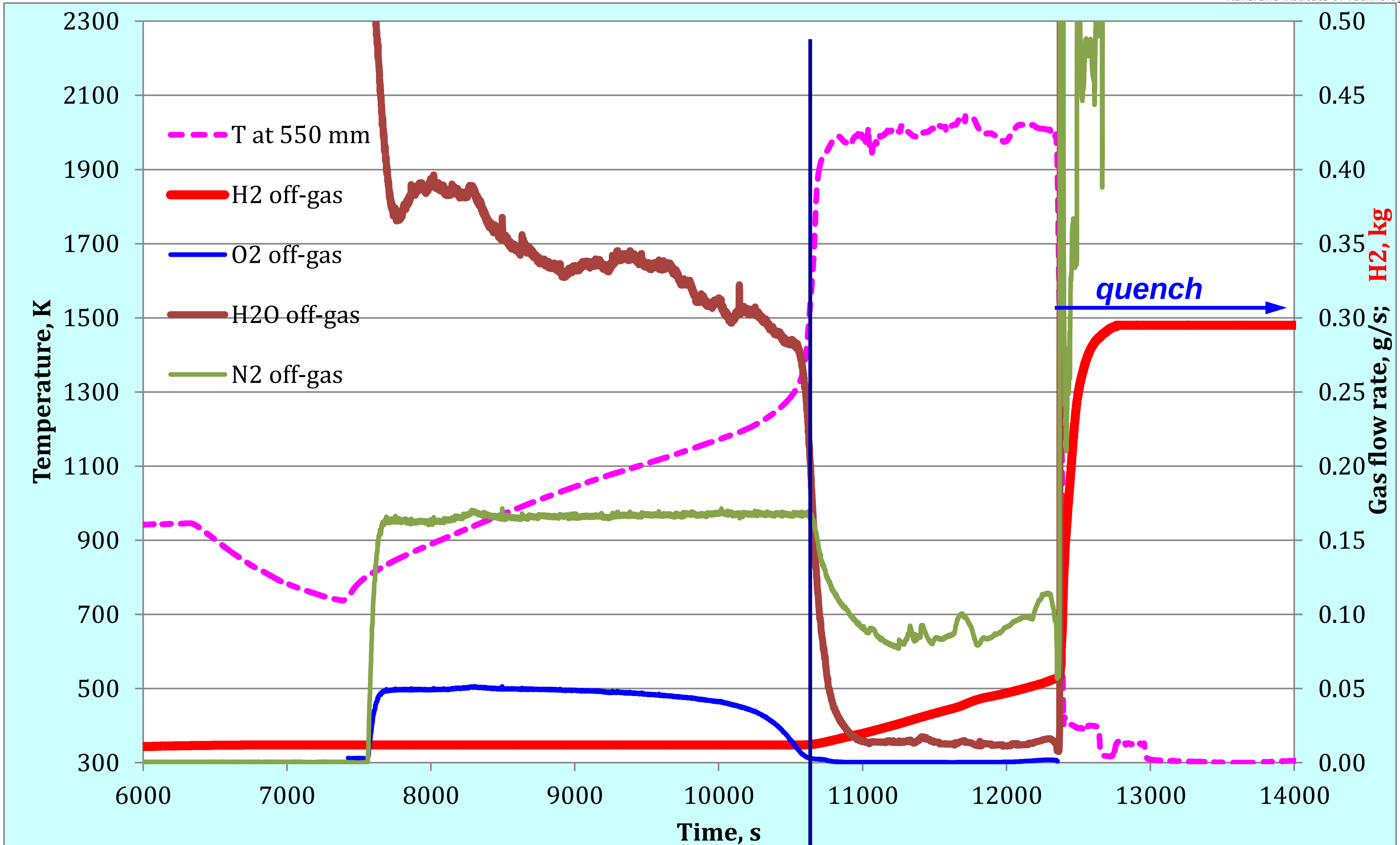
Highest elevation with strong temperature escalation during air ingress: 850 mm

Failure of absorber rods



t=10530 s: helium and aerosol release

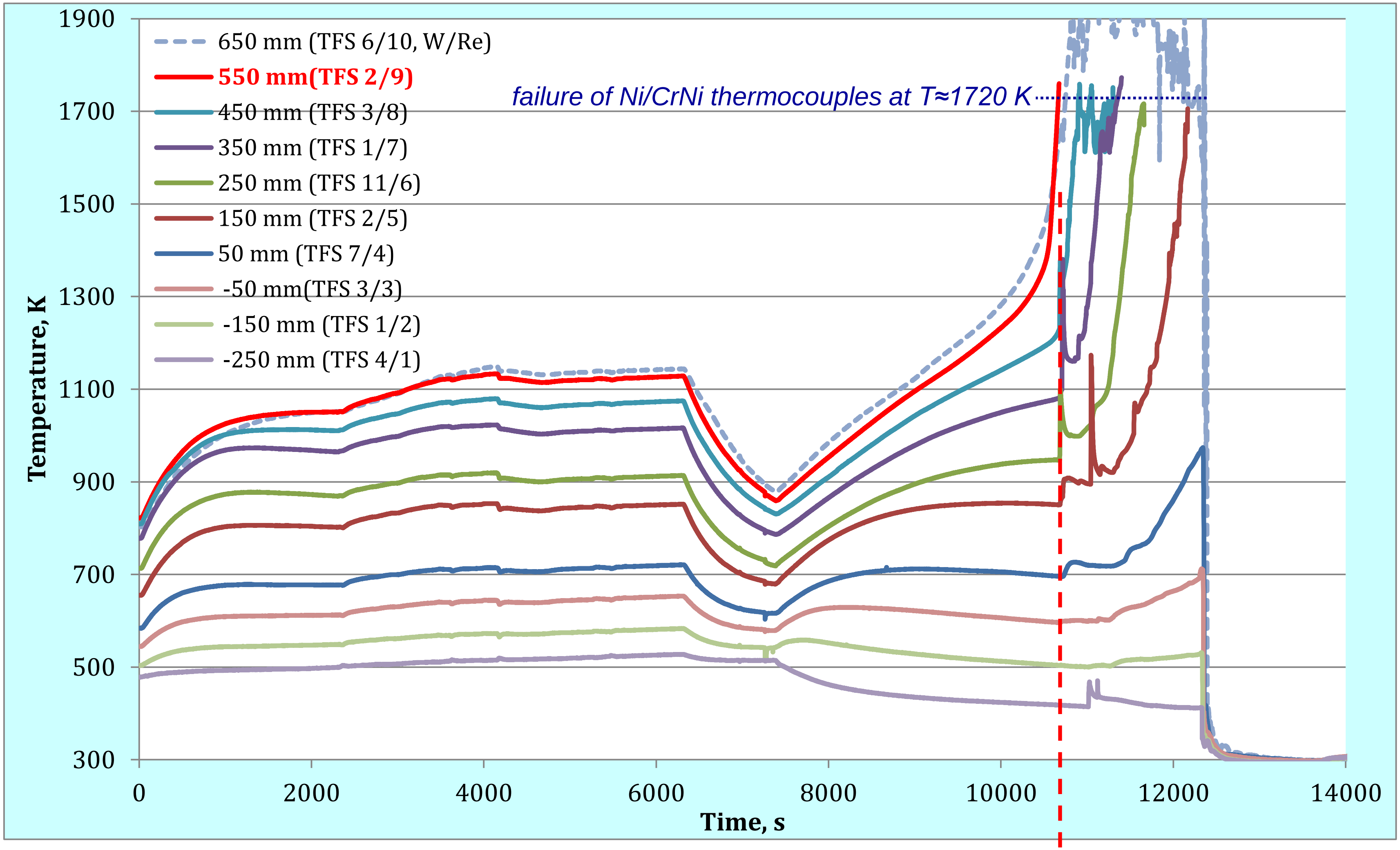
Outlet gas behaviour during air ingress: starvation phenomena



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

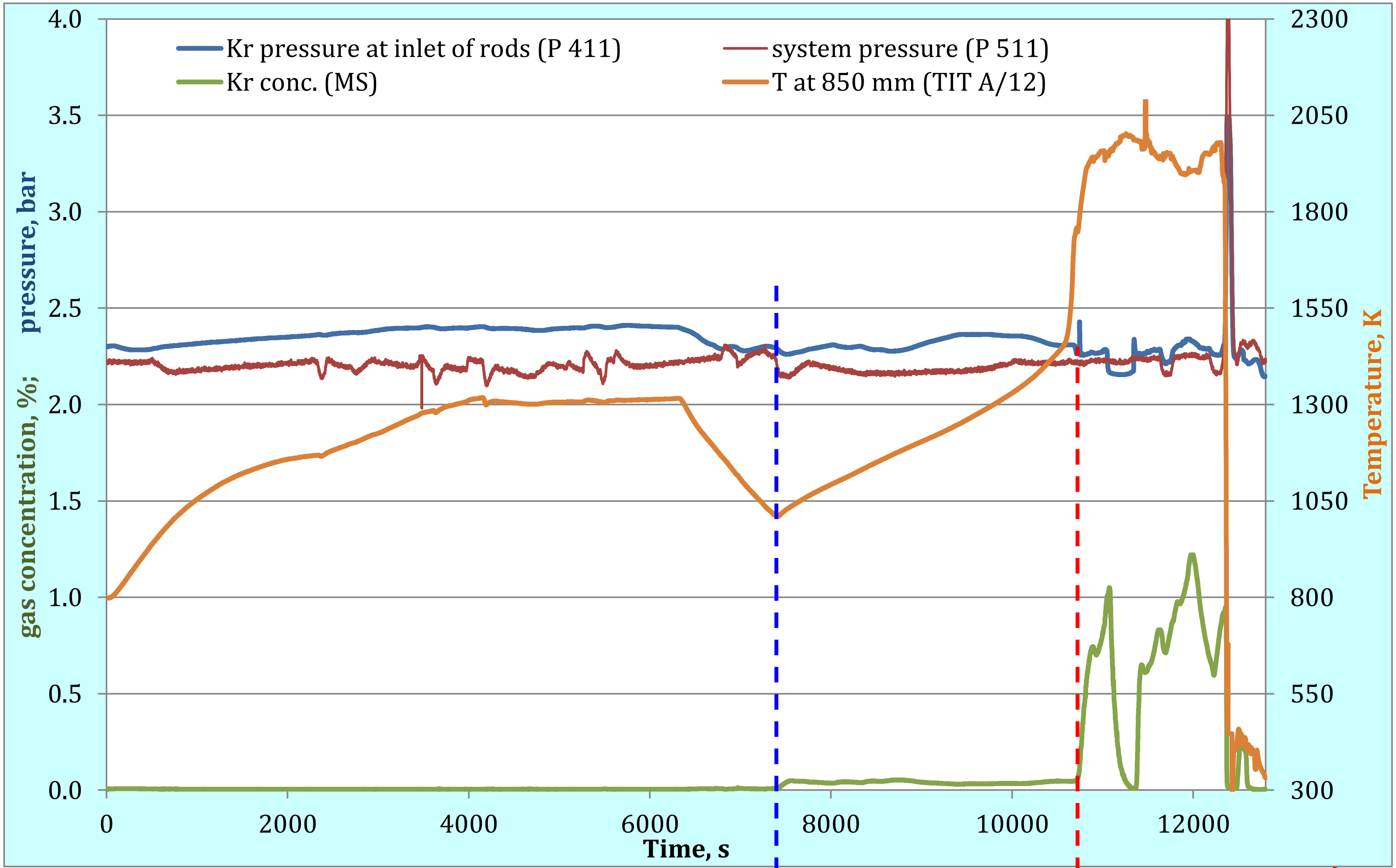
t≈10600 s: oxygen starvation, H_2 increase
steam and nitrogen consumption

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

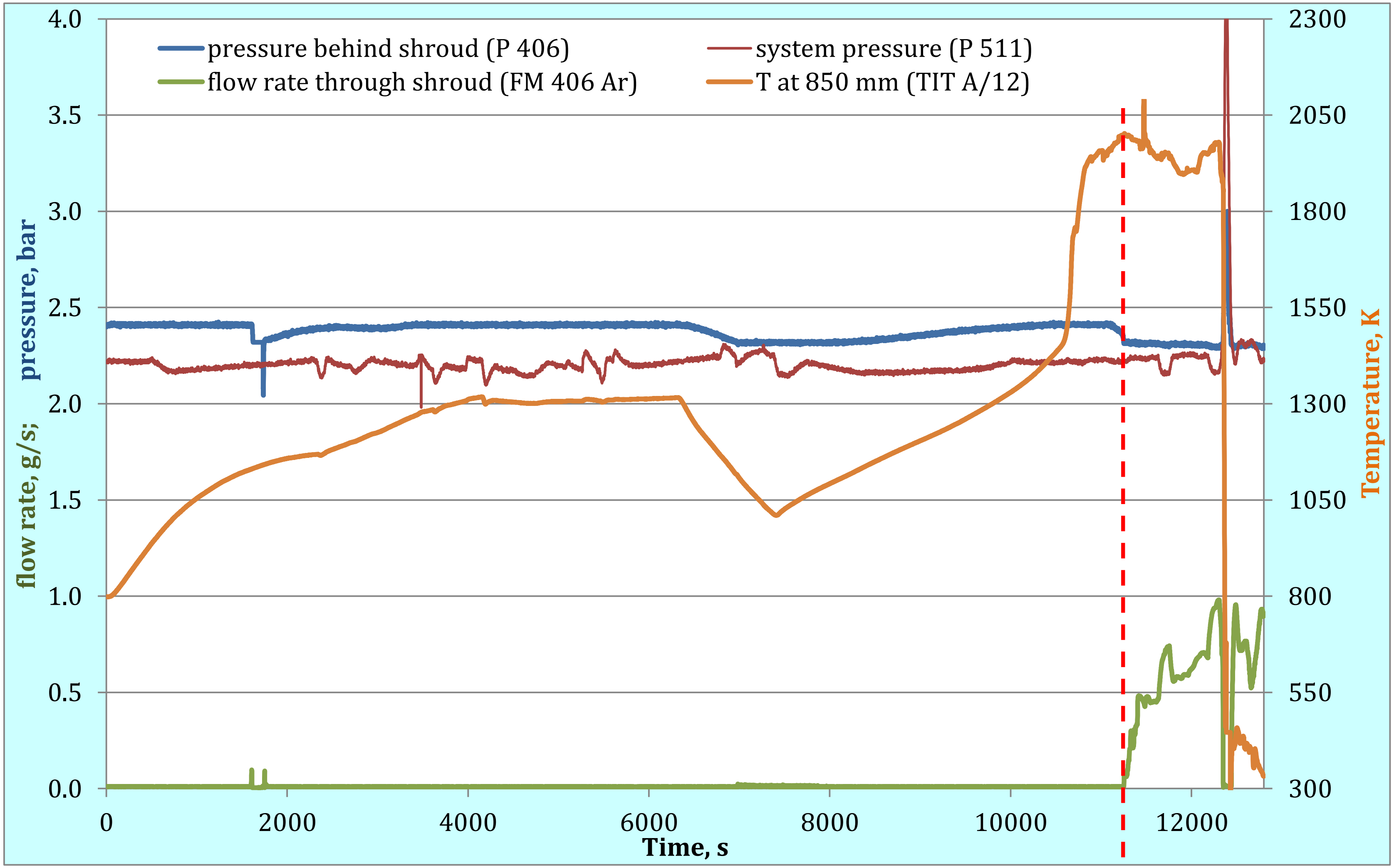
Failure of claddings (Kr release)



small Kr leakage (cladding cracks?)

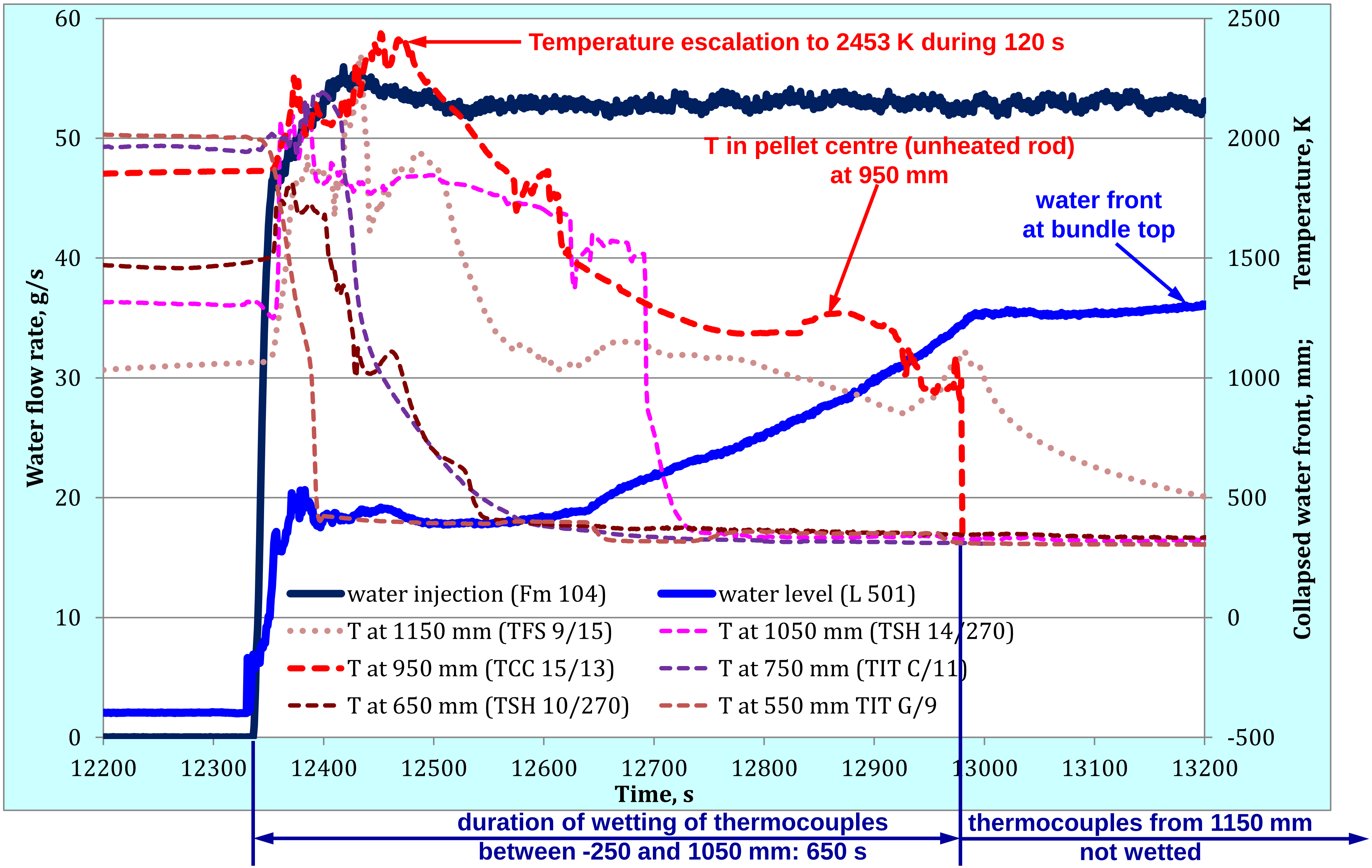
t=10730 s: cladding failures

Failure of shroud (additional Ar flow)



t=11253 s: shroud failure

Water and temperatures during the quench stage



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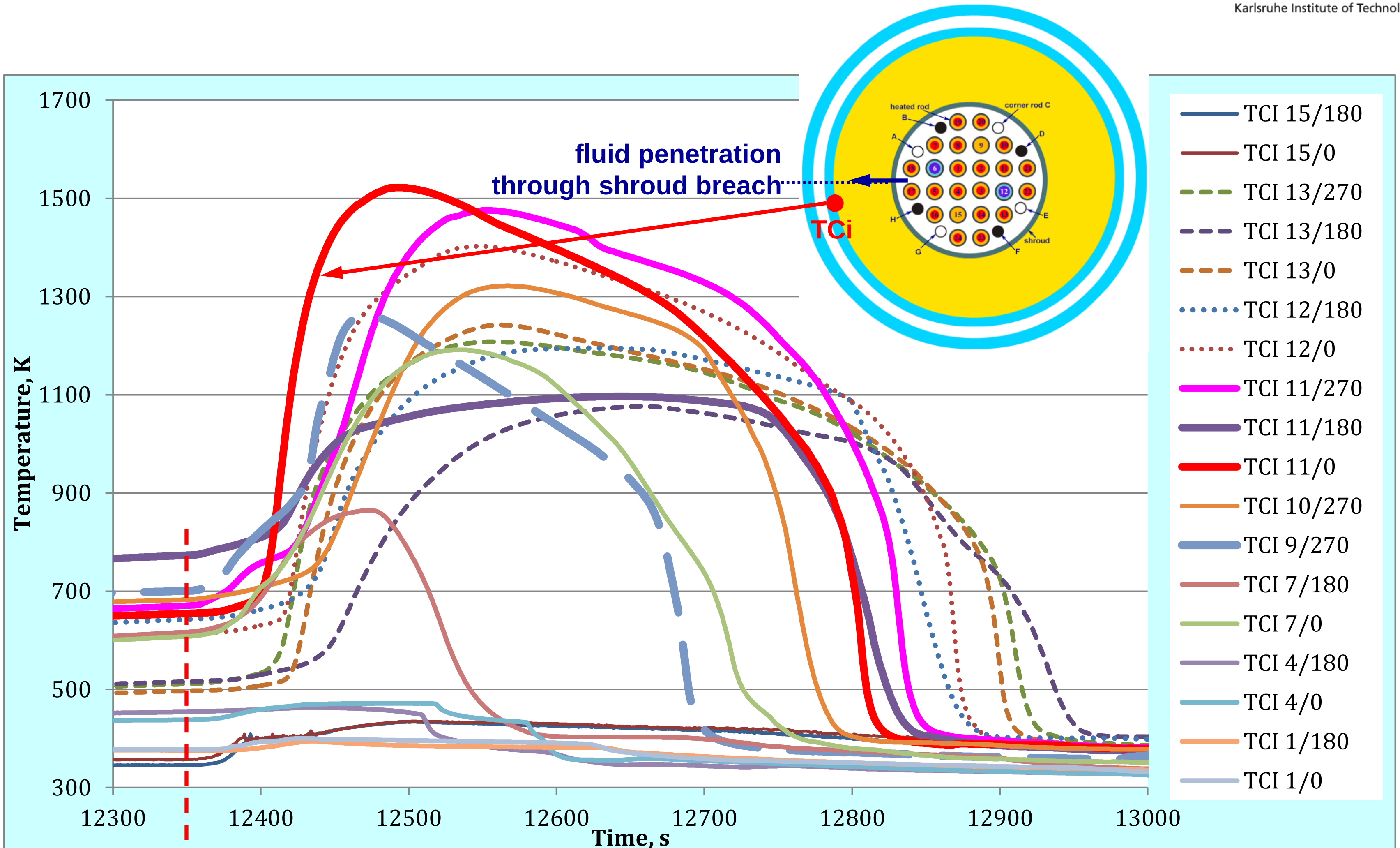
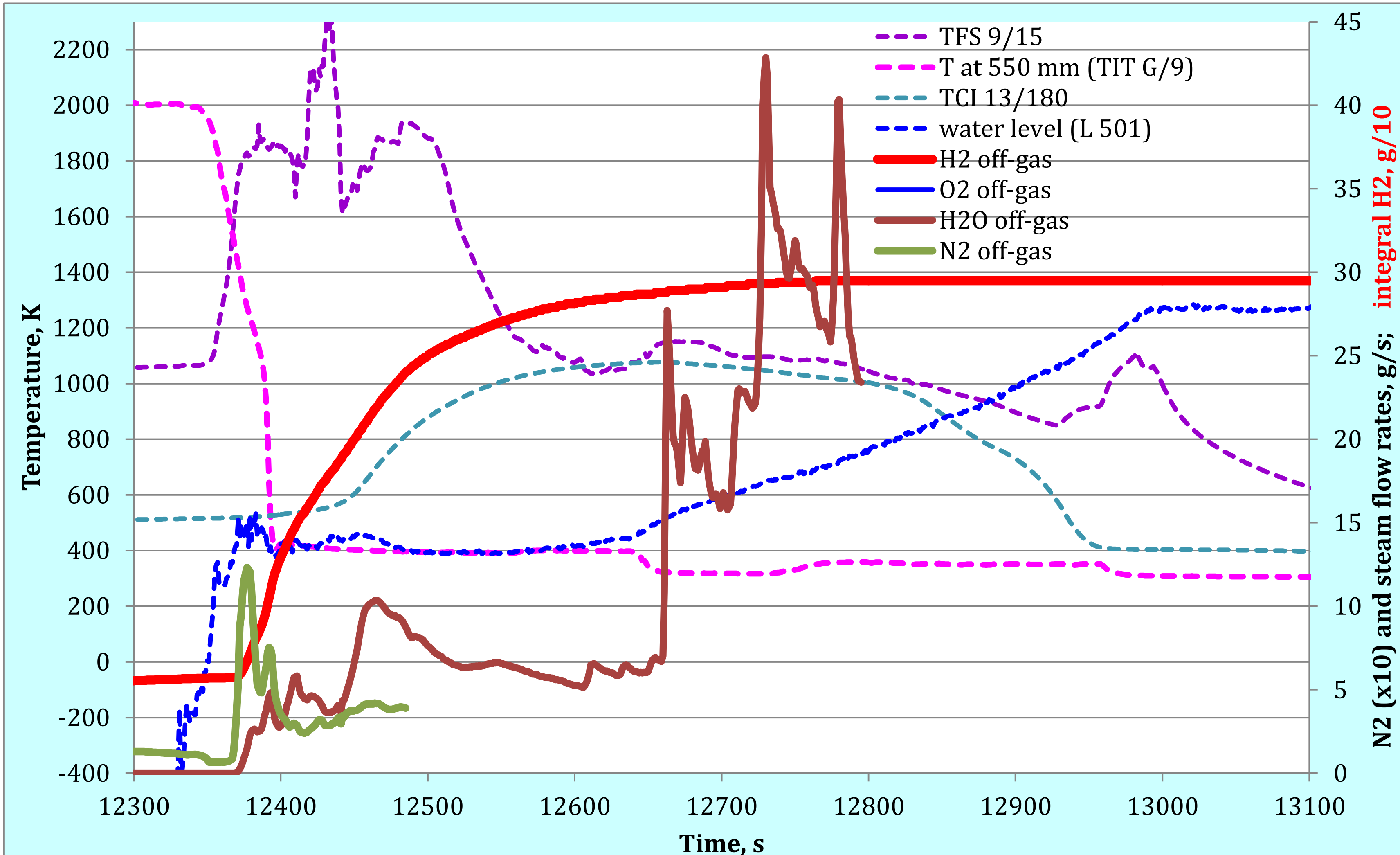
Readings of thermocouples at inner surface of cooling jacket after quench initiation (water injection from bottom)



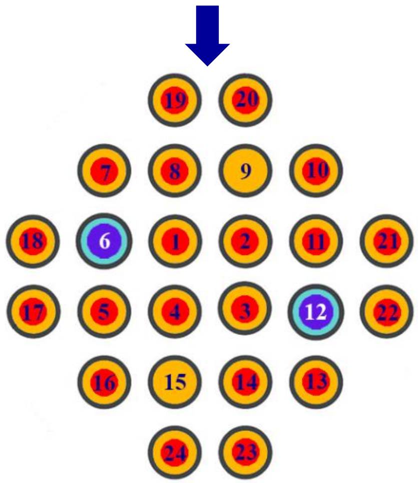
t=12330 s: quench initiation

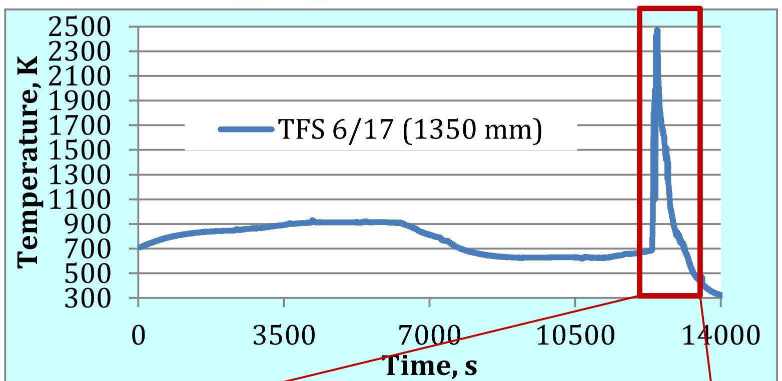
Gas release during the quench stage

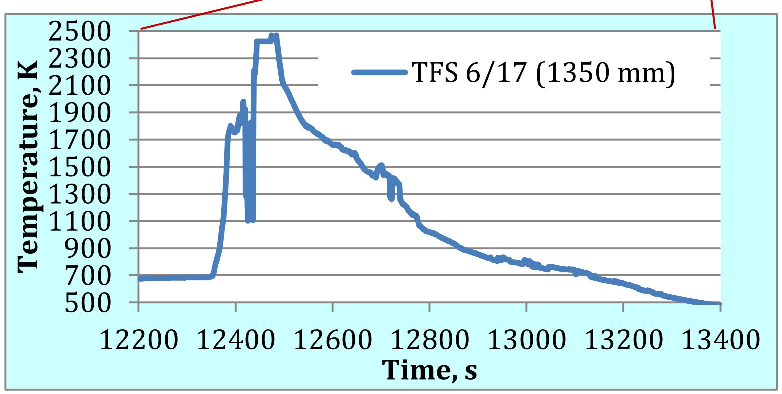


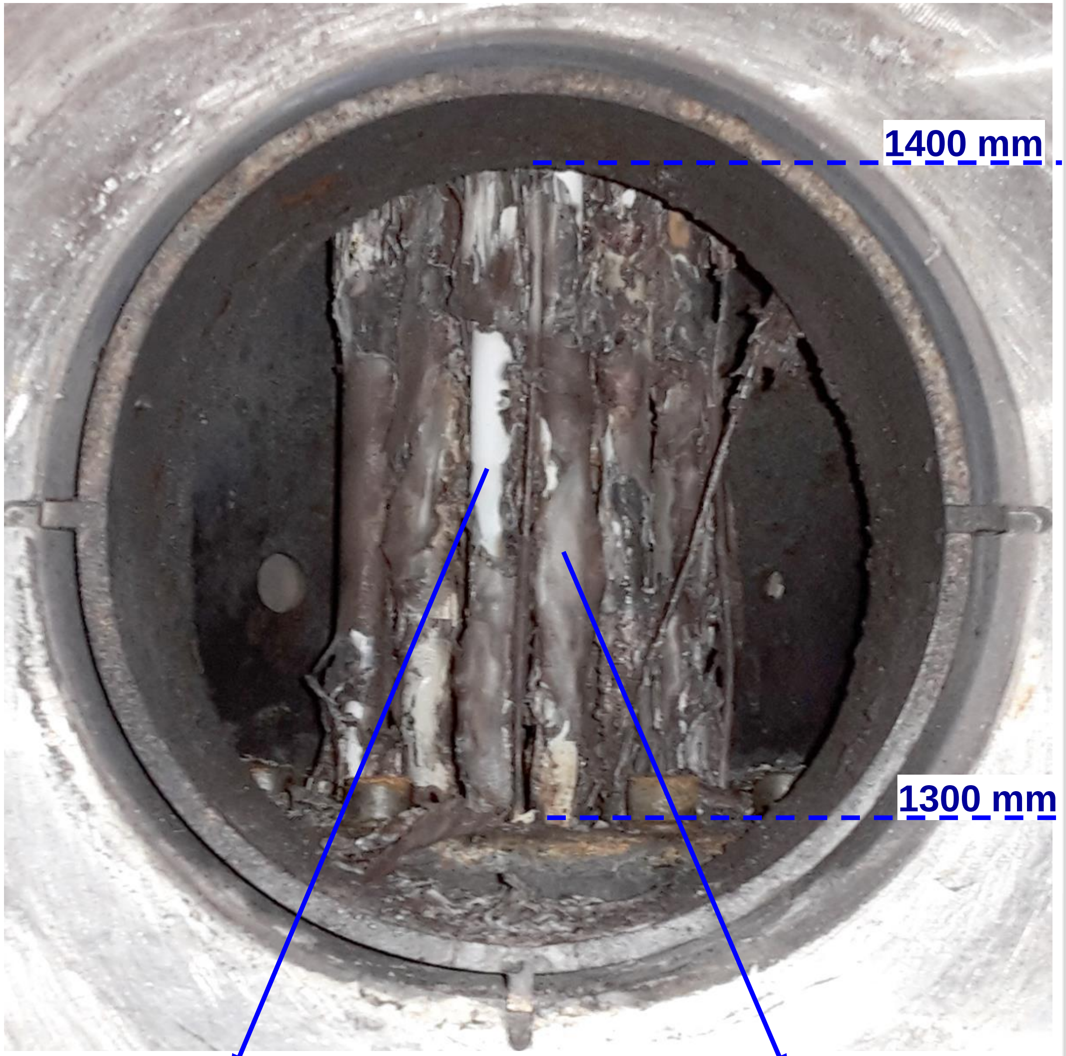
released hydrogen: 238 g
released nitrogen: >54 g

Overview of the bundle at bundle top





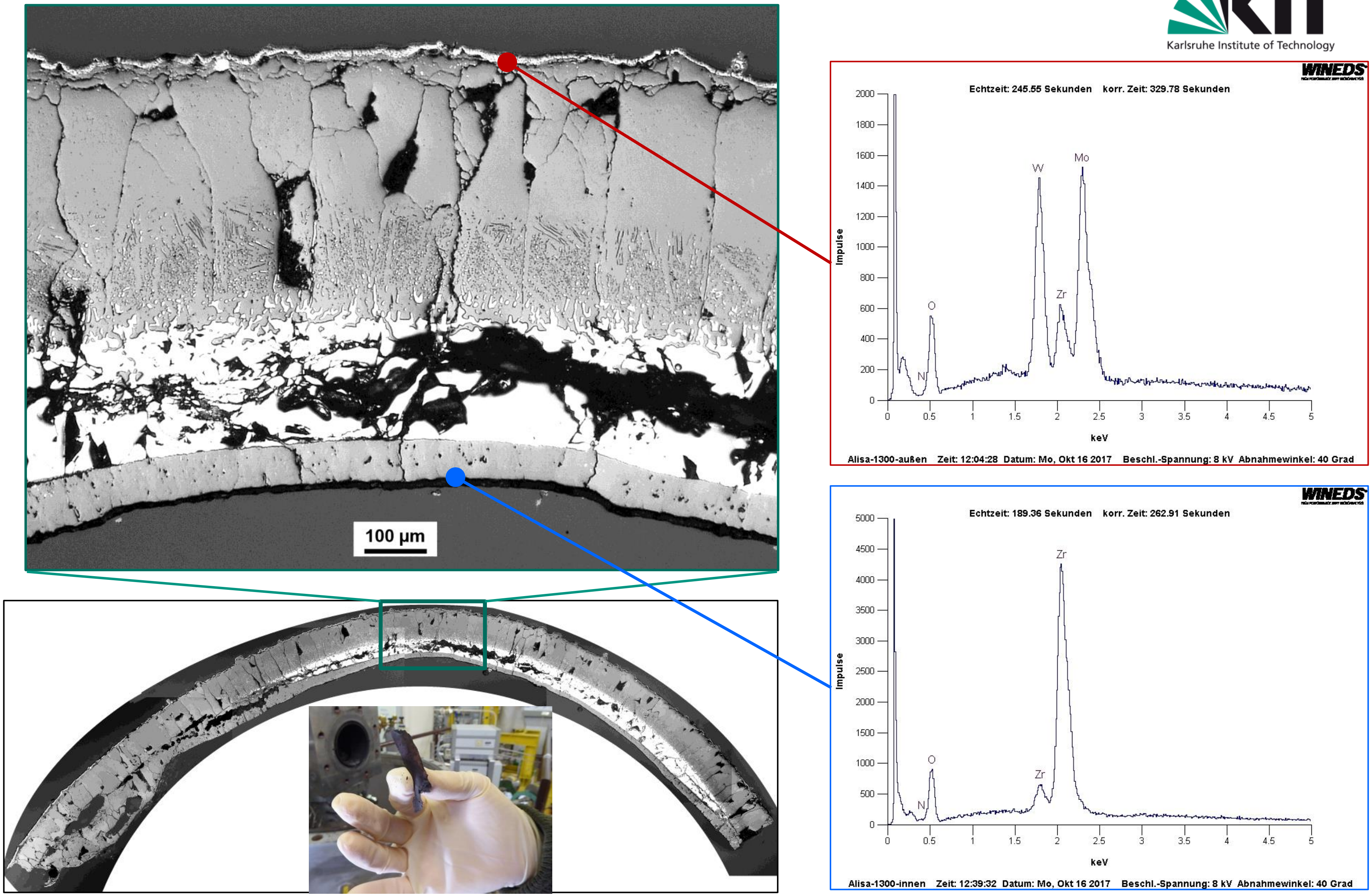




ZrO_2 coating of Mo heater

oxidised cladding

Analysis of cladding segment spalled at 1350 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 ≈130 µm of oxide layer (similar to QUENCH-16), a long period of oxygen starvation during the air+steam ingress phase (1770 s instead 800 s for the QUENCH-16 test performed 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.
- 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).
- 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.

Summary (cont.)

- During starvation period about *100 and 450 g oxygen and steam* correspondingly were consumed. During the steam consumption about *45 g hydrogen* were released. In the same period the partial consume of *nitrogen (about 120 g)* was registered.
- The bundle temperatures between elevations 550 and 850 mm stabilised at melting of Zr alloys.
- 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 cladding segments from rods. Metallographic investigations of spalled parts showed strong oxidation of cladding outer surface (about 350 µm ZrO_2) and moderate oxidation of cladding inner surface (about 110 µm ZrO_2). No nitride and melt formation were indicated at these upper elevations.
- The bundle will be prepared for further investigations.

Acknowledgment

The QUENCH-18 experiment was supported and partly sponsored by the ALISA project. The bundle materials were provided by AREVA.

The authors would like to thank all participants of the QUESA project for the pre-test calculations.

Thank you for your attention

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