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Results of the QUENCH-DEBRIS bundle test

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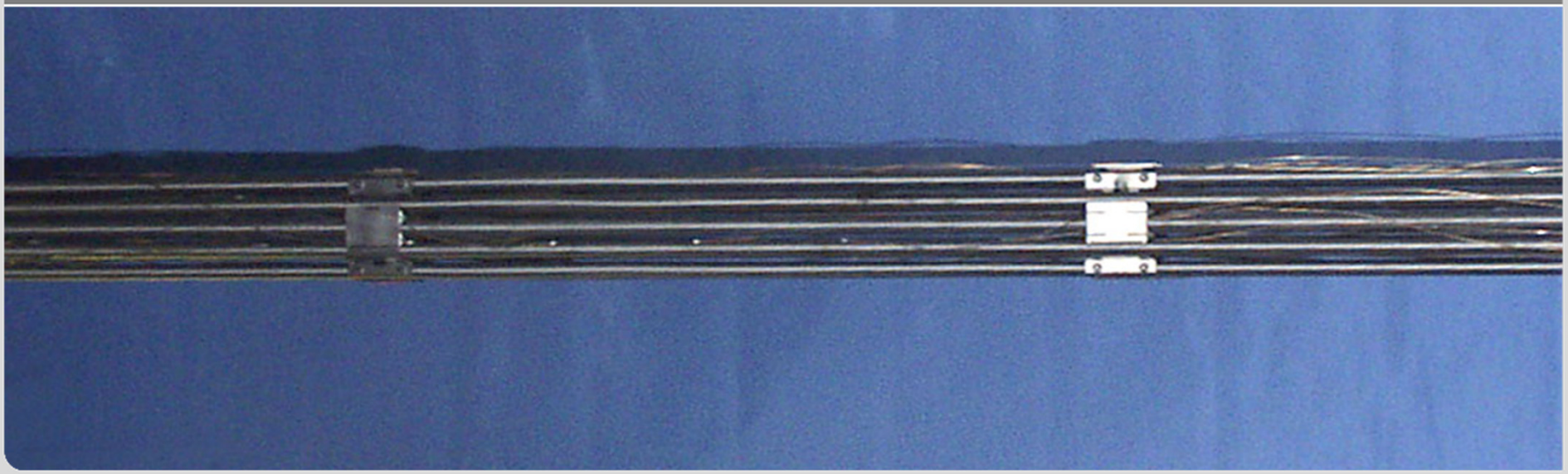
Institute for Applied Materials; Program NUKLEAR



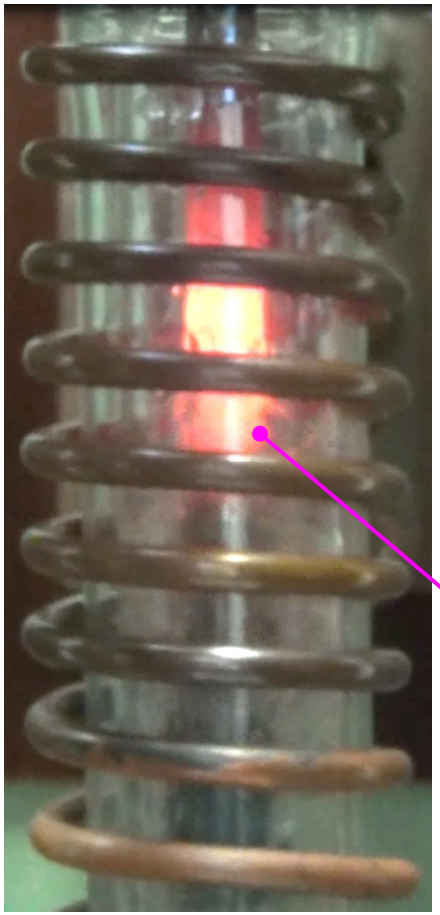
Objectives

- investigation of debris bed formation for bundle with completely oxidised Zry-4 claddings filled with segmented pellet simulators

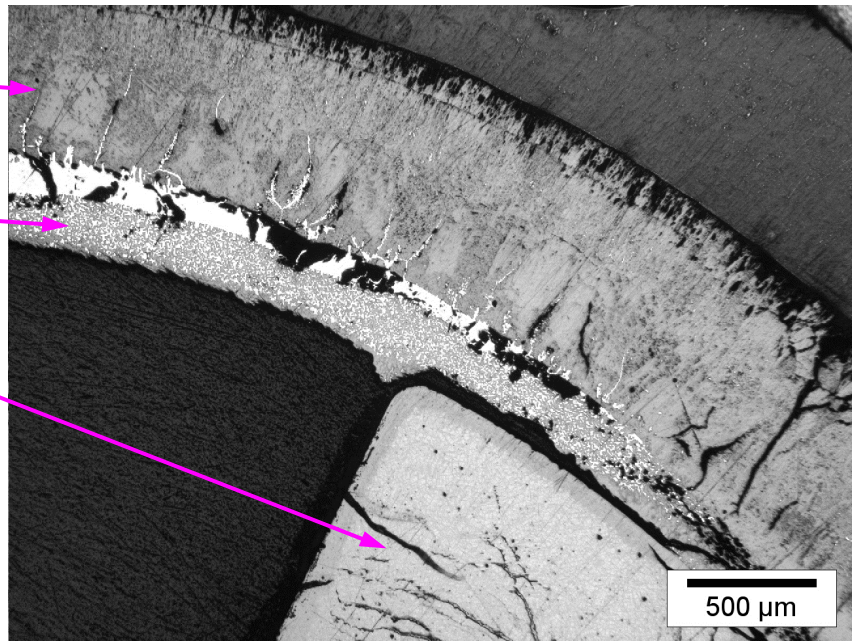
- investigation of cooling of degraded bundle during the water reflood from bottom

Quench single rod test with completely oxidized cladding filled with segmented pellets.

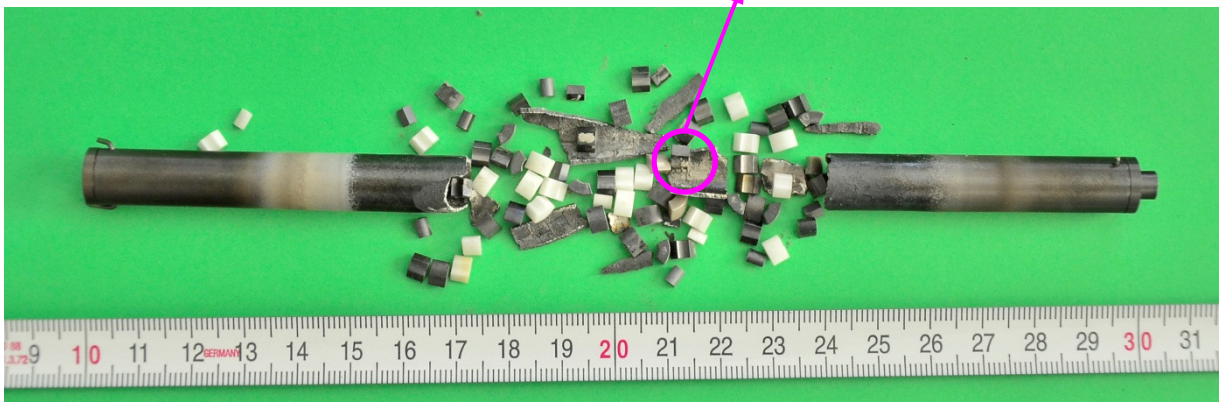
Oxidation at 1773 K during 11600 s, quench with water 80 g/h



sample inside inductive furnace during quench



sample was destroyed during handling

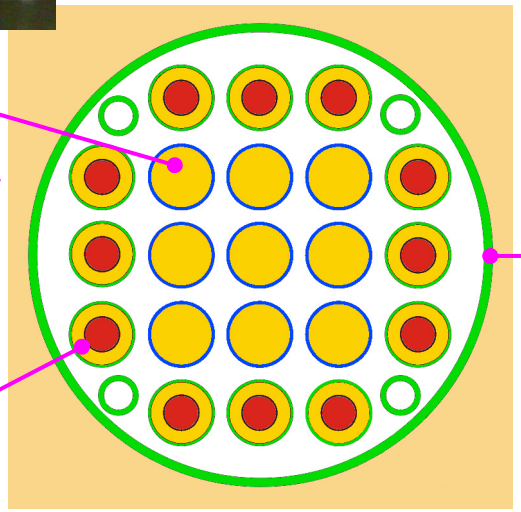


Test bundle preparation

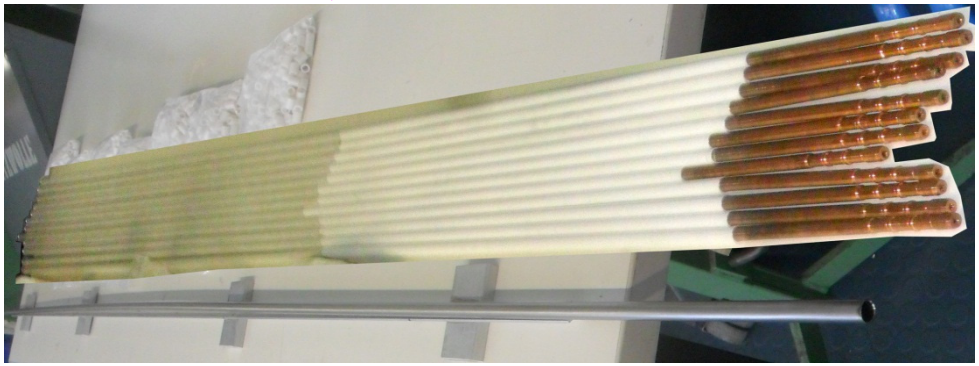
Zry cladding filled with ZrO_2 pellet segments and ZrO_2 powder

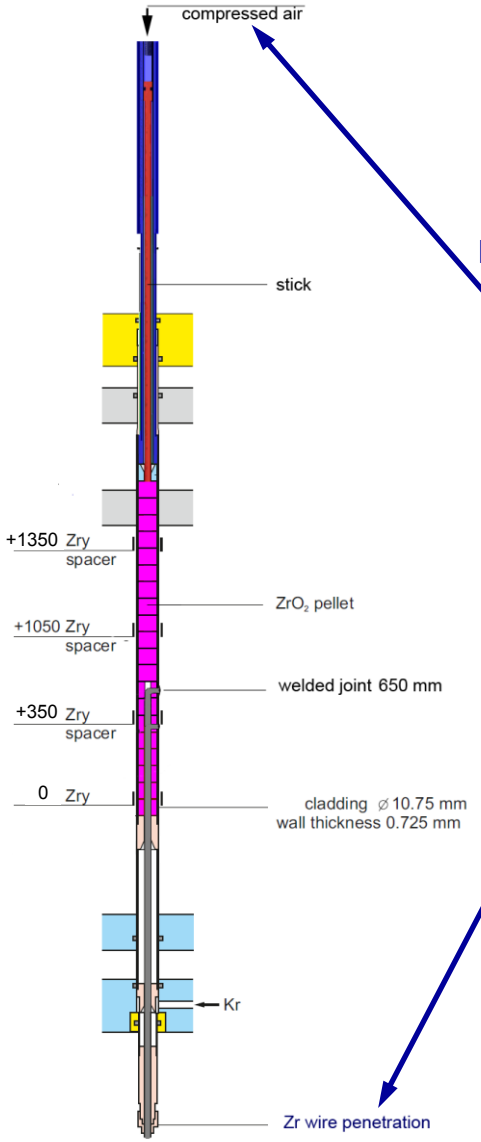
9 unheated rods with Zry-4 cladding

12 heated rods with Hf cladding



Hf shroud



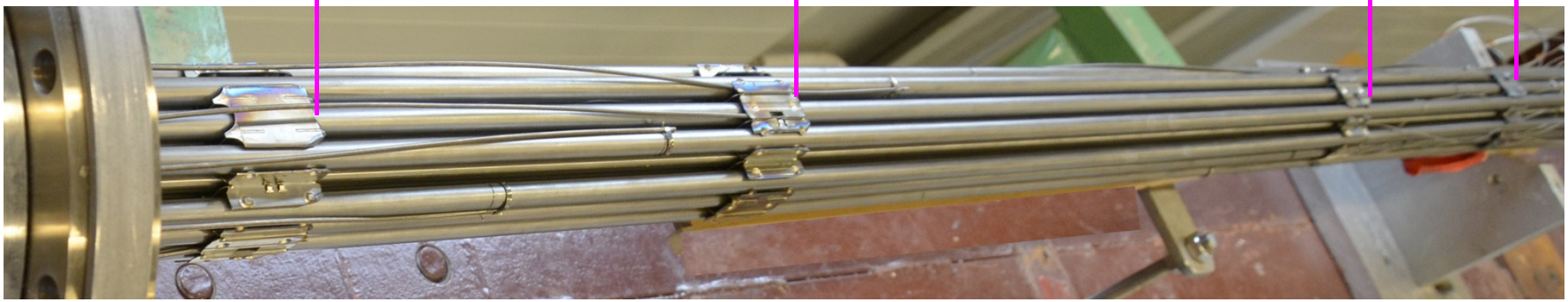


load 100 – 1000 N

Two features of unheated test rods

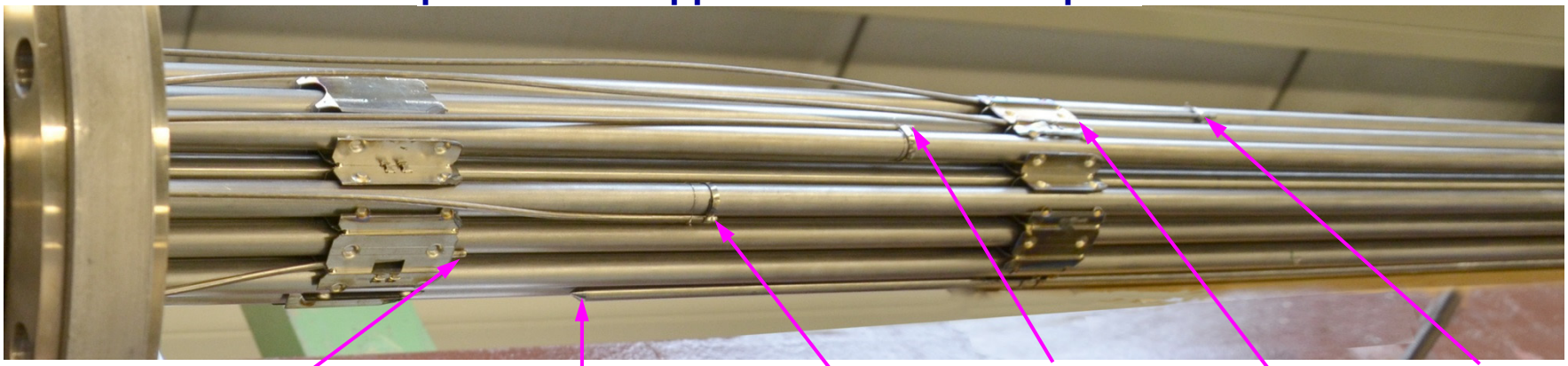
check of through going oxidation

Bundle composition

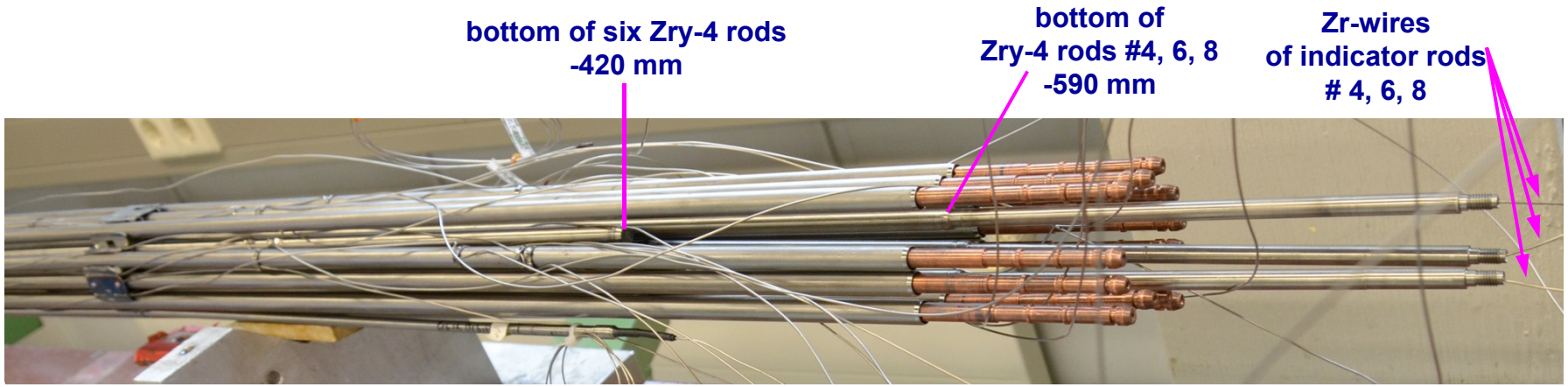


positions of grid spacers

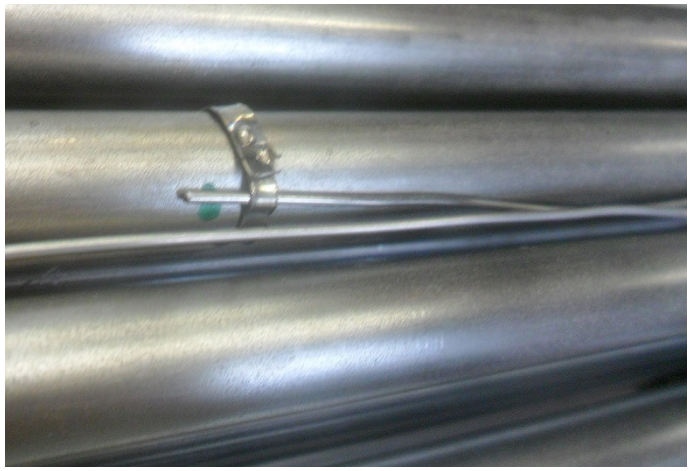
positions of upper W/Re thermocouples



Bundle elements at bundle bottom



bundle bottom



fastening of NiCrNi thermocouple

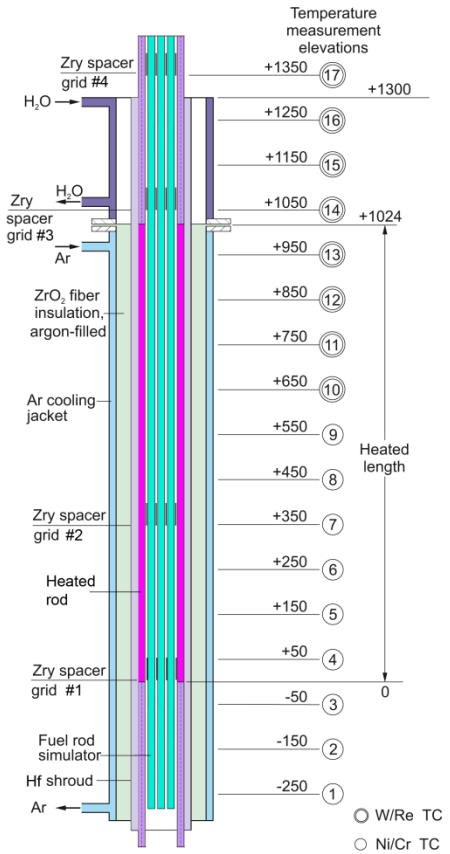
Post-test: overview of mostly intact Hf-shroud (only several cracks) after dismounting of heat insulation

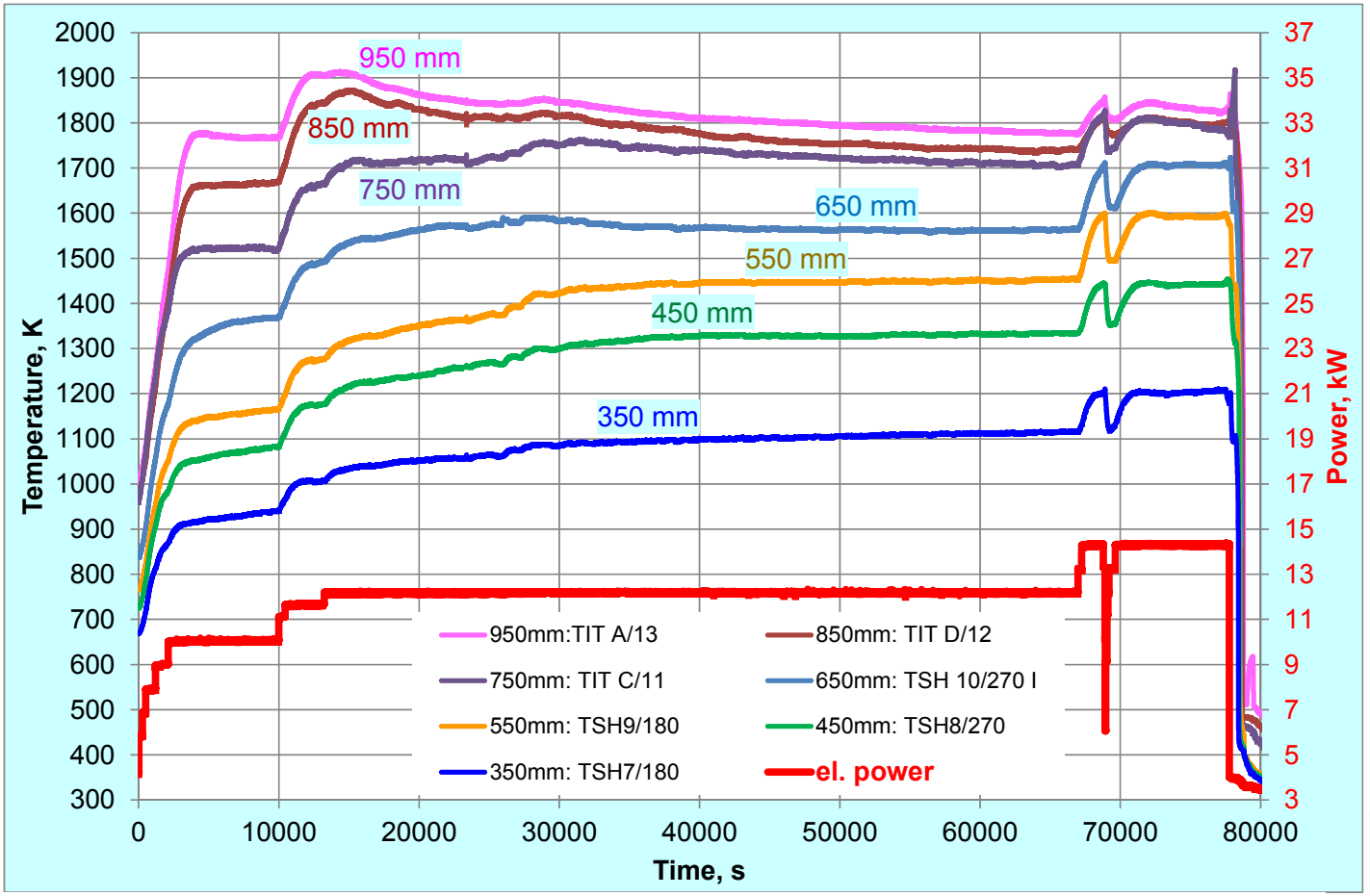
0°

90°

180°

Test scenario: el. power and TC readings at different elevations

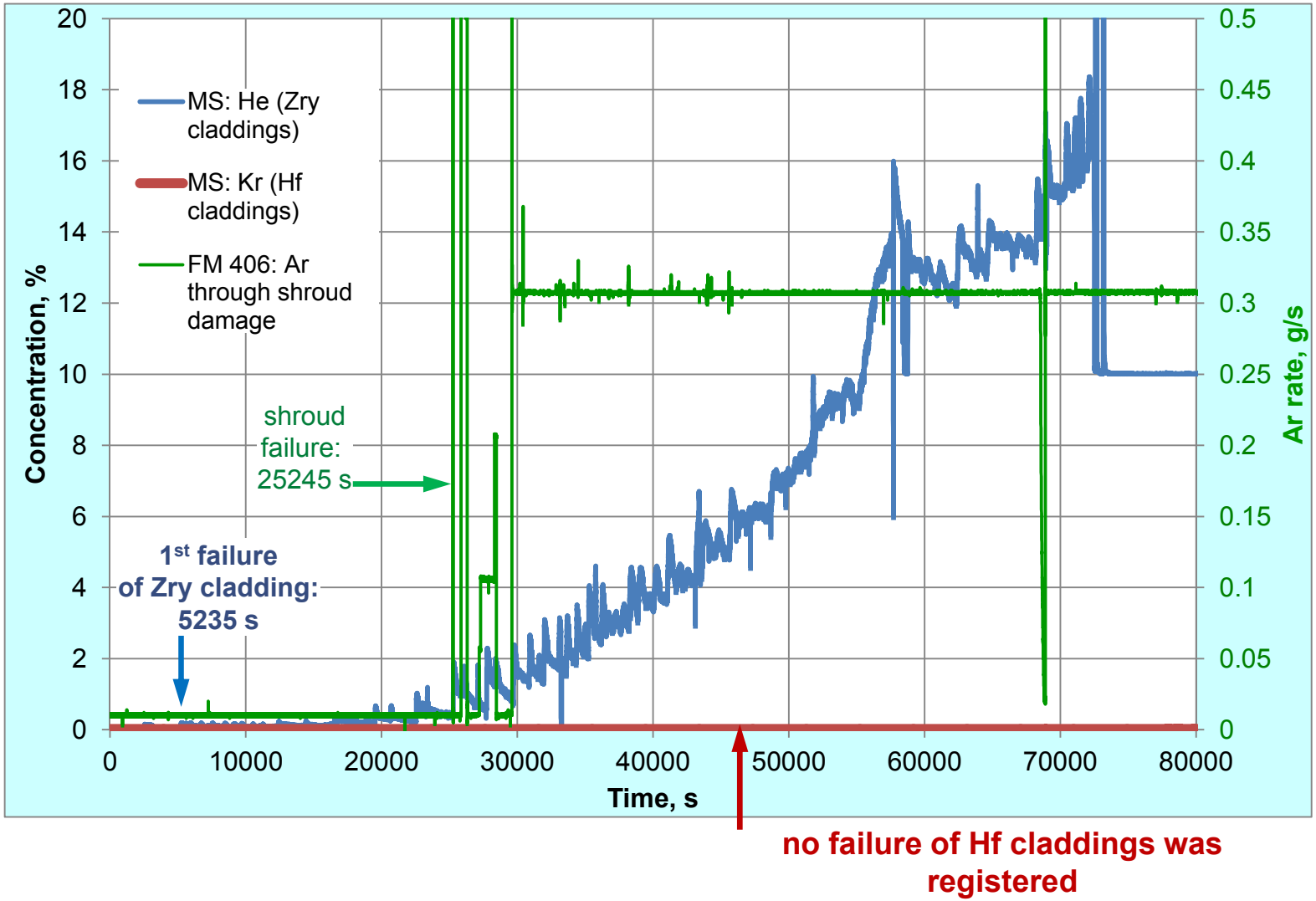




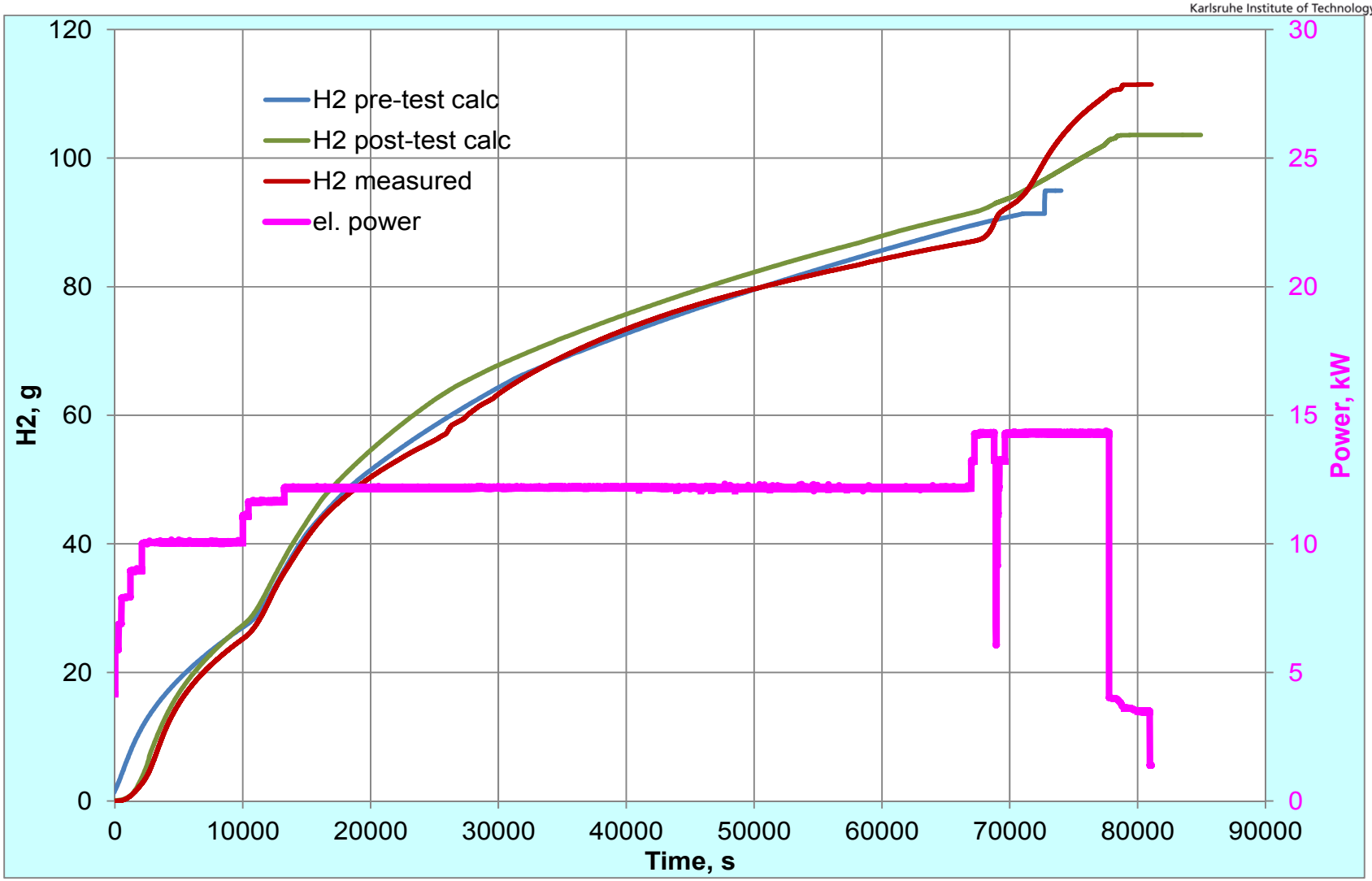
1) pre-oxidation stage with 2 g/s steam and 2 g/s Ar. Complete oxidation of Zry-4 clads between 650 and 1150 mm

2) Test termination: reflood from bottom with water flow rate 10 g/s.

Failures of Zry claddings and Hf shroud

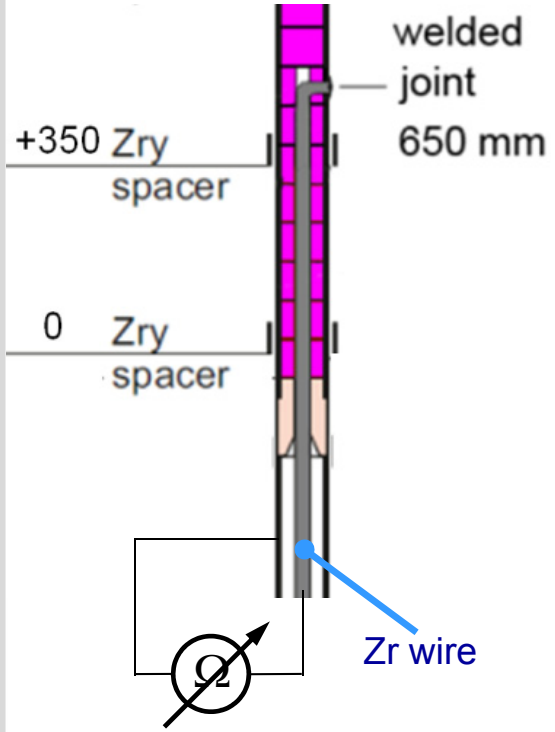


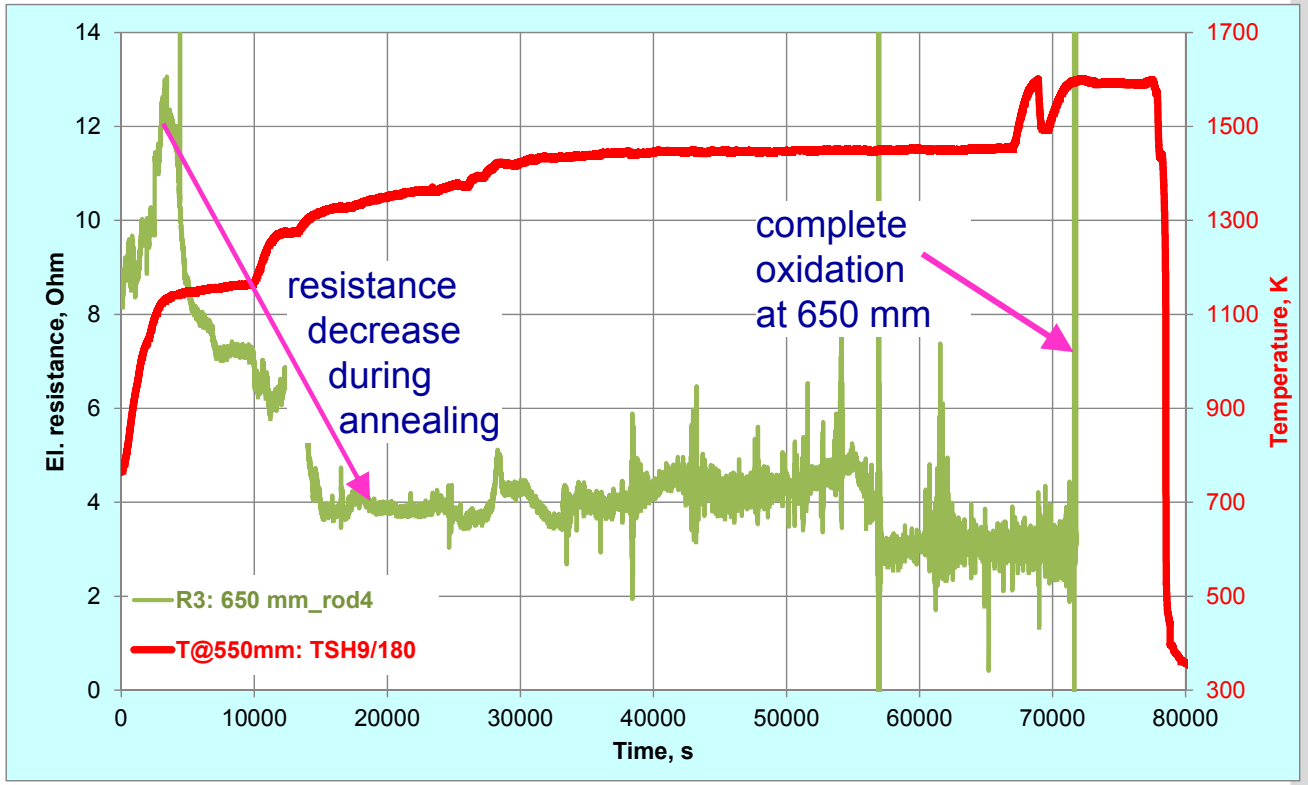
Integral criterion of bundle oxidation progression: hydrogen release during oxidation of Zry and Hf parts



the course of the experiment closely followed the pre-test prediction

Indication of complete oxidation at 650 mm by el. resistance measurement





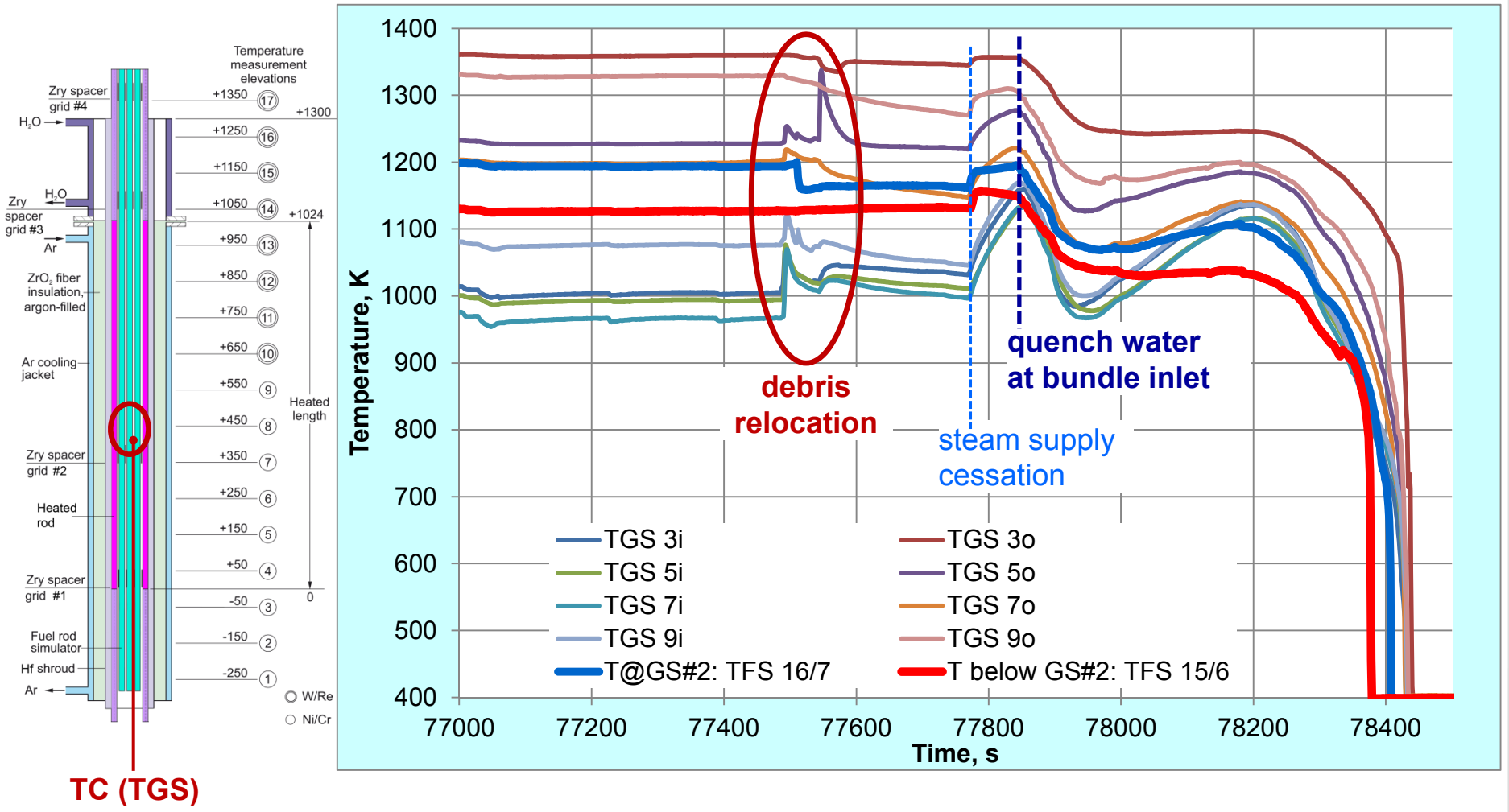
3 welded joints:

R1 at 550 mm for rod #8,

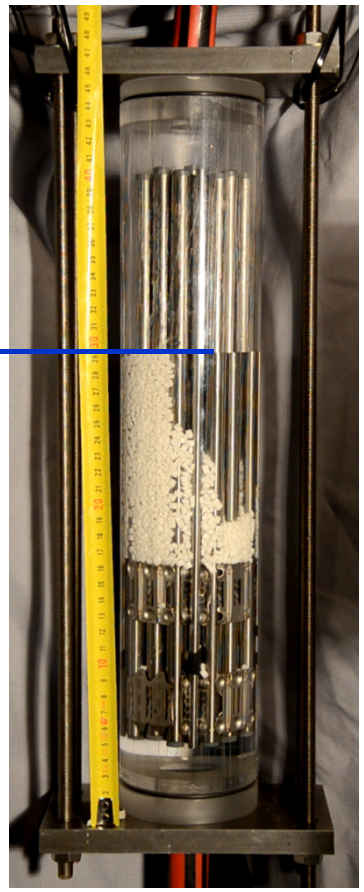
R2 at 650 mm for rod #2,

R3 at 650 mm for rod #4

Indication of debris relocation to GS#2 (reaction of thermocouples TGS installed at the top of GS#2)



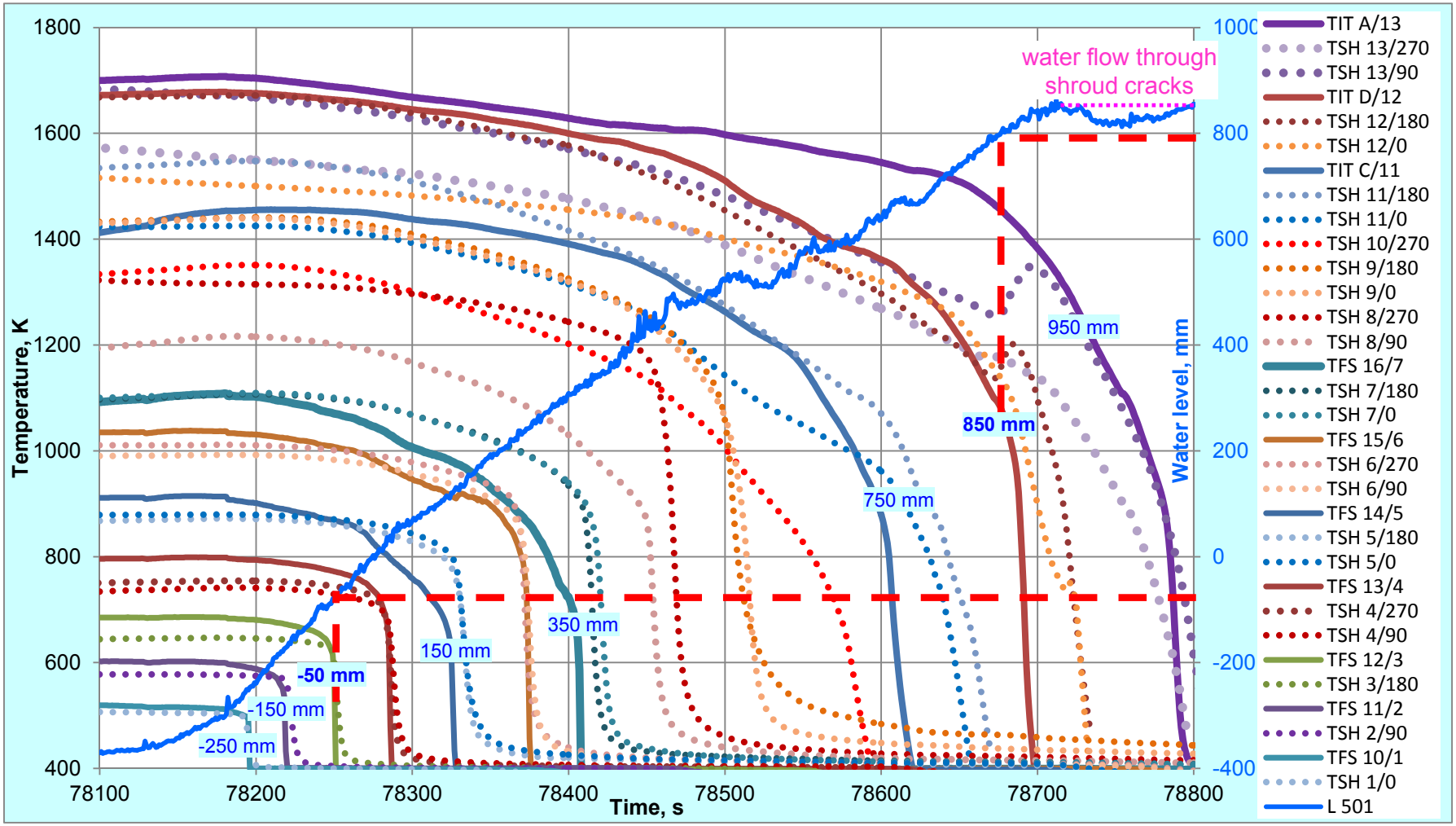
Reflood simulation with pellet debris inside 21-rod-bundle. Cold water flow rate 10 g/s



δt=27 s: **v = 5 mm/s**

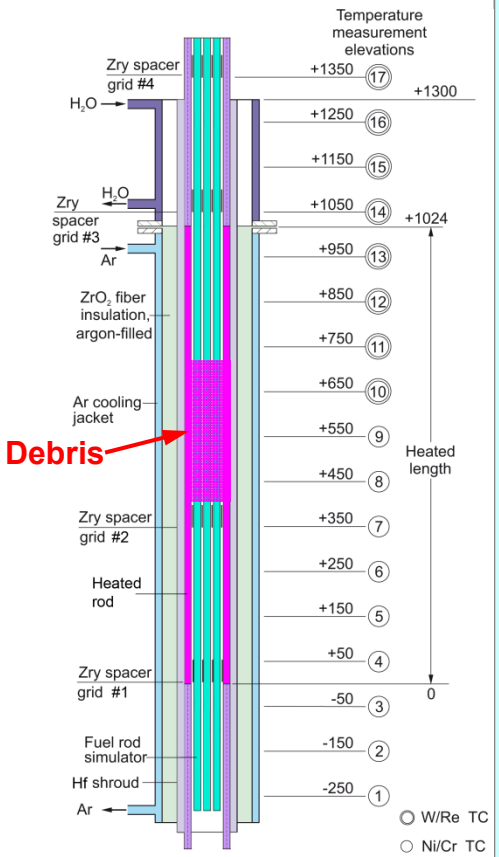
δt=28 s: **v = 3 mm/s**

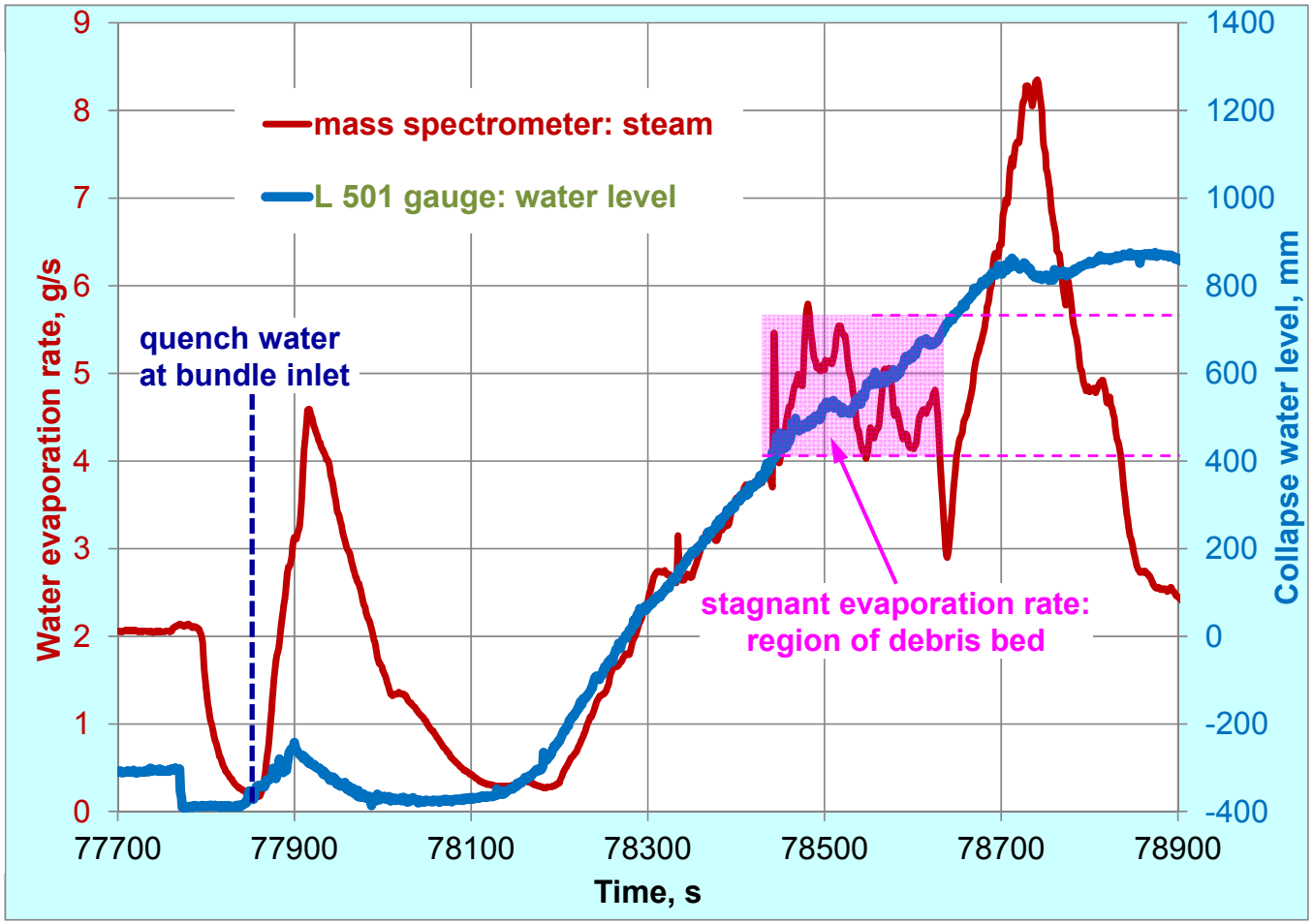
Quench phase: collapse water level and TC wetting



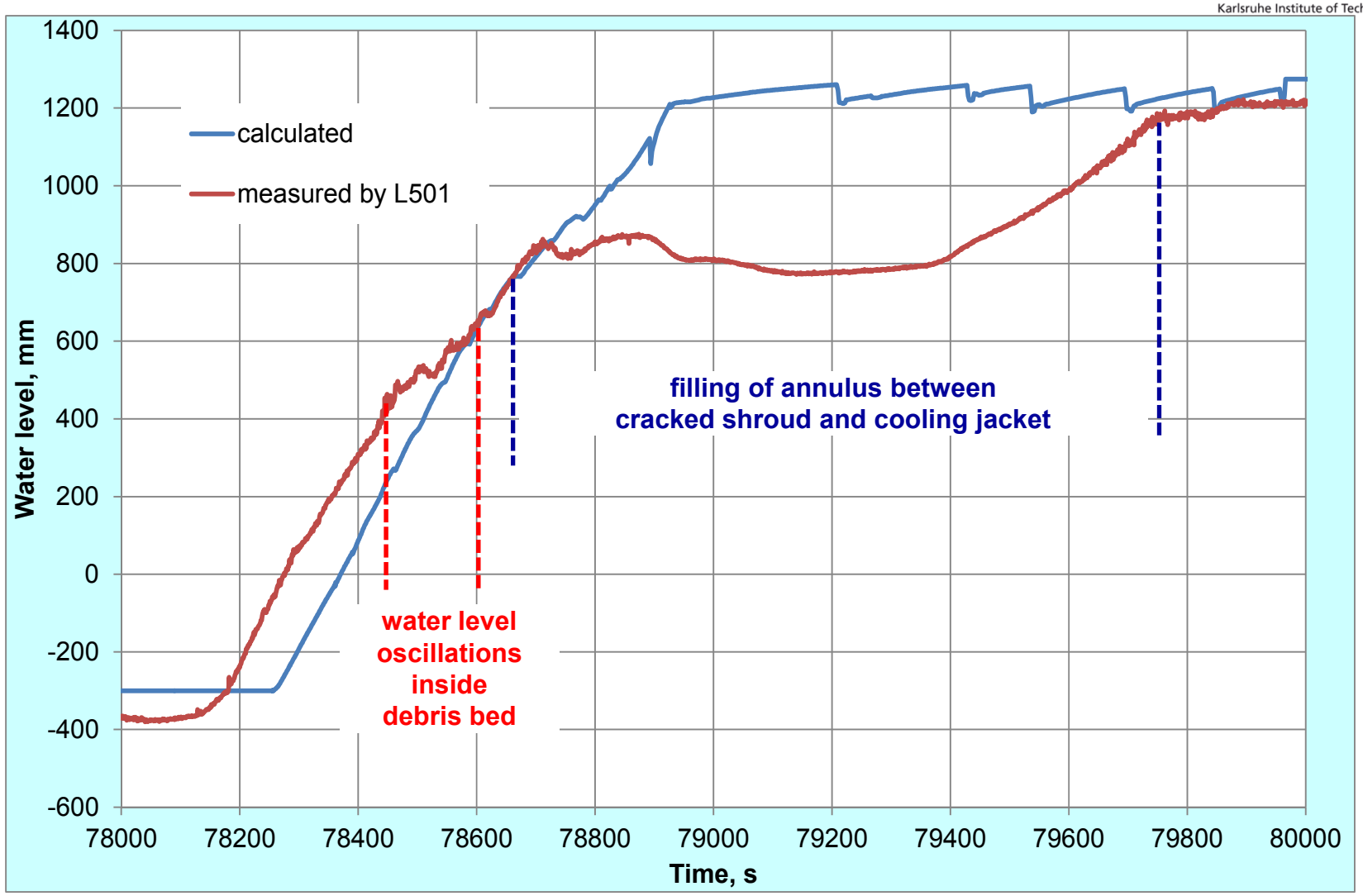
TC wetting at high elevation by 2-phase fluid

Quench phase: water level oscillations and evaporation rate



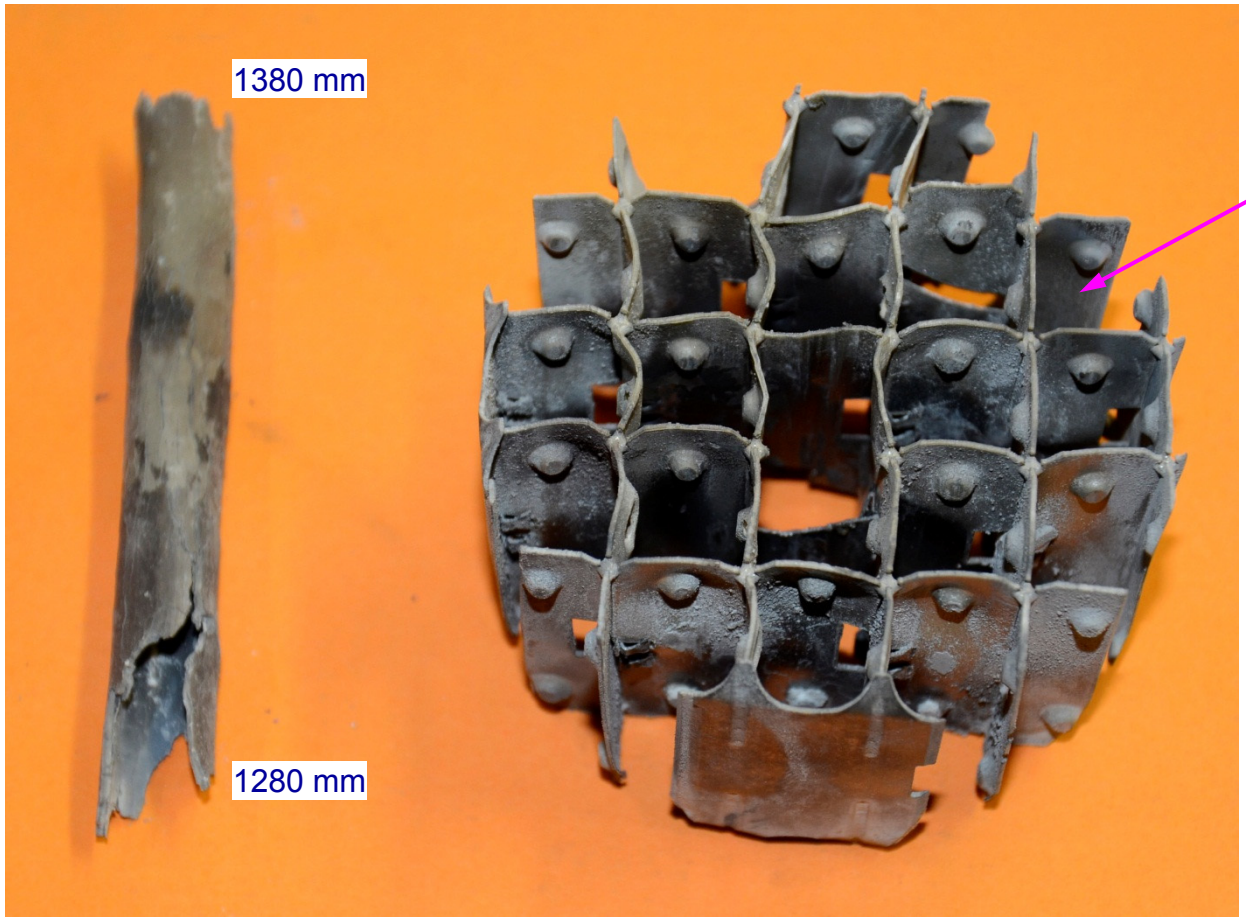


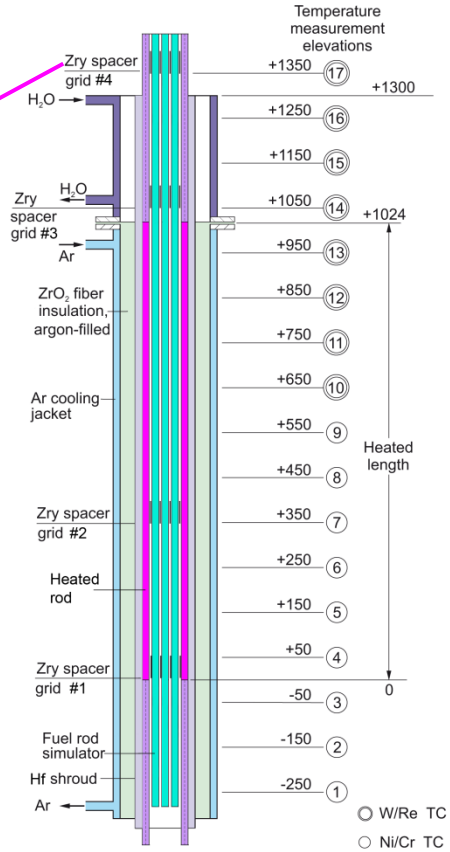
Quench phase: measured and calculated water level



averaged good agreement between pre-calculated and measured results, but no prediction for water level oscillations

Withdrawn grid spacer #4 (1350 -1390 mm) and remnant of cladding

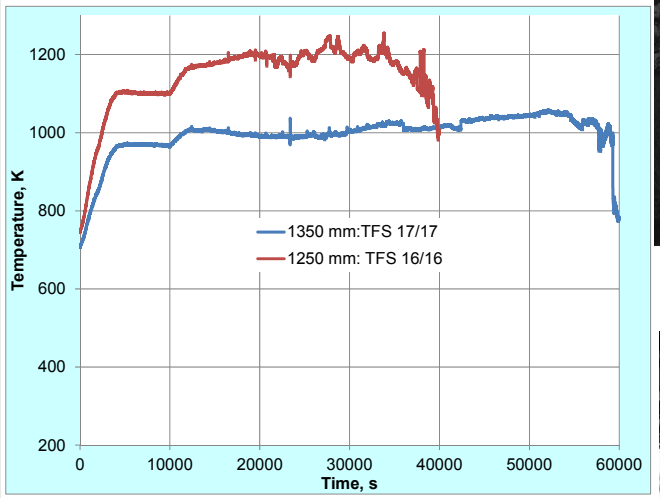


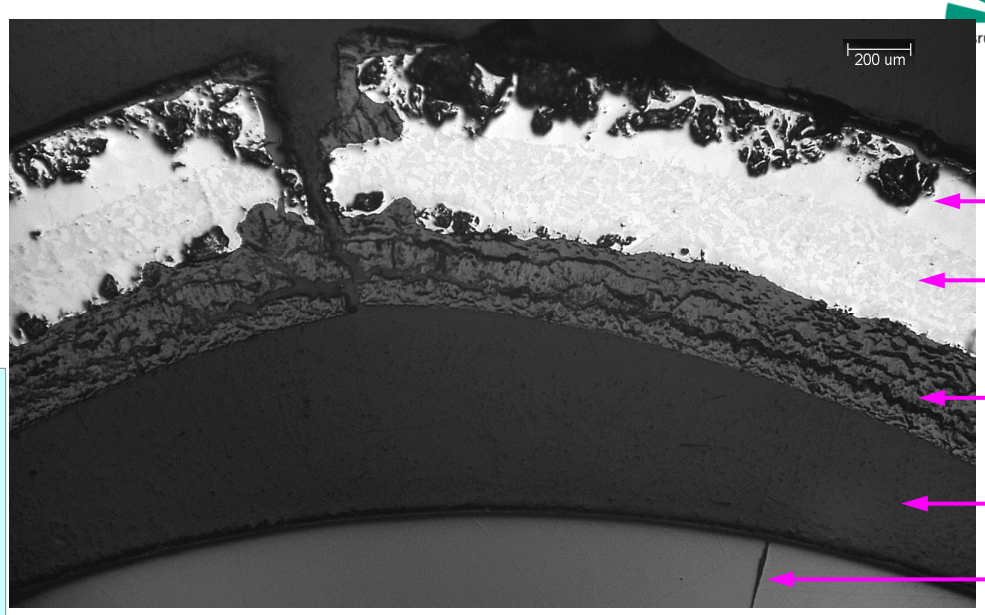


remnant of rod #8:
significantly oxidised

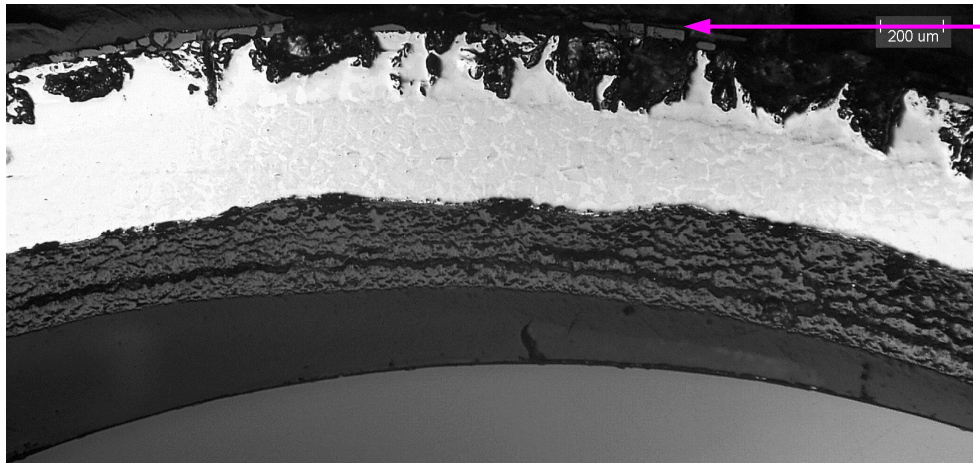
GS #4:
completely oxidised

Structure of oxidized Zry cladding remnant at 1328 mm, T ≈ 1000 K





0°



180°

α-Zr(O)

prior β-Zr

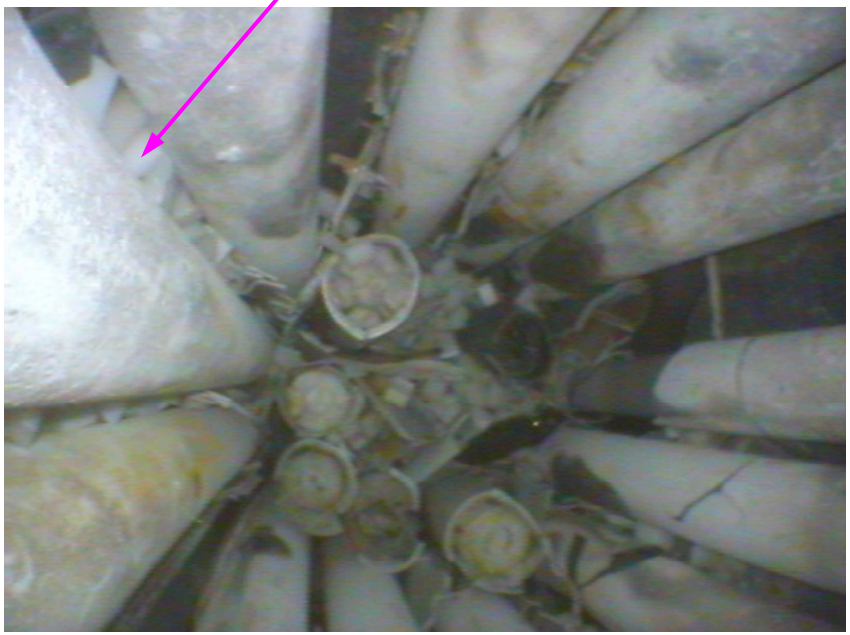
thick inner oxide layer (breakaway)

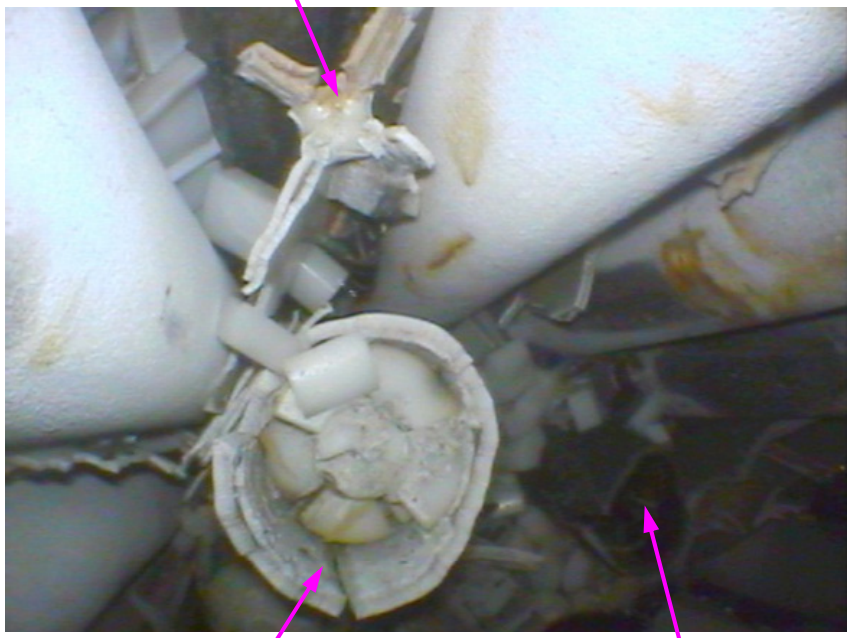
gap

upper not segmented pellet

thin outer ZrO_2 (starvation, spalling?)

Top view of grid spacer #3 (1090 mm)





Endoscope observation of debris relocated under GS #3

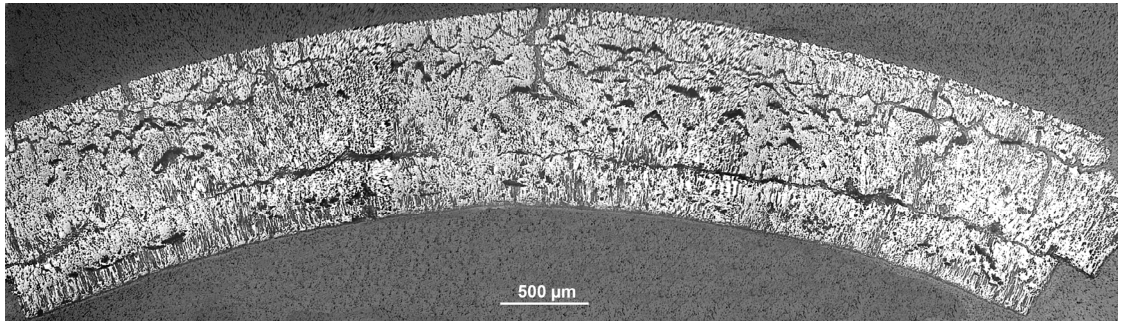
sintered pellets at 950 mm

pellet segments at 920 mm
between Zry and Hf claddings

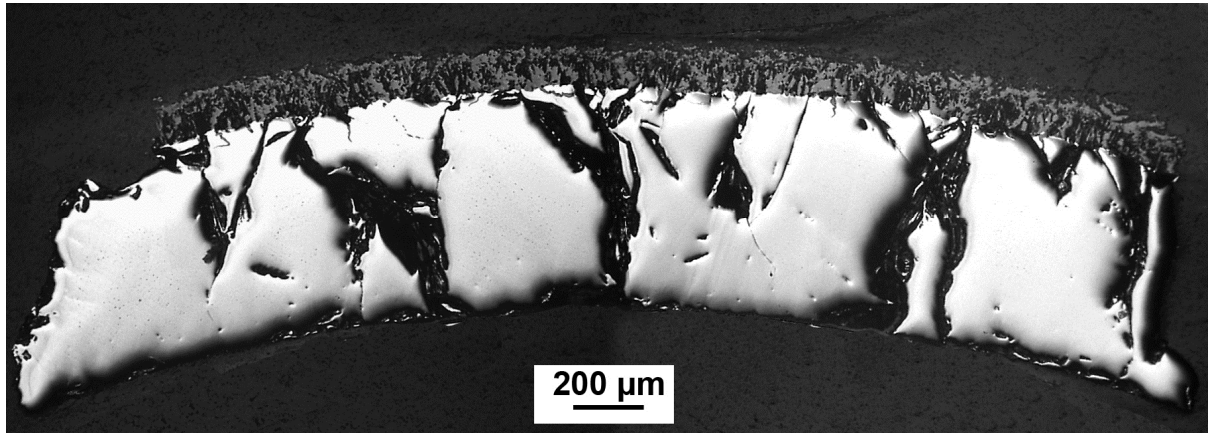
blockage at elevation 910 mm

Debris collected at the top of grid spacer #3 (1090 mm)

Structure of claddings at elevations 1050 mm



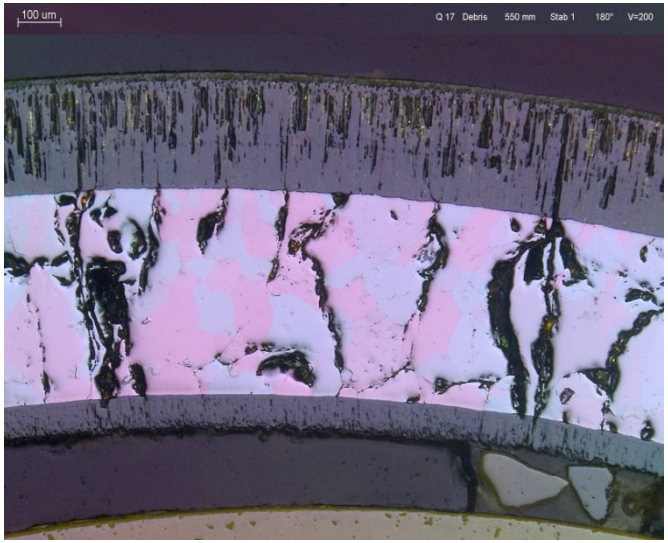
completely oxidized Zry cladding (segment of tube debris)



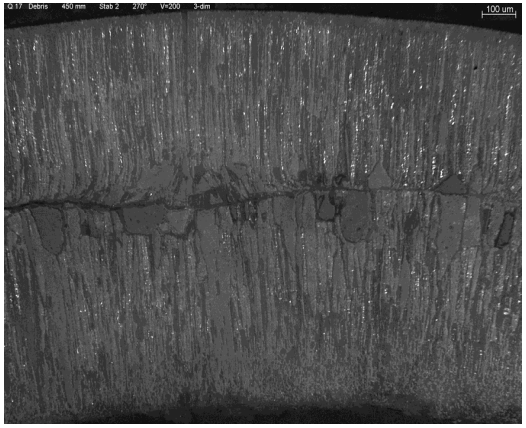
partially oxidized Hf cladding (deleted segment of cladding)

Structure of Zry claddings between 450 and 750 mm

450 mm: outer ZrO_2 75 µm, inner ZrO_2 25 µm,
α-Zr(O) 70 µm (outer and inner), prior β-Zr rest



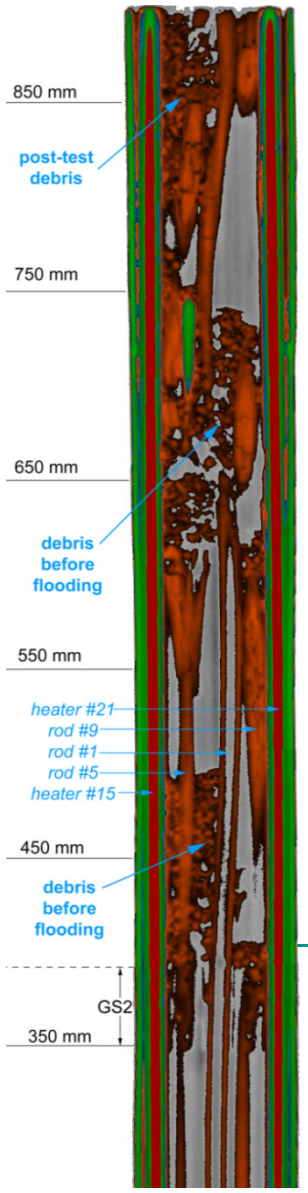
550 mm: outer ZrO_2 250 µm, inner ZrO_2 75 µm, α-Zr(O) rest



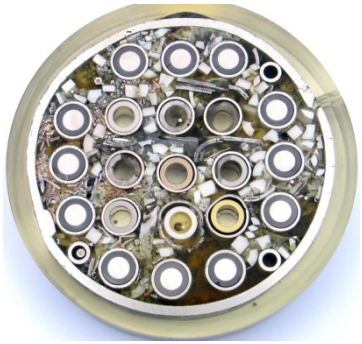
650 mm: completely oxidised

750 mm: completely oxidised

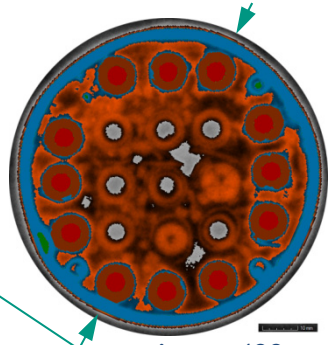
X-ray tomography



bundle composition



cross-section at 400 mm: metallography



cross-section at 400 mm: tomography; blockage 85%

Summary

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- The QUENCH-17 bundle test with 9 unheated internal rods (Zry-4 claddings) and 12 heated external rods (Hf claddings) was performed in two stages: 1) long pre-oxidation stage (78000 s) at T_{pct}=1750 K with complete oxidation of Zry-4 claddings between about 650 and 1150 mm, maximum oxidation of Hf claddings about 30%; 2) reflood stage with slow flooding from bottom (10 g/s, or about 3 mm/s through the debris bed).

- Hf claddings of heated rods were intact during whole test, Hf shroud was failed at 850 mm after 25000 s. First failure of Zry-4 cladding was registered at 5500 s. Noticeable internal oxidation was observed at upper bundle elevations.

- Mechanical impact on the end of pre-oxidation caused debris relocation to grid spacers at 1050 mm and 350 mm. Some Zry-4 claddings were not significantly damaged; the pellet segments relocated from the failed rods were captured between corresponding neighbour rods. Ceramics debris collected at the top of grid spacers consist of separate pellet segments and **relatively large cladding segments**.

- The **porosity** of debris bed is **significant**, no dense packing of debris particles was observed. **Large empty volumes** formed due to bending of rods. The maximum bundle blockage was about 85%.

- Steam production rate was **stagnated** during propagation of flooding water through the debris collected above grid spacers at 350 mm.

- Despite additional gas flow from breaches in the shroud and unheated rods, the course of the experiment closely followed the pre-test prediction, indicating that those events did not impact the test conduct.

- Impact of debris bed on reflooding remains open question. Detailed analysis of the reflood is planned in the near future to examine the latter question.

Acknowledgment

The authors would like to thank Mrs. U. Peters, Mrs. U. Stegmaier and Mrs. J. Laier and for intensive work during test preparation and post-test investigations

Thank you for your attention

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