First results of the bundle test QUENCH-19 with FeCrAl claddings.

J. Stuckert, M. Große, J. Laier, J. Moch, U. Peters, U. Stegmaier, M. Steinbrück (KIT),
K. Terrani (ORNL)

The QUENCH-19 bundle experiment with FeCrAl(Y) claddings and 4 FeCrAl(Y) spacer grids as well as 8 KANTHAL APM corner rods and KANTHAL APM shroud was conducted at KIT on 29th August 2018. This was performed in cooperation with the Oakridge National Laboratory (ORNL).

The test objective was the comparison of FeCrAl(Y) and ZIRLO™ claddings under similar electrical power and gas flow conditions. In common with the previous QUENCH-15 experiment, the bundle was heated by a series of stepwise increases of electrical power from room temperature to a maximum of ≈600 °C in an atmosphere of flowing argon (3.45 g/s) and superheated steam (3.6 g/s). The bundle was stabilised at this temperature, the electrical power being ≈4 kW. During this time the operation of the various systems was checked.

In a first transient, the electrical power was controlled with the same electrical power history as the QUENCH-15 test. As a result, the bundle was heated to peak cladding temperature of about 1000 °C reached at about 4000 s. It showed a slowed bundle heating than for the QUENCH-15 bundle (1200 °C reached at about 3000 s). In this test phase about 0.3 g of hydrogen were produced (QUENCH-15: 23.3 g).

In the following phase, the power was increased continuously to 18.12 kW (corresponds to maximal power of the QUENCH-15 test). After reaching of this value the power was kept constant during about 2000 s. At the end of this phase the maximal peak cladding temperature of T_{pct}≈1500 °C was reached. Much lower heating rate in comparison to QUENCH-15 was measured. Exceeding T_{pct}≈1400 °C sharp increase of hydrogen release rate was observed.

Then reflood was initiated at ≈9100 s, connected with switching the argon injection to the top of the bundle, first rapidly filling the lower plenum of the test section with 4 kg of water, and continuing by injecting ≈48 g/s of water. The electrical power was reduced to 4.1 kW during the reflood.

A temperature excursion was not observed. The temperatures at all elevations decrease immediately after water injection. The total hydrogen release during the whole test was 9.2 g compared to 47.6 g in the QUENCH-15 test with much shorter high electrical power phase.

The videoscope observation of the bundle at the positions of the withdrawn corner rods showed the damage of several claddings at the bundle elevations between 850 and 1000 mm. The claddings were failed either due to interaction with melted thermocouples (mostly) or by spalling of small annular cladding parts.

Karlsruhe Institute of Technology

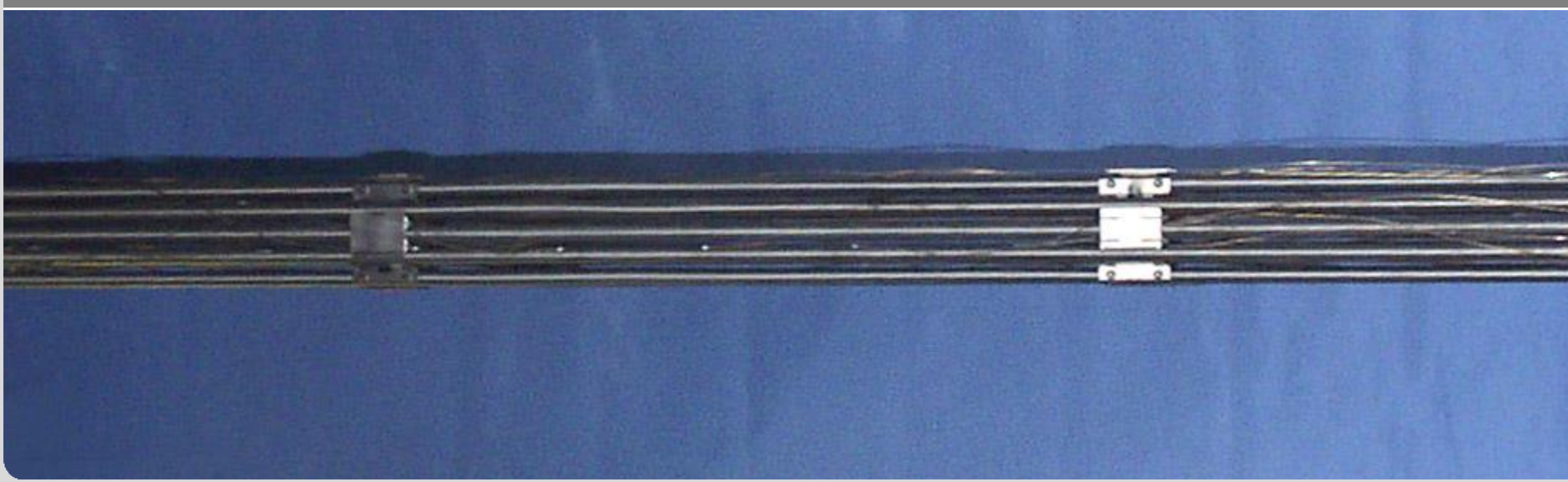
Institute for Applied Materials

First results of the bundle test QUENCH-19 with FeCrAl claddings

J. Stuckert, M. Große, J. Laier, J. Moch, U. Peters, U. Stegmaier, M. Steinbrück (KIT), K. Terrani (ORNL)

QWS-24, Karlsruhe 2018

Institute for Applied Materials; Program NUSAFE



Chemical compositions and oxidation in steam of FeCrAl alloys

Karlsruhe Institute of Technology

Material	Fe	Cr	Al	Y	Si	Mn	C	comment
Conventional Kanthal APM	Balance	22	5.8	-	0.7	0.4	0.08	used for shroud and corner rods in QUENCH-19
FeCrAl(Y) alloy B136Y3 (ORNL)	**Balance**	**13***	**6.2**	**0.03**			**0.01**	used for **claddings** of heated rods in QUENCH-19

*reduced in comparison to Kanthal to decrease the hardening under irradiation

$$\Delta m/S = K_m\sqrt{t}$$

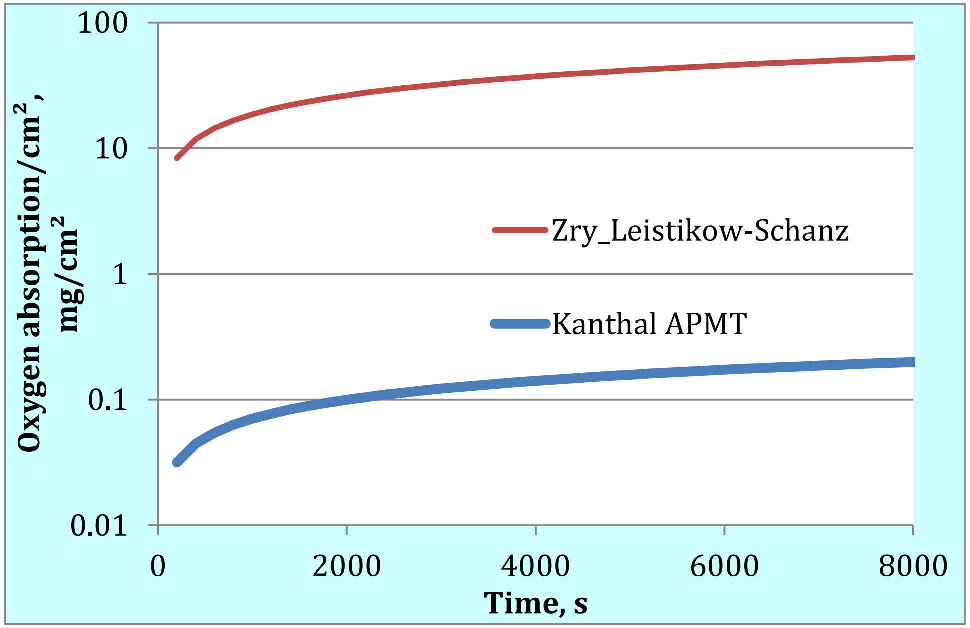
$$K_m(T) = K_0 \exp(-\frac{E_0}{RT})$$

Material	E_0 (J/mol)	K_0 ($g/cm^2s^{0.5}$)
Zry-4*	87144	0.724
APMT**	172000	2.8

Oxidation kinetics in steam

*G. Schanz, FZKA 6827, https://publikationen.bibliothek.kit.edu/270054544/3814367

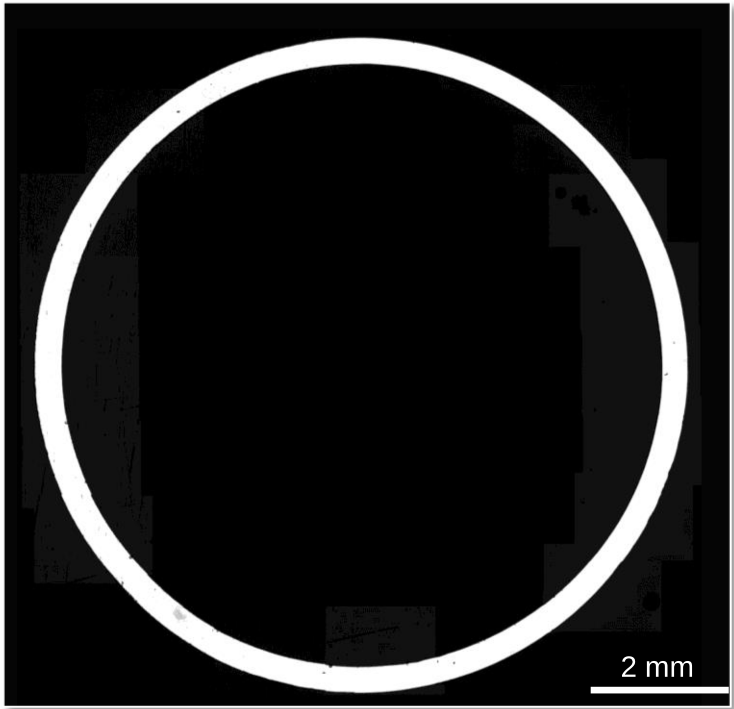
**K. Field et al., ORNL/SPR-2018/905, https://info.ornl.gov/sites/publications/Files/Pub114121.pdf



Oxidation in steam at 1200 °C in comparison with Zry-4

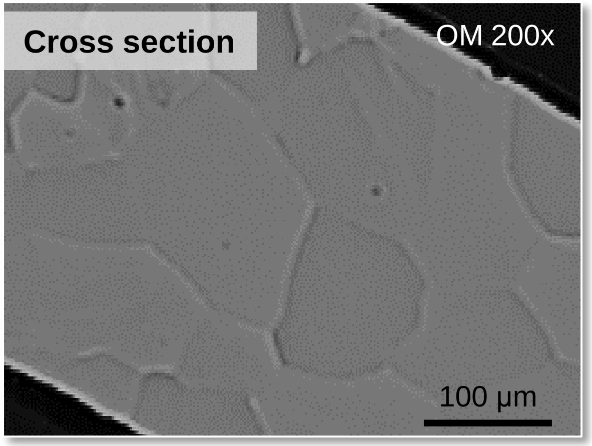
Cladding tubes B136Y3 (by Century Tubes Inc./ORNL)

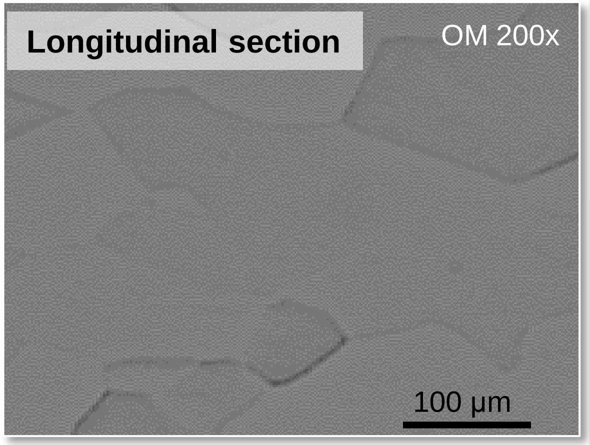
Karlsruhe Institute of Technology



- Made by **cold-drawing**
- OD: 9.52 mm
- WT: 382 µm ± 12 µm
- Grain size: ~80-100 µm

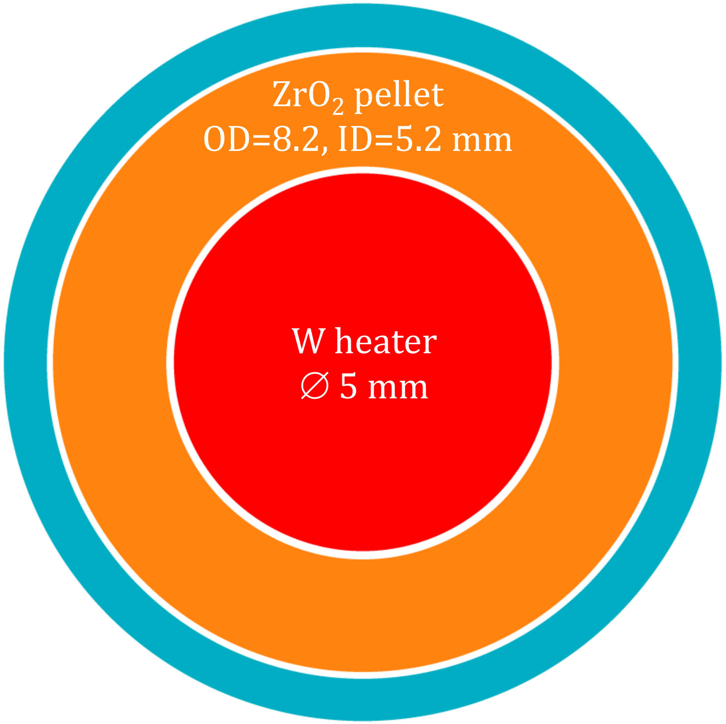
Hardness: 254 ± 7 HV



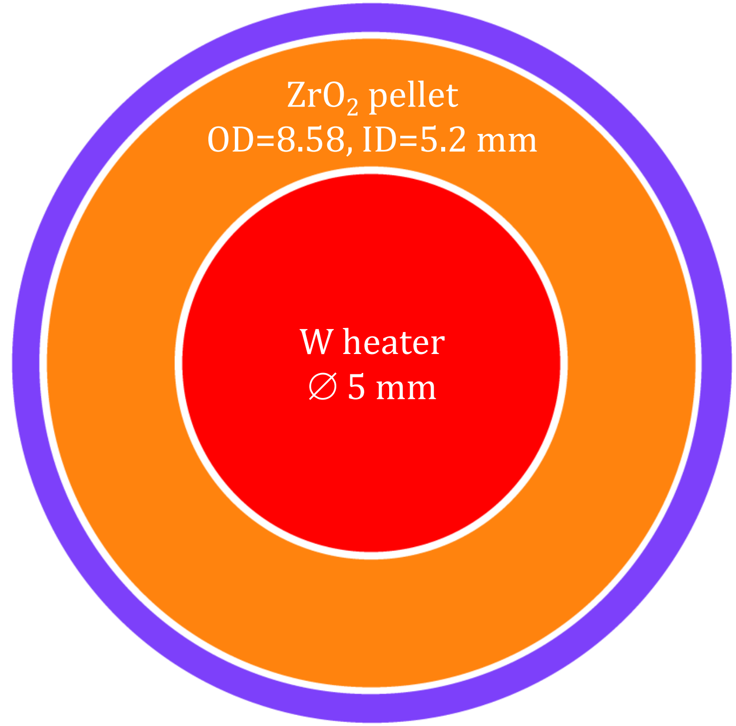


Cross sections of fuel rod simulators (in comparison to reference test QUENCH-15 with ZIRLO claddings)

Karlsruhe Institute of Technology



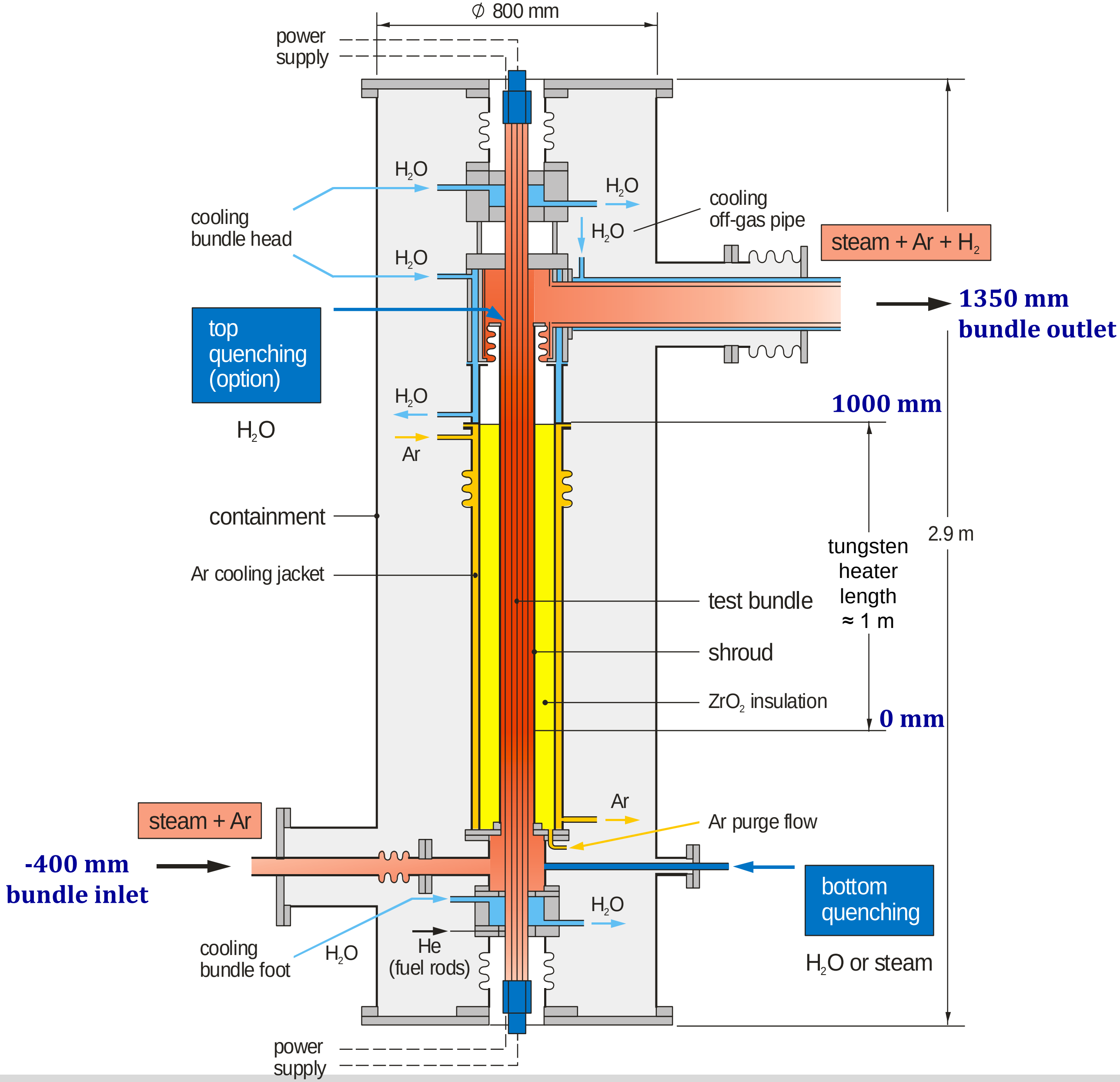
QUENCH-15 (**ZIRLO** cladding with OD=9.5 mm, **WT=572 µm**)



QUENCH-19 (**FeCrAl(Y)** cladding with OD=9.52 mm, **WT=381 µm**)

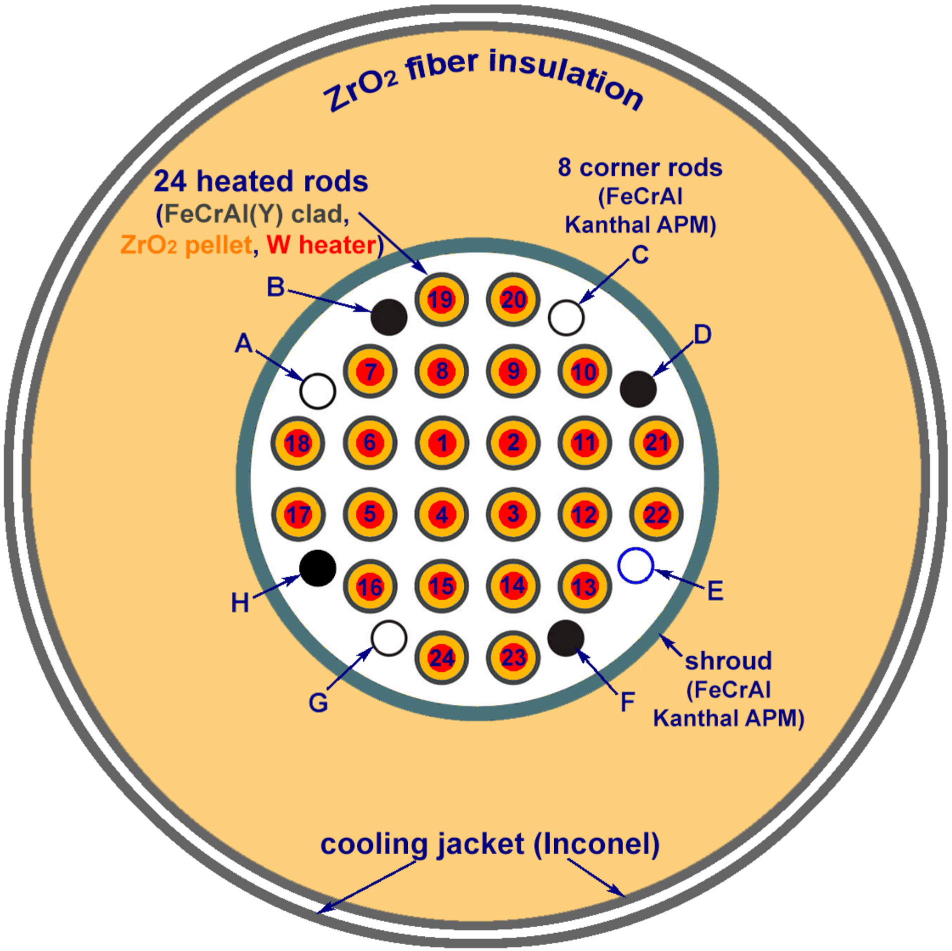
	heat capacity	heat conductivity	thermal expansion	melting point
FeCrAl (Kanthal)	≈ 460 J/(kg·K)	≈ 11 W/(m·K)	$14 \cdot 10^{-6}$ /K	≈ 1790 K
ZIRLO	≈ 270 J/(kg·K)	≈ 23 W/(m·K)	$5.7 \cdot 10^{-6}$ /K	≈ 2030 K

QUENCH test section

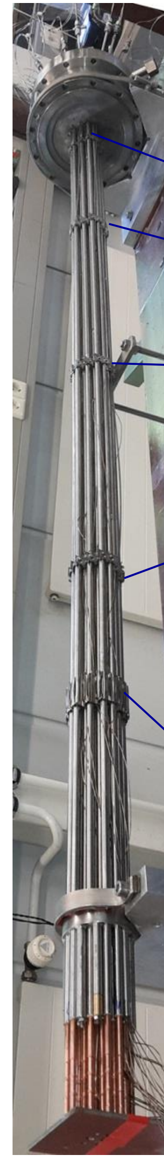


Composition of test bundle QUENCH-19

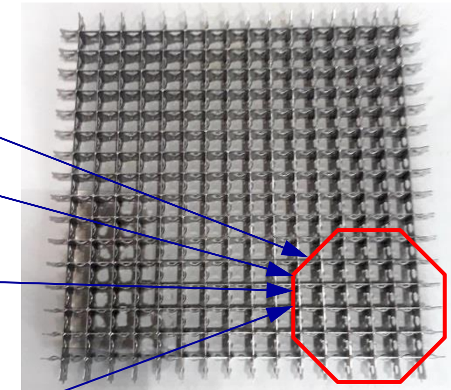
Karlsruhe Institute of Technology



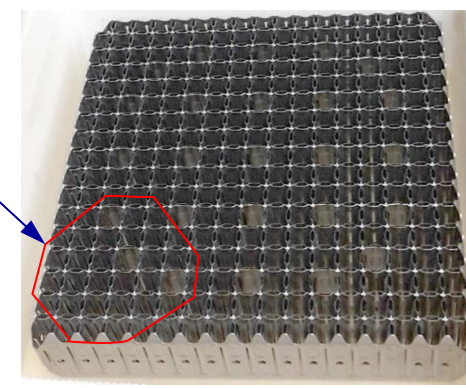
cross section
(arrangement the same as for QUENCH-15)



test bundle (length 2m)

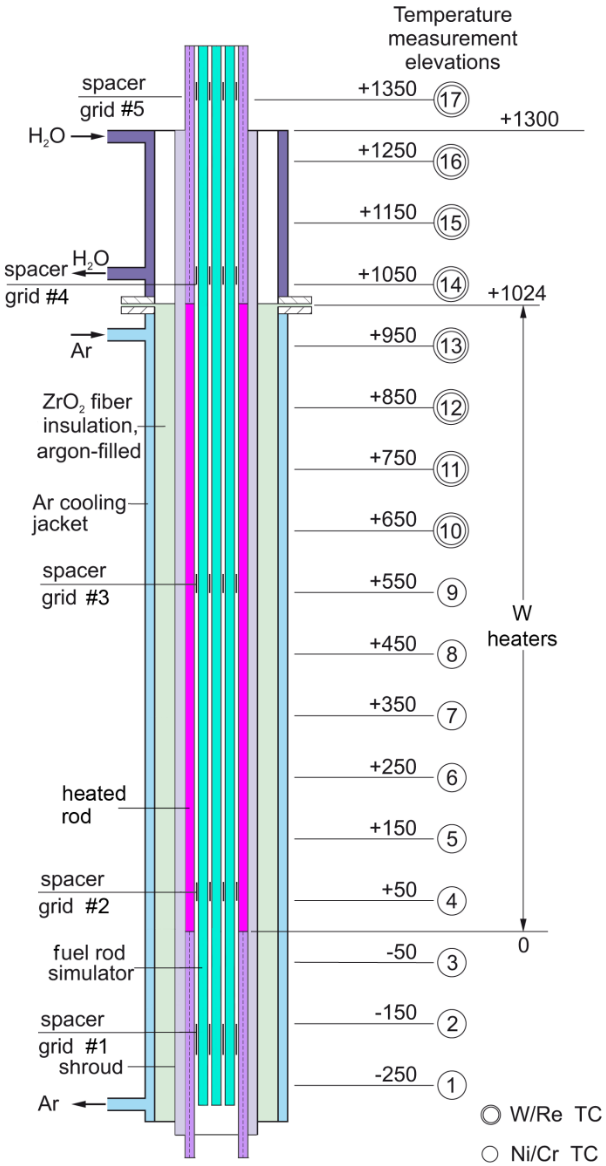


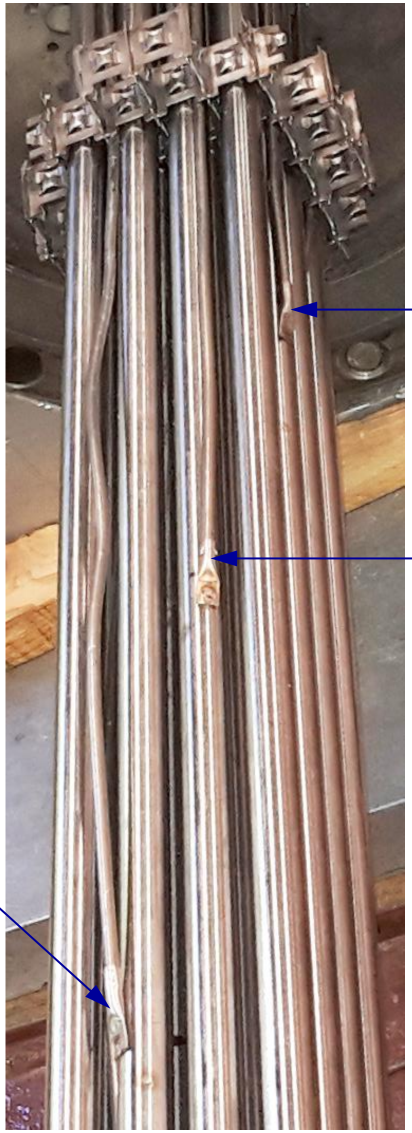
ORNL FeCrAl(Y) **spacer grids**:
height 22 mm,
sheet thickness 0.5 mm



AREVA Inconel **spacer grid**:
height 45 mm,
sheet thickness 0.5 mm

QUENCH-19 bundle instrumentation (thermocouples at cladding surface)





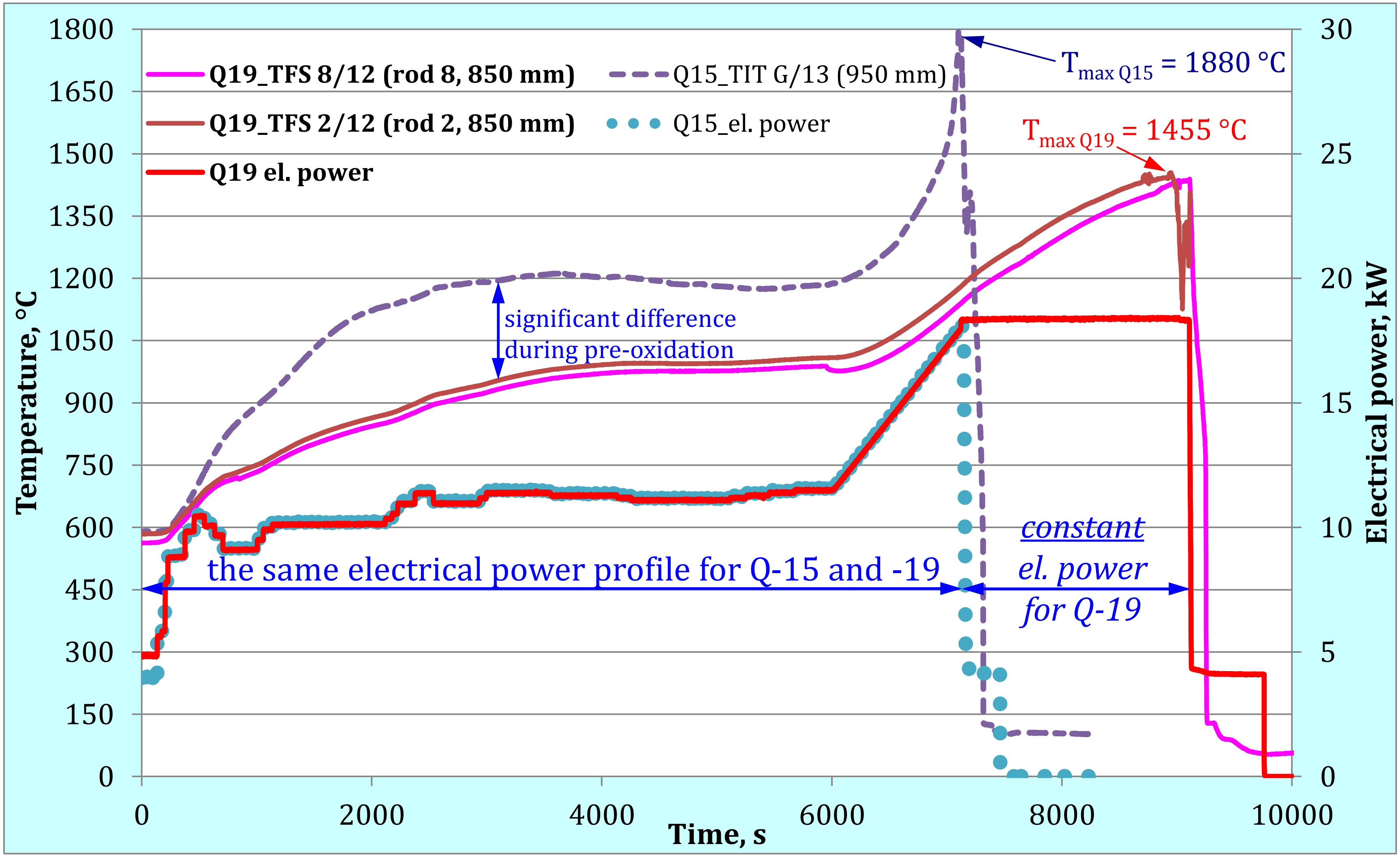
TFS 12/15
W/Re TC sheathed by steel
at 1150 mm, rod #12

TFS 14/14
W/Re TC sheathed by steel
at 1050 mm, rod #14

TFS 15/13
W/Re TC sheathed by steel
at 950 mm, rod #15

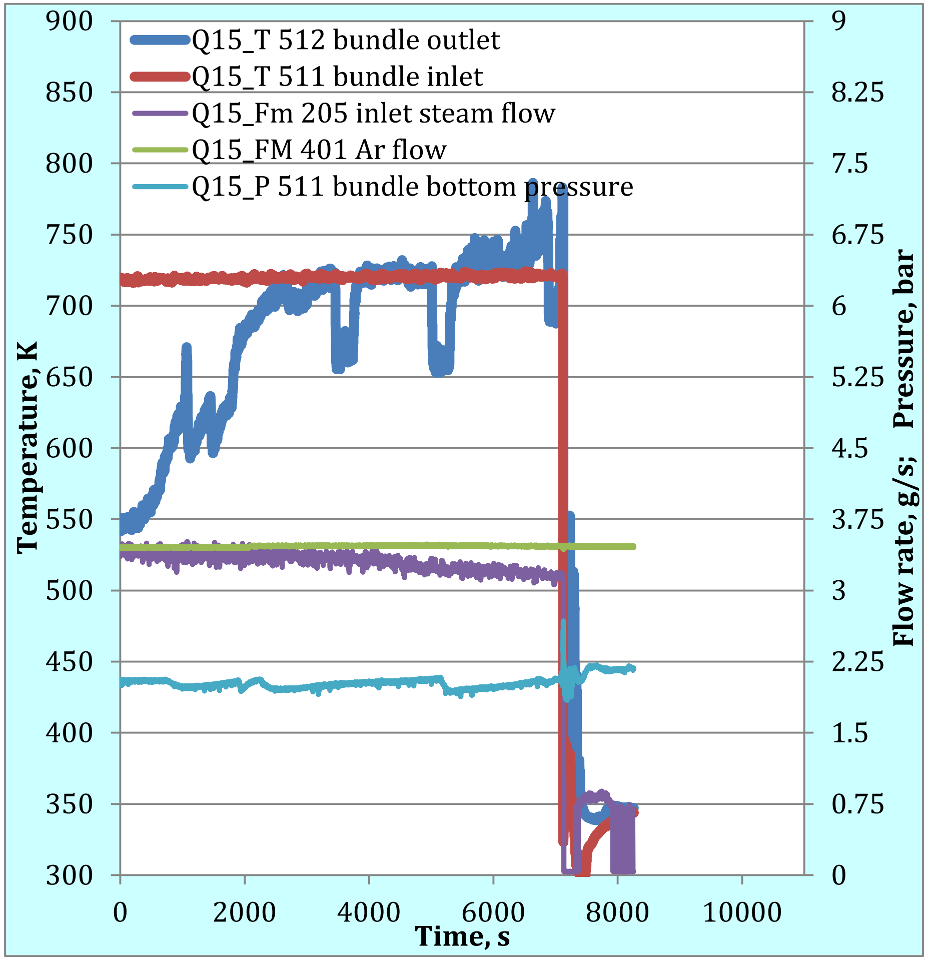
Test performance: comparison of QUENCH-15 (ZIRLO) and -19 (FeCrAl)

Karlsruhe Institute of Technology

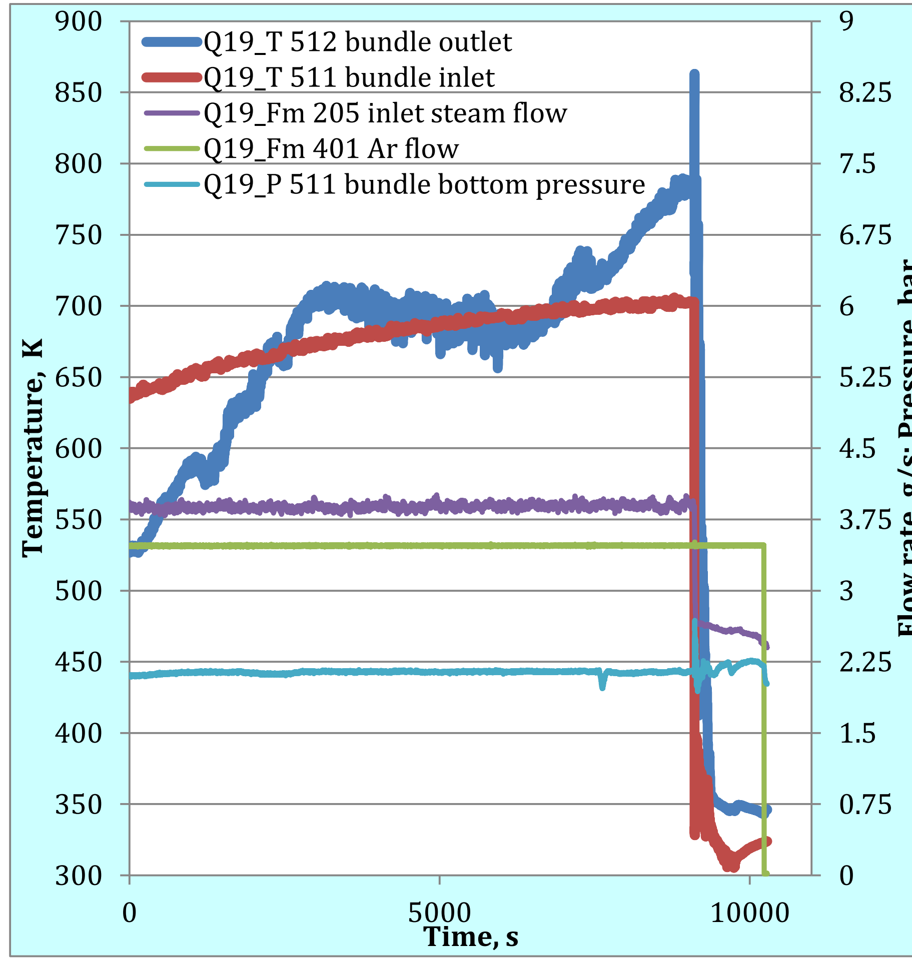


Energy release during Q15 pre-oxidation (i.e. until 6000 s): **electrical E_e = 63.7 MJ, chemical E_{ch} = 3.5 MJ** ⟹ $E_{ch} \ll E_e$

Parameters of gas atmosphere at bundle inlet and outlet

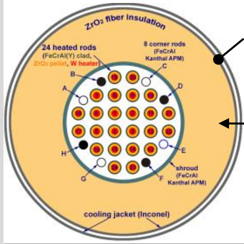


QUENCH-15:
inlet gas (steam + Ar) $T_g \approx 720$ K;
steam flow rate $3.2 < F_s < 3.4$ g/s;
Ar flow rate $F_{Ar} = 3.5$ g/s



QUENCH-19:
inlet gas (steam + Ar) $640 < T_g < 700$ K;
steam flow rate $F_s \approx 3.8$ g/s;
Ar flow rate $F_{Ar} = 3.5$ g/s

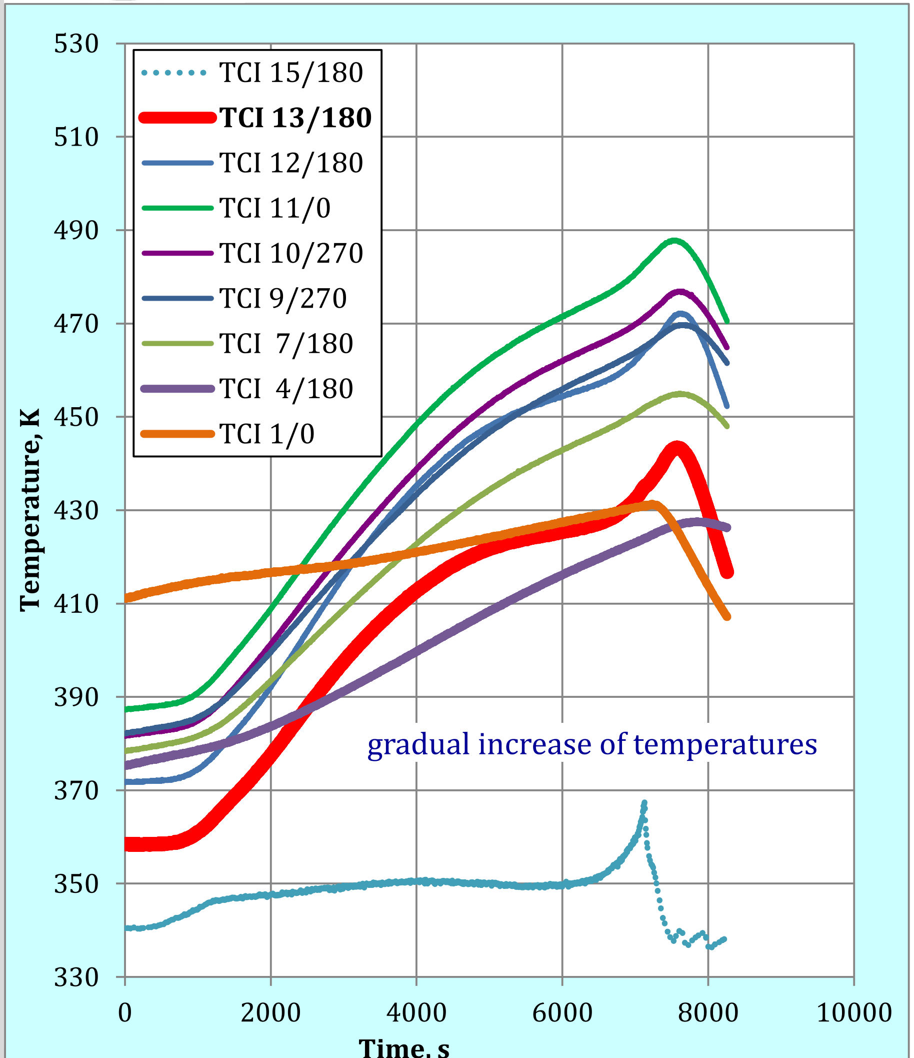
(Q15 ≈ Q19)
similar inlet and outlet

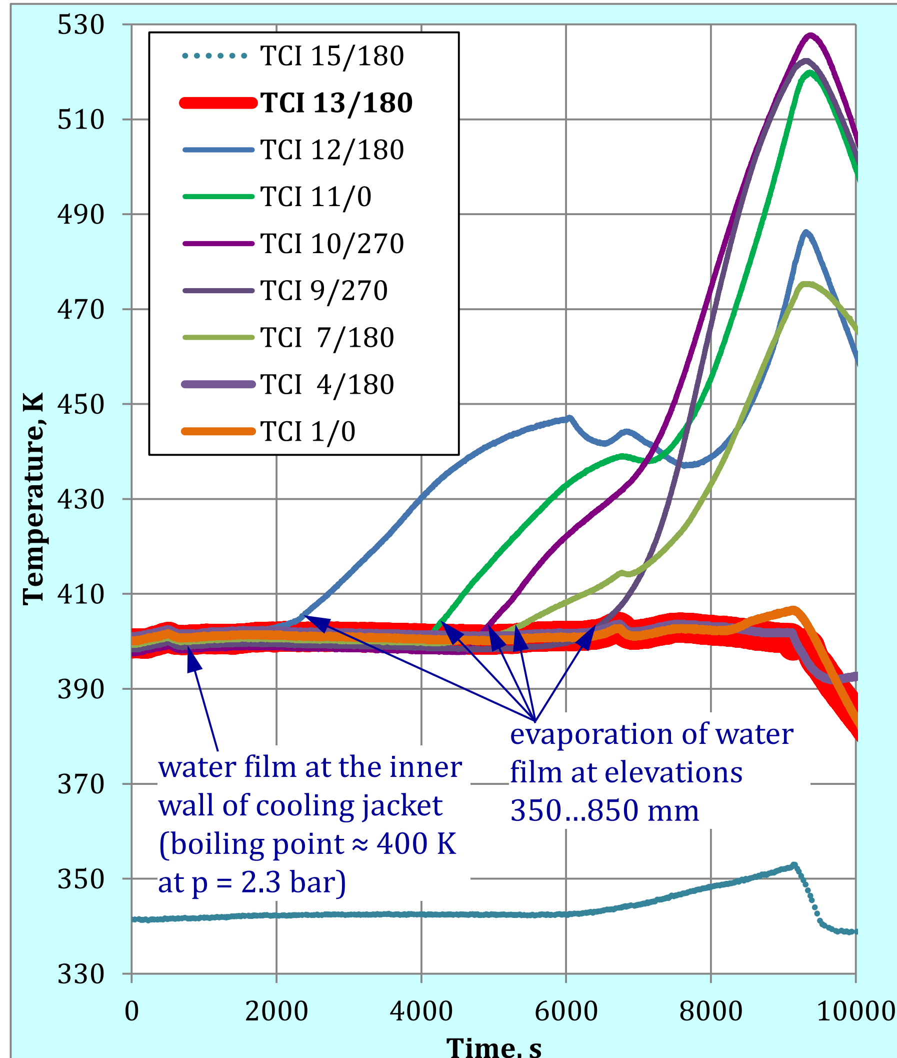


Boundary conditions (temperatures behind heat insulation)

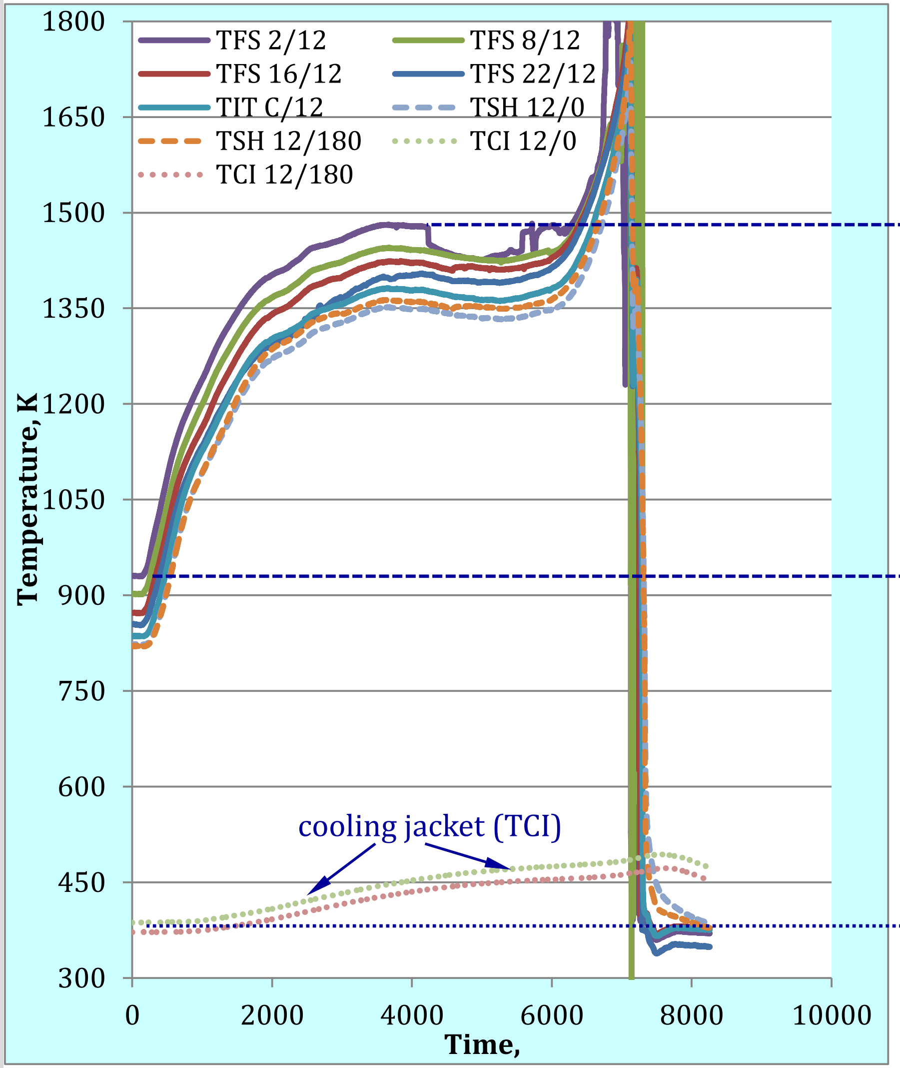
(Q15 ≠ Q19)

porous heat insulation filled with dry Ar in Q15 and **with humid Ar in Q19** (leakage of steam into insulation)

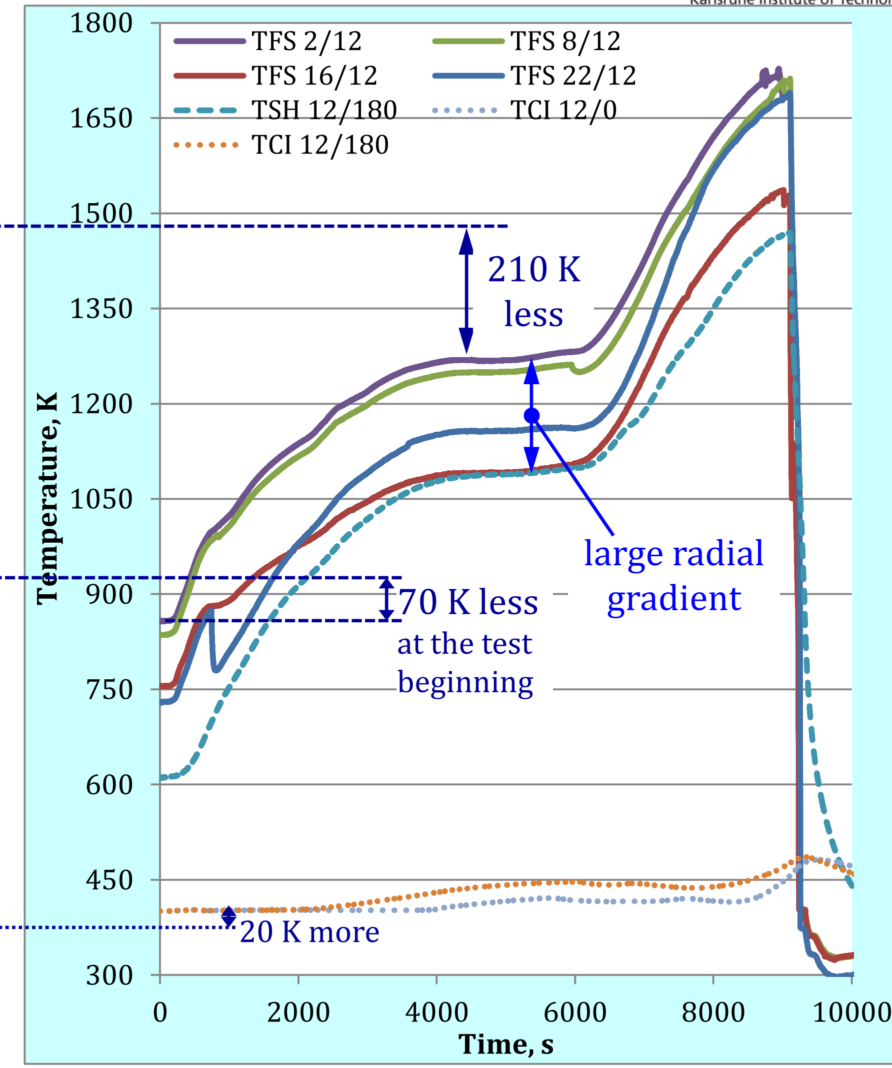




Readings of thermocouples at 850 mm (hottest elevation for QUENCH-19)



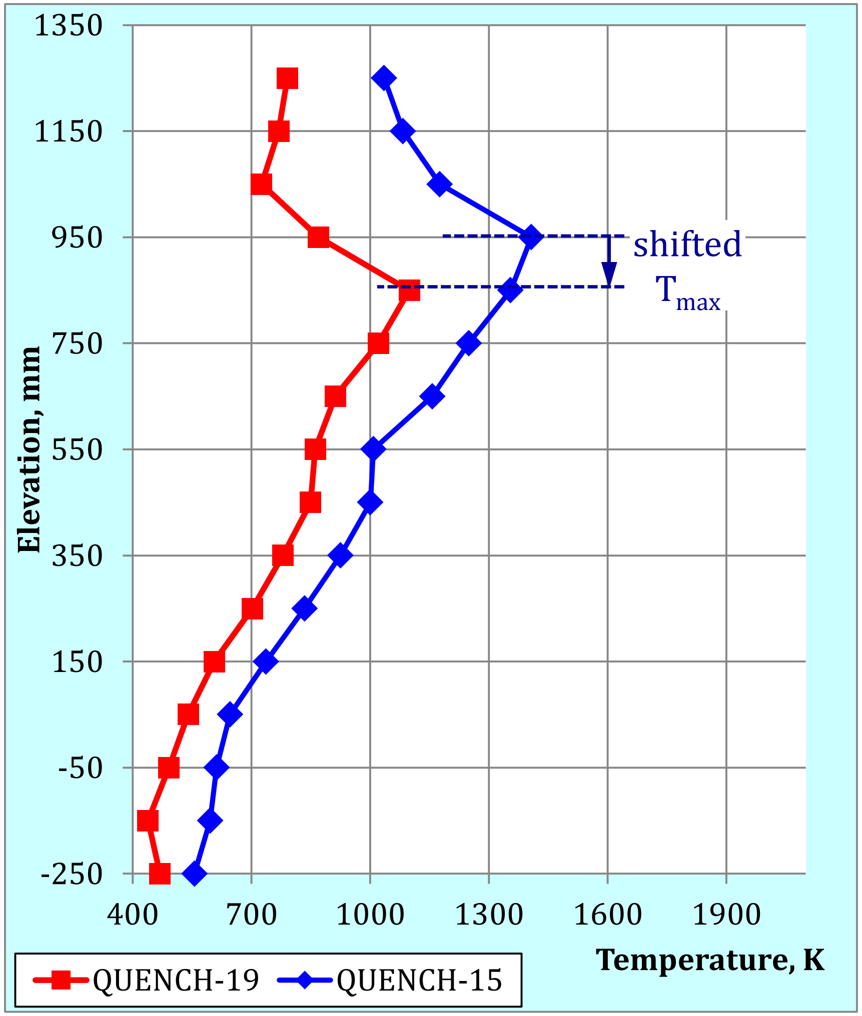
QUENCH-15:
strong T escalation
during transient



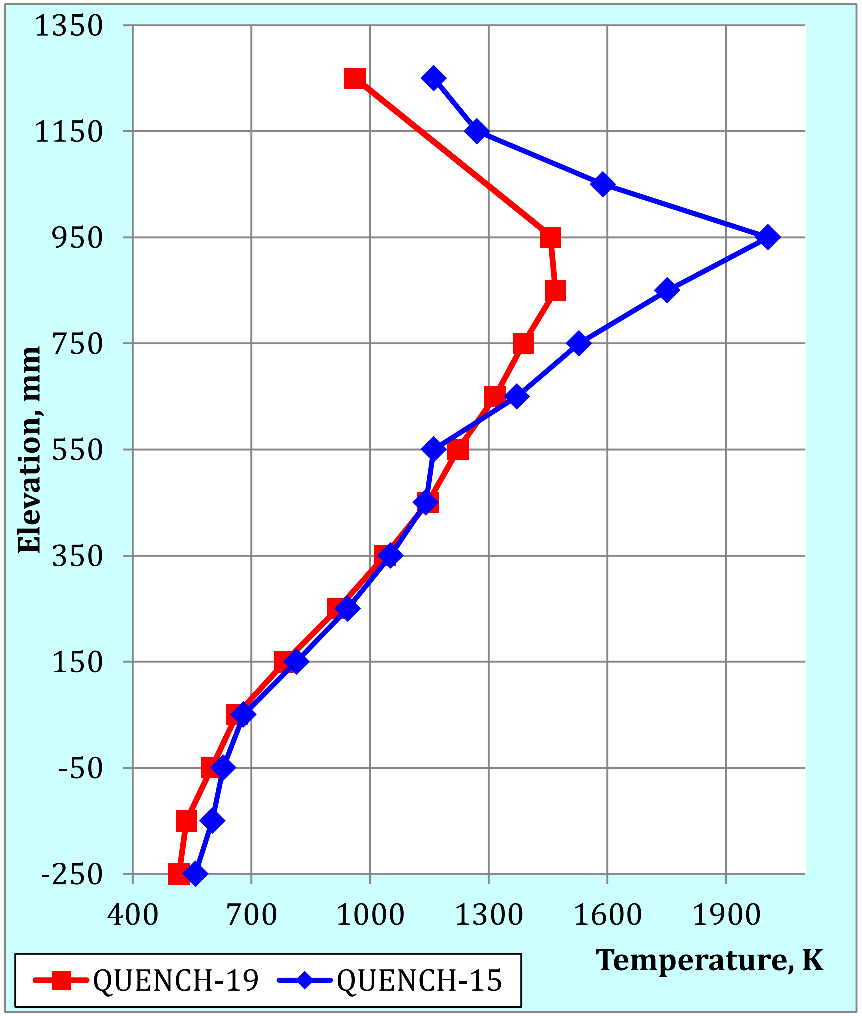
QUENCH-19: 1) **no temperature escalation during extended transition;**

2) special features of test (the reason is not yet clarified):
a) lower temperatures ; b) larger radial ∇T.

Axial temperature profiles at shroud

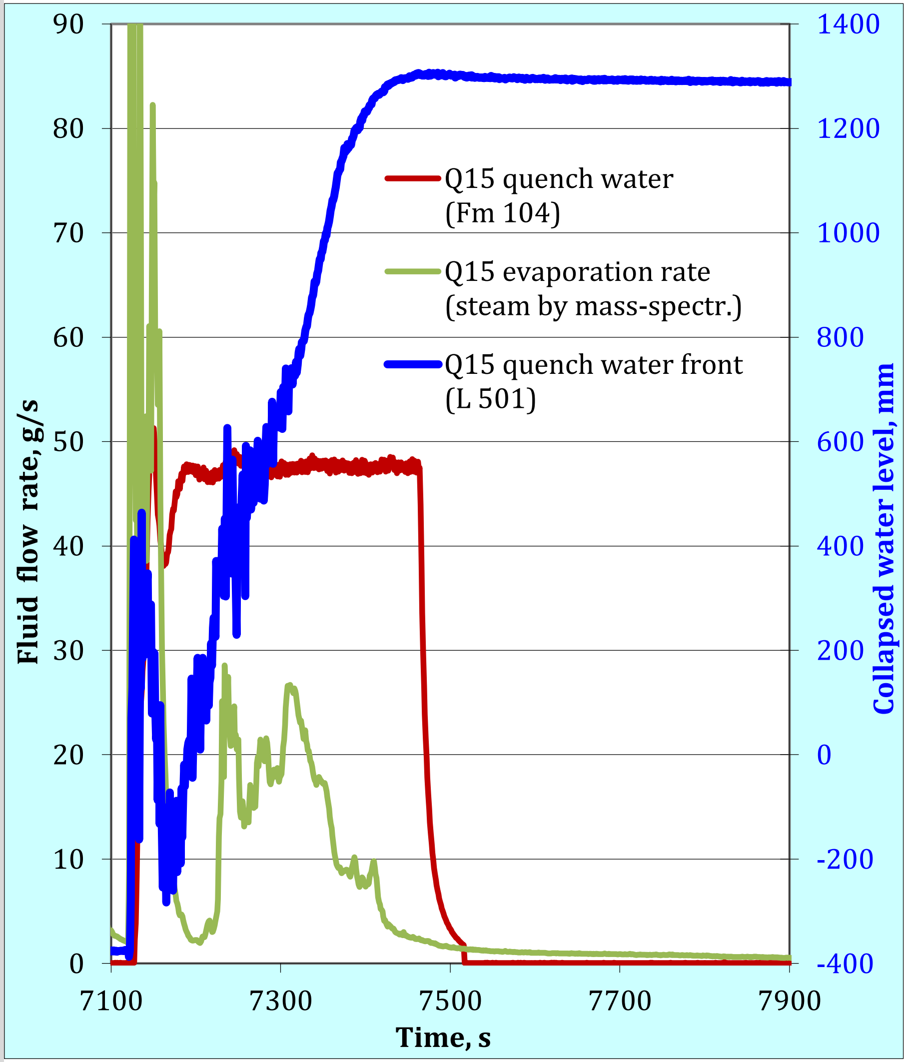


at the beginning of transient

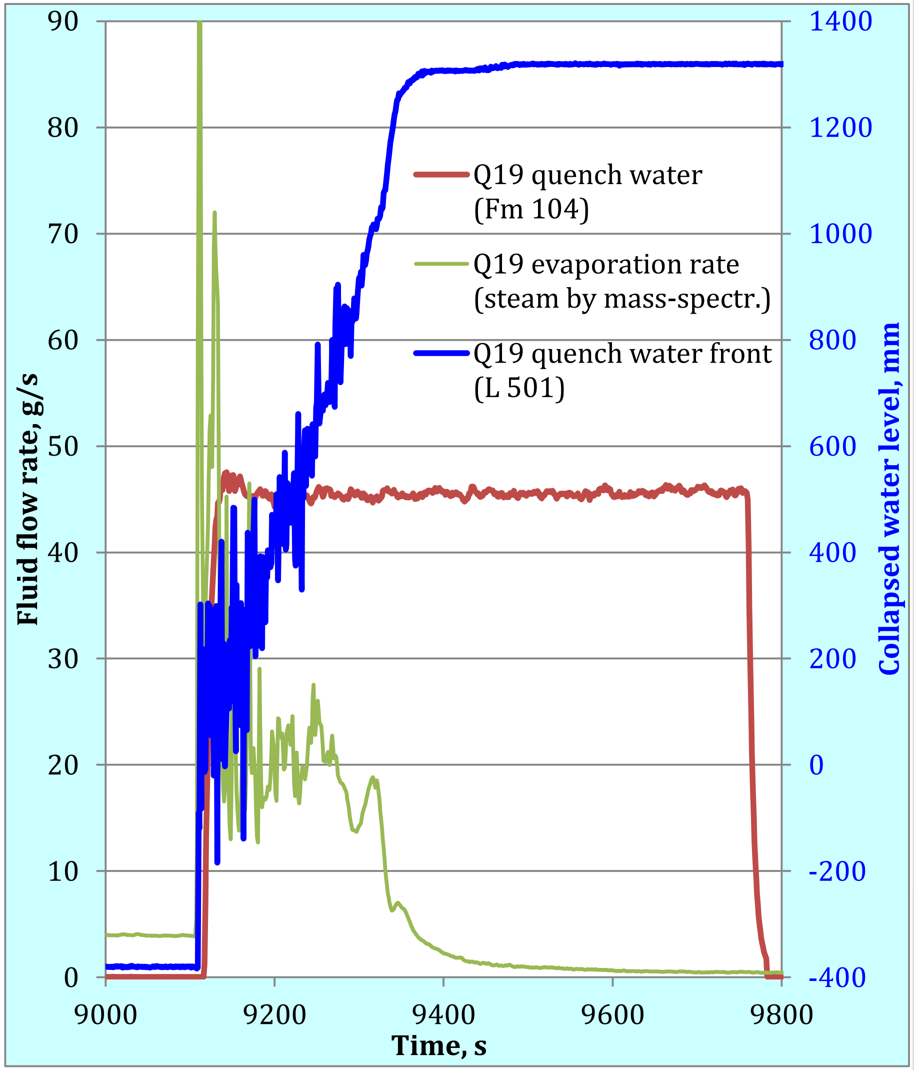


at the onset of reflood

Quench stage: evaporation of injected water, collapsed water front progress

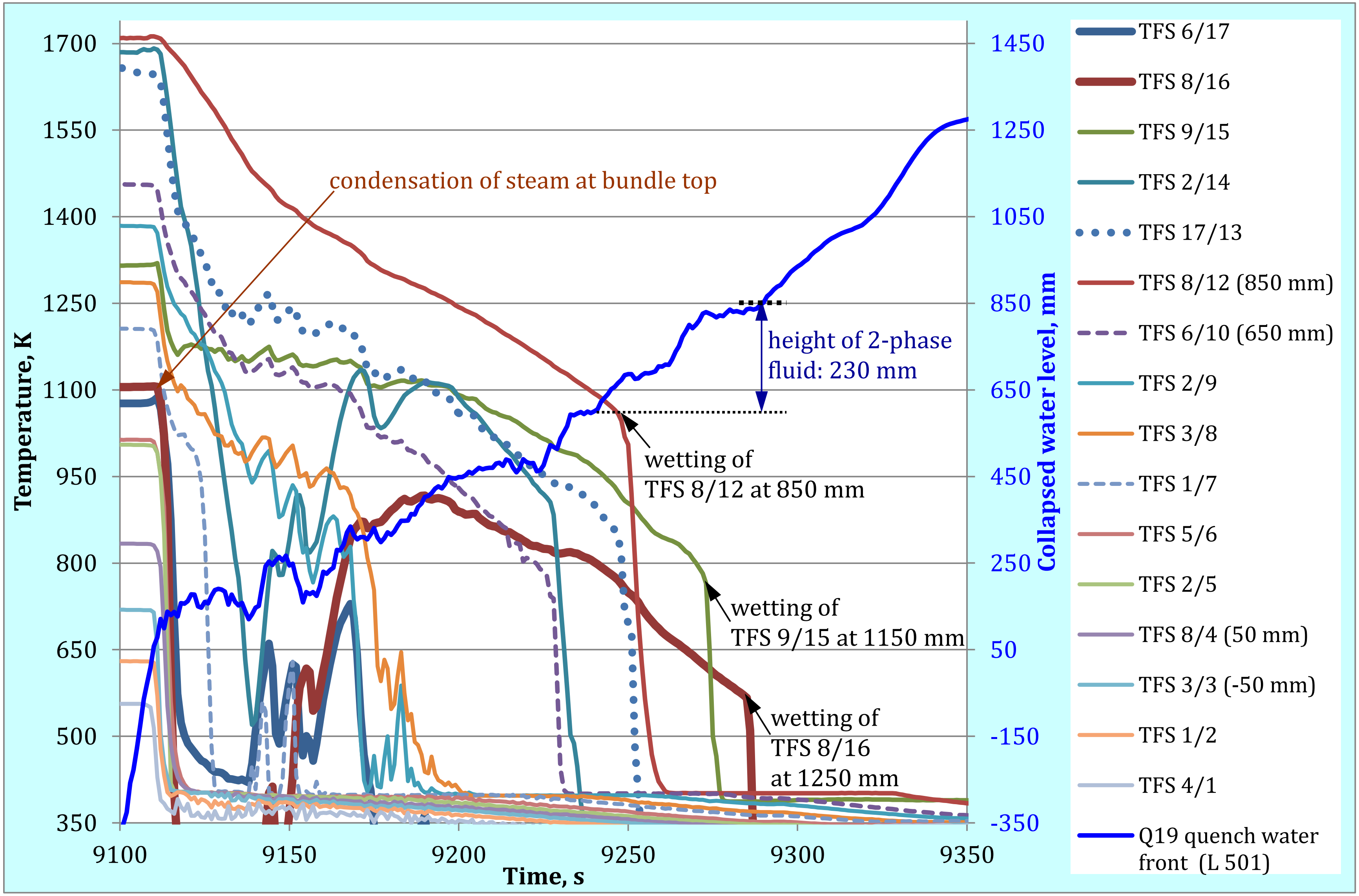


QUENCH-15: water rise duration 330 s

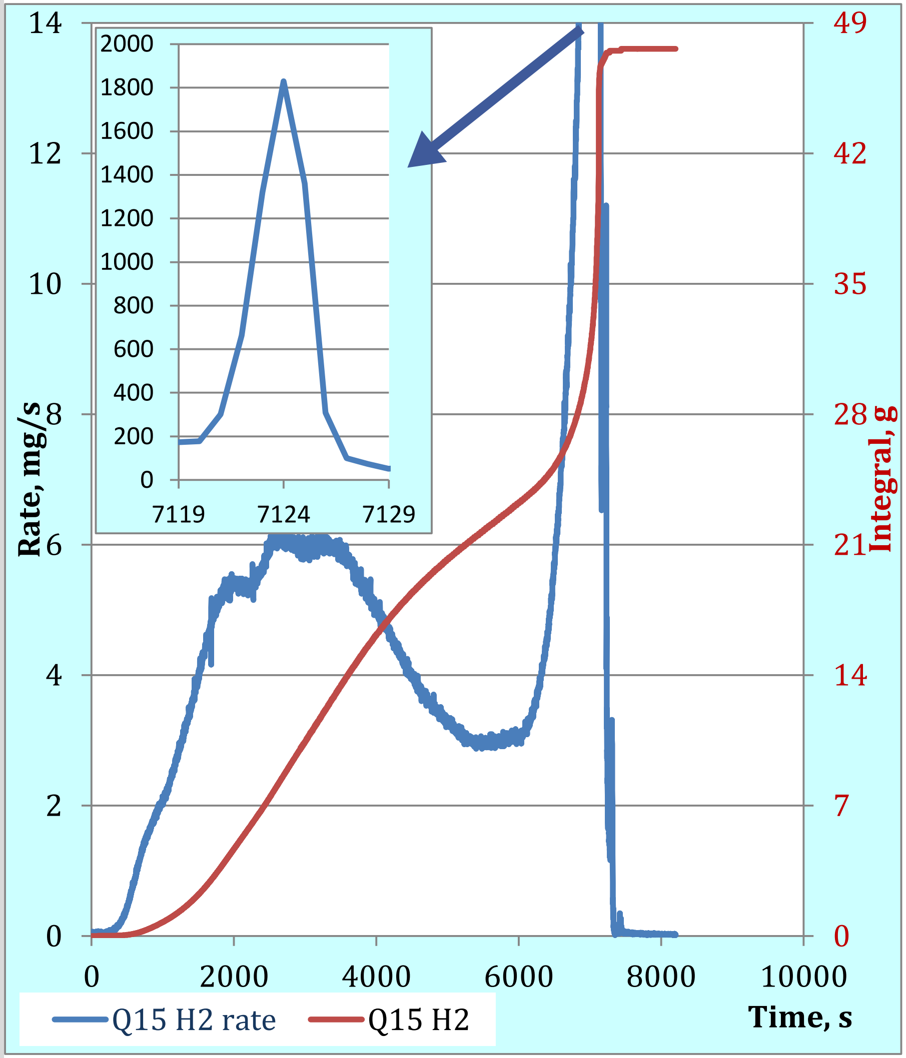


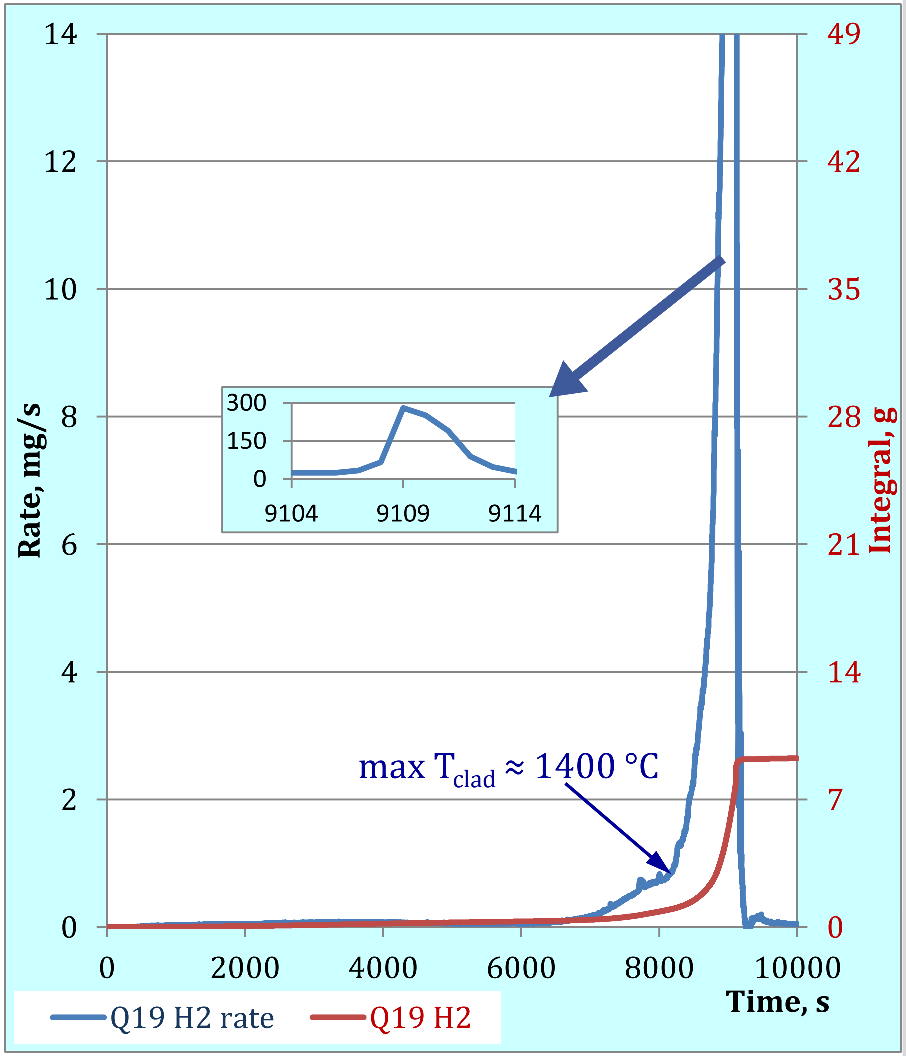
QUENCH-19: water rise duration 270 s

QUENCH-19: wetting of thermocouples by two-phase fluid



Hydrogen release



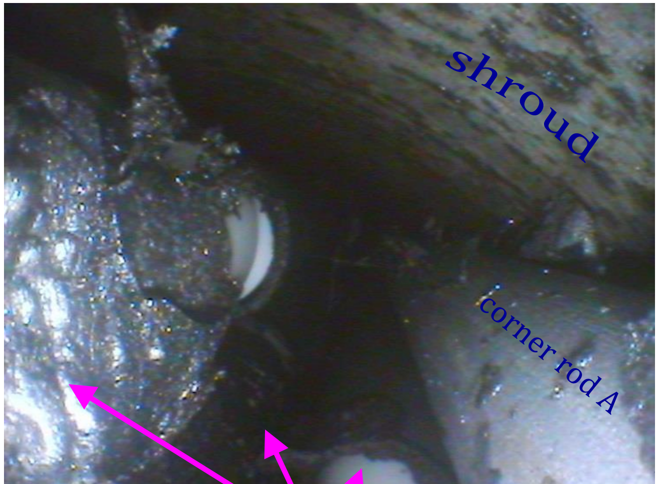


QUENCH-15: max rate 1830 mg/s; totally 47.6 g H_2

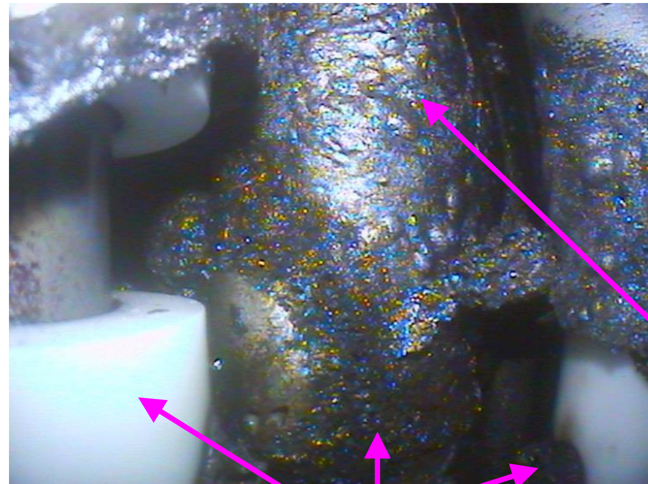
QUENCH-19: max rate 280 mg/s; totally 9.2 g H_2

QUENCH-19: videoscope observations of damaged (partly melted) claddings at upper part of heated zone

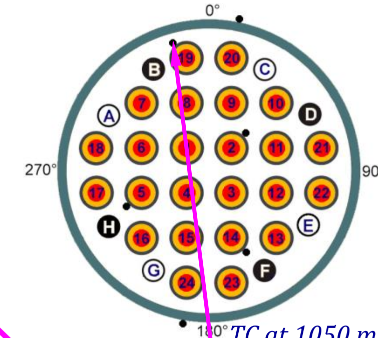
Karlsruhe Institute of Technology



rods 19, 8, 7
(front look at 1000 mm)

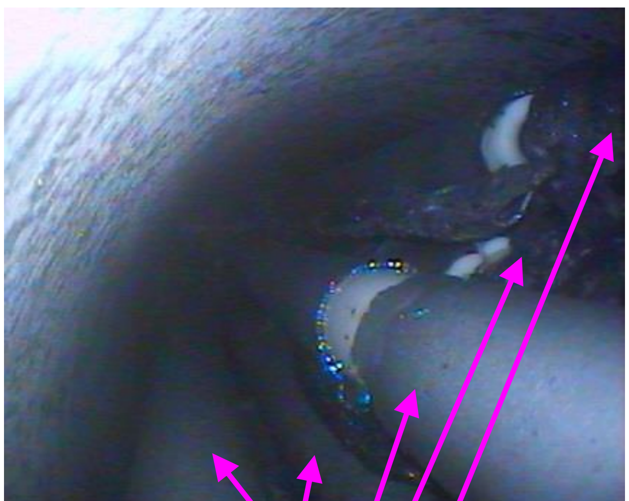


rods 19, 8, 7
(side look at 1000 mm)

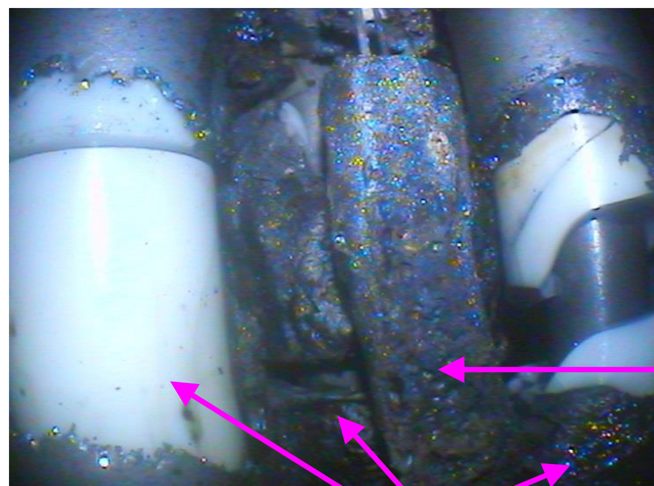


TC at 1050 mm

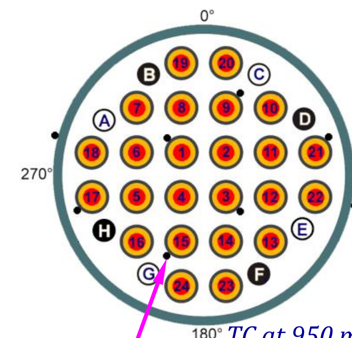
melt from TFS 19/14



rods 5, 17, 16, 15, 24
(front look at 950 mm)



rods 16, 15, 24
(side look at 950 mm)

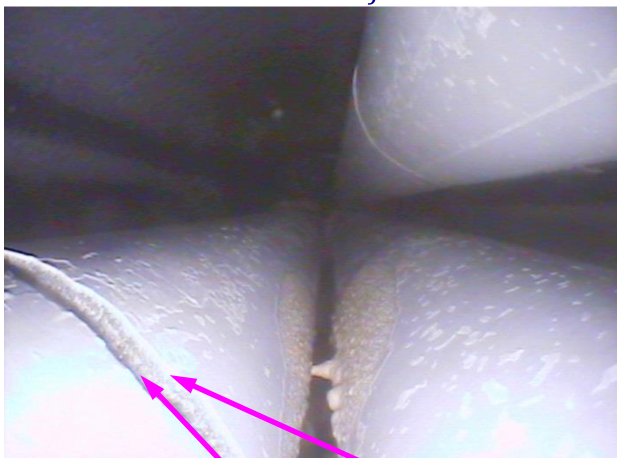


TC at 950 mm

TFS 15/13

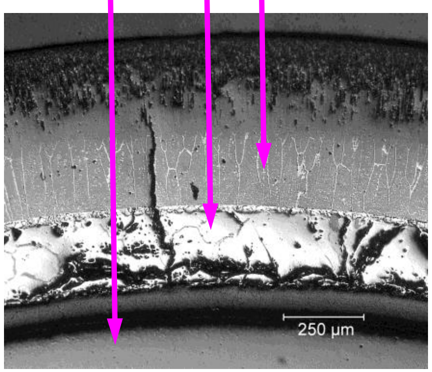
Videoscope observations of claddings at hottest positions of bundles QUENCH-15 (ZIRLO) and -19 (FeCrAl)

__Q15__: circumferential cladding cracks at hottest elevation of 950 mm



thick oxide

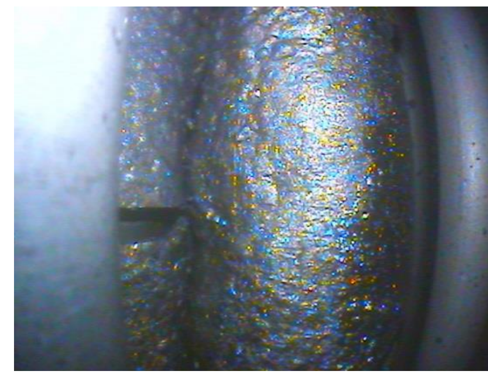
partially molten metal captured between pellet and oxide



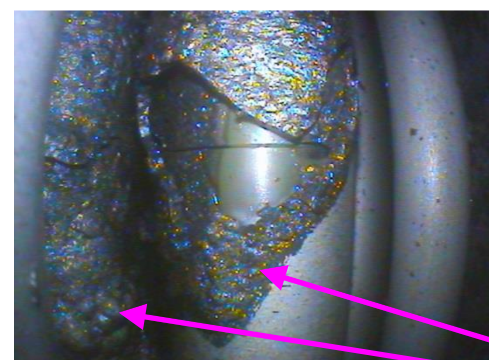
molten claddings of rods 13 and 12 (**Q19** front look at 1000 mm)

900 mm

pellet



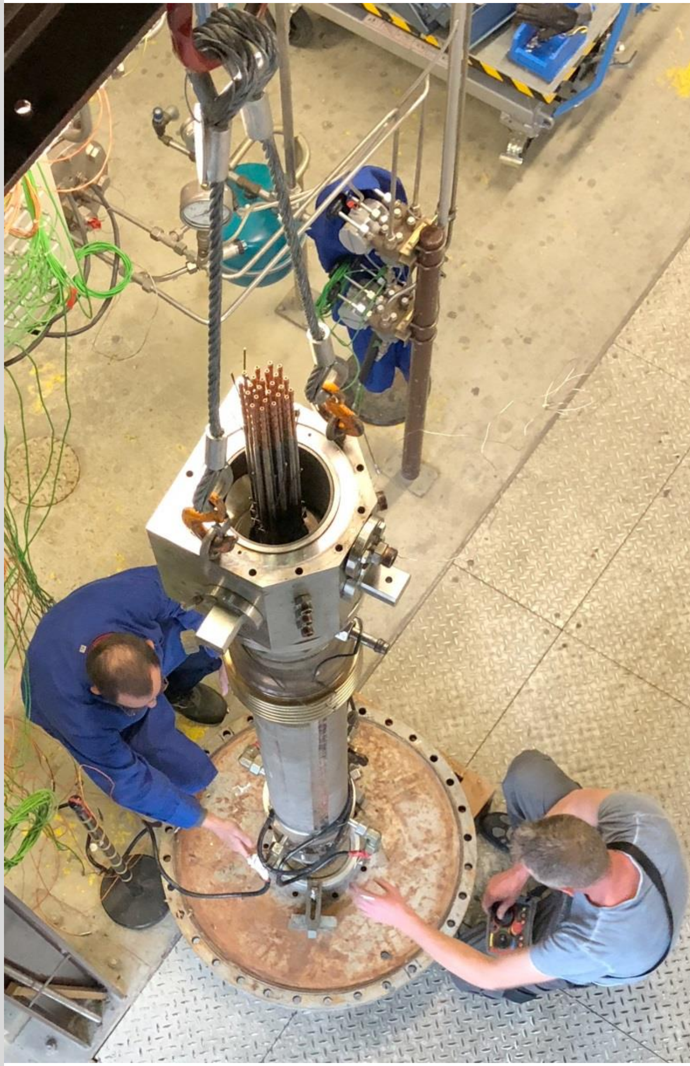
850 mm



800 mm

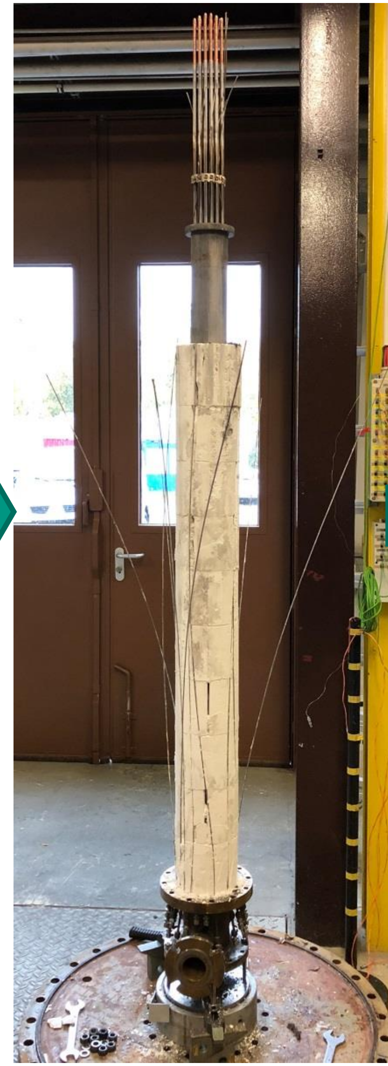
Q19 side look: molten claddings of rods 14 and 13

QUENCH-19 bundle extracting



Bundle inside cooling jacket

jacket removed

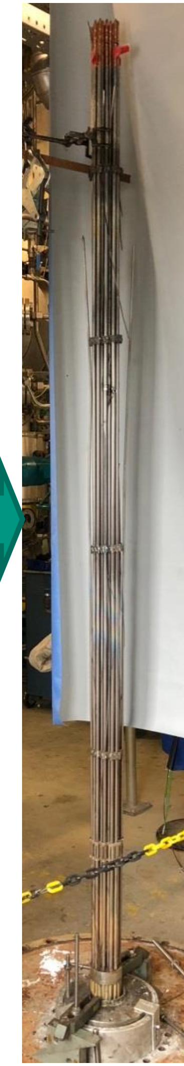


Bundle surrounded by porous ZrO_2 heat insulation

insulation removed

Bundle surrounded by FeCrAl shroud (KANTHAL APM)

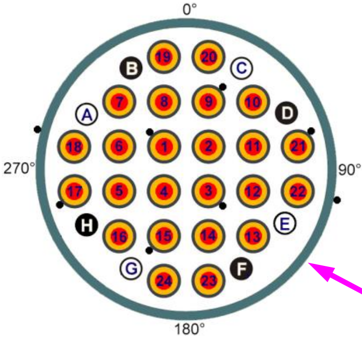
shroud removed

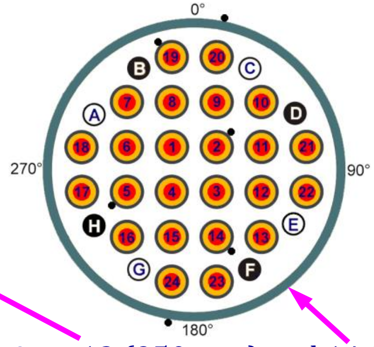


Bundle

QUENCH-19 bundle at elevations between 900 and 1100 mm: cladding damages by molten thermocouple steel (AISI 304) sheaths

Karlsruhe Institute of Technology

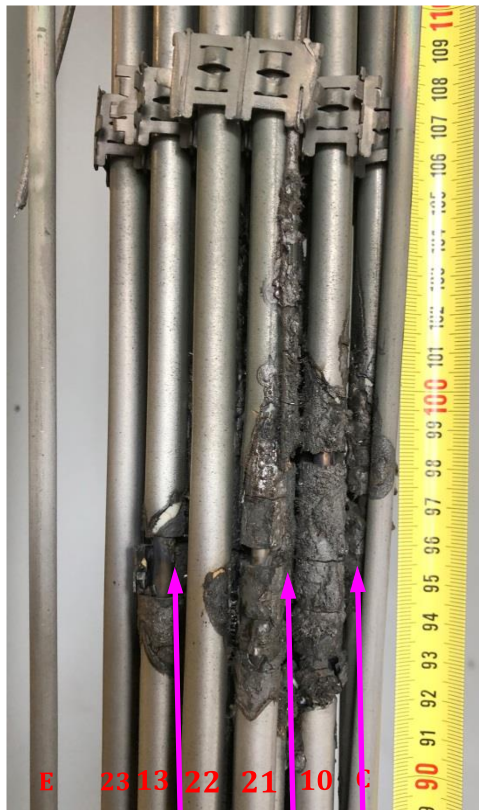




Positions of TC (•) at elevations 13 (950 mm) and 14 (1050 mm)

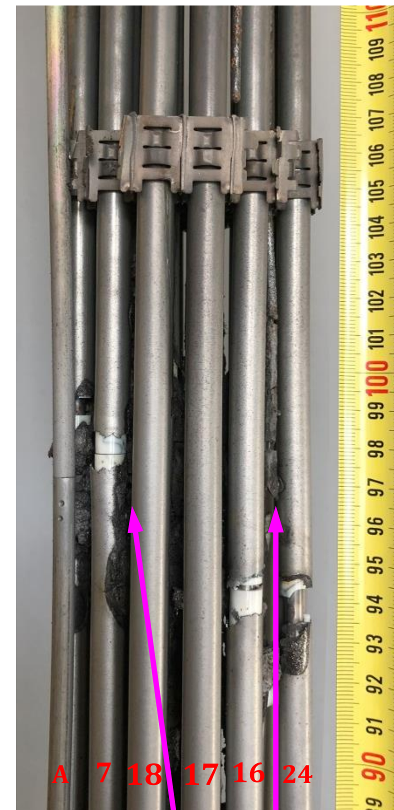
- the melting range of 304 steel is 1400…1450°C
- the melting range of FeCrAl alloys is 1500…1520°C

0°: TFS 9/13 and 19/14



90°: TFS 3/13, 21/13, 9/13

180°: TFS 15/13 and 14/14



270°: TFS 1/13, 15/13

Summary

- The QUENCH-19 test with bundle containing 24 heated rods with FeCrAl(Y) cladding and 4 FeCrAl(Y) spacer grids as well as 8 KANTHAL APM corner rods and KANTHAL APM shroud was performed at KIT on August 29, 2018 with similar electrical power history as reference test QUENCH-15 (ZIRLO™ claddings).
- Four test stages of QUENCH-19:

  1) pre-oxidation during about 6000 s (similar to QUENCH-15),

  2) transient during about 1130 s (similar to QUENCH-15),

  3) <u>extended period</u> with constant electrical power of 18.32 kW during 1970 s (to extend the temperature increase stage),

  4) test termination by water flooding with rate of 48 g/s (similar to QUENCH-15).
- The peak cladding temperatures during the pre-oxidation stage were about 200 K lower in comparison to QUENCH-15. The radial temperature gradient was noticeable larger in comparison to QUENCH-15. The reason of these test differences are not yet completely clarified.

Summary (cont.)

- Much lower heating rate in comparison to QUENCH-15 was measured. A temperature of about 1150°C was reached at the time point as a local melting of QUENCH-15 claddings occurred. No temperature escalation was observed during the extended transient. Maximum cladding temperature measured before reflood was about 1460 °C.
- The coping time was about 3200 s (≈ 1200 s for QUENCH-15).
- Sharp increase of hydrogen release rate was observed about 800 s before reflood. Probable trigger of this event could be the melting of steel thermocouple claddings. The maximum hydrogen release rate reached before reflood was 280 mg/s (1830 mg/s for QUENCH-15). Total hydrogen production 9.2 g (47.6 g for QUENCH-15).
- Many claddings were damaged at elevations between 850 and 1000 mm: 1) by interaction with melted thermocouples or 2) parts of claddings were spalled (probably due to thermal expansion followed by quench shrinkage).

Karlsruhe Institute of Technology

Acknowledgment

The QUENCH-19 experiment was supported by the KIT program NUSAFE and partly sponsored by ORNL. The cladding materials and thermocouples were provided by ORNL. IKET/KIT colleagues were involved into bundle dismounting.

The authors would like to thank all colleagues involved in the pre-test calculations (GRS, ORNL, PSI).

Thank you for your attention

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

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