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

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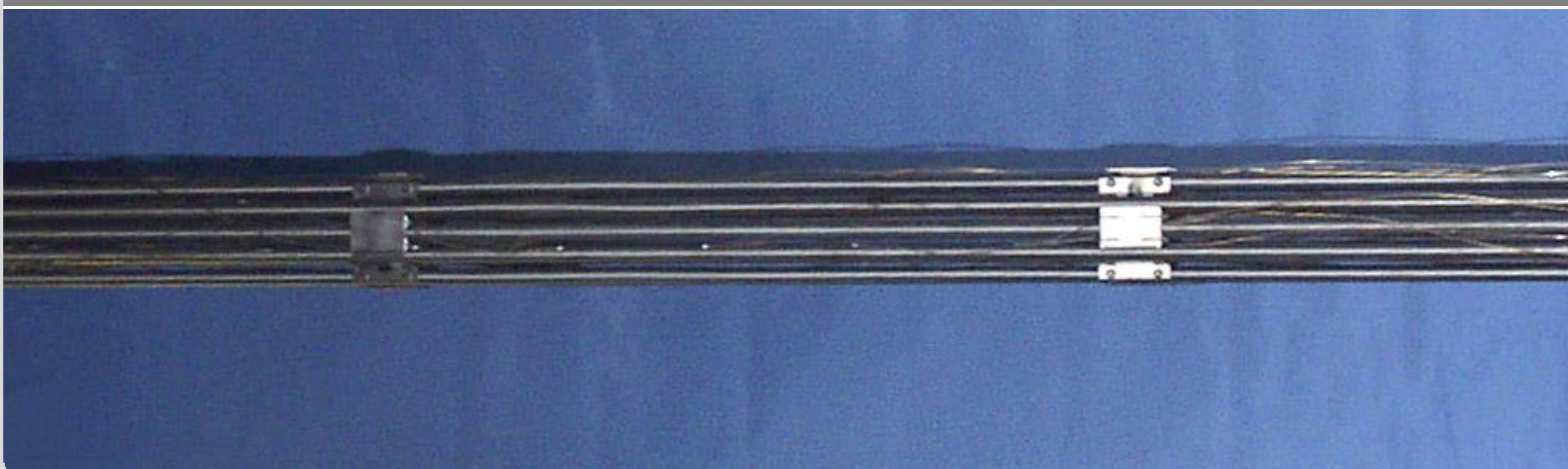
Institute for Applied Materials; Program NUSAFE



Chemical compositions and oxidation in steam of FeCrAl alloys

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
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

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

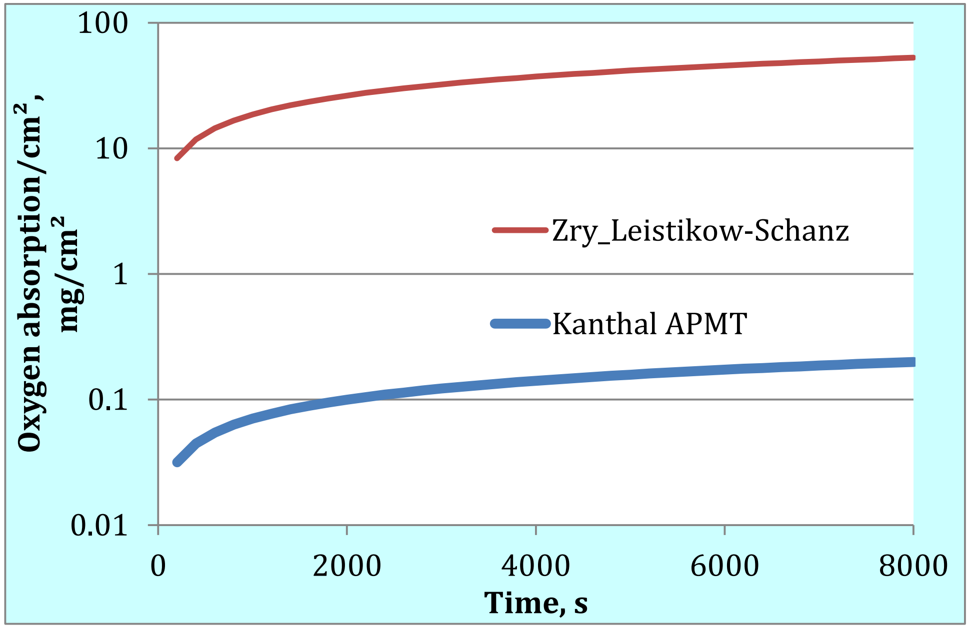
$$K_m(T) = K_0 \exp(-\frac{E_0}{RT})$$

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

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

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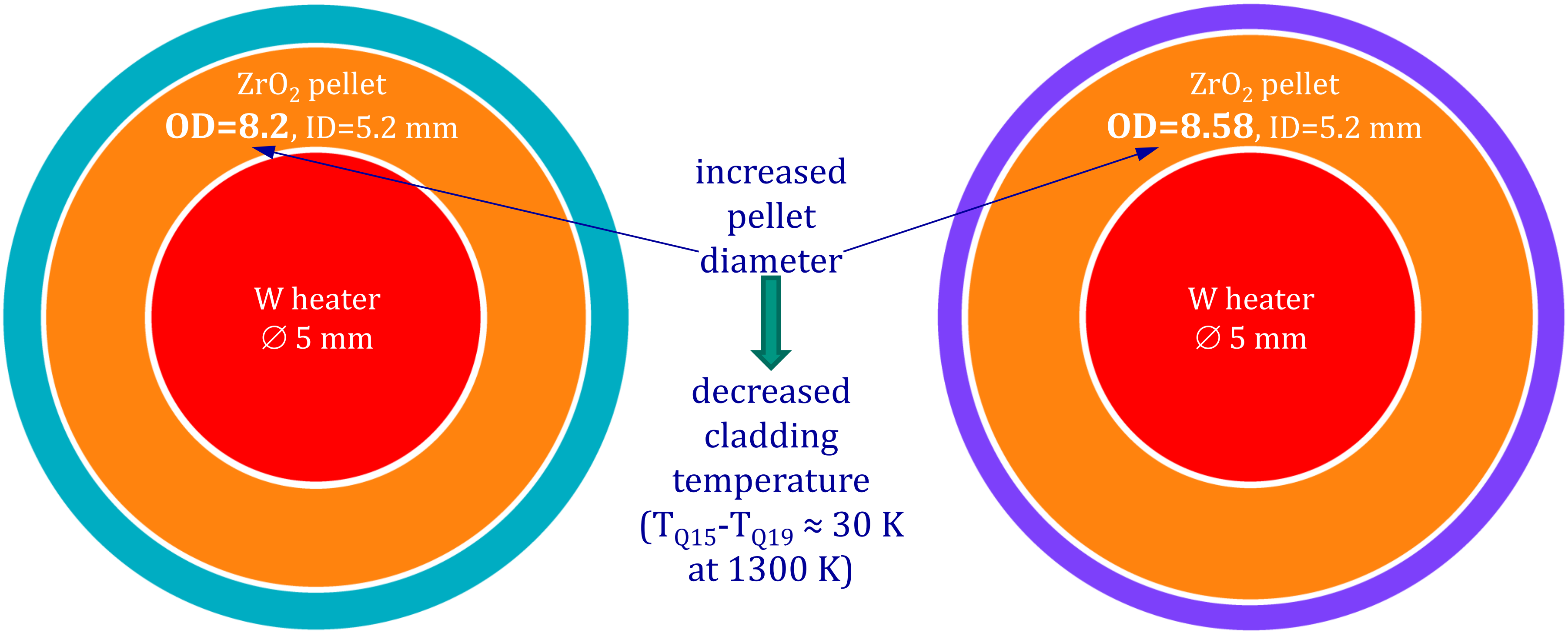
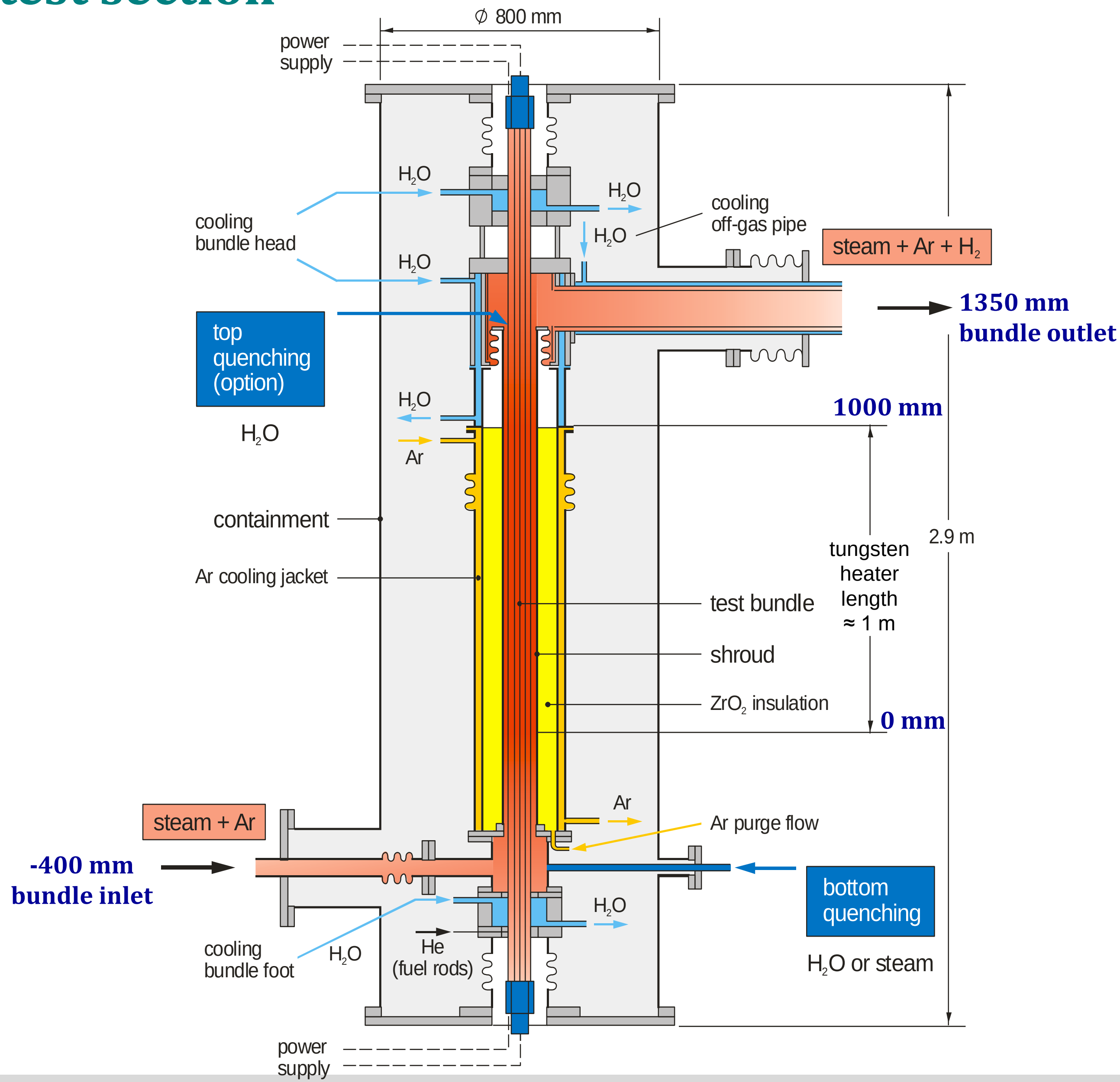


QUENCH-15 (**ZIRLO** cladding with OD=9.5 mm, **Wall Thickness=572 µm**)

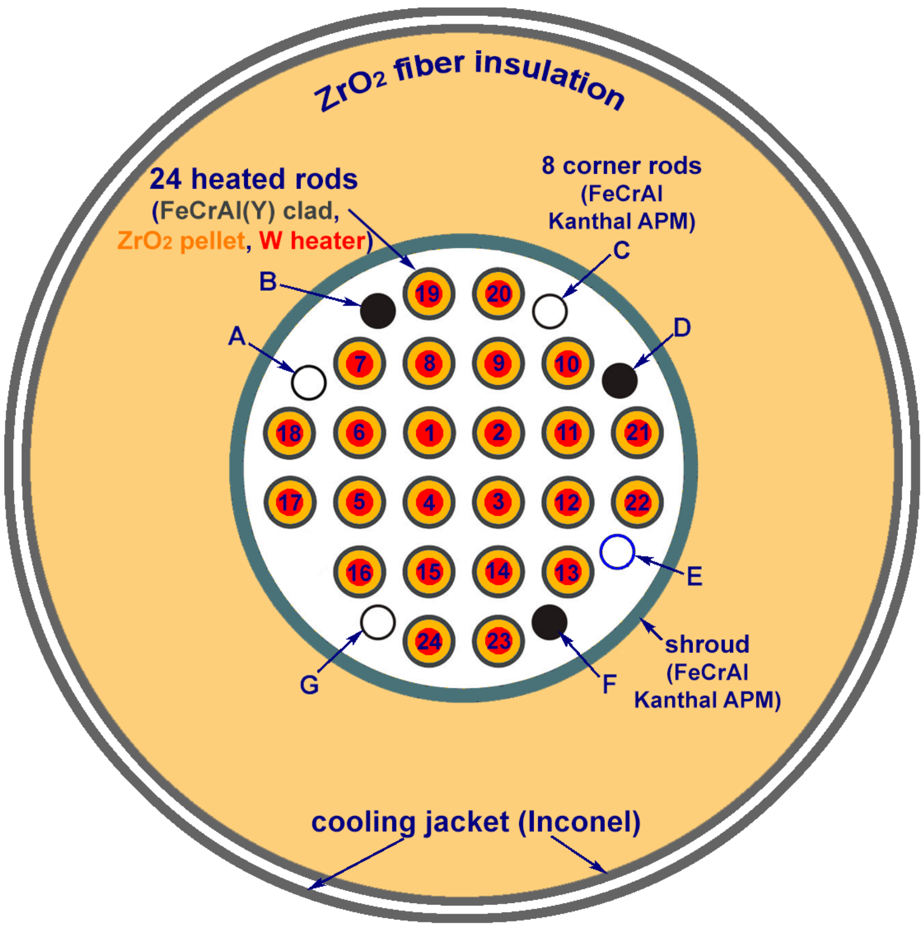
QUENCH-19 (**FeCrAl(Y)** cladding with OD=9.52 mm, **Wall Thickness=381 µm**)

	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

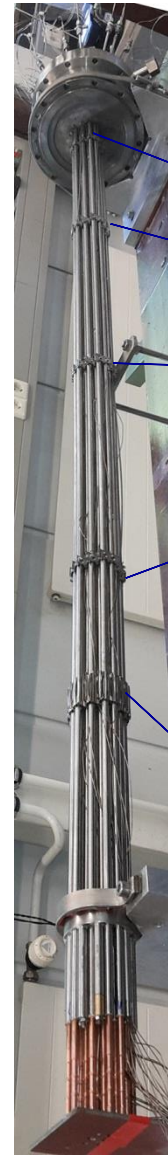
QUENCH test section



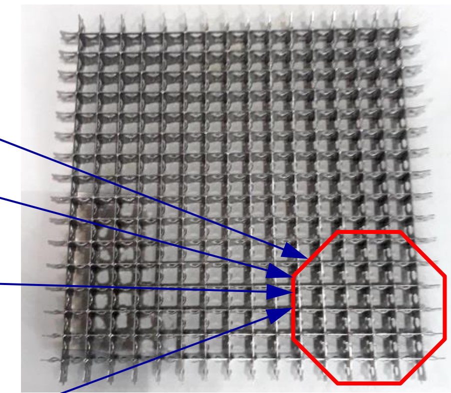
Composition of test bundle QUENCH-19



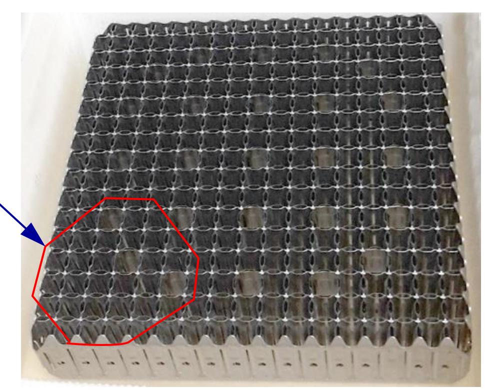
cross section
(arrangement the same as for QUENCH-15)



test bundle (length 2m)

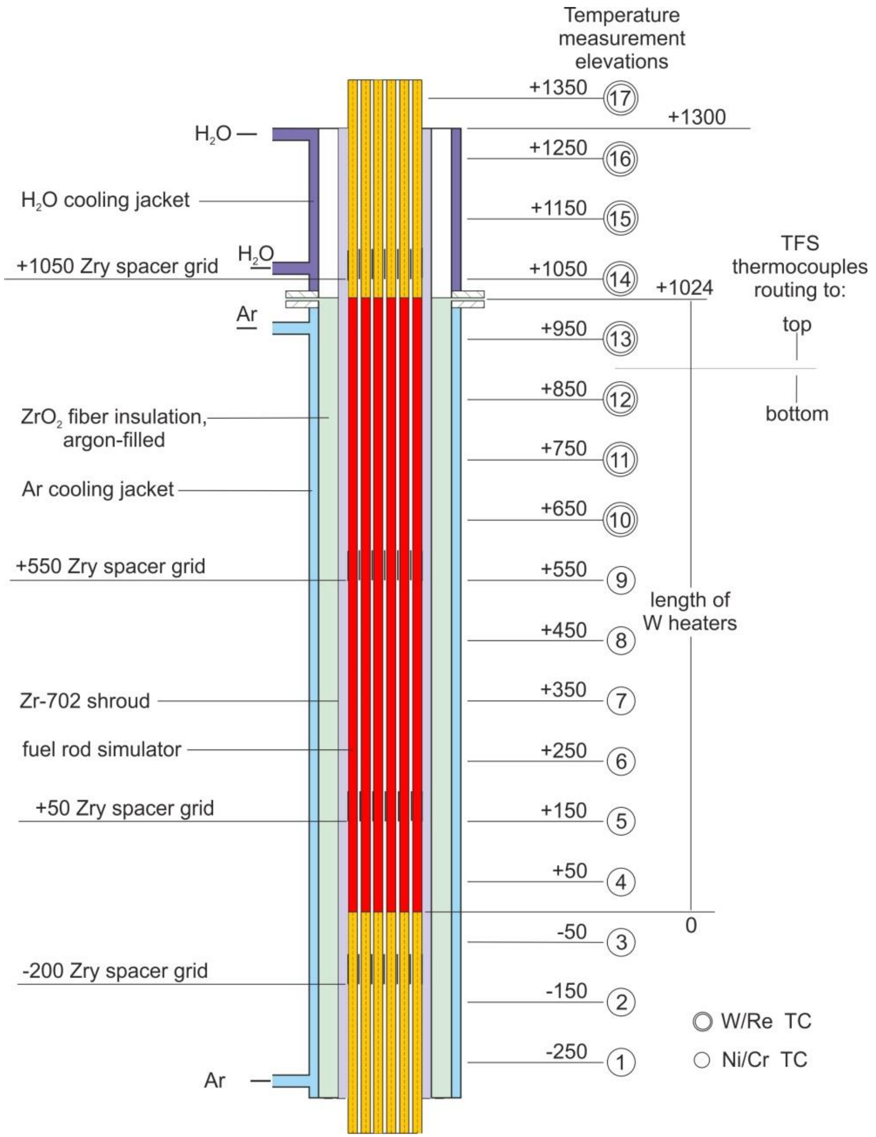


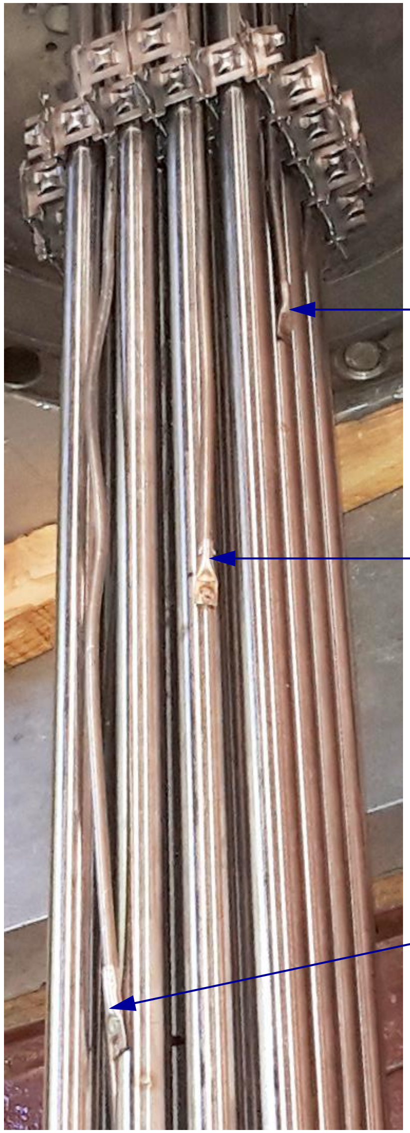
ORNL Kanthal AF **spacer grids**:
height 22 mm,
sheet thickness 0.5 mm



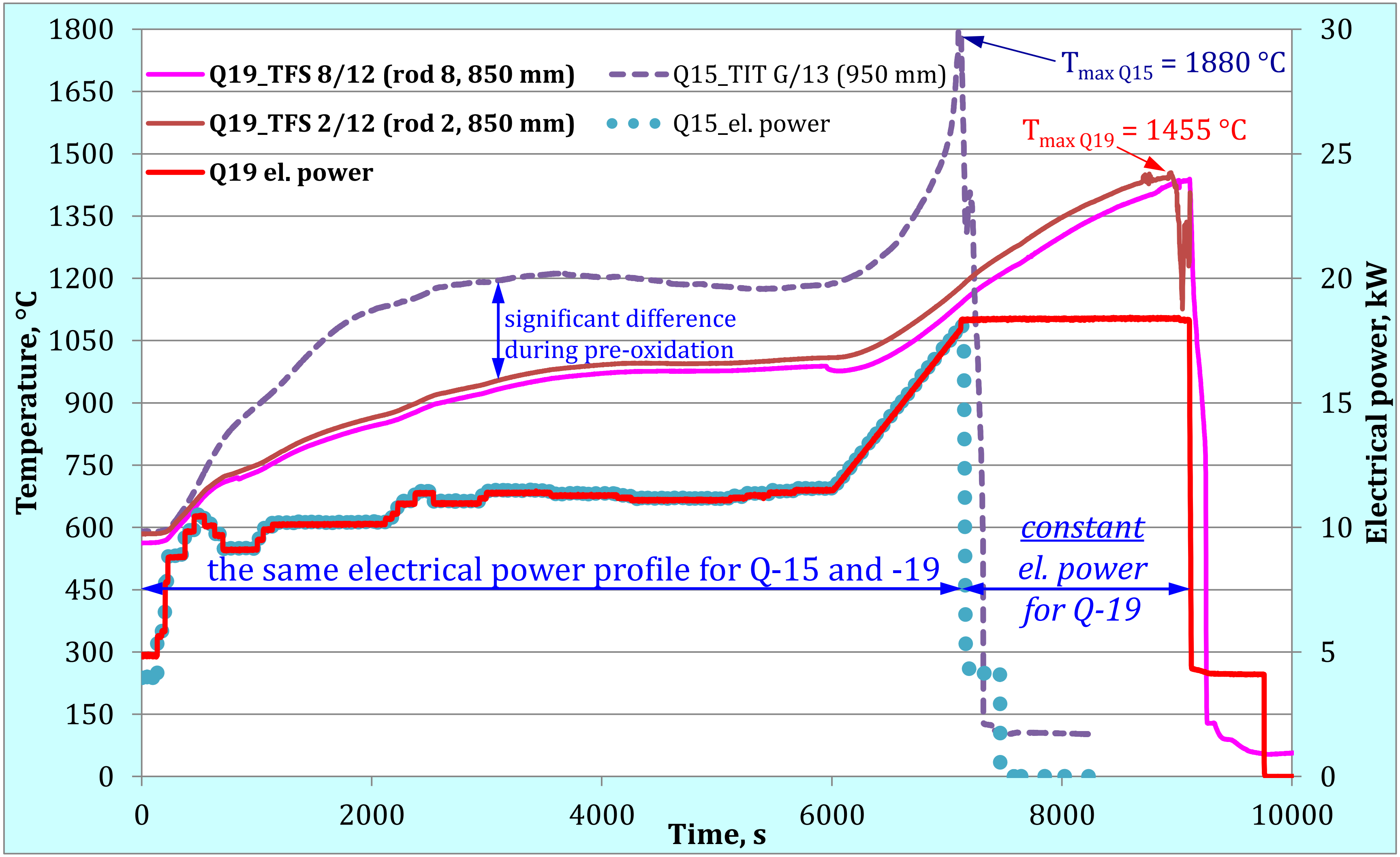
AREVA Inconel **spacer grid**:
height 45 mm,
sheet thickness 0.5 mm

QUENCH-19 bundle instrumentation (thermocouples at cladding surface)



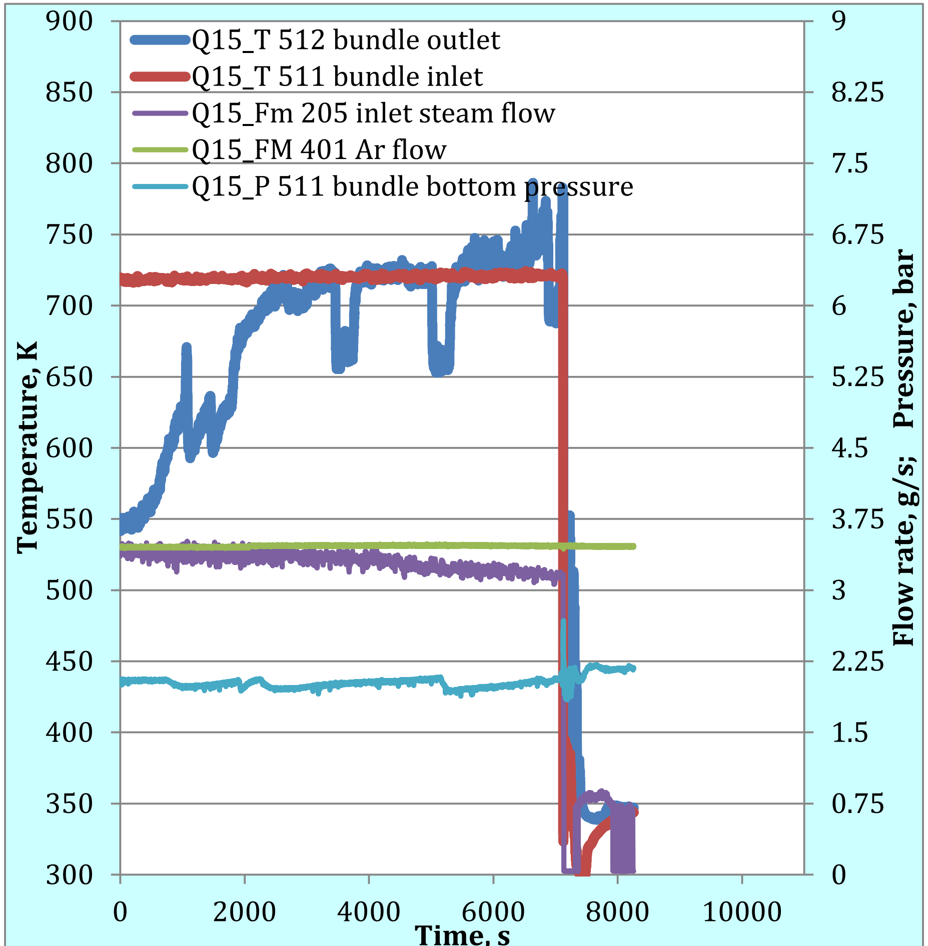


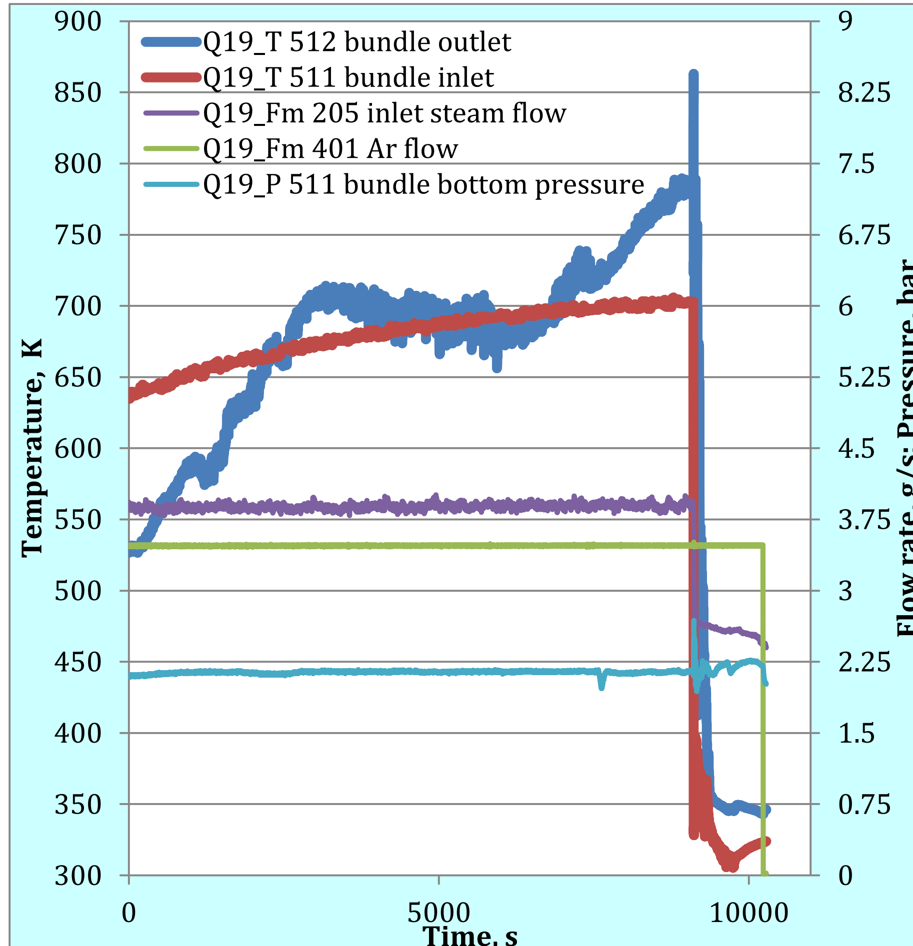
Test performance: comparison of QUENCH-15 (ZIRLO) and -19 (FeCrAl)



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

Parameters of gas atmosphere at bundle inlet and outlet

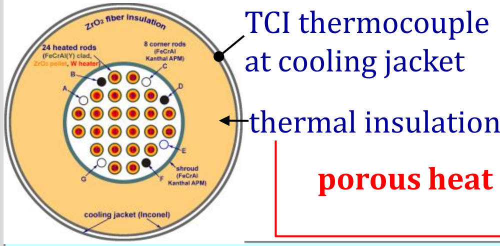




QUENCH-15:
inlet gas (steam + Ar) $T_g \approx$ **720 K**;
steam flow rate $3.2 < F_s < 3.4$ g/s;
Ar flow rate $F_{Ar} = 3.5$ g/s

different conditions for the inlet steam could cause decrease of cladding T up to 100 K in QUENCH-19

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

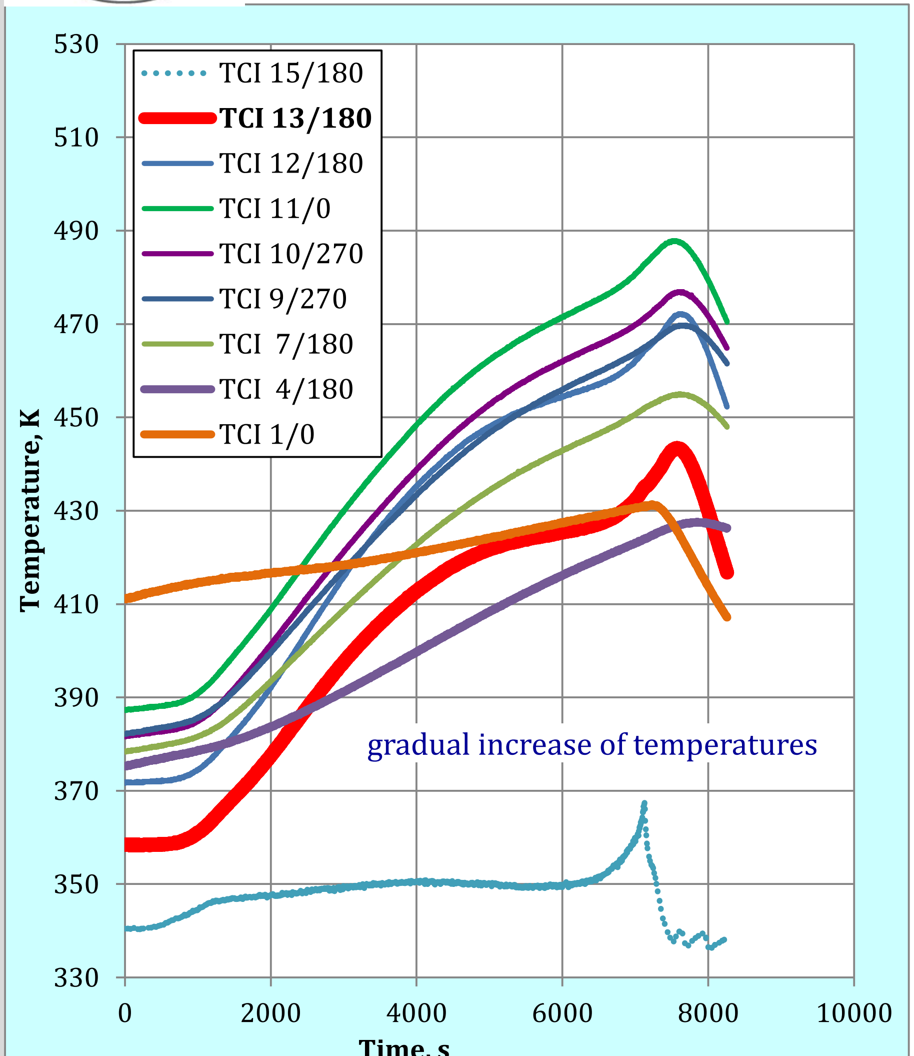


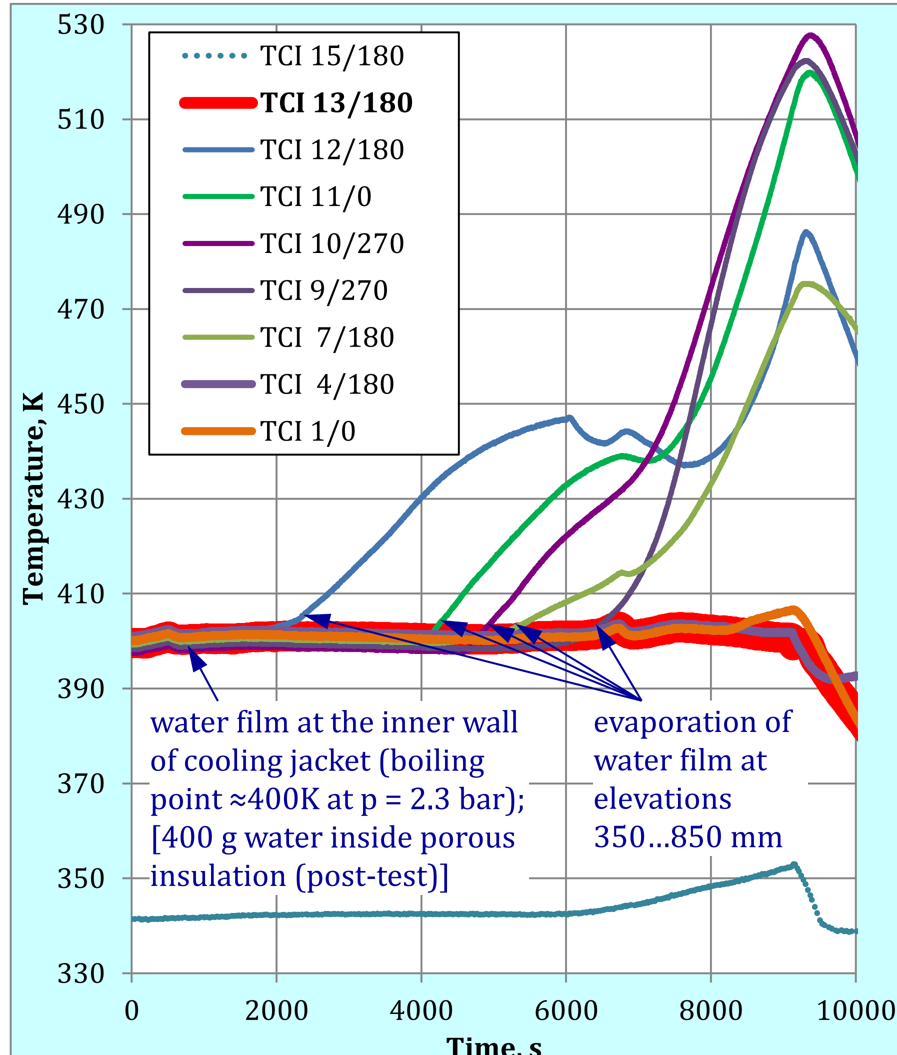
Boundary conditions (temperatures behind heat insulation)

(QUENCH-15 ≠ QUENCH-19)

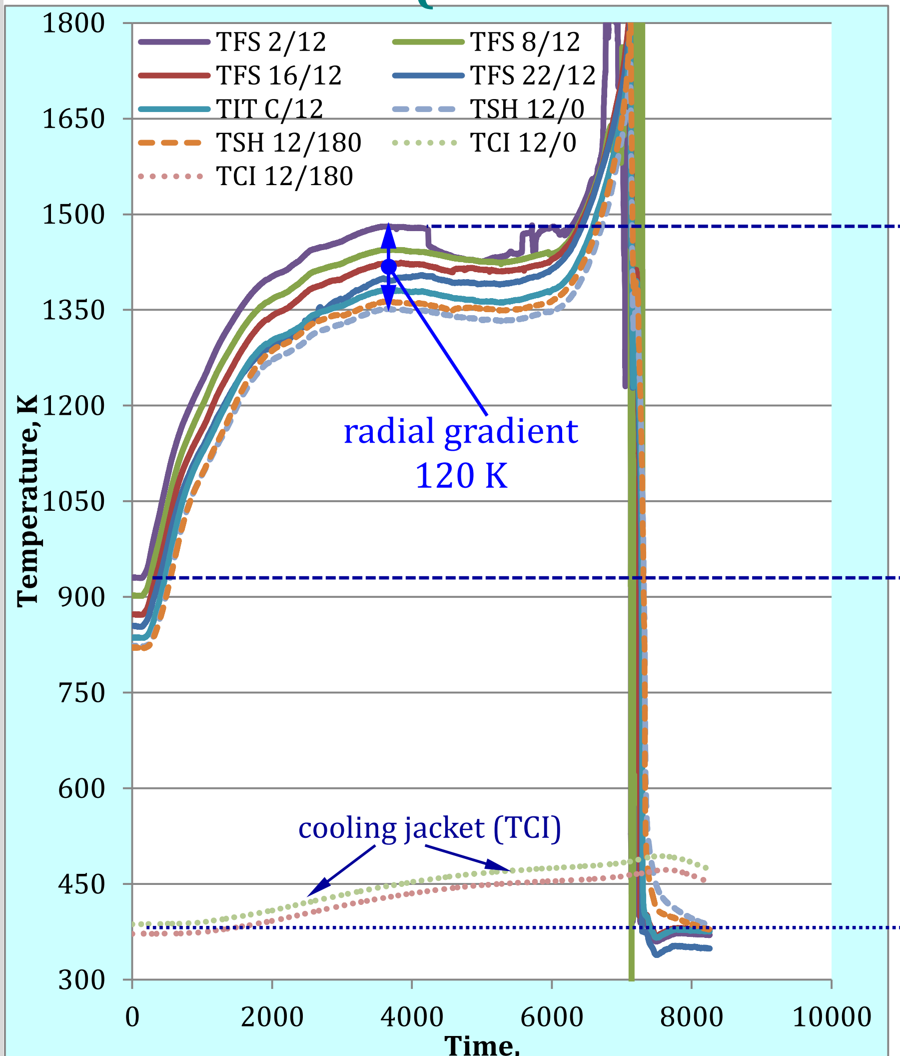
porous heat insulation filled with dry Ar in Q15 and **with humid Ar in Q19** (leakage of steam into insulation)

Possible result: stronger radial temperature gradient in QUENCH-19

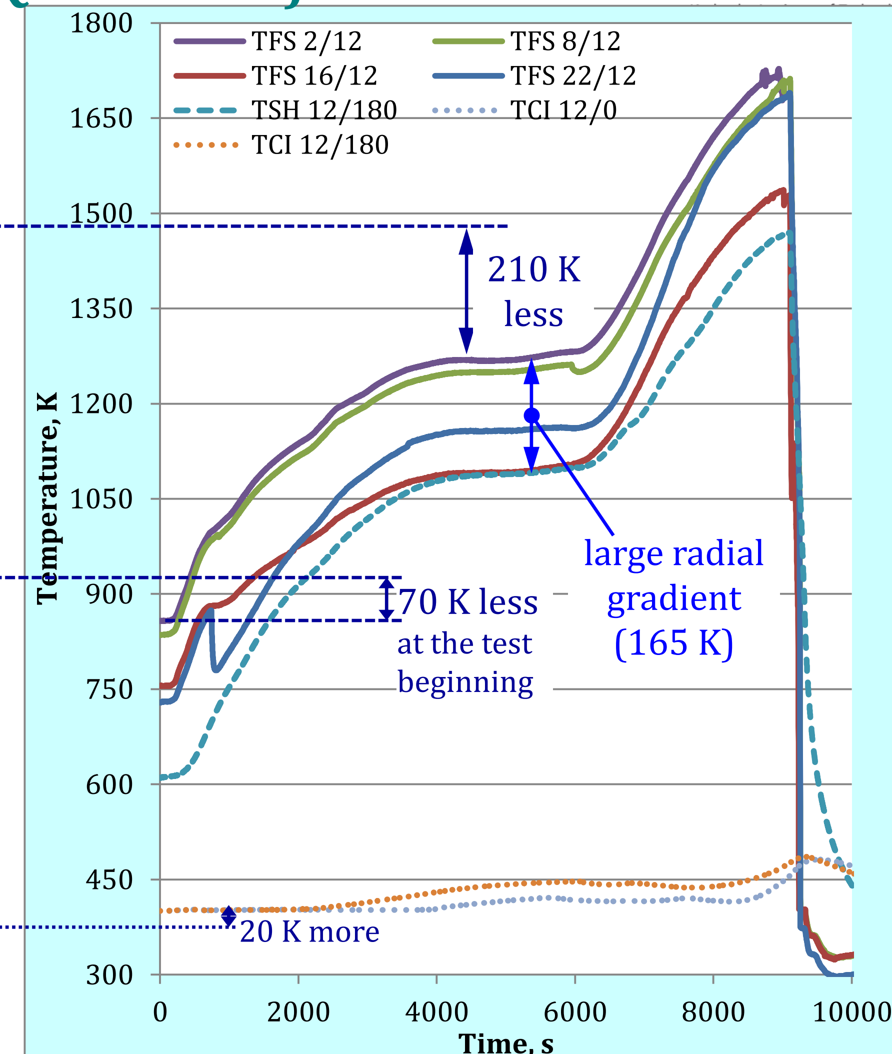




Readings of thermocouples at 850 mm (hottest elevation for QUENCH-19)

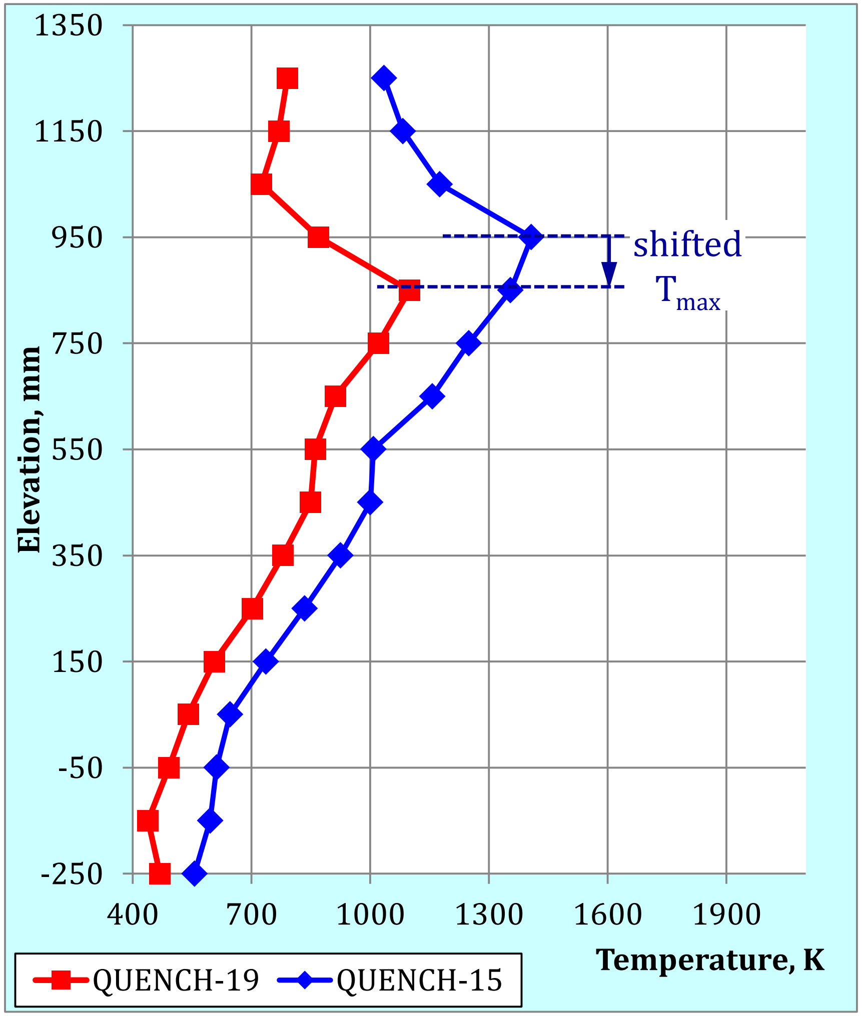


QUENCH-15:
strong T escalation
during transient

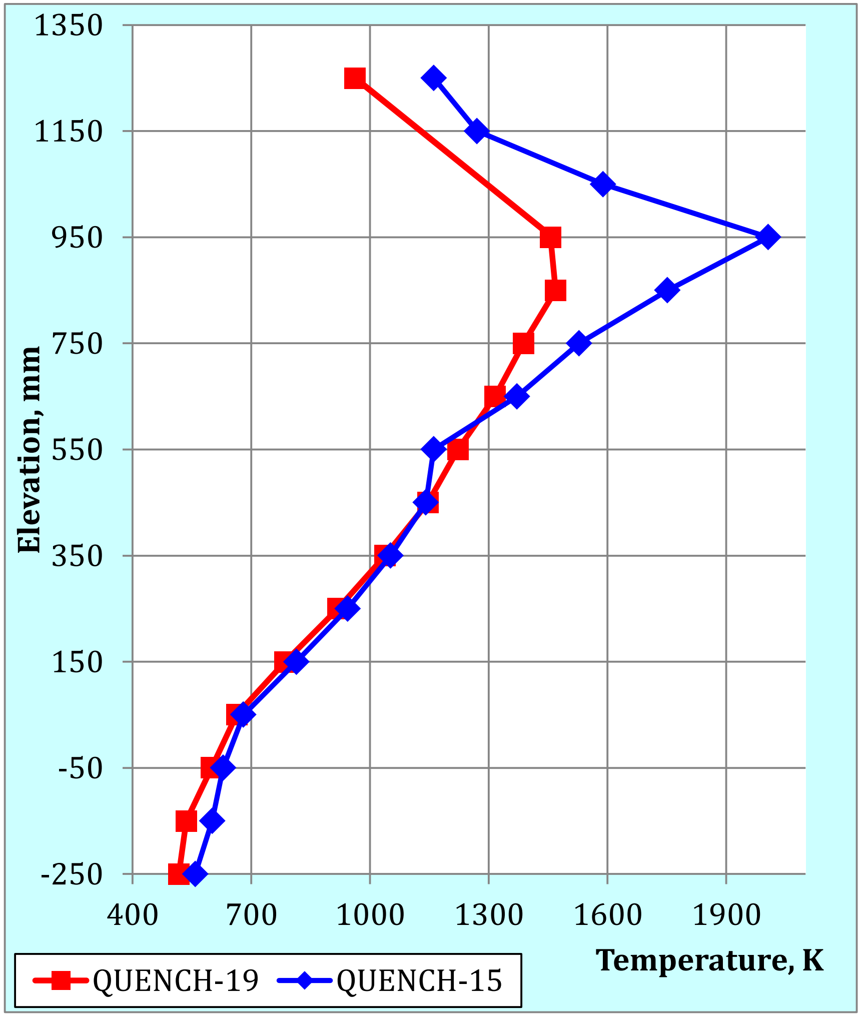


QUENCH-19: 1) **no temperature escalation during extended transition**;
2) special features of test: a) lower clad temperatures (due to other gas temperature and thicker pellet);
b) larger radial ∇T (due to steam in heat insulation).

Axial temperature profiles at shroud

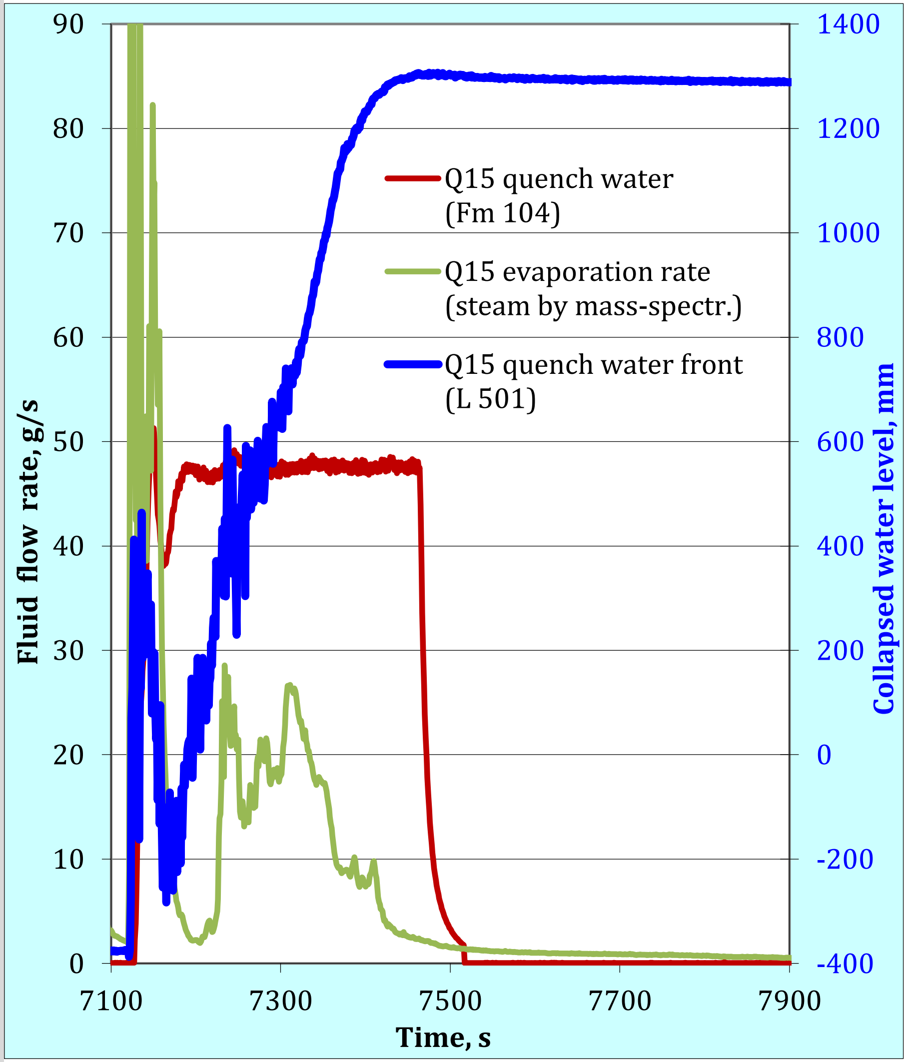


at the beginning of transient

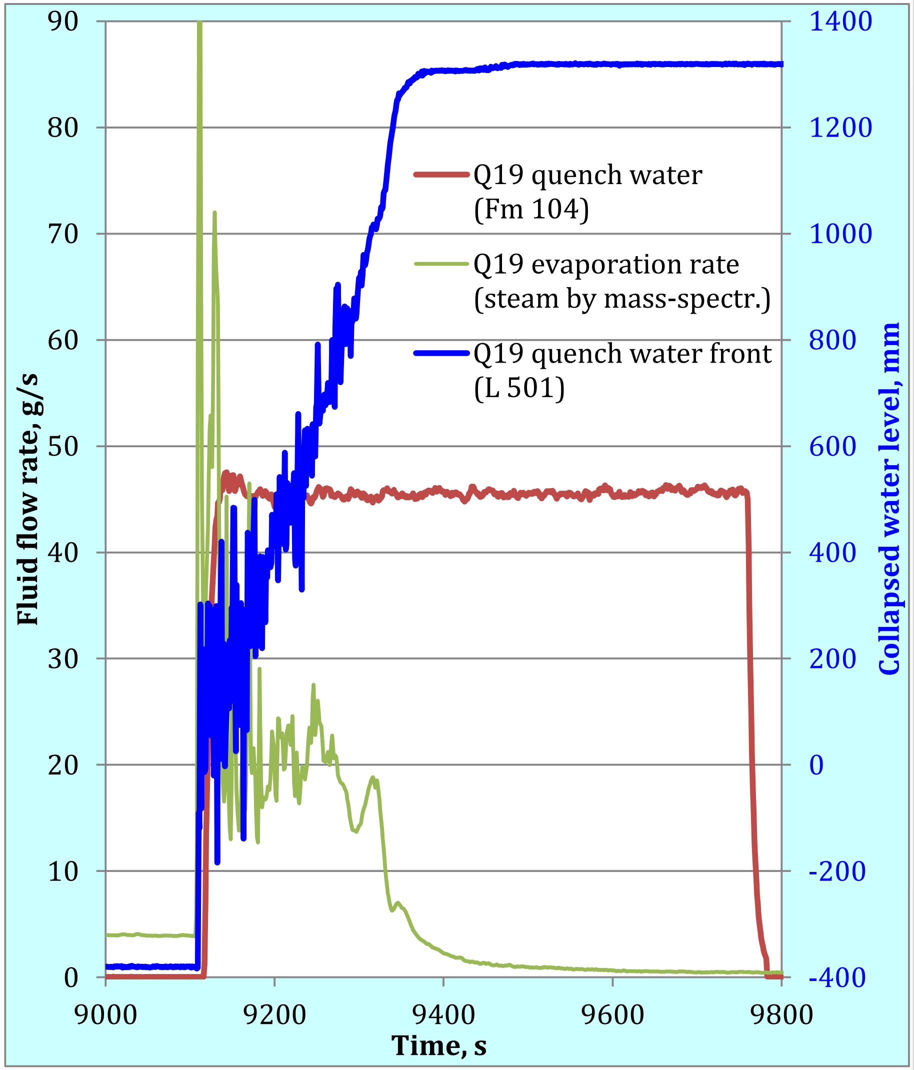


at the onset of reflood

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

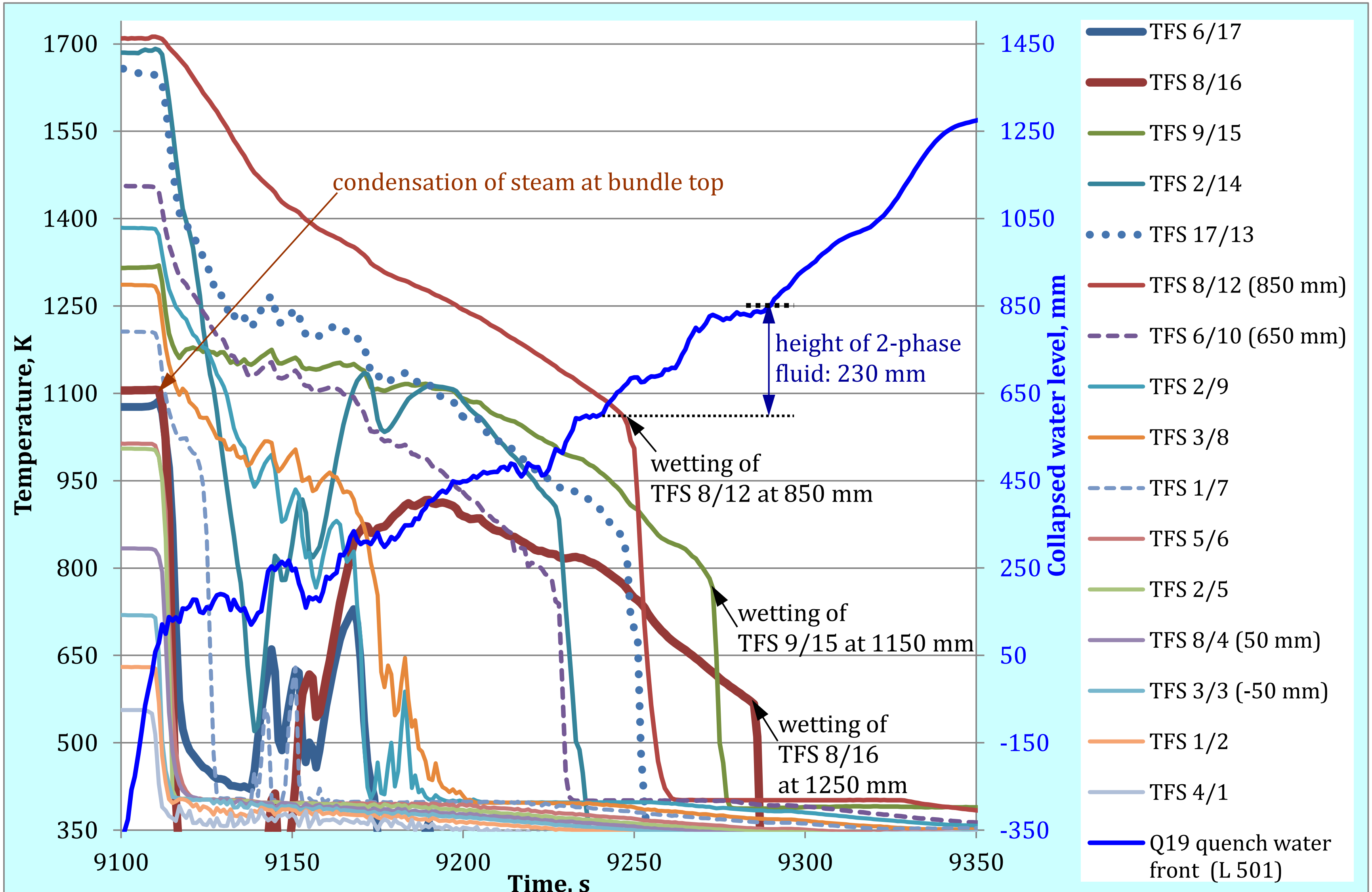


QUENCH-15: water rise duration 330 s

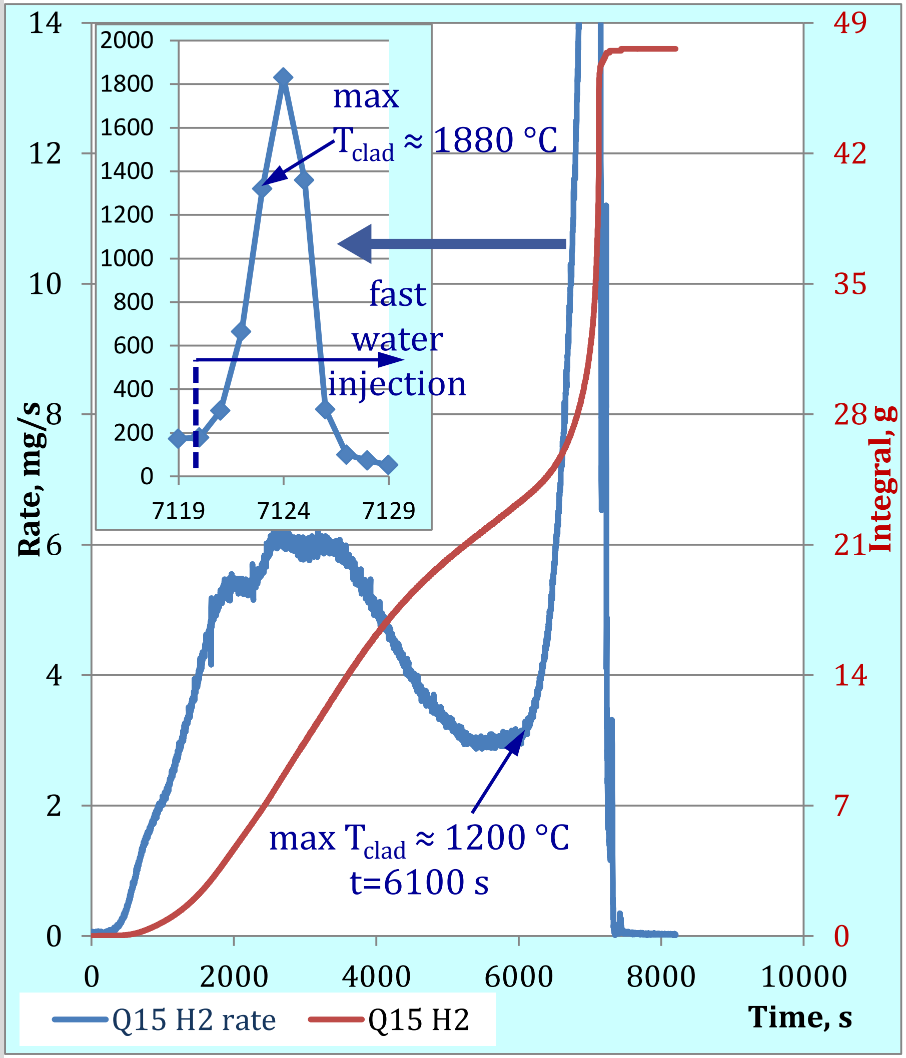


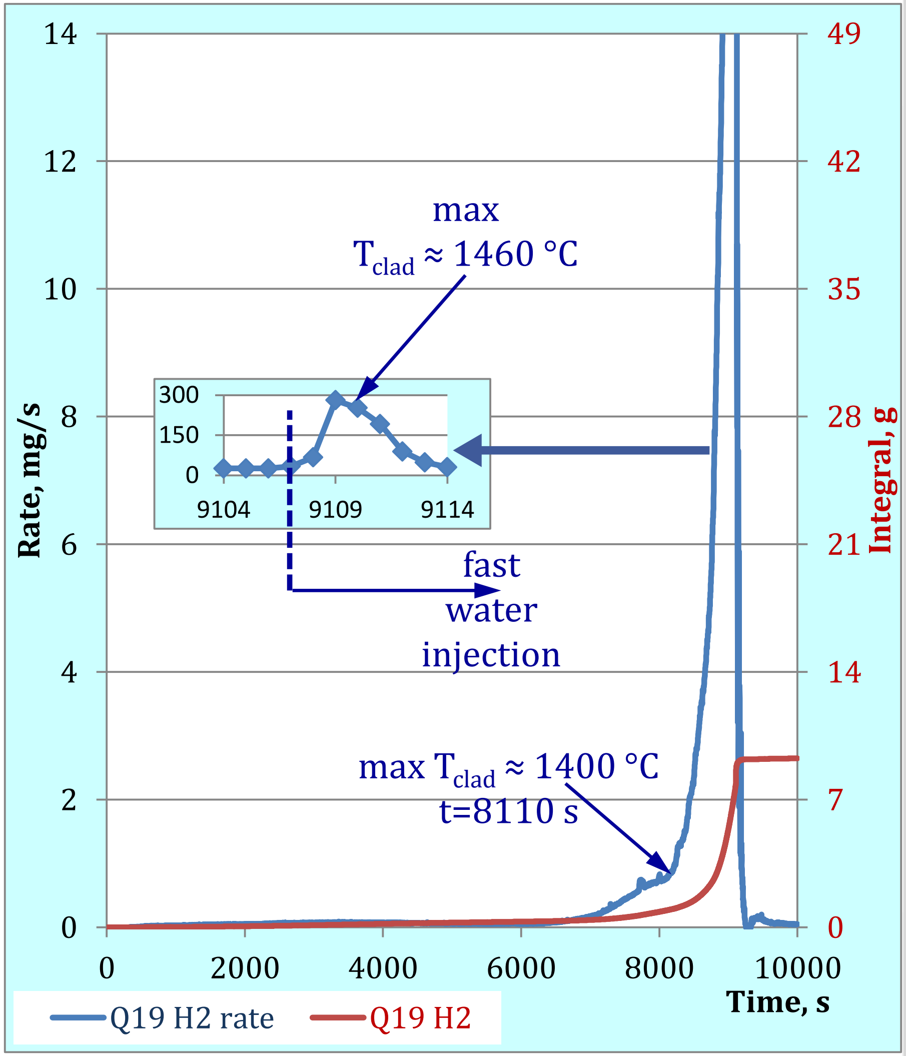
QUENCH-19: water rise duration 270 s

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



Hydrogen release

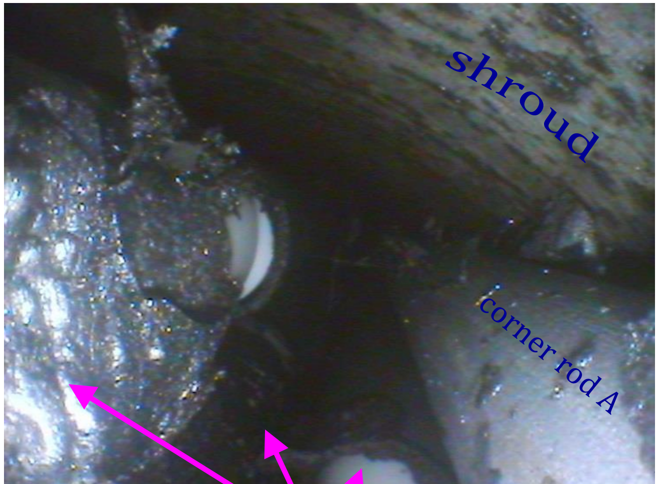




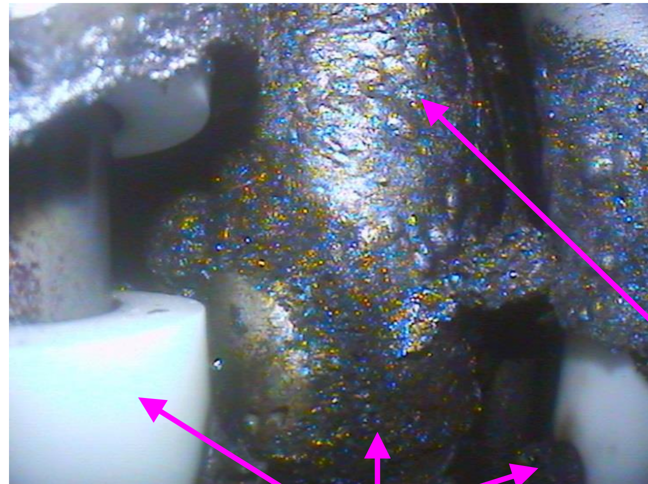
QUENCH-15: max rate 1830 mg/s; totally 47.6 g H_2

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

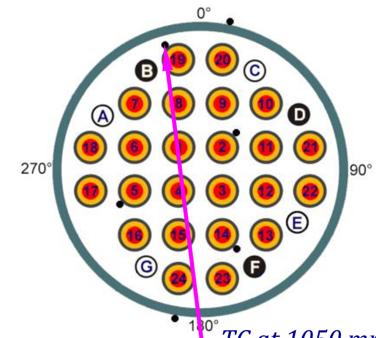
QUENCH-19: videoscope observations of damaged (partly melted) claddings at upper part of heated zone



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

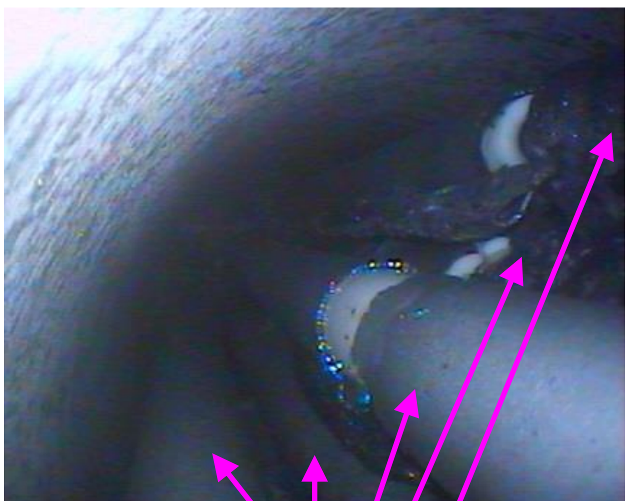


rods 19, 8, 7
(side look at 1000 mm)

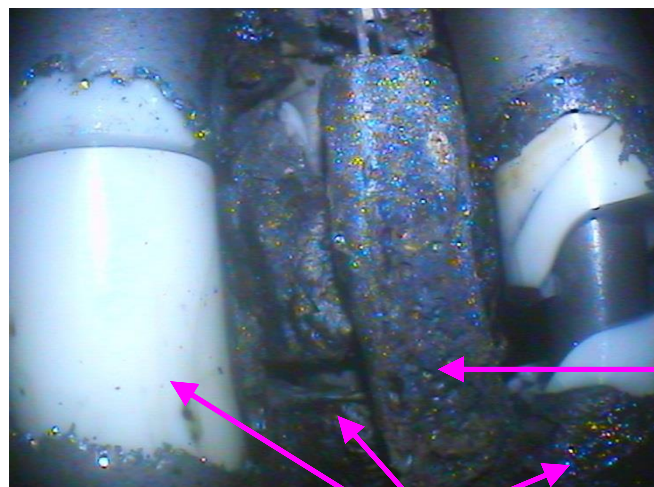


TC at 1050 mm

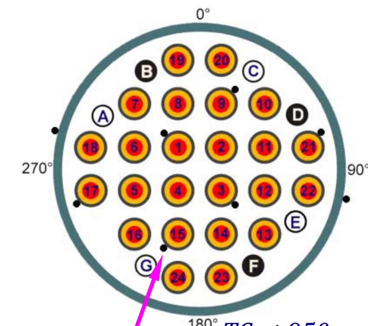
melt from TFS 19/14



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



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

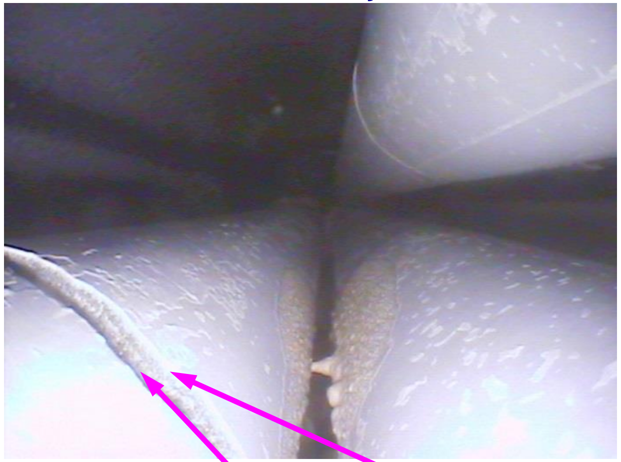


TC at 950 mm

TFS 15/13

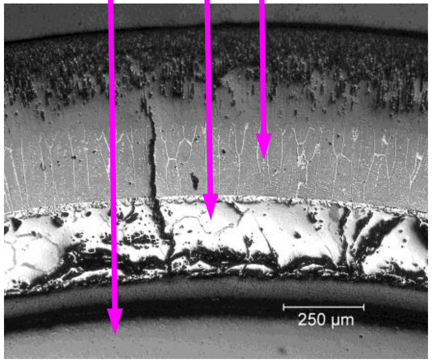
Videoscope observations of claddings at hottest positions of bundles QUENCH-15 (ZIRLO) and -19 (FeCrAl)

__Q15__: circumferential cladding cracks at hottest elevation of 950 mm

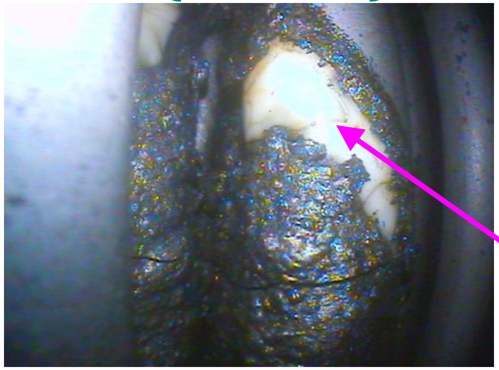


thick oxide

partially molten metal captured between pellet and oxide



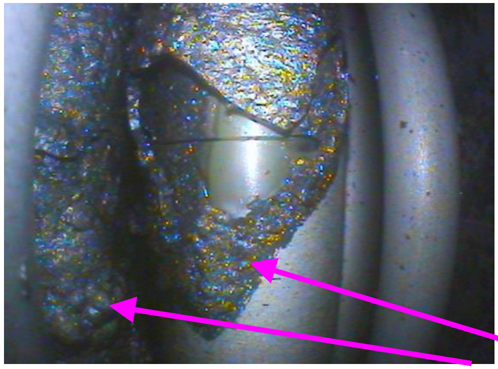
molten claddings of rods 13 and 12
(**Q19** front look at 1000 mm)



900 mm

pellet

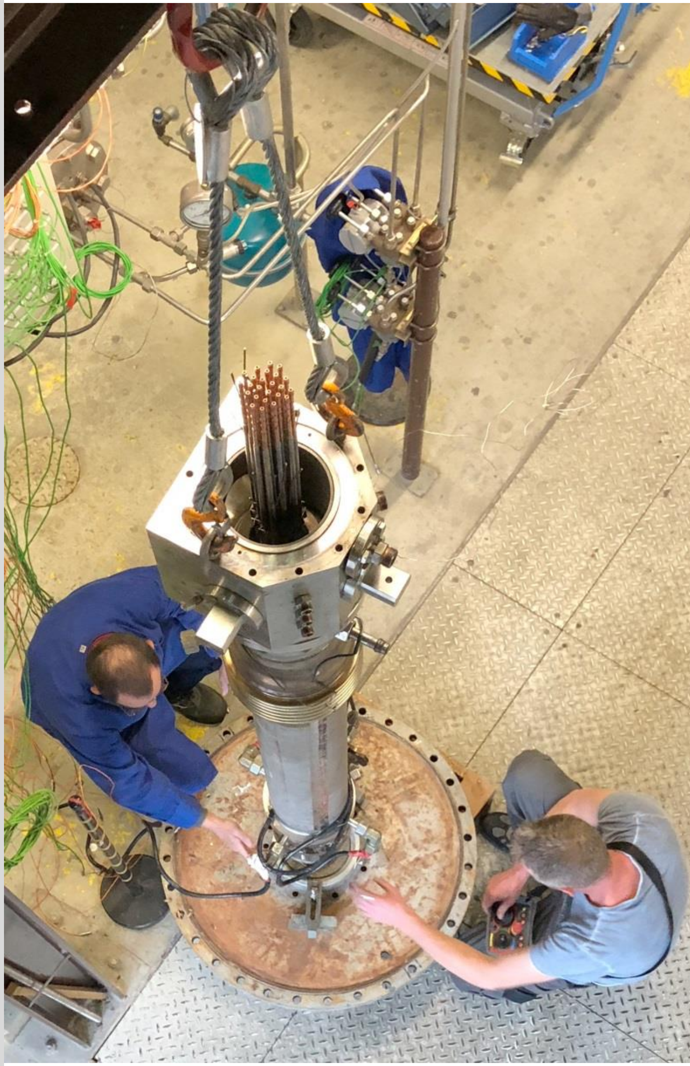
850 mm



800 mm

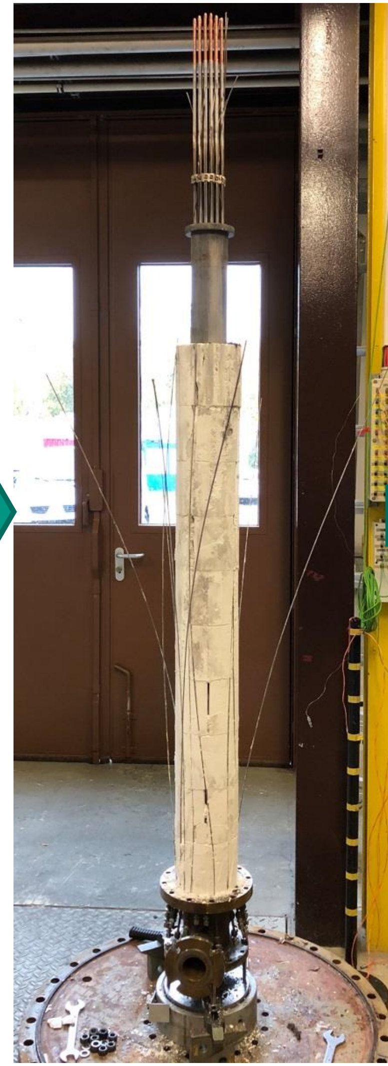
Q19 side look: molten claddings of rods 14 and 13

QUENCH-19 bundle extracting



Bundle inside cooling jacket

jacket removed

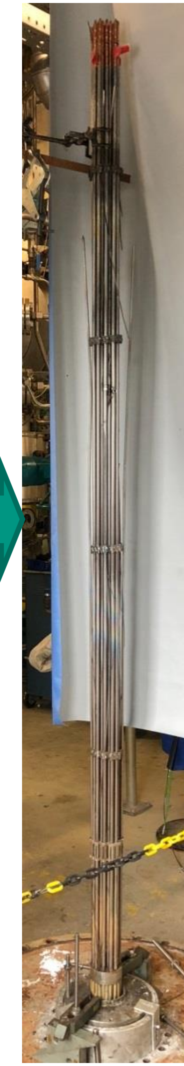


Bundle surrounded by porous ZrO_2 heat insulation

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

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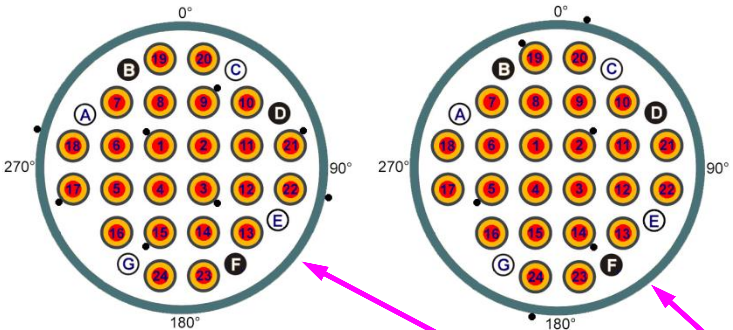
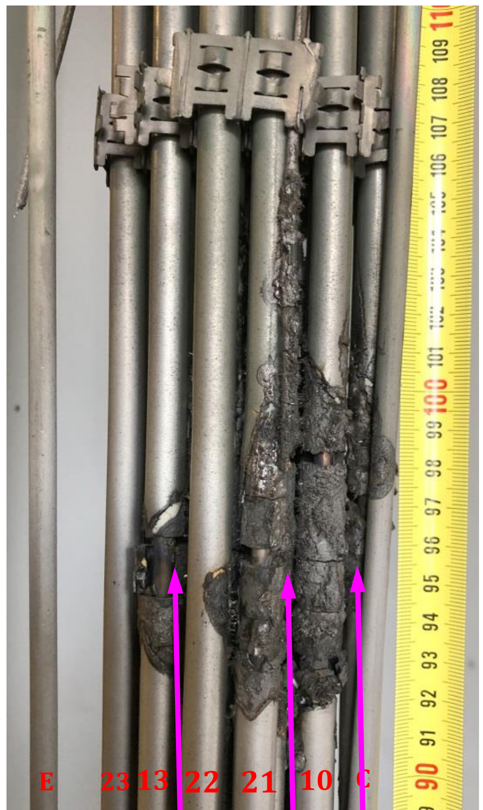


Positions of TC (•) at elevations 13 (950 mm) and 14 (1050 mm)

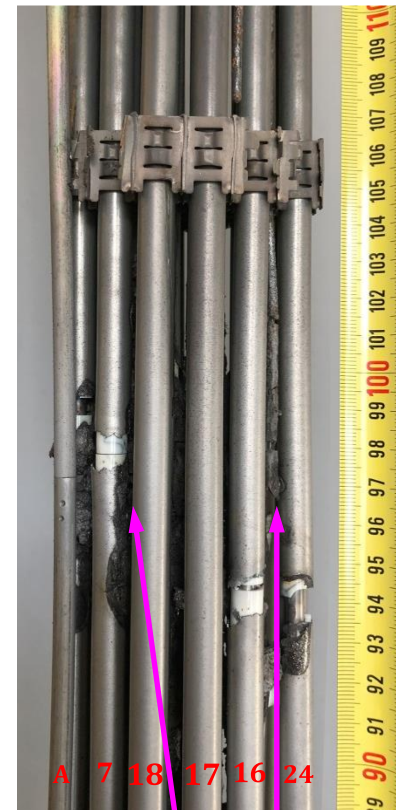
- the melting range of 304 steel is 1400…1450°C
- the melting range of FeCrAl alloys is 1500…1520°C

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 B136Y cladding tubes and 4 Kanthal AF 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). Not similar conditions were 1) cooler steam-Ar flow, and 2) humid Ar inside the heat insulation for QUENCH-19.

➢ 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) extended period 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 reasons of these test differences should be 1) different boundary conditions (cooler gas flow, humid heat insulation), 2) larger pellet diameter, 3) different properties of bundle materials (lower thermal conductivity, higher heat capacity and thermal expansion of FeCrAl).

Summary (cont.)

- Much lower heating rate in comparison to QUENCH-15 was measured. No temperature escalation was observed during the extended transient. Maximum cladding temperature measured before reflood of the QUENCH-19 bundle was about 1460 °C (QUENCH-15: 1880 °C). Reason: negligible heat release during slight FeCrAl oxidation.
- The coping time was ≈3200 s (≈1200 s for QUENCH-15). However, this comparison should be made with care due to different boundary conditions for two tests.
- Significant increase of hydrogen release was observed at temperatures above 1375 °C. Probably, the protective Al_2O_3 was disappeared either due to evaporation of $Al(OH)_3$ or due to dissolution in the metallic matrix.
- 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 few claddings were spalled (probably due to thermal expansion followed by quench shrinkage).

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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/