Karlsruhe Institute of Technology

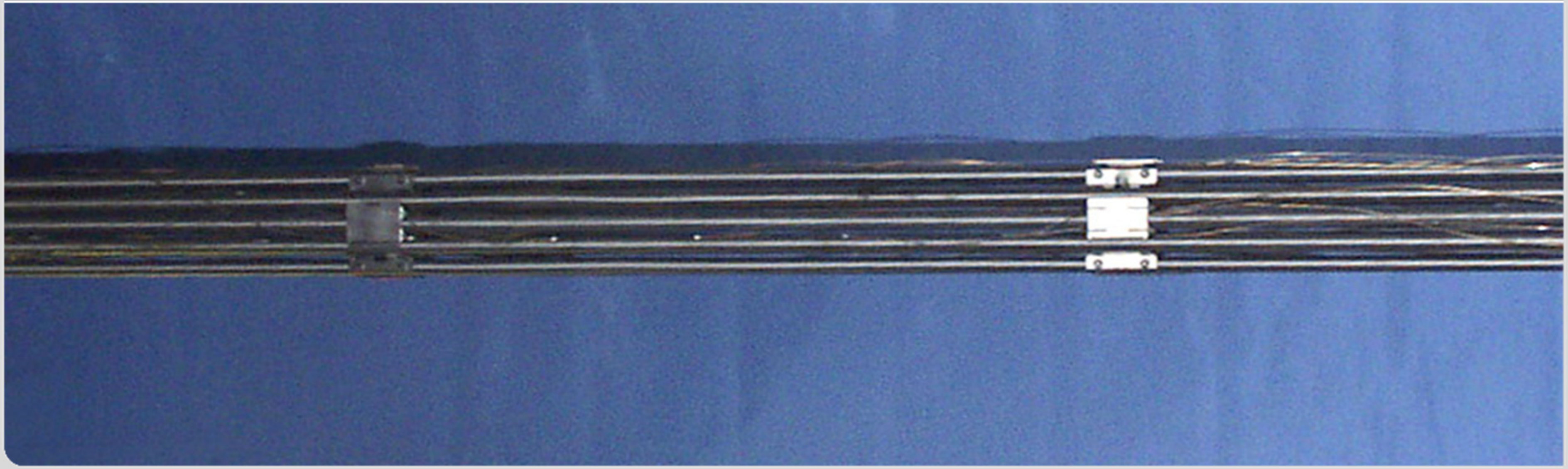
Institute for Applied Materials

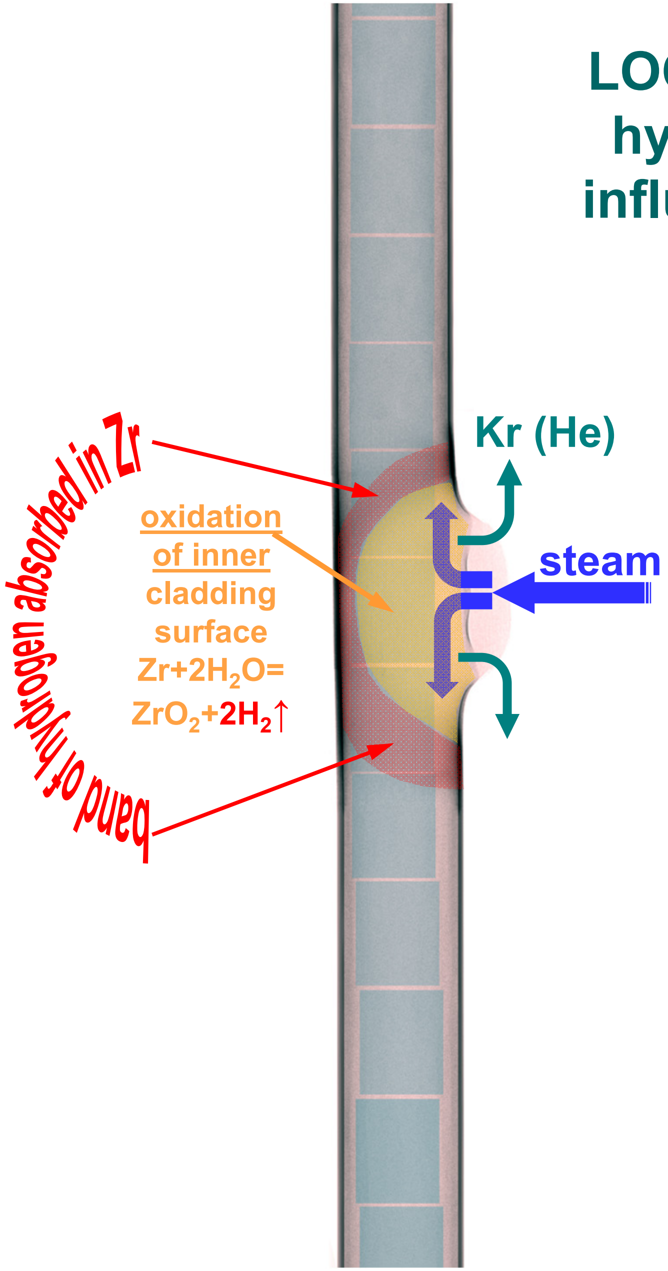
First results of the high temperature bundle test QUENCH-L3HT with optimized ZIRLO™ claddings

J. Stuckert, M. Große, J. Moch, C. Rössger, M. Steinbrück, M. Walter

QWS-20, Karlsruhe 2014

Institute for Applied Materials; Program NUKLEAR





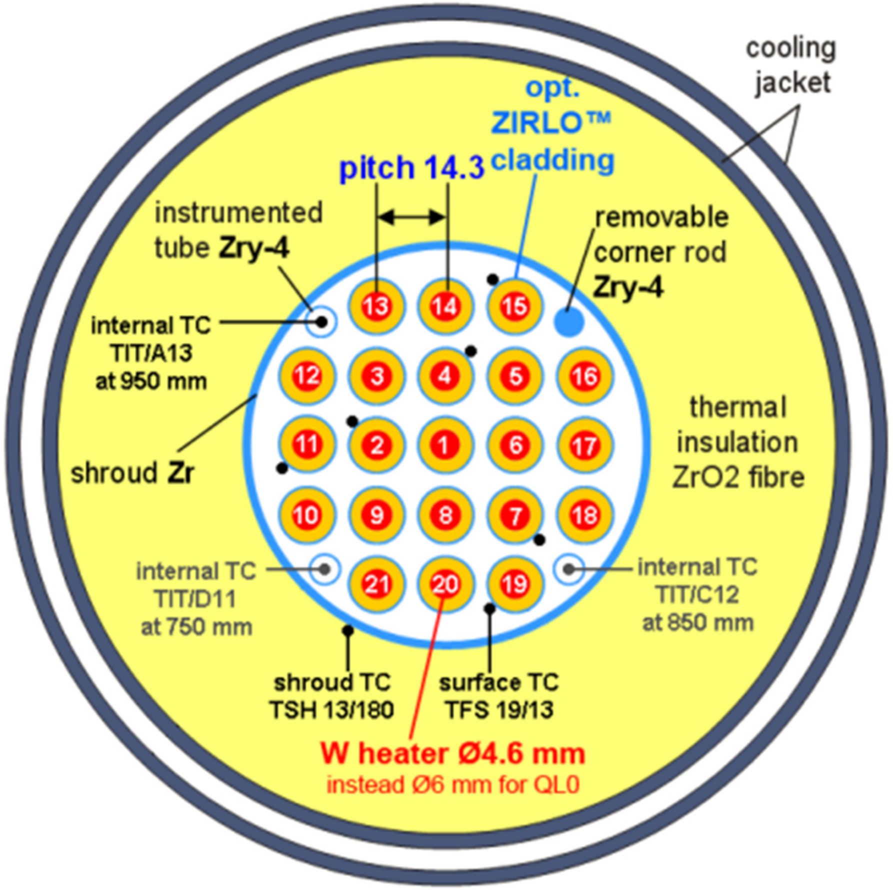
LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement

Karlsruhe Institute of Technology

Sequence of phenomena:

- cladding ballooning and burst, relief of inner rod pressure
- steam penetration through the burst opening, steam propagation in decreasing gap between cladding and pellet
- oxidation of inner cladding surface with hydrogen release
- absorption of hydrogen by cladding at the boundary of inner oxidised area at temperatures higher of the phase transition $\alpha \rightarrow (\alpha+\beta)$ in Zr alloy
- local embrittlement of cladding near to burst opening

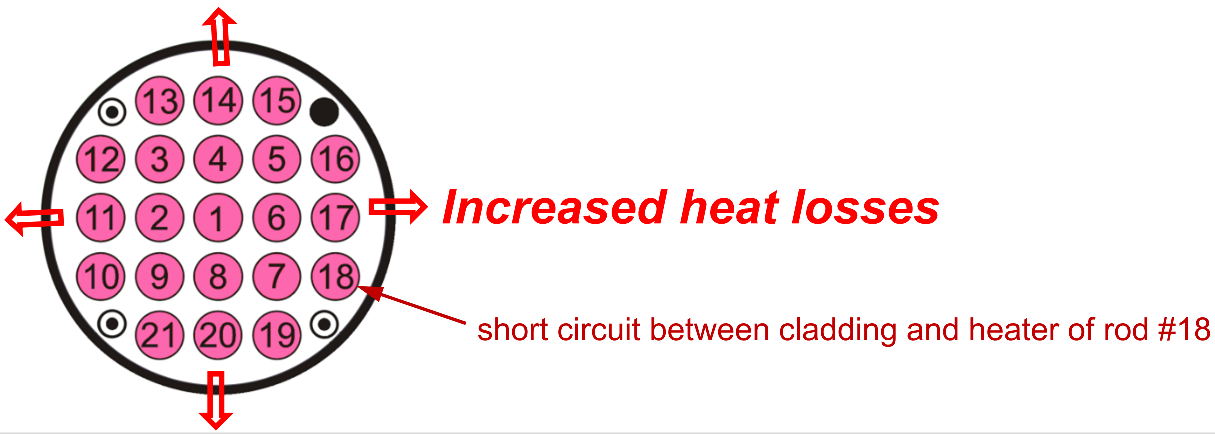
Cross-section of the QUENCH-L3HT bundle



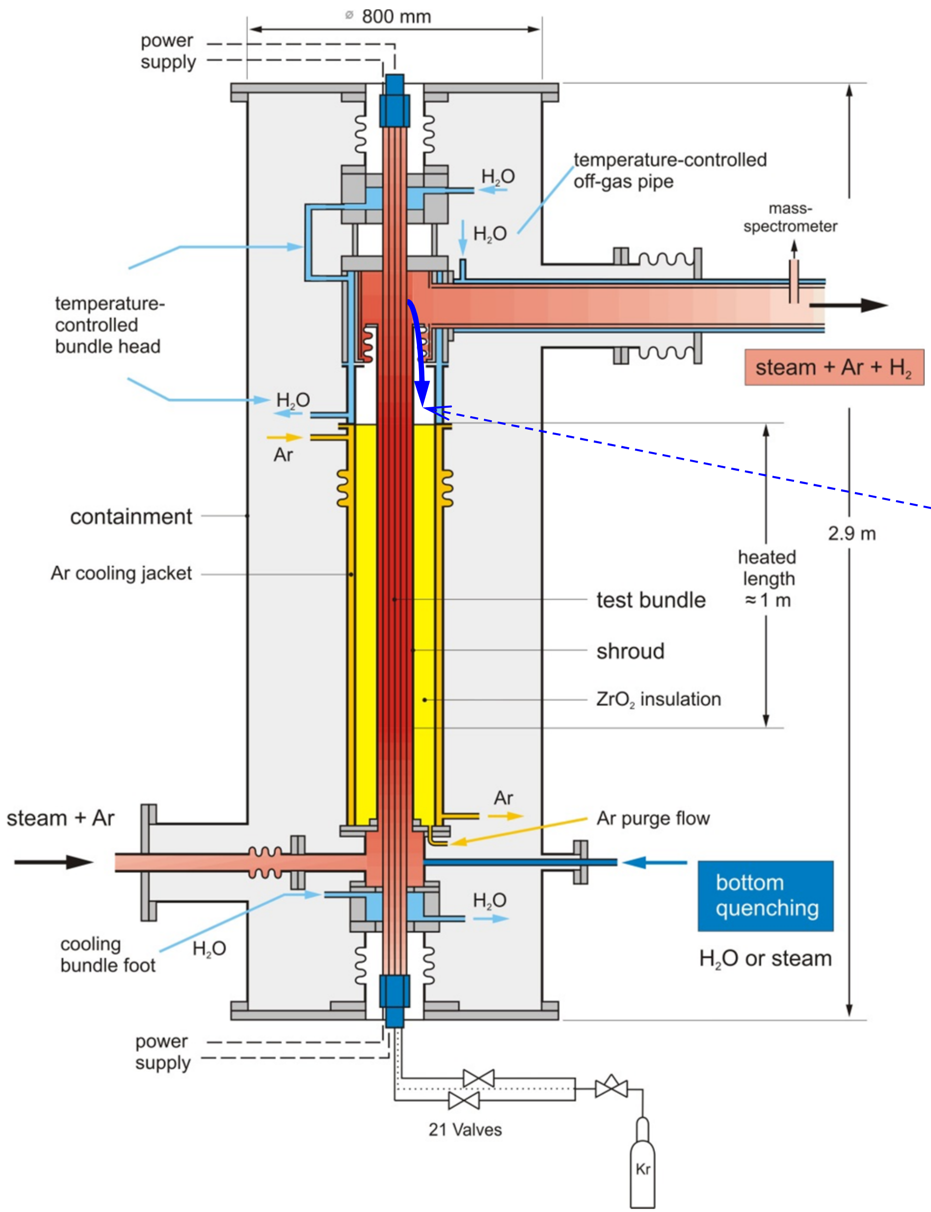
1) The use of ***tungsten*** heaters with smaller diameter (***4.6 mm***) instead tungsten heaters (QUENCH-L0) or tantalum heaters (QUENCH-L1) with diameter of 6 mm has allowed to reach a **higher heat rate**.
2) All rods are filled with Kr with p = 55 bar at Tpct = 800 K (similar to QUENCH-L1).

Peculiarities of the QUENCH-L3HT test

- The QUENCH-LOCA-3HT test was performed according to a typical LBLOCA transient with maximal heat-up rate 7.5 K/s. However, due to technical problems the transient was terminated at *not prototypical* peak cladding temperature of more than 1500 K.
- Continuous steam leakage from the test channel into the space between shroud and cooling jacket was occurred due to failed seal at the bundle top. Therefore, the porous heat insulator outside of the shroud was filled not only with argon gas but additionally with steam (higher heat conductance and heat capacity). As result, 1) during the heat-up phase took place increased *heat losses* and 2) the following cool-down phase was slow.
- The post-test inspection showed damage of insulation coating on the heater surface of one outer fuel rod simulator. The damage occurred during the heat-up phase and could be the additional reason for decreased heat-up rate for outer ring of heated rods.
- Increased rod bending due to mechanical constraints caused by higher temperatures.

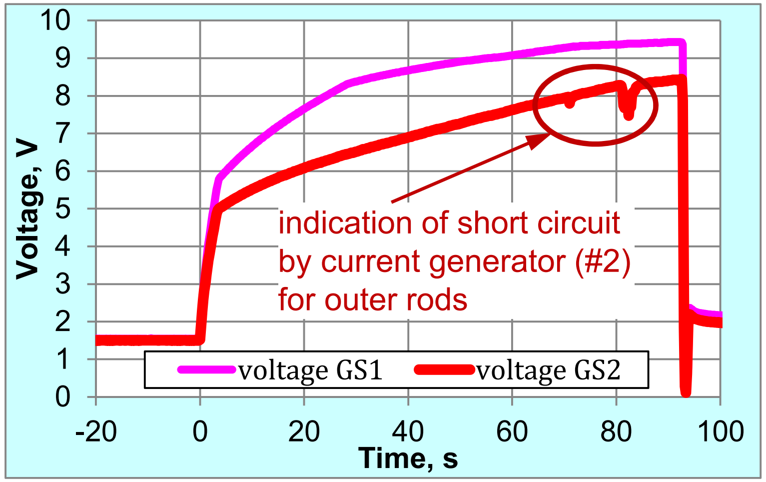


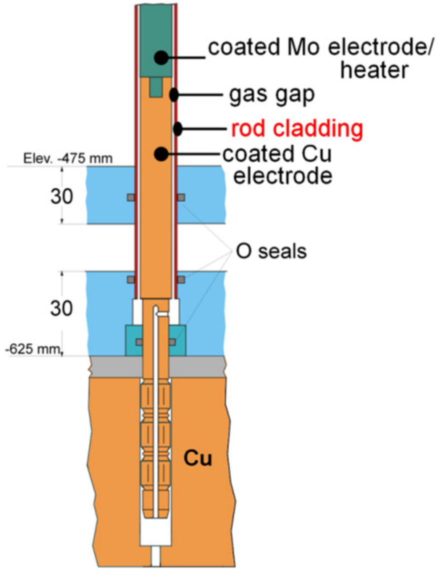
QUENCH-LOCA test section: leakage during QUENCH-L3HT



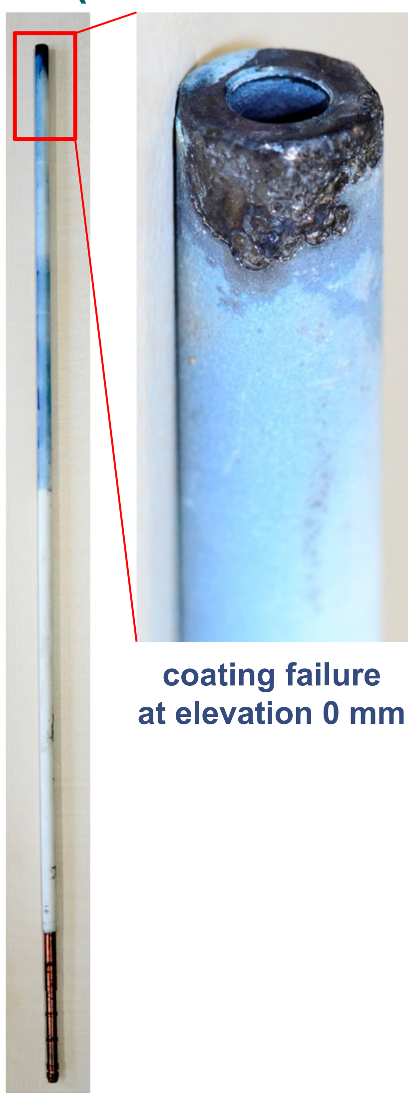
steam leakage into shroud heat insulation
due to failure of ring seal

Short circuit between Mo-heater and cladding due to electrode coating failure (rod #18 of QL3HT)



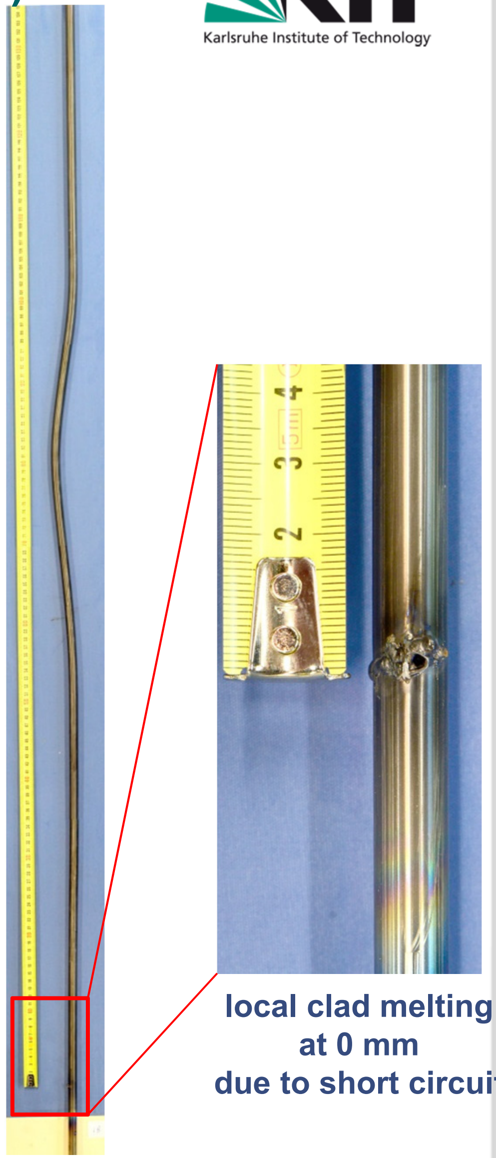


low part of rod:
el. power and gas supply



lower electrode of rod #18

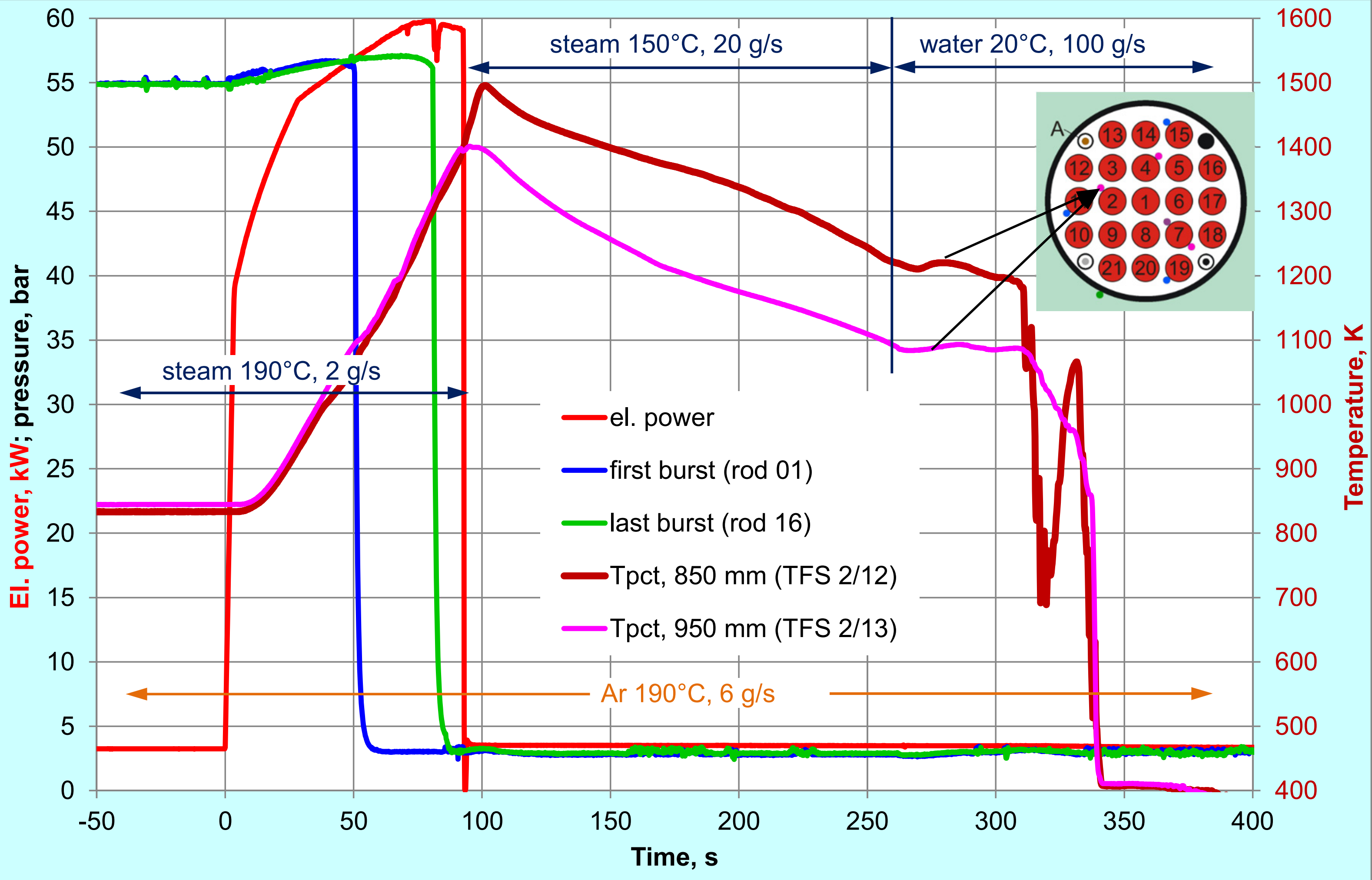
coating failure at elevation 0 mm



rod #18

local clad melting at 0 mm due to short circuit

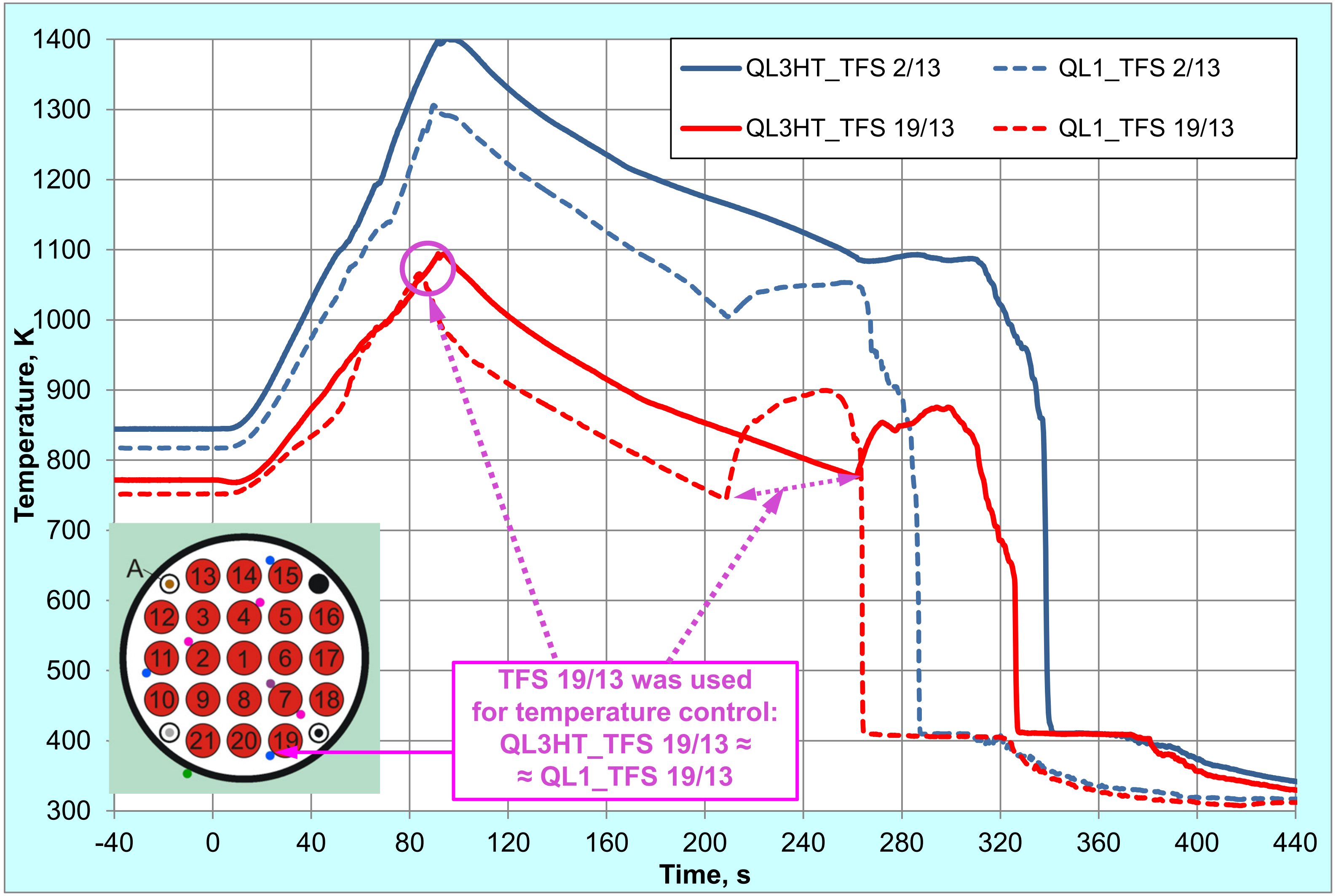
Progress of the QUENCH-L3HT test



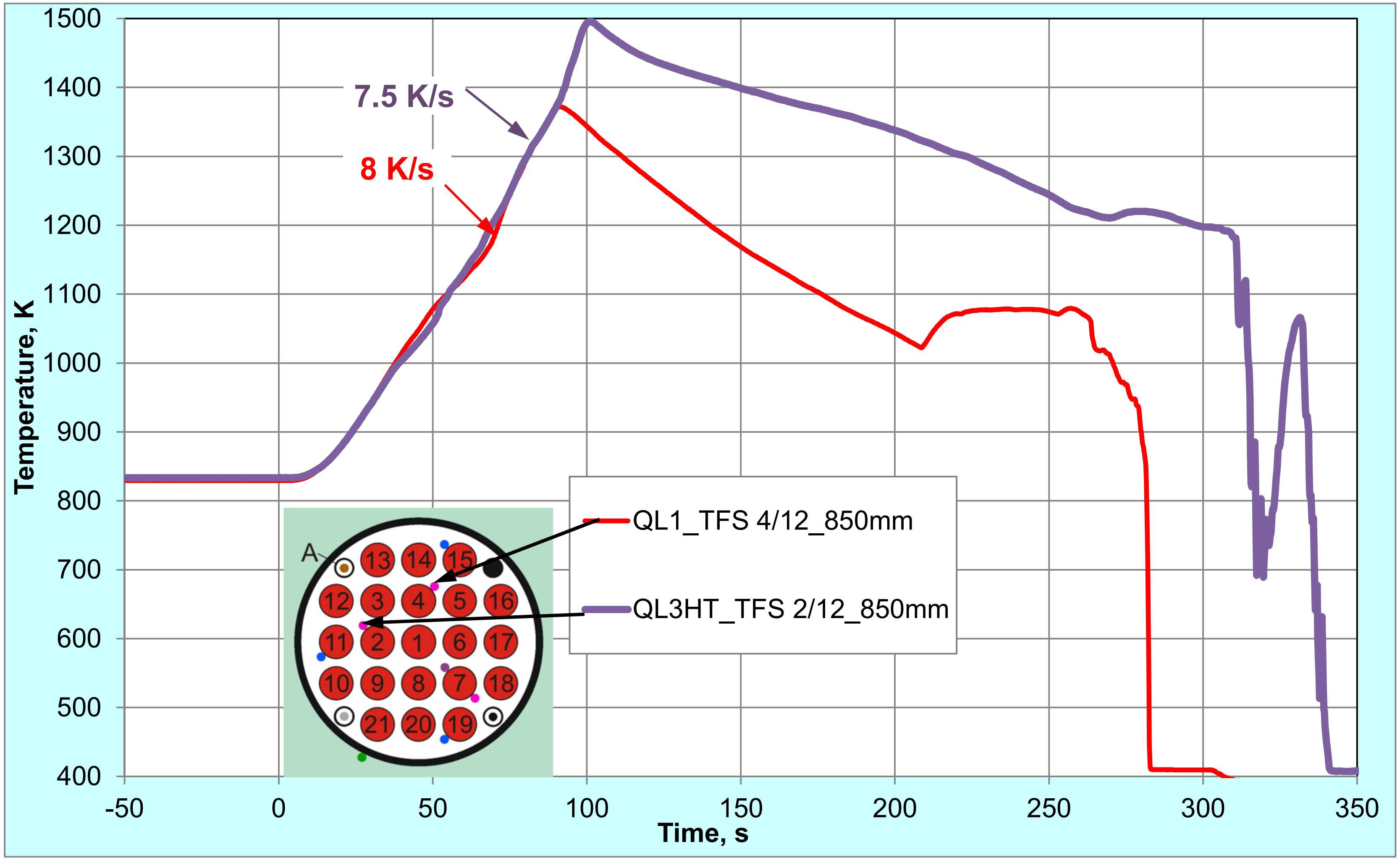
***1) maximal reached power** (comparison):*
QUENCH-L1 (Ta-heaters, Ø 6 mm): 58.5 kW,

2) Temperature escalation at 850 mm on 91.4 s

Conduct of QUENCH-L3HT test on the basis of QUENCH-L1 temperature history: similar temperatures for outer rods on the end of transition and cool-down phases

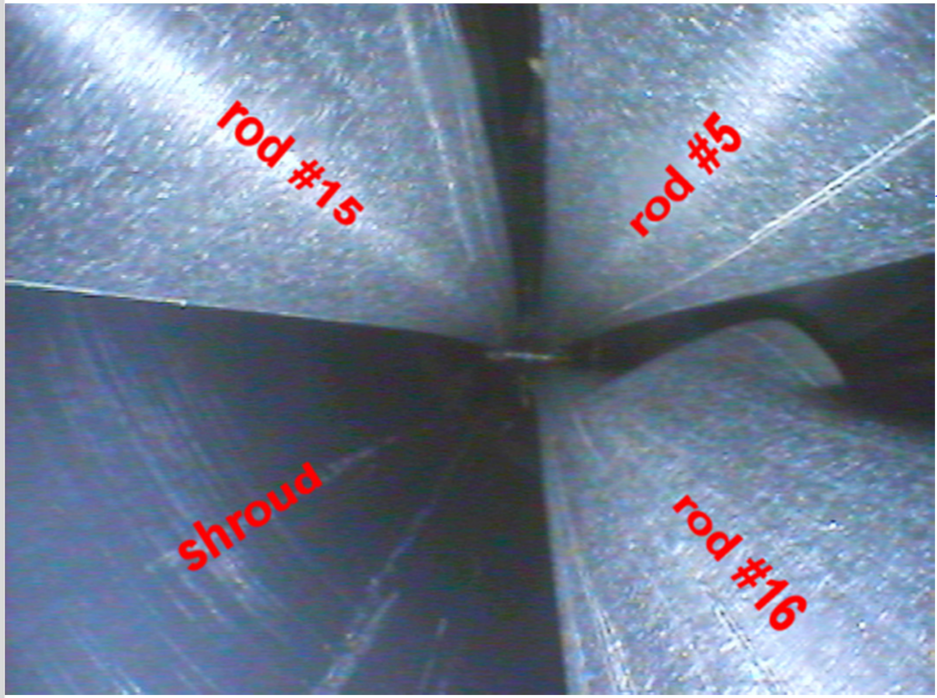


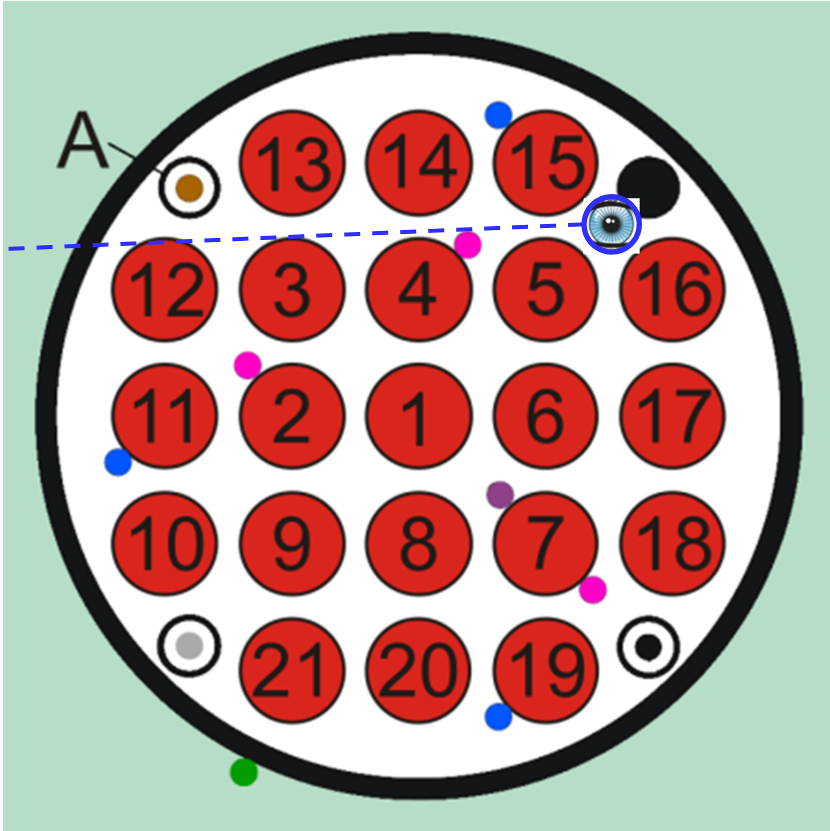
Maximal cladding temperatures of internal rods in hottest region of QUENCH-L1 (Zry-4, reference test) and -L3HT bundles



QL3HT vs. QL1: similar transient, higher Tpct, delayed cool-down

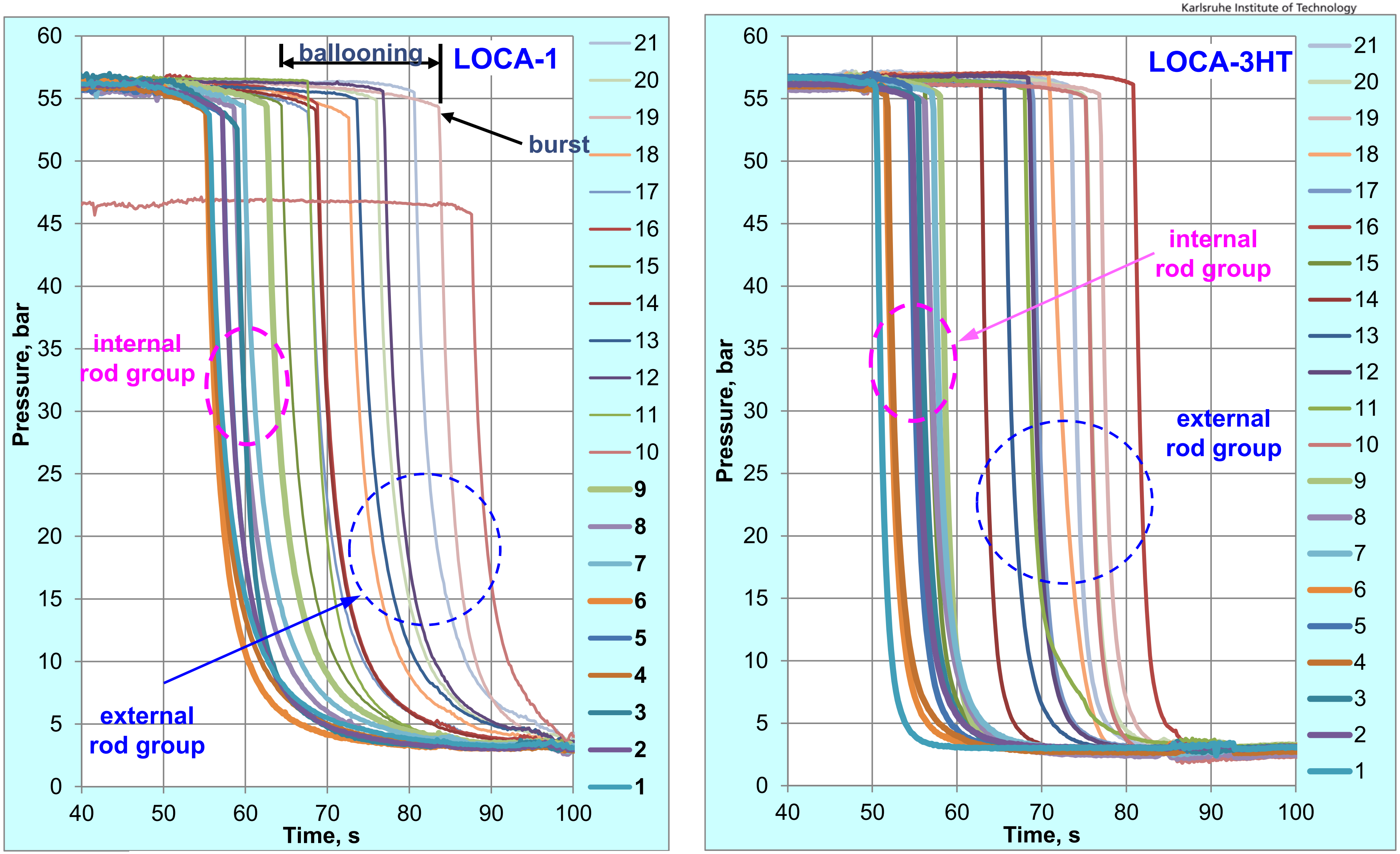
QL3HT: videoscope observations





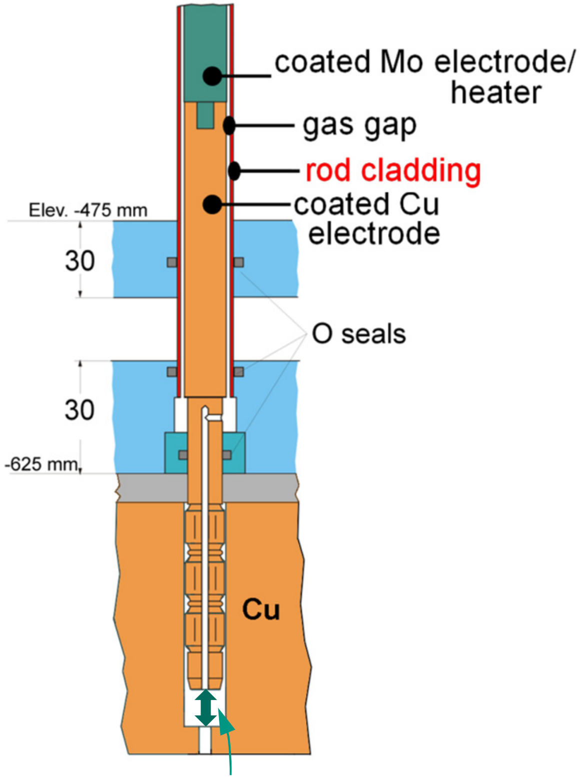
ballooning and burst of cladding tubes at elevation 950 mm (camera position)

Rod pressure evolution during heating phase for QUENCH-L1 and -L3HT: burst time indication



duration of decrease of the inner pressure to the system pressure: $\tau_0 \approx 30$ s

QUENCH-L3HT: bundle between spacers GS3 (550 mm) and GS4 (1050 mm).
Rod bending due to 1) limitation of axial thermal expansion of W-Mo heater (Tpct > 1250°C); 2) non-uniform cladding axial expansion.



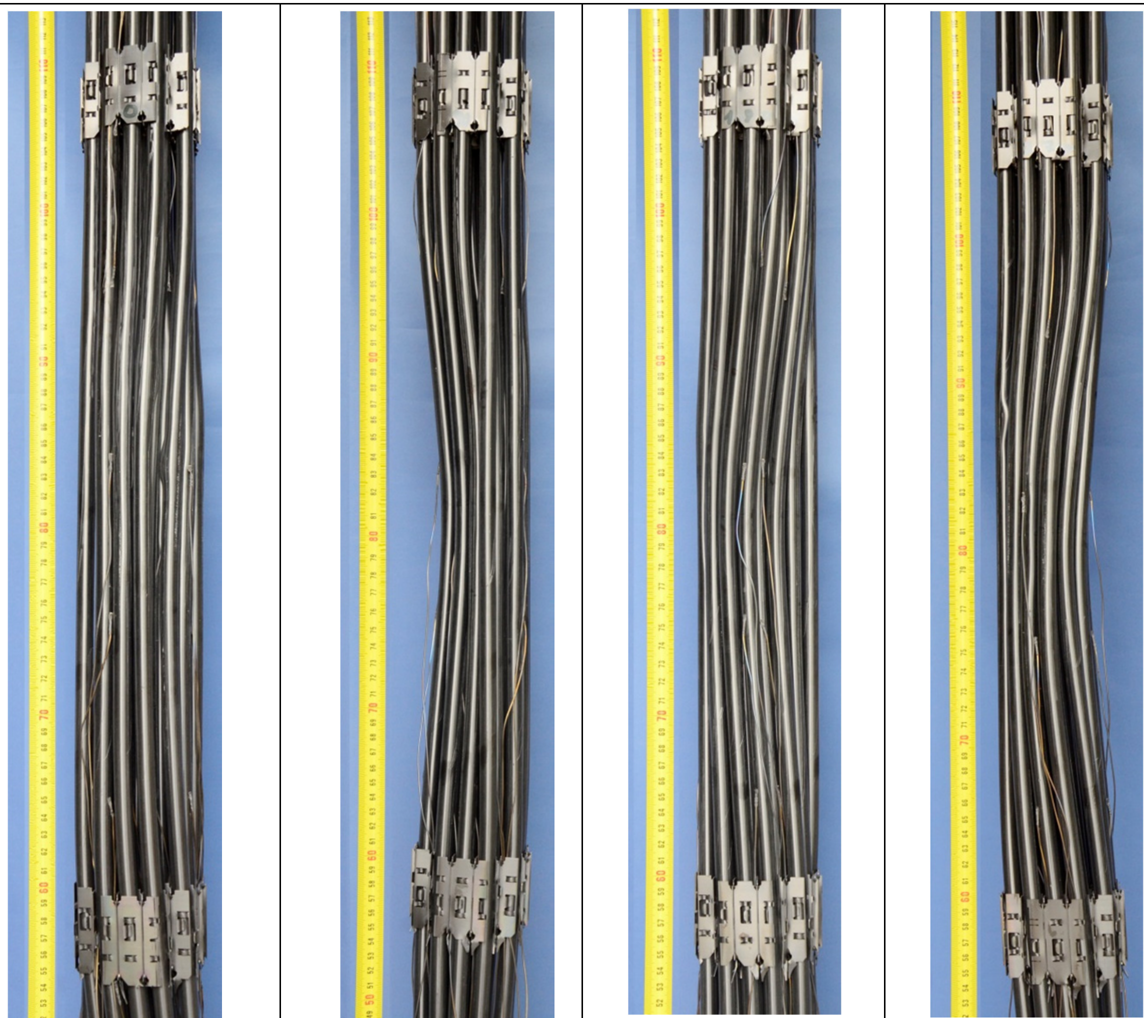
actual gap was 5 mm

gap must be:

> 5 mm for QL1 (Tpct < 1100°C)

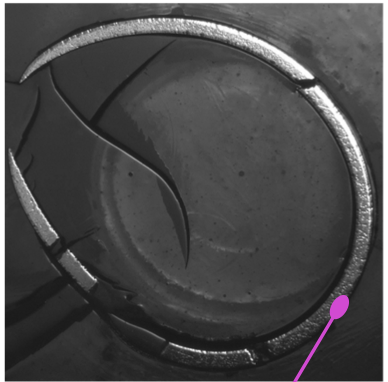
> 6.5 mm for QL3HT (1250°C)

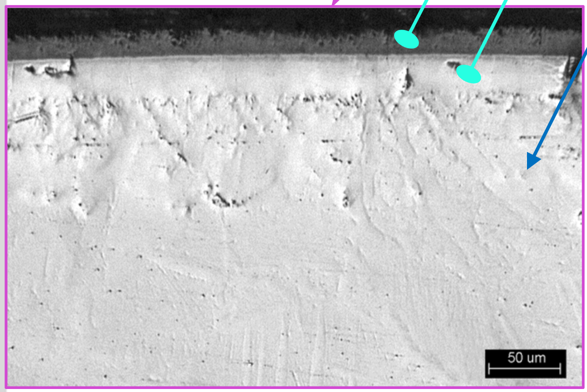
6.5 - 5 = 1.5 mm → bending <u>20 mm</u> between grid spacers



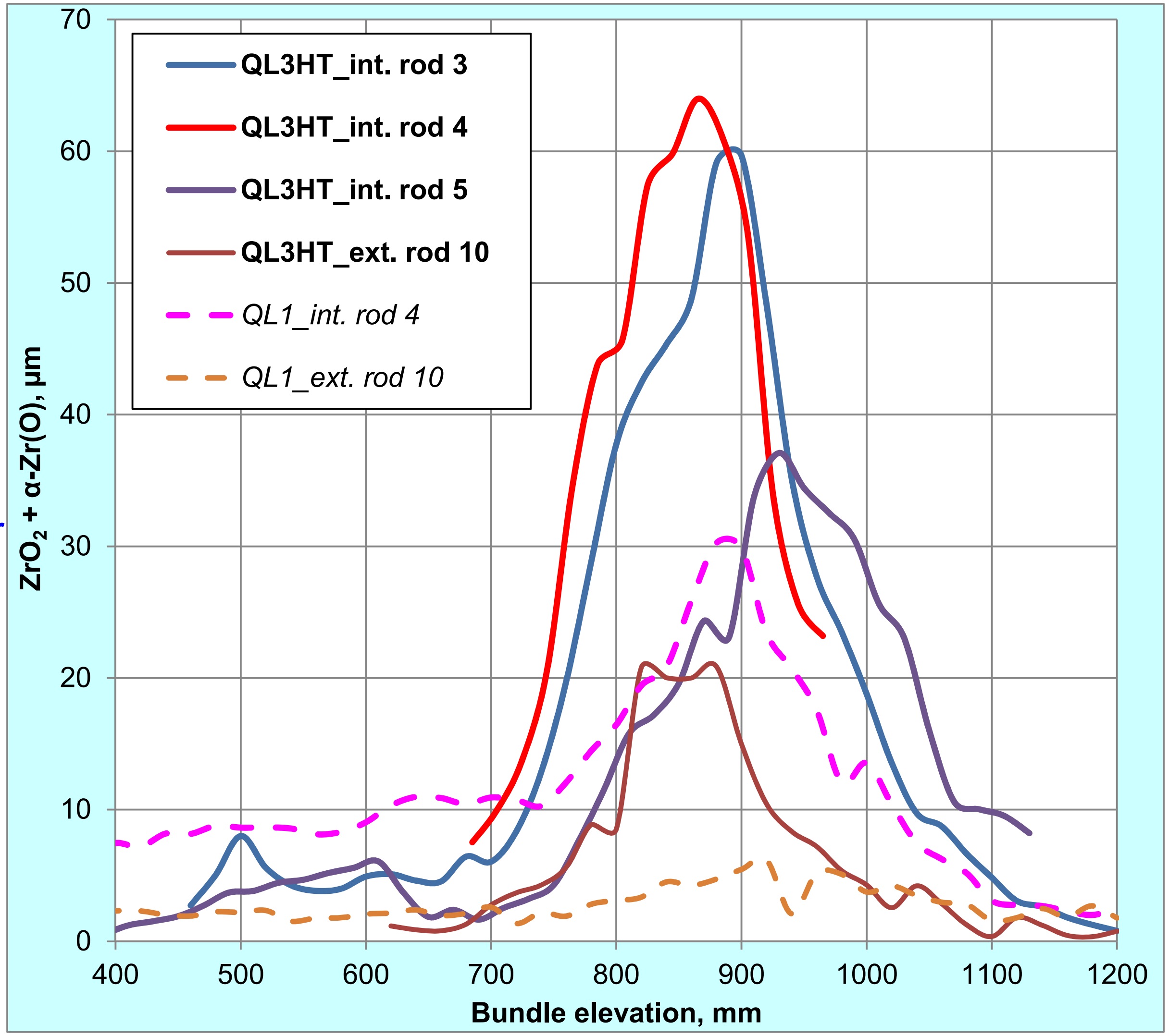
0°	90°	180°	270°

Cladding oxidation degree for QL3HT and QL1: total thickness of outer ZrO_2 and α-Zr(O) layers
(tangential average of eddy-current measurements)





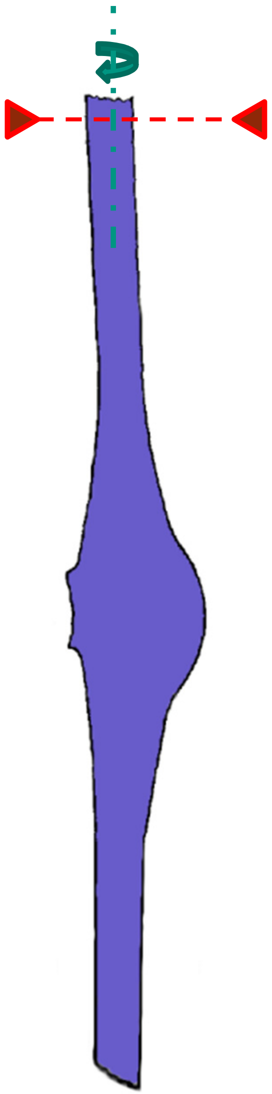
(QUENCH-L1; rod #1)

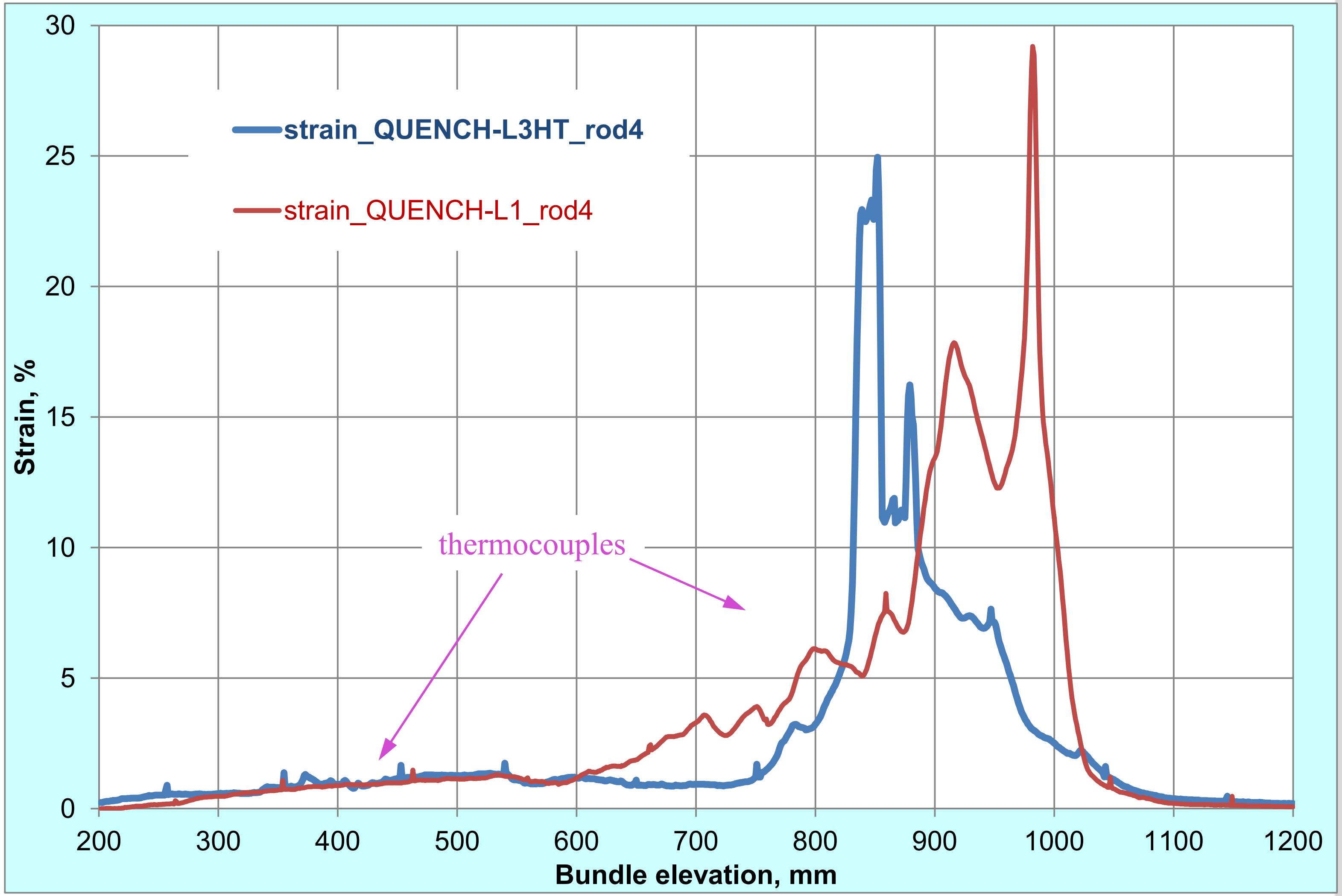


Consistence with higher temperatures and increased radial T gradient for QL3HT

Laser profilometer: axial strain distribution for rod #4.

Estimation of maximal blockage of coolant channels.

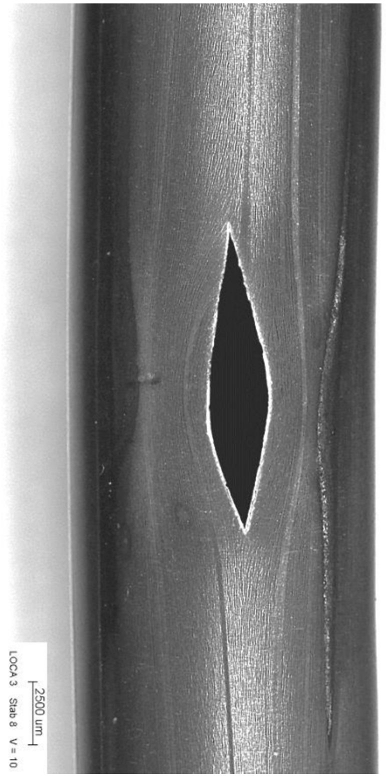




Calculation: for coplanar positions of all burst openings (max blockage B): B_{QL1}= 46%; B_{QL3HT}= 35%

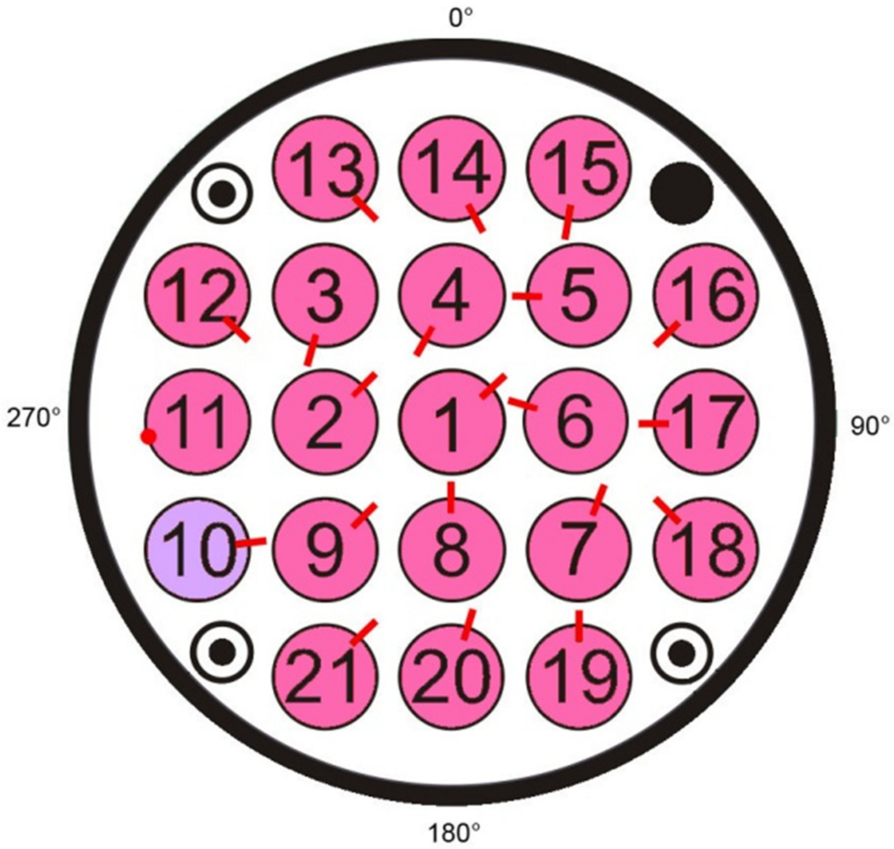
QUENCH-L3HT: burst openings of several claddings

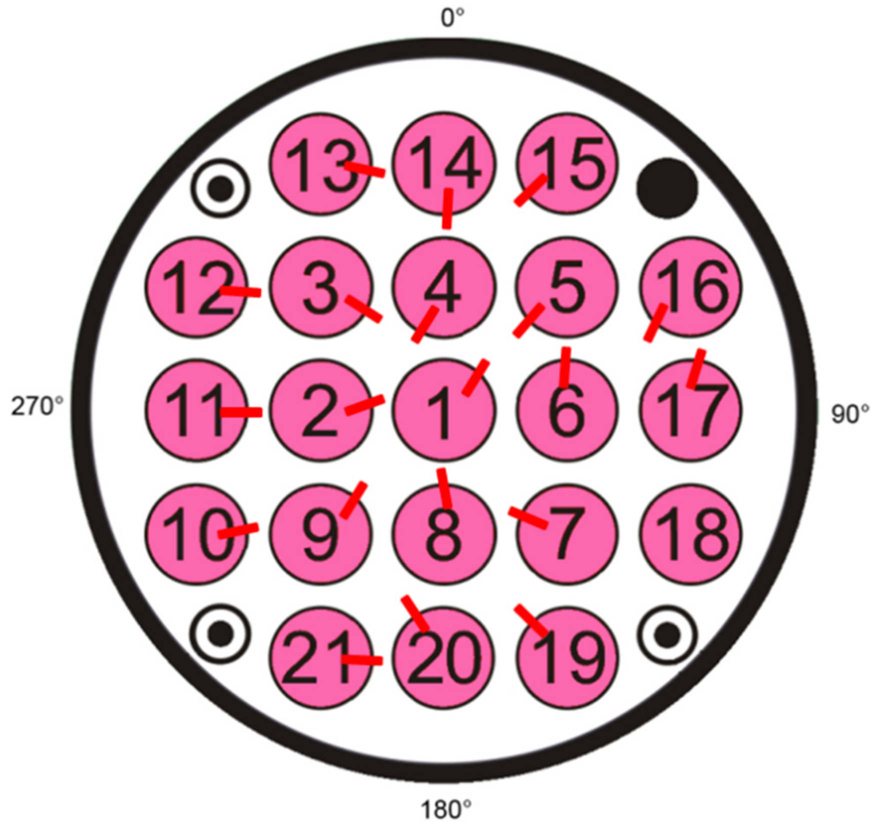
Karlsruhe Institute of Technology

		 welding traces of TC TFS 7/12 i	
rod **#2**: elevation 900 mm H_{op}= 17.2 mm max W_{op} = 4.7 mm A_{op} = 50.7 mm²	rod **#5**: elevation 908 mm H_{op}= 13.5 mm max W_{op} = 3.0 mm A_{op} = 24.0 mm²	rod **#7**: elevation 850 mm H_{op}= 16.6 (10.6) mm max W_{op} = 3.4 mm A_{op} = 29.7 (25.2) mm²	rod **#8**: elevation 837 mm H_{op}= 11.6 mm max W_{op} = 2.3 mm A_{op} = 15.9 mm²

IAM
Institute for Applied Materials

Circumferential position of burst openings

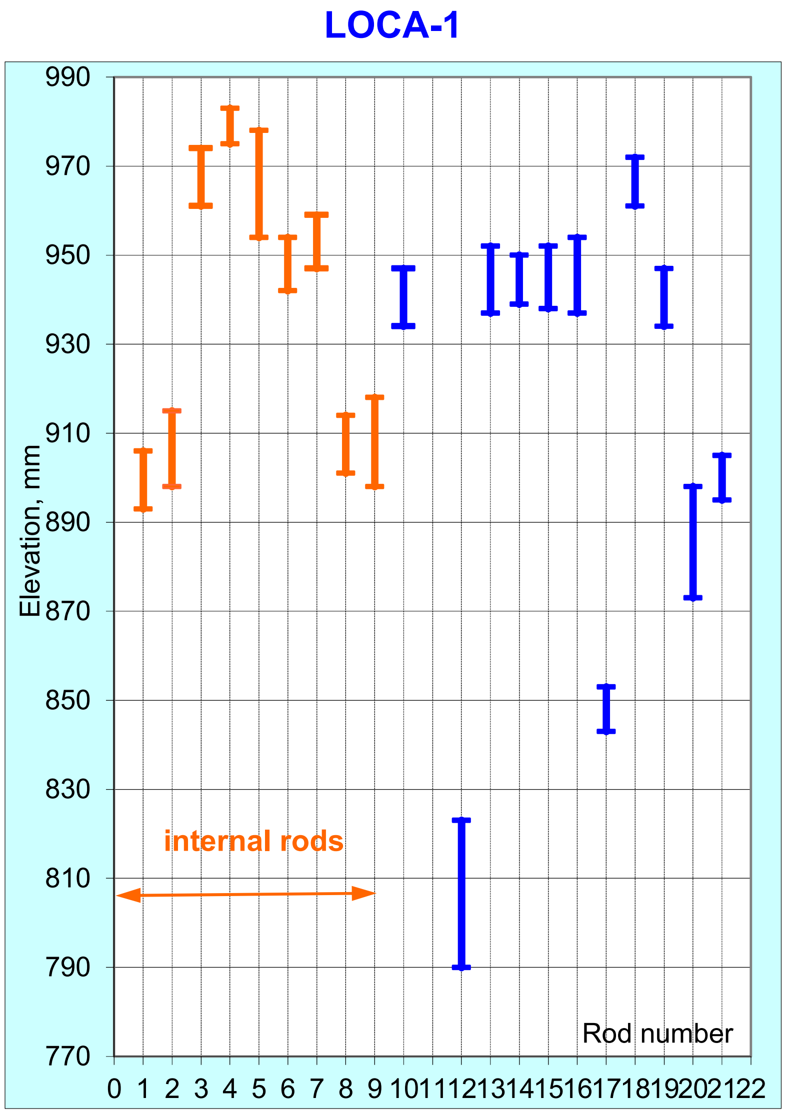


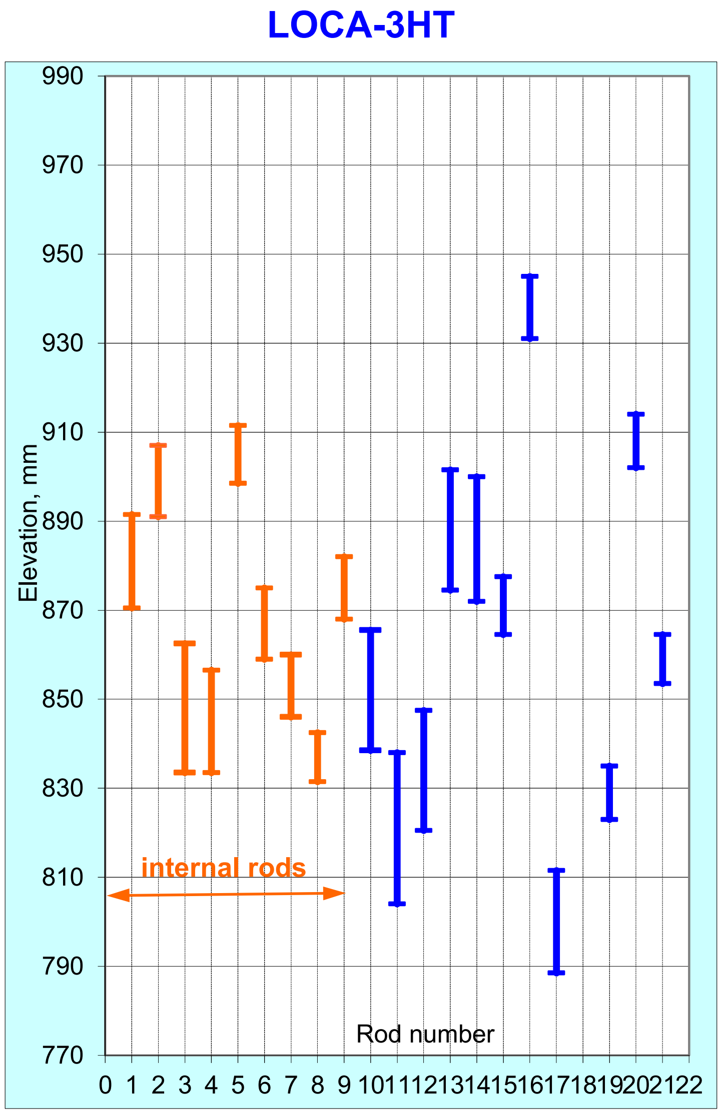


LOCA-1:
not strong orientation
to bundle center

LOCA-3HT:
similar to LOCA-1
excluding adjacent rods
6, 7, 17

Length and axial position of burst openings





Burst parameters

LOCA-1

Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	**4**	**55.2**	**1154**
	6	**55.2**	**1110**
	1	**55.6**	**1169 (Max)**
	5	**57.2**	**1104**
	2	**57.2**	**1132**
	8	**58.6**	**1132**
	3	**59.0**	**1118**
	7	**59.8**	**1074 (Min)**
	9	**62.6**	**1162**
Outer rods	15	64.4	1159
	17	67.6	1104
	11	*67.6*	1056
	14	68.6	1154
	16	68.8	1156
	18	72.6	1081
	13	73.6	1147
	20	76.0	1105
	12	76.8	1092
	21	80.6	1140
	19	83.6	1163
	10	87.6	1143

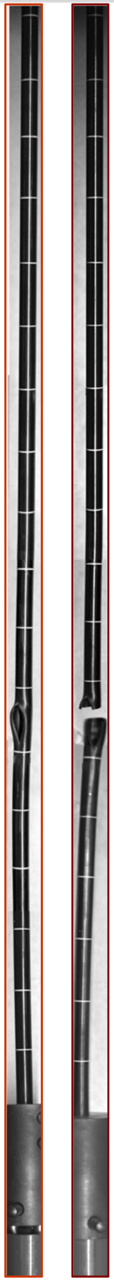
average burst T : 1126 ± 33 K = 853 ± 33 °C

LOCA-3HT

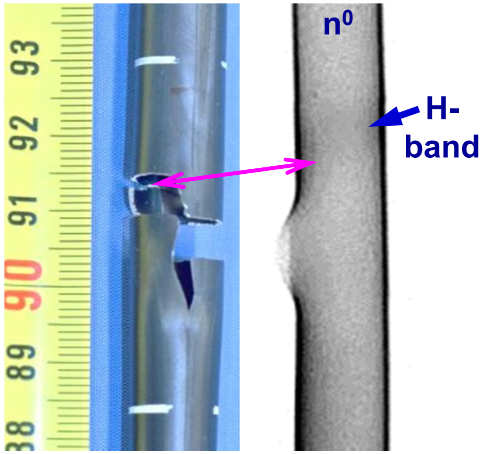
Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	**1**	**50.2**	**1112**
	4	**51.4**	**1123**
	6	**51.6**	**1030**
	5	**54.4**	**1121**
	2	**54.6**	**1122**
	3	**55.6**	**1153**
	8	**56.2**	**1167**
	7	**57**	**1169**
	9	**58.2**	**1147**
Outer rods	***15***	***56.4***	**1114**
	14	63	1155
	13	65.8	1143
	11	68.2	1176
	12	68.6	1187
	17	69	1090
	18	71 (short circuit)	-
	21	73.6	1039
	10	75.2	1161
	20	75.2	1066
	19	77	1073
	16	81	1198

average burst T : 1127 ± 48 K = 854 ± 48 °C

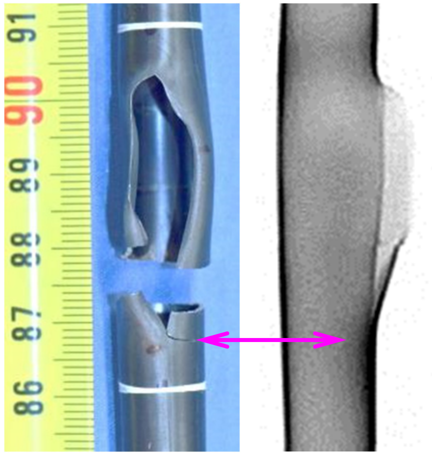
QL3HT; tensile tests (at room temperature): ruptures due to stress concentration, moderate influence of secondary hydrogenation



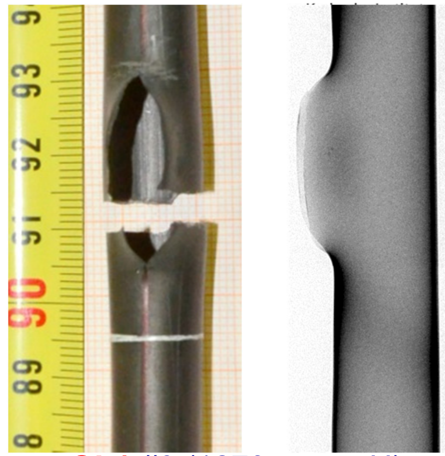
clad #13



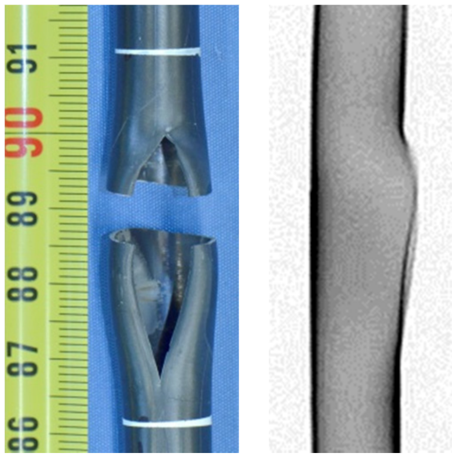
#5: crack at H band (>2000 wppm H); fracture stress 185 MPa, fracture strain 0.3%



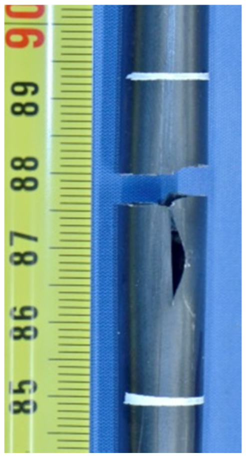
#14: crack at H spot; fracture stress 75 MPa, strain 0.1%



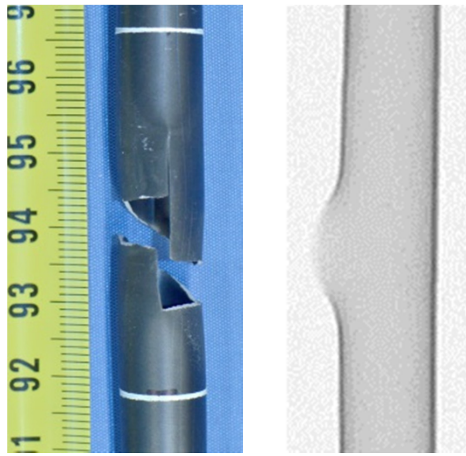
QL1 #9 (1270 wppm H): fracture stress 307 MPa, strain 0.6%



#13 stress conc. and H spot, fracture data: stress 73 MPa, strain 0.2%



#15 no H, fracture data: stress 172 MPa, strain 0.15%



#16 no H, fracture data: stress 492 MPa, strain 12%

Summary

- The first stage (transient) of the QUENCH-LOCA-3HT test was performed according to a typical LBLOCA transient with maximal heat-up rate 7.5 K/s. However, due to technical problems the transient was terminated at *not prototypical* peak cladding temperature of more than 1500 K (at bundle elevation 850 mm). As result, increased cladding oxidation was occur.
- Not prototypical increased rod bending occurred due to axial limitation of thermal expansion.
- Due to low ballooning degree the maximum of *virtual coplanar* blockage ratio of cooling channel (35%) was lower in comparison to QUENCH-L1 (46%). Due to moderate blockage a good bundle coolability was kept for both bundles.
- The cladding burst occurred at temperatures between 1030 and 1200 K; the average burst temperature was 1127 ± 48 K (QUENCH-L1: 1126 ± 33 K). The inner rod pressure relief to the system pressure during about 30 s.
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual strengths or ductility is sufficient for reflood) – consistently with previous tests.
- Five claddings were tested (one from inner rods and four from outer rods) in tensile tests and failed due to stress concentration at the burst position – similar to rods of the QUENCH-L1 bundles. Two claddings showed additionally circumferential crack propagation probably at positions of secondary tube hydrogenation.

Acknowledgment

The QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB). The optimized ZIRLO™ claddings and Zircaloy-4 spacer material was provided by Westinghouse Electric Sweden.

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

Thank you for your attention

https://www.iam.kit.edu/wpt/loca/
http://www.iam.kit.edu/wpt/471.php
http://quench.forschung.kit.edu/