Karlsruhe Institute of Technology

Institute for Applied Materials

First results of the bundle test QUENCH-L2 with M5® claddings

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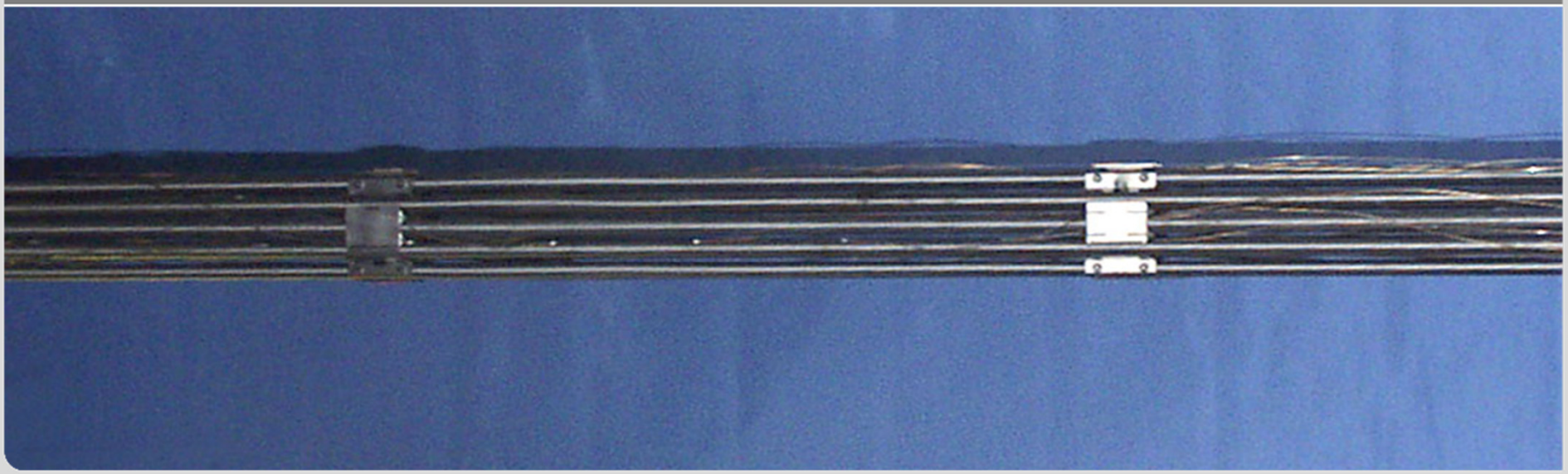
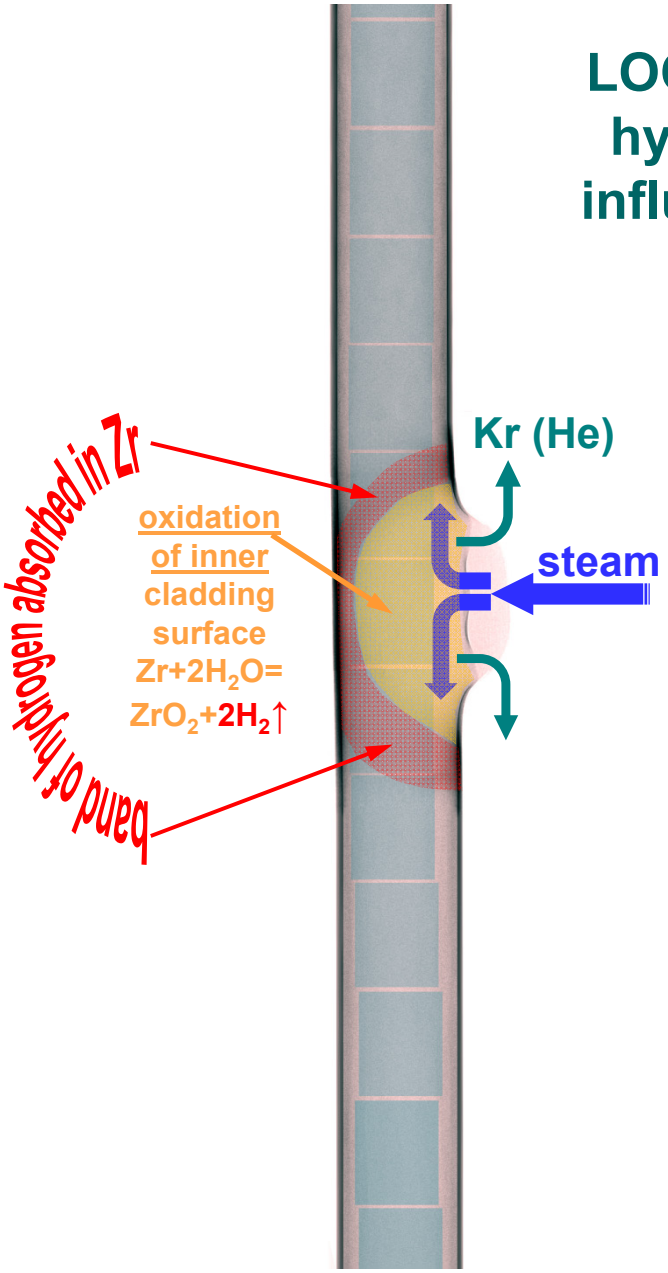
Institute for Applied Materials; Program NUKLEAR



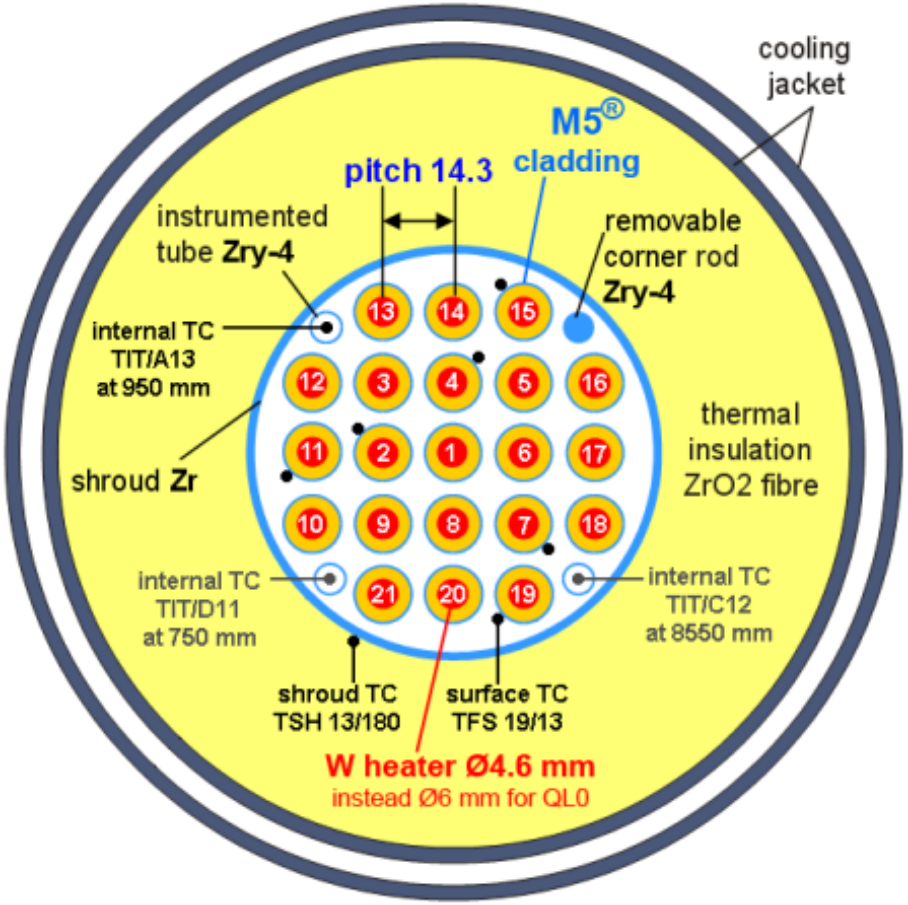
LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement



Sequence of phenomena:

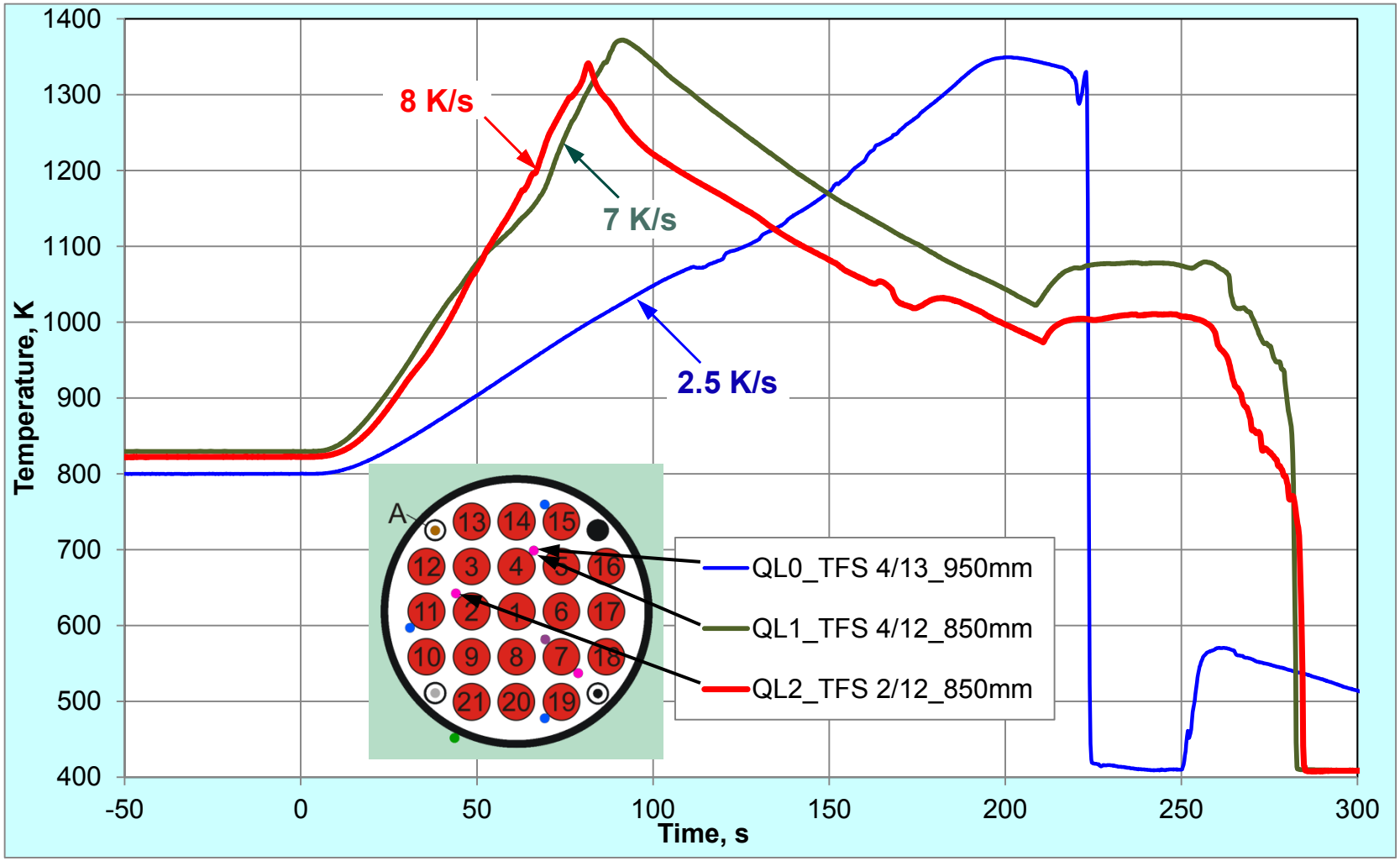
- cladding ballooning and burst, relief of inner rod pressure
- steam penetration through the burst opening, steam propagation in decreasing gap between cladding and pellet
- oxidation of inner cladding surface with hydrogen release
- absorption of hydrogen by cladding at the boundary of inner oxidised 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-L2 bundle



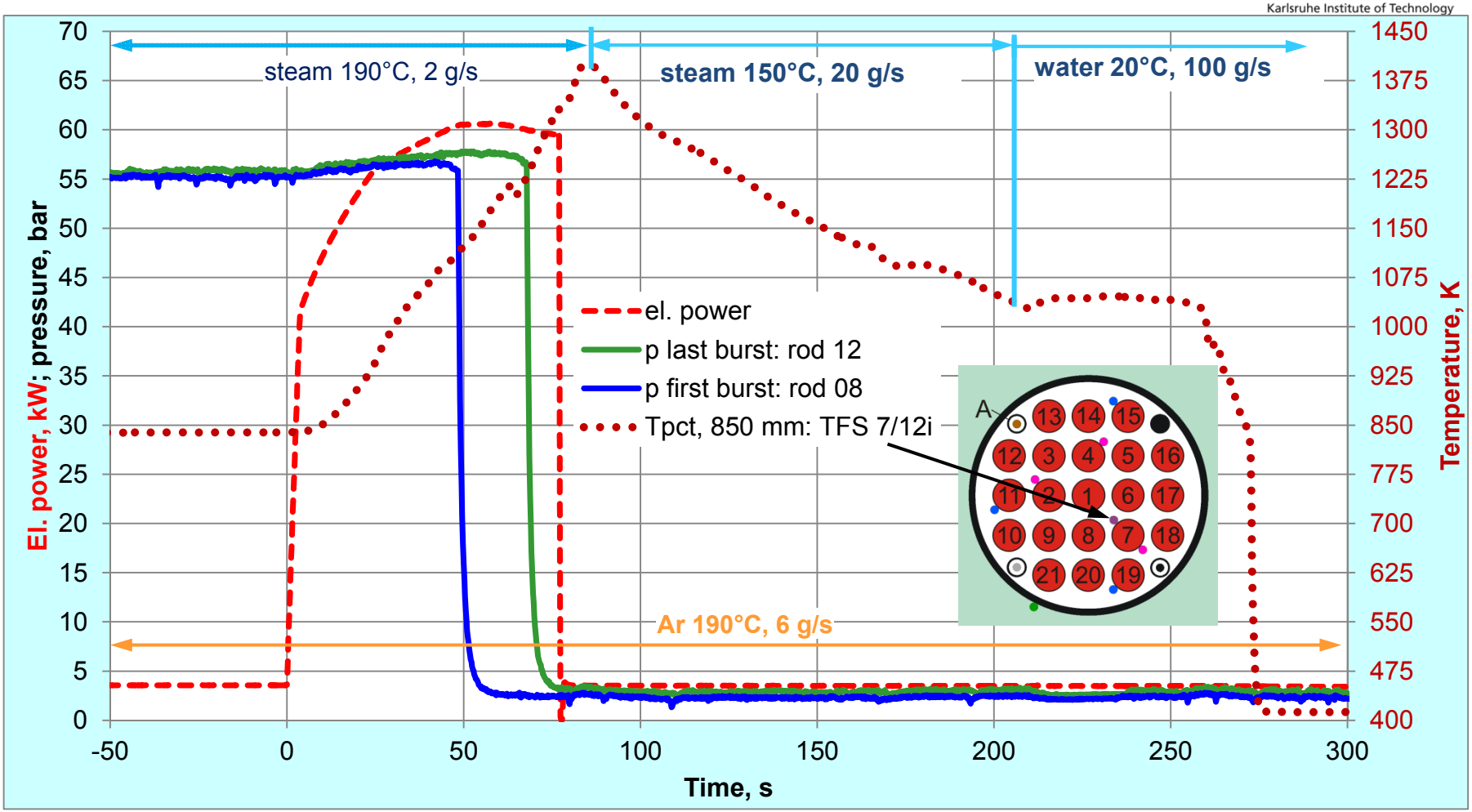
1) The use of ***tungsten*** heaters with smaller diameter (***4.6 mm***) instead tungsten heaters (QUENCH-L0) or tantalum heaters (QUENCH-L1) with diameter of 6 mm has allowed to reach a **higher heat rate**.
2) All rods are filled with Kr with p=55 bar at Tpct=800 K (similar to QUENCH-L1).

Maximal cladding temperatures of internal rods in hottest region of QUENCH-L0, -L1 and -L2 bundles



similar temperature histories for QUENCH-L1 (reference, Zry-4) and -L2 (M5®)

Scenario of the QUENCH-L2 test



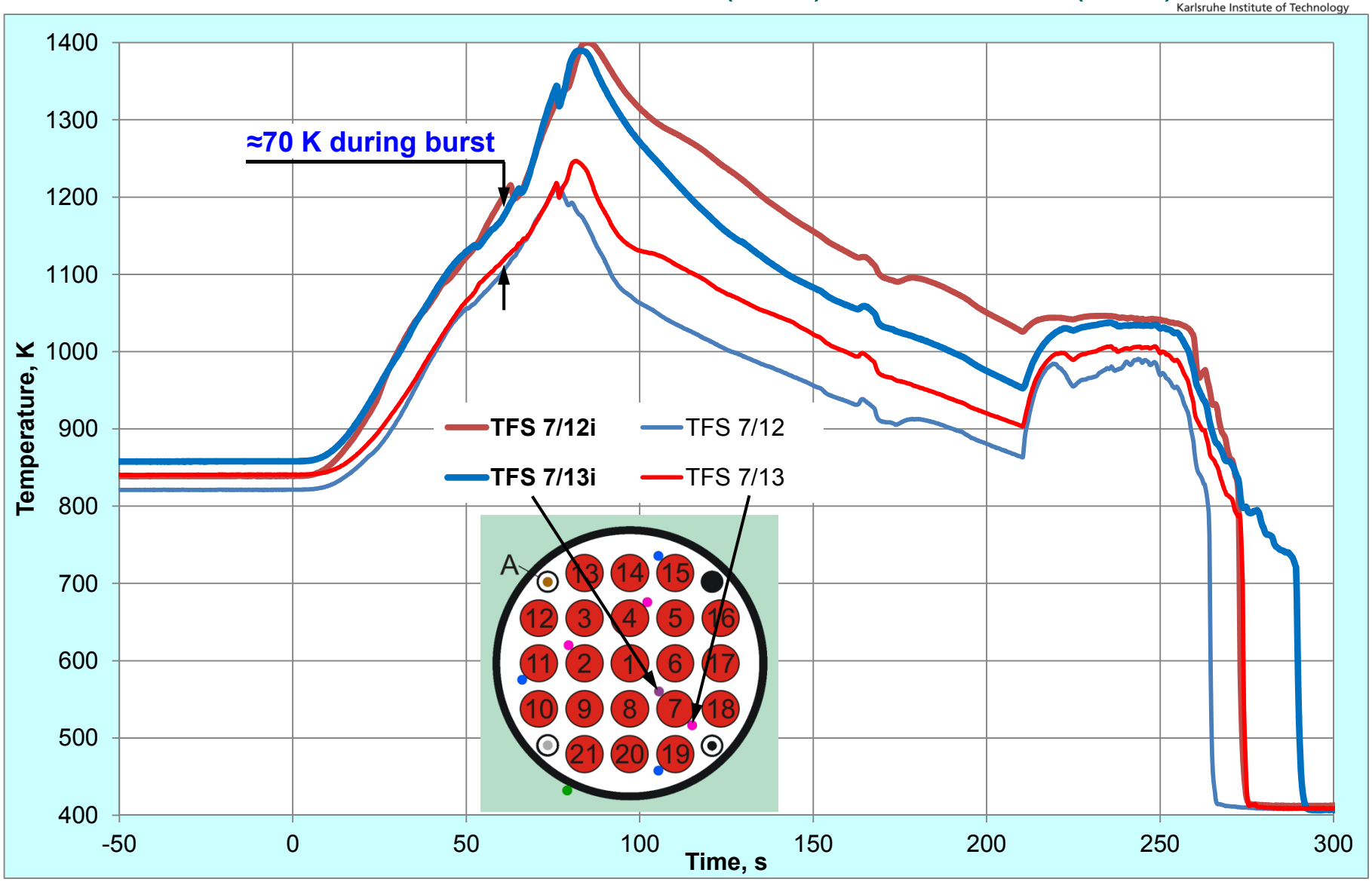
maximal reached power:

QUENCH-L1 (Ta-heaters, Ø 6 mm): 58.5 kW,

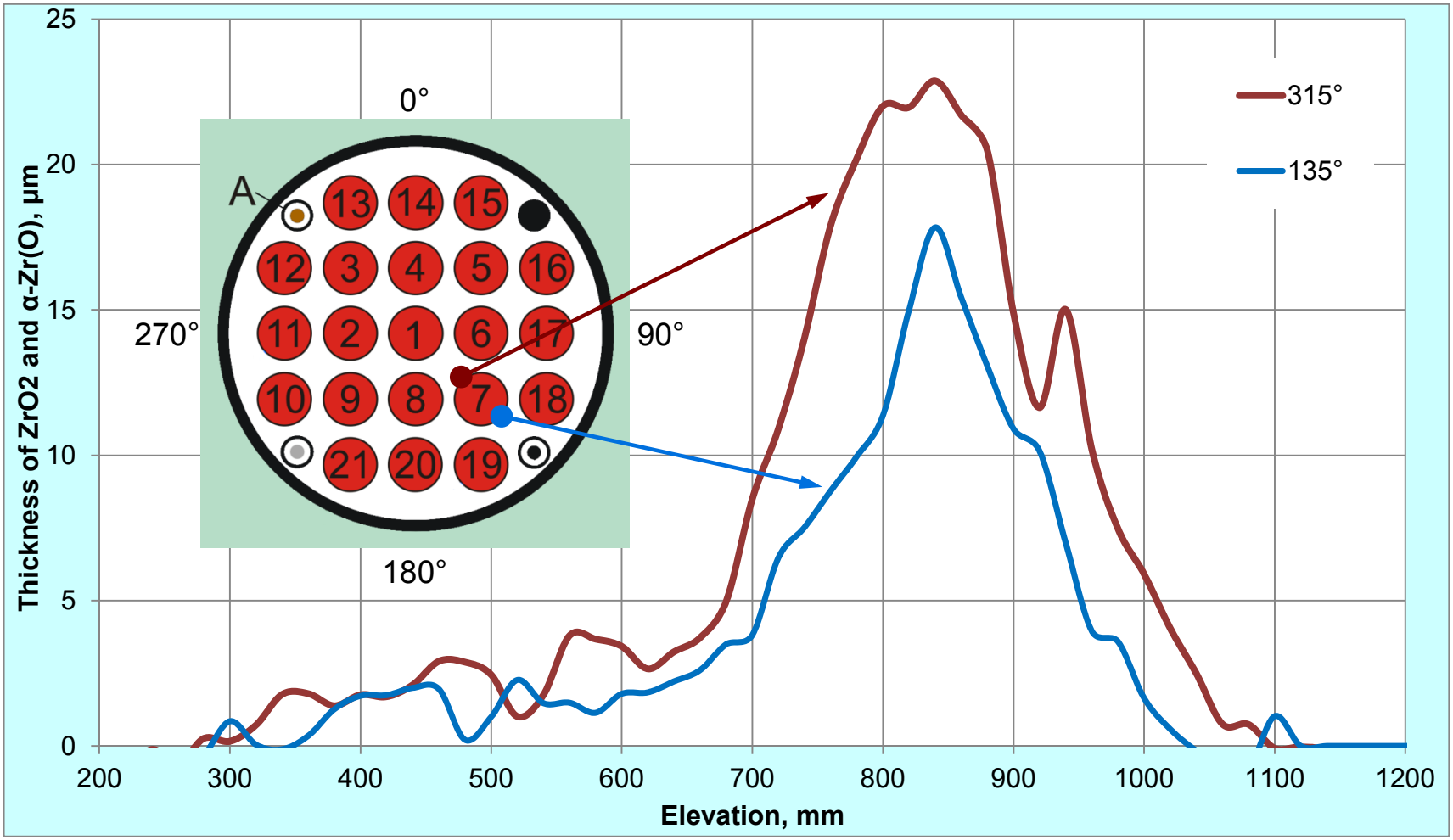
QUENCH-L2 (W-heaters; Ø 4.6 mm): 60.5 kW

QL2: circumferential temperature gradient

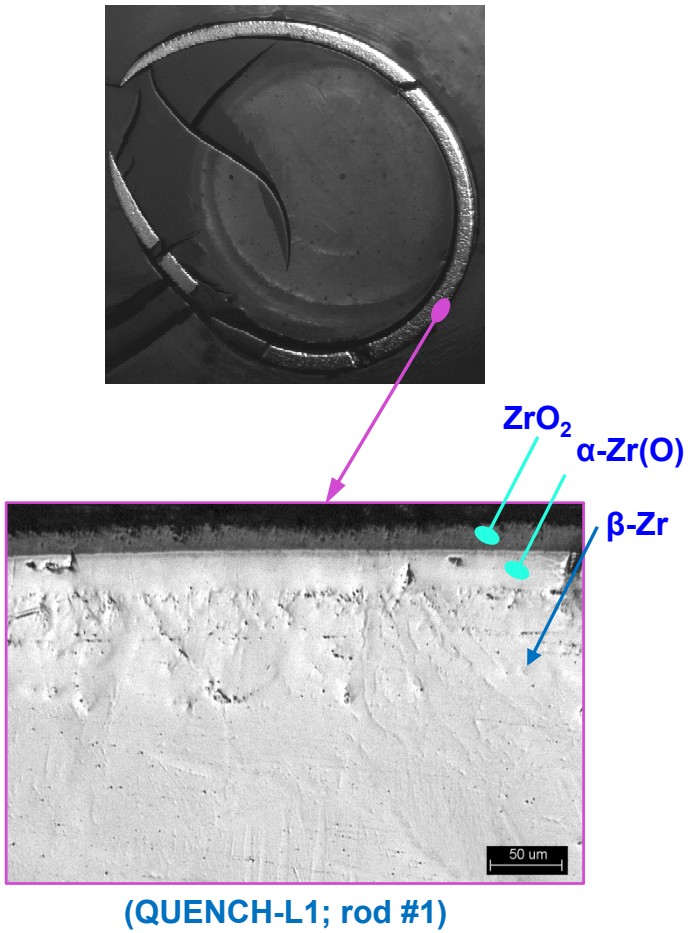
for rod #7 at hottest elevations 850 mm (7/12) and 950 mm (7/13)



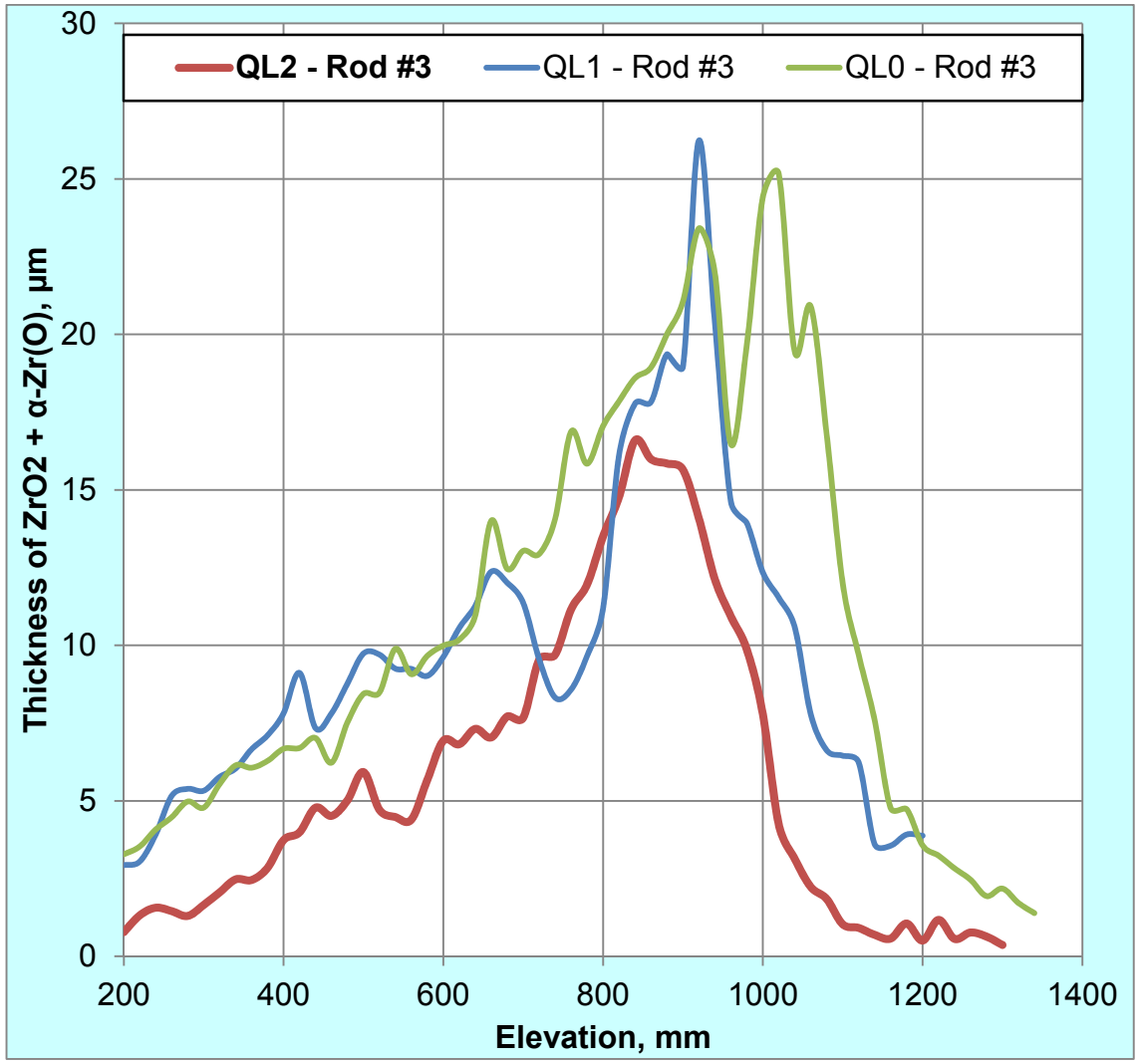
QL2: circumferential oxidation gradient (post-test eddy current measurements)



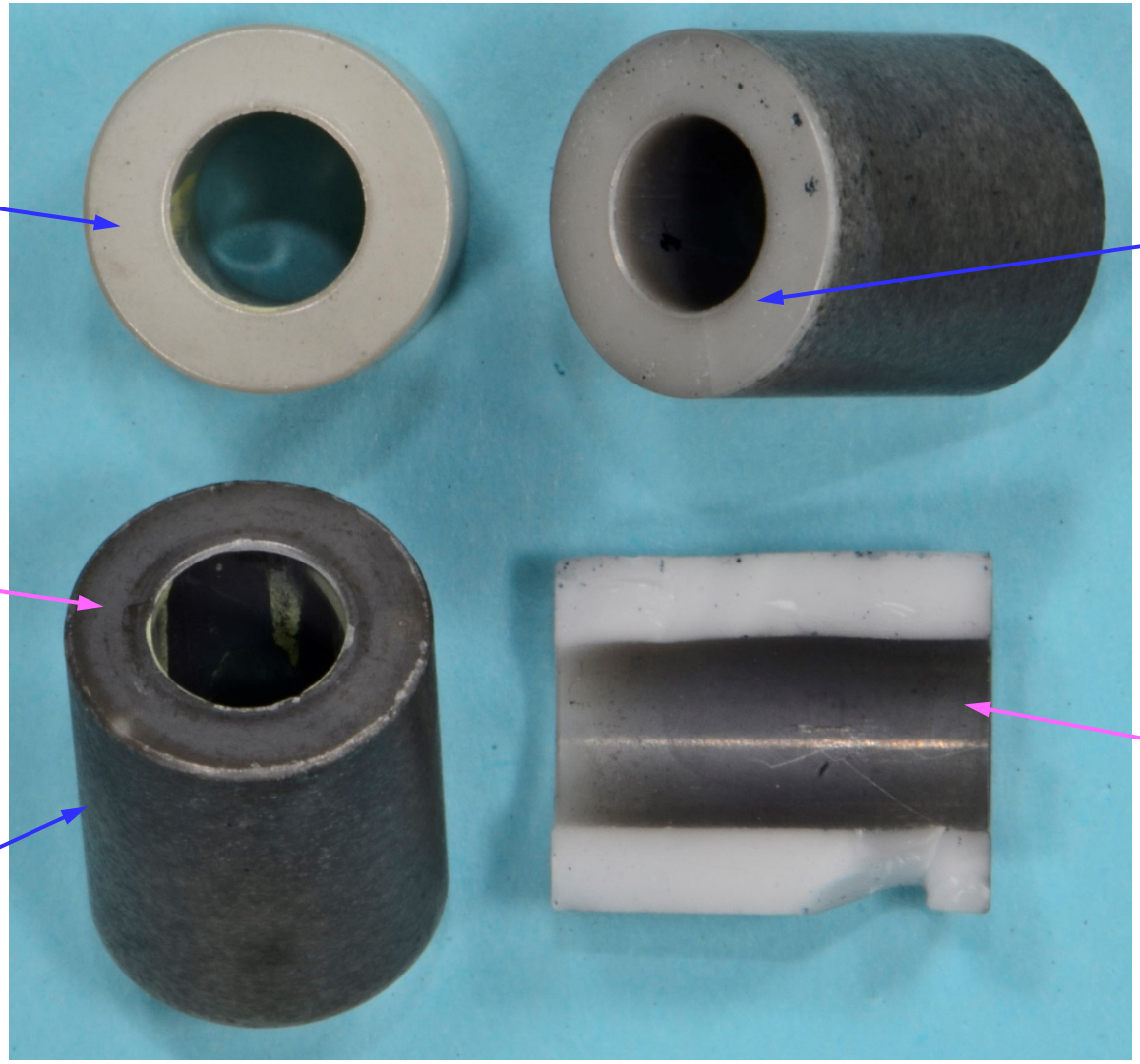
Cladding oxidation degree: total thickness of outer ZrO_2 and α-Zr(O) layers (tangential average of eddy-current measurements)



(QUENCH-L1; rod #1)



Metal-vapour-phase deposition on the pellet surface



original ZrO_2 pellet

post-test ZrO_2 pellet good contacted with adjacent pellet: negligible coating of frontal surface

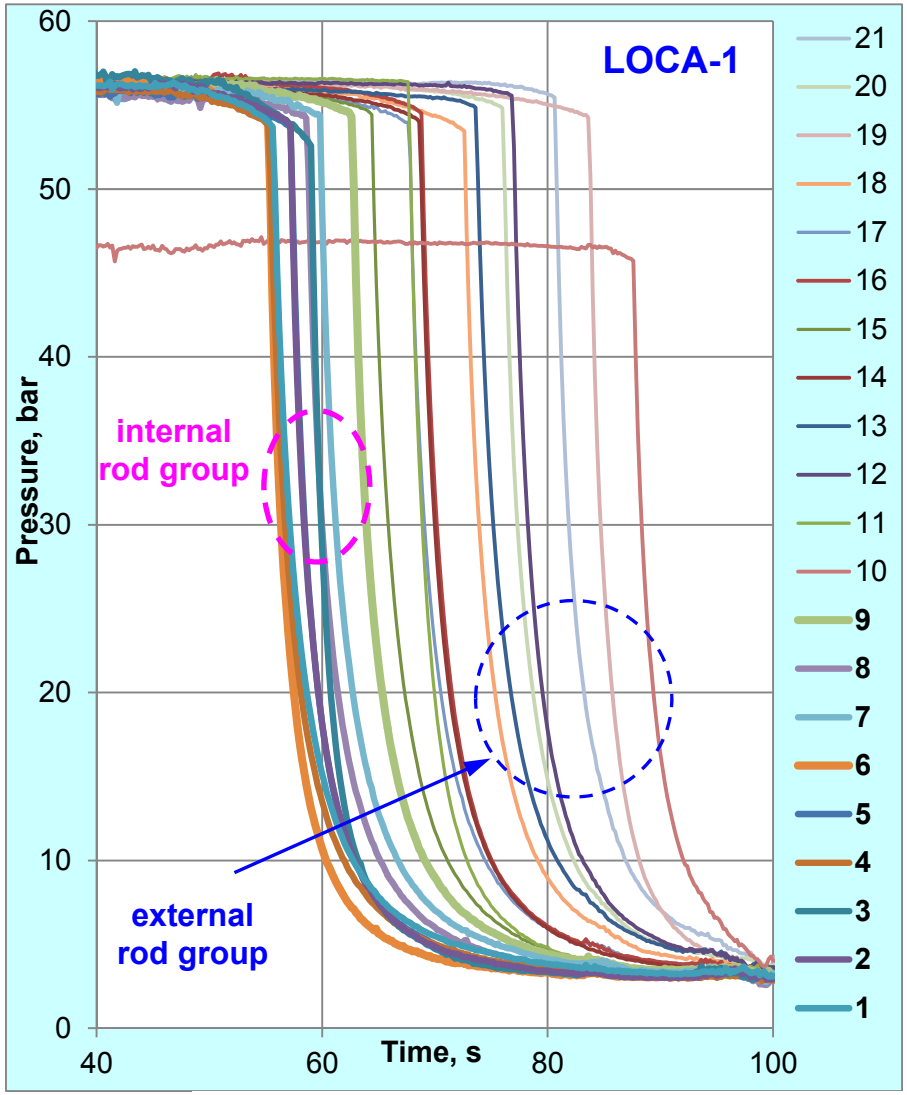
post-test ZrO_2 pellet with large gap to adjacent pellet: significant coating of frontal surface

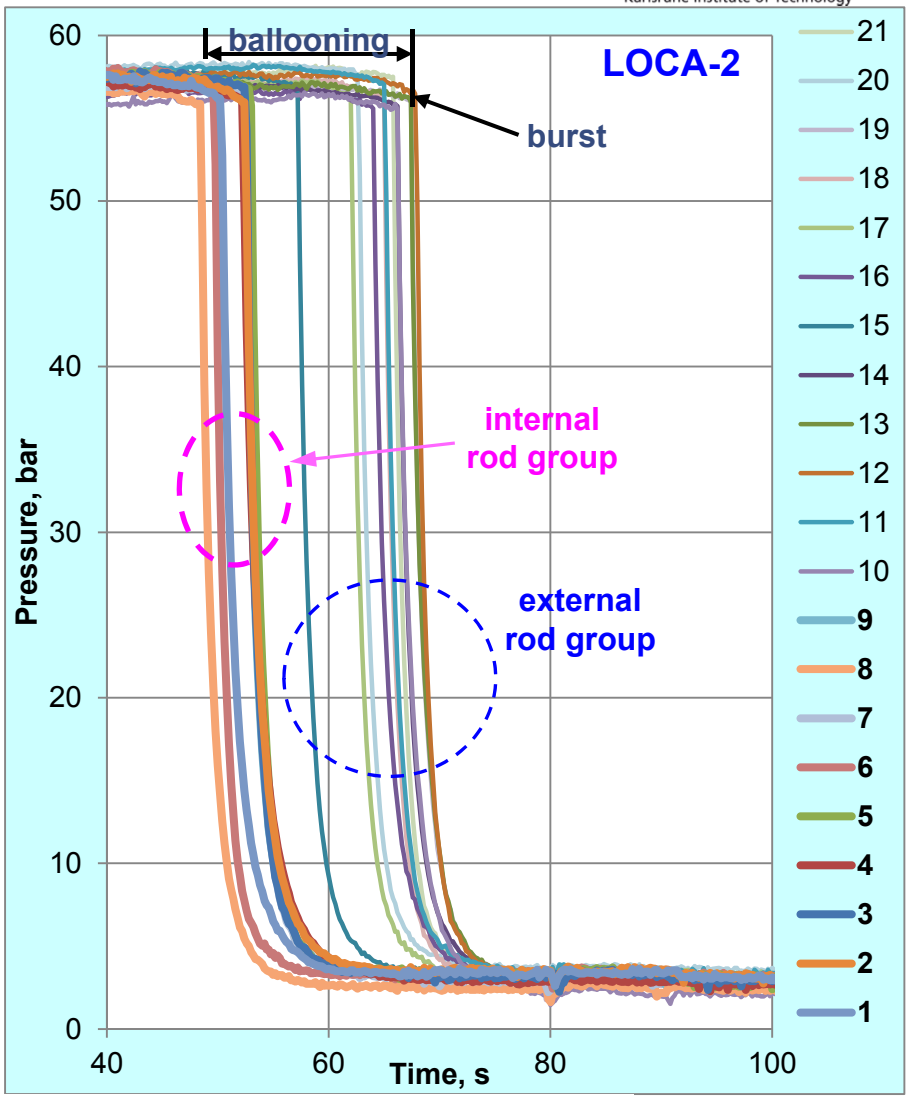
(deposition of W and Zr)

deposition of Zr

deposition of W at inner surface of cracked pellet

Rod pressure evolution during heating phase for QUENCH-L1 and -L2: burst time indication (coincided with MS results on Kr release)





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

Post-test QL2 bundle view between GS3 and GS4: rod bending

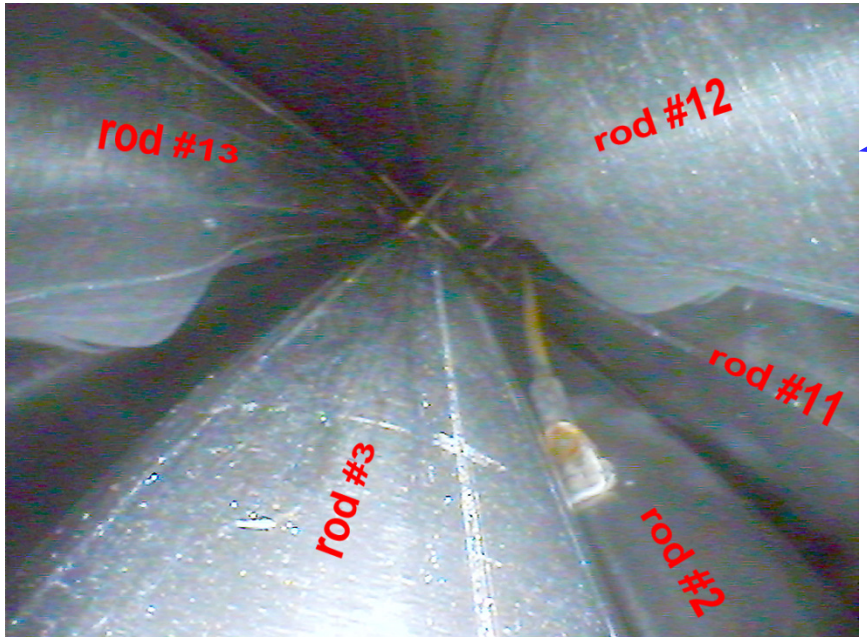
0°

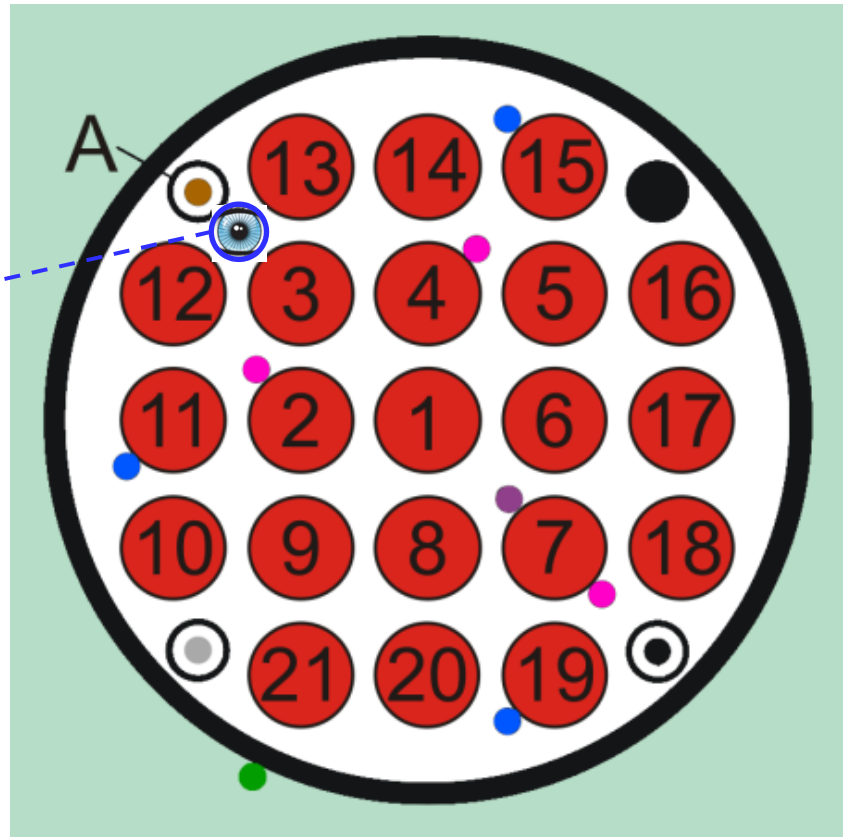
90°

180°

270°

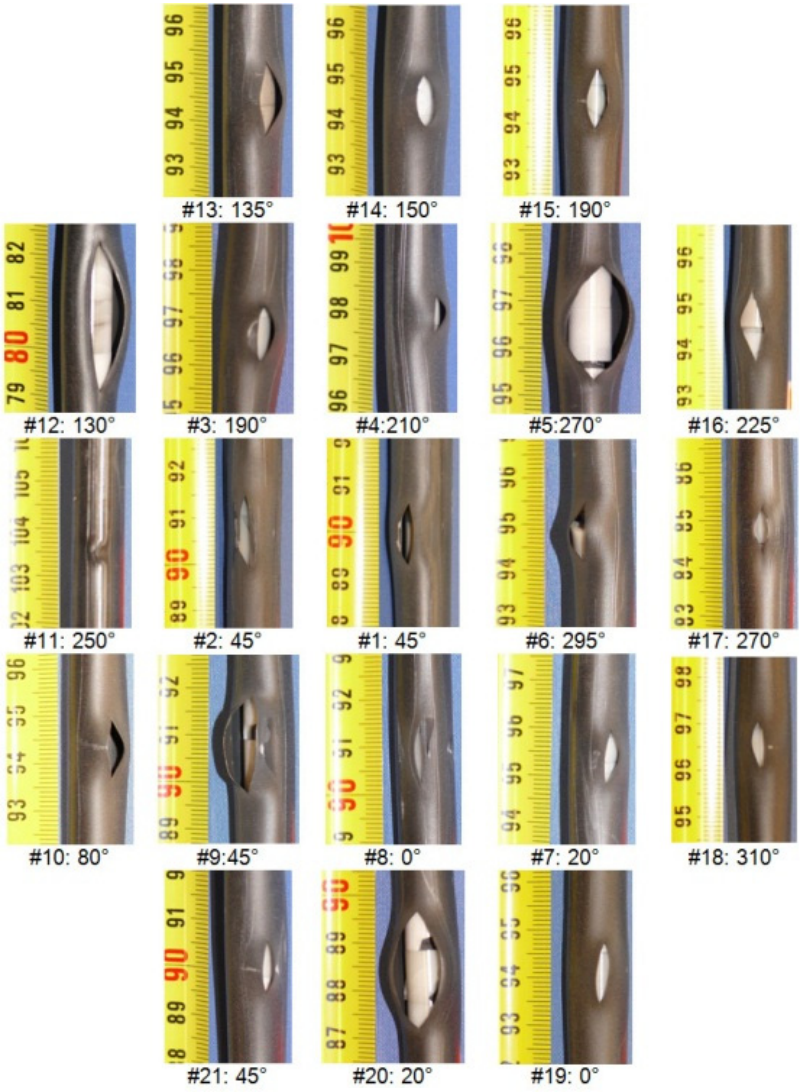
QL2: videoscope observations



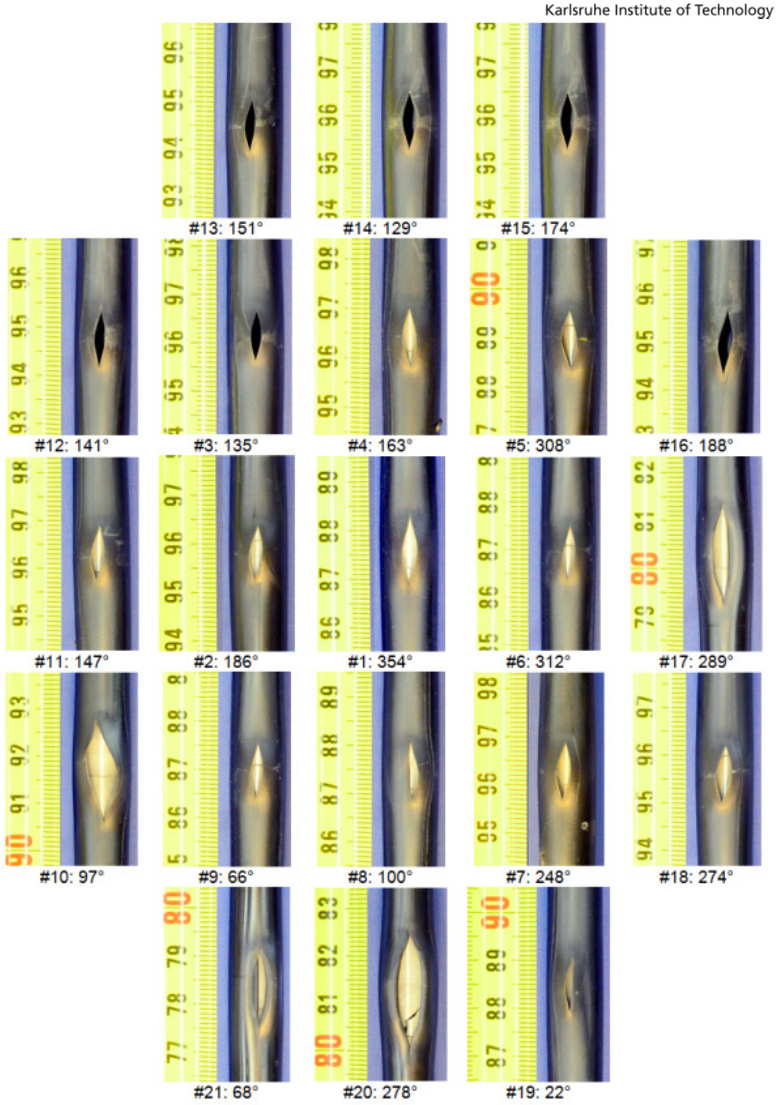


ballooning and burst of cladding tubes at elevation 950 mm

Overview of burst openings

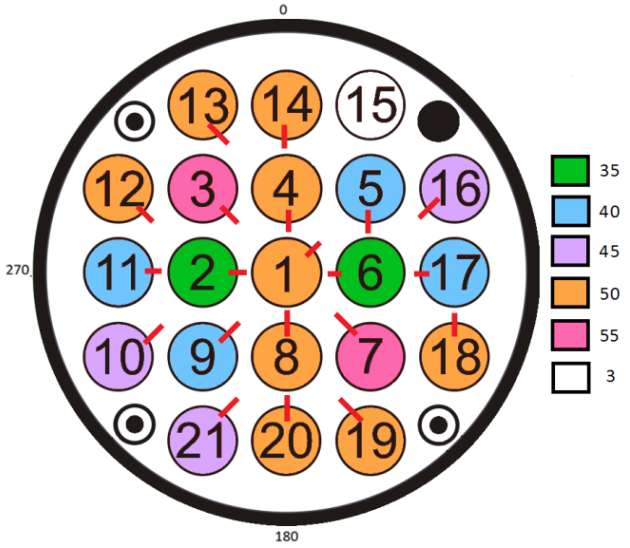


LOCA-1

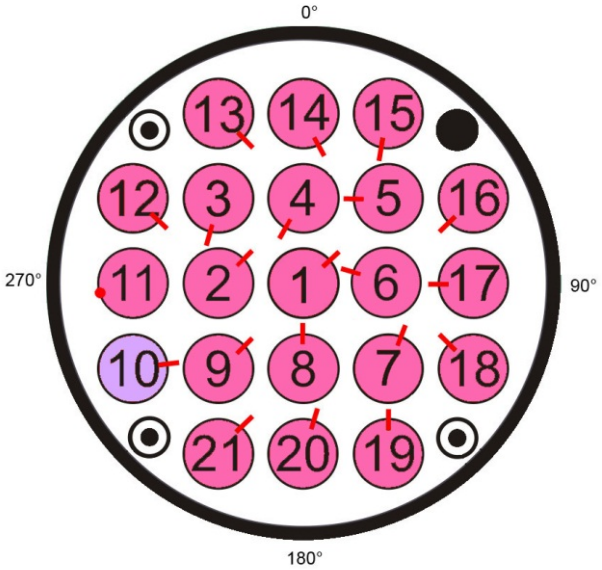


LOCA-2

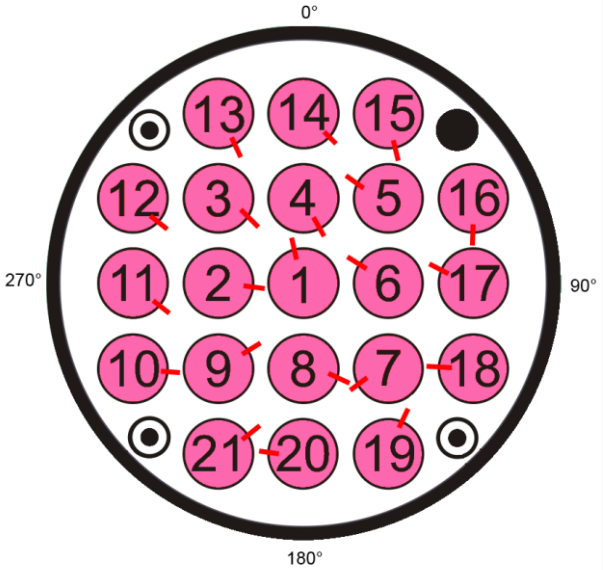
Circumferential position of burst openings



LOCA-0:
openings oriented to bundle center due to strong radial T gradient



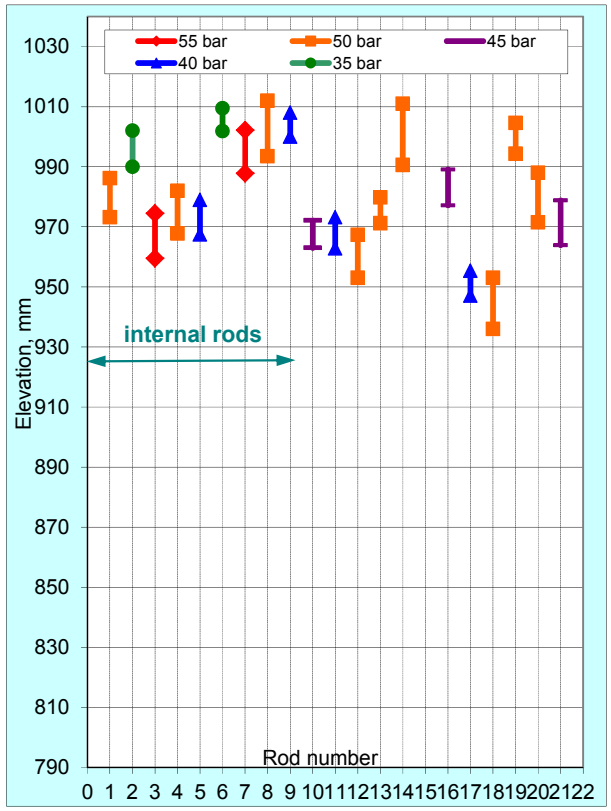
LOCA-1:
not strong orientation to bundle center



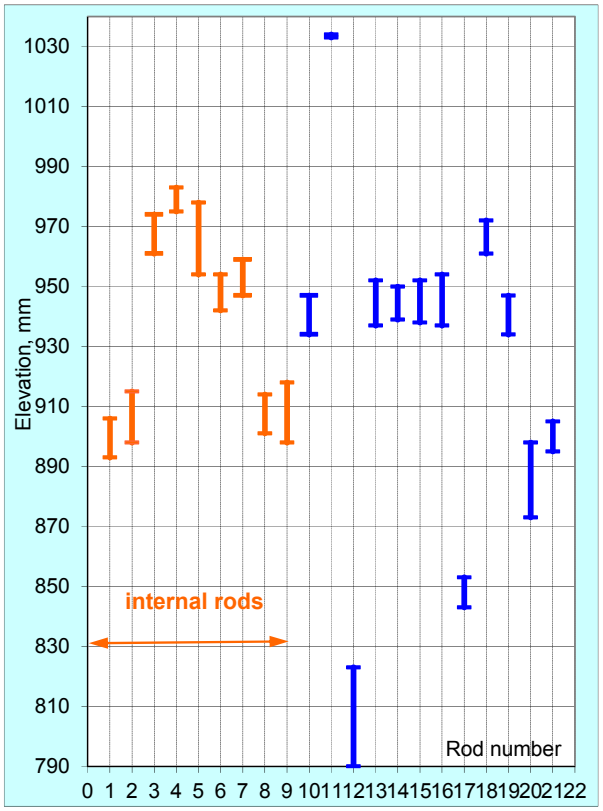
LOCA-2:
similar to LOCA-1 excluding adjacent rods 7, 8, 20

Length and axial position of burst openings

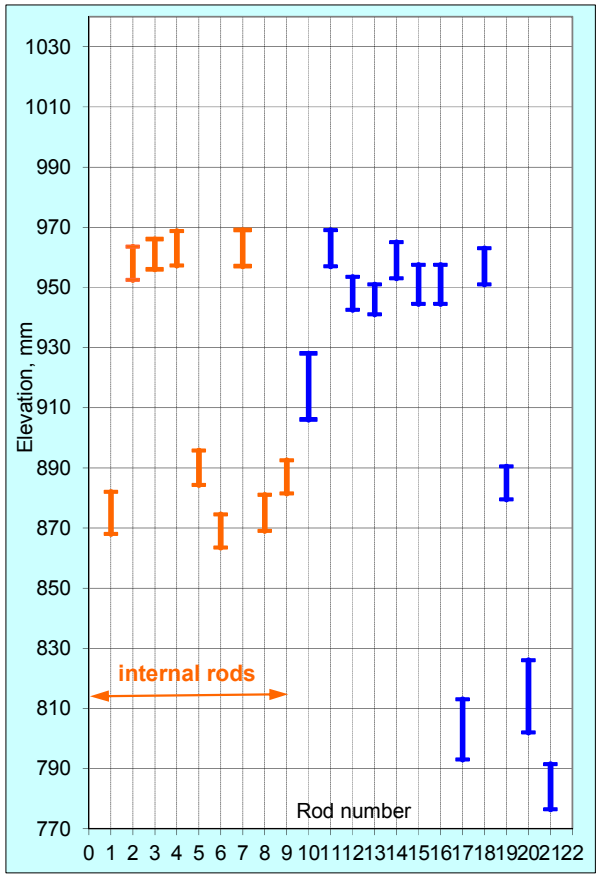
LOCA-0



LOCA-1



LOCA-2



Burst-Parameters

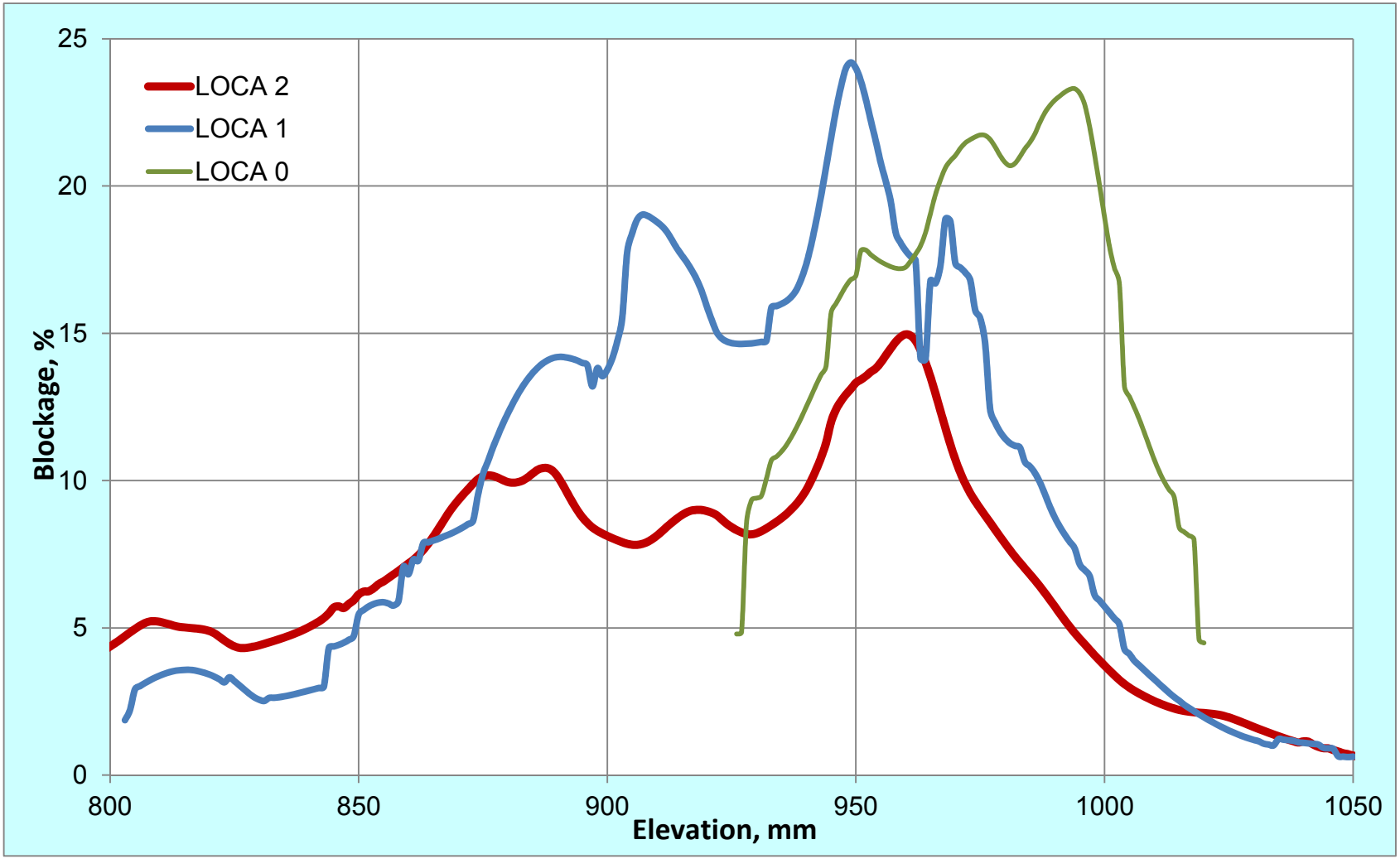
LOCA-1

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

LOCA-2

Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	**8**	**48.4**	**1113**
	6	**49.8**	**1121**
	1	**50.4**	**1135**
	4	**52.4**	**1167**
	2	**52.6**	**1167**
	9	**52.7**	**1162**
	3	**52.7**	**1168**
	7	**52.9**	**1136**
	5	**53.1**	**1163**
Outer rods	15	57.2	1124
	17	62	1102
	20	62.8	1110
	16	64	1143
	18	65	1139
	11	65	1145
	21	65.8	1050 (Min)
	10	66.2	1125
	14	66.2	1167
	13	67.4	1178
	19	67.4	1093
	12	67.8	1195 (Max)

Cooling channel blockage for LOCA-0, LOCA-1 and LOCA-2



Summary

- Test QUENCH-LOCA-2 test was performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR with maximal heat-up rate 8 K/s, cooling phase lasted 120 s and terminated with 3.3 g/s/rod water flooding.
- The maximum temperature of 1400 K was reached on the end of the heat-up phase at elevation 850 mm. Tangential temperature gradient across a rod was up to 70 K on the burst onset.
- Due to low ballooning degree the maximum blockage ratio of cooling channel (15% at 960 mm) was lower in comparison to QUENCH-L0 and -L1 (about 23%). Due to moderate blockage a good bundle coolability was kept for all three bundles.
- The cladding burst occurred at temperatures between 1050 and 1195 K (similar to QUENCH-L1). The inner rod pressure relief to the system pressure during about 35 s (similar to QUENCH-L0 and -L1).
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual ductility is sufficient).
- The first two experiments (QUENCH-L0 and -L1) show that formation of hydrogen-containing bands is expected first above 930°C. The corresponding studies for QUENCH-L2 are in progress.

Acknowledgment

The QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB).

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

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