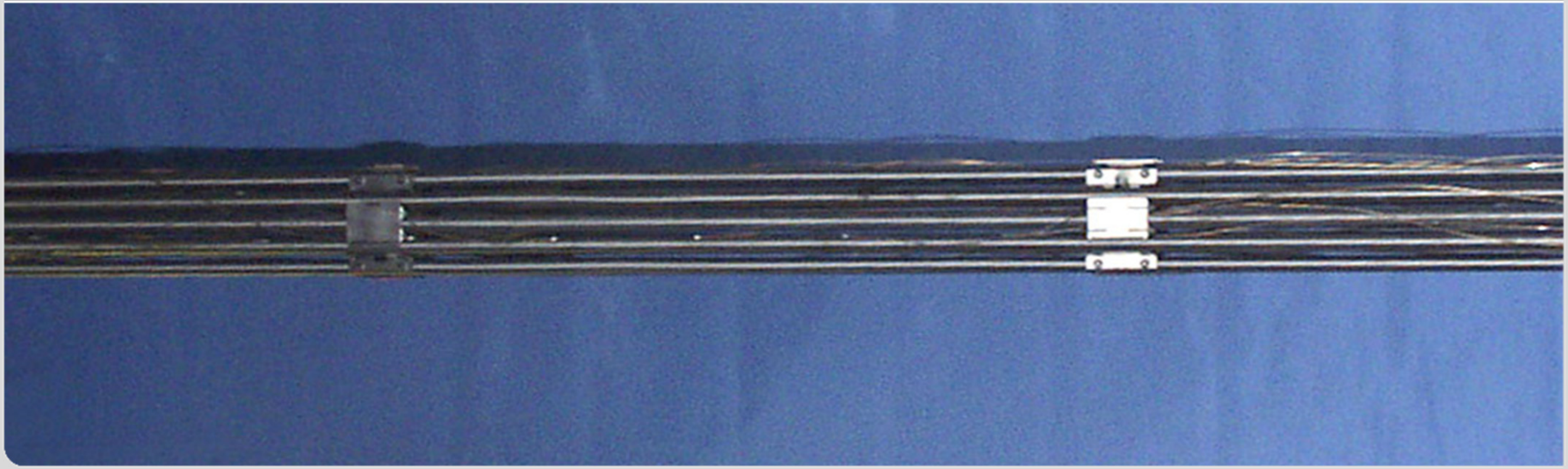
First results of the bundle test QUENCH-L4 with hydrogenated M5® claddings

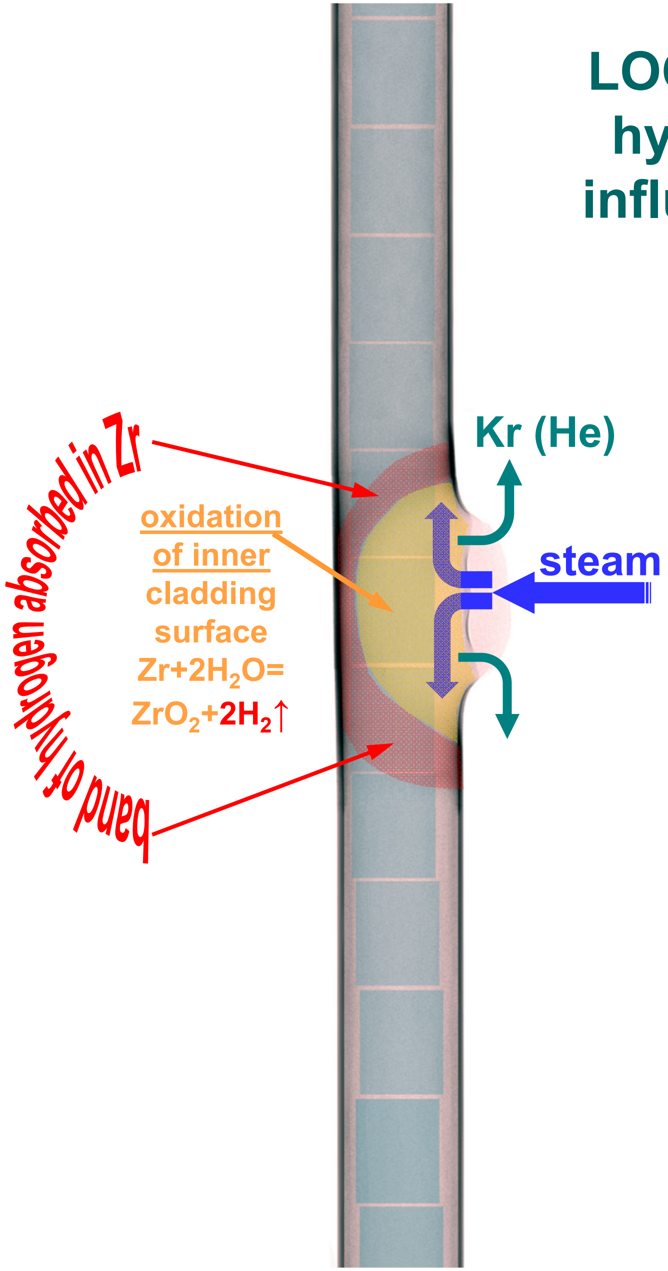
J. Stuckert, M. Große, J. Moch, C. Rössger, M. Steinbrück

QWS20, Karlsruhe 2014

Institute for Applied Materials; Program NUKLEAR



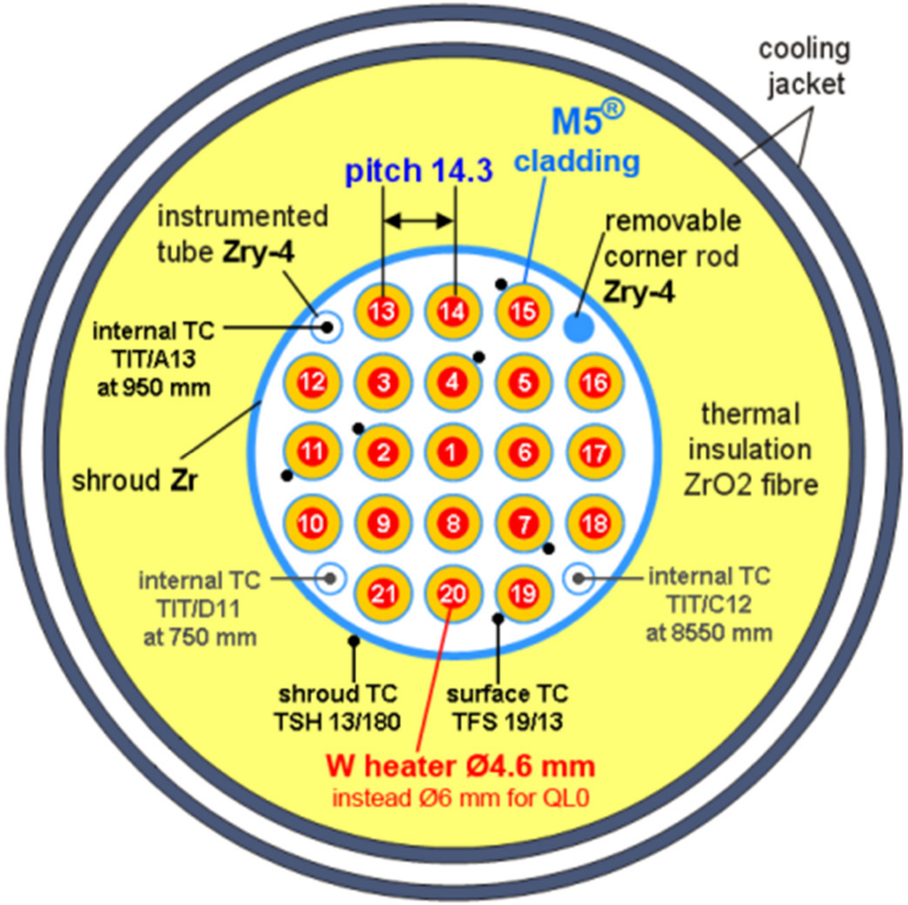
LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement



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

QUENCH-L4: test with hydrogenated claddings



Features of bundles QL2 (fresh M5®) and QL4 (pre-hydrogenated M5®):

1) The use of tungsten heaters with smaller diameter (4.6 mm) instead tungsten heaters (QUENCH-L0) 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.

QUENCH-L4: test with hydrogenated claddings

21 pre-hydrogenated tubes (100 wppm H), each welded from 3 segments with lengths 500,1200, 500 mm

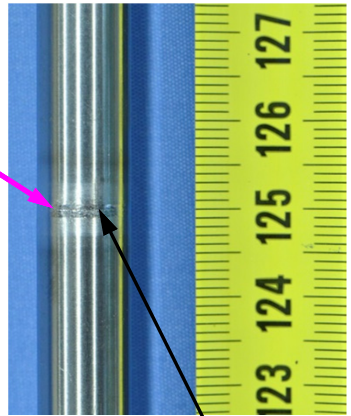
Zry-4 spacer 1410 mm

Zry-4 spacer 1050 mm

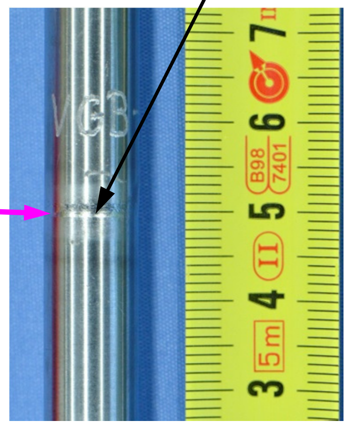
Zry-4 spacer 550 mm

Zry-4 spacer 150 mm

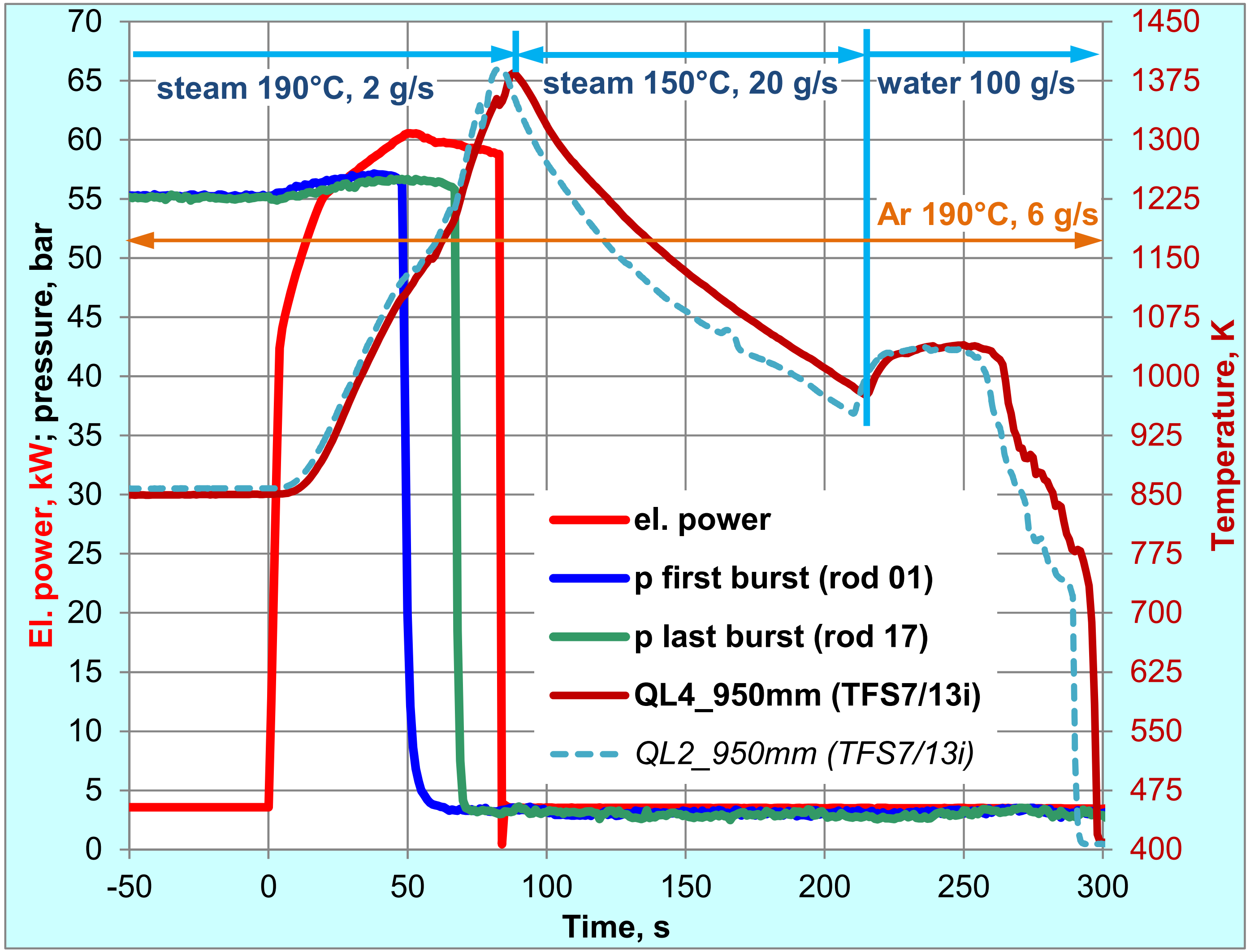
Inconel spacer -100 mm

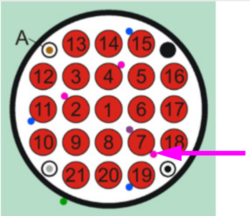


welded joints

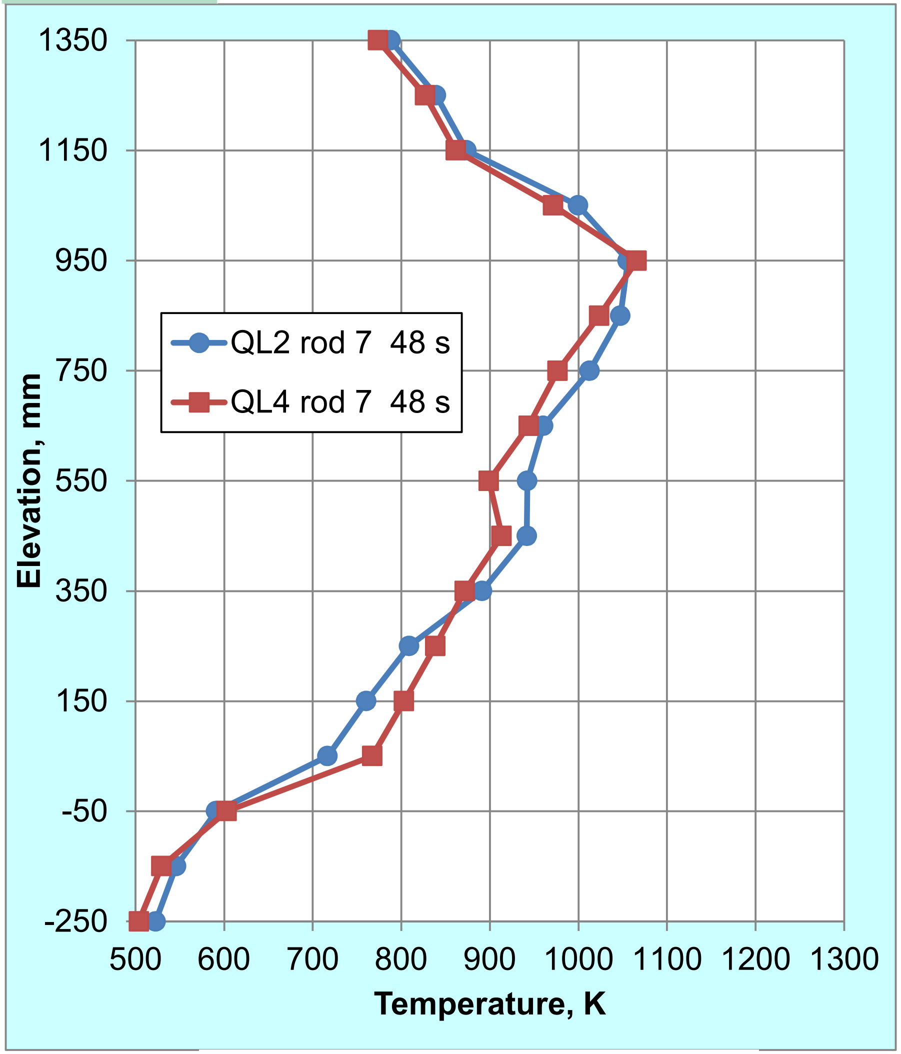


QUENCH-L4: test progress.
Comparison with QUENCH-L2 temperature.

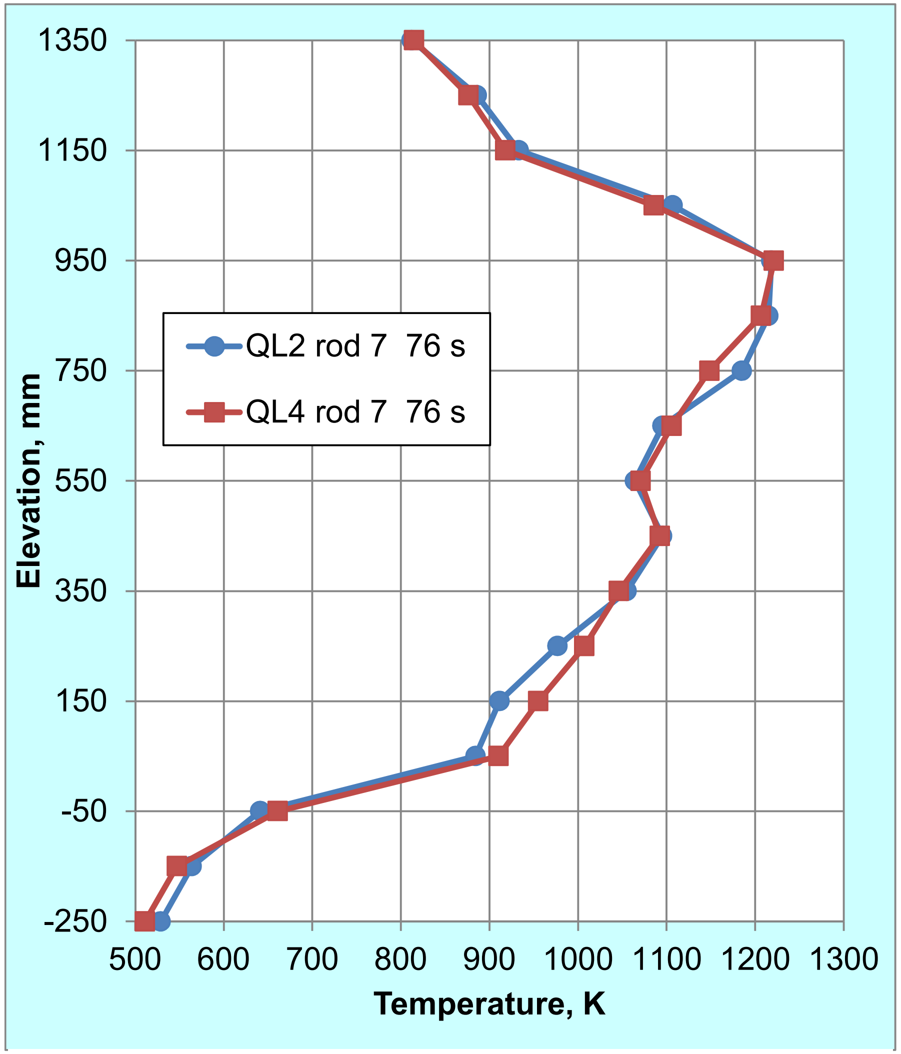




QL2 and QL4: similar axial temperature distribution for inner rod

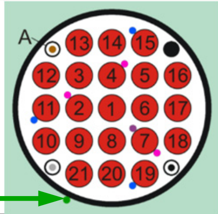


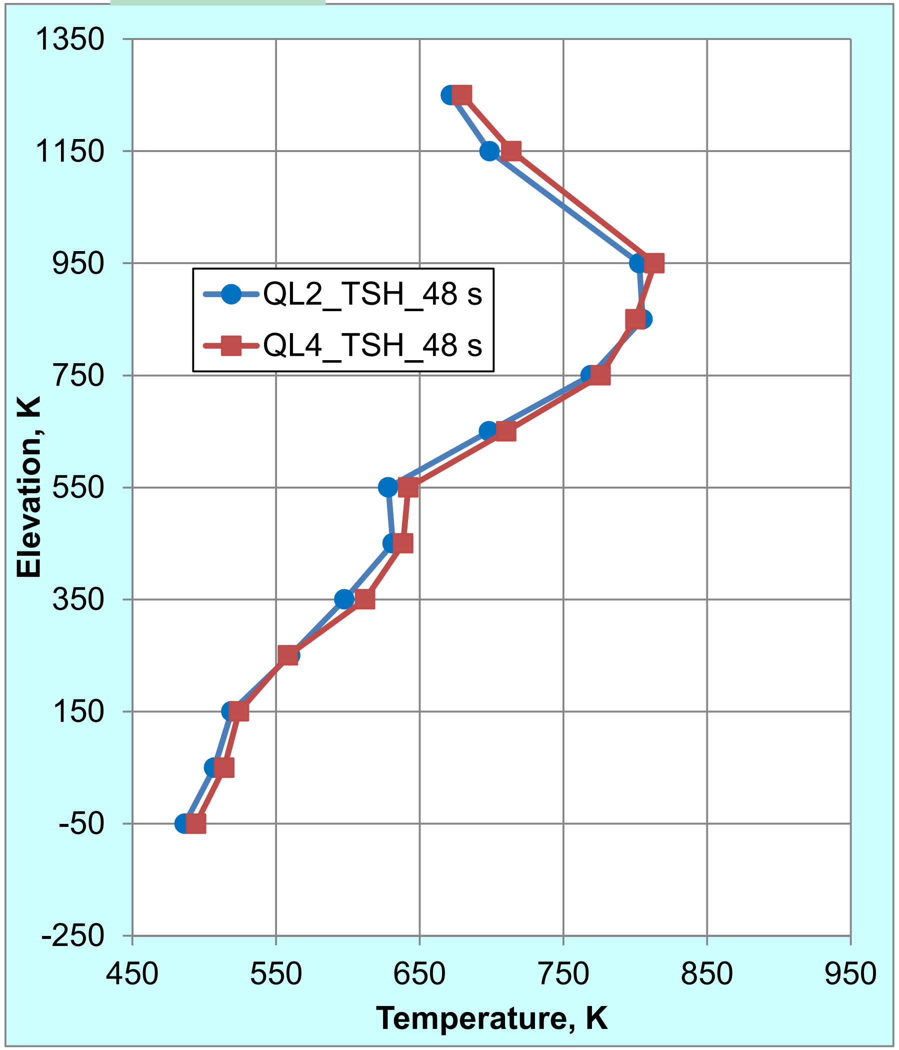
on first cladding burst (t = 48 s)



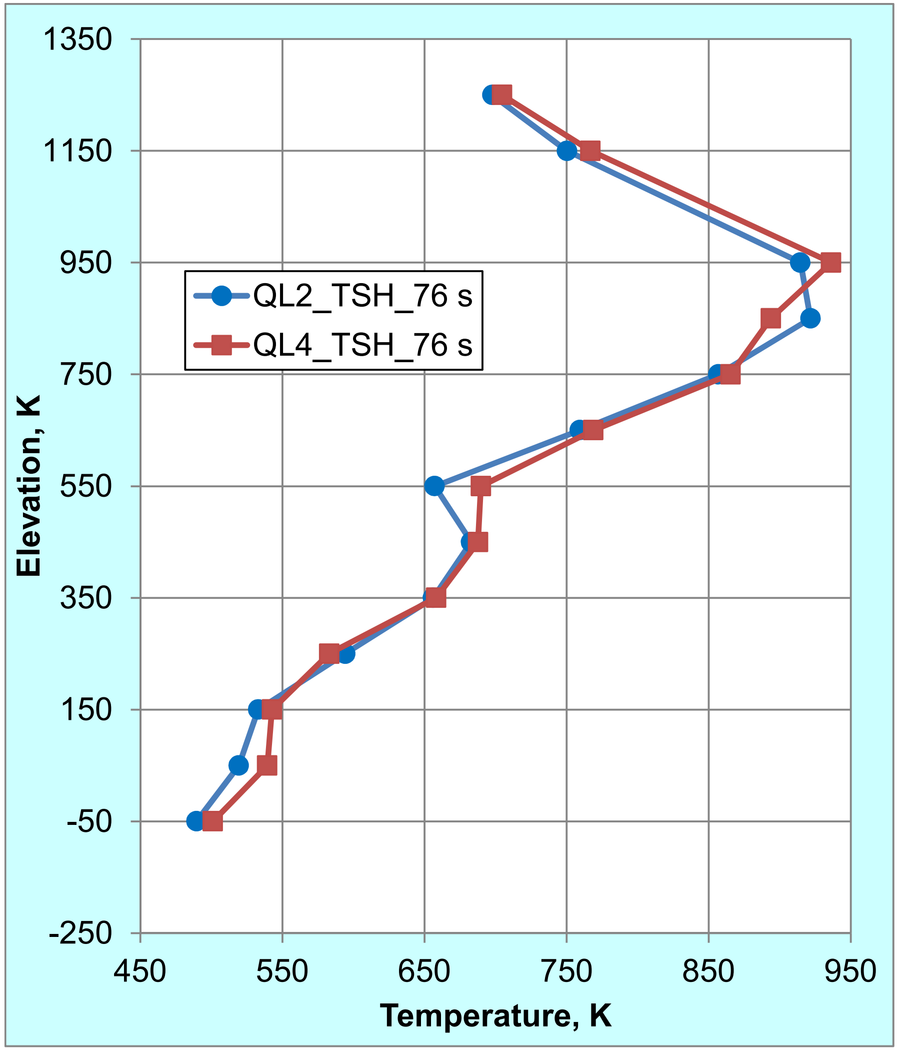
on the end of transition (power switch on t = 76 s)

QL2 and QL4: axial temperature distribution for shroud; $T_{QL4} - T_{QL2} \approx$ 15…20 K



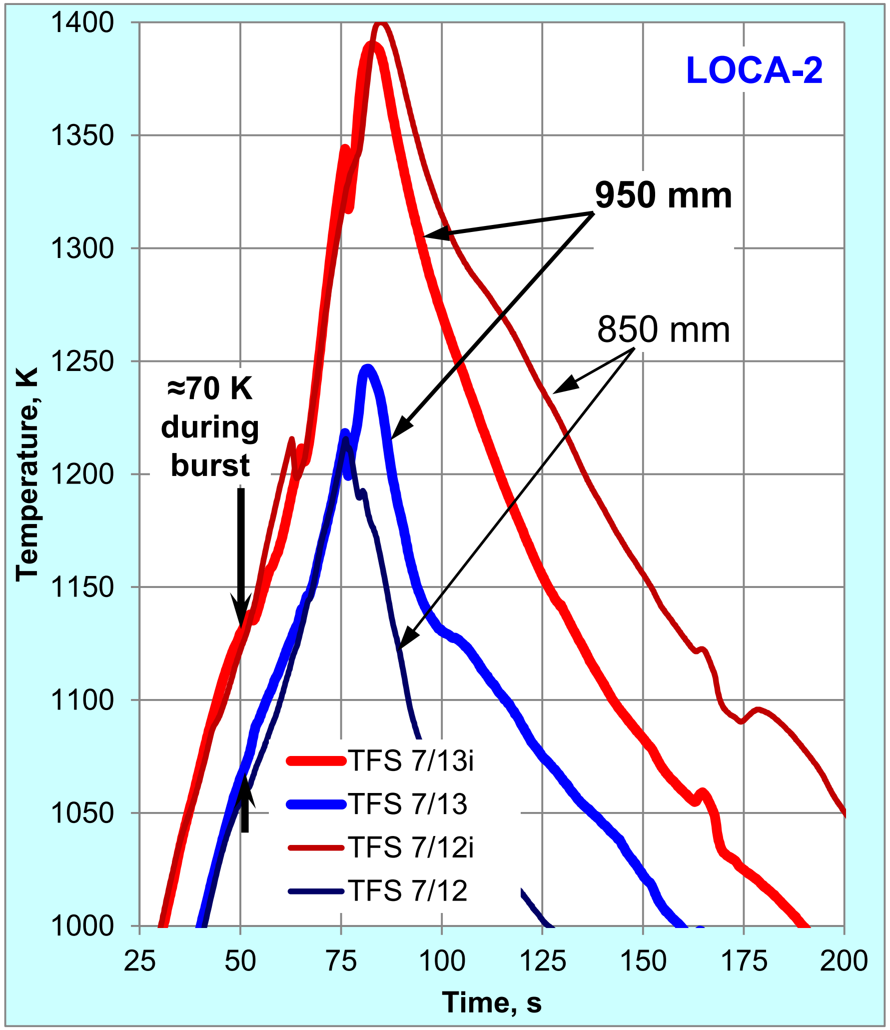


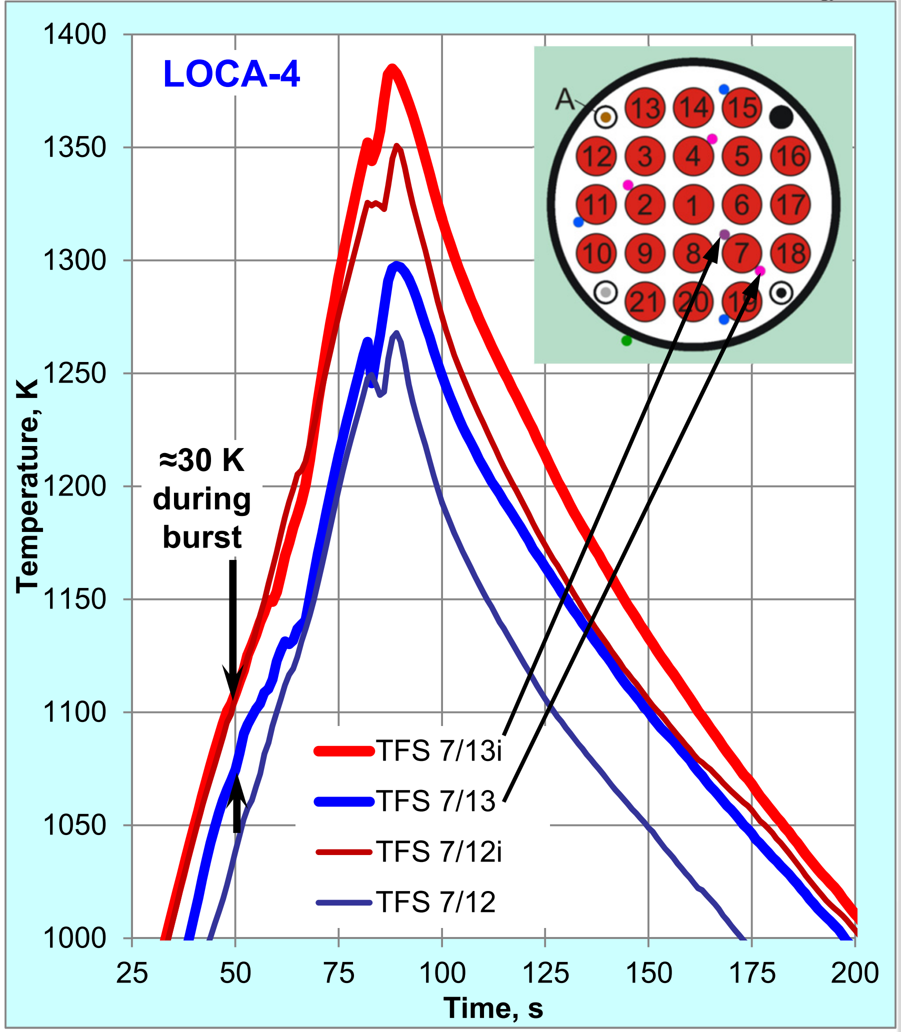
on first cladding burst (t = 48 s)



on the end of transition (power switch on t = 76 s)

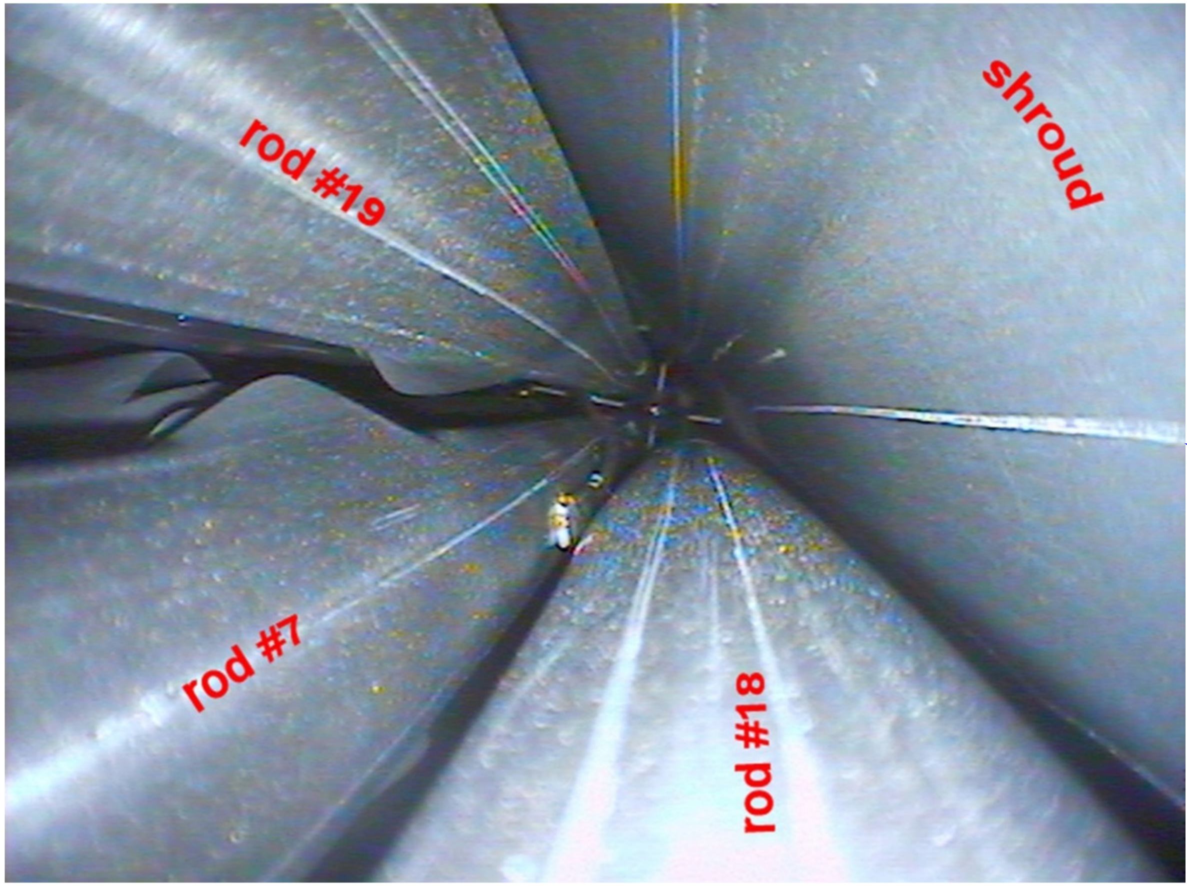
QL2 and QL4: radial temperature gradient
for rod #7 at hottest elevations 850 mm (7/12) and 950 mm (7/13)

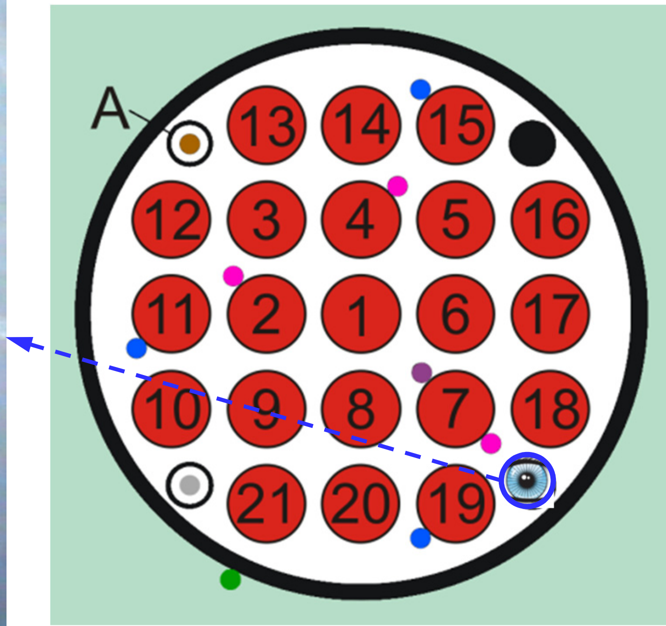




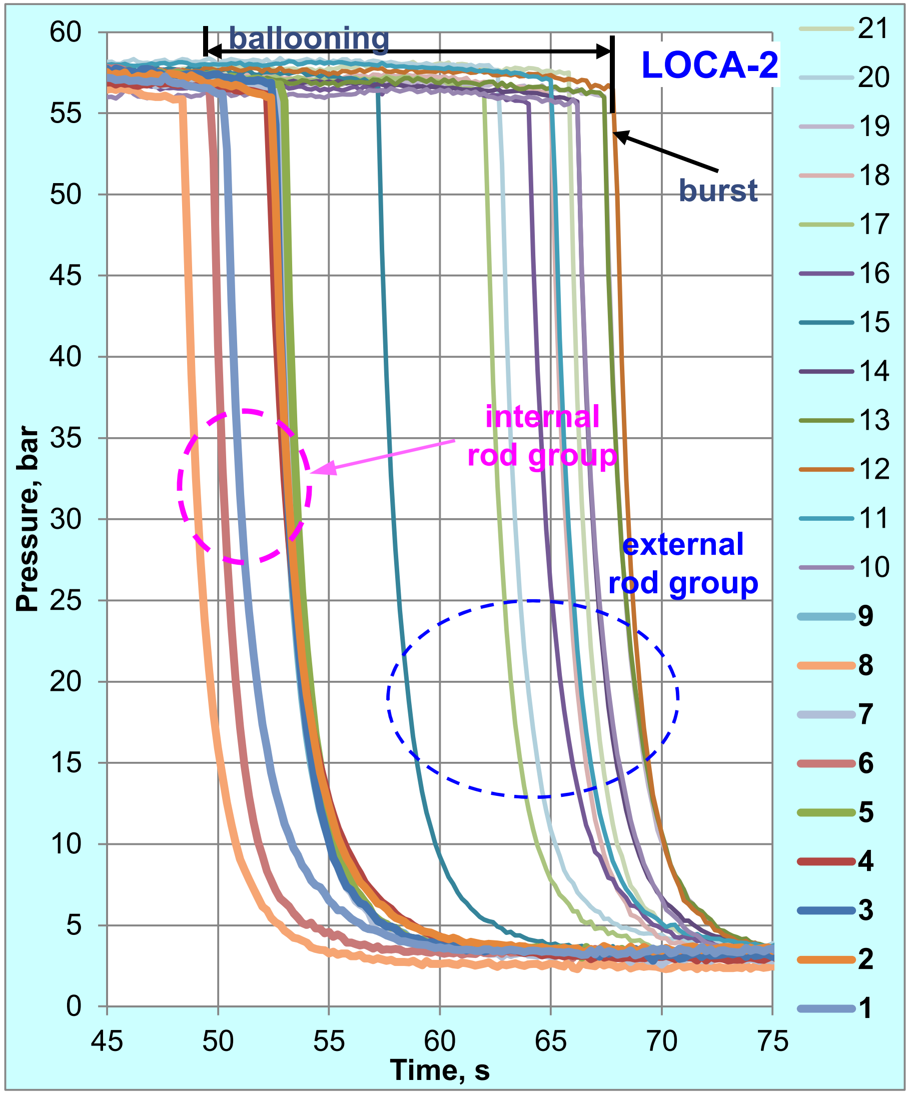
Lower radial temperature gradient for the LOCA-4 bundle due to decreased heat lost through the heat insulation; as result – more homogeneous radial conditions for ballooning and burst processes

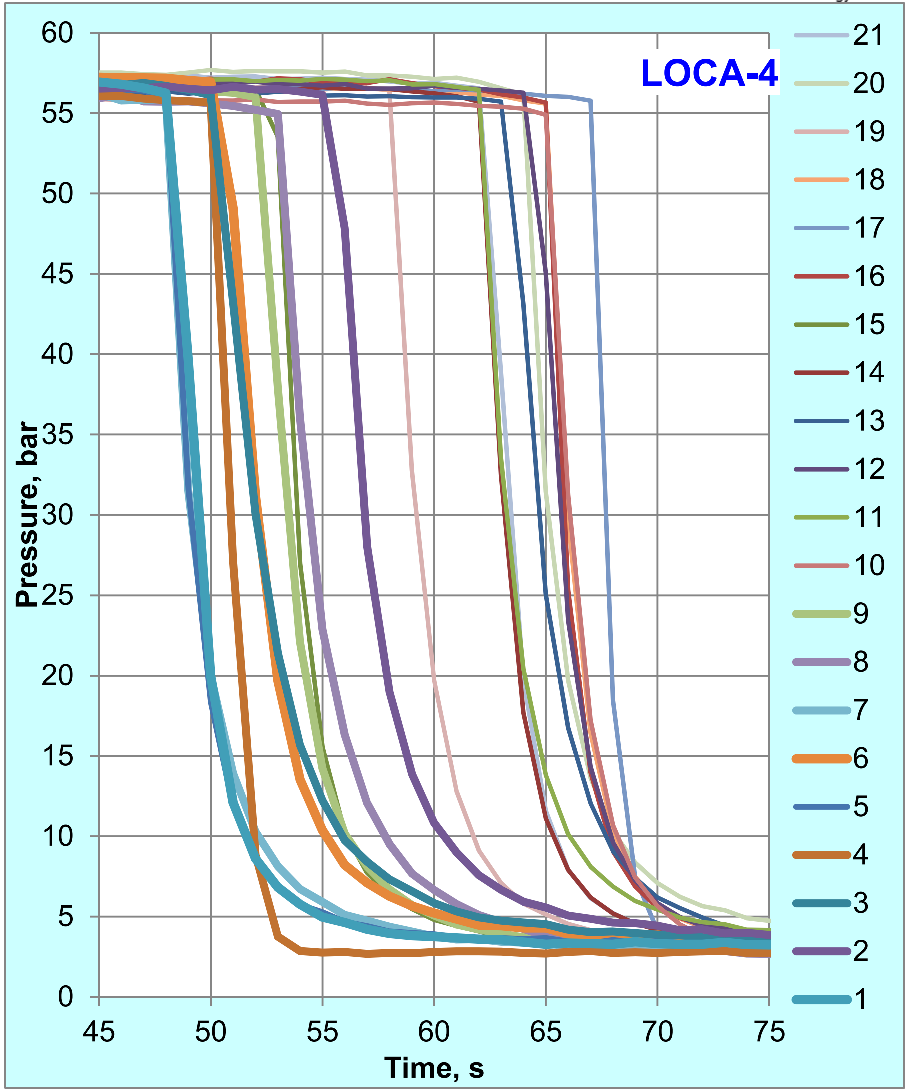
QUENCH-L4: Ballooning and burst of cladding tubes at elevations 930 - 950 mm (videoscope)





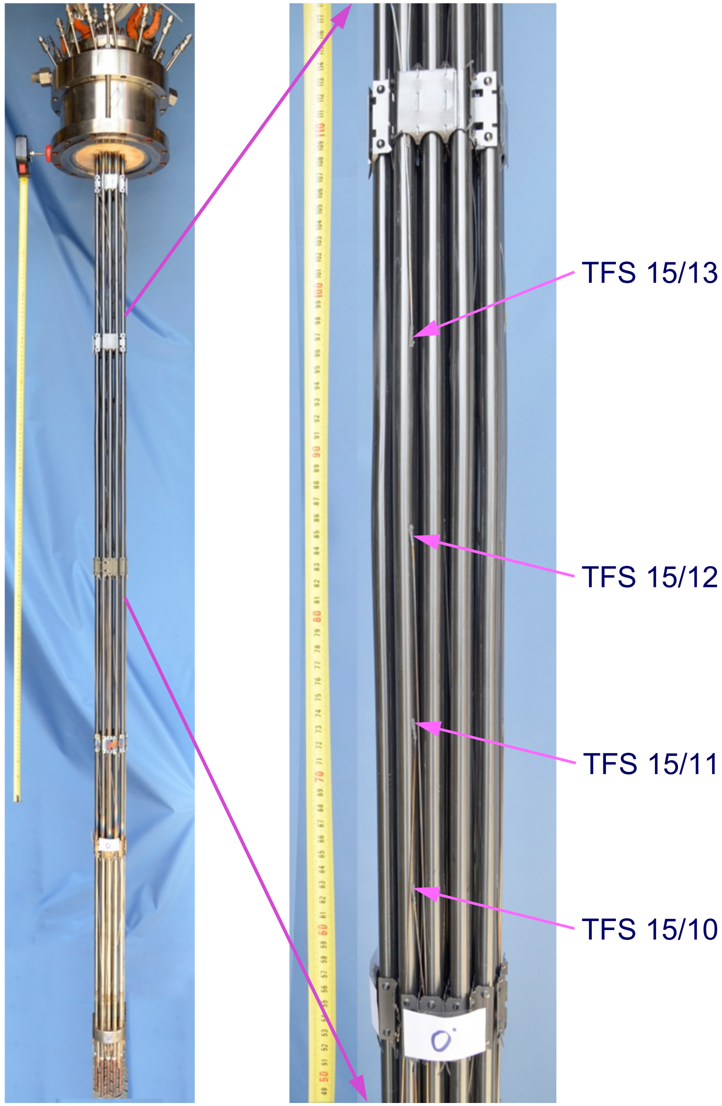
Rod pressure evolution during heating phase for QUENCH-L2 and -L4: burst time indication



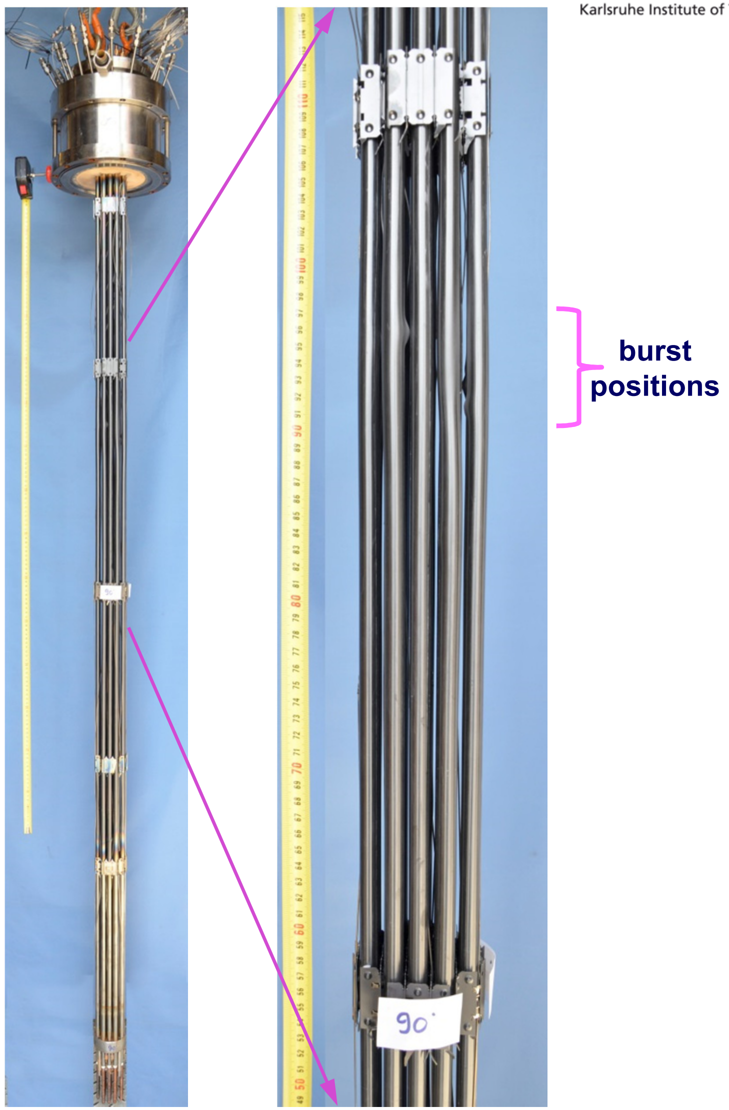


duration of decrease of the inner pressure to the system pressure: $\tau_0 \approx 30$ s

Views of bundle at angle positions of 0° and 90°: negligible rod bending and intact thermocouples



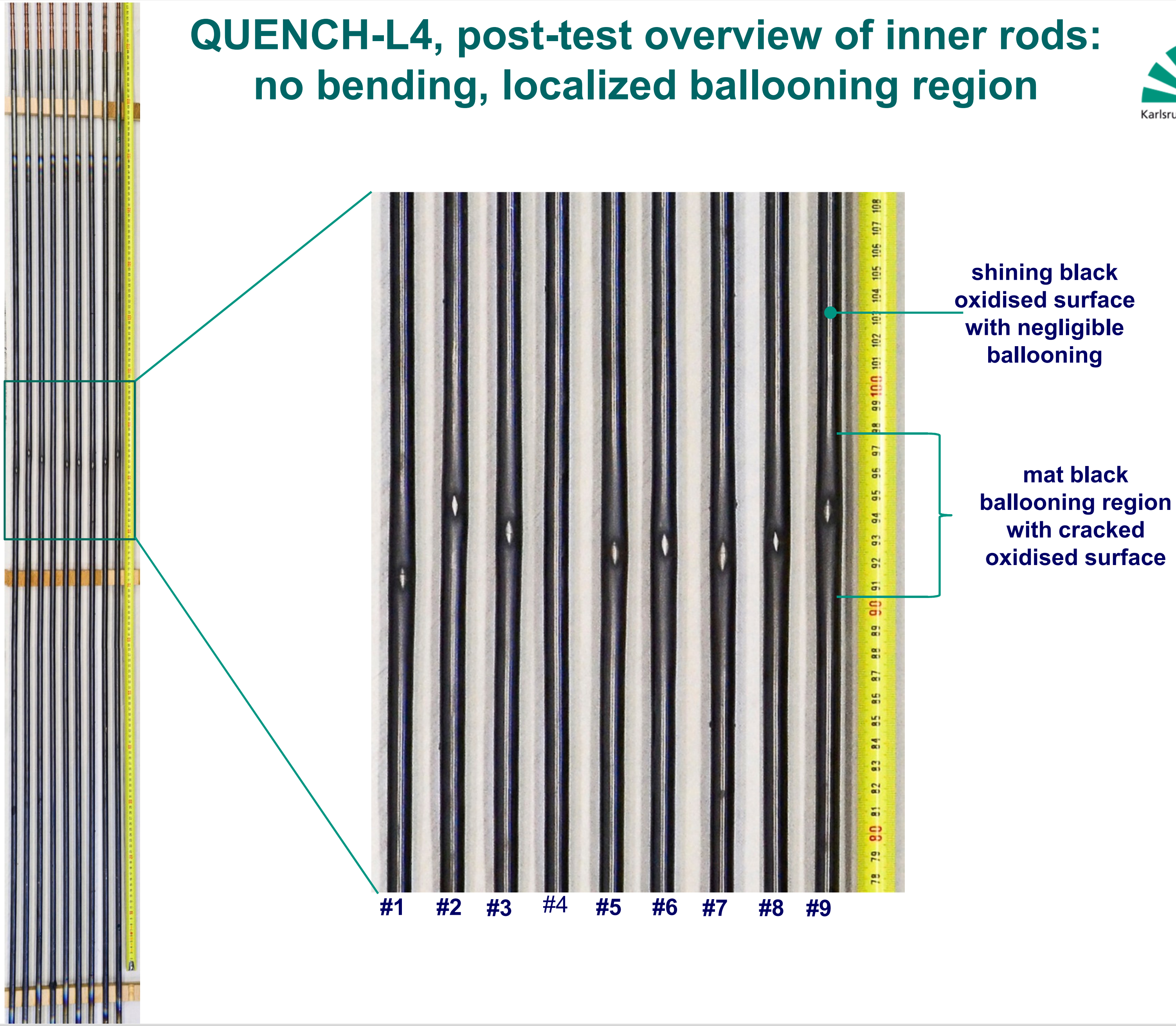
0°



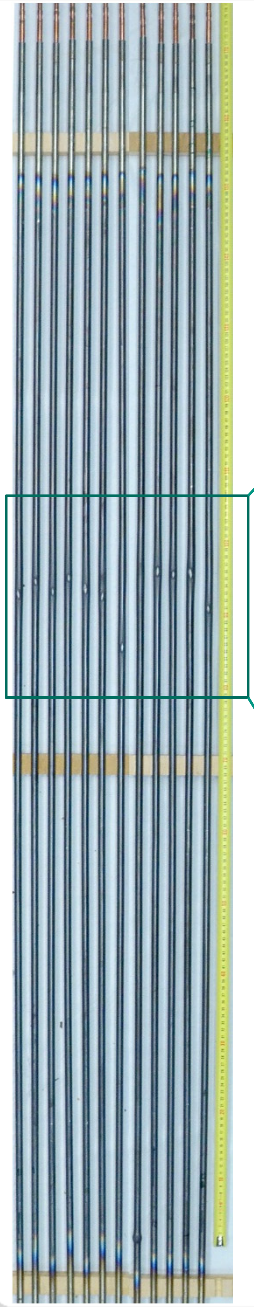
90°

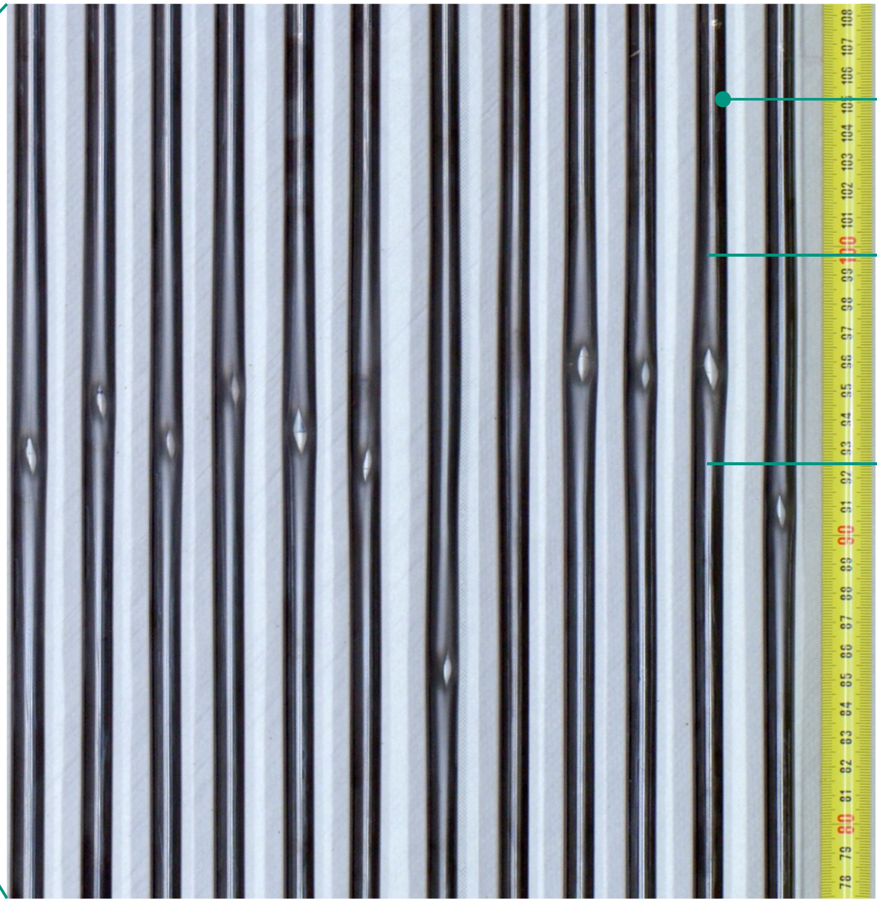
QUENCH-L4, post-test overview of inner rods: no bending, localized ballooning region

Karlsruhe Institute of Technology



QUENCH-L4, post-test overview of outer rods: no bending, localized ballooning region

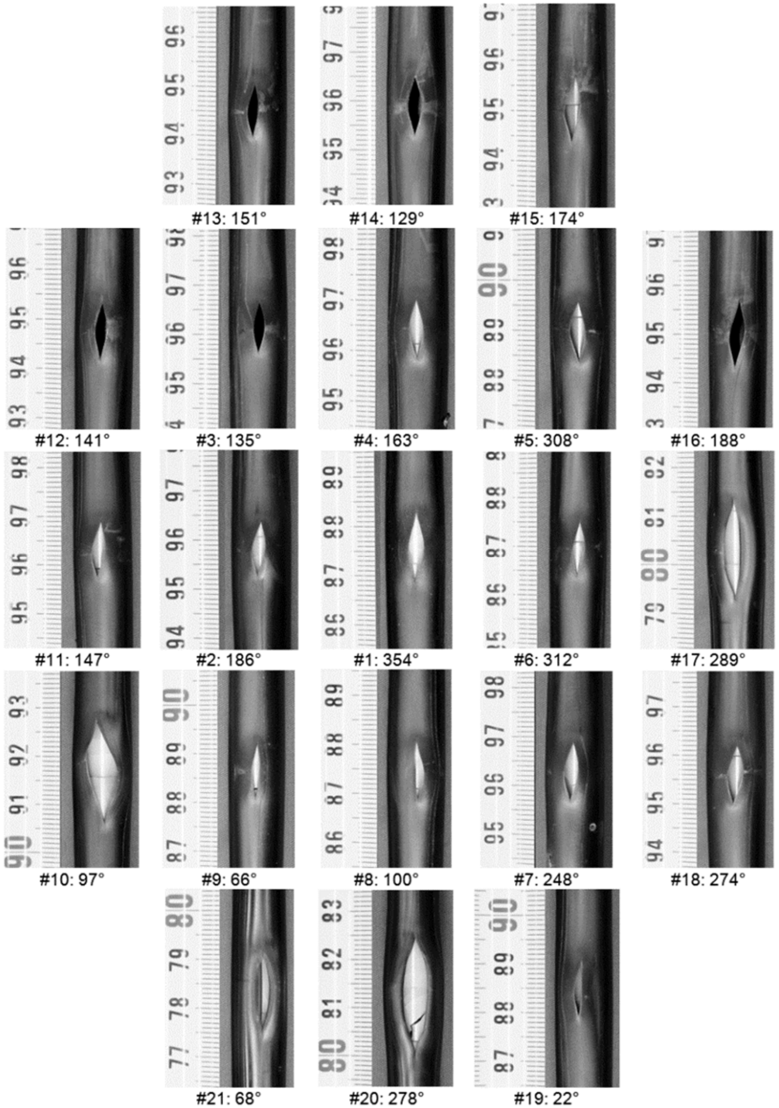




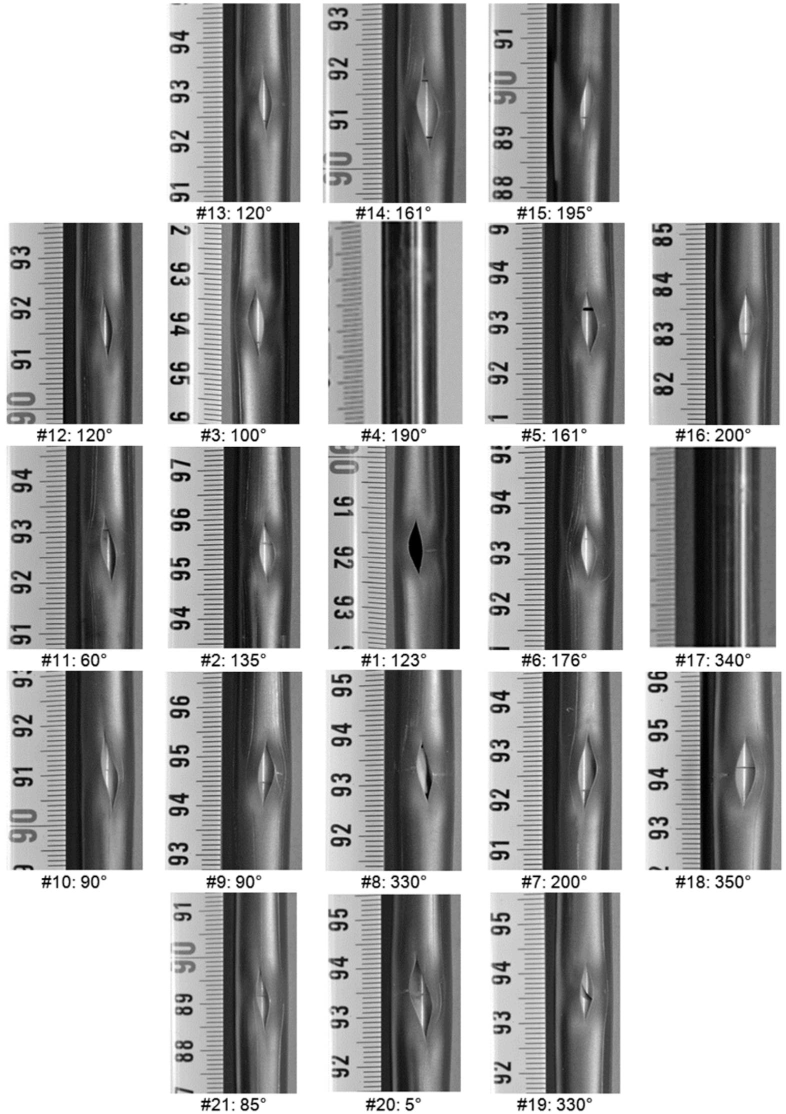
Burst openings of QL2 and QL4 bundles

Karlsruhe Institute of Technology

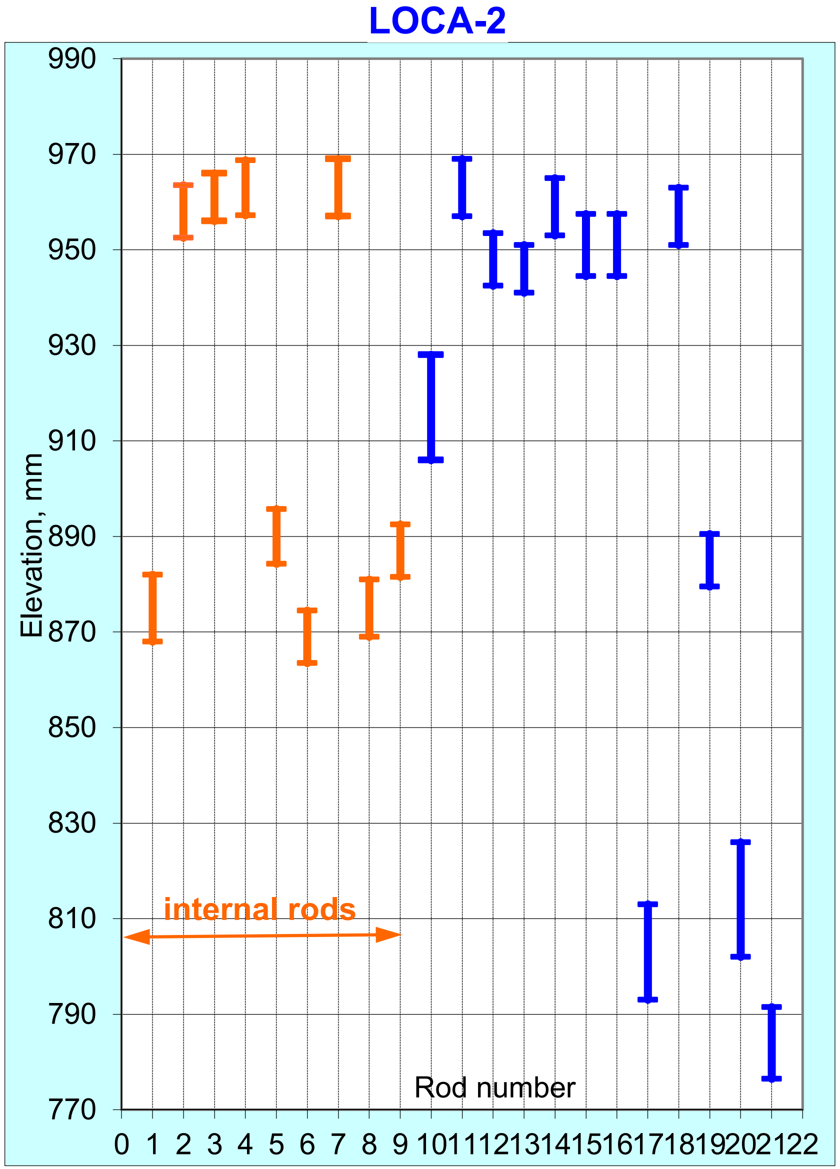
QL2 burst openings

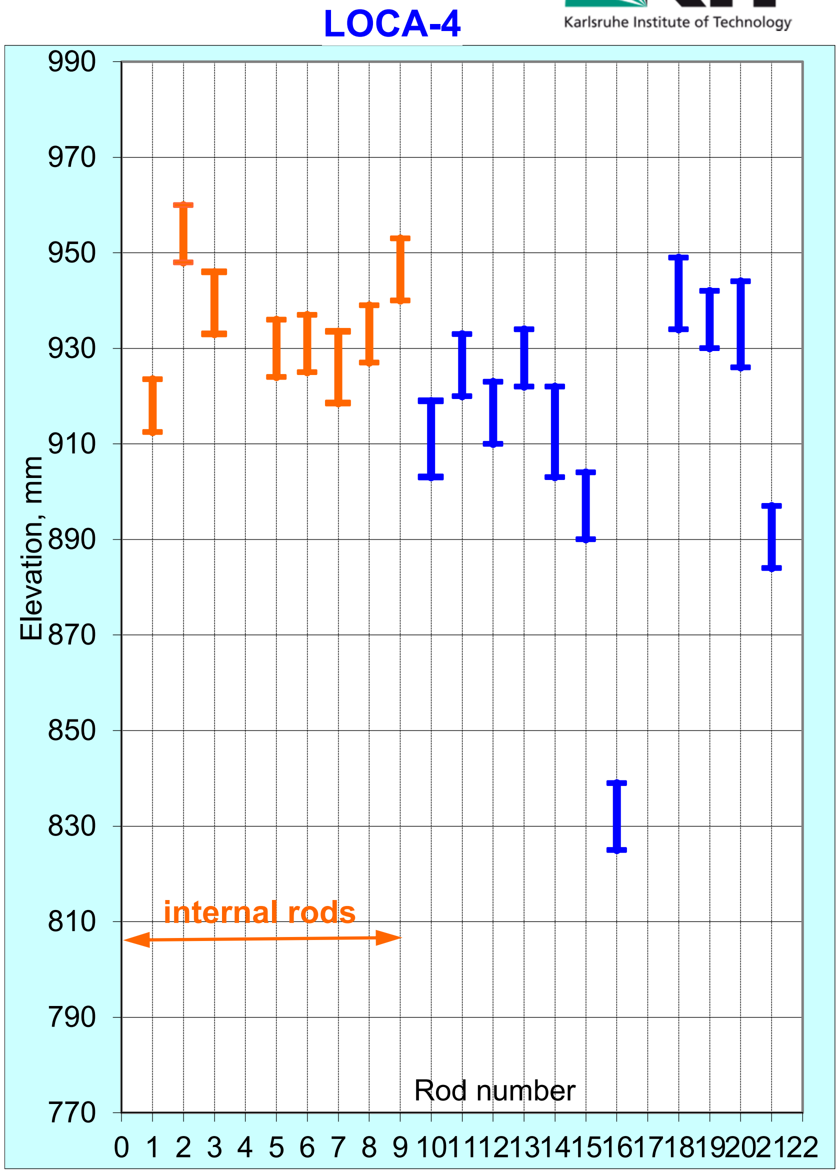


QL4 burst openings



Length and axial position of burst openings

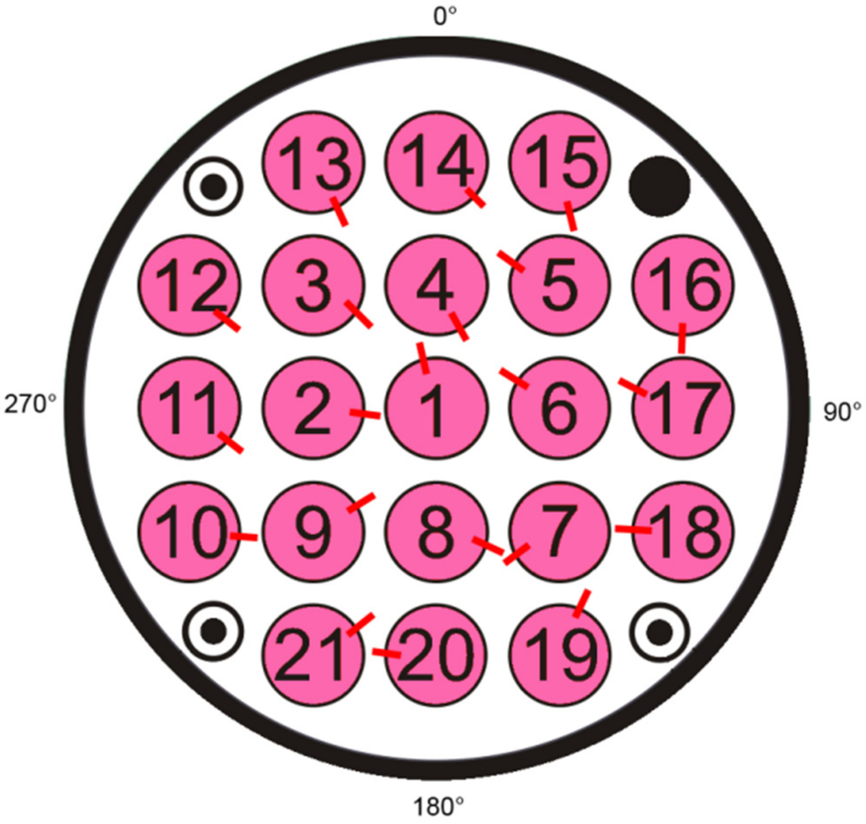




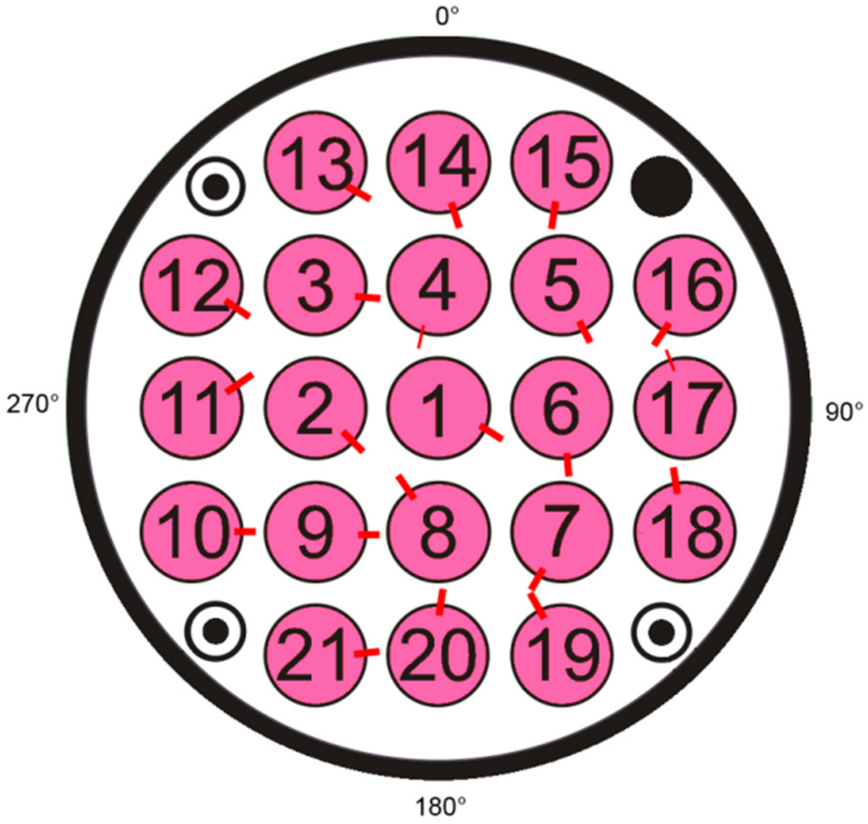
Circumferential position of burst openings

Karlsruhe Institute of Technology

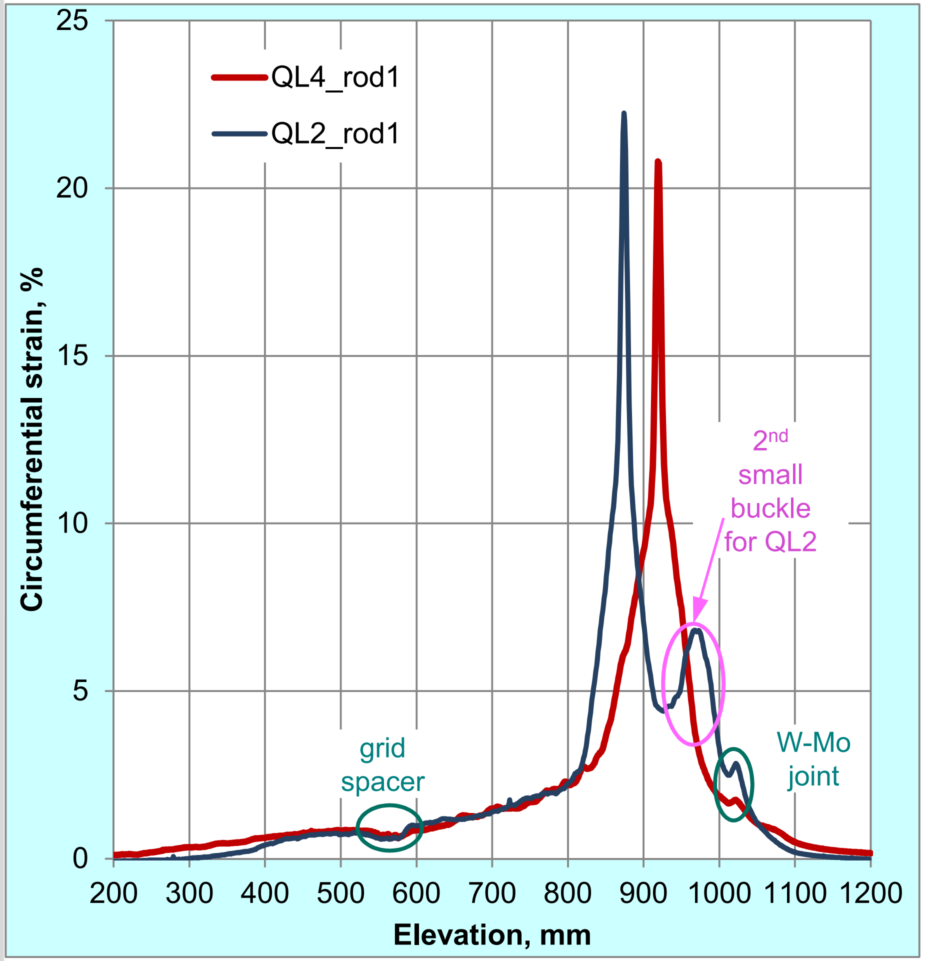
LOCA-2

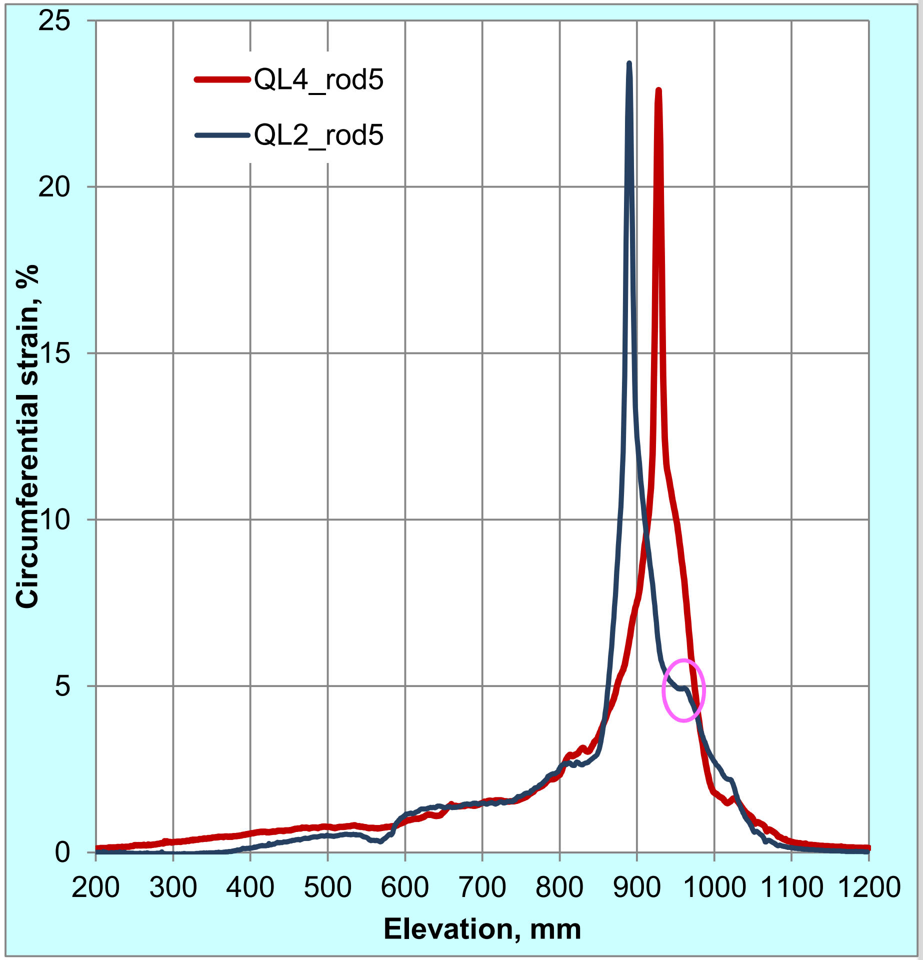


LOCA-4

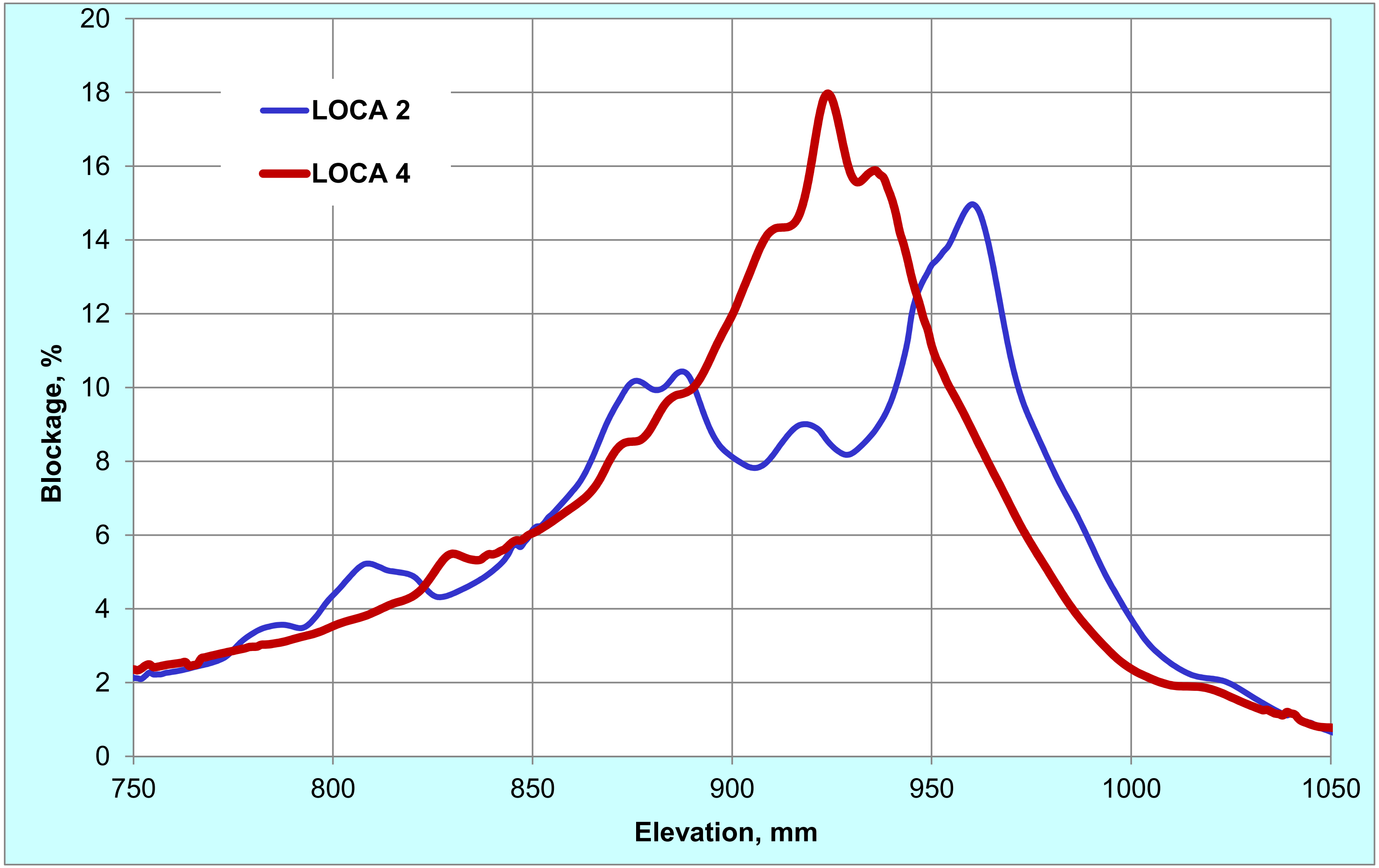


Circumferential strain for QUENCH–L2 and –L4 rods due to cladding ballooning: similar profiles, however 2 buckles for QL2





Cooling channel blockage for LOCA-2 and LOCA-4



Calculation: for coplanar positions of all burst openings (max blockage B): B_{QL1}= 28%; B_{QL4}= 27%

Burst Parameters

LOCA-2

Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	1	50	1135
	2	53	1167
	3	53	1168
	4	52	1167
	5	53	1163
	6	50	1121
	7	53	1136
	8	48	1113
	9	53	1162
Outer rods	10	66	1125
	11	65	1145
	12	68	1195 (Max)
	13	67	1178
	14	66	1167
	15	58	1124
	16	64	1143
	17	62	1102
	18	65	1139
	19	67	1093
	20	63	1110
	21	66	1050 (Min)

average burst T: 1138 ± 34 K = 865 ± 34 °C

LOCA-4

Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	1	48	1086
	2	55	1121
	3	50	1106
	4	50	
	5	48	1101
	6	50	1108
	7	48	1100
	8	53	1125
	9	52	1119
Outer rods	10	65	1072
	11	62	1067 (Min)
	12	64	1132
	13	63	1151 (Max)
	14	62	1149
	15	***53***	1074
	16	65	1137
	17	67	
	18	65	1137
	19	58	1082
	20	64	1096
	21	62	1077

average burst T: 1107 ± 27 K = 834 ± 27 °C

QUENCH-L4: videoscope observations of cladding inner surface

360°

90°

270°

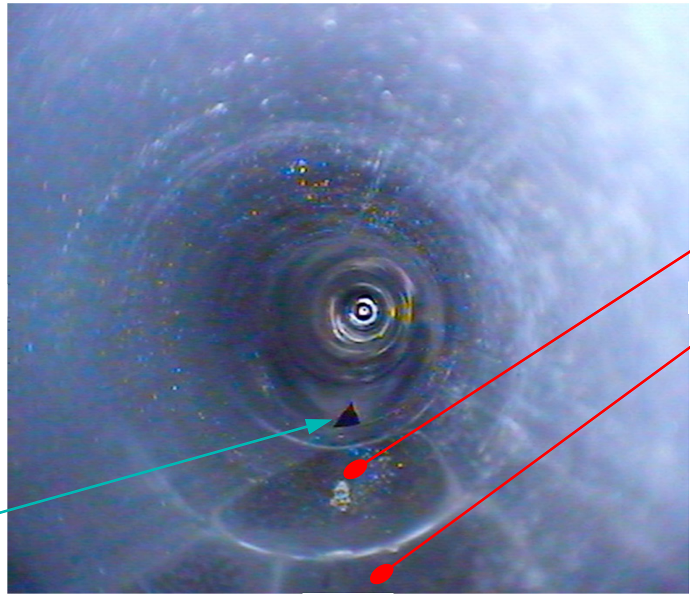
180°

burst opening at 940 mm

QL4, inner surface of clad #18

300°

30°

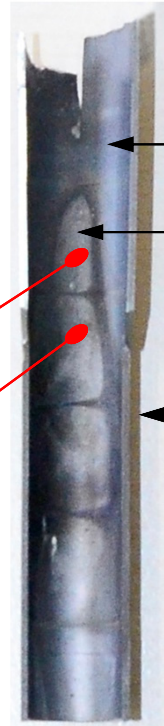


210°

120°

burst opening at 920 mm

QL4, inner surface of clad #1



oxidised inner surface

metal

contact between adjacent pellets (deposition of W from heaters)

similar structure of inner clad surface for QL2, rod #8

Summary

- The QUENCH-LOCA-4 test with pre-hydrogenated M5® claddings (≈100 wppm H) was performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR with the same parameters as the QUENCH-LOCA-2 test with fresh M5® claddings: maximal heat-up rate 8 K/s, cooling phase lasted 120 s and terminated with 3.3 g/s/rod water flooding.
- Similar to QUENCH-LOCA-2, the maximum temperature of 1400 K was reached on the end of the heat-up phase at elevation 950 mm. Tangential temperature gradient across a rod was up to 30 K on the burst onset.
- Due to more close axial localisation of ballooned region the maximum blockage ratio of cooling channel (18% at 925 mm) was negligible higher in comparison to QUENCH-L2 (15% at 960 mm). Due to moderate blockage a good bundle coolability was kept for both bundles.
- The cladding burst occurred at temperatures between 1067 and 1151 K (QUENCH-L2: 1050 and 1195 K). The inner rod pressure relief to the system pressure during about 30 s (similar to QUENCH-L2).
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual strengths or ductility is sufficient).
- Influence of secondary hydrogenation: neutron radio- and tomography, metallographic investigations and tensile tests are in progress.

Acknowledgment

The QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB). The unirradiated pre-hydrogenated M5® claddings and Zircaloy-4 spacer material was provided by AREVA.

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/