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First results of the bundle test QUENCH-L3 with optimized ZIRLO™ claddings

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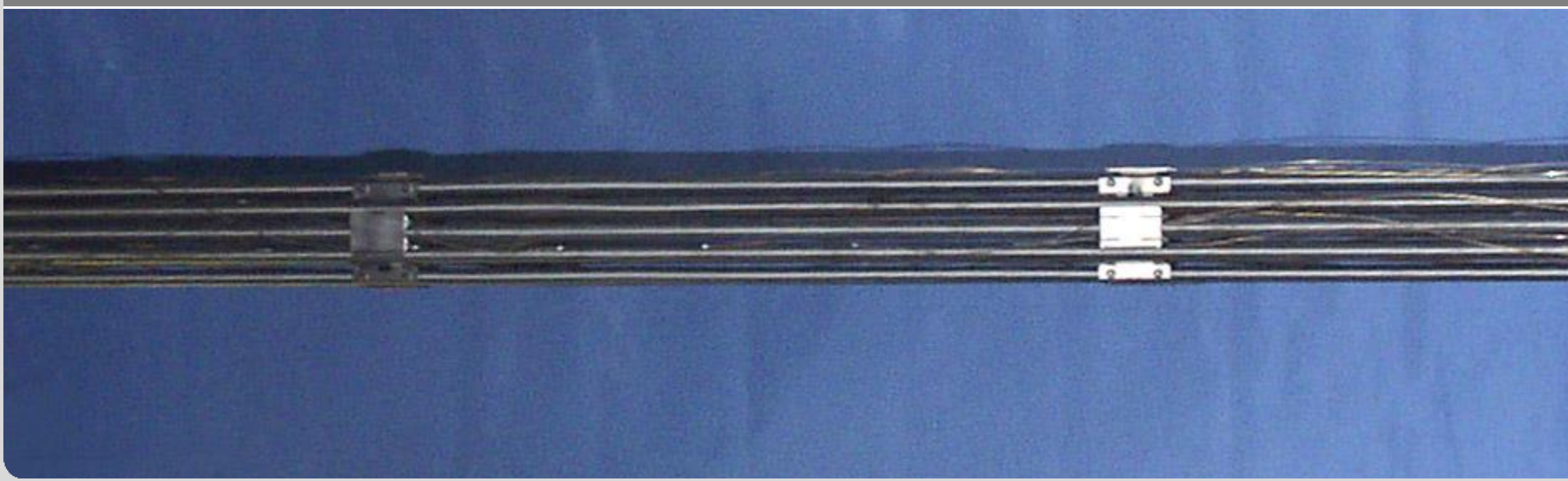
Institute for Applied Materials; Program NUKLEAR



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Abstract

The QUENCH-LOCA-3 test with as-received optimized ZIRLO™ claddings was performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR with similar test parameters as the reference QUENCH-LOCA-1 test with fresh Zry-4 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-1, the maximum temperature of 1350 K was reached on the end of the heat-up phase at elevation 950 mm. Radial temperature gradient across a rod, caused by heat loss through the shroud and local contact of pellets to cladding after small cladding bending, was up to 70 K on the burst onset.

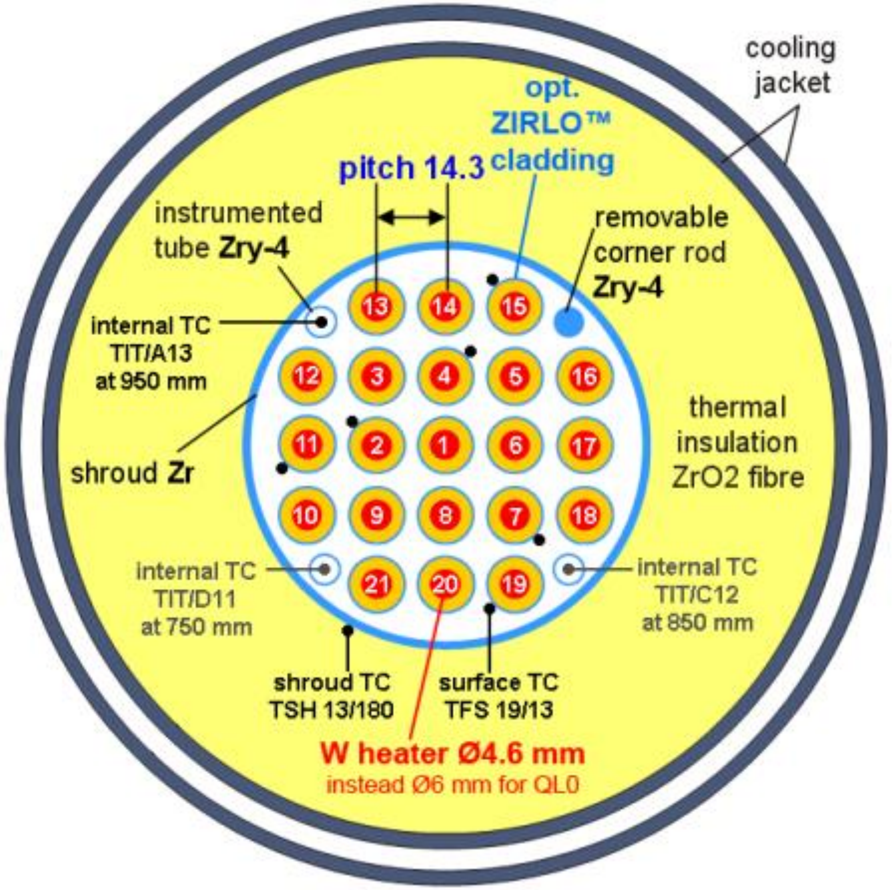
The cladding burst occurred at temperatures between 1064 and 1188 K (QUENCH-LOCA-1: 1074 and 1169 K). Average burst temperature for the claddings of the QUENCH-LOCA-3 bundle was 1117 K (1126 K for QUENCH-LOCA-1).

The maximum blockage ratio of cooling channel (21% at 918 mm) was slightly lower in comparison to QUENCH-LOCA-1 (25% at 946 mm). Due to moderate blockage good bundle coolability was kept for both bundles.

During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual strengths or ductility is sufficient).

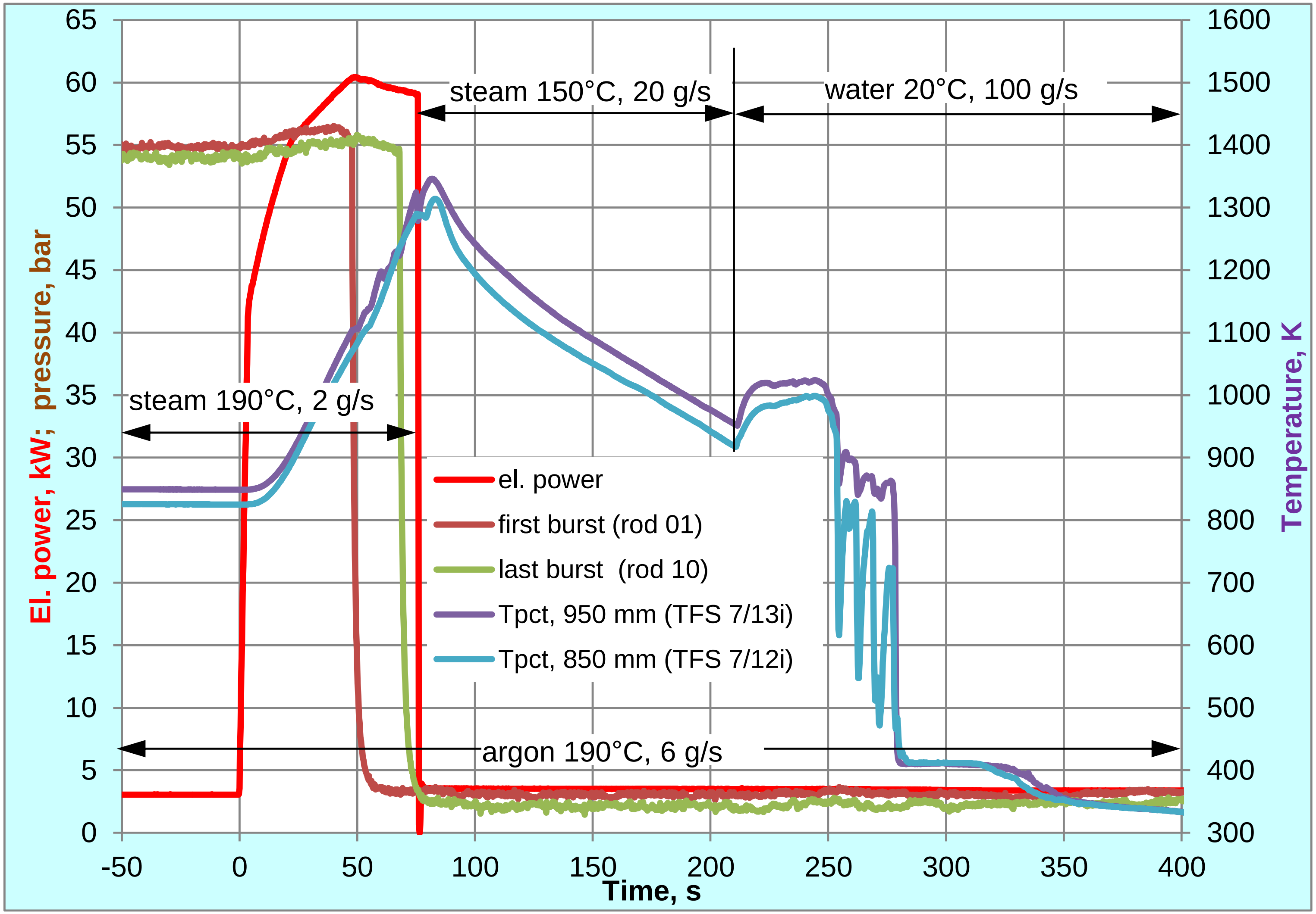
Influence of secondary hydrogenation on results of tensile tests at room temperature: only one cladding failed at hydrogen band; seven claddings failed due to stress concentration at edges of burst opening (similar to all QUENCH-LOCA-1 claddings with hydrogen concentration less of 1500 wppm); thirteen claddings failed after necking far away from the burst openings.

Cross-section of the QUENCH-L3 bundle

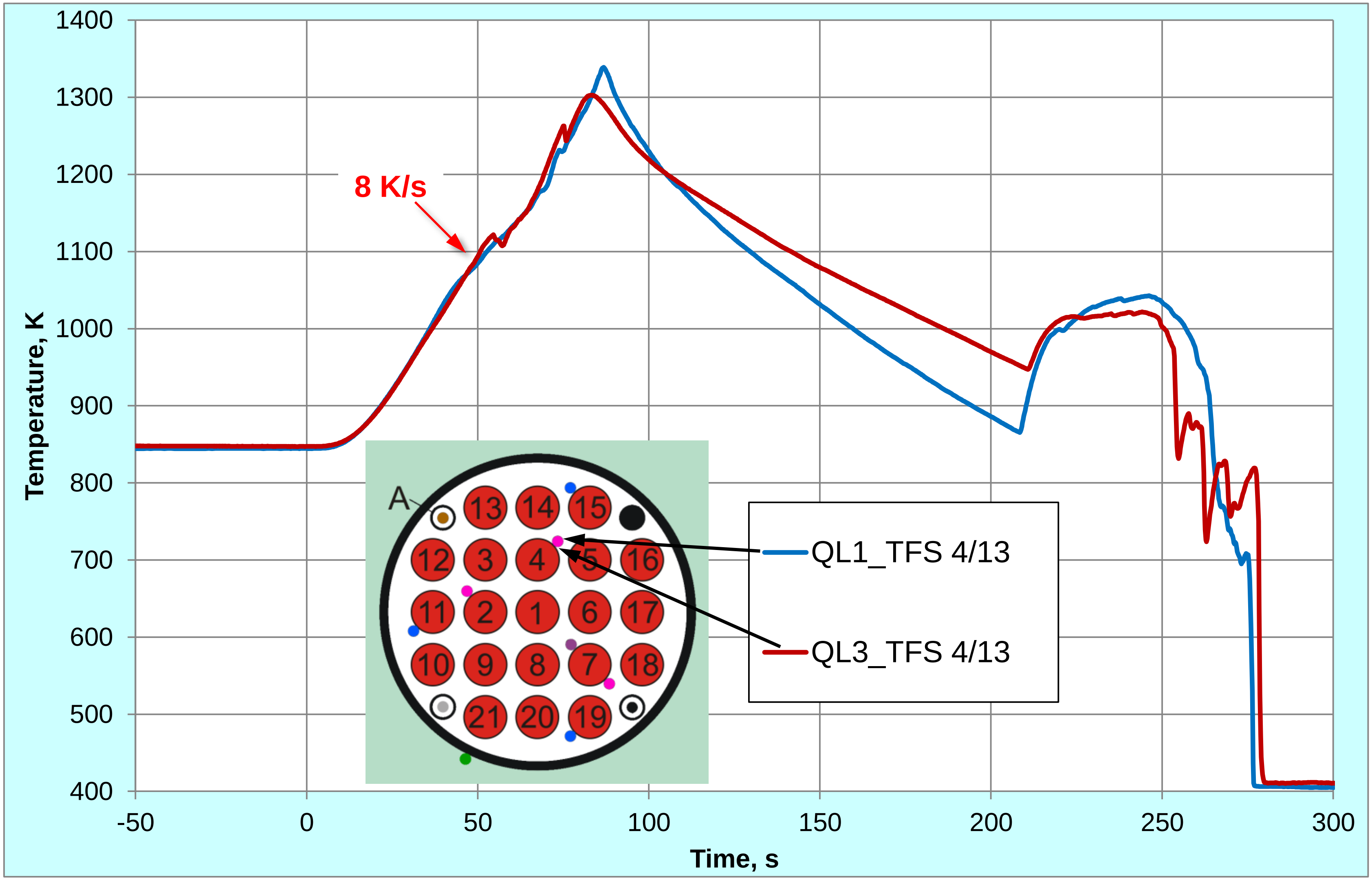


1) The use of ***tungsten*** heaters with smaller diameter (***4.6 mm***) instead tungsten heaters (QUENCH-L0) or tantalum heaters (QUENCH-L1) with diameter of 6 mm has allowed to reach a **higher heat rate**.
2) All rods are filled with Kr with p=55 bar at T_{pct}=800 K (similar to QUENCH-L1).

QUENCH-L3: test progress



Maximal cladding temperatures of internal rods in hottest region of QUENCH–L1 (Zry-4, reference test) and –L3 bundles (elevation 950 mm)



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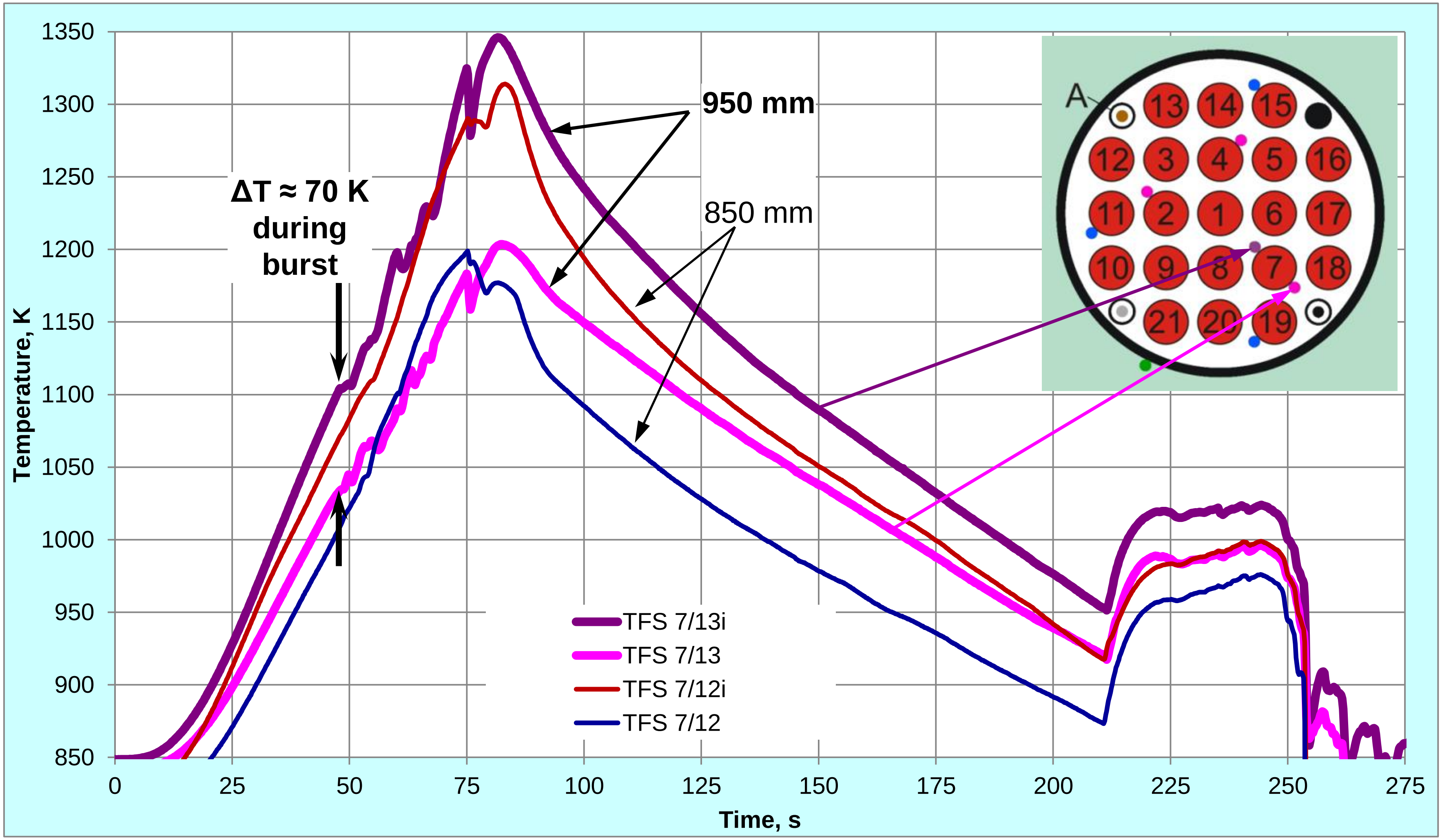
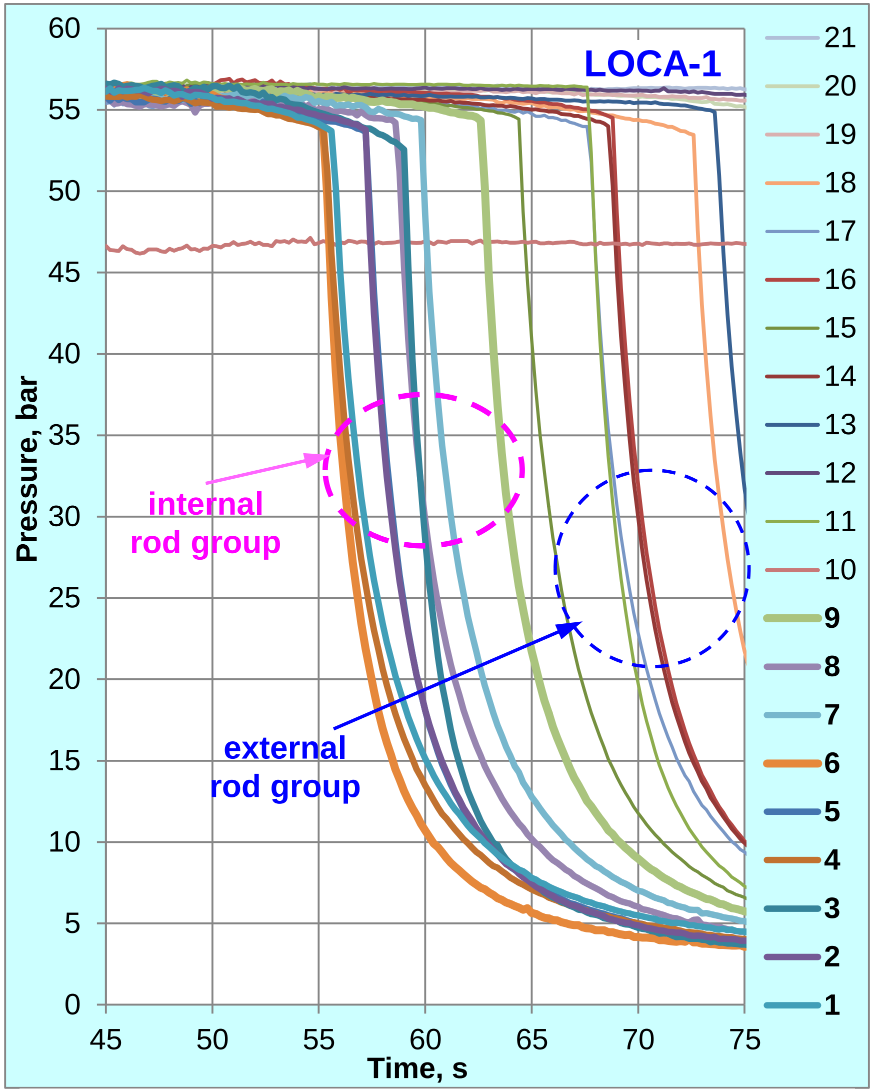
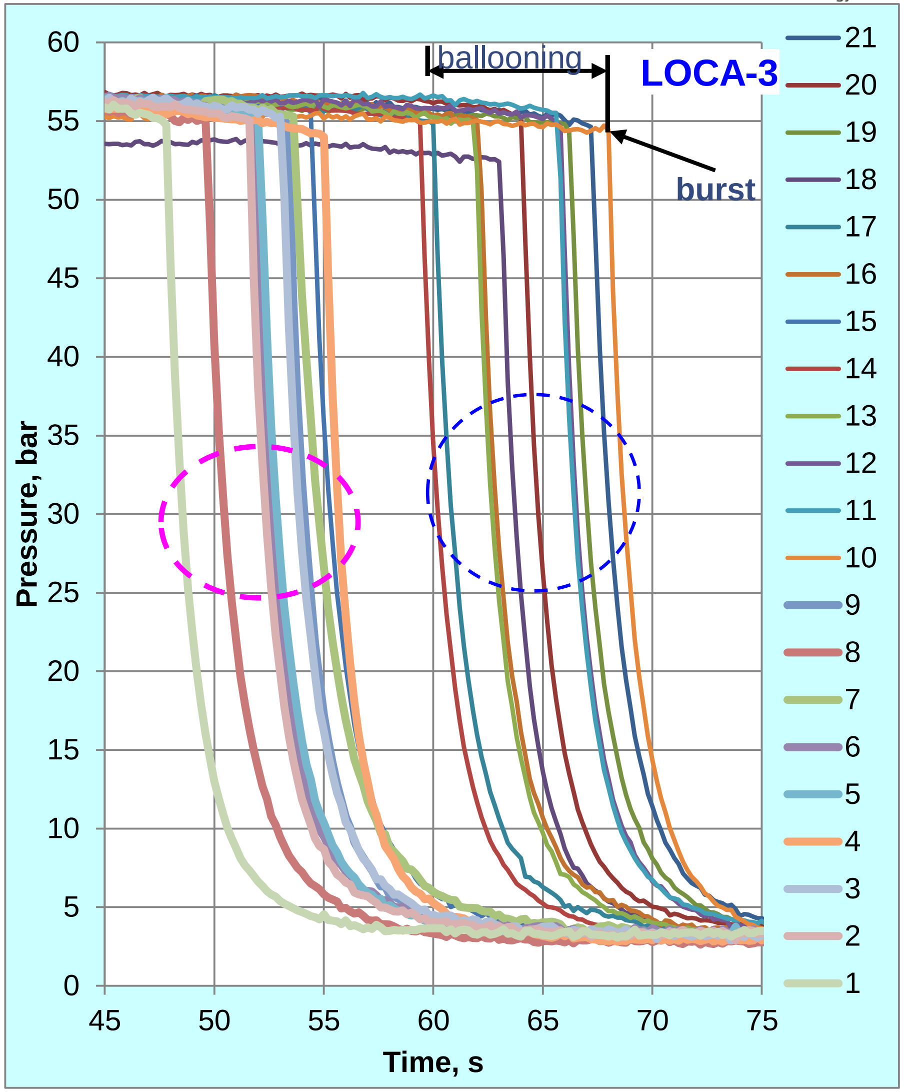
QUENCH-L3: radial temperature gradient ΔT
for rod #7 at hottest elevations 850 mm (7/12) and 950 mm (7/13)



Rod pressure evolution during heating phase for QUENCH-L1 (reference test with Zry-4) and QUENCH-L3: burst time indication

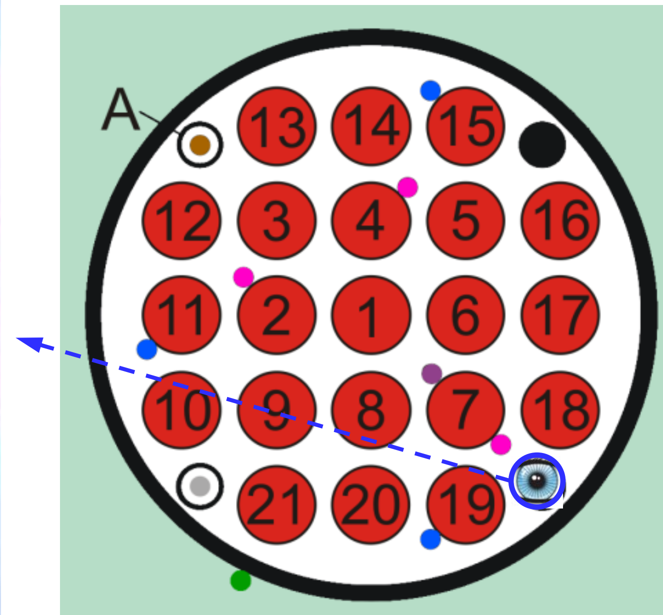


pressure decrease to system pressure: $\tau_0 \approx 38$ s



pressure decrease to system pressure: $\tau_0 \approx 30$ s

QUENCH-L3: Ballooning and burst of cladding tubes at elevation 950 mm (videoscope)



Burst parameters

LOCA-1

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

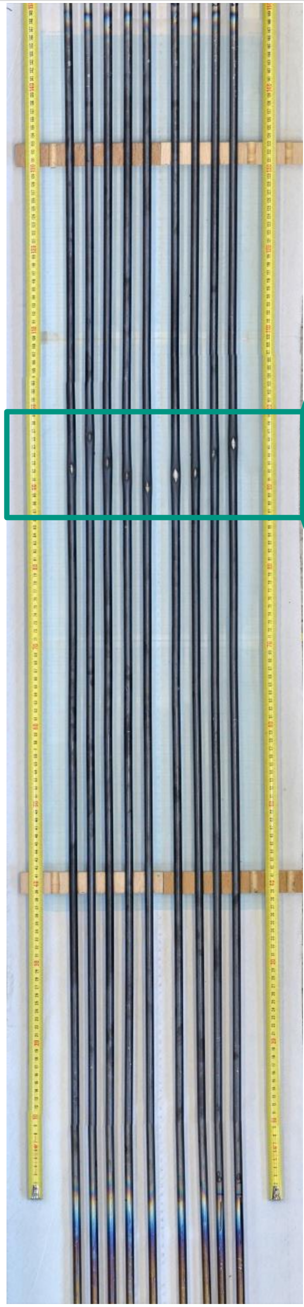
average burst T: 1126 ± 33 K = 853 ± 33 °C

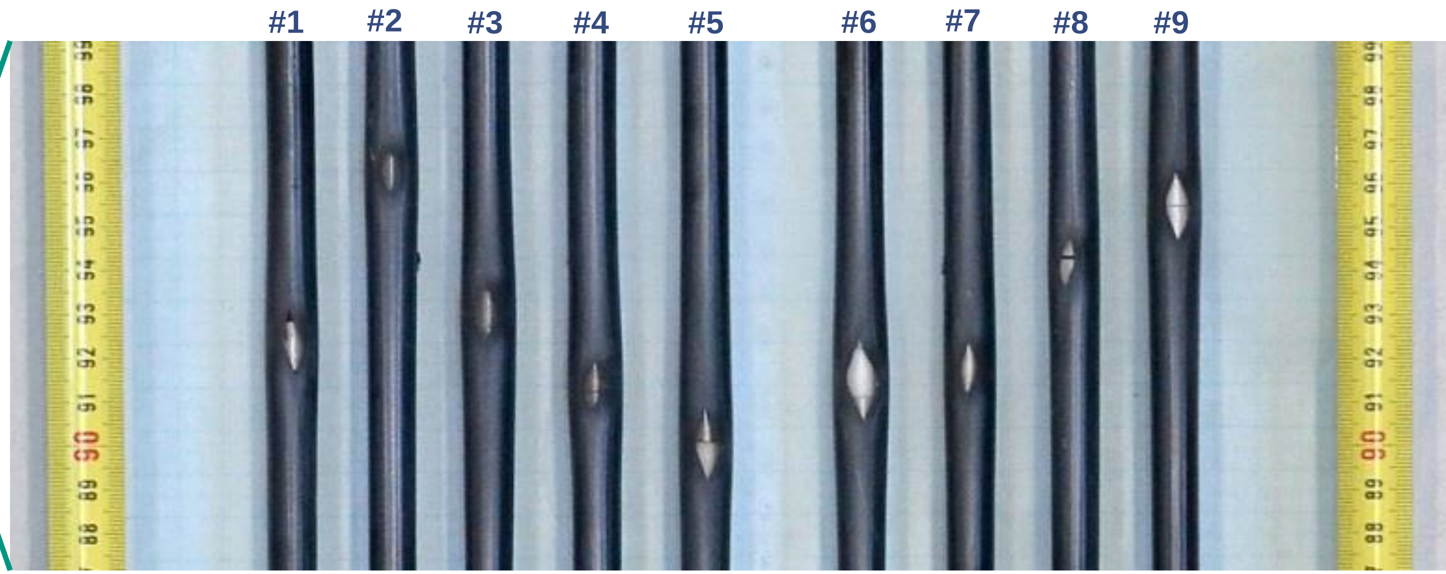
LOCA-3

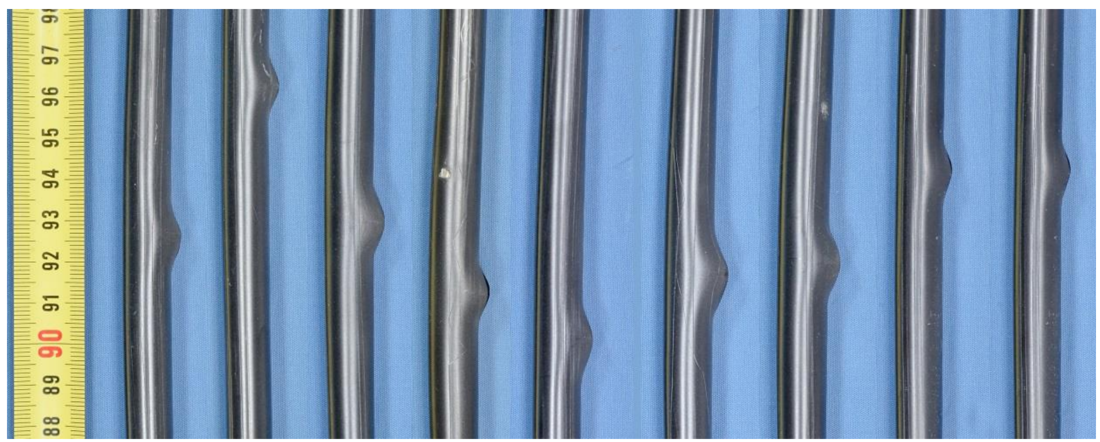
Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	**1**	**47.8**	**1103**
	2	**51.6**	**1140**
	3	**53**	**1111**
	4	**55**	**1108**
	5	**52**	**1109**
	6	**51.8**	**1112**
	7	**53.6**	**1124**
	8	**49.6**	**1107**
	9	**53.2**	**1132**
Outer rods	10	68	1188 (Max)
	11	65.6	1126
	12	65.8	1175
	13	61.8	1138
	14	59.4	1124
	15	*54.4*	1105
	16	62	1142
	17	60	1094
	18	63	1114
	19	66.2	1073
	20	64	1064 (Min)
	21	67.2	1073

average burst T: 1117 ± 30 K = 844 ± 30 °C

QUENCH-L3: 9 inner rods

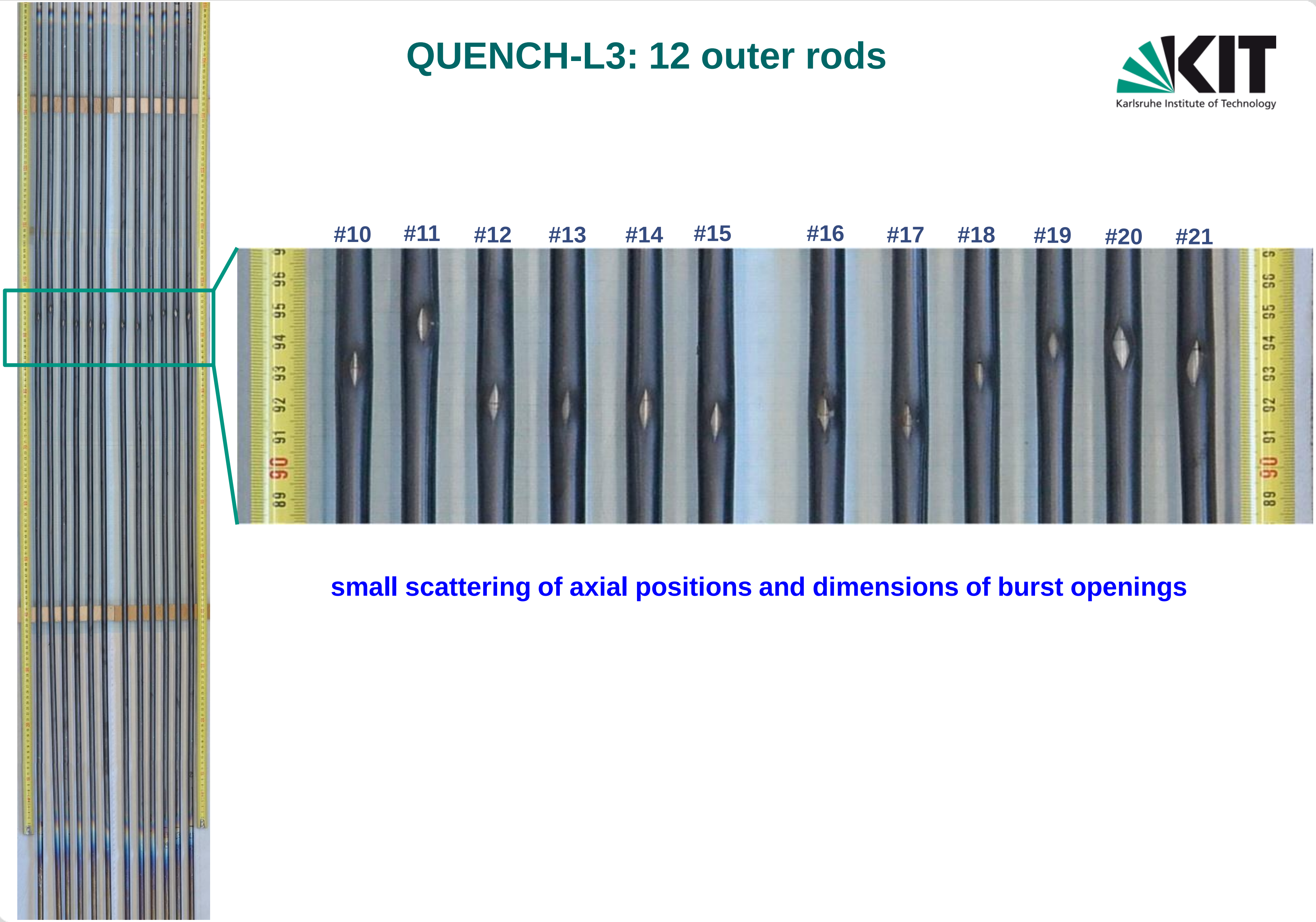






average bending 1.1% oppositely to burst direction: buckling due to simultaneous thermal expansion and friction at grid spacers

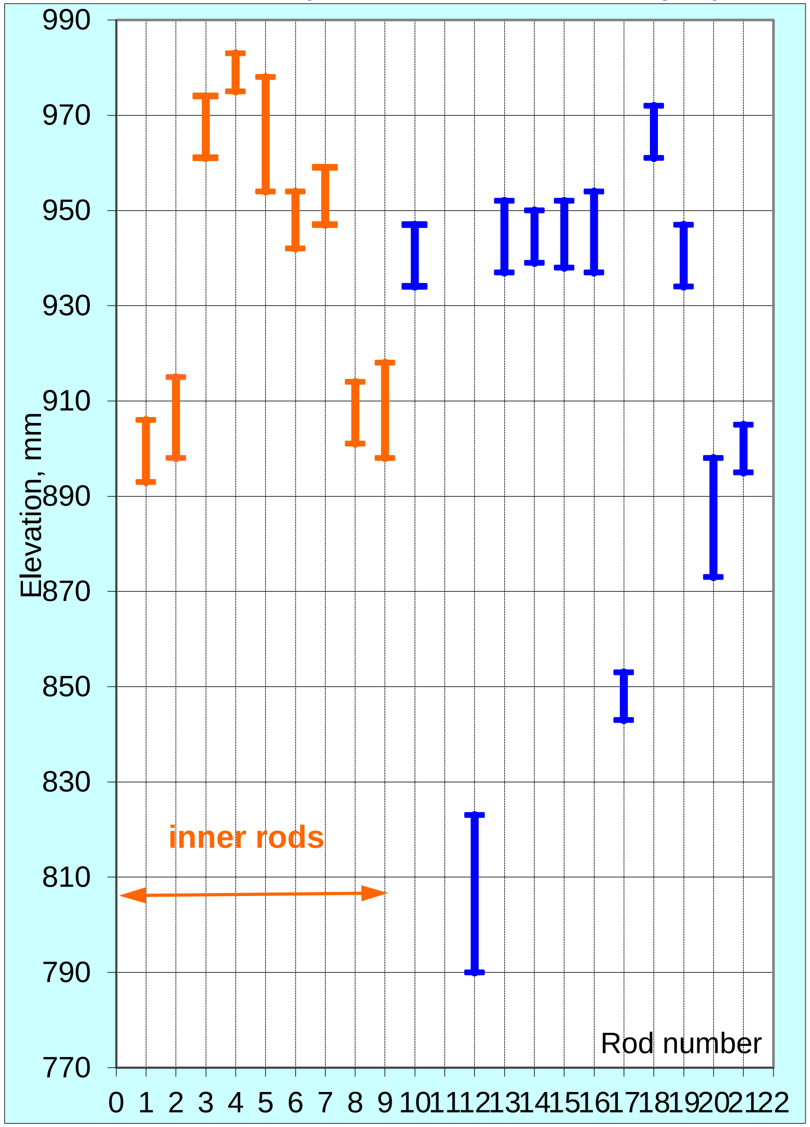
QUENCH-L3: 12 outer rods



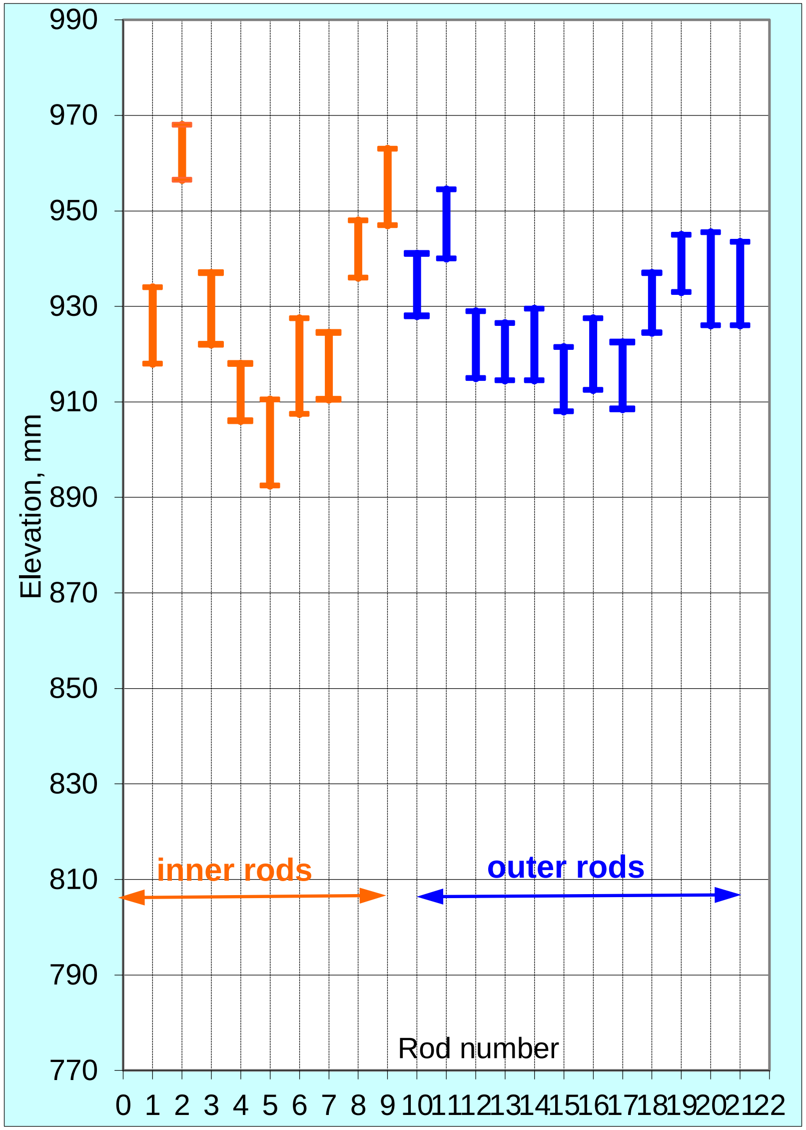
small scattering of axial positions and dimensions of burst openings

Length and axial position of burst openings

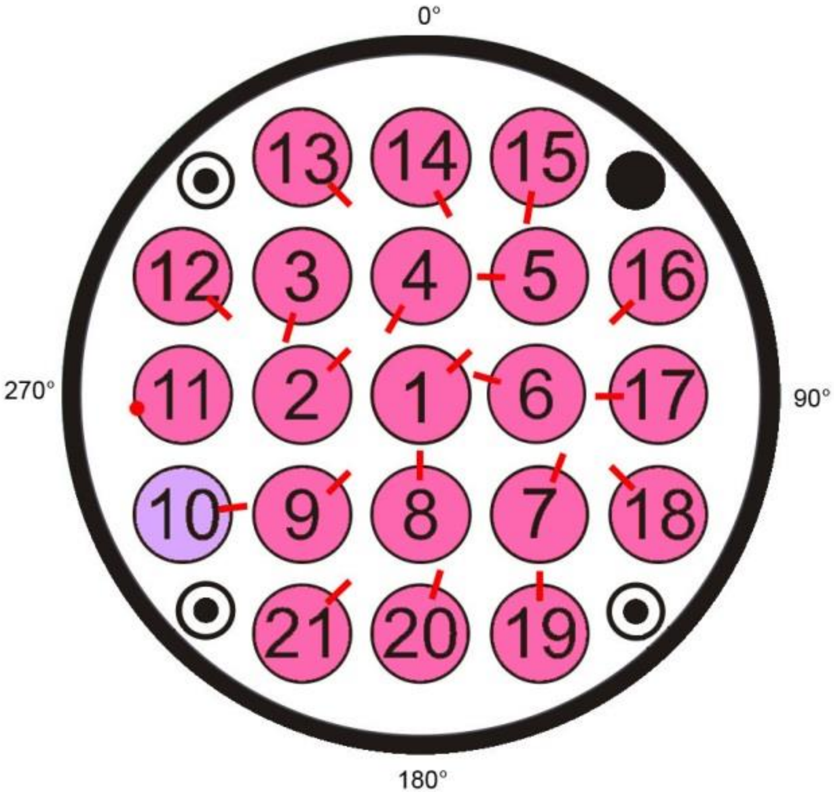
LOCA-1 (reference test with Zry-4)



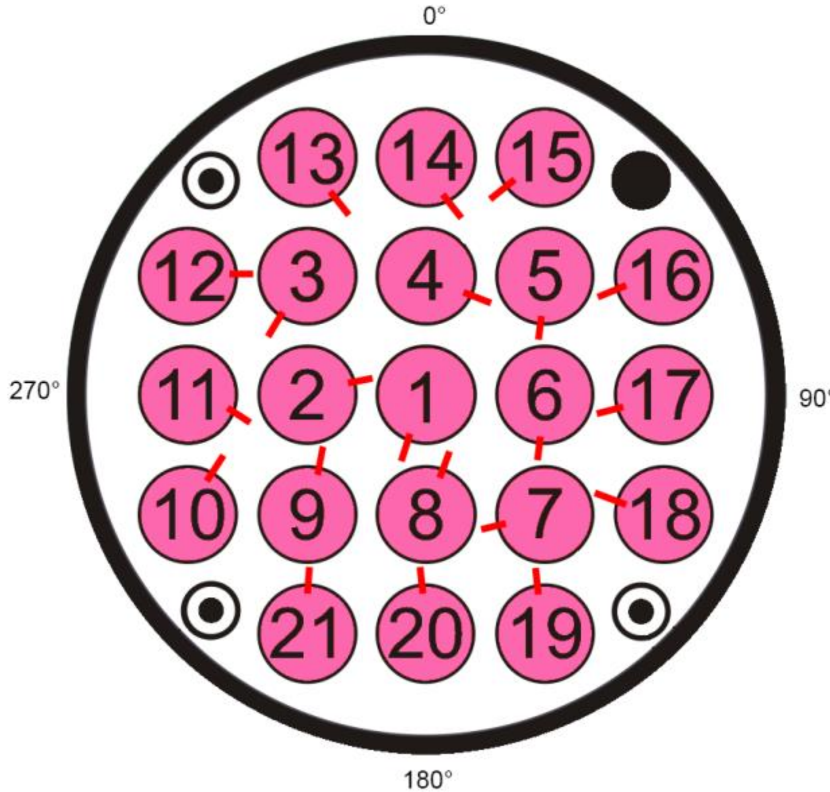
LOCA-3



Circumferential position of burst openings



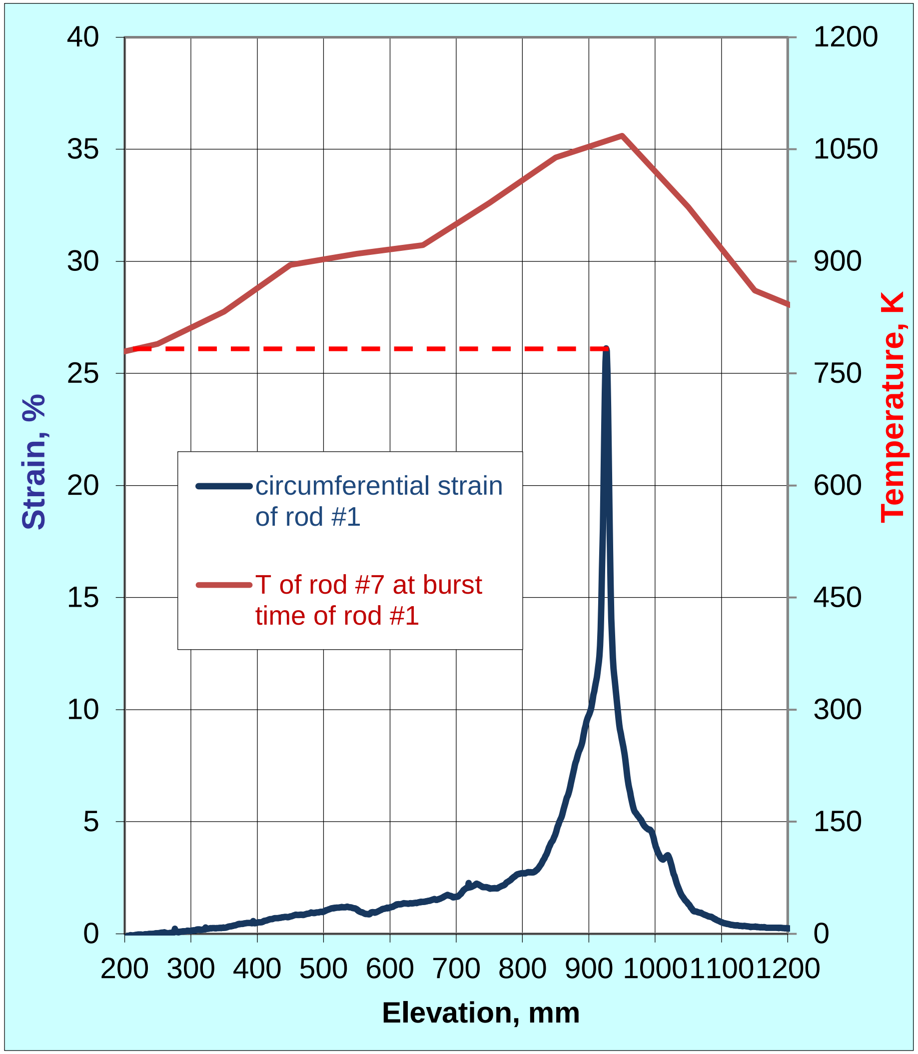
LOCA-1 (reference test with Zry-4)



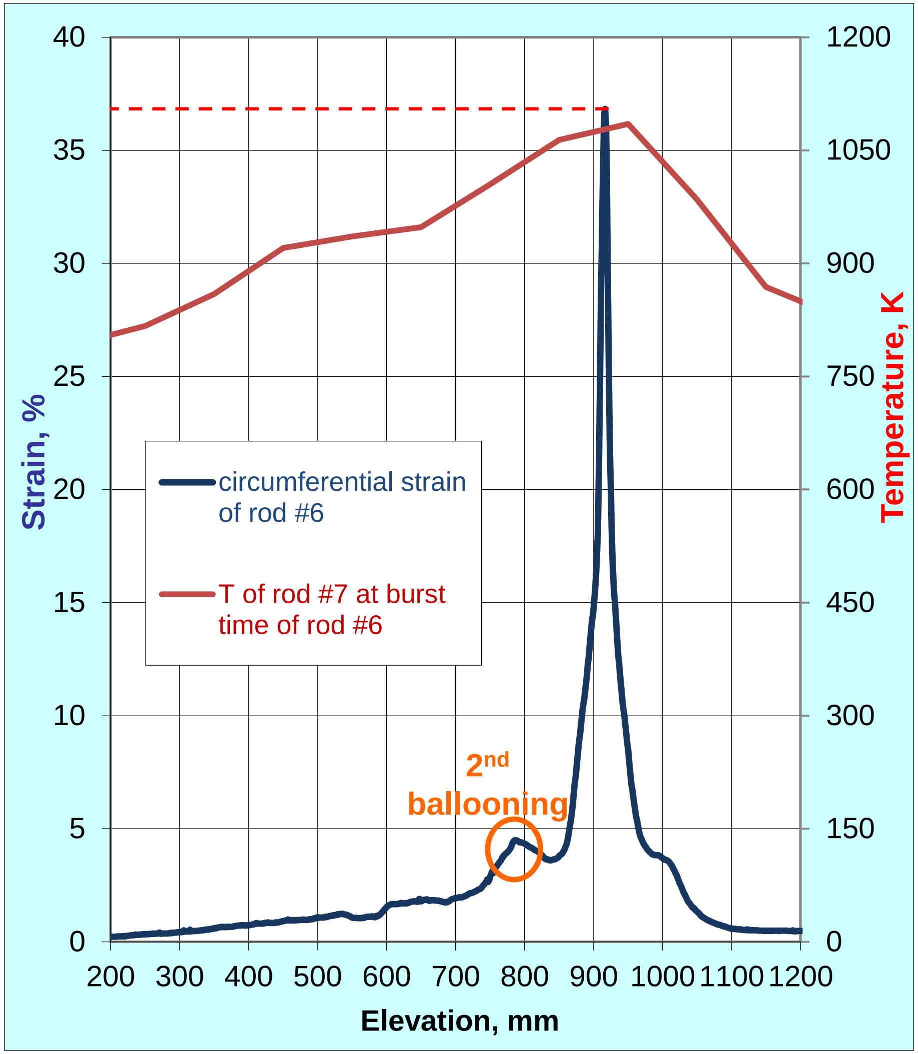
LOCA-3

burst openings oriented predominantly to bundle center due to pronounced radial temperature gradient

QUENCH-L3: Circumferential strain (laser scanner)

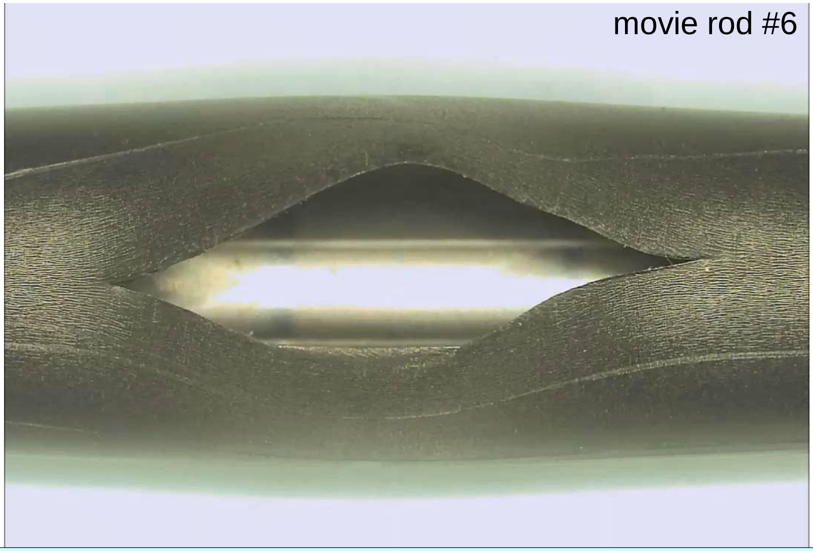


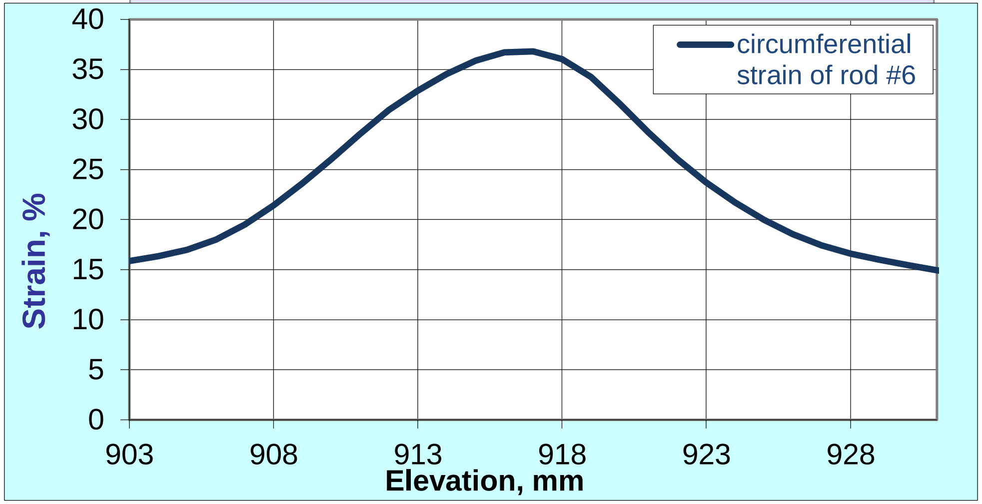
rod #1: central rod, typical strain **< 27%**



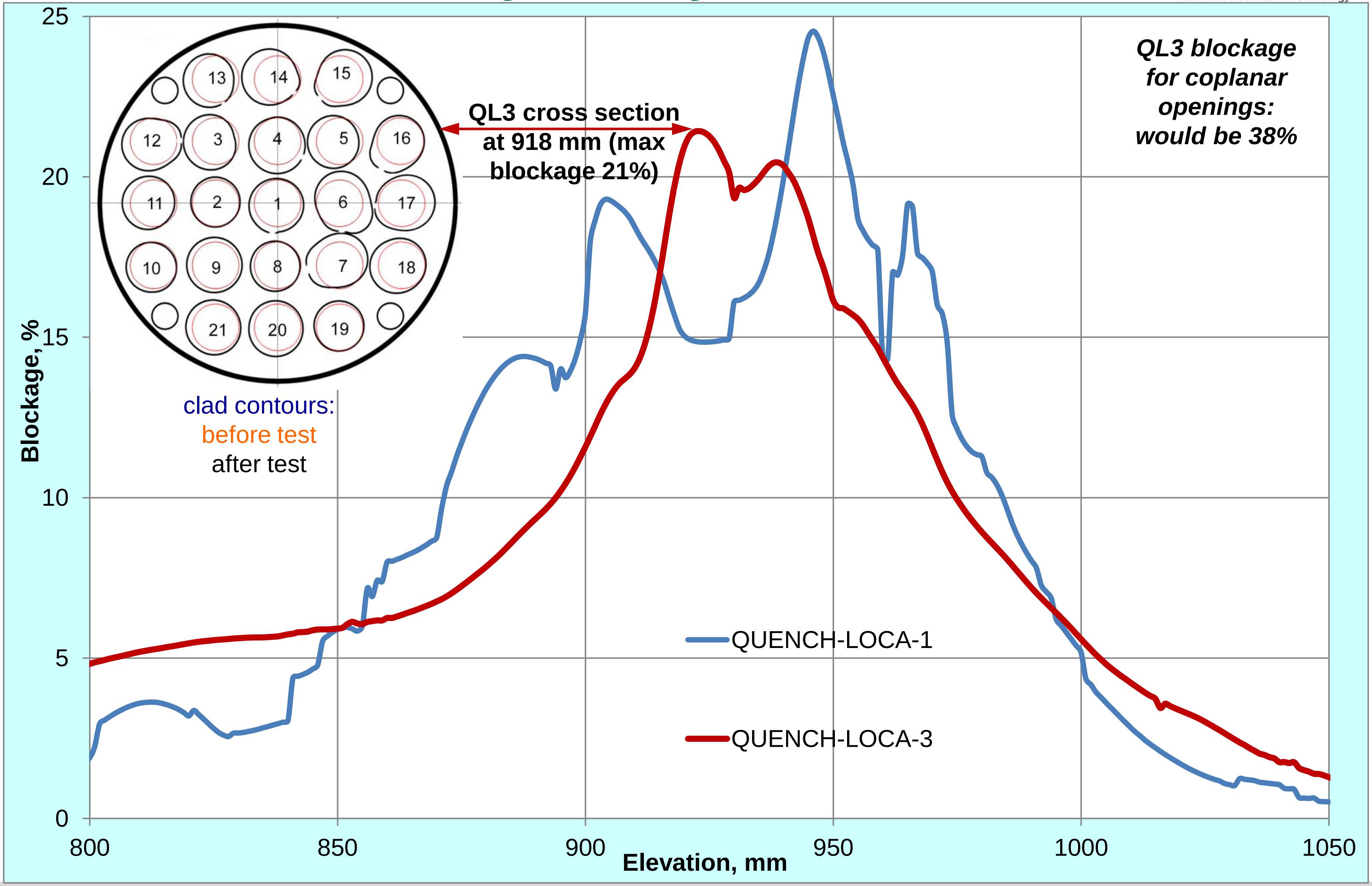
rod #6: maximal strain of 37%

QUENCH-L3: Circumferential strain (laser scanner) and burst position overview

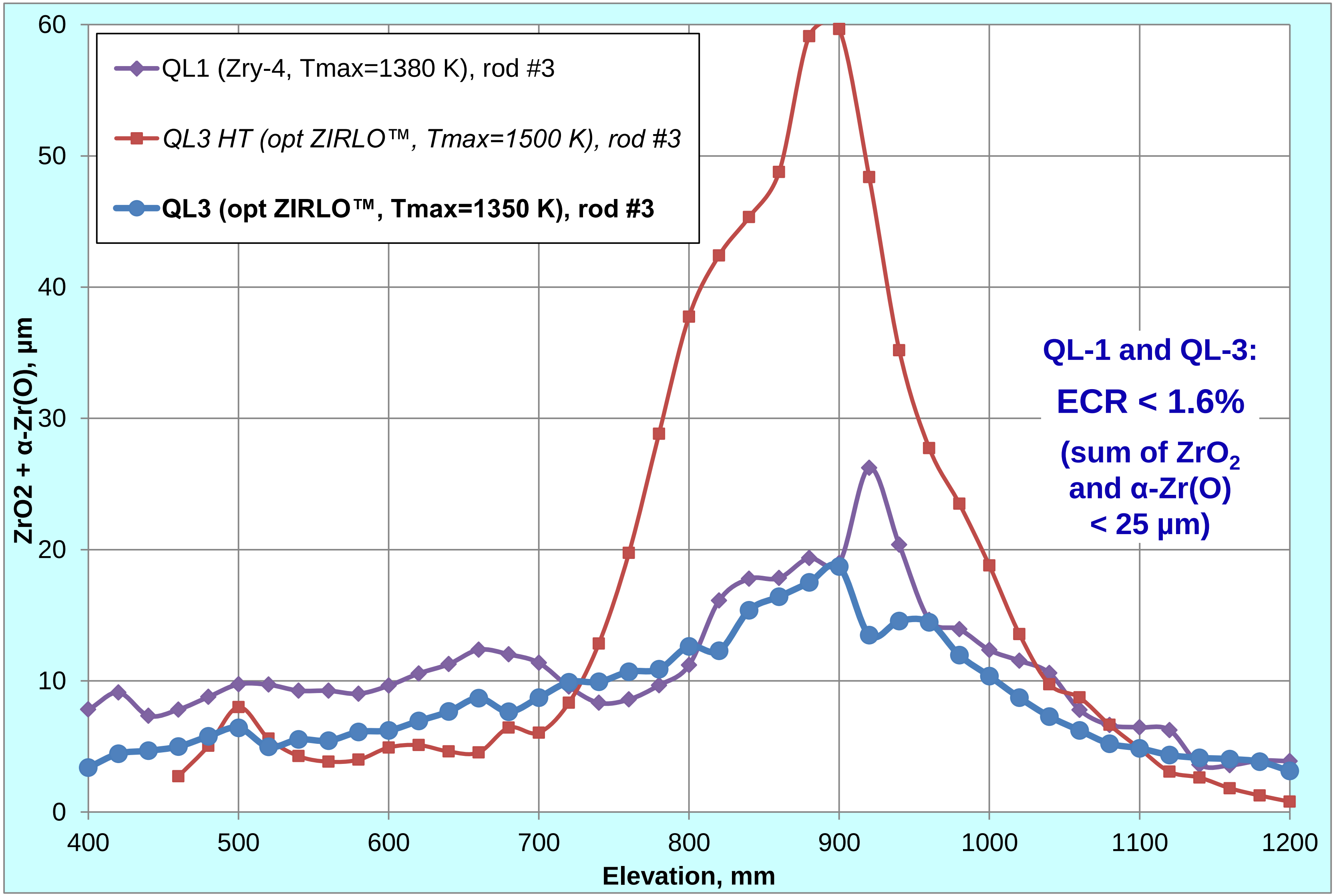




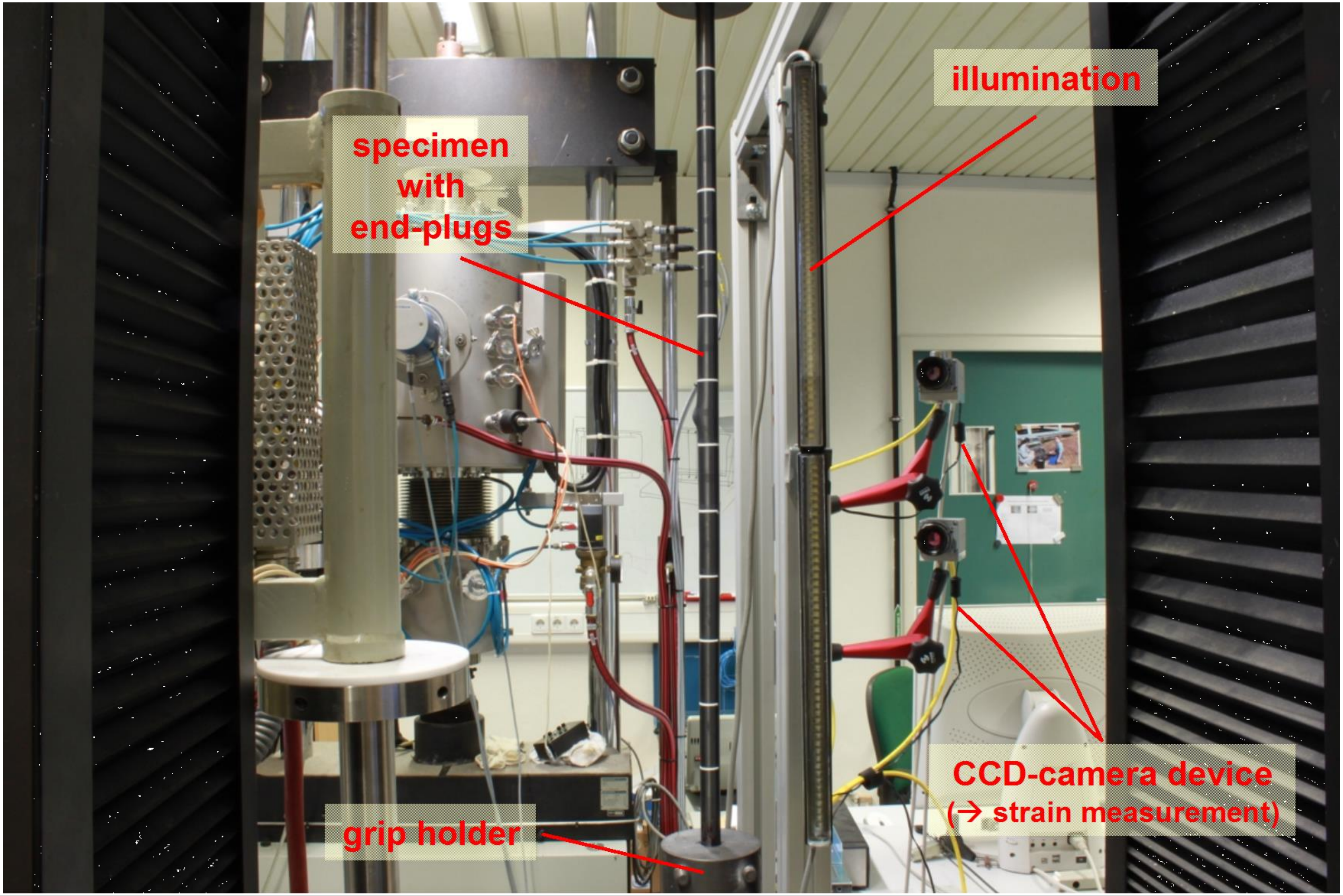
Cooling channel blockage for QL-1 and QL-3 bundles



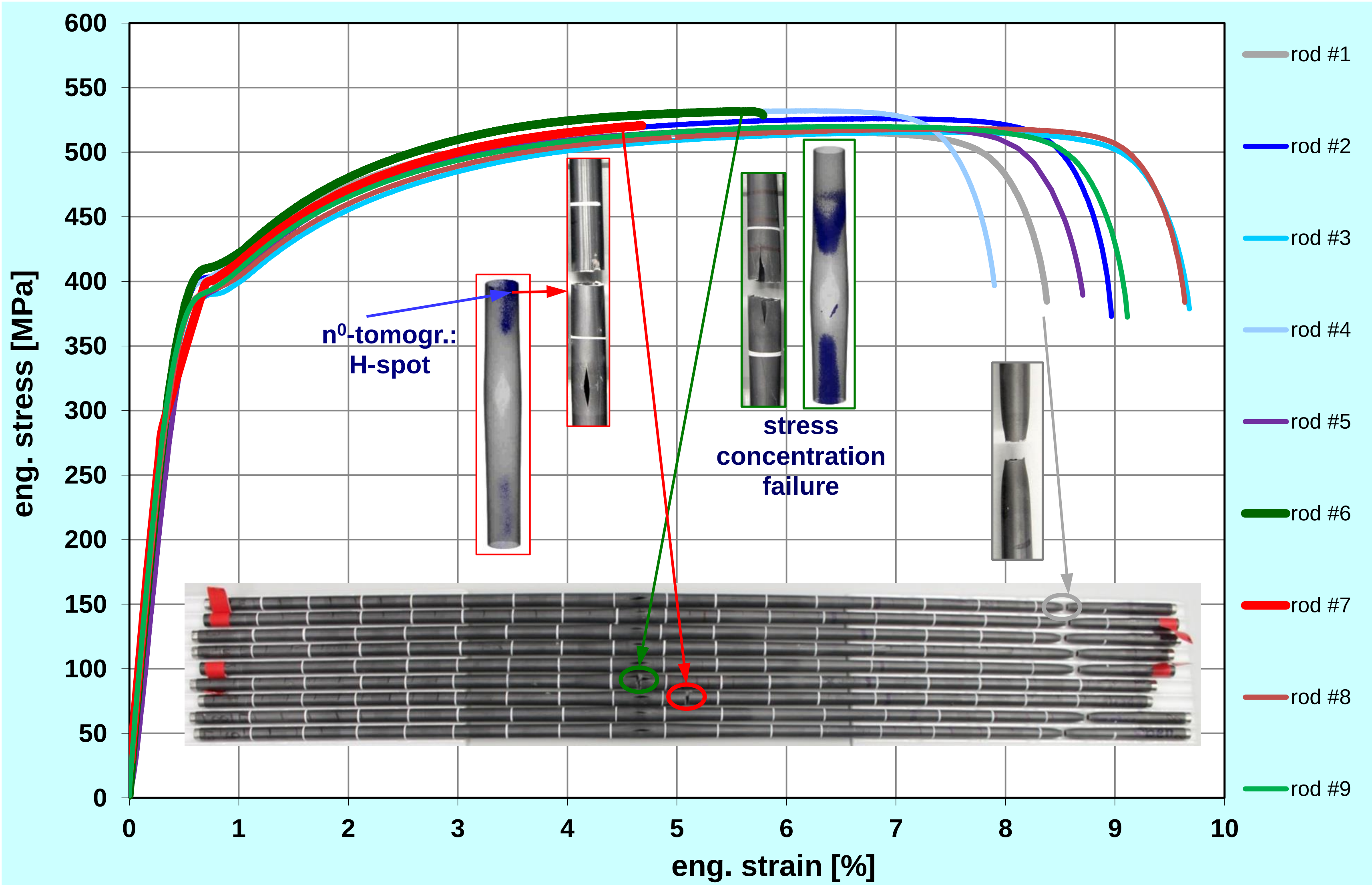
Comparison of oxidation degree for QL-1, -3, -3HT (eddy current measurements at outer clad surface)



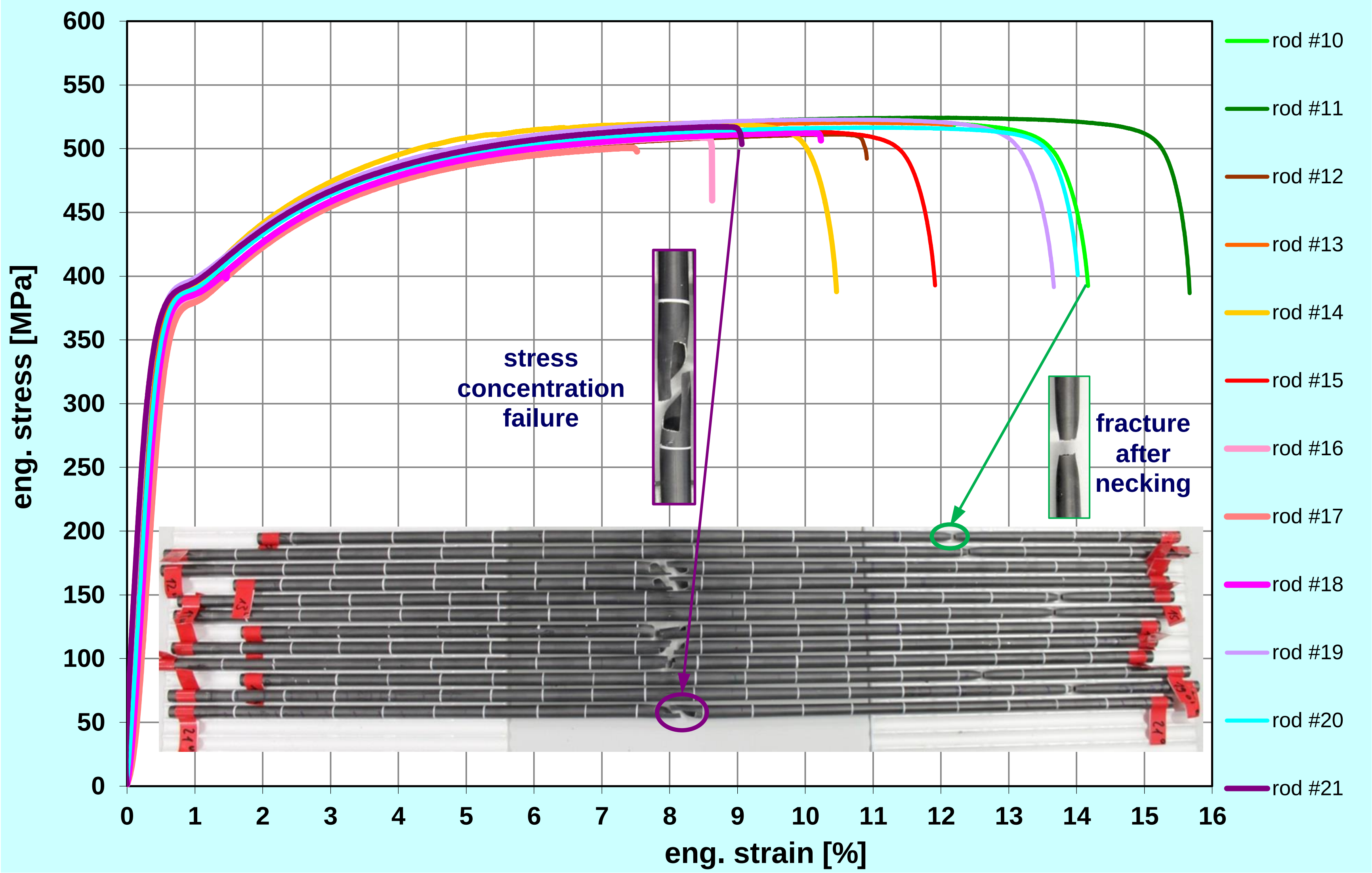
Test set-up for tensile tests with claddings from QUENCH-LOCA bundles



QUENCH-L3: tensile tests at RT with inner rods, fractures at H-bands (1 rod), through opening and due to necking (7 rods)



QUENCH-L3: tensile tests at RT with outer rods, fractures due to micro-cracks at the burst opening edges (6 rods) and necking (6 rods)



Failure behaviour of QUENCH-LOCA claddings tested in tension

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QL3 (opt. ZIRLO™)

QL1 (Zry-4)

QL0 (Zry4)

stress concentration at opening tips

hydrogen band

stress concentration

fracture after necking

Tensile properties of opt. ZIRLO™ claddings tested after QUENCH-L3

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sample	ultimate tensile stress [MPa]	fracture stress [MPa]	elongation at fracture [%]	failure behaviour
rod #1	516	384	8.4	fracture after necking
rod #2	526	373	9.0	fracture after necking
rod #3	515	379	9.7	fracture after necking
rod #4	532	379	7.9	fracture after necking
rod #5	520	386	8.7	fracture after necking
rod #6	**531**	**529**	**5.8**	***stress concentration at opening middle***
rod #7	**521**	**521**	**4.7**	**H-band**
rod #8	518	384	9.6	fracture after necking
rod #9	520	372	9.1	fracture after necking
rod #10	521	392	14.2	fracture after necking
rod #11	524	387	15.7	fracture after necking
rod #12	**511**	**492**	**10.9**	***stress concentration at opening tips***
rod #13	**520**	**517**	**12.2**	***stress concentration at opening tips***
rod #14	520	388	10.5	fracture after necking
rod #15	514	393	11.9	fracture after necking
rod #16	**509**	**459**	**8.6**	***stress concentration at opening tips***
rod #17	**501**	**498**	**7.5**	***stress concentration at opening tips***
rod #18	**512**	**506**	**10.2**	***stress concentration at opening tips***
rod #19	523	391	13.7	fracture after necking
rod #20	517	401	14.0	fracture after necking
rod #21	**517**	**503**	**9.1**	***stress concentration at opening tips***

fracture of clads

H-band: 1 clad,

stress conc.: 7 clads,

necking: 13 clads

Summary

- The QUENCH-LOCA-3 test with as-received opt. ZIRLO™ claddings was performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR with similar test parameters as the QUENCH-LOCA-1 test with fresh Zry-4 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-1, the maximum temperature of 1350 K was reached on the end of the heat-up phase at elevation 950 mm. Circumferential temperature gradient across a rod was up to 70 K on the burst onset.
- The maximum blockage ratio of cooling channel (21% at 918 mm) was slightly lower in comparison to QUENCH-L1 (25% at 946 mm). Due to moderate blockage a good bundle coolability was kept for both bundles.
- The cladding burst occurred at temperatures between 1064 and 1188 K (QUENCH-L1: 1074 and 1169 K). Average burst temperatures: 1126 K (853°C) for QUENCH-L1 and 1117 K (844°C) for QUENCH-L3.
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual strengths or ductility is sufficient).
- Influence of secondary hydrogenation on results of tensile tests at RT: only one cladding failed at hydrogen band; seven claddings failed due to stress concentration at edges of burst opening (similar to all QL1 clads with <1500 wppm hydrogen); thirteen clads failed after necking far away from burst opening.

Acknowledgment

The QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB). The unirradiated optimized ZIRLO™ claddings and spacer material were provided by WESTINGHOUSE.

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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