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Results of the reference bundle test QUENCH-L1 with Zircaloy-4 claddings and future planning of the QUENCH-LOCA program

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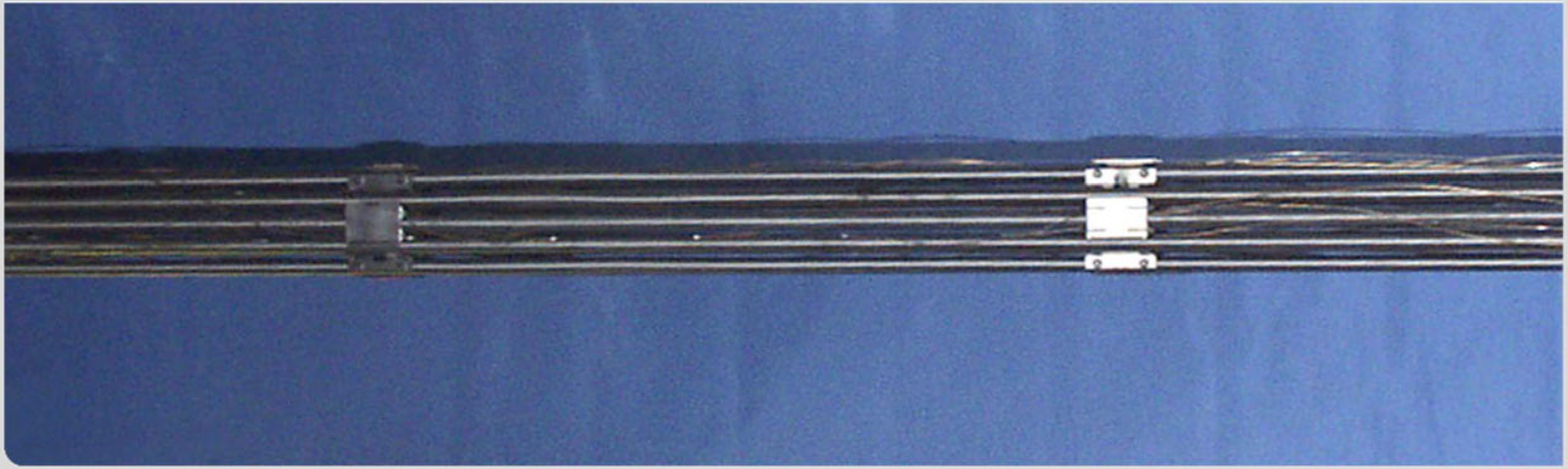
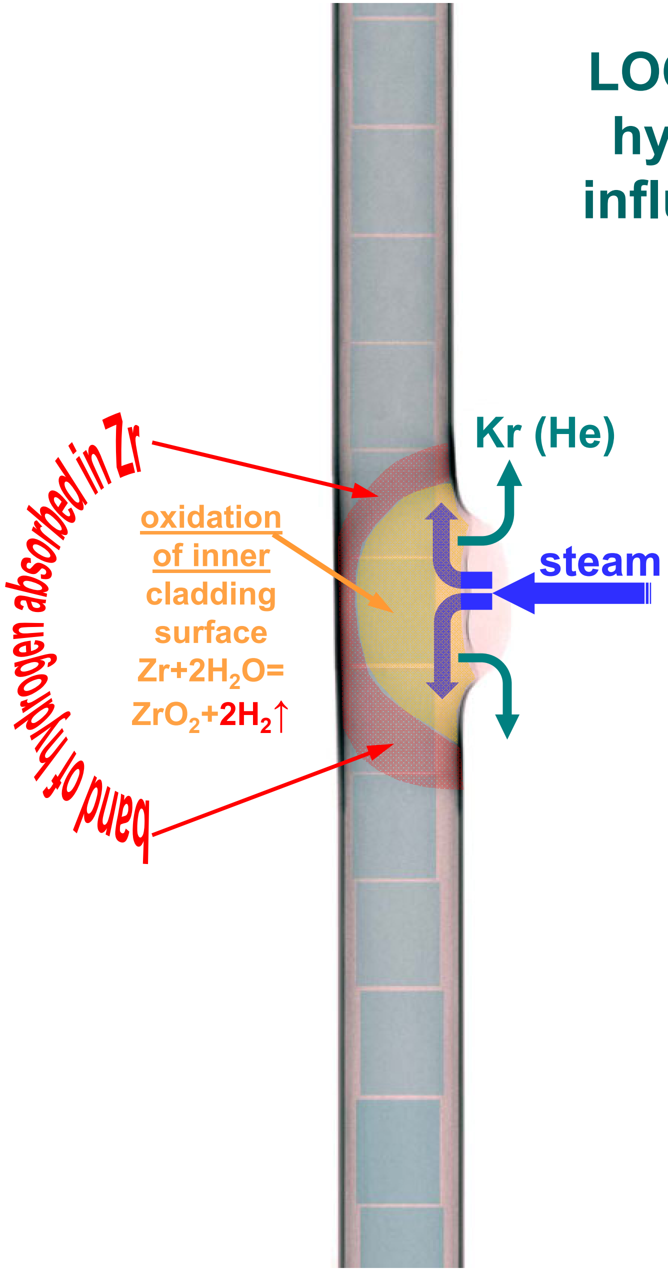
Institute for Applied Materials; Program NUKLEAR





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

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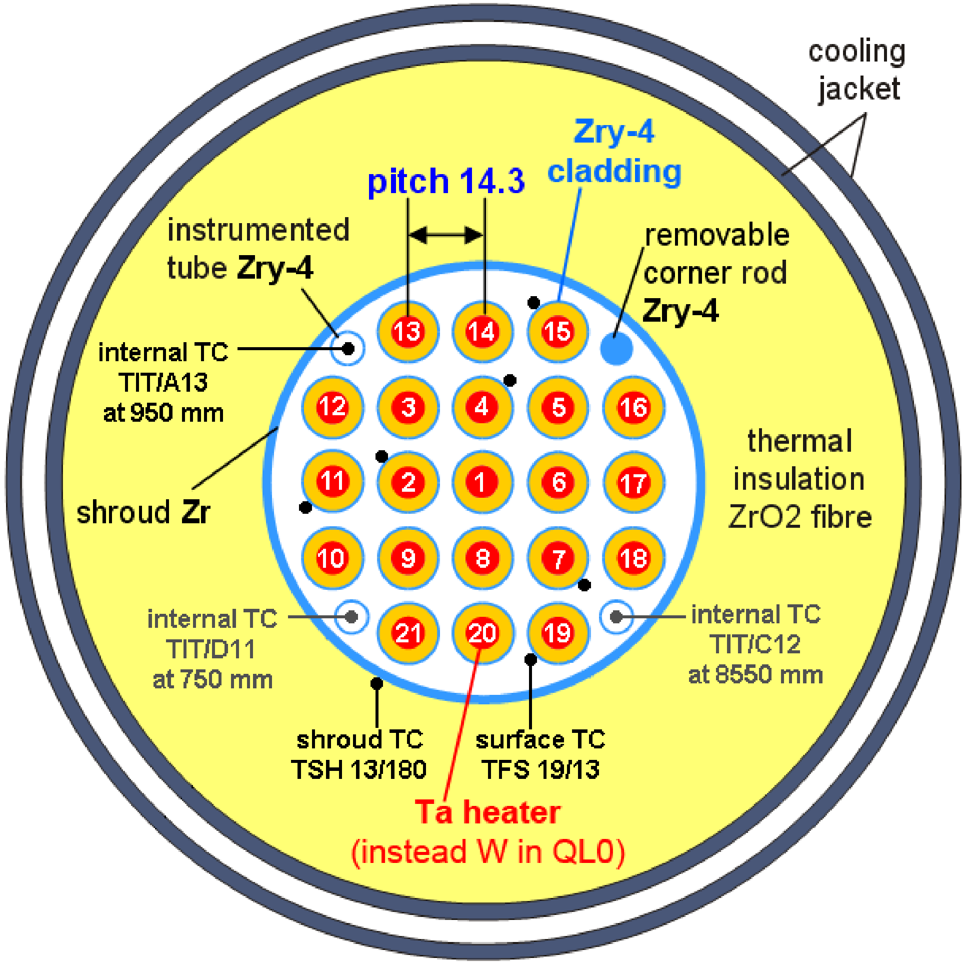
Sequence of phenomena:

- 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
- local embrittlement of cladding near to burst opening

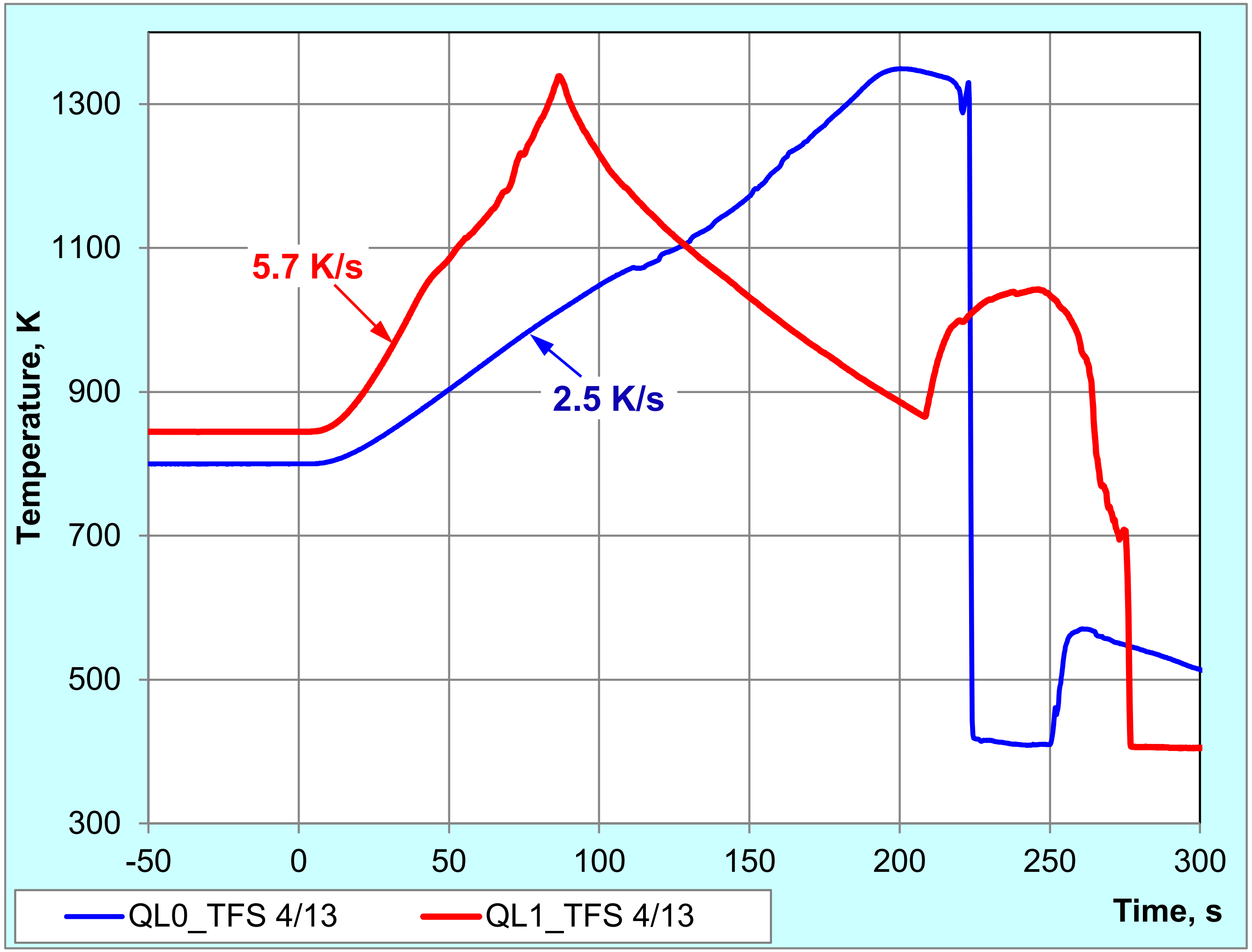
Cross-section of the QUENCH-L1 bundle



all rods filled with Kr with p=55 bar

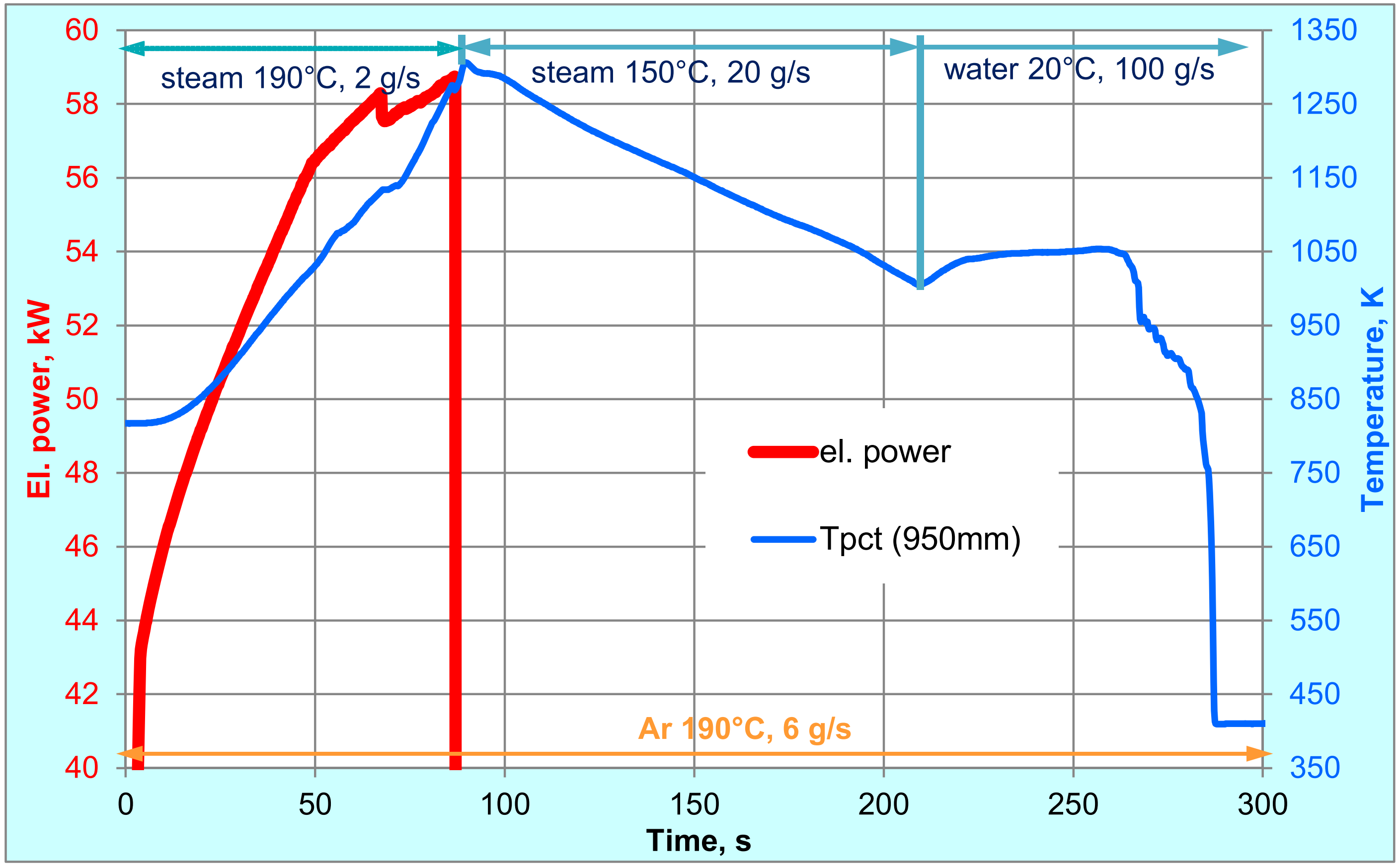
at Tpct=800 K

Comparison of cladding temperatures at hottest bundle elevation of 950 mm for QUENCH-L0 and -L1



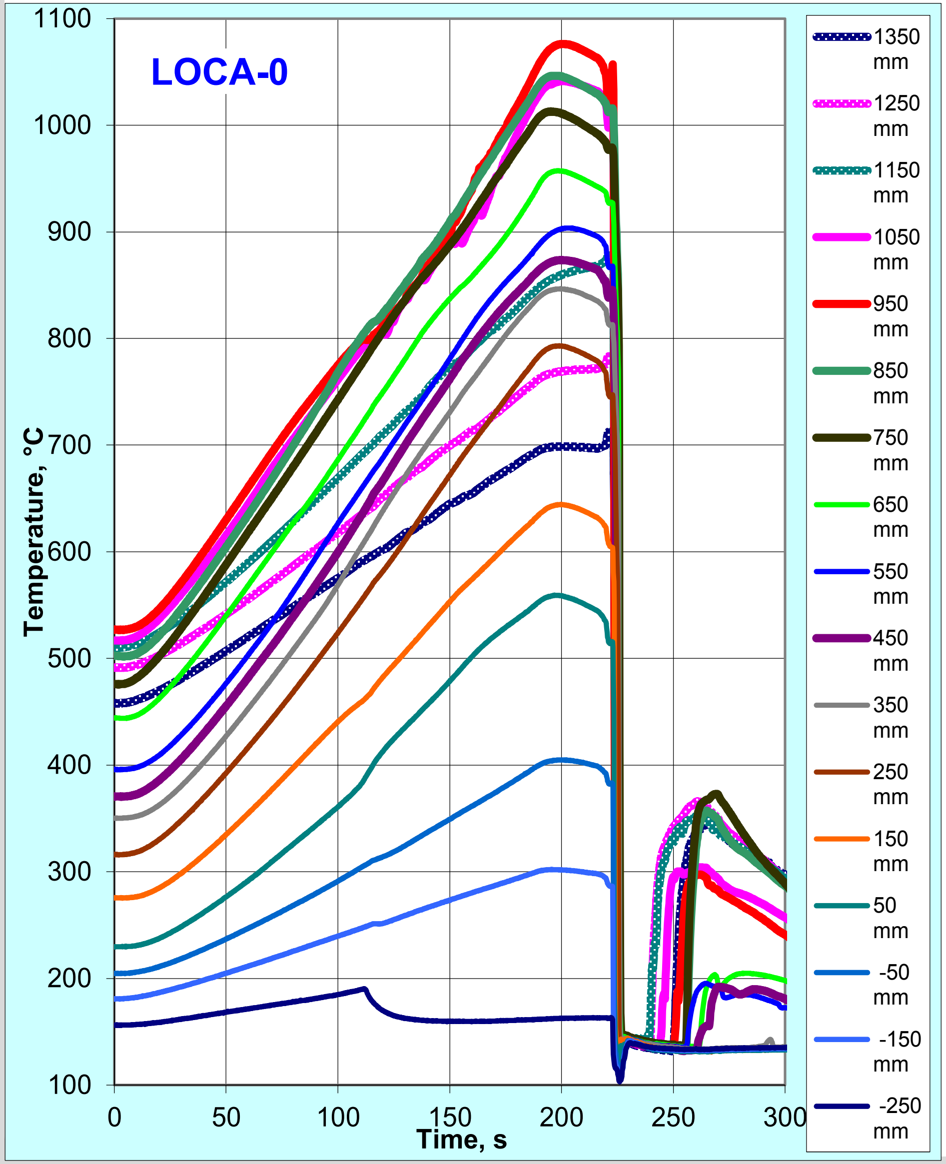
enhancements for QUENCH-L1:
1) prototypical high heating rate; 2) prototypical cool-down phase

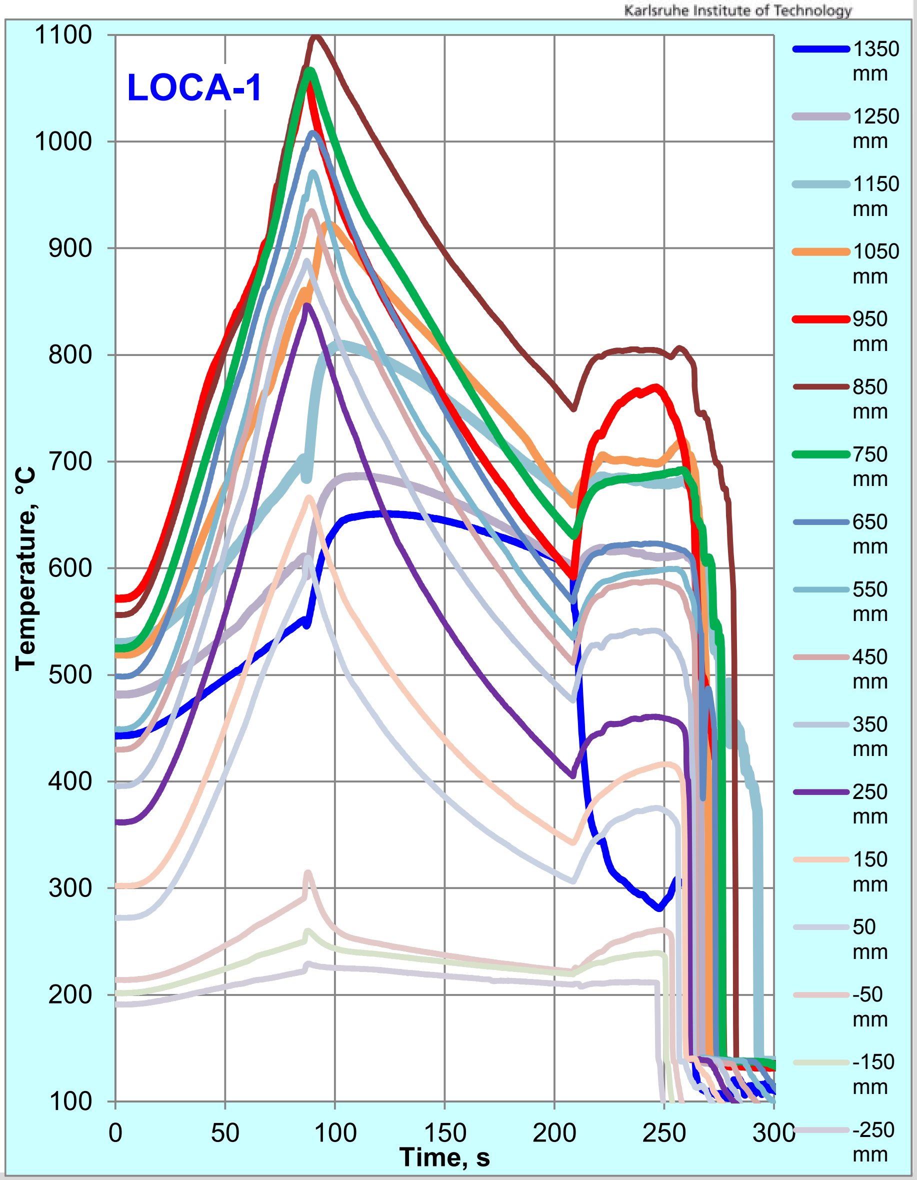
Scenario of the QUENCH-L1 test



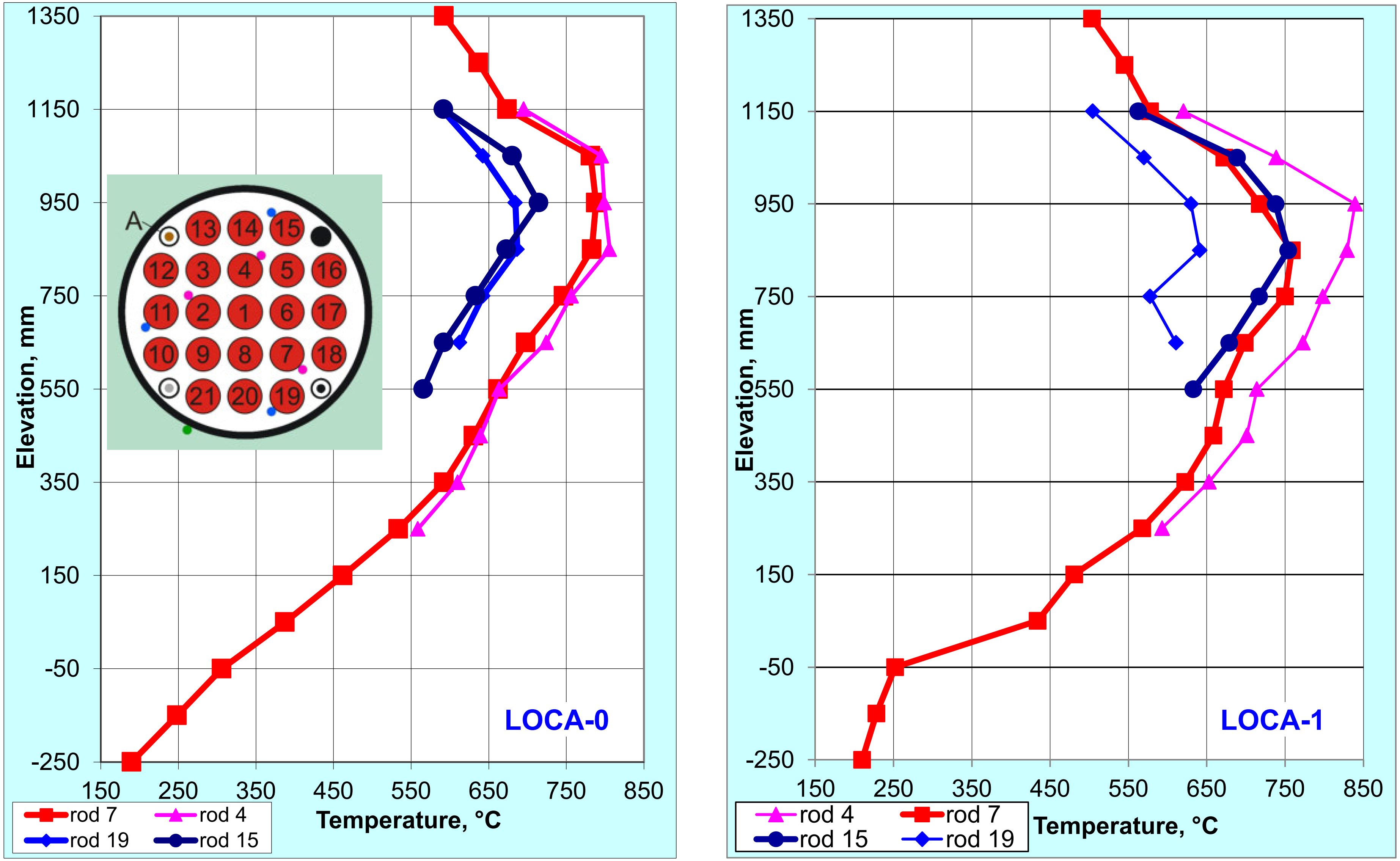
maximal reached power:
QUENCH-L1 (Ta-heaters, Ø 6 mm): 58.5 kW,
QUENCH-L0 (W-heaters; Ø 6 mm): 43 kW

Comparison of maximal cladding temperatures at different elevations for QUENCH-L0 and -L1

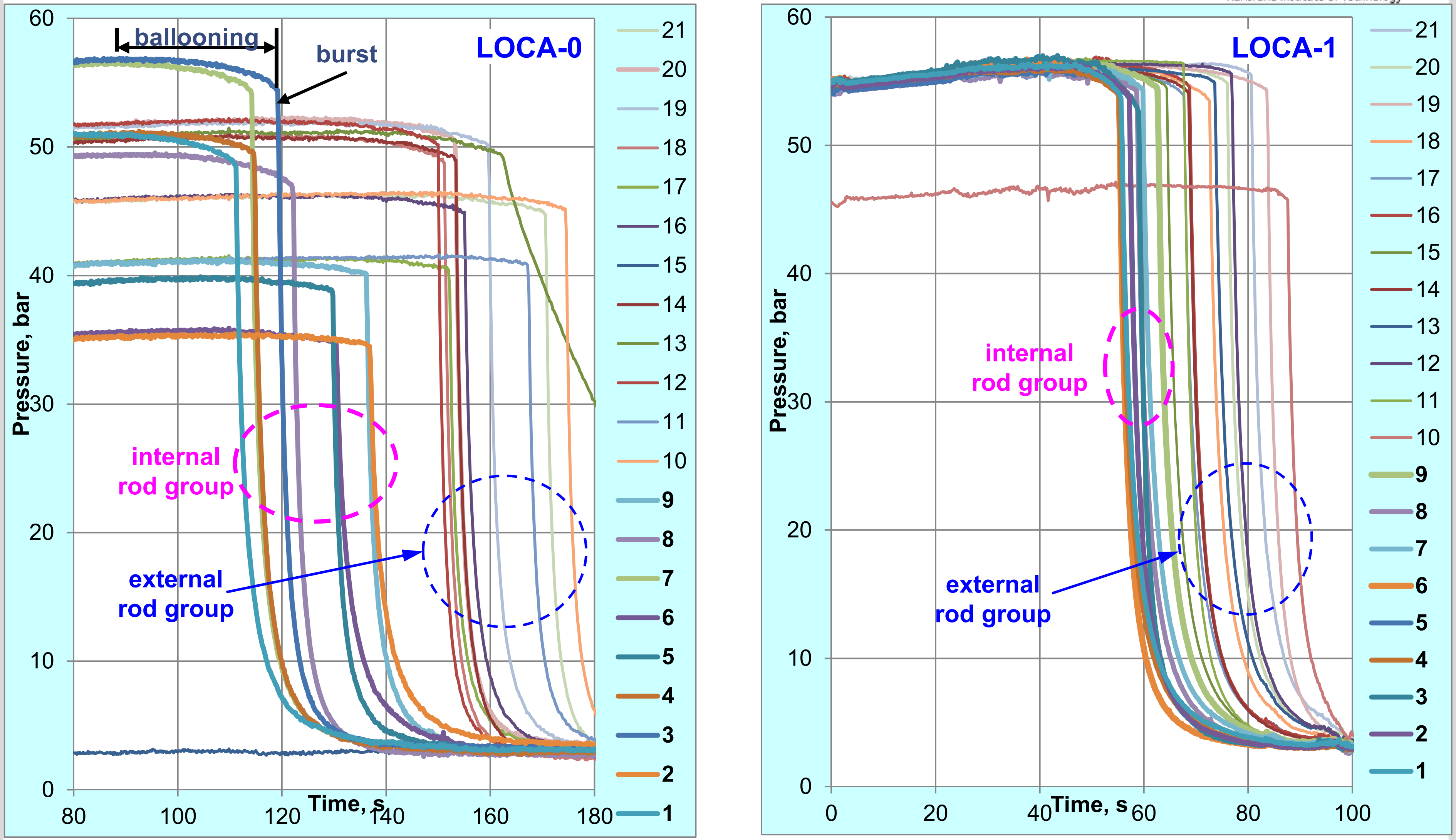




Axial and radial temperature distribution on first burst case for QUENCH-L0 (111 s, rod #1) and -L1 (55 s, rod #4)



Rod pressure evolution during heating phase for QUENCH-L0 and -L1: burst time indication (coincided with MS results on Kr release)



duration of decrease of the inner pressure to the system pressure: $\tau_0 \approx 38$ s

Post-test QL1 bundle view between GS3 and GS4

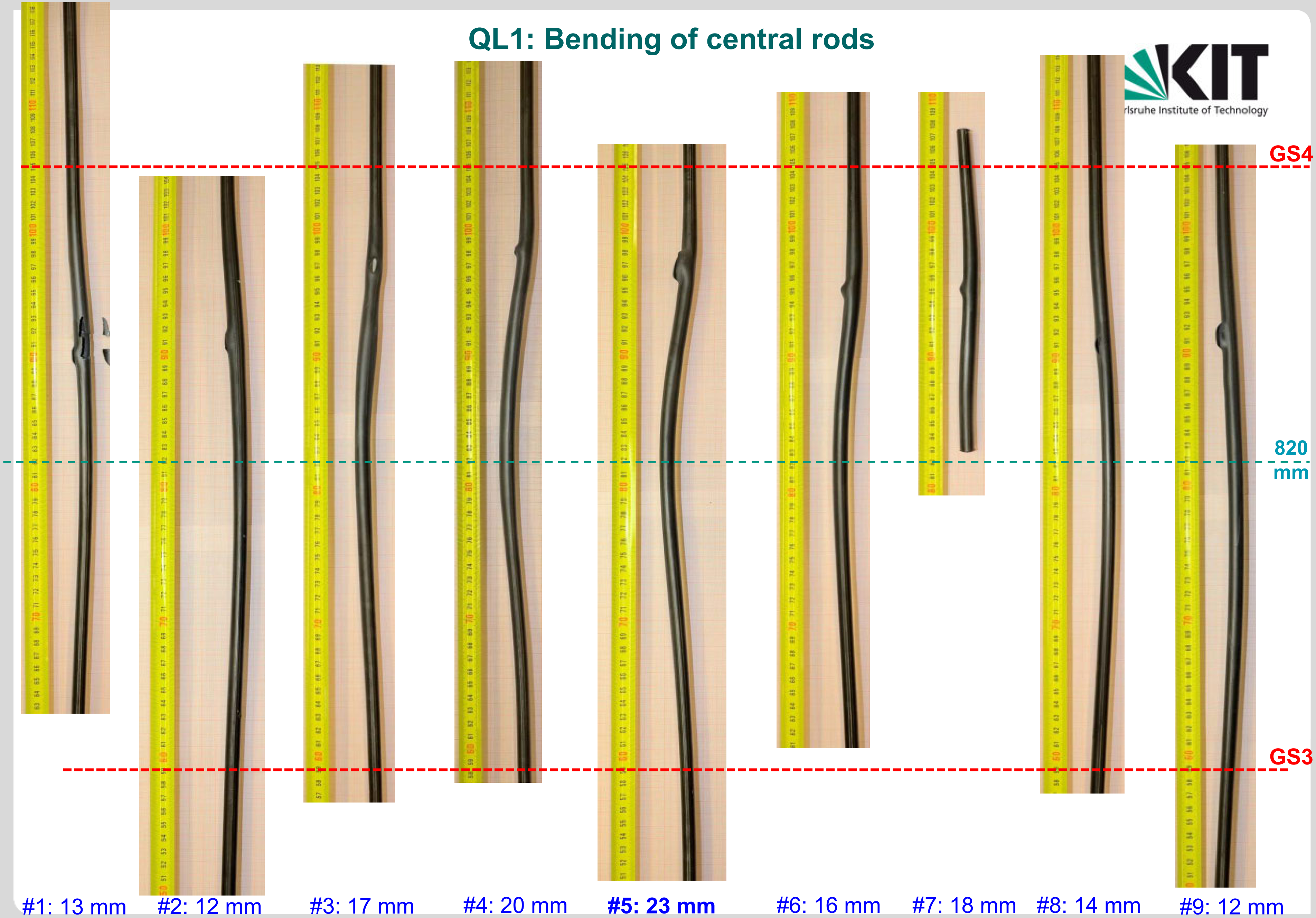

0°


90°

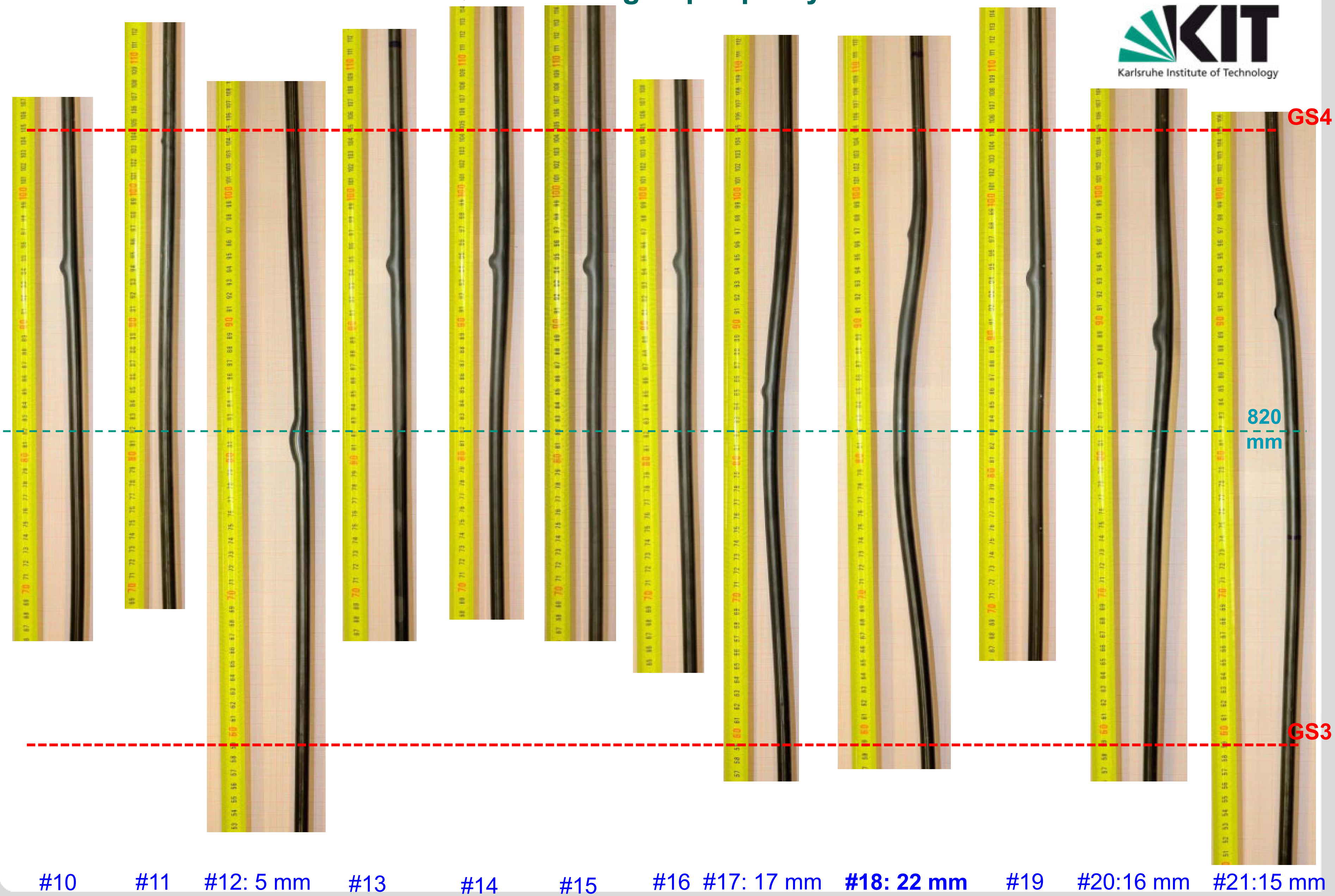

180°: rod bending


270°

QL1: Bending of central rods



QL1: Bending of periphery rods



QL1: estimation of rod position near to middle position between two spacer grids according to measured rod bending and videoscope observations

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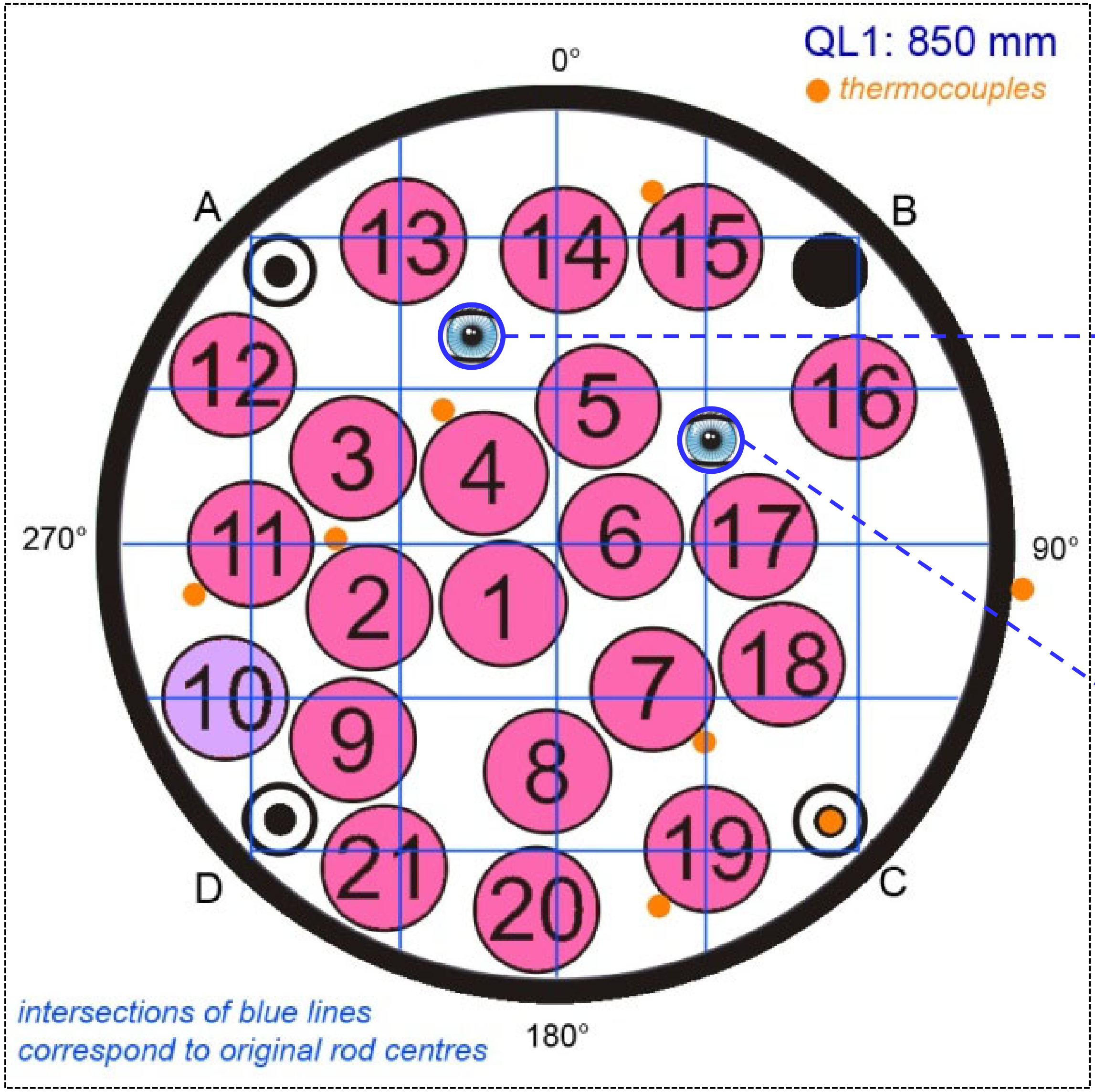
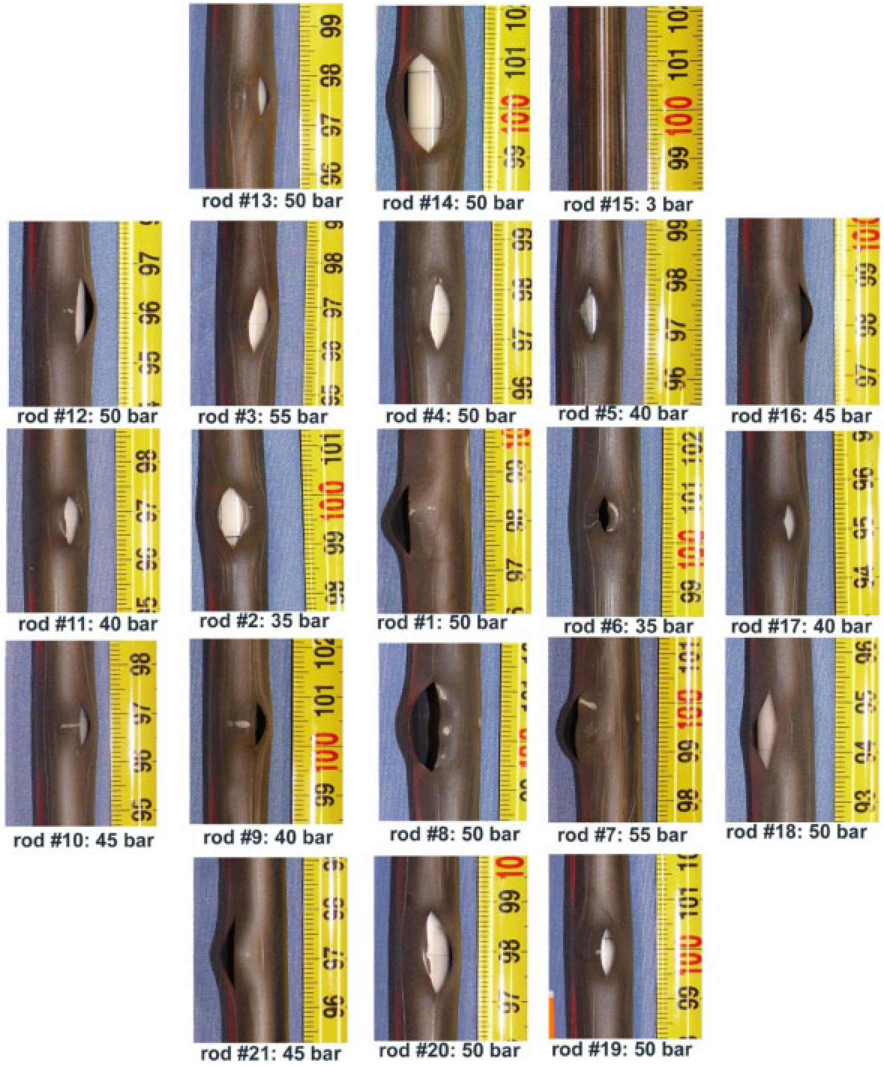


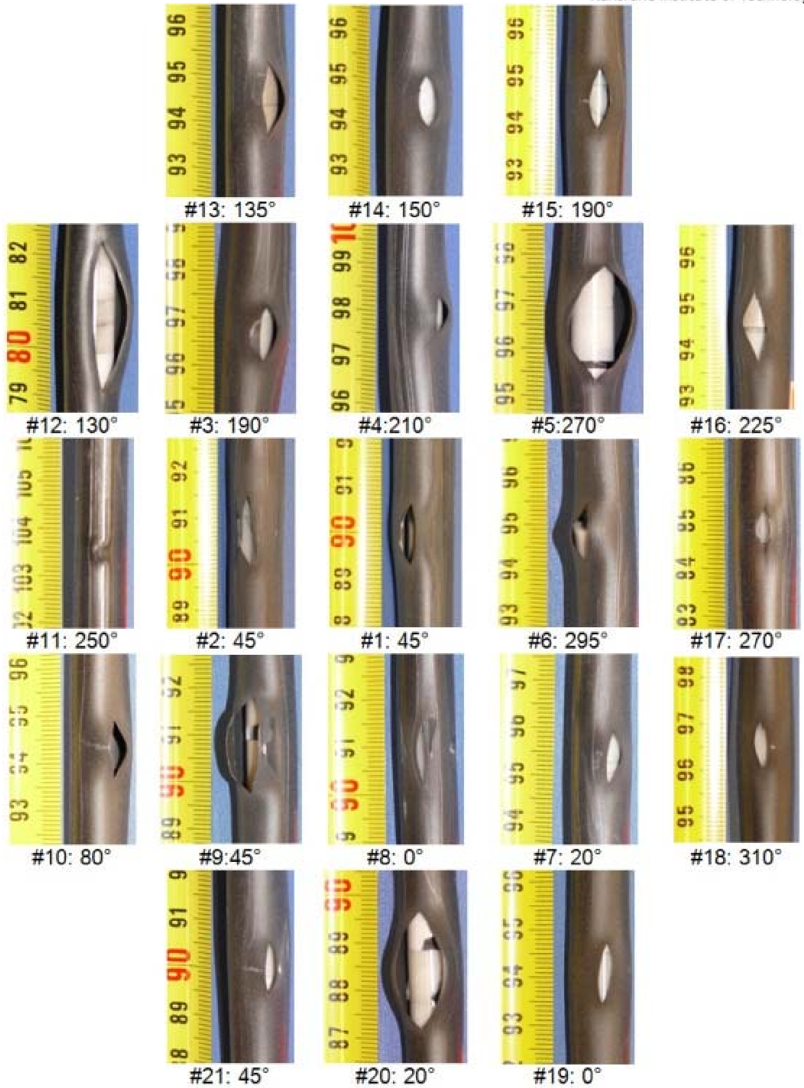
850 mm: touched rods # 3, 4, 5

950 mm: touched rods # 5, 6, 17

Overview of burst openings

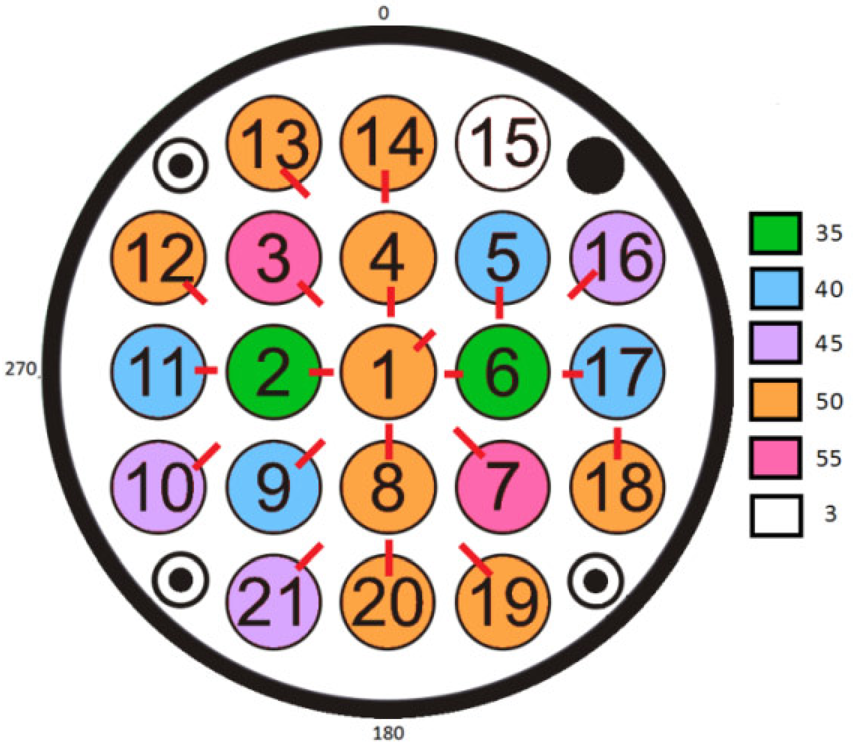


LOCA-0

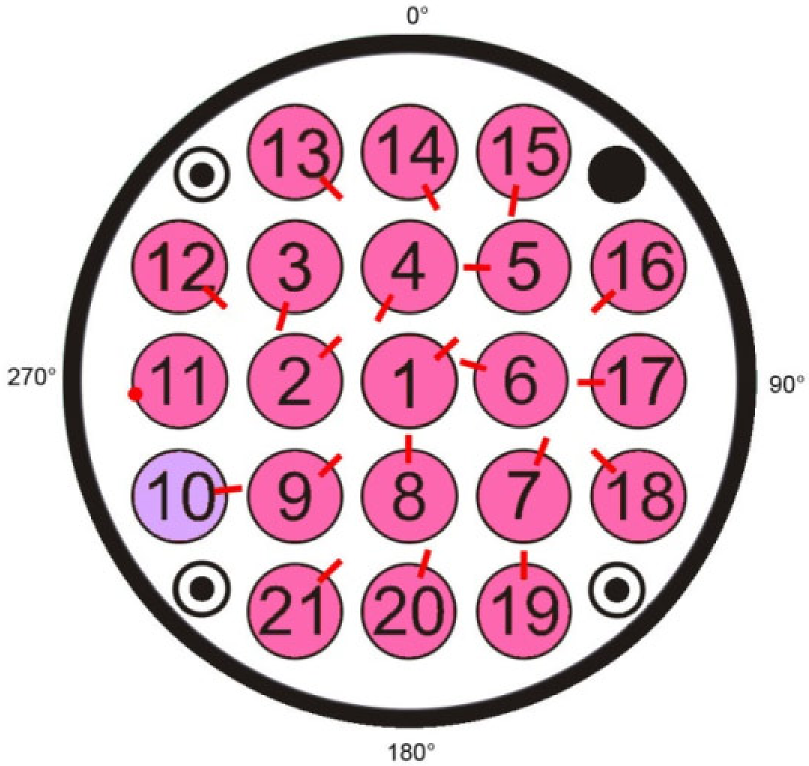


LOCA-1

Circumferential position of burst openings



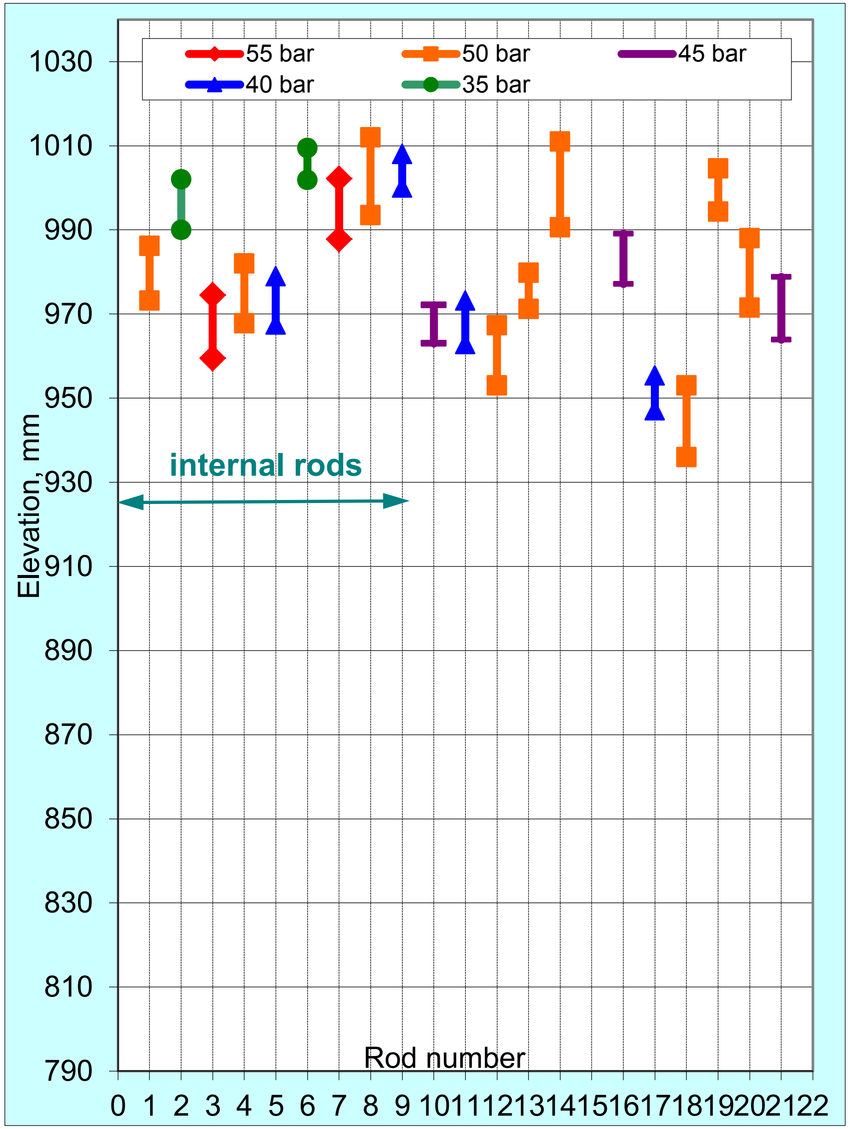
LOCA-0:
openings oriented
to bundle center
due to strong radial T gradient



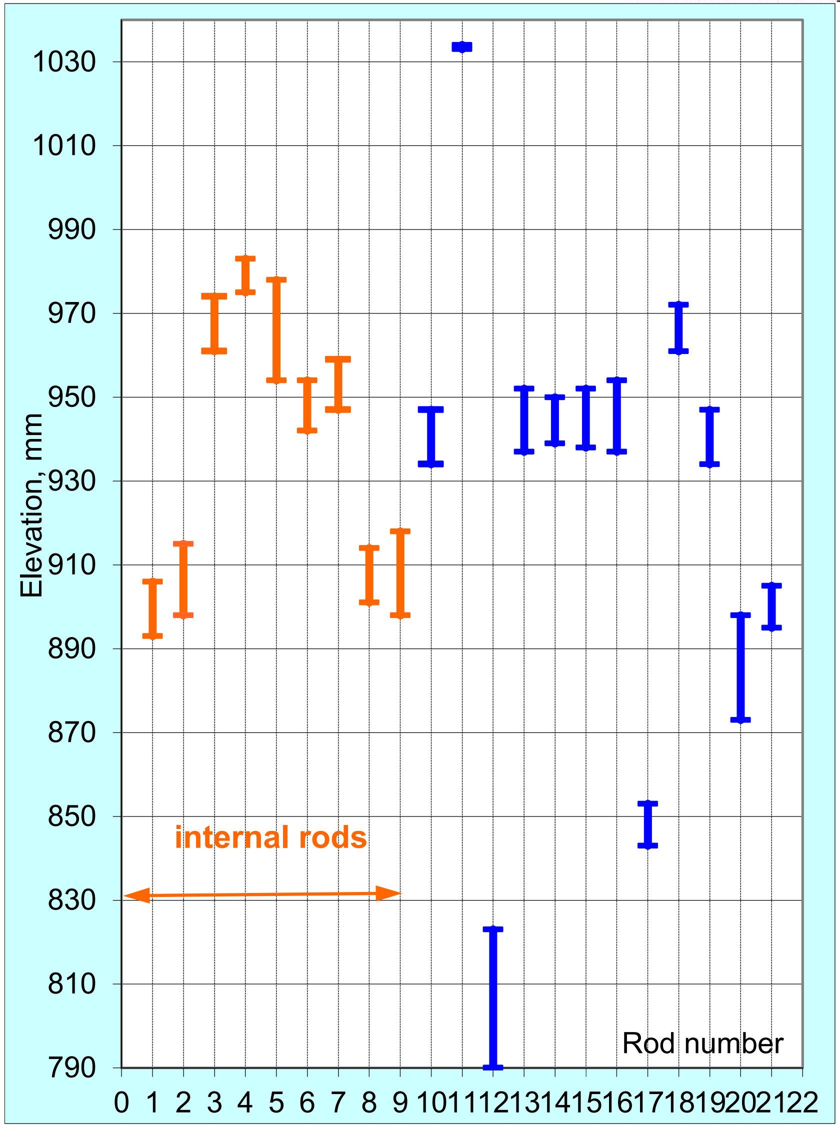
LOCA-1:
not strong orientation
to bundle center

Length and axial position of burst openings

LOCA-0



LOCA-1



Burst-Parameters

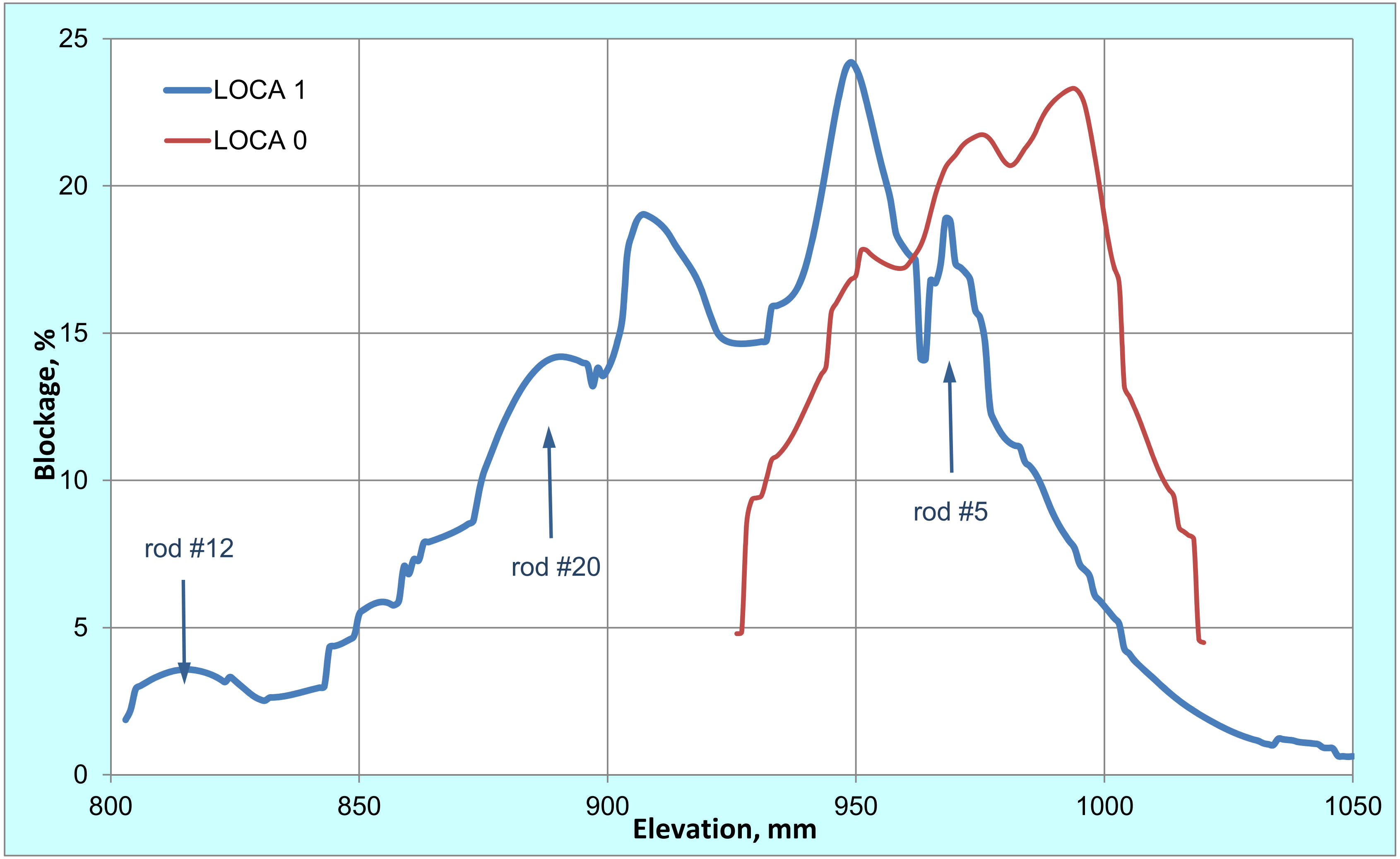
LOCA-0

Rod group	Rod #	Burst time, s	Burst temperature, interpolated, °C
Center	**1**	**111.2**	**914**
	7	**114.2**	**888**
	4	**114.6**	**867**
	3	**119.2**	**881**
	8	**122.0**	**880**
	5	**129.6**	**911**
	6	**130.4**	**910**
	9	**136.2**	**939**
	2	**136.8**	**940**
Periphery	12	150.0	891
	18	151.2	907
	17	152.0	933
	20	153.2	**849 (Min)**
	14	153.4	898
	16	155.0	894
	19	159.6	929
	13	162.5	880
	11	167.2	**948 (Max)**
	21	170.6	870
	10	174.4	865

LOCA-1

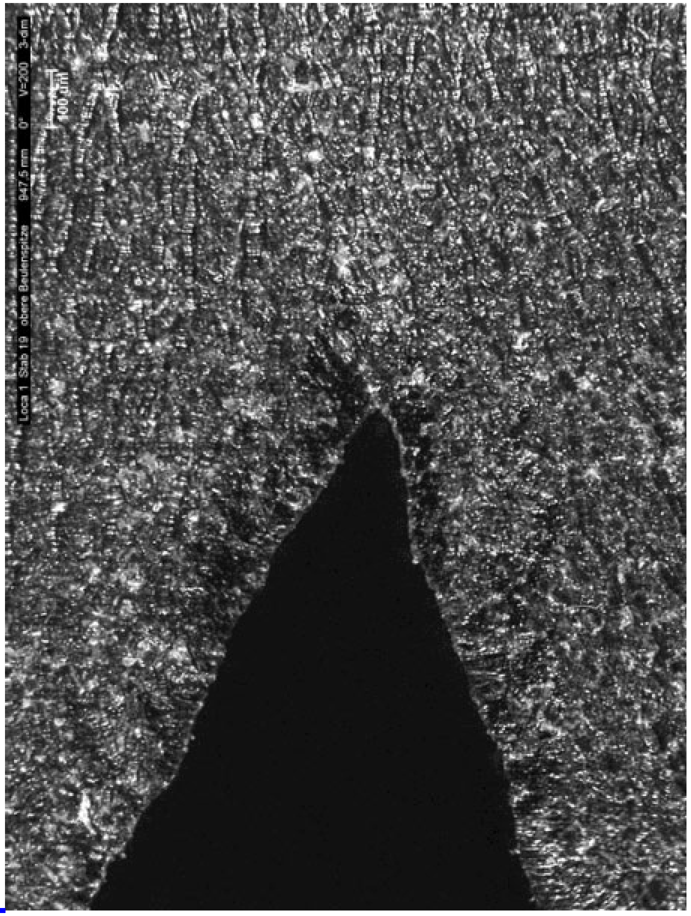
Rod group	Rod #	Burst time, s	Burst temperature, interpolated, °C
Zentralstäbe	**4**	**55.2**	**881**
	6	**55.2**	**837**
	1	**55.6**	**896 (Max)**
	5	**57.2**	**831**
	2	**57.2**	**859**
	8	**58.6**	**859**
	3	**59.0**	**845**
	7	**59.8**	**801 (Min)**
	9	**62.6**	**889**
Peripheriestäbe	15	64.4	886
	17	67.6	831
	11	*67.6*	*783*
	14	68.6	881
	16	68.8	883
	18	72.6	808
	13	73.6	874
	20	76.0	832
	12	76.8	819
	21	80.6	867
	19	83.6	890
	10	87.6	870

Cooling channel blockage for LOCA-0 and LOCA-1



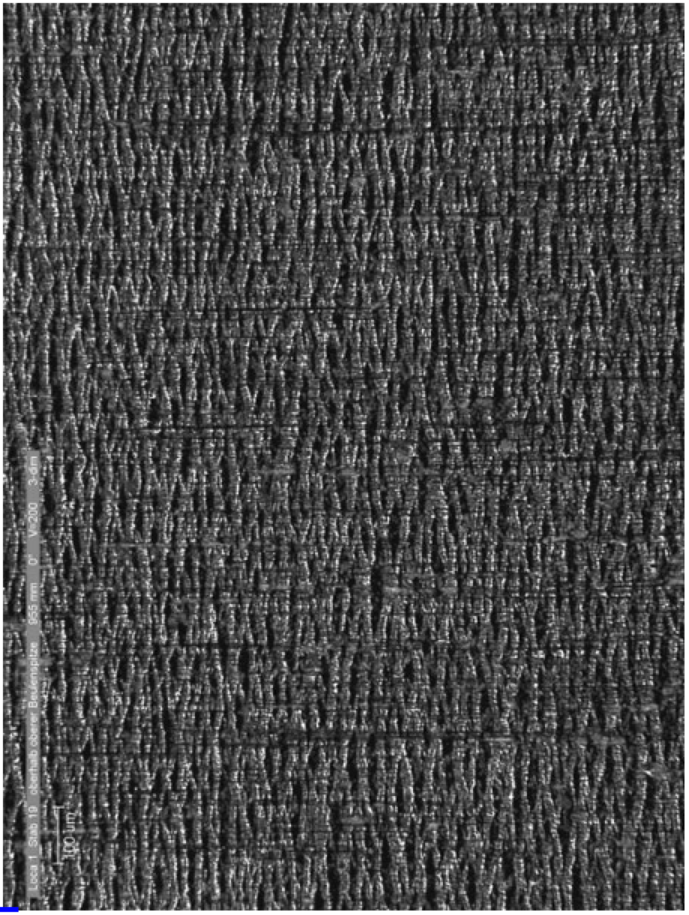
LOCA-1, oxidised outer surface of ballooning region (rod #19): typical tree bark structure with micro cracks formed due to strain during ballooning

940 mm

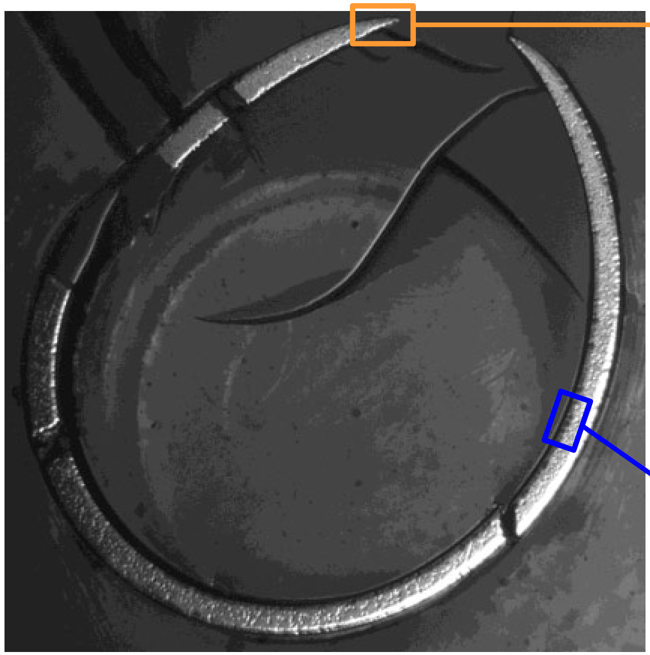


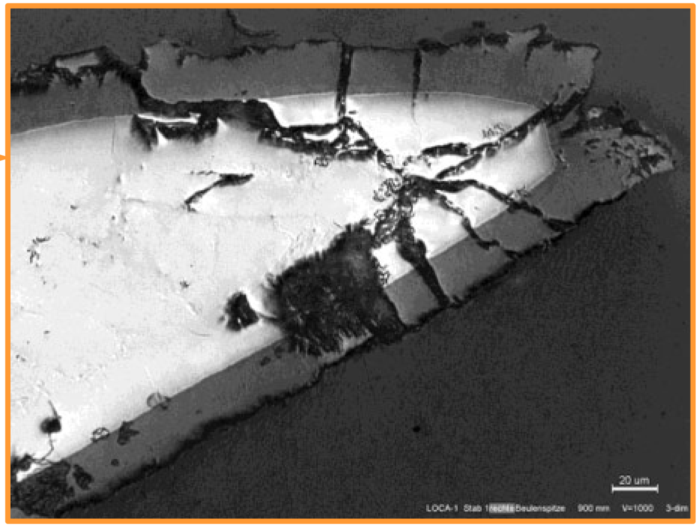
100 µm

955 mm

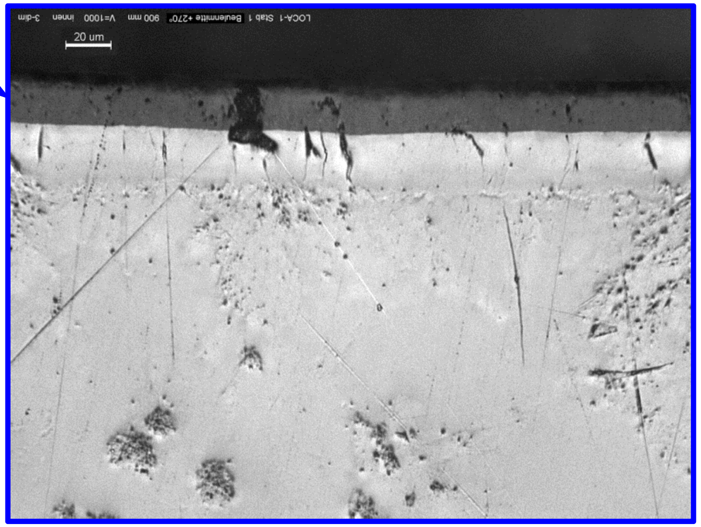


Outer and inner cladding oxidation at 900 mm for LOCA-1, rod #1



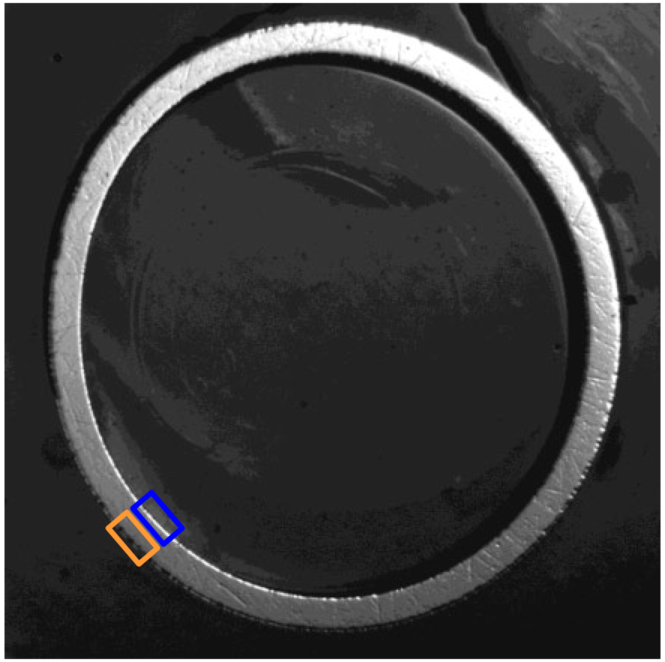


inner and outer oxide:
20 µm

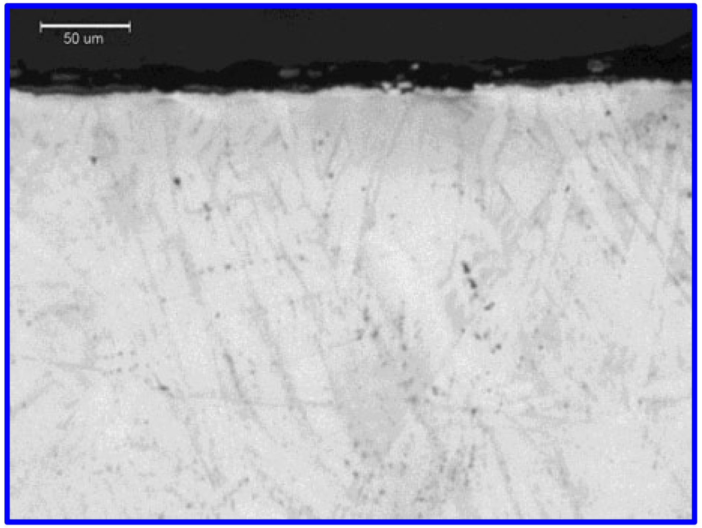


inner oxide:
20 µm

Outer and inner cladding oxidation at 920 mm of LOCA-1, rod #1

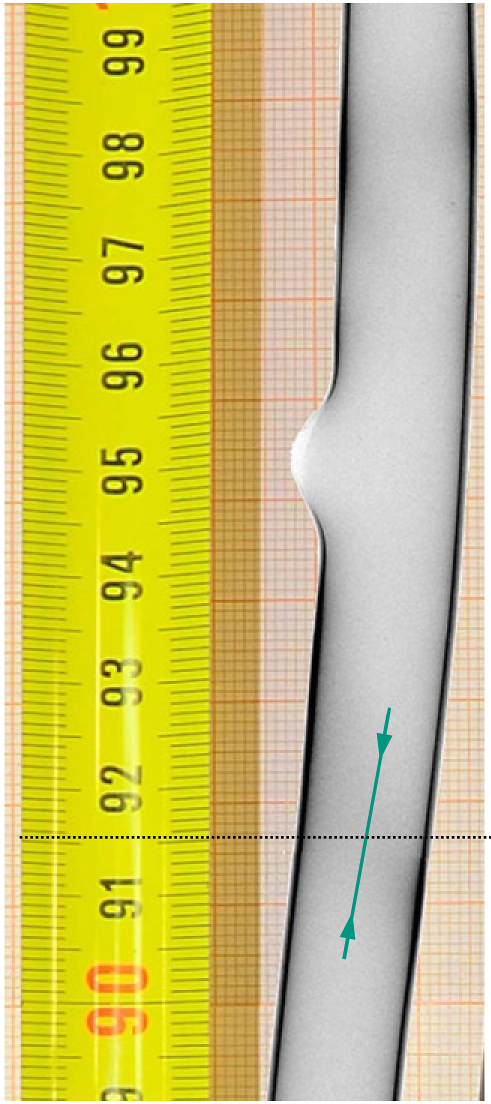


outer oxide: **12 µm**

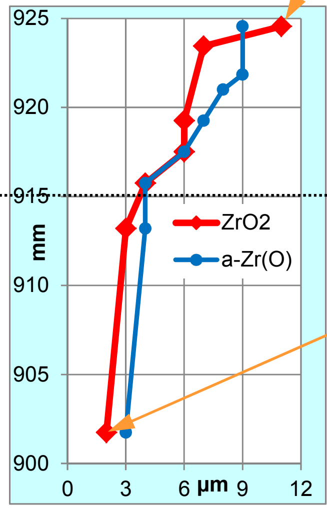


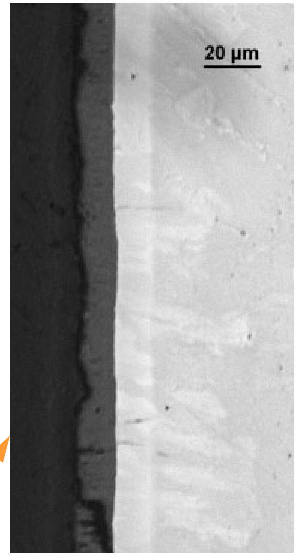
inner oxide: **4 µm**

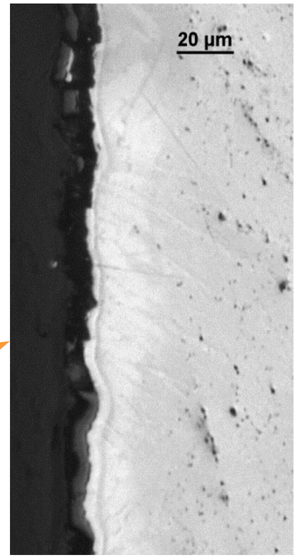
QL1, rod #6: axial distribution of inner oxidation in region of secondary hydrogenation

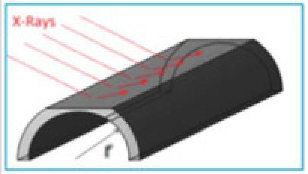


metallographic measurements along longitudinal cut:

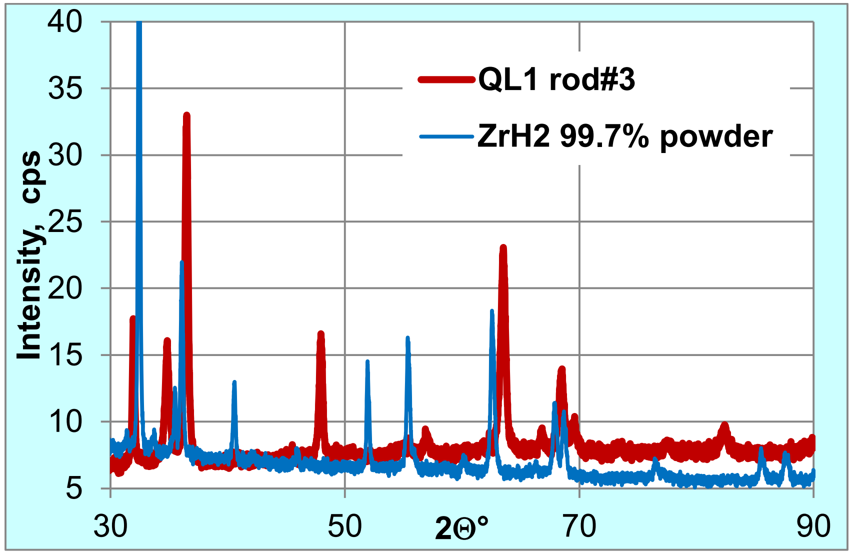


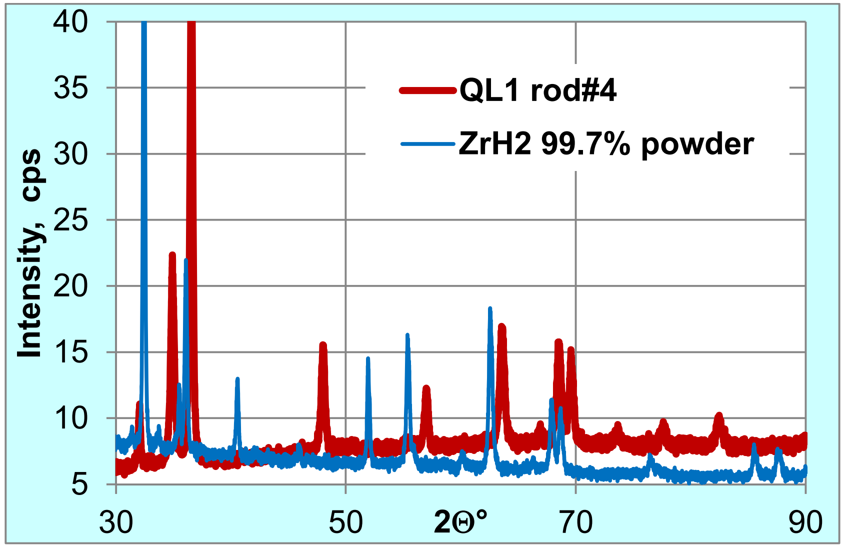


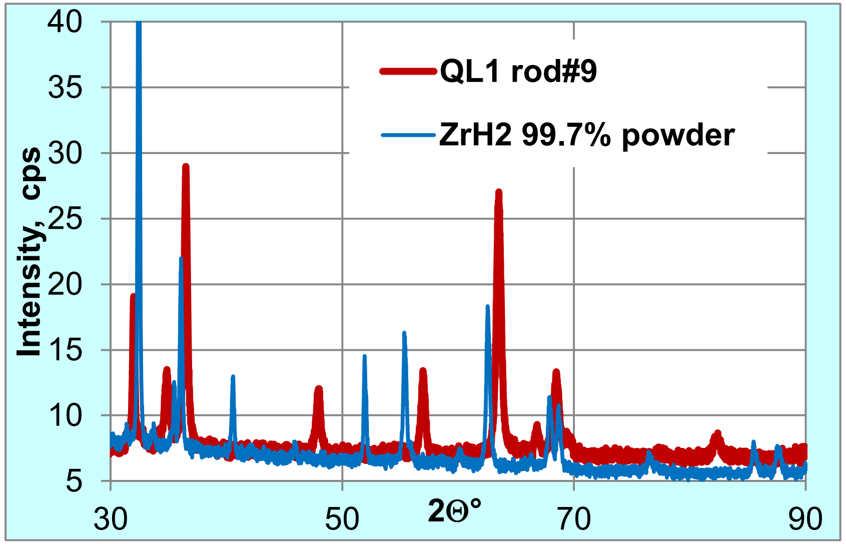


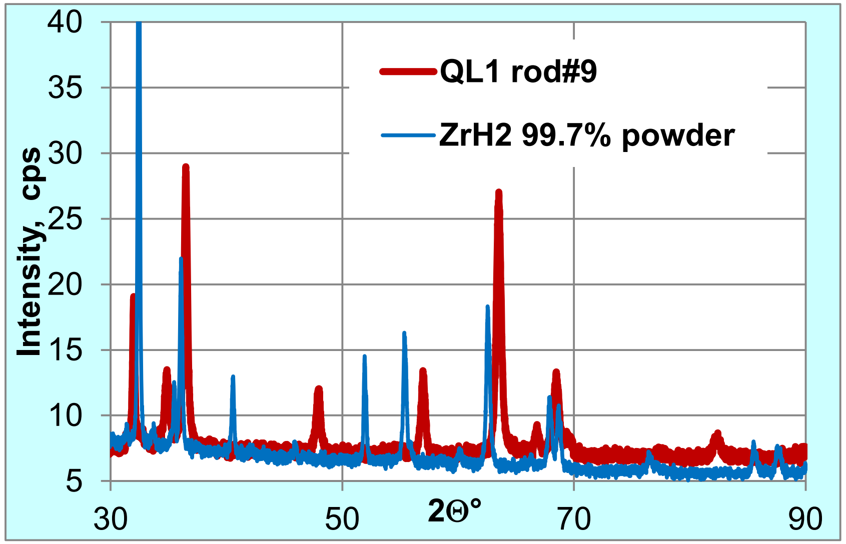


QL1, results of X-ray (λ=154 pm) diffractometry: no evidence of hydrides with sizes more 10 nm

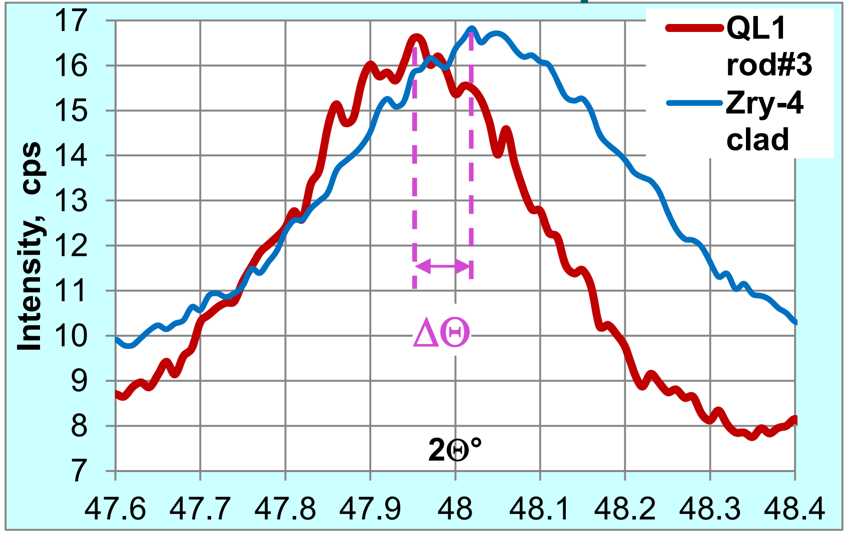




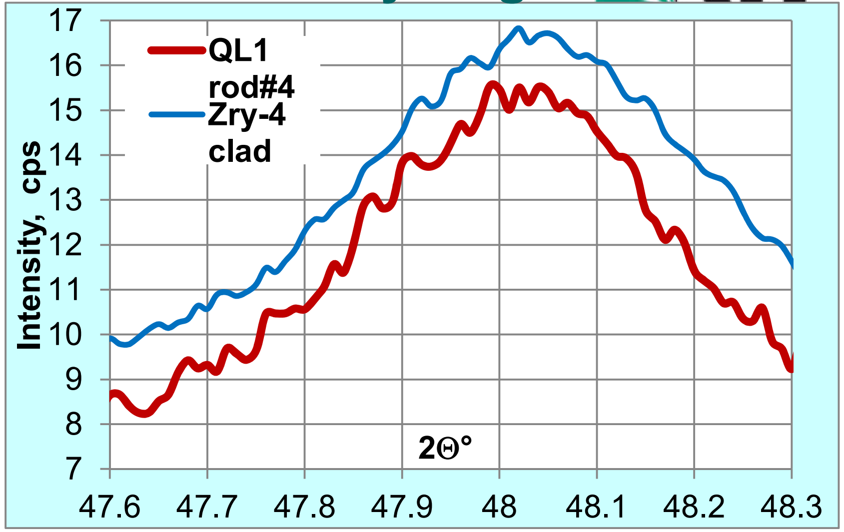




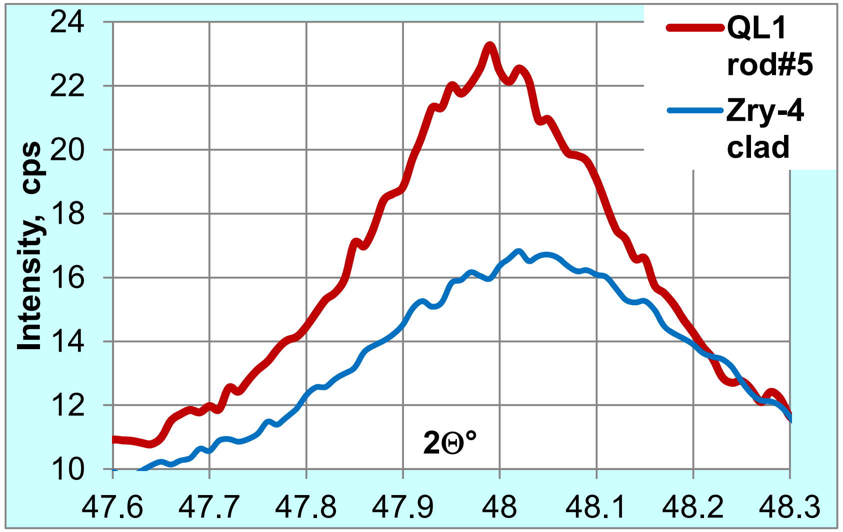
QL1, shift of XRD peaks: increase of lattice parameters due to dissolved hydrogen



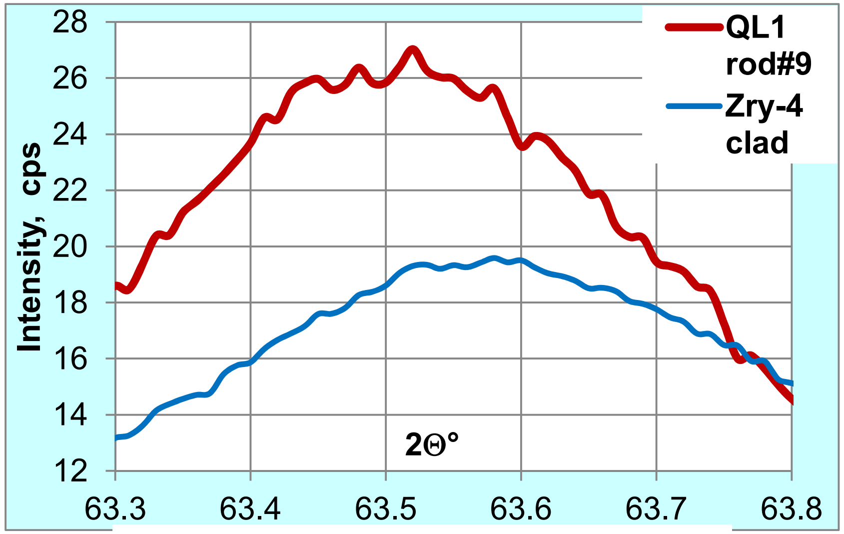
ΔΘ = -0.07° → C_H ≈ 260 wppm



ΔΘ = -0.02° → C_H ≈ 75 wppm

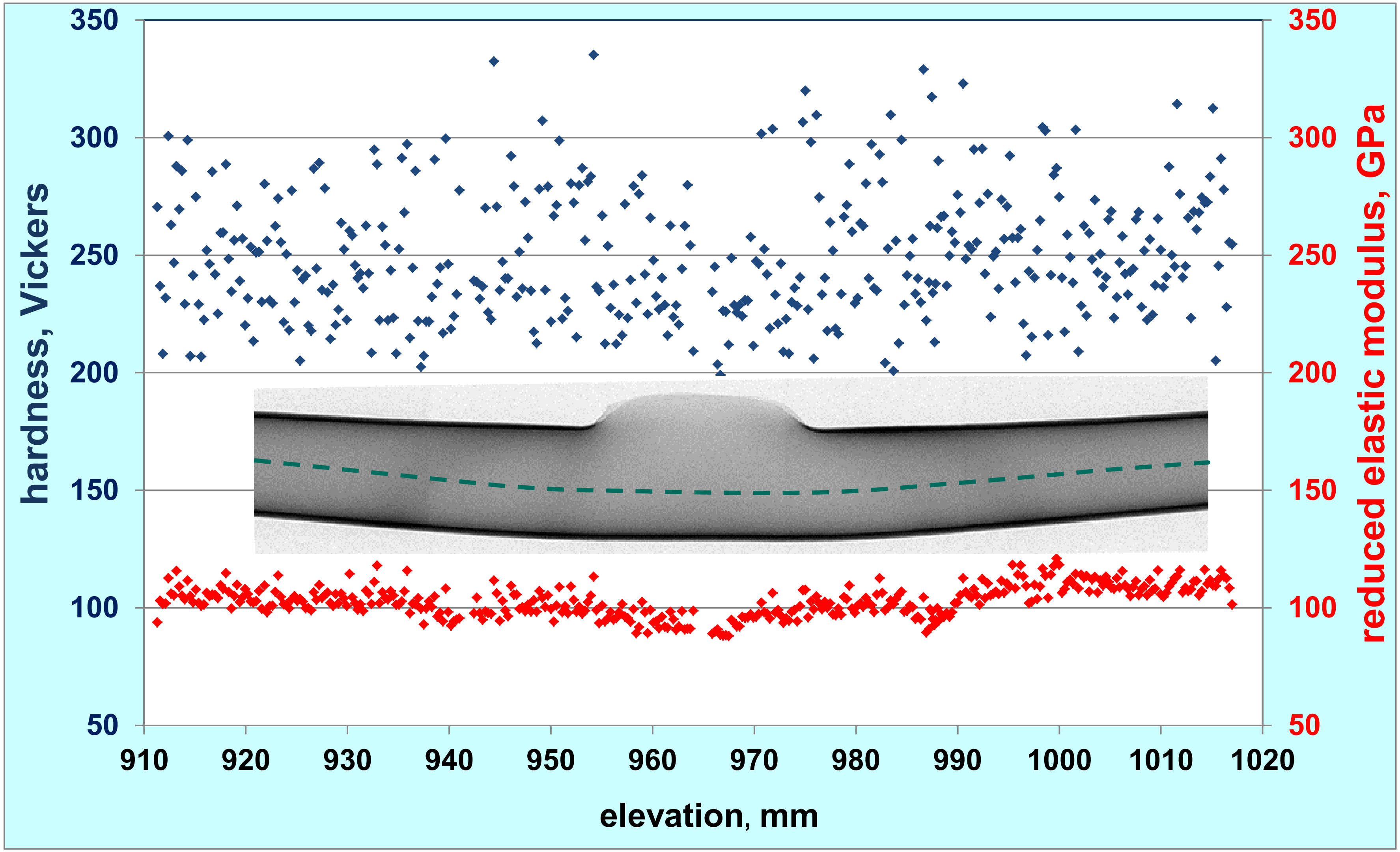


ΔΘ = -0.04° → C_H ≈ 150 wppm

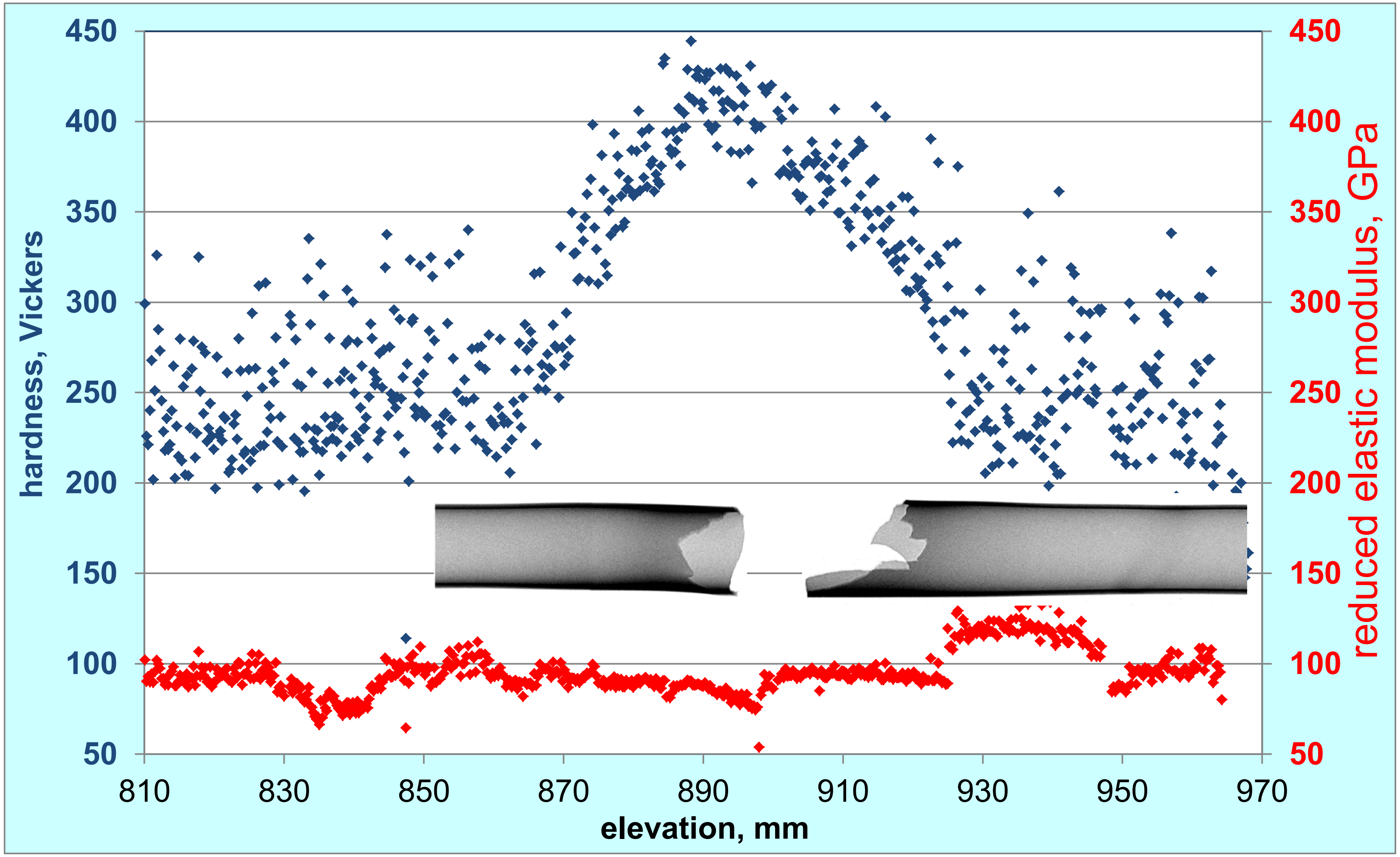


ΔΘ = -0.05° → C_H ≈ 190 wppm

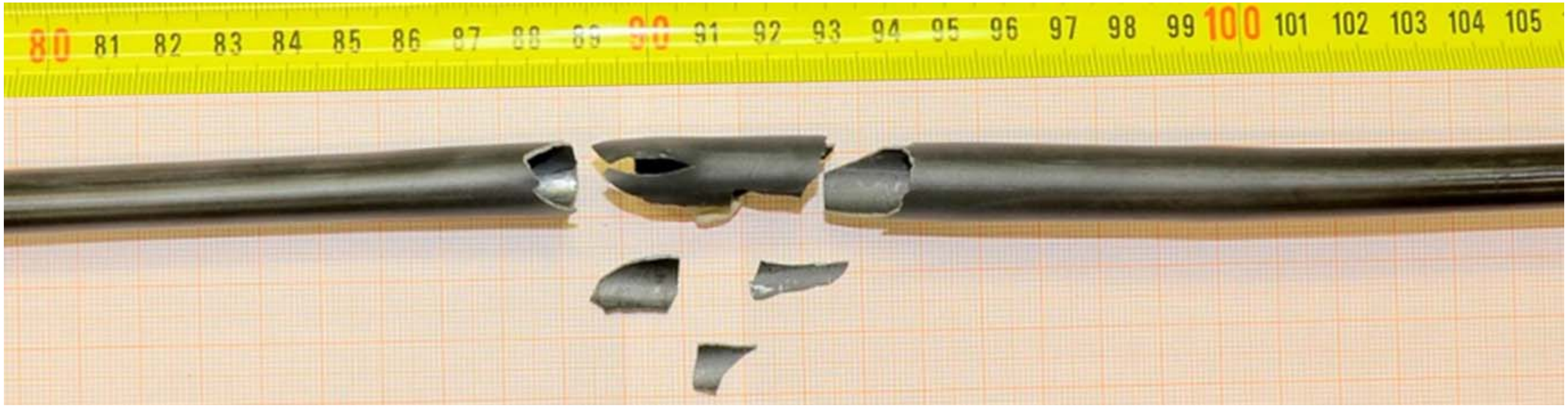
QL1 rod #5, micro hardness and Young's module of cladding measured at longitudinal section: hydrogen bands not detected

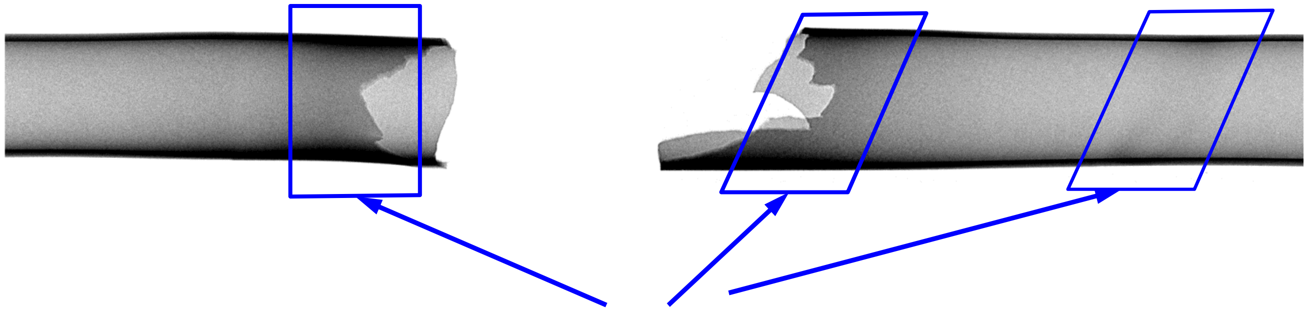


QL1 rod #1, micro hardness and Young's module of cladding measured at longitudinal section: hydrogen bands detected



QL1, central rod #1: brittle rupture during handling





n^0-radiography: hydrogenated bands
(secondary hydrogenation during oxidation of the inner cladding surface through the burst opening)

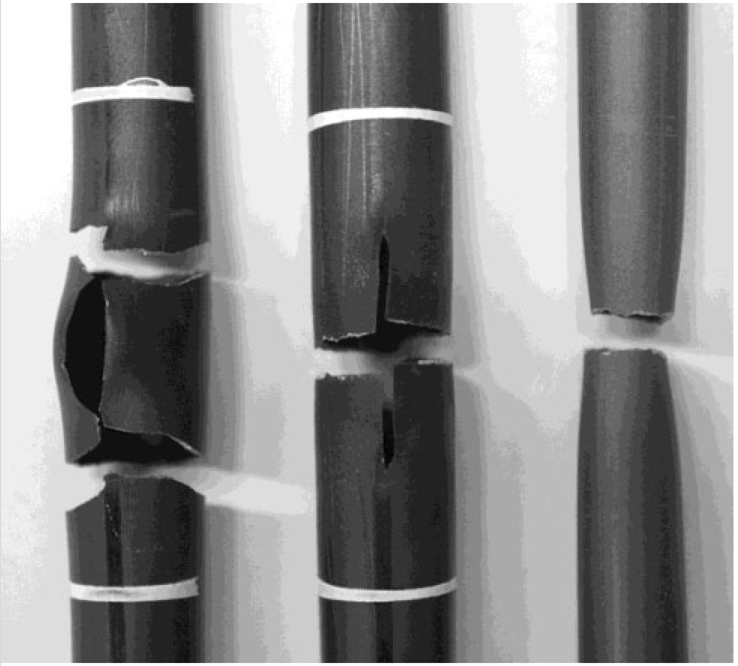
max hydrogen concentration in hydrogenated bands (according to estimation derived for QL0):

$$C_H(t) \approx 2 \cdot 10^3 \cdot \frac{k_{H2}\,\overline{p}_{H2}}{\rho_{Zry} L R \overline{T}}\, t \approx 1500\, wppm$$

for $\overline{T}$=1173 K and t=150s, $\overline{p}$=6000Pa

Failure behavior during tensile tests

QL0: 3 types



hydrogen embrittlement (inner rods with C_H~2000wppm)

stress concentration (outer rods with C_H~1000wppm)

necking (outer rods)

QL1: only stress concentration (excepted rod #1 brittle ruptured during handling)

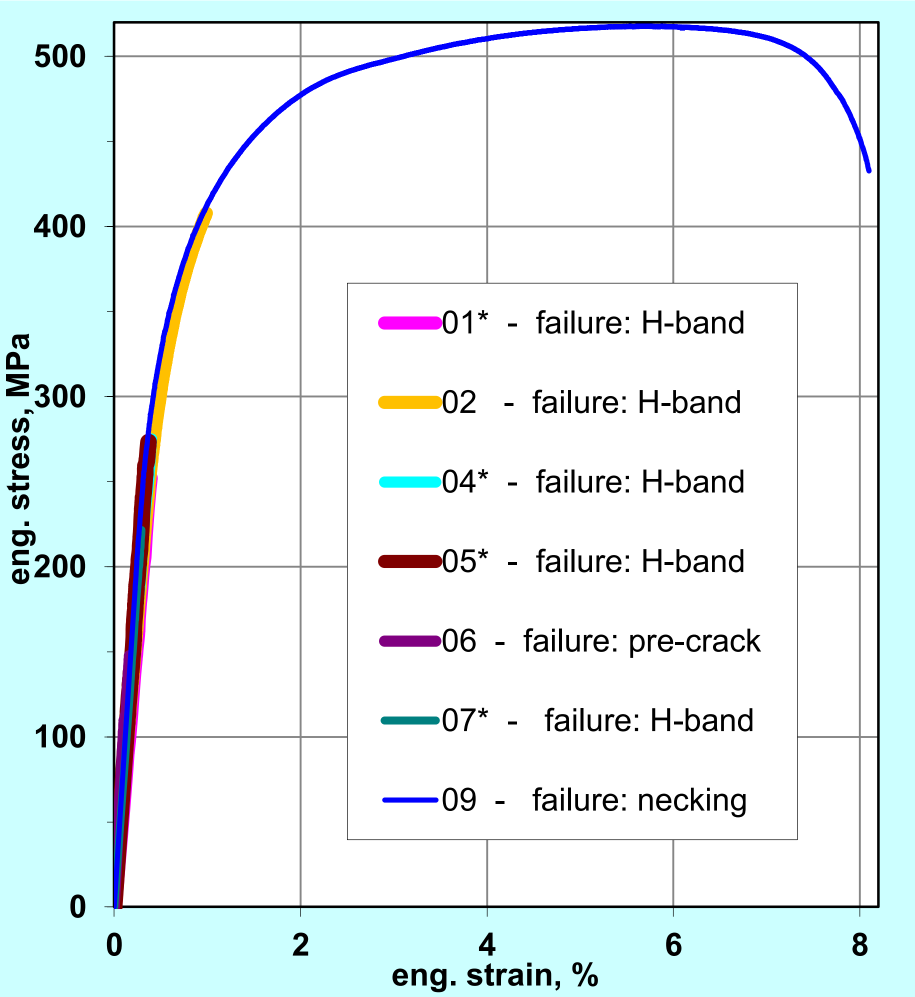
rod #4

rod #6

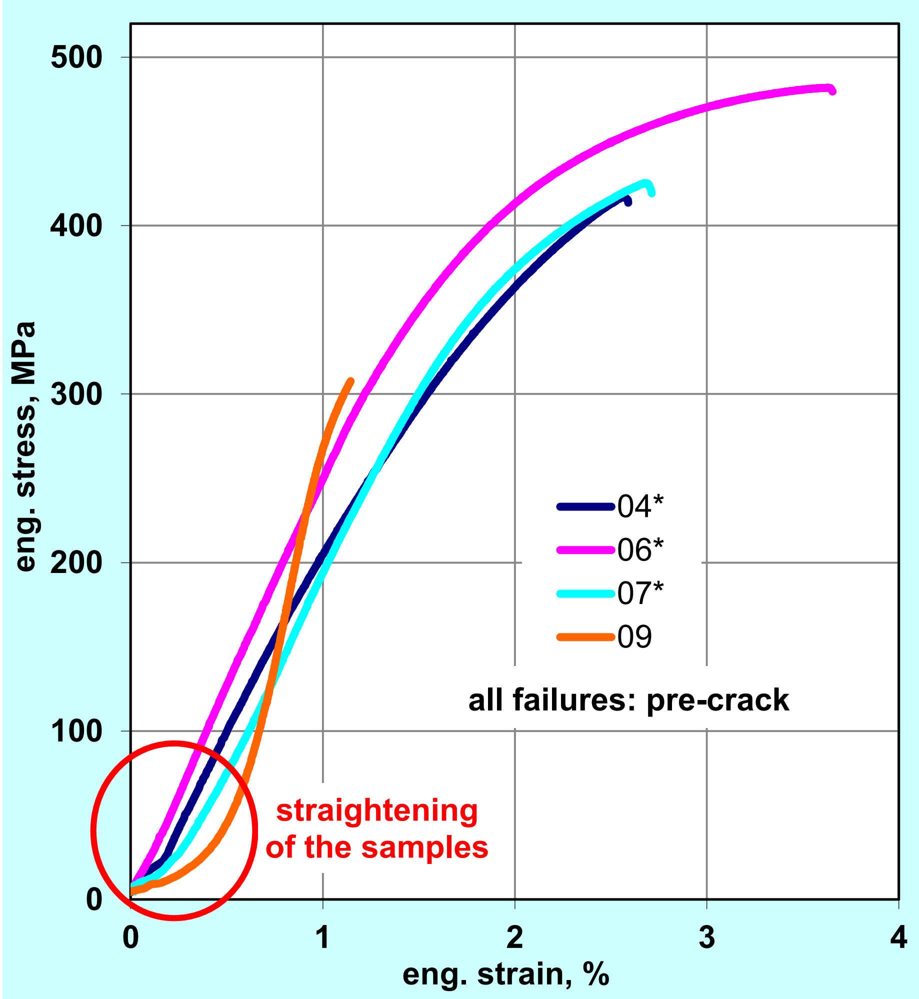
rod #9

Tensile tests for inner rods

QL0 sample length 500 mm or 250 mm*

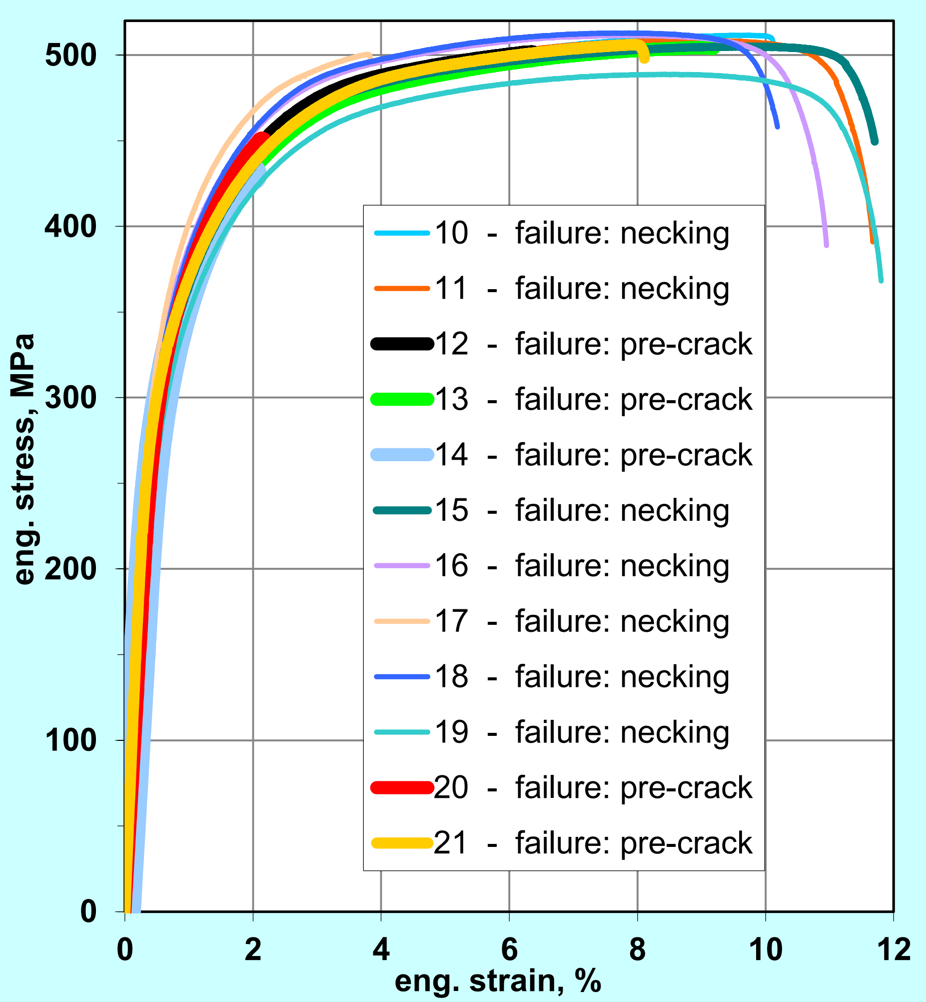


QL1 sample length 1000 mm or 250 mm*

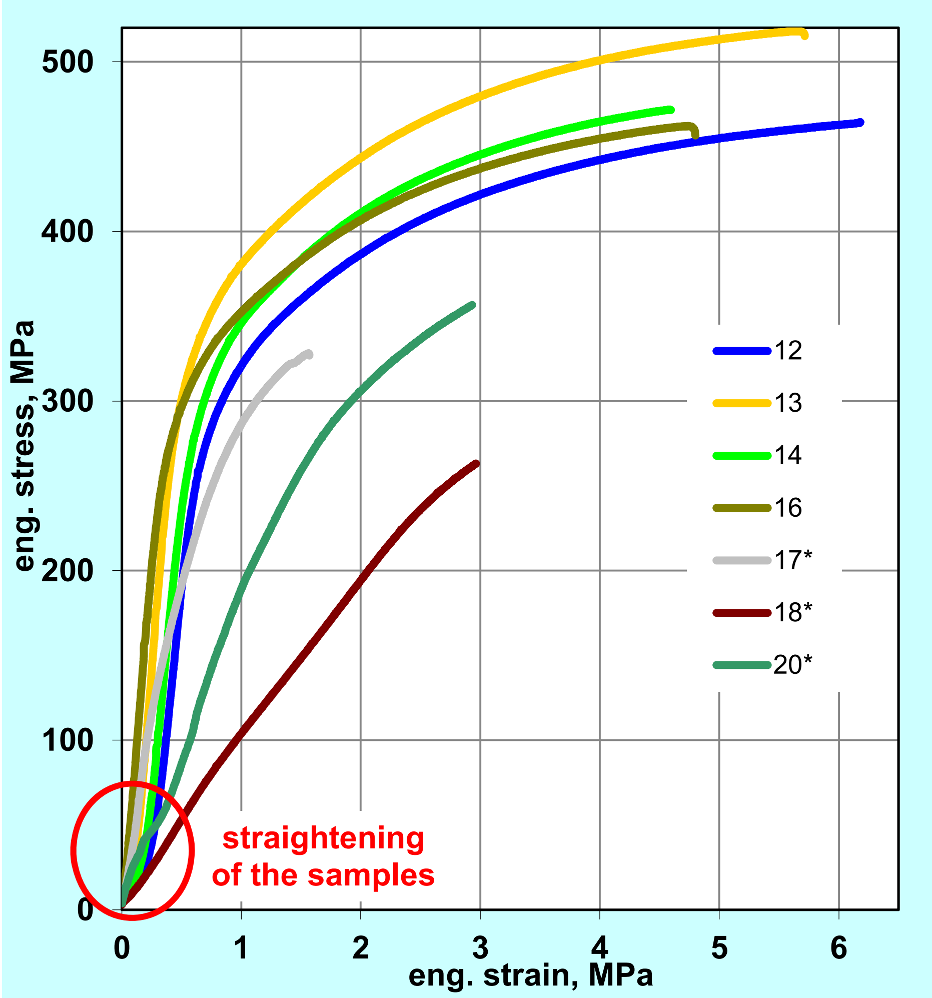


Tensile tests for outer rods

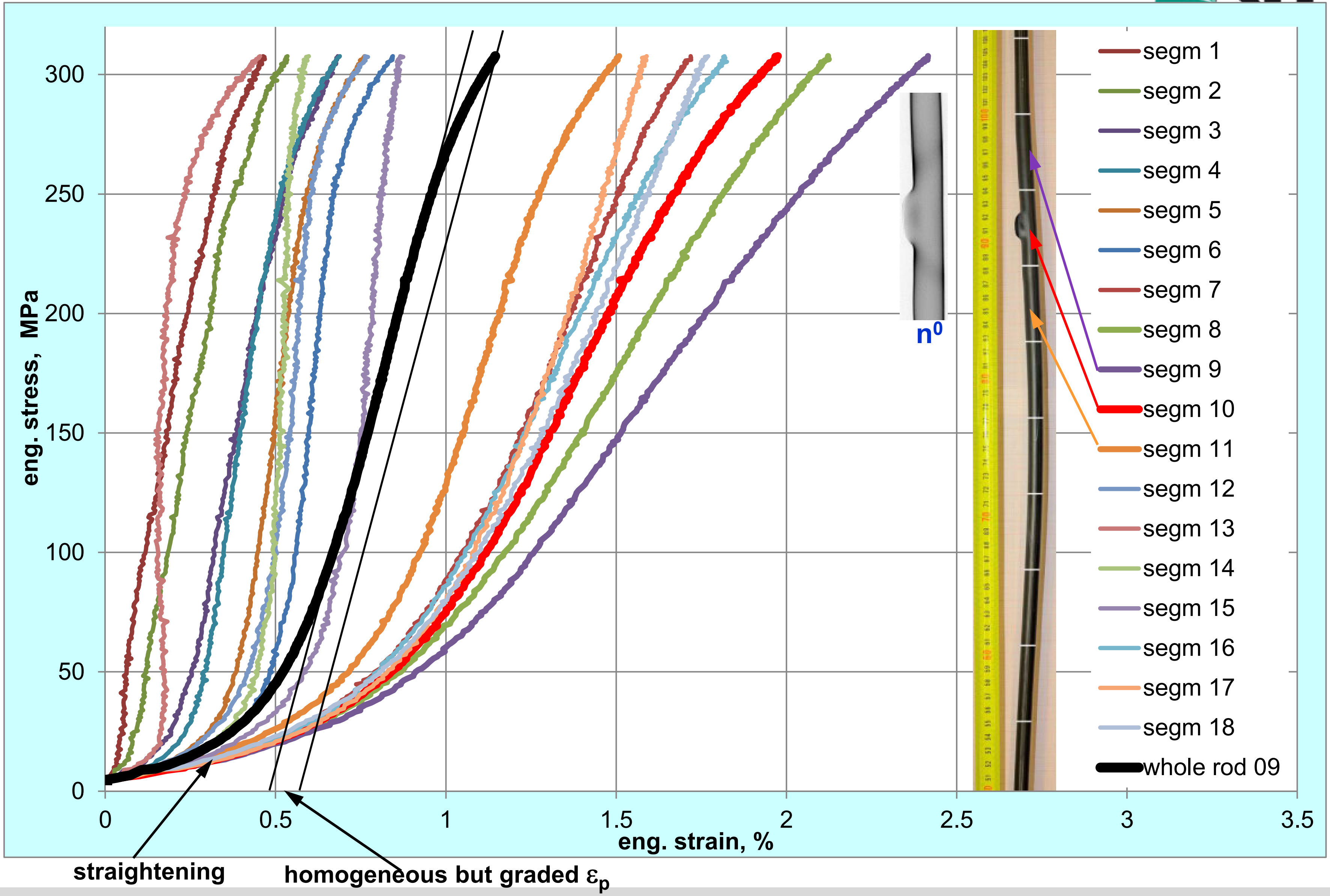
QL0 sample length 500 mm



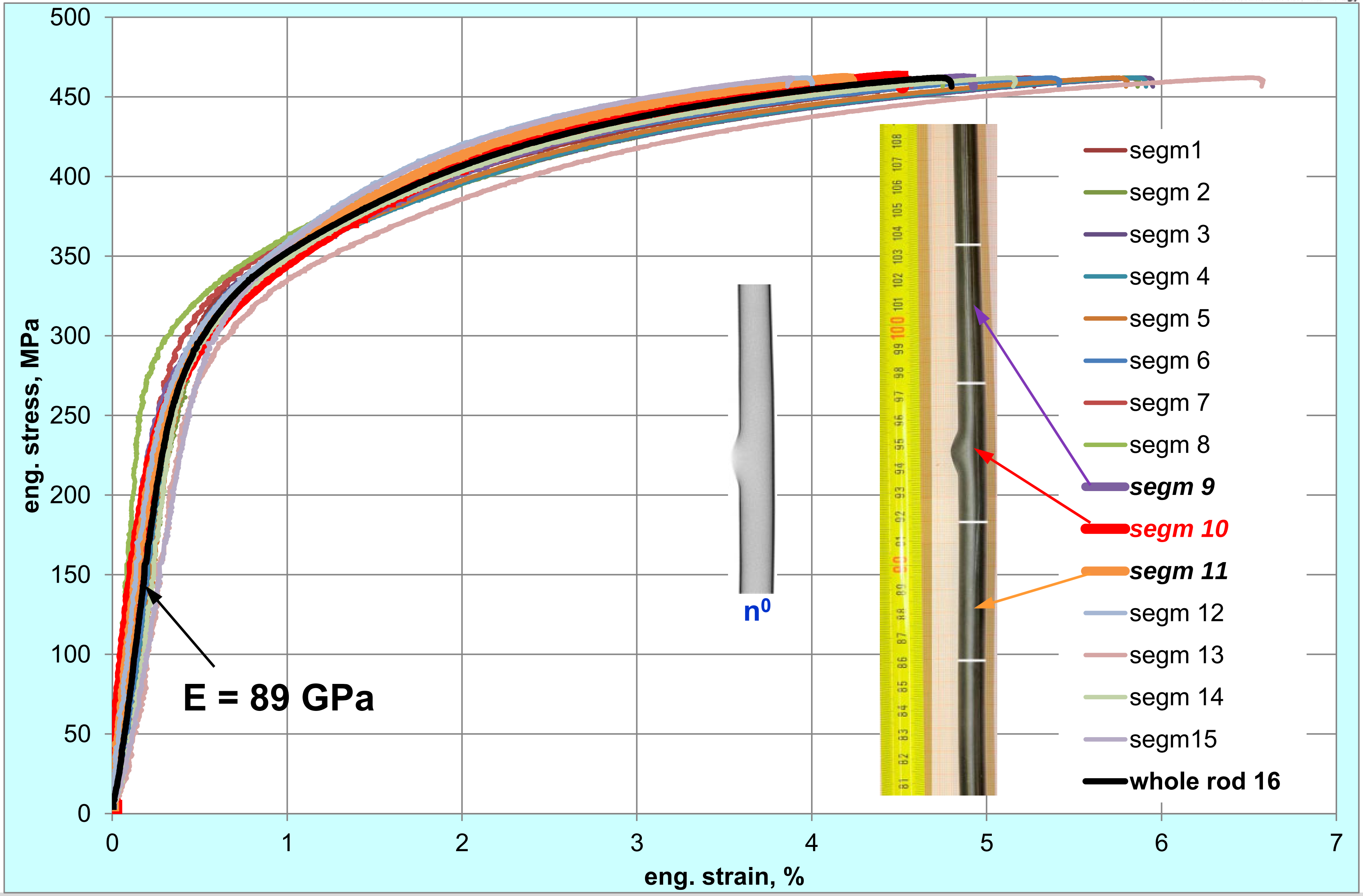
QL1 sample length 1000 mm or 250 mm*



QL1: tensile test with bended rod #09 with detected secondary hydrogenation



QL1: tensile test with not bended rod #16 without detected secondary hydrogenation



Results of tensile tests

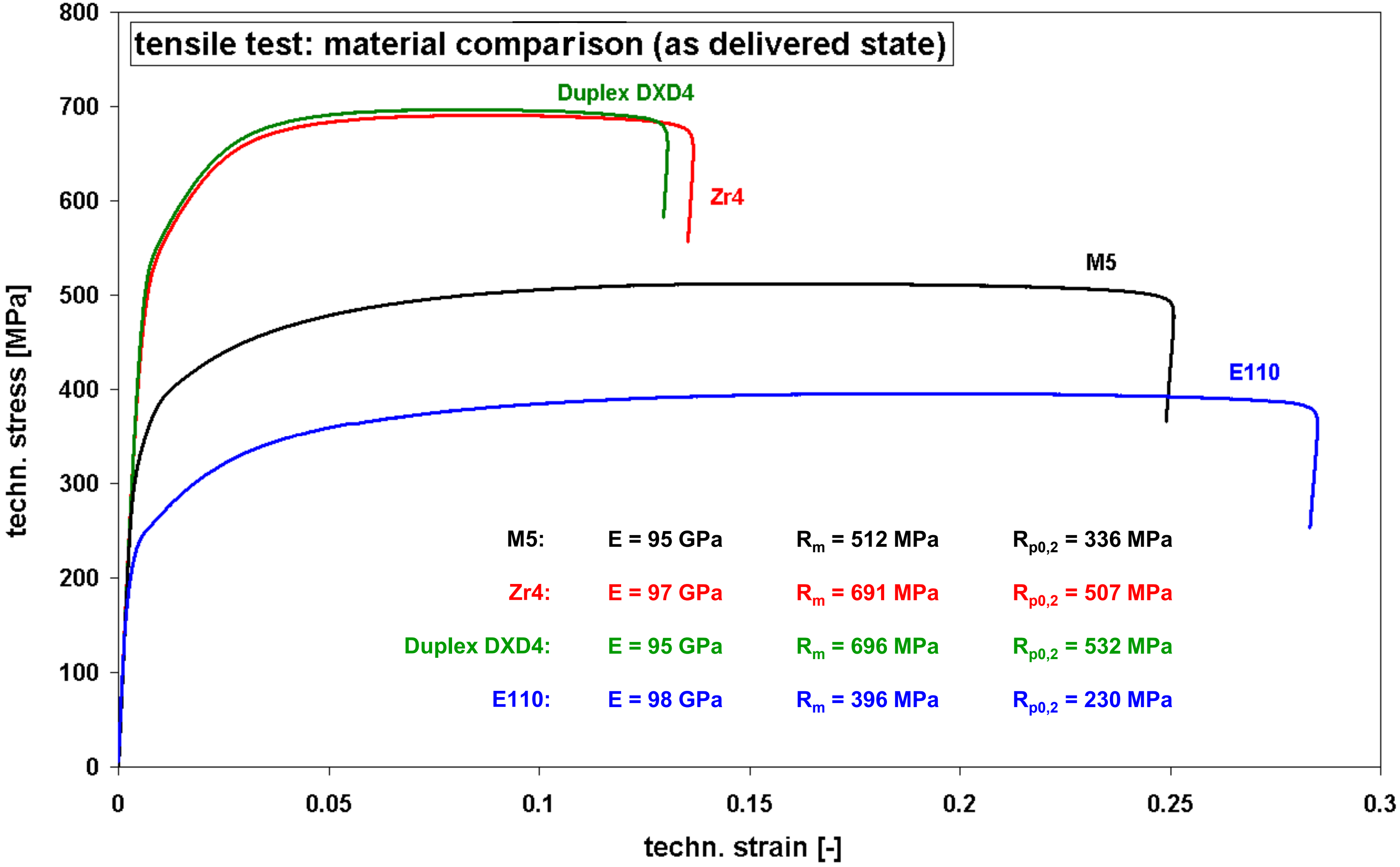
QL0

rod l_0=500 mm *l_0=250 mm	ultimate tensile strength [MPa]	fracture stress [MPa]	elongation at fracture [%]	rupture based on:
01*	254	254	0.38	hydrogen embrittlement
02	408	408	0.99	hydrogen embrittlement
04*	276	276	0.40	hydrogen embrittlement
05*	274	274	0.37	hydrogen embrittlement
06	148	148	0.16	stress concentration
07*	222	222	0.29	hydrogen embrittlement
09	518	433	8.10	necking
10	512	507	10.12	necking
11	509	391	11.67	necking
12	502	499	6.44	stress concentration
13	504	504	9.18	stress concentration
14	430	430	1.97	stress concentration
15	505	450	11.70	necking
16	512	389	10.95	necking
17	501	497	3.83	*failure at stuck pellet*
18	513	458	10.19	necking
19	489	368	11.80	necking
20	452	447	2.20	stress concentration
21	506	498	8.11	stress concentration

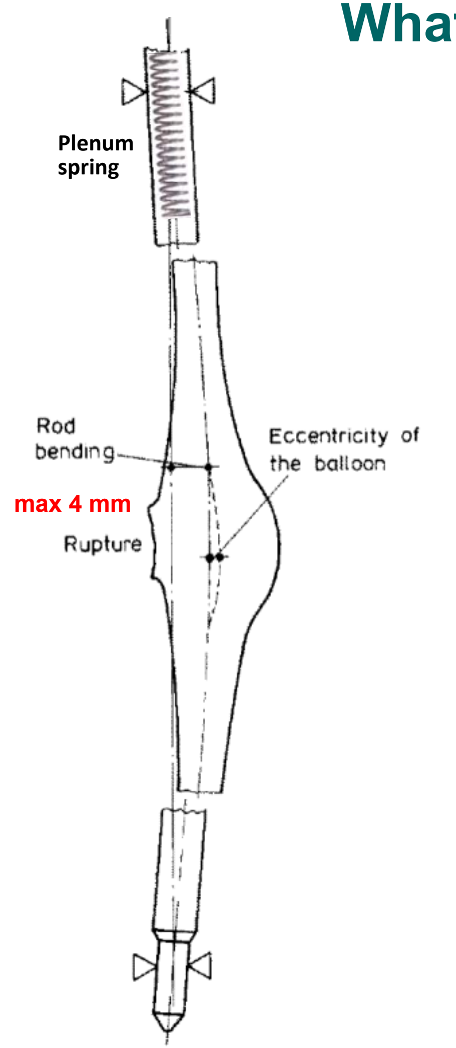
QL1

rod l_0=1000 mm *l_0 = 250 mm	ultimate tensile strength [MPa]	fracture stress [MPa]	elongation at fracture (graded) [%]	rupture based on:
04*	416	414	0.75 (0.68)	stress concentration
06*	499	481	1.70 (1.68)	stress concentration
07*	436	425	1.03 (0.81)	stress concentration
09	307	307	0.59 (0.09)	stress concentration
12	464	464	5.50 (5.27)	stress concentration
13	518	515	5.13 (5.03)	stress concentration
14	471	471	3.96 (3.80)	stress concentration
16	462	456	4.31 (4.10)	stress concentration
17*	333	327	0.33 (0.33)	stress concentration
18*	270	263	0.19 (0.19)	stress concentration
20*	367	356	1.13 (1.06)	stress concentration

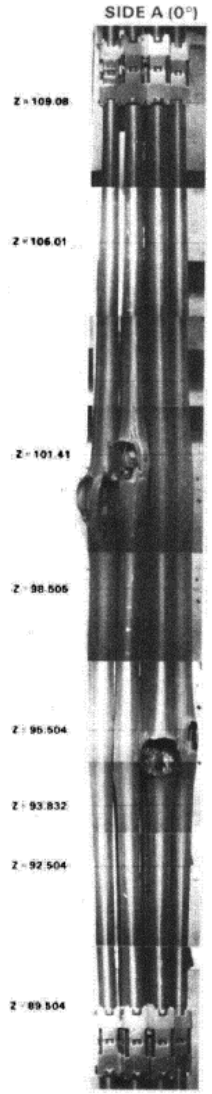
Tensile tests with different as-delivered claddings: different ultimate tensile strengths and ductile elongations



What is prototypical rod bending rate?



Results of the *FR2* *in-pile single rod tests*: out-of-pile results [Chung], showing significant bending below 840°C (α-Zr(O)) and negligible values above 840°C, **were not confirmed** by the in-pile tests. However, the orientation of the rod bend was consistent with out-of-pile results, i.e., the rupture was on the inside of the bend.



NRU MT-4 (1982) in-pile bundle test: no noticeable bending

High temperature PHEBUS-FPT1 in-pile test

Choice of heaters: ductile Ta (->significant rod bending) or rigid W (→ negligible rod bending)

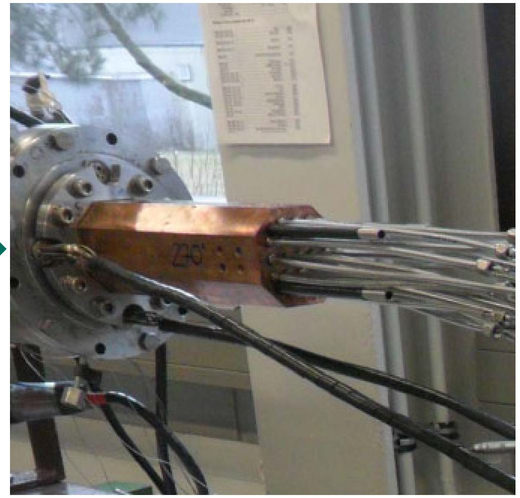
Two locations of friction during the thermal expansion:

1. (prototypical) friction between oxidised grid spacers and ballooned claddings

2. (not prototypical) friction inside the electrode group

Cu electrodes

Cu electrodes with Au slide contacts



Cu block putted on electrodes

Summary

- Test QUENCH-LOCA-1 test was performed according to prototypical scenario with heat-up rate 5.7 K/s and cooling phase lasted 120 s and terminated with 3.3 g/s/rod water flooding
- The maximum temperature of 1373 K was reached on the end of the heat-up phase at elevation 850 mm (for QUENCH-L0 at 950 mm)
- Strong rod bending up to 23 mm was observed - significantly more in comparison to results of the QUENCH-L0 test
- The maximum blockage ratio of cooling channel (24%) was observed at elevation 950 mm (similar blockage of QUENCH-L0 was observed at 990 mm)
- The cladding burst occurred at temperatures between 1073 and 1173 K (for QUENCH-L0 between 1123 K and 1223 K). The inner rod pressure relief to the system pressure during about 40 s (similar to QUENCH-L0)

Summary (cont.)

- Similar to QUENCH-L0, the oxide layer thickness on the inner cladding surface was measured up to 25 µm at burst elevations and less 2 µm at hydrogenated bands.
- No zirconium hydrides with sizes more 10 nm were detected. Concentration of hydrogen dissolved in matrix estimated as < 300 wppm.
- All claddings (excluding central rod #1) were fractured due to stress concentration (stregthened due to bending?) at the burst position – similar to inner rods of QL0 with hydrogen concentration about 1000 wpmm. Rod #1 was destroyed brittle during pulling out of heater with hand.
- Future bundle tests supposed to perform with tungsten heaters to avoid significant rod bending caused partially by electrodes friction.

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Thank you for your attension

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