Post-test investigations of the QUENCH-LOCA-4 bundle (hydrogenated M5® claddings)

J. Stuckert, M. Große, A. Pshenichnikov, C. Rössger, M. Walter

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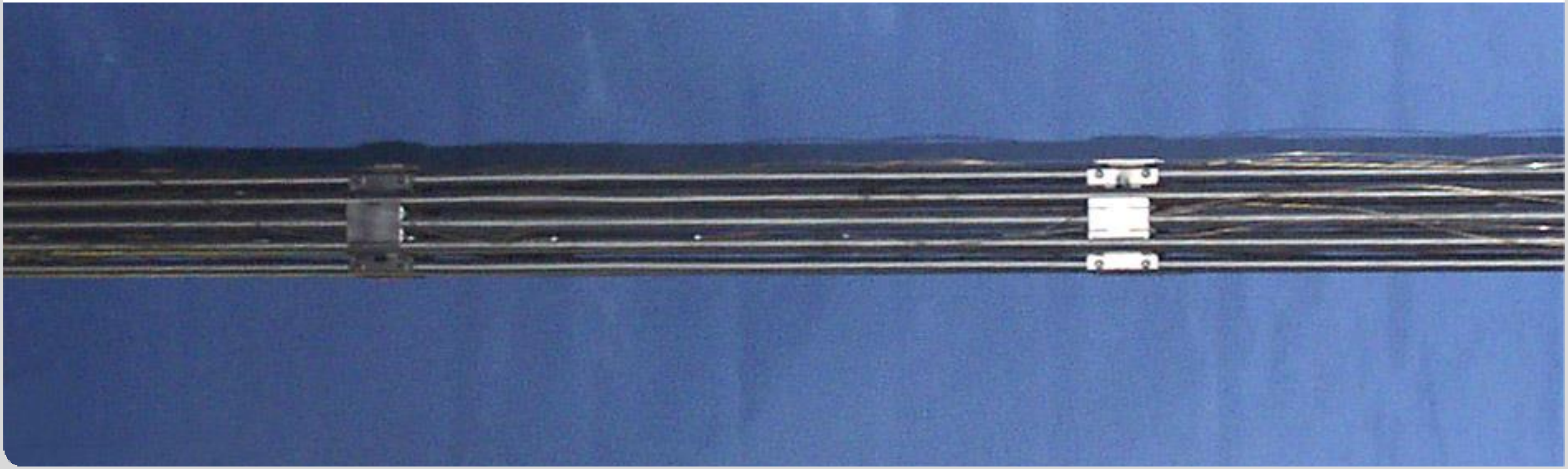

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Abstract

The QUENCH-LOCA-4 bundle test with pre-hydrogenated M5® claddings (≈100 wppm hydrogen) 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. 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 30 K on the burst onset.

The cladding wall thinning from 725 µm to 450 µm due to ballooning was observed at the burst side along 50 mm below and above burst opening (post-test ultrasound measurement). The cladding burst occurred at temperatures between 1067 and 1151 K (QUENCH-LOCA-2: 1050 and 1195 K). The inner rod pressure relief to the system pressure during about 30 s (similar to QUENCH-LOCA-2). Post-test measurements showed following average burst opening parameters: maximum width 3.3 ± 0.7 mm; length 13.1 ± 1.9 mm (similar to QUENCH-LOCA-2 with not pre-hydrogenated M5® claddings).

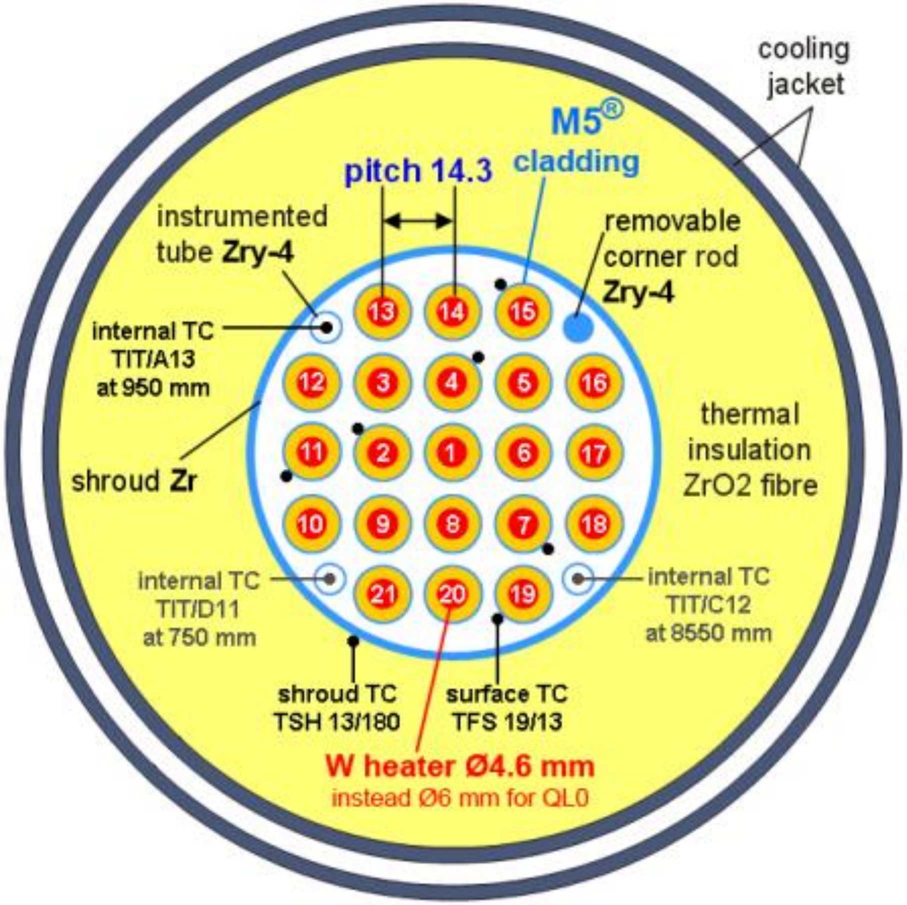
Due to more close axial localisation of ballooned region the maximum blockage ratio of cooling channel (18% at 925 mm) was negligible higher in comparison to QUENCH-LOCA-2 (15% at 960 mm). Due to moderate blockage good bundle coolability was kept for both bundles.

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

Tensile tests evidenced fracture at hydrogen bands (similar to the QUENCH-LOCA-0 commissioning test with Zry-4 claddings): three inner rods were fractured due to this embrittlement. Eight peripheral rods were fractured due to stress concentration at burst opening edges (similar to ten claddings of QUENCH-LOCA-2 test with not pre-hydrogenated M5® claddings). All other tensile tested claddings failed after necking far away from the burst region.

XRD analysis detected hydrides inside hydrogen bands. Elaborated EBSD analysis showed that 1) the hydrides have µm-sizes and distributed in matrix intra- as well inter-granularly; 2) areas with secondary hydrogenation have a strong distorted lattice.

QUENCH-L4: test with hydrogenated claddings



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

1) The use of <u>tungsten</u> heaters with smaller diameter (<u>4.6 mm</u>) 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

Zry-4 spacer
1410 mm

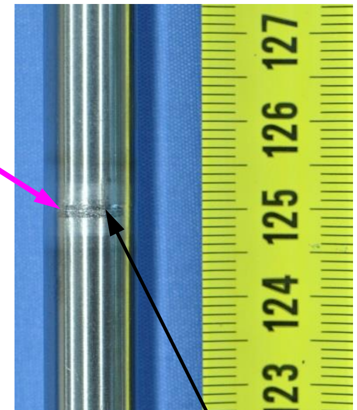
Zry-4 spacer
1050 mm

Zry-4 spacer
550 mm

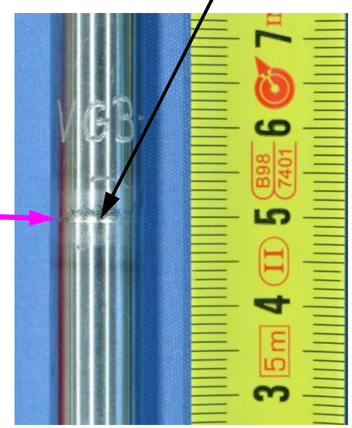
Zry-4 spacer
150 mm

Inconel spacer
-100 mm

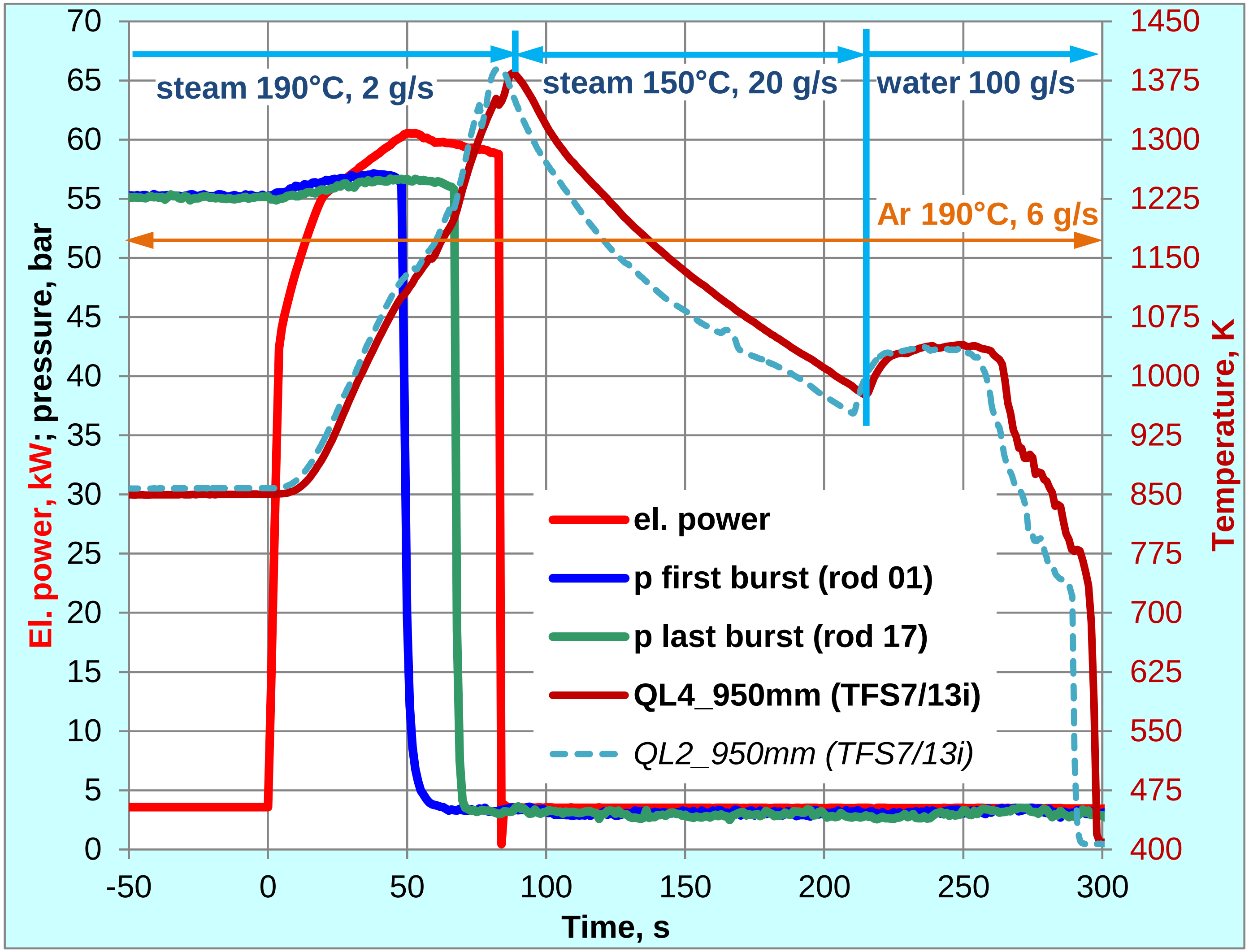
21 pre-hydrogenated tubes (100 wppm H), each welded from 3 segments with lengths 500,1200, 500 mm

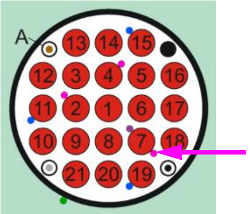


welded joints

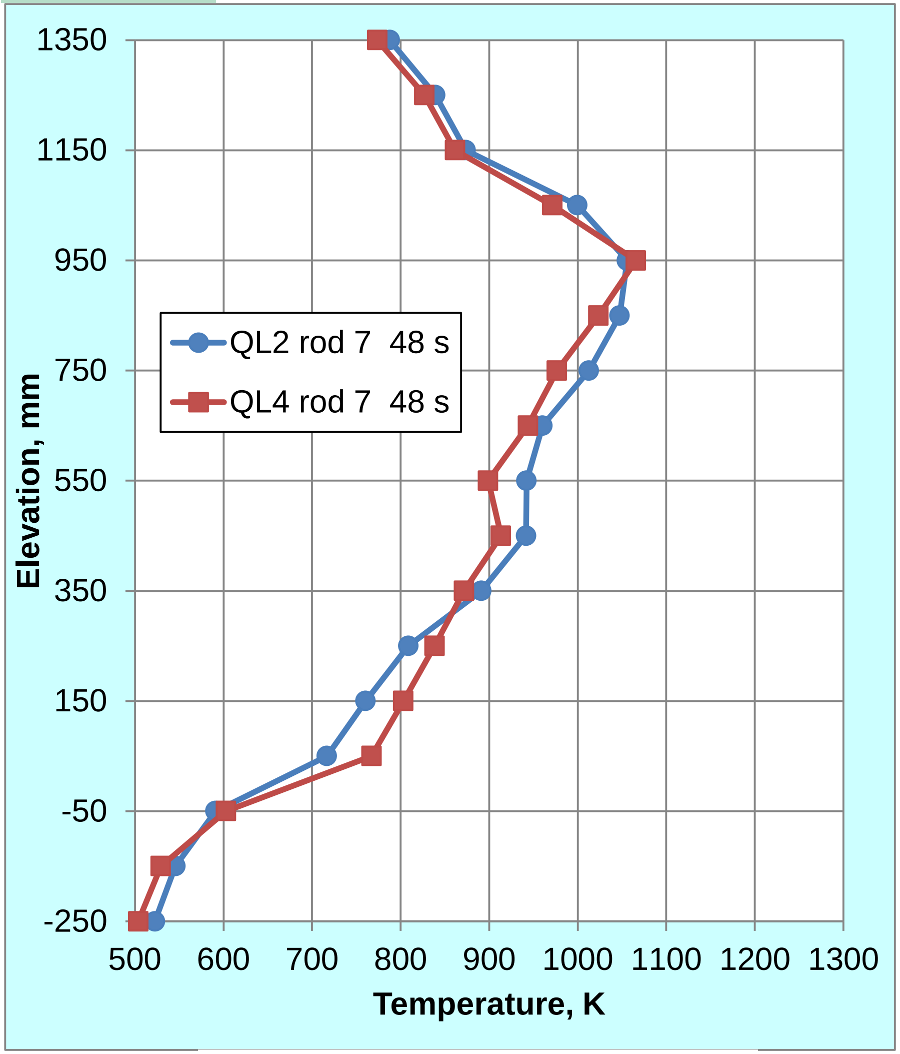


QUENCH-L4: test progress.
Comparison with QUENCH-L2 temperature.

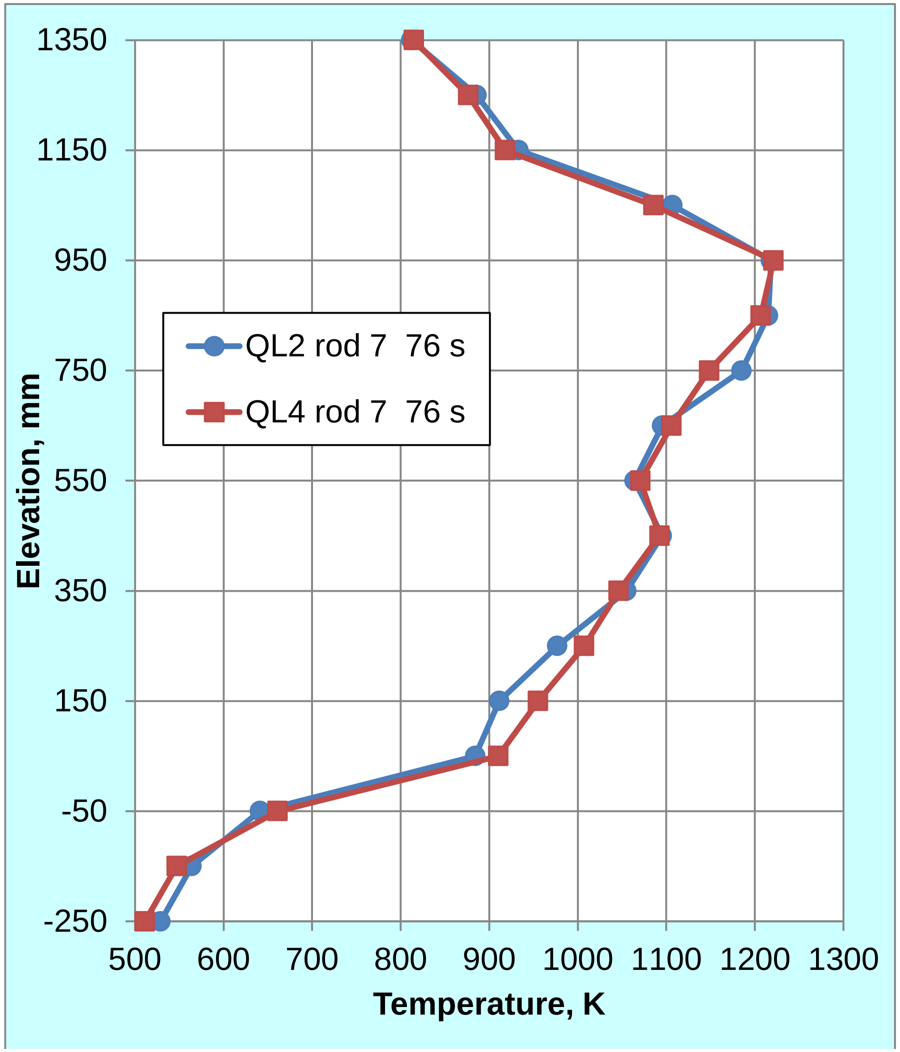




QL2 and QL4: similar axial temperature distribution for inner rod

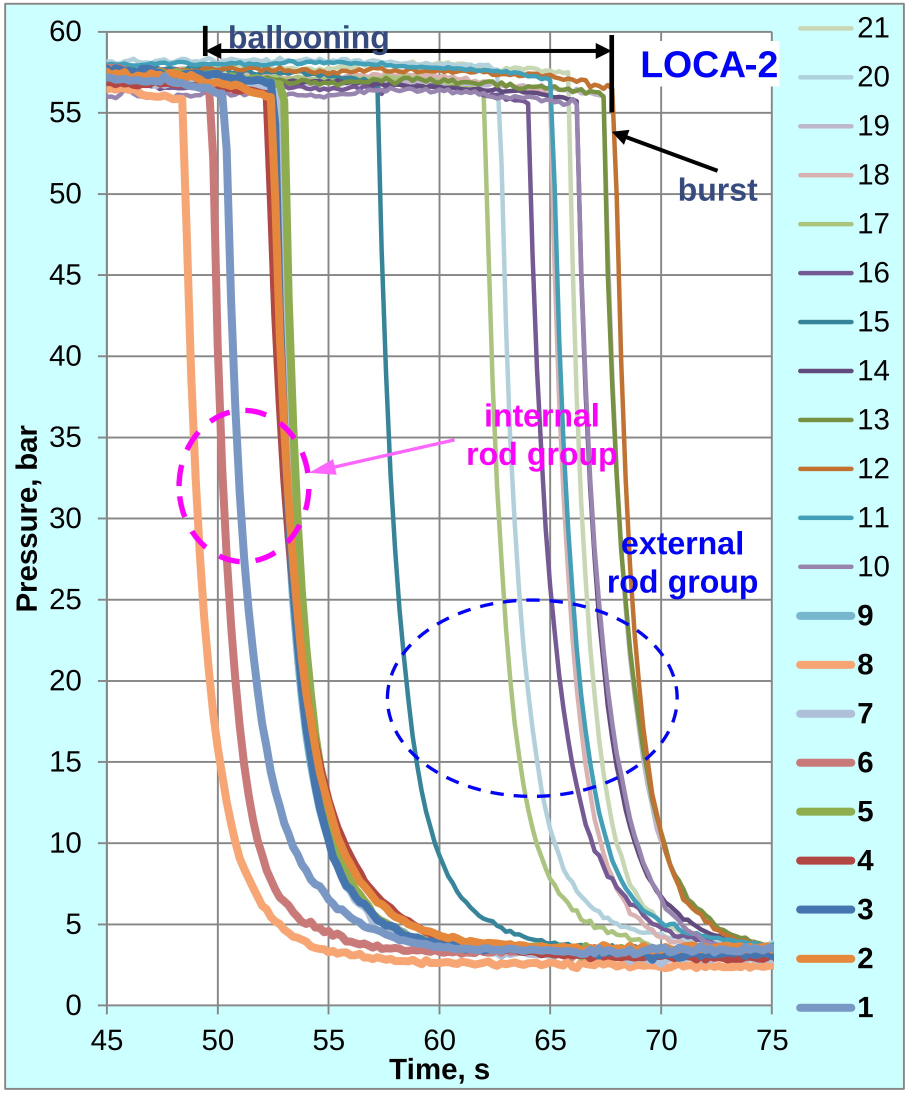


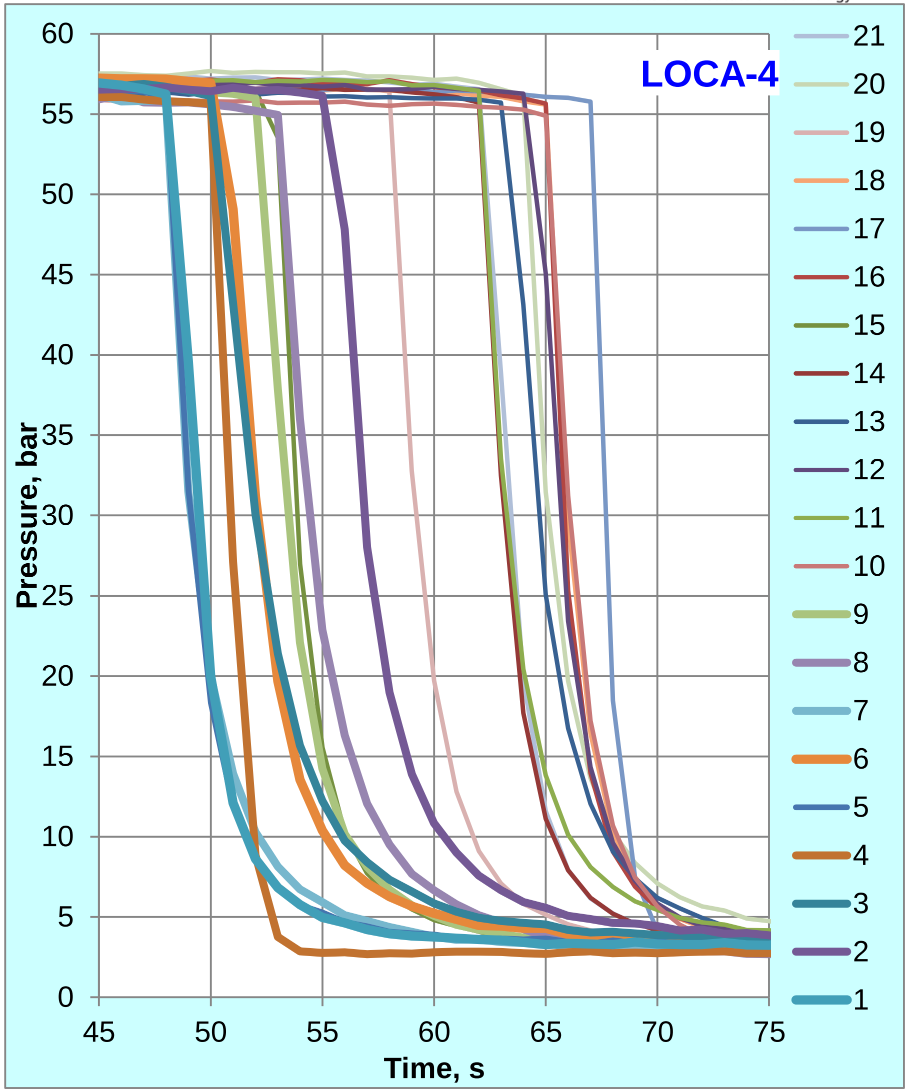
on first cladding burst (t = 48 s)



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

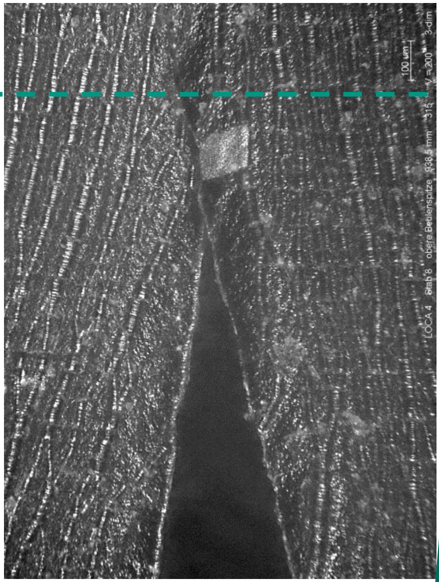
Rod pressure evolution during heating phase for QUENCH-L2 and -L4: burst time indication

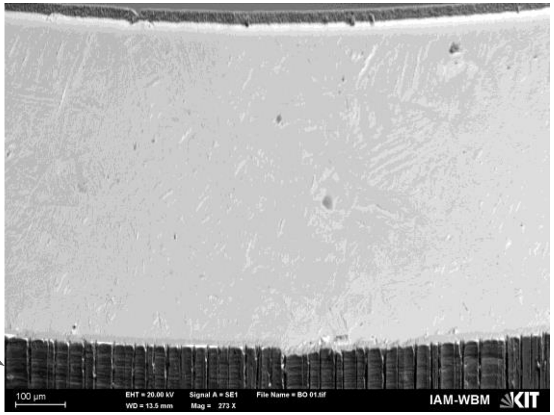




duration of decrease of the inner pressure to the system pressure: $\tau_0 \approx 30$ s

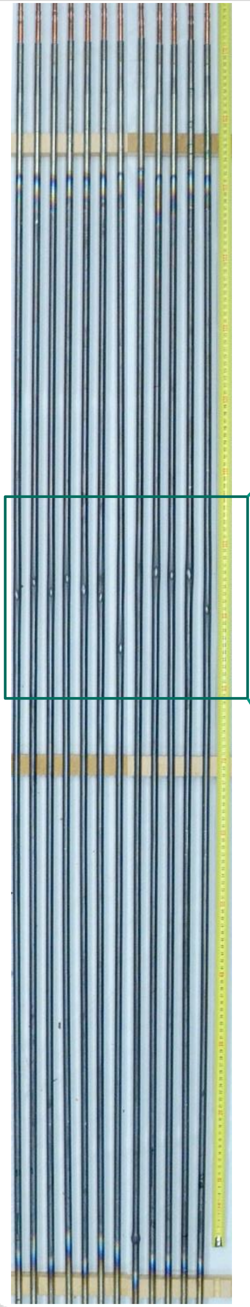
QUENCH-L4, post-test overview of inner rods: no bending, localized ballooning region





SEM: longitudinal cracks formed in oxide during ballooning, 30 cracks/mm

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



Burst time and temperature

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

Burst geometrical parameters

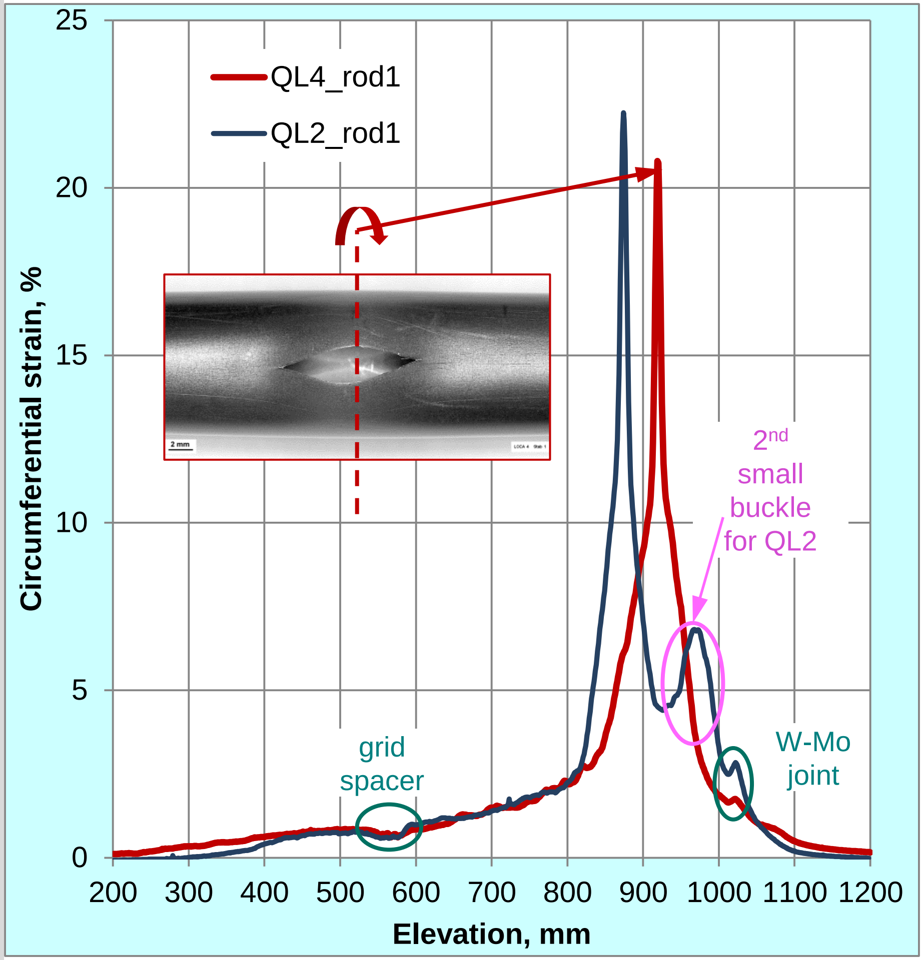
rod	max burst width, mm	burst length, mm	burst area, mm²
1	3.4	14	29
2	2.9	11	20
3	2.5	10	15
4	2.9	11,5	21
5	3.0	11,5	21
6	2.6	11	17
7	3.1	12	23
8	3.3	12	24
9	1.7	11	12
10	6.6	22	85
11	2.8	12	21
12	2.5	11	19
13	2.4	10	15
14	3.1	12	23
15	2.4	13	25
16	3.4	13	27
17	3.9	20	66
18	3.3	12	24
19	1.8	11	12
20	5.5	24	94
21	1.5	15	16

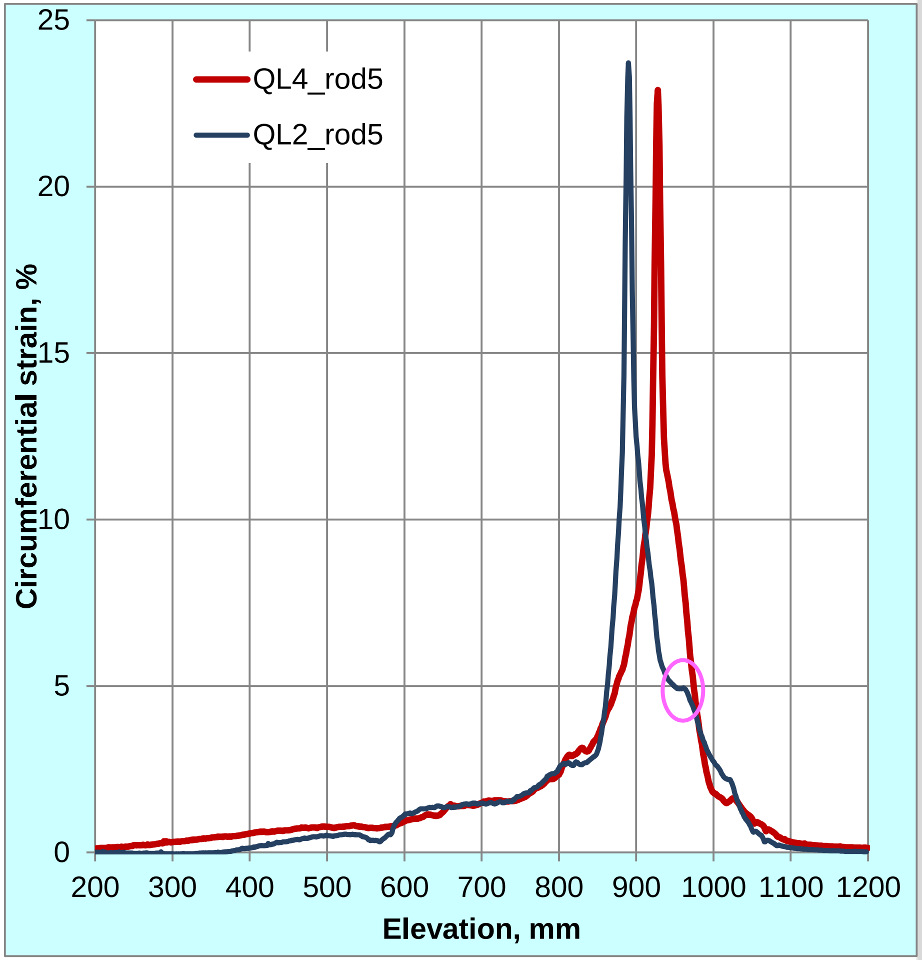
QL2; average burst opening parameters: width 3.1 ± 1.2 mm; length 13.5 ± 4.0 mm

rod	max burst width, mm	burst length, mm	burst area, mm²
1	3.0	11	20
2	3.1	12	21
3	3.3	13	25
4			
5	3.3	12	24
6	3.1	11	20
7	4.0	16	34
8	3.2	12	21
9	3.4	13	26
10	3.4	16	26
11	3.0	12	20
12	2.4	12	16
13	2.7	12	18
14	4.5	18	40
15	2.8	13	18
16	2.8	13	20
17			
18	4.1	14	34
19	2.6	11	17
20	4.8	16	39
21	2.7	12	19

QL4; average burst opening parameters: width 3.3 ± 0.7 mm; length 13.1 ± 1.9 mm

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





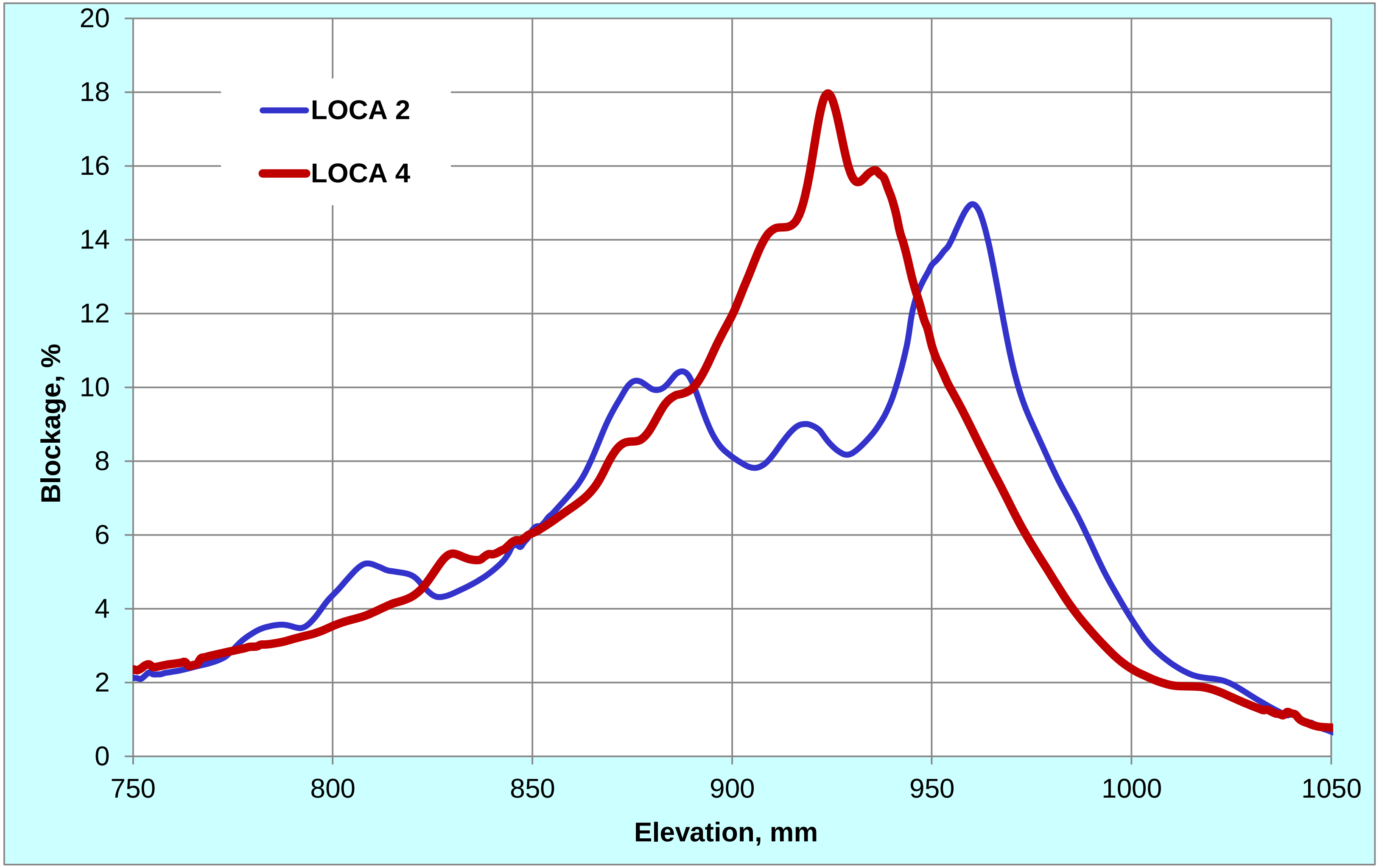
QL4, rod 1

QL2, rod 1

QL4, rod 5

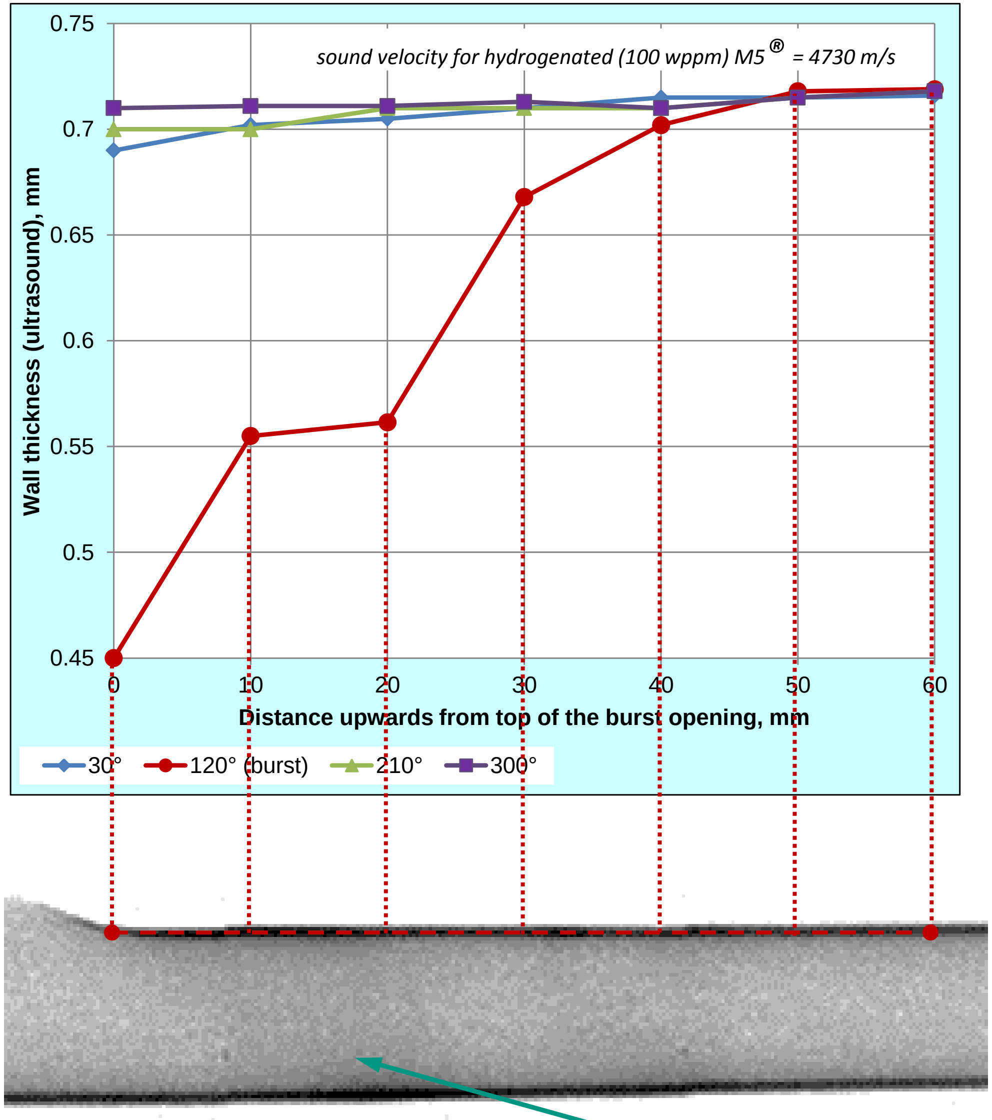
QL2, rod 5

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%

QUENCH-L4: cladding wall thinning at the burst opening side due to ballooning /ultrasound measurement of wall thickness for rod #1/



neutron radiography above burst opening: localization of hydrogen band (dark)

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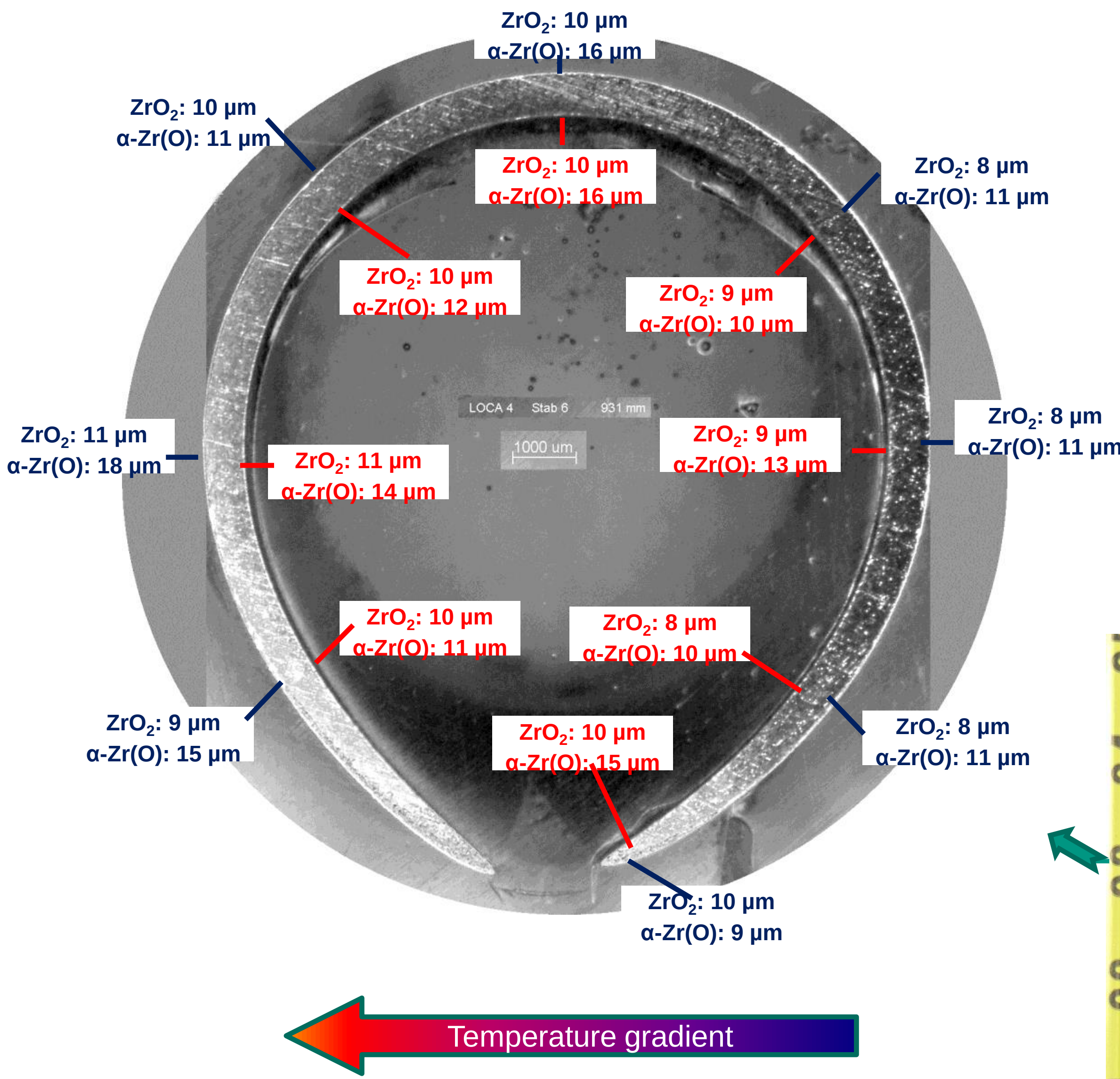
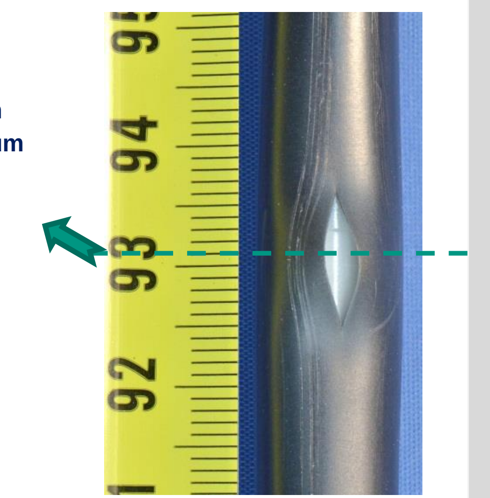
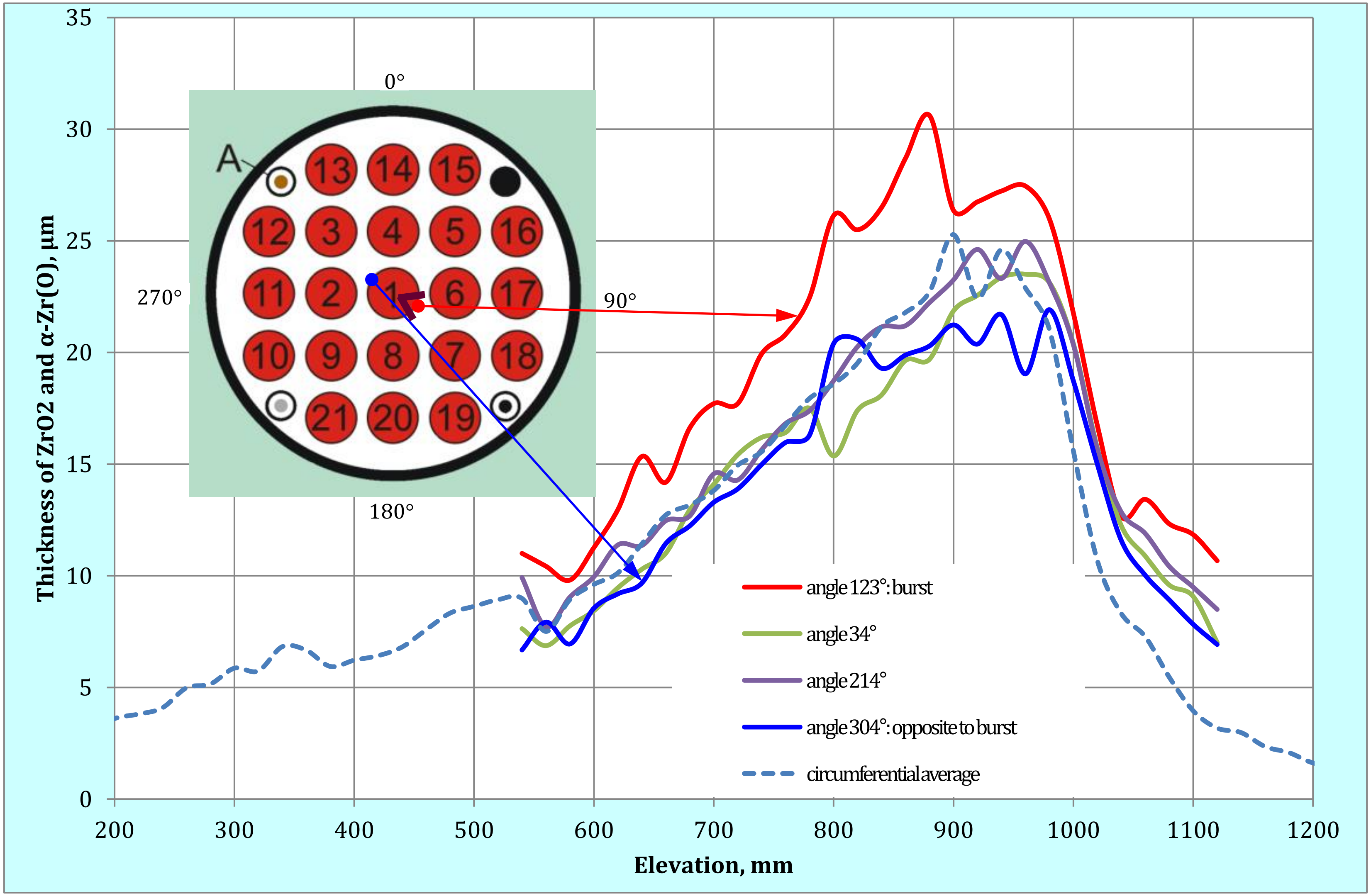
QUENCH-L4; thicknesses of ZrO_2 and α-Zr(O) layers at outer and inner surfaces of cladding #6 at burst elevation 931 mm; top view

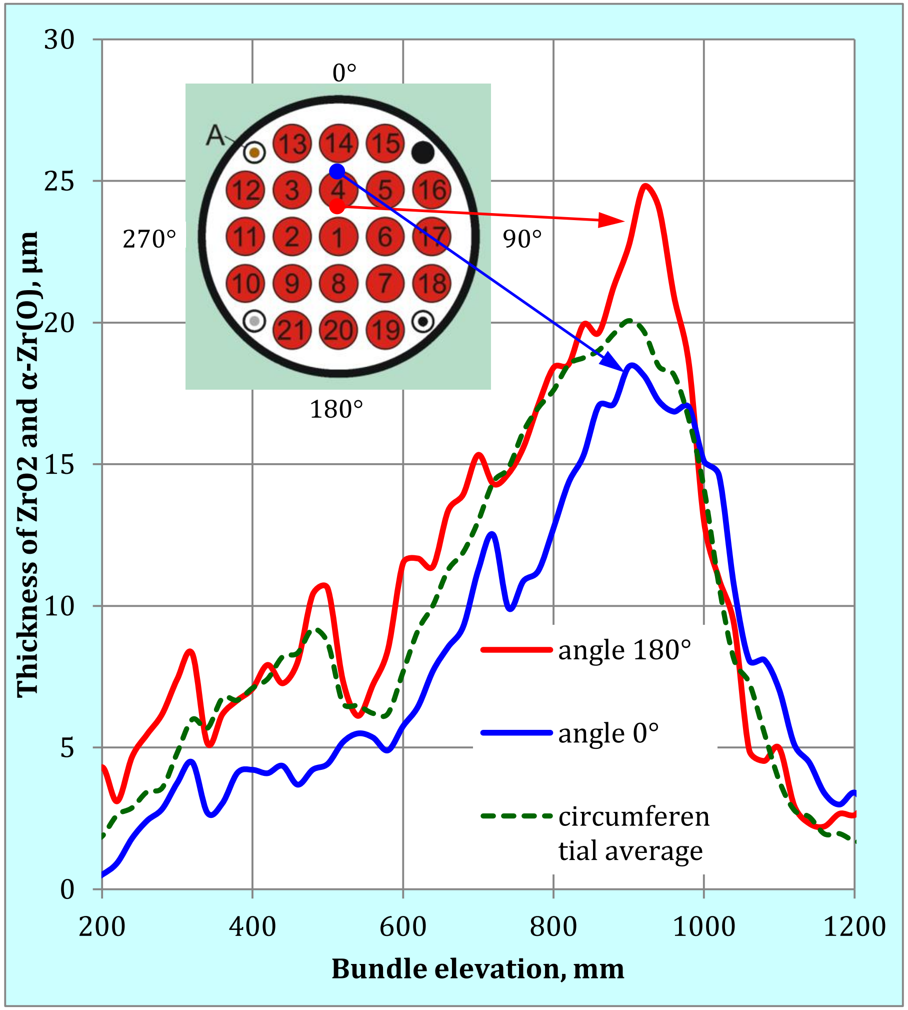




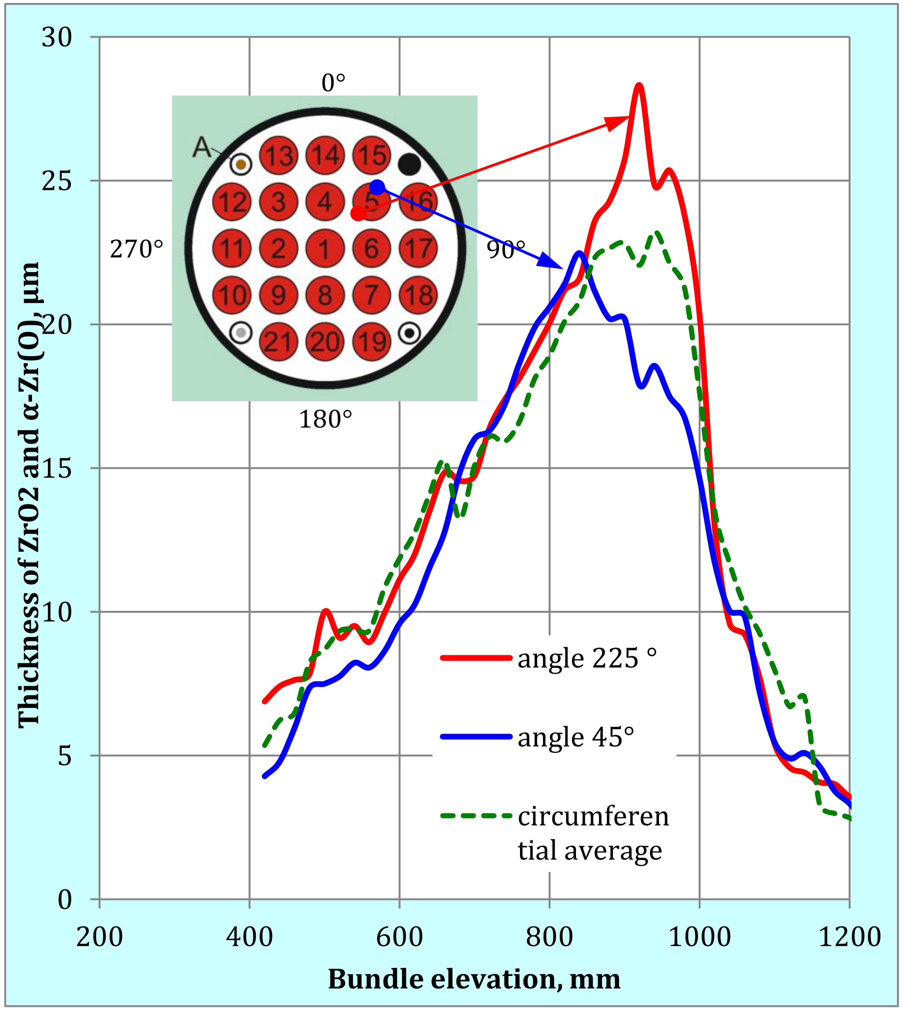
Oxidation of clad external surface: eddy current data for rod #1



Oxidation of clad external surface: eddy current data for rods #4 and #5



rod #4



rod #5

QUENCH-L4: videoscope observations of cladding inner surface

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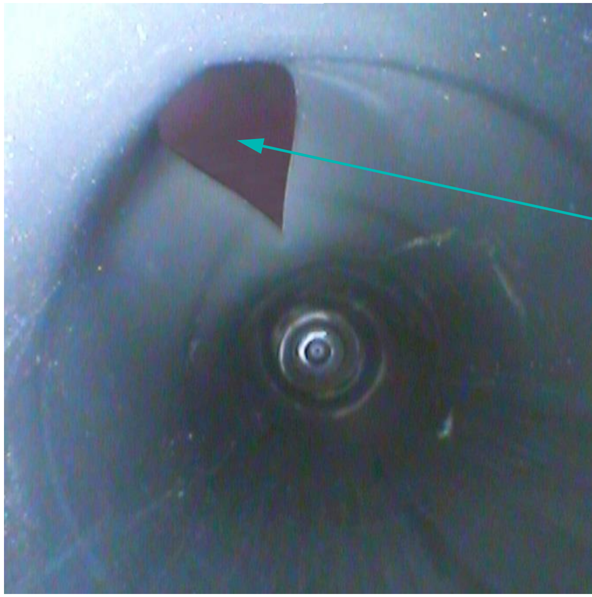
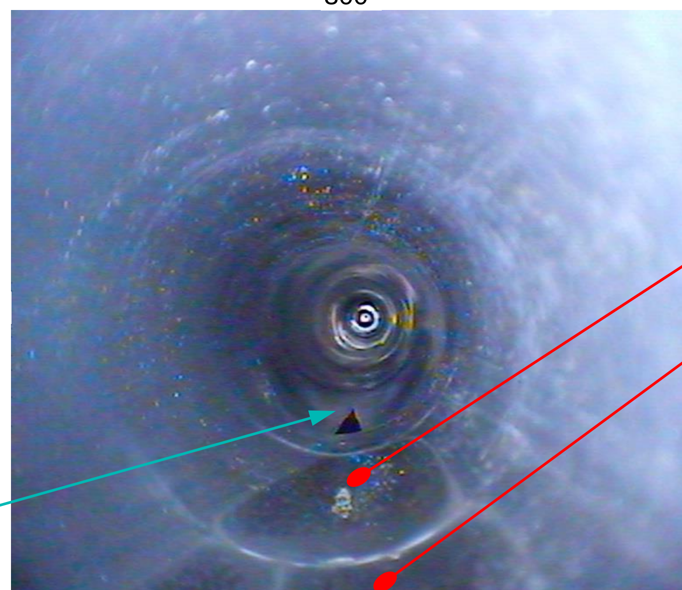
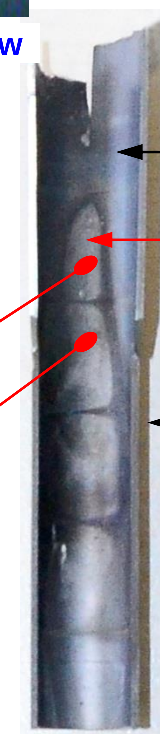


QL4, inner surface of clad #18

QL4, inner surface of clad #6, top view



QL4, inner surface of clad #1



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

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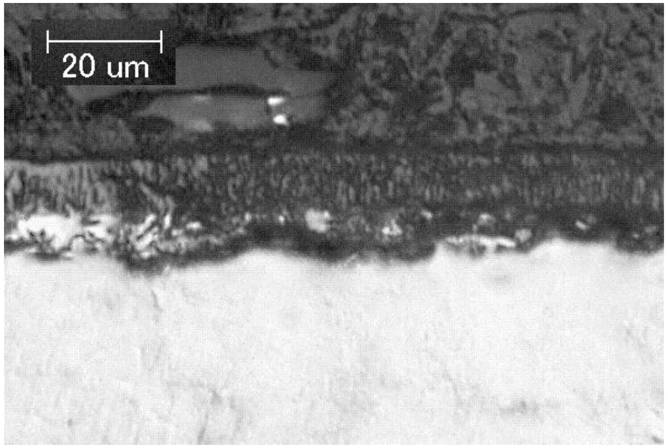
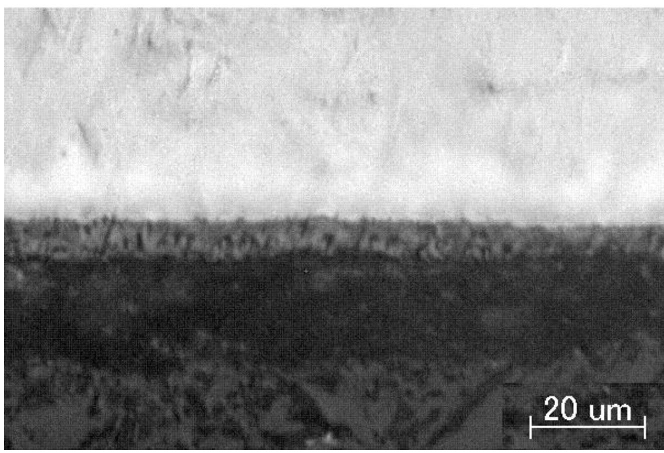
QUENCH-L4: correspondence between practically absence of inner oxide layer (contact clad↔pellet) and hydrogen spot for rod #6

clad side oppositely to burst opening (356°)

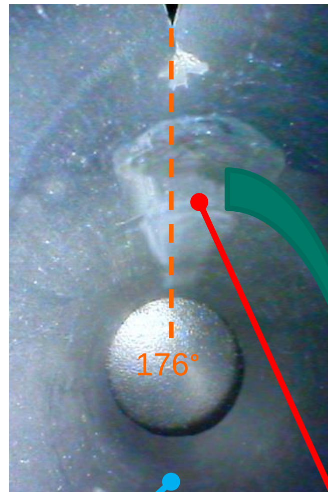


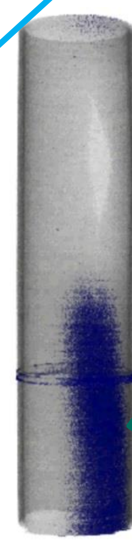
outer clad surface



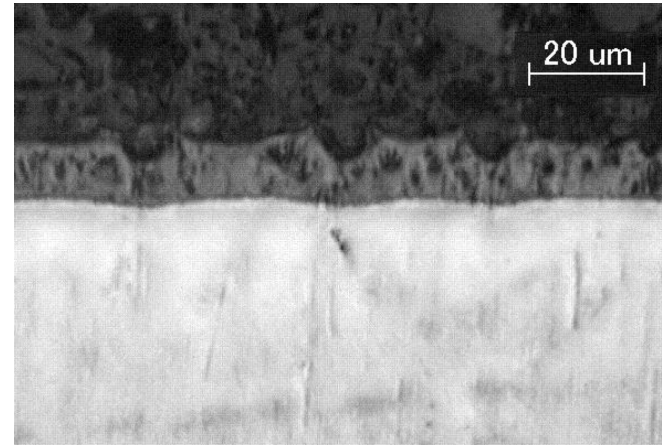
internal clad surface: relatively thick oxide layer

videoscope: below burst opening

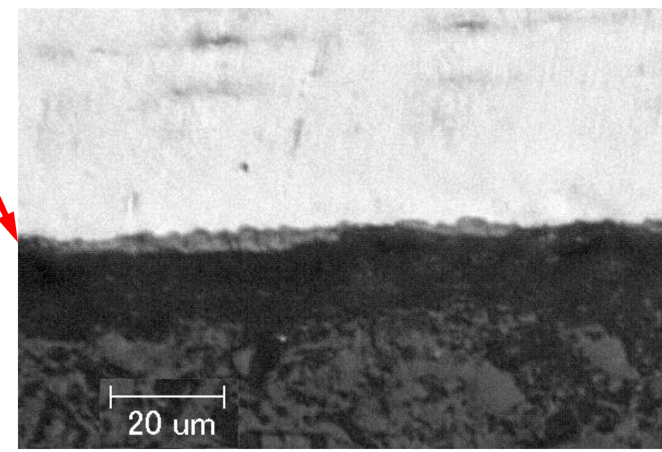




clad side at burst opening line (176°)

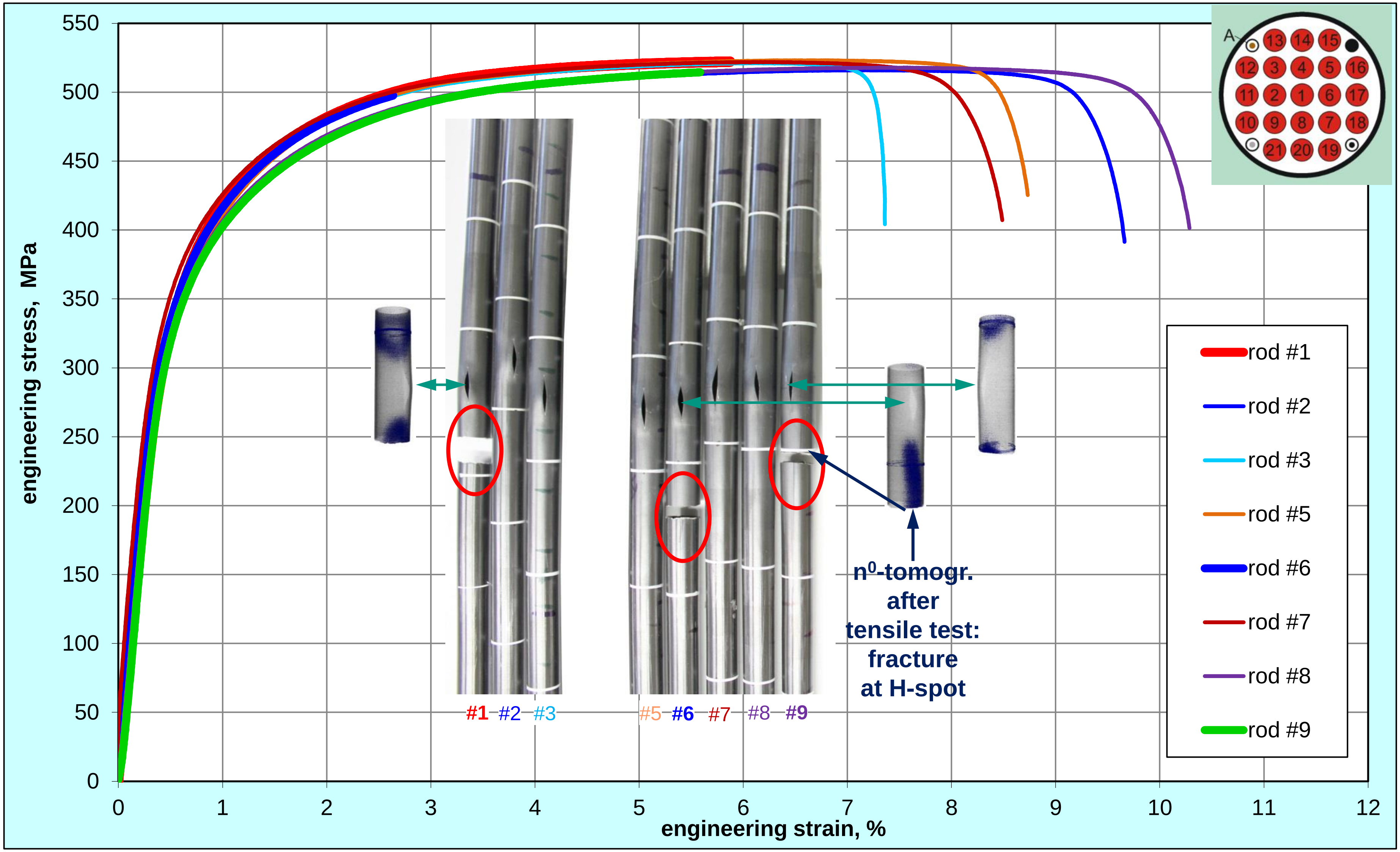


outer clad surface

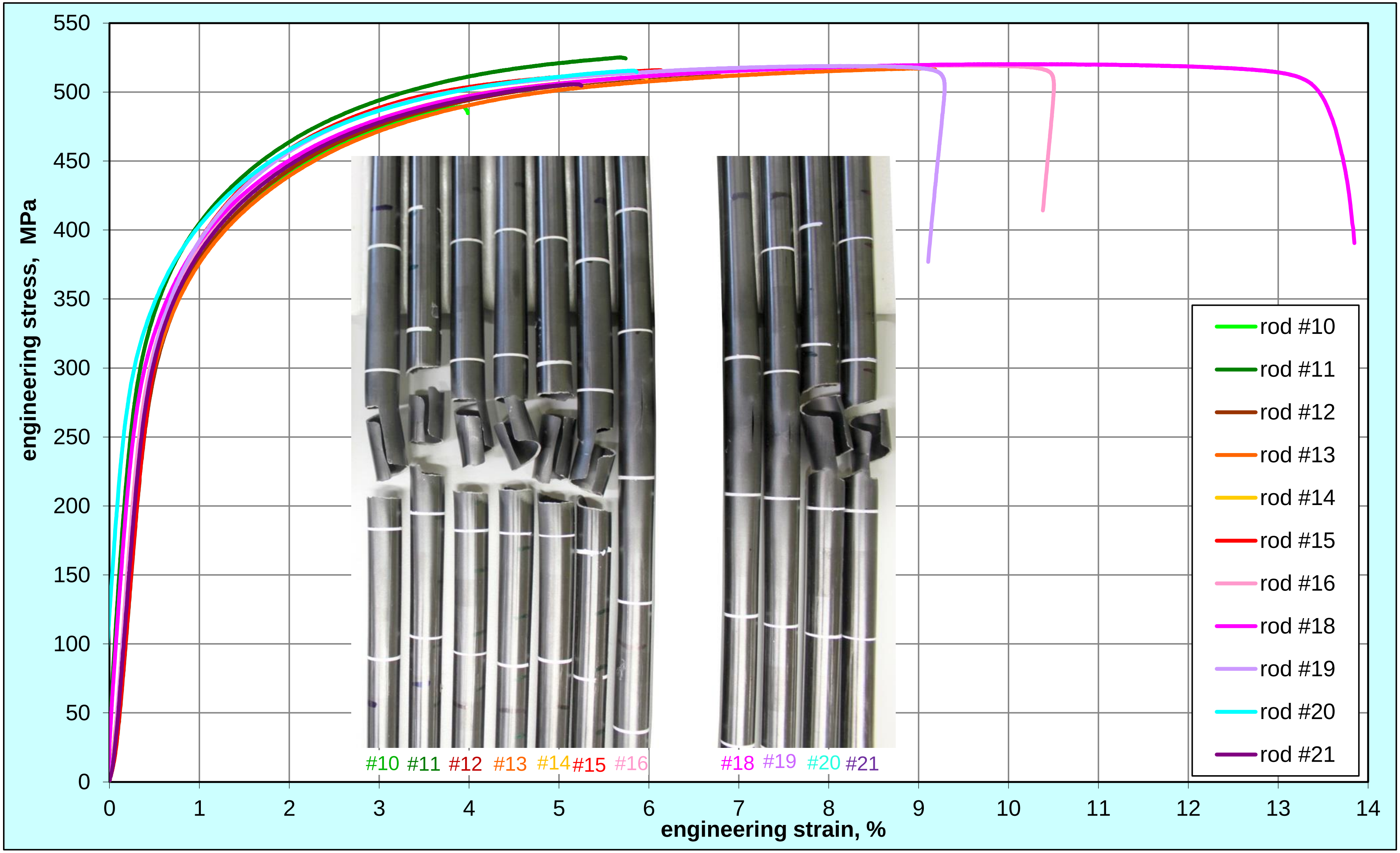


internal clad surface at contact pellet ↔cladding: only local spots of very thin oxide layer

QUENCH-L4: tensile tests at RT with inner rods, fractures at hydrogen-bands (3 rods) and due to necking (5 rods)



QUENCH-L4: tensile tests at RT with outer rods, fractures due to micro-cracks at the burst opening edges (8 rods) and necking (3 rods)



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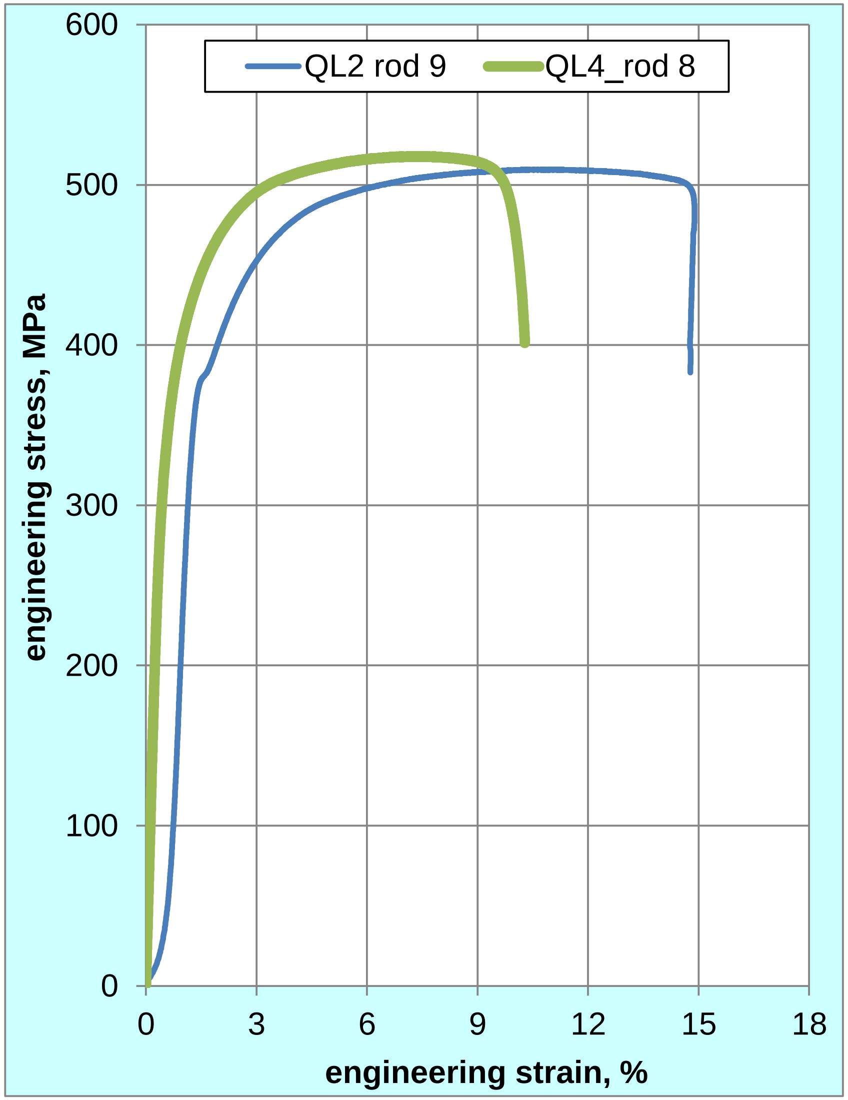
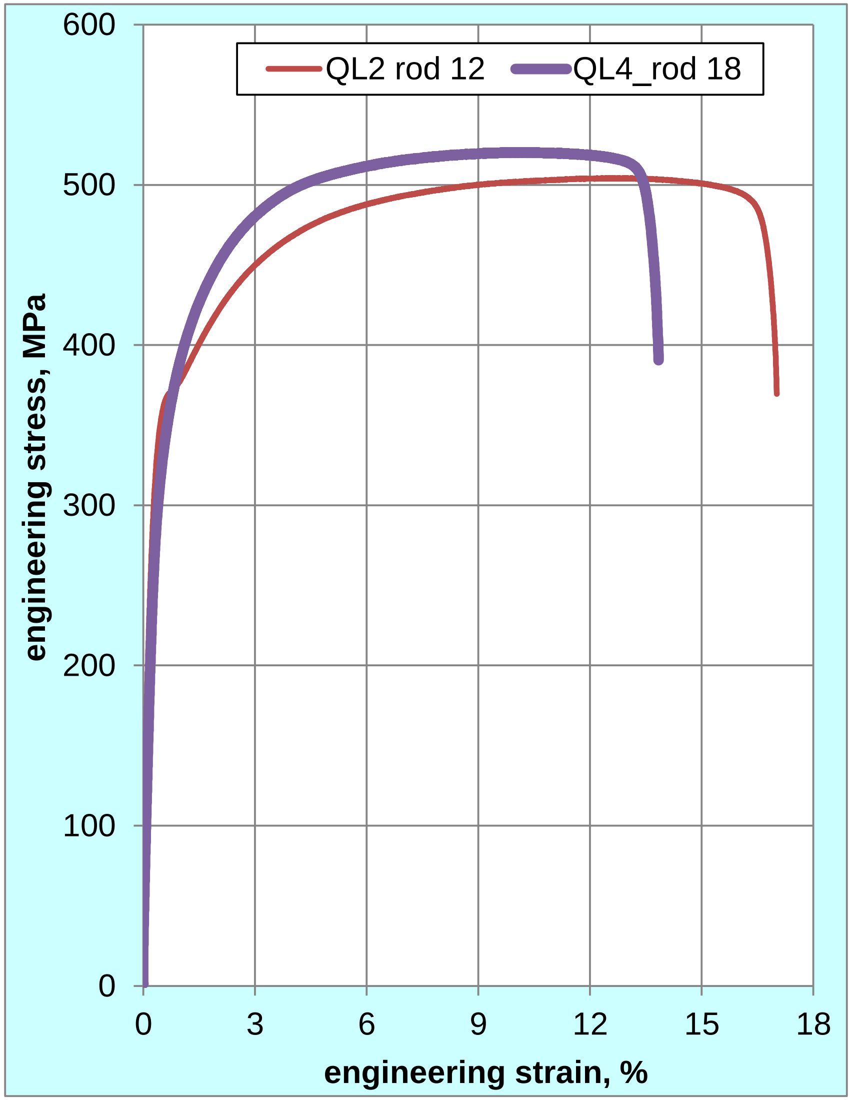
QUENCH–L4 (hydr. clads) and –L2 (not hydr. clads): tensile test results for claddings failed due to necking

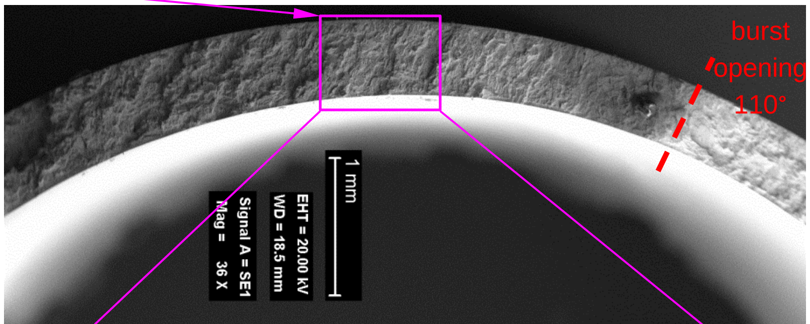


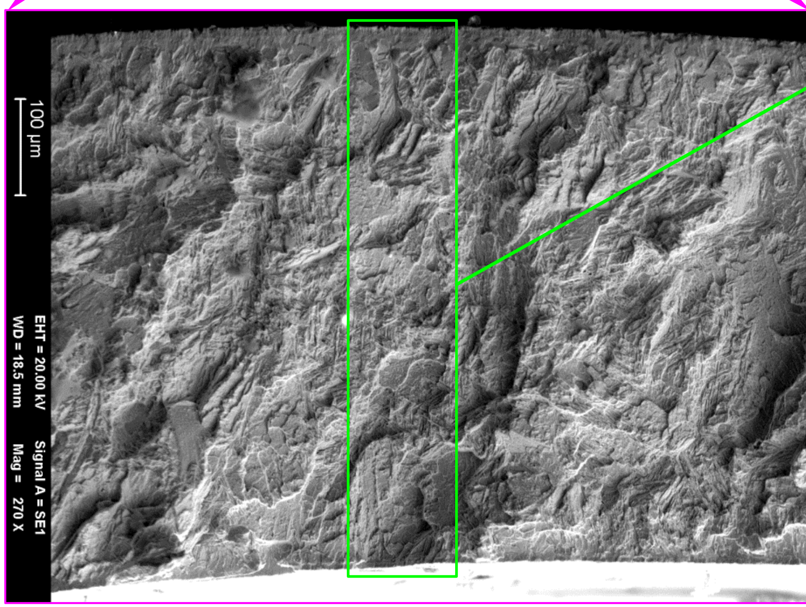
inner rods with greatest strain

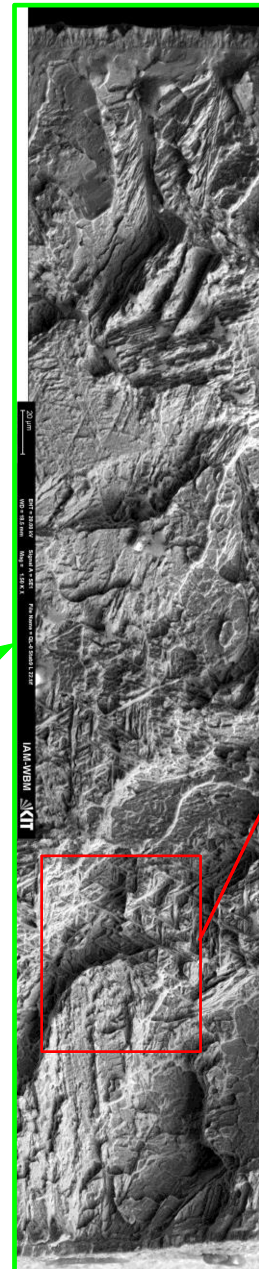


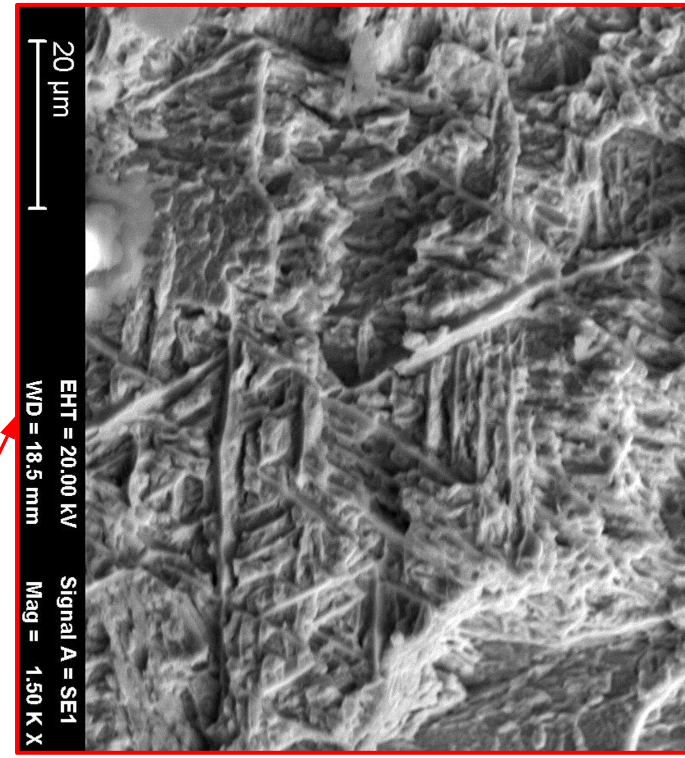
peripheral rods with greatest strain

QUENCH-L4; SEM image of fractured surface of rod #9 near to burst: brittle fracture at H-spot

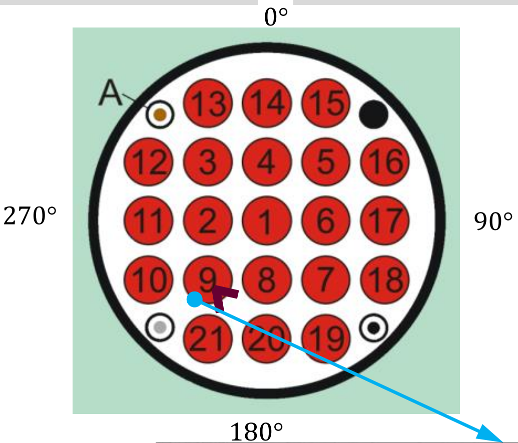




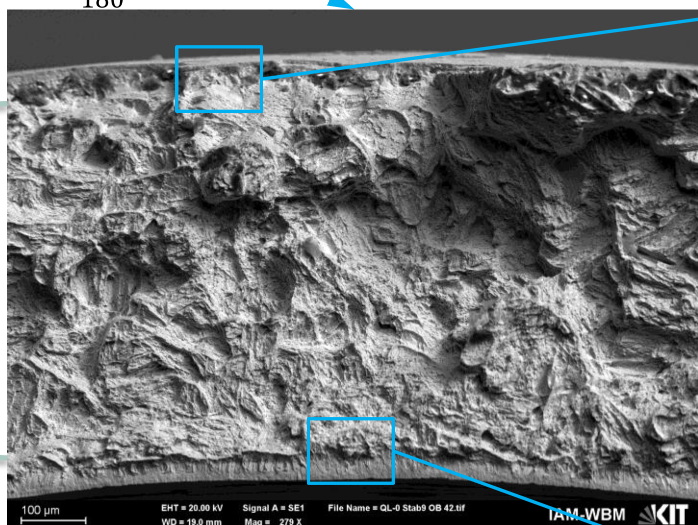


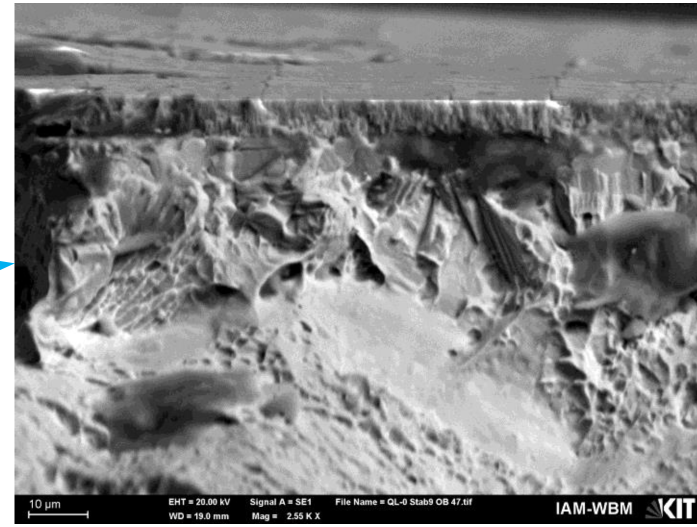


QUENCH-L4; SEM image of fractured surface of rod #9 90° to burst: ductile fracture



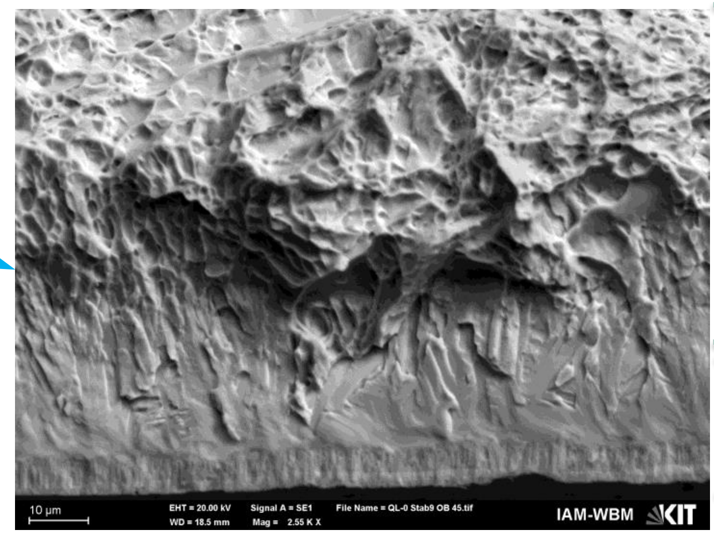
ductile dimples structure





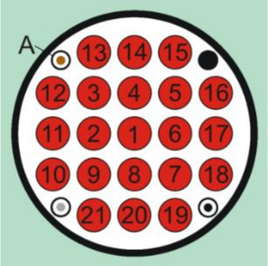
brittle ZrO_2 and α-Zr(O)

mostly ductile dimples structure



ductile dimples structure

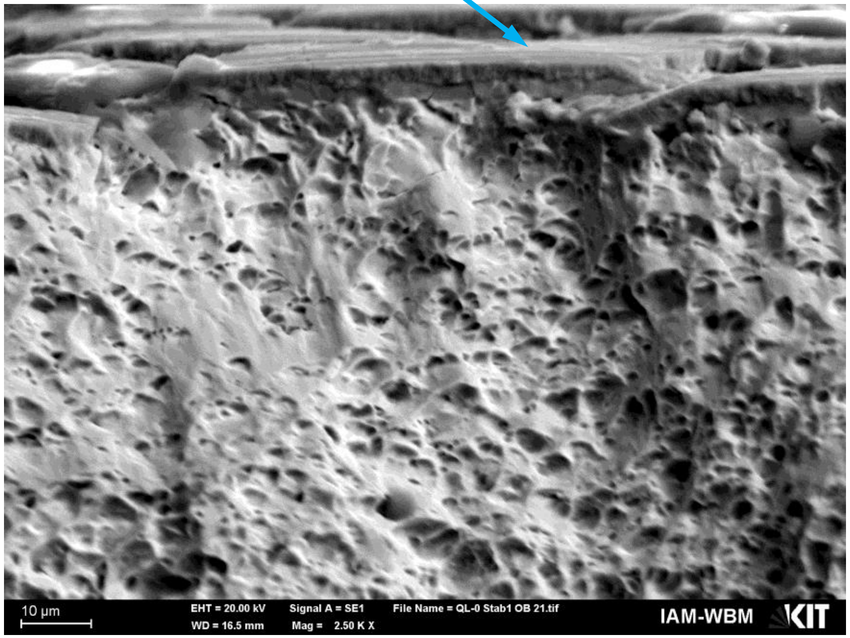
brittle α-Zr(O) and ZrO_2



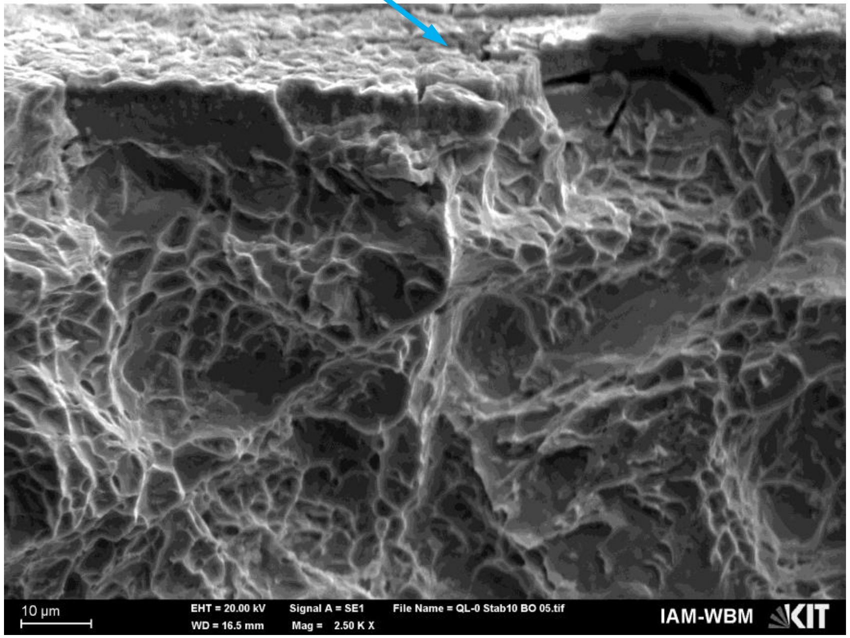
QUENCH-L4; SEM images of typical fractured surface of rod #10 after tensile test: ductile fracture

outer oxidised cracked surface

inner oxidised surface

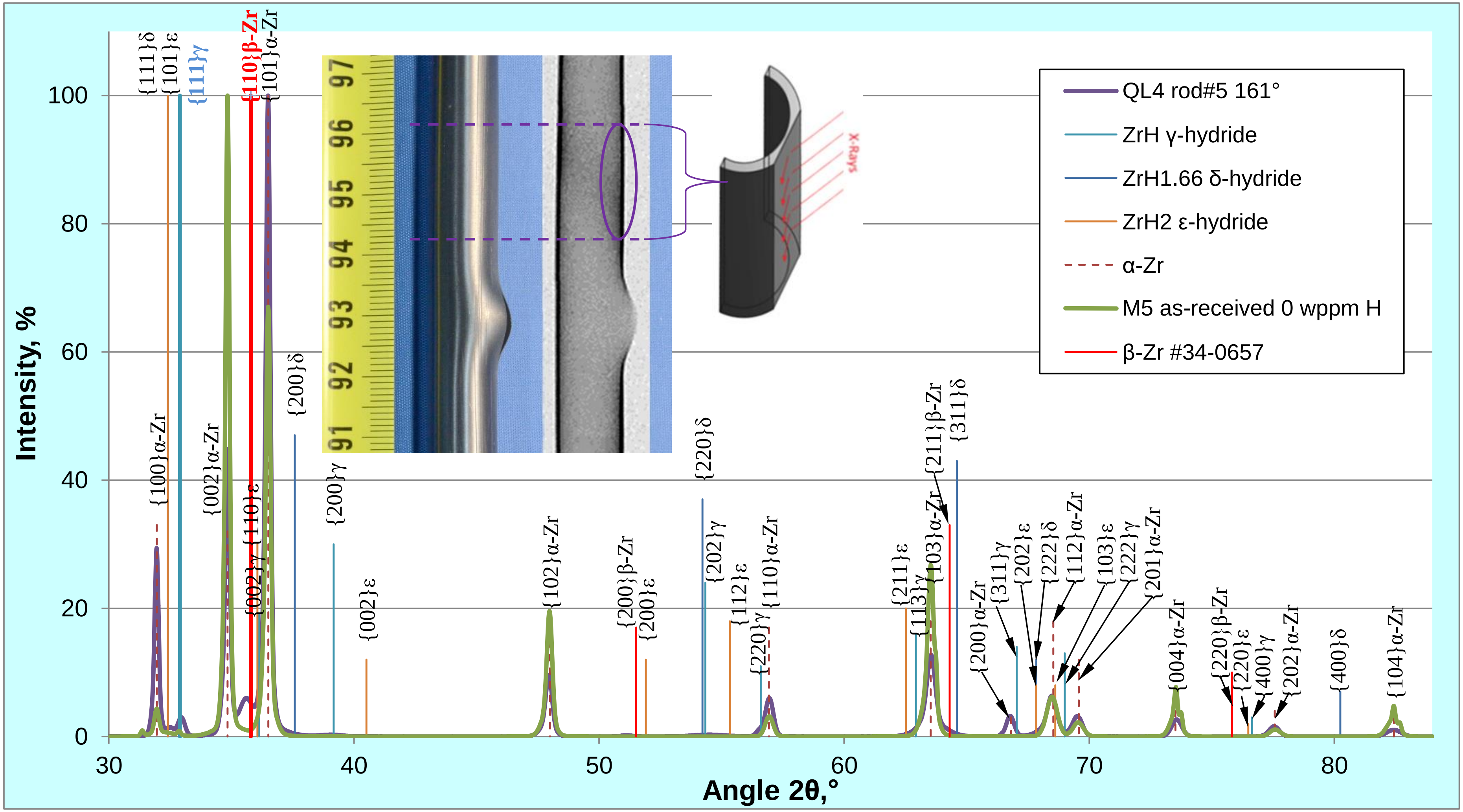


outer surface



inner surface

QUENCH-L4, rod 5; XRD analysis



QUENCH-L4, rod 6; EBSD analysis near to burst (931 mm)

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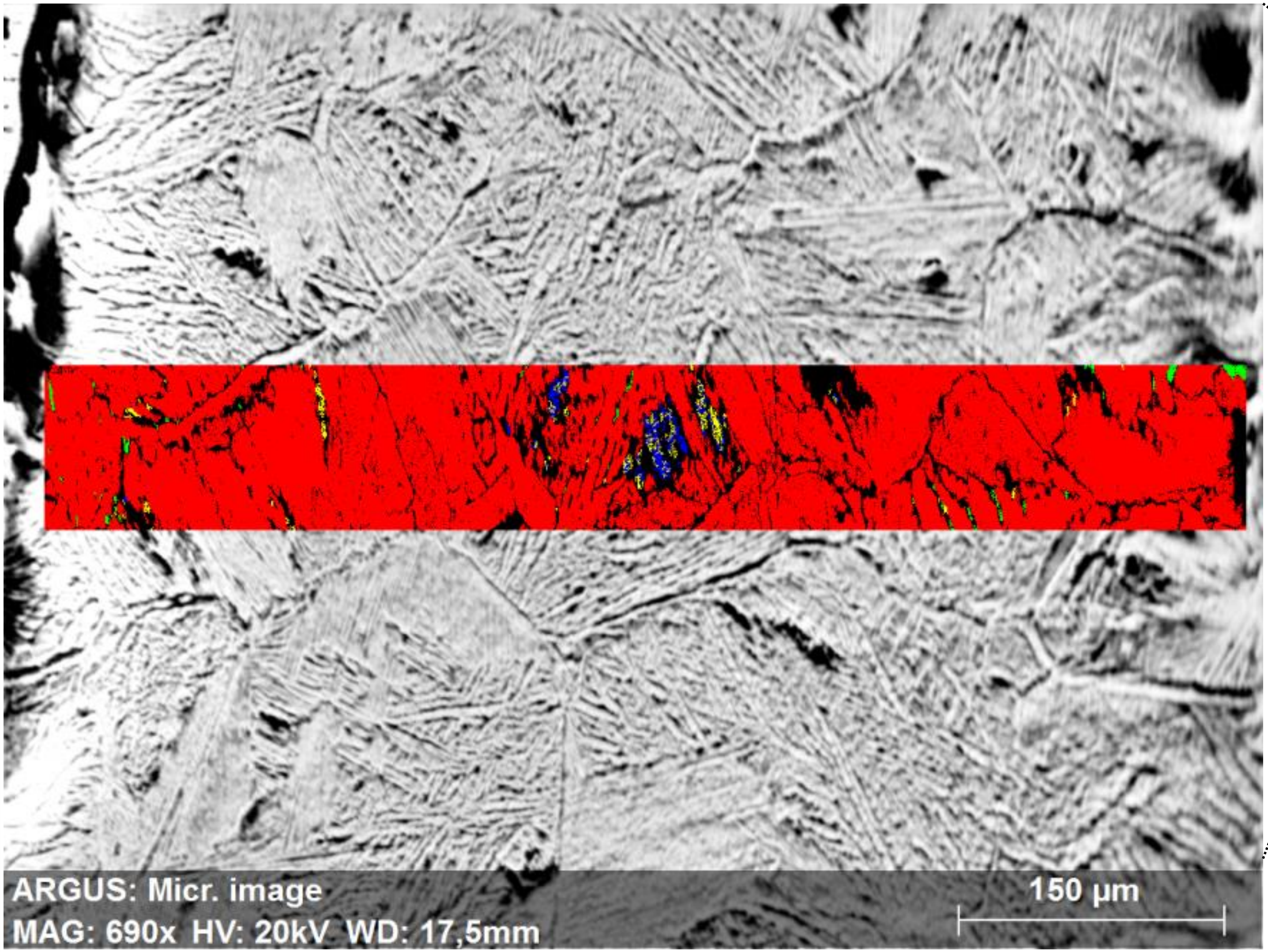

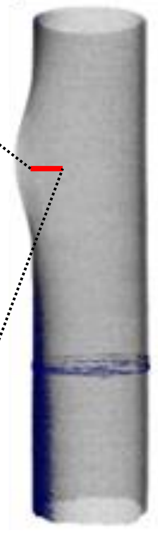

red needles: Zr

yellow areas: $ZrH_{1.6}$ (δ-hydride s)

blue points: ZrH (γ-hydrides)

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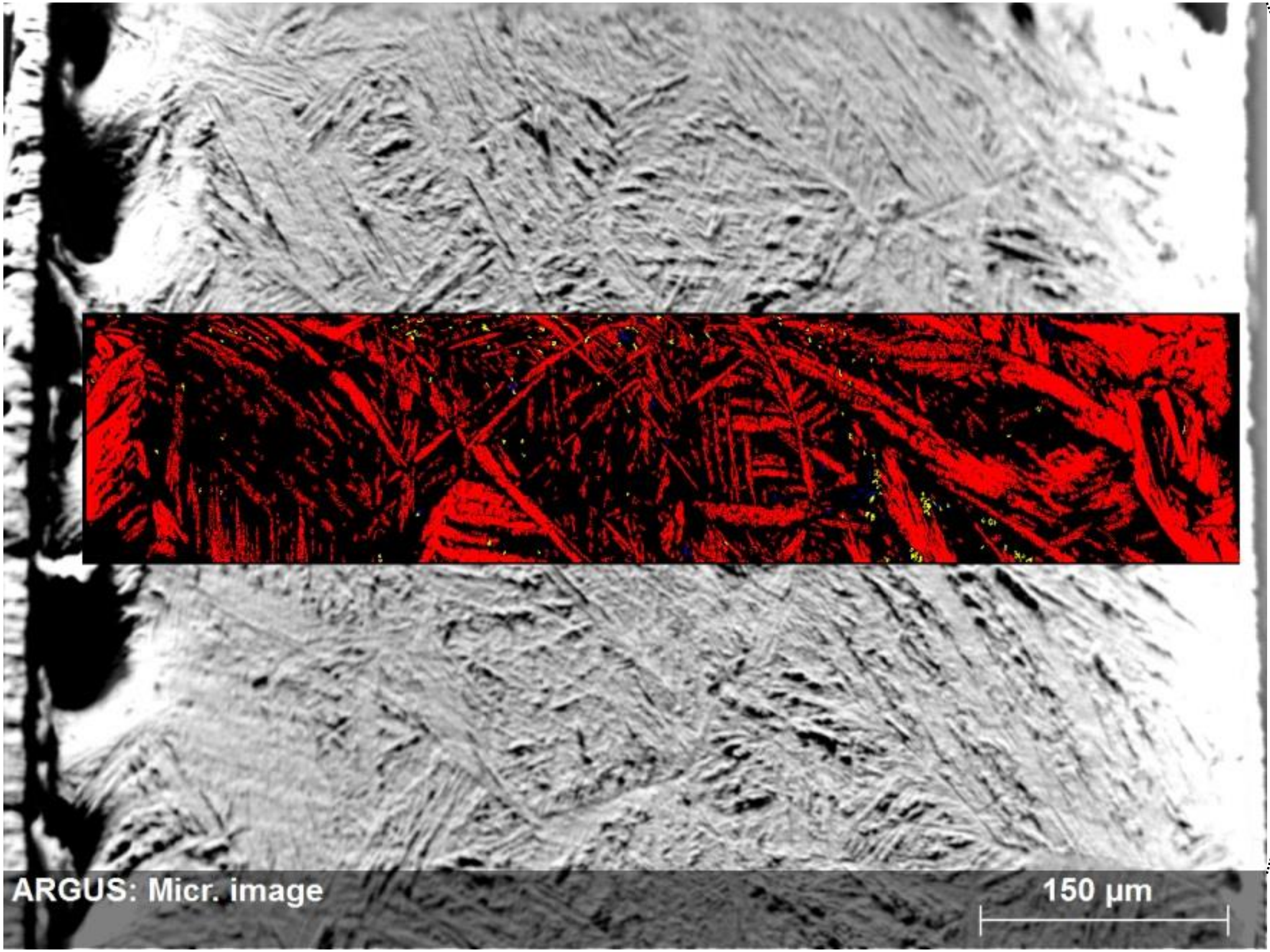
QUENCH-L4, rod 6; EBSD analysis at hydrogen band (912 mm)

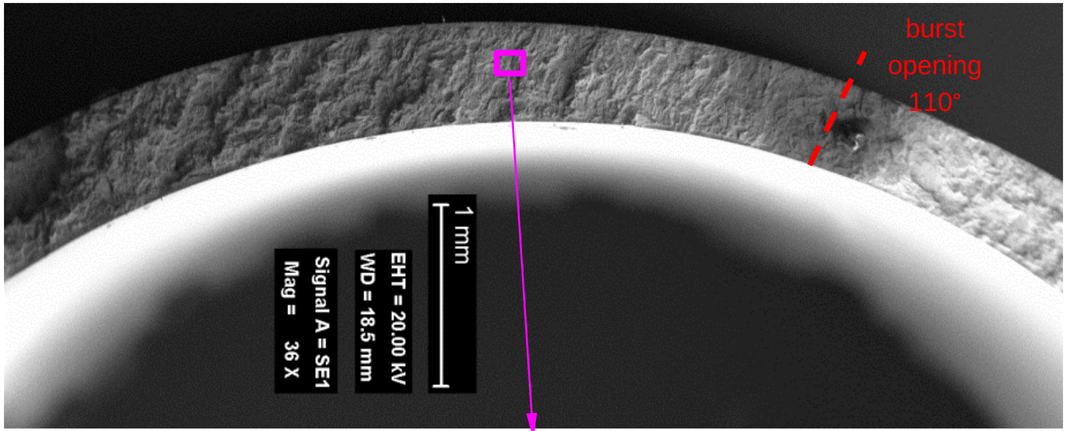


black areas: not recognized strong distorted lattice

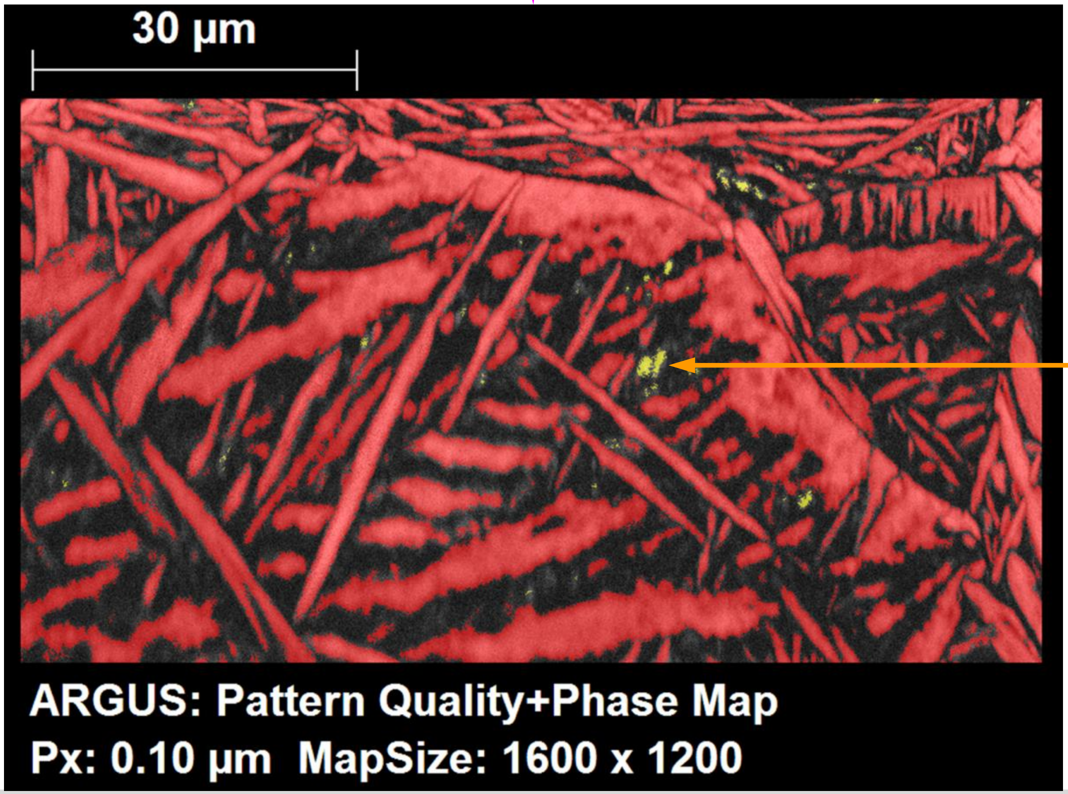
red needles: Zr

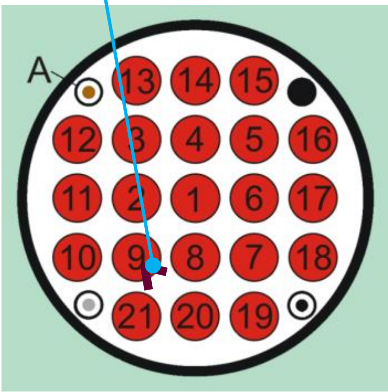
yellow areas: $ZrH_{1.6}$ (δ-hydride s)

QUENCH-L4, rod #9; EBSD analysis of fracture (after polishing and etching)



fracture
at H-spot





red needles: Zr

yellow areas: $ZrH_{1.6}$ (δ-hydride s)

black areas: not recognized structure with distorted lattice

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.
- 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).
- The cladding wall thinning from 725 µm to 450 µm due to ballooning was observed at the burst side along 50 mm below and above burst opening (ultrasound measurement).
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed (residual strengths or ductility is sufficient).
- 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.
- Average burst opening parameters: width 3.3 ± 0.7 mm; length 13.1 ± 1.9 mm (similar to QL2 with not pre-hydrogenated claddings).
- Tensile tests evidenced fracture at hydrogen bands (similar to QL0 with Zry-4 claddings): three inner rods were fractured due to this embrittlement. Eight peripheral rods were fractured due to stress concentration at burst opening edges (similar to ten claddings of QL2 test with not pre-hydrogenated claddings). All other tensile tested claddings failed after necking far away from burst region.
- XRD analysis detected hydrides inside hydrogen bands. Elaborated EBSD analysis showed that 1) the hydrides have µm-sizes are distributed in matrix intra- as well inter-granular; 2) areas with secondary hydrogenation have a strong distorted lattice.

Acknowledgment

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Thank you for your attention

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