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First results of the bundle test QUENCH-L5 with pre-hydrogenated opt. ZIRLO™ claddings

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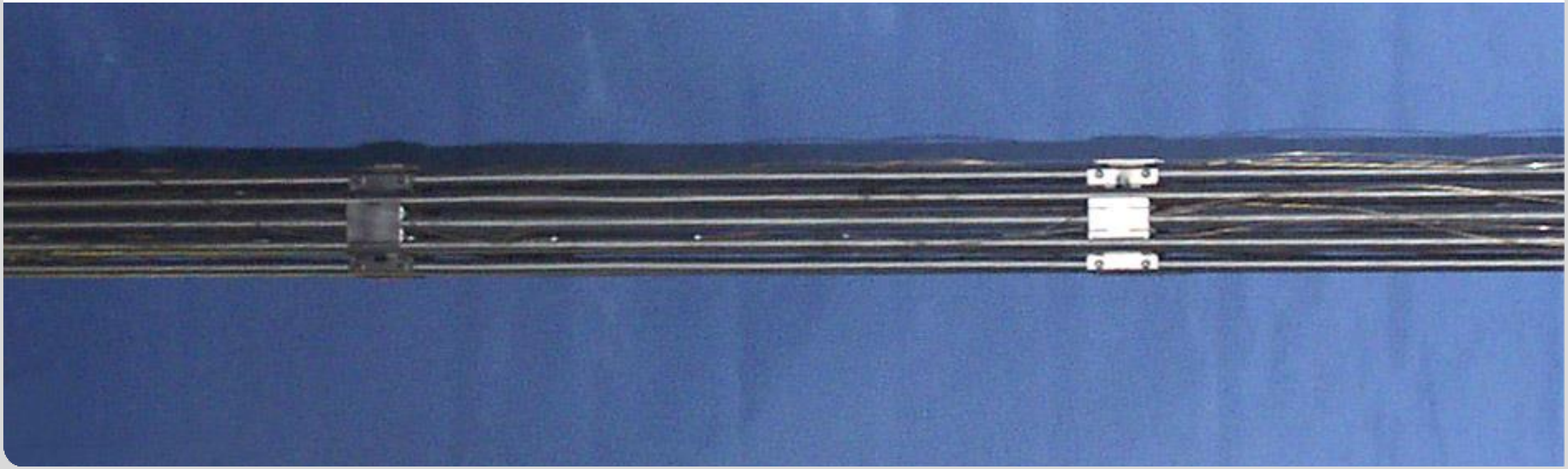
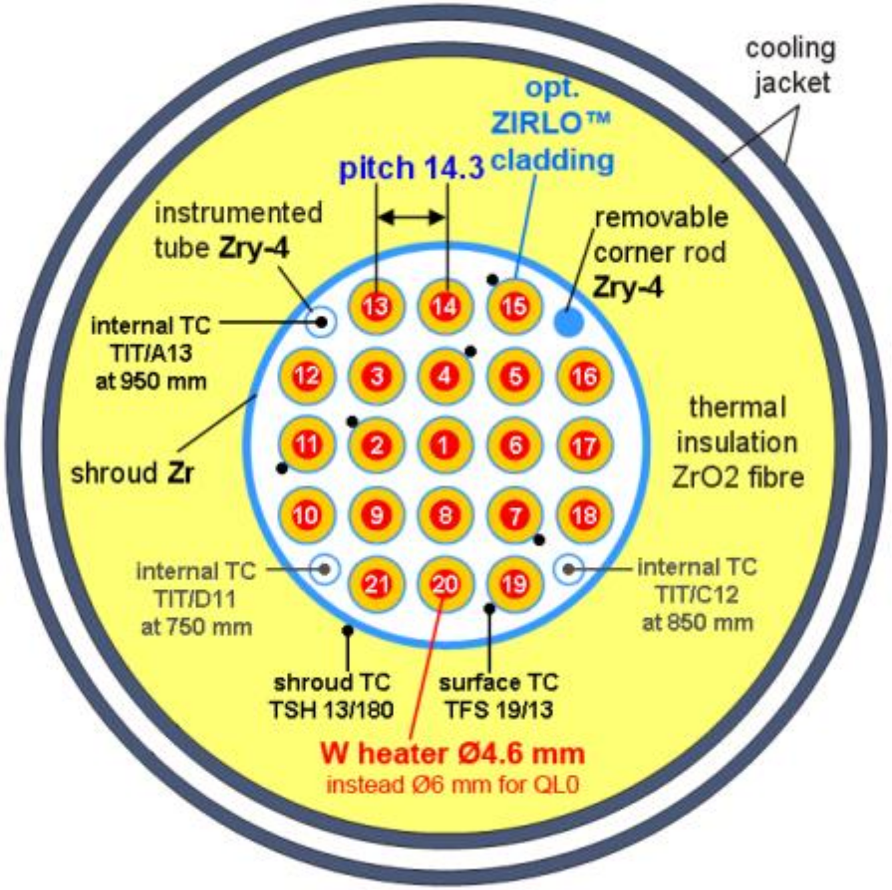
Institute for Applied Materials; Program NUKLEAR



Cross-section of the QUENCH-L3 and -L5 bundles



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-L5: test with hydrogenated claddings

Zry-4 spacer
1410 mm

Zry-4 spacer
1050 mm

Zry-4 spacer
550 mm

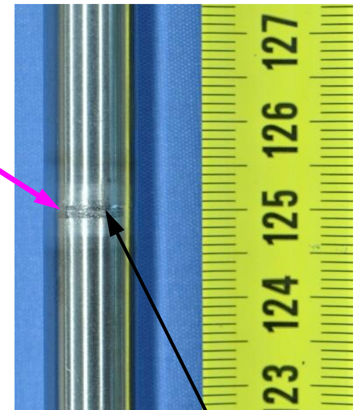
Zry-4 spacer
150 mm

Inconel spacer
-100 mm

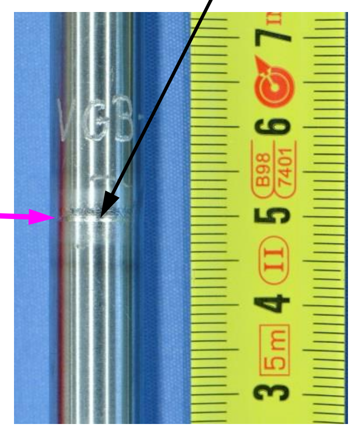
21 pre-hydrogenated tubes,

each welded from 3 segments

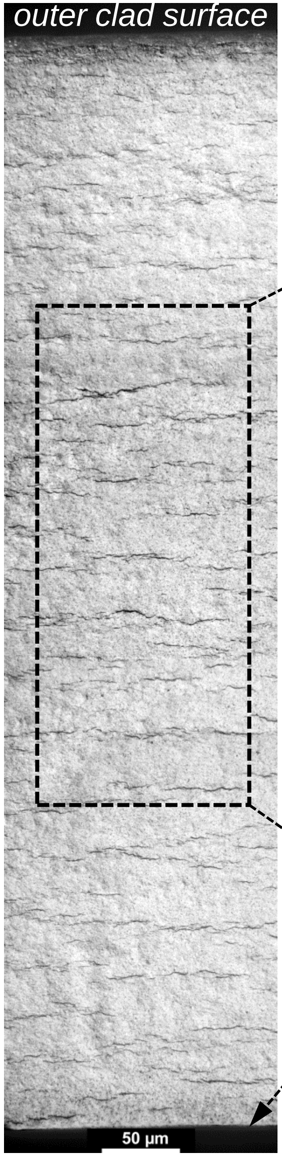
with lengths 500 (0 wppm),1200 (300 wppm H), 500 mm (0 wppm)



welded joints

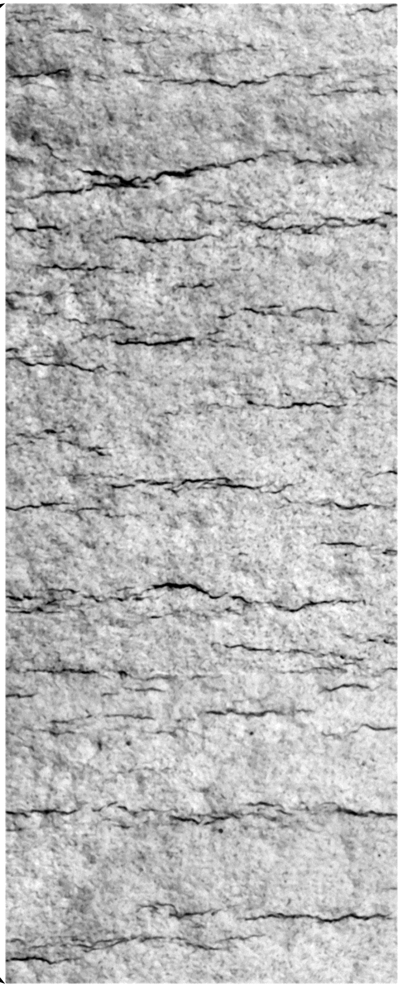


QUENCH-L5: hydrides inside the prototype cladding with 300 wppm H

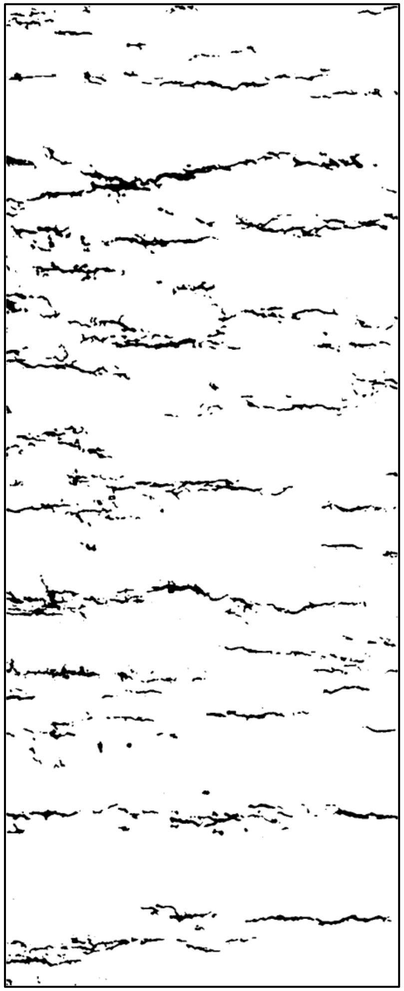


inner clad surface

cladding cross section



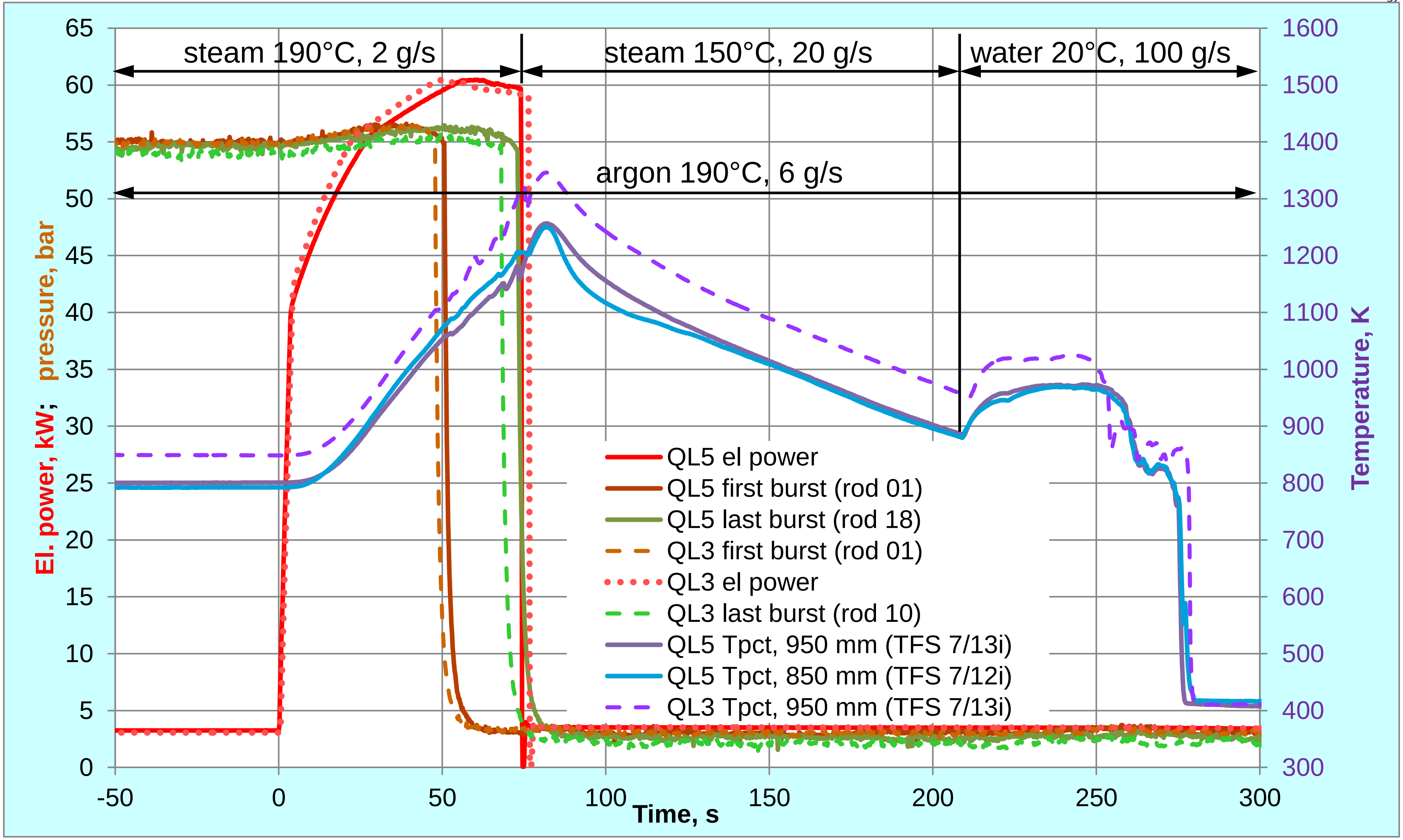
middle of cladding



hydrides: 5% of area

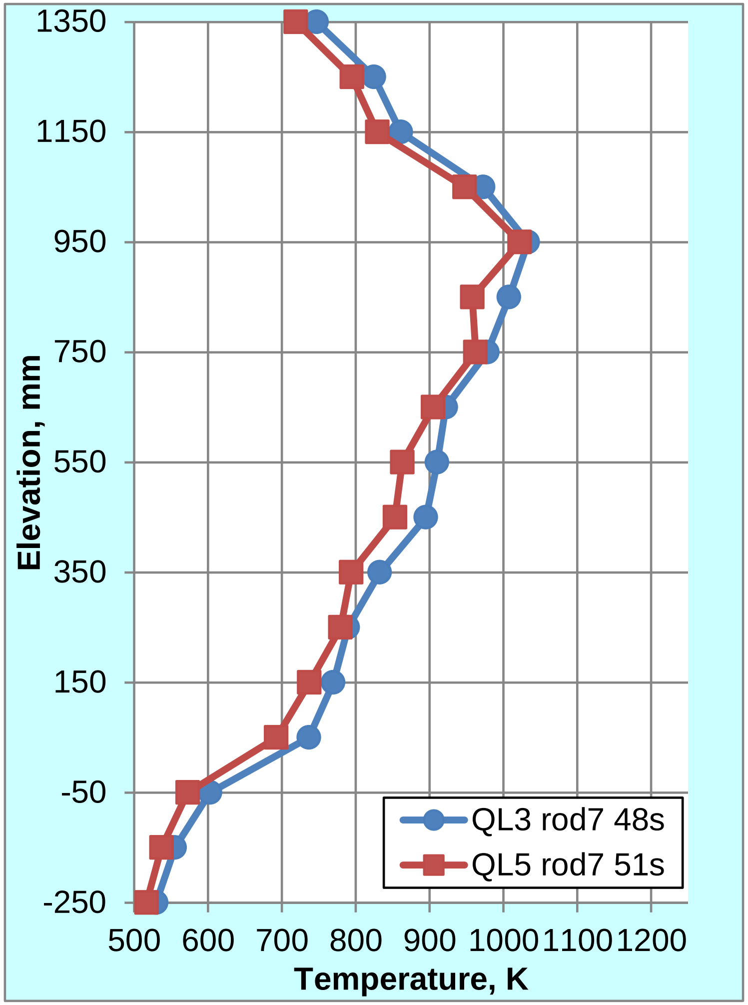
to compare: QL4 with 100 wppm has 2%

QUENCH-L5: test progress, comparison with QL-3 (ZIRLO without pre-hydrogenation)

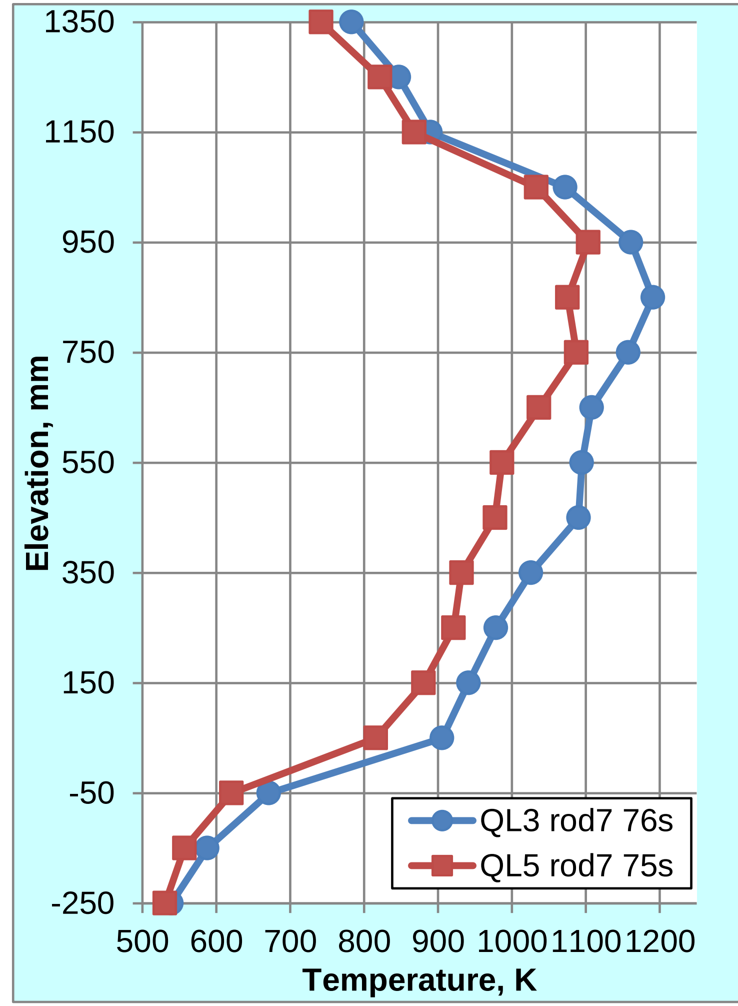


initial temperature on the test start about 50 K lower (800 K instead 850 K) in comparison to QUENCH-L3

Axial temperature profiles for QUENCH-L3 and -L5

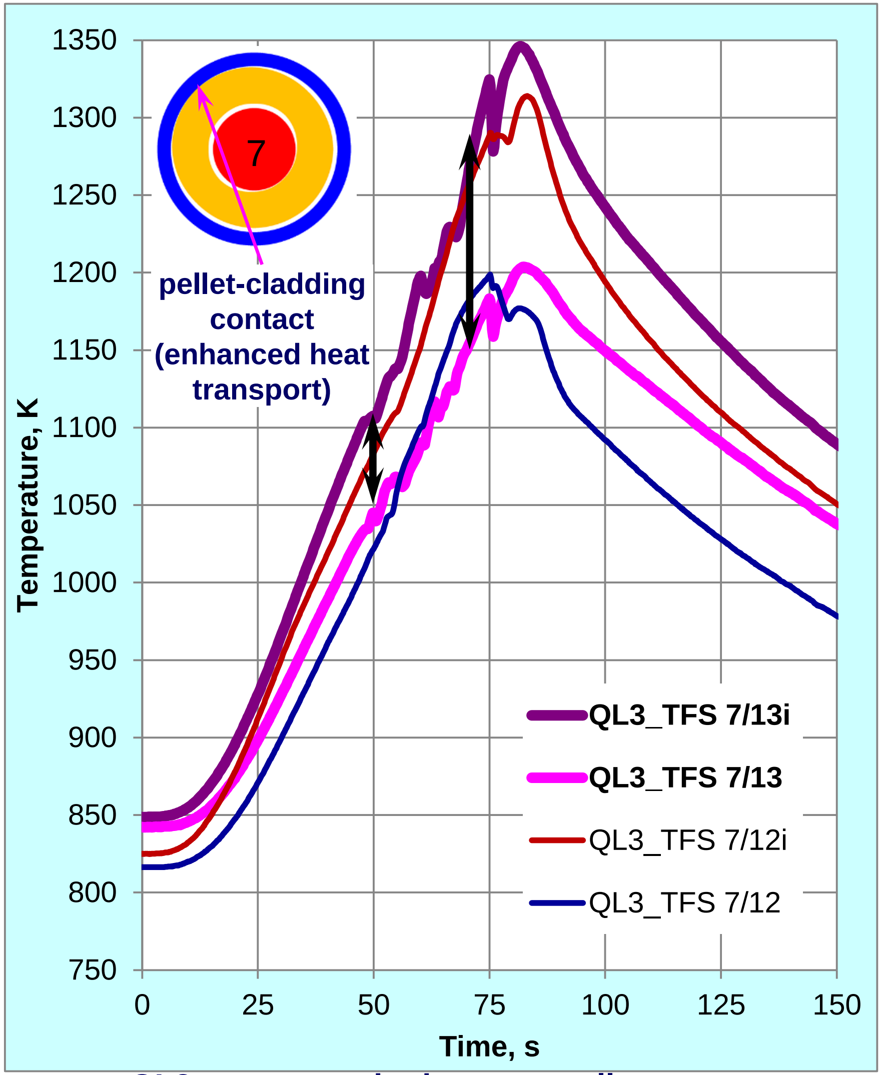


on the first cladding burst

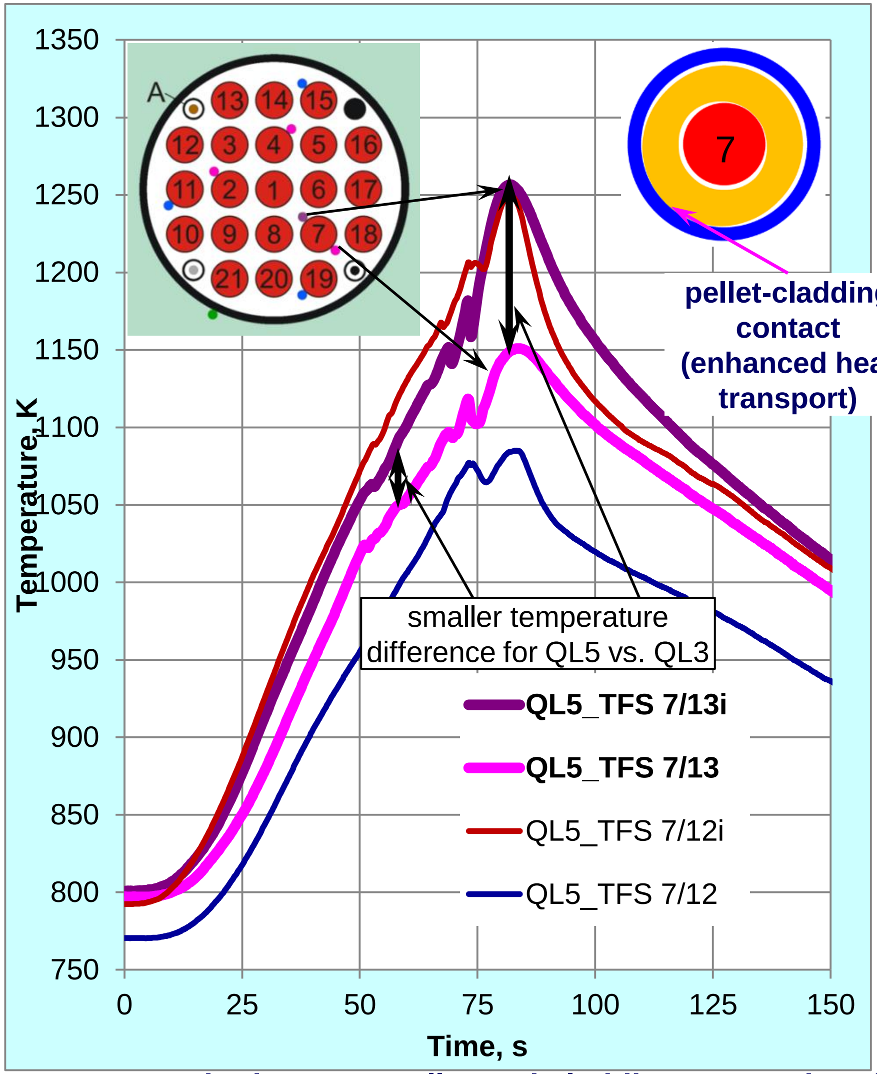


on the end of transient

Radial temperature difference as superposition of *global* heat loss through shroud and *local* pellet shifting

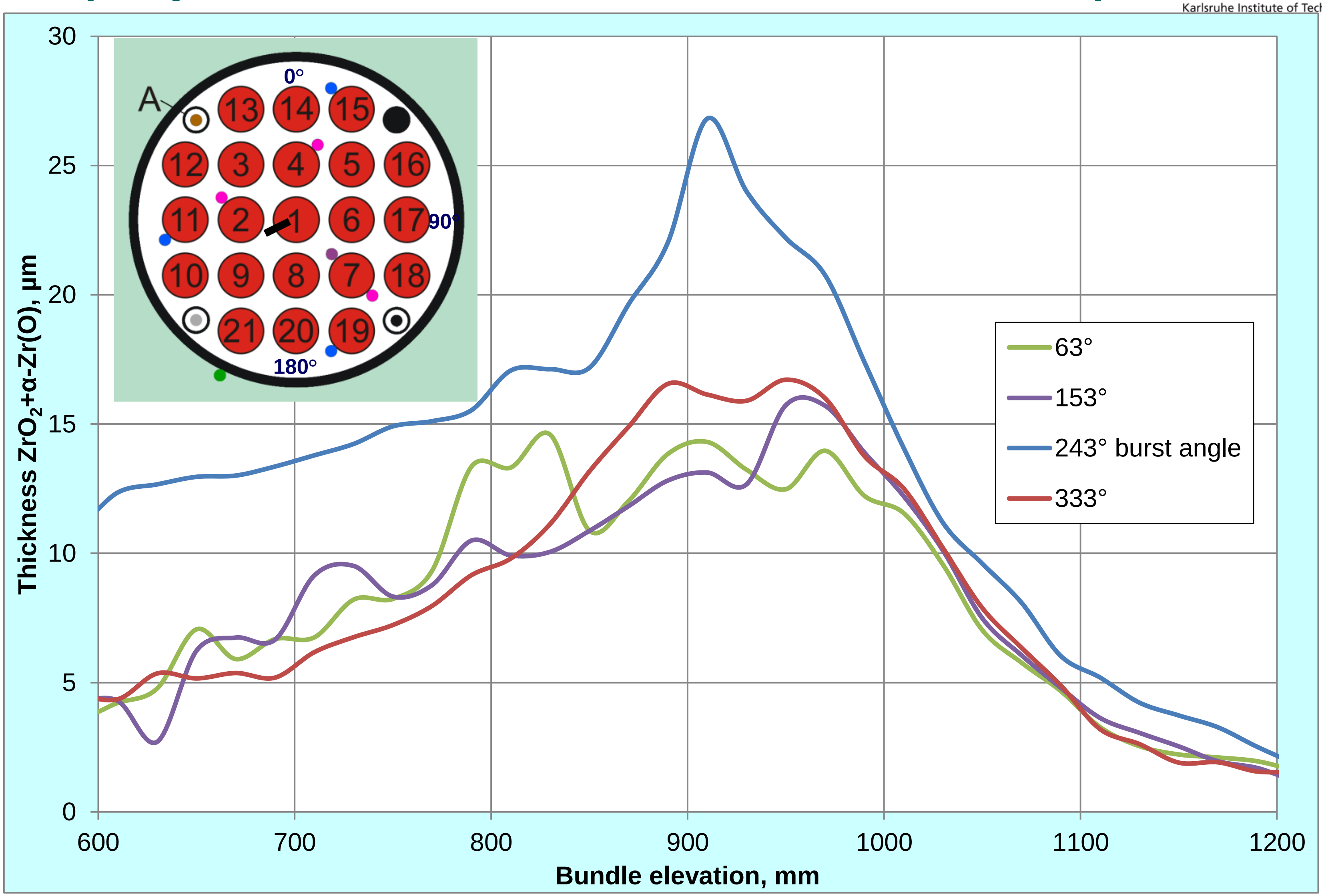


QL3: contact point between pellet and cladding near to bundle centre



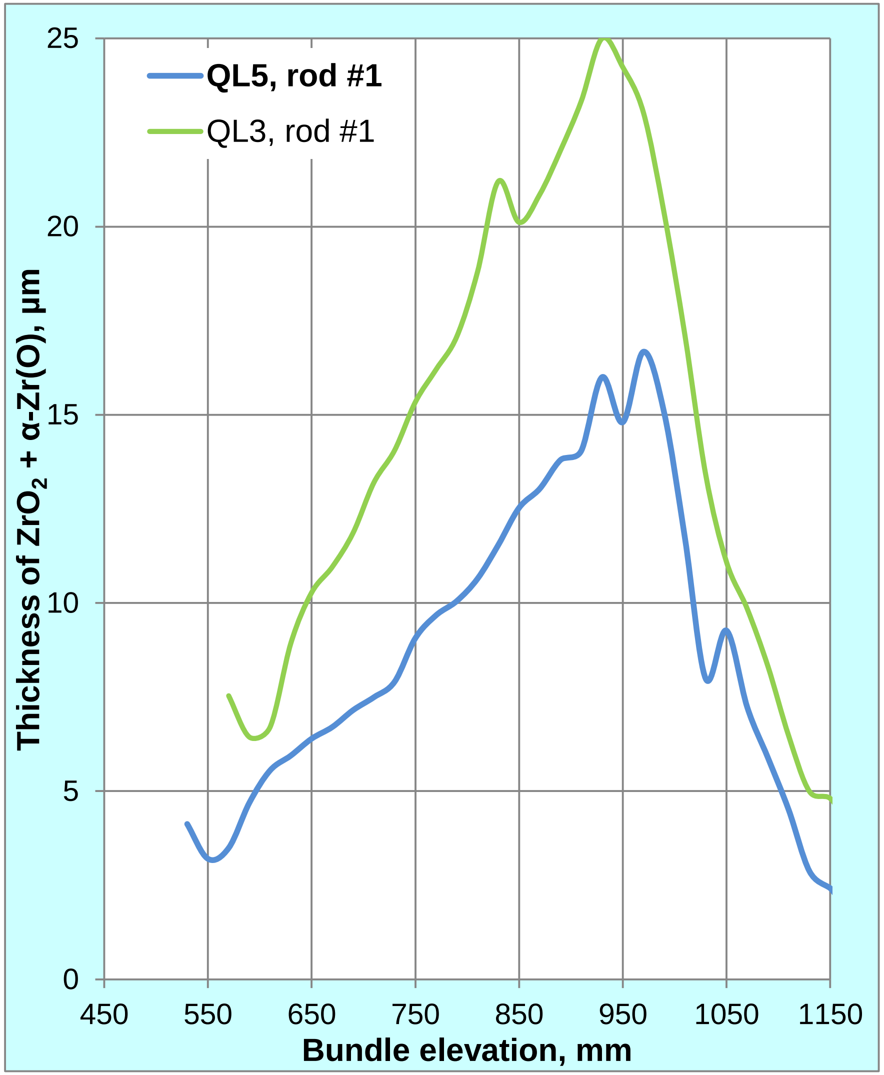
QL5: contact point between pellet and cladding near to bundle periphery decreased circumferential temperature difference

QL-5: oxidation of rod #1
(eddy current measurements at outer clad surface)

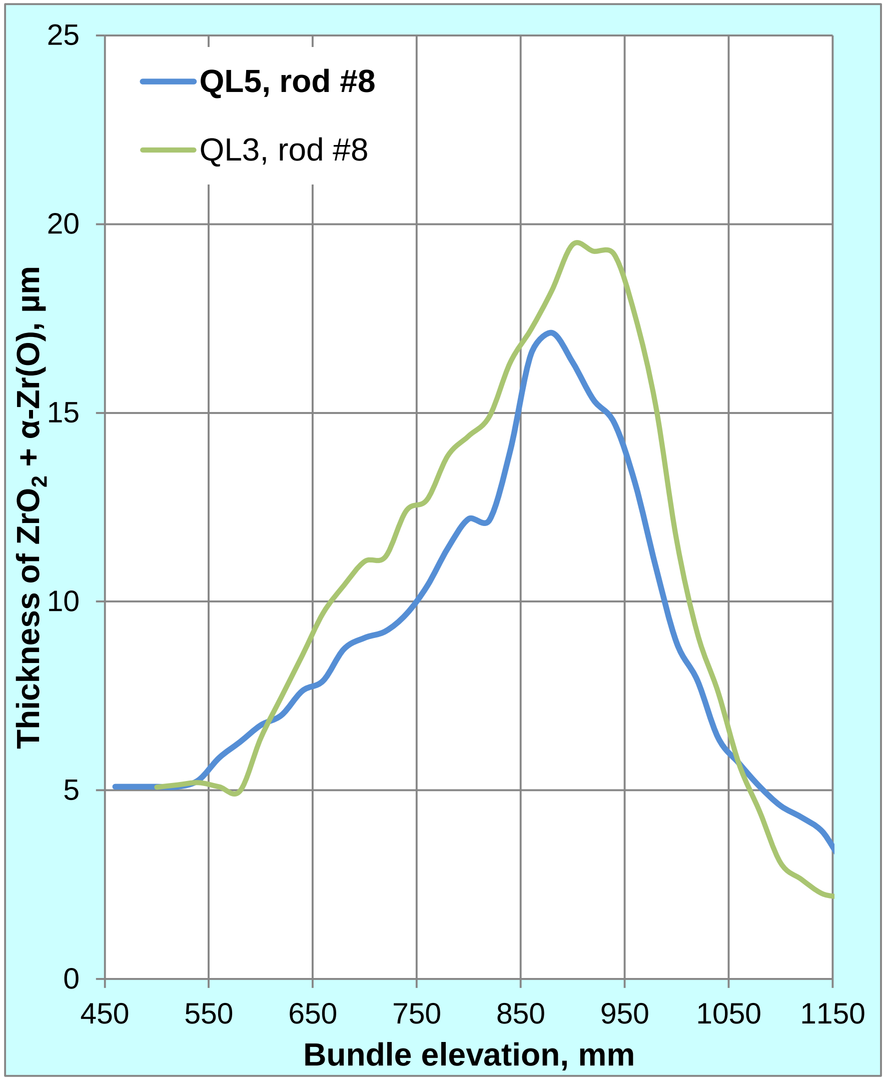


hottest rod side at 243° (burst line)

Comparison of oxidation for QL-5 and QL-3 (eddy current measurements at outer clad surface)



central rod: QL3 oxidation rate noticeably higher



rod #8: QL3 oxidation rate slightly higher

Rod pressure evolution during heating phase for QUENCH-L3 and -L5: burst time indication; similar pressure relief for both tests

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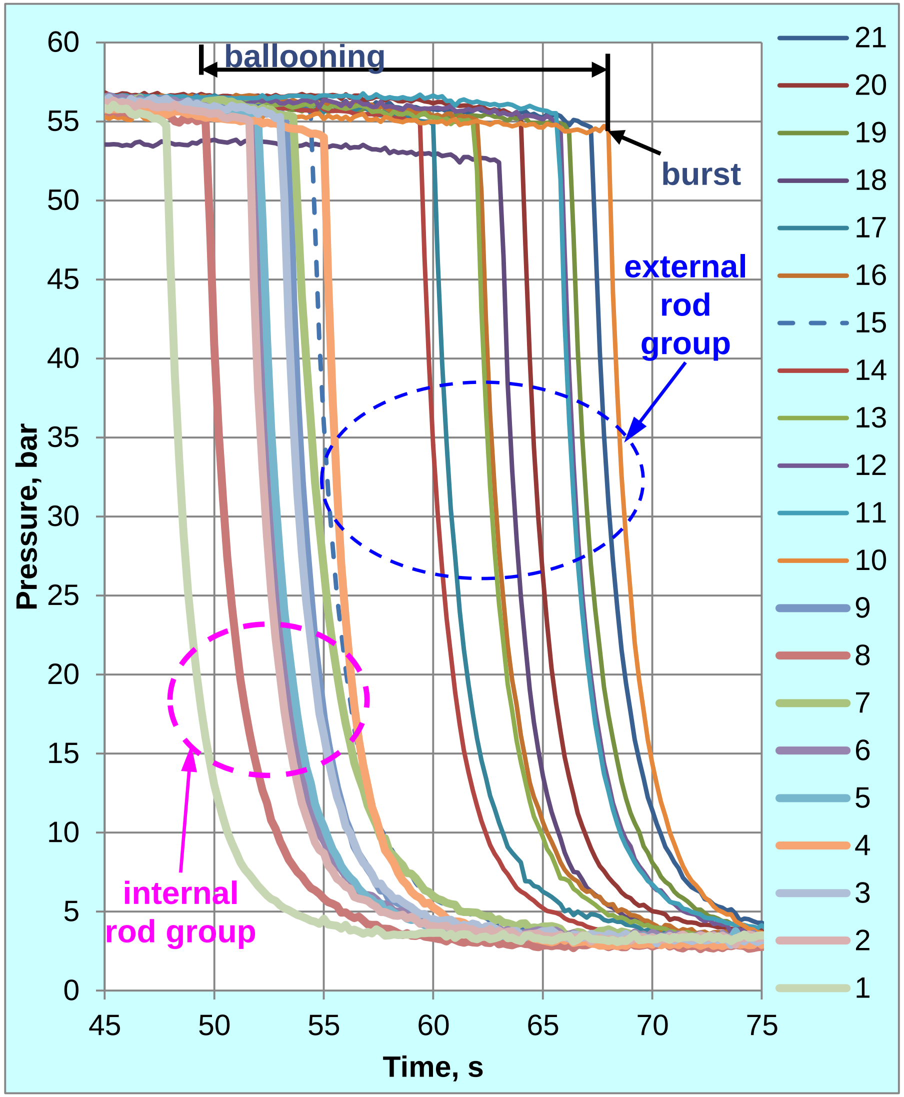
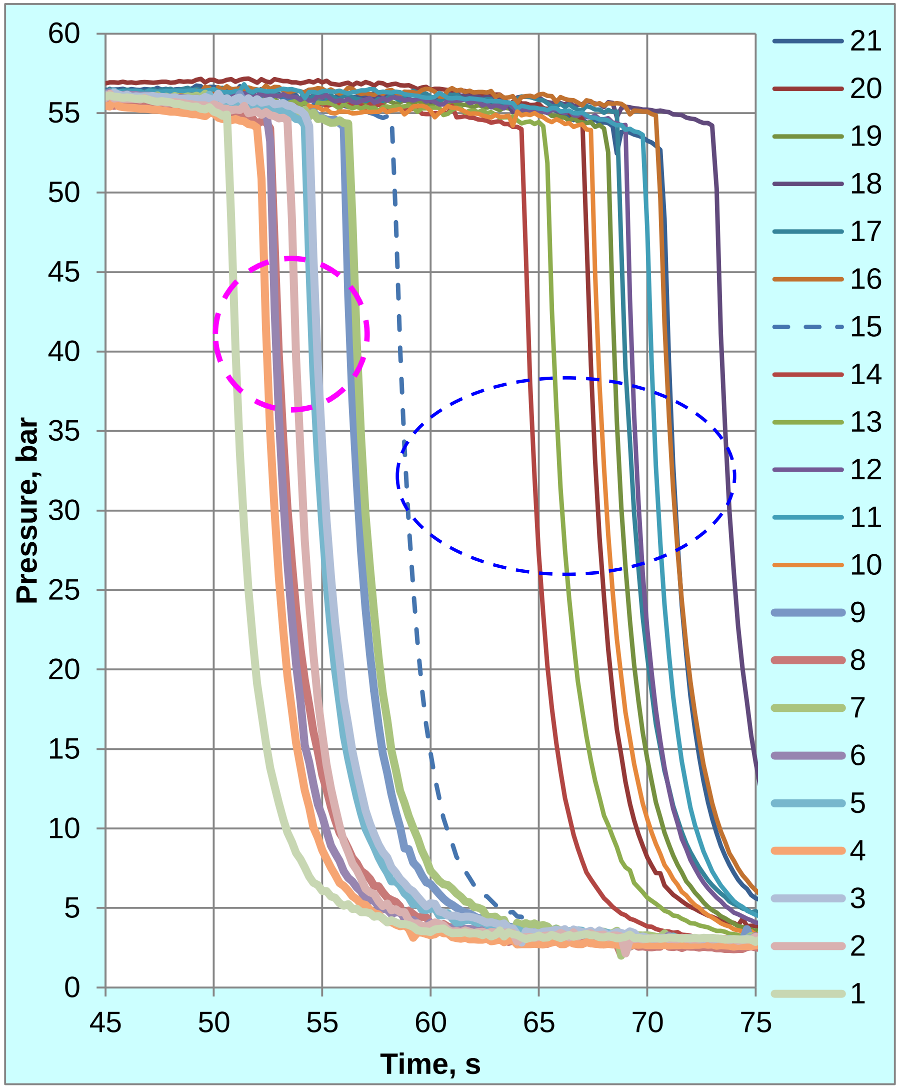


QL3



QL5

Burst parameters:
decrease of burst temperature for hydrogenated tubes

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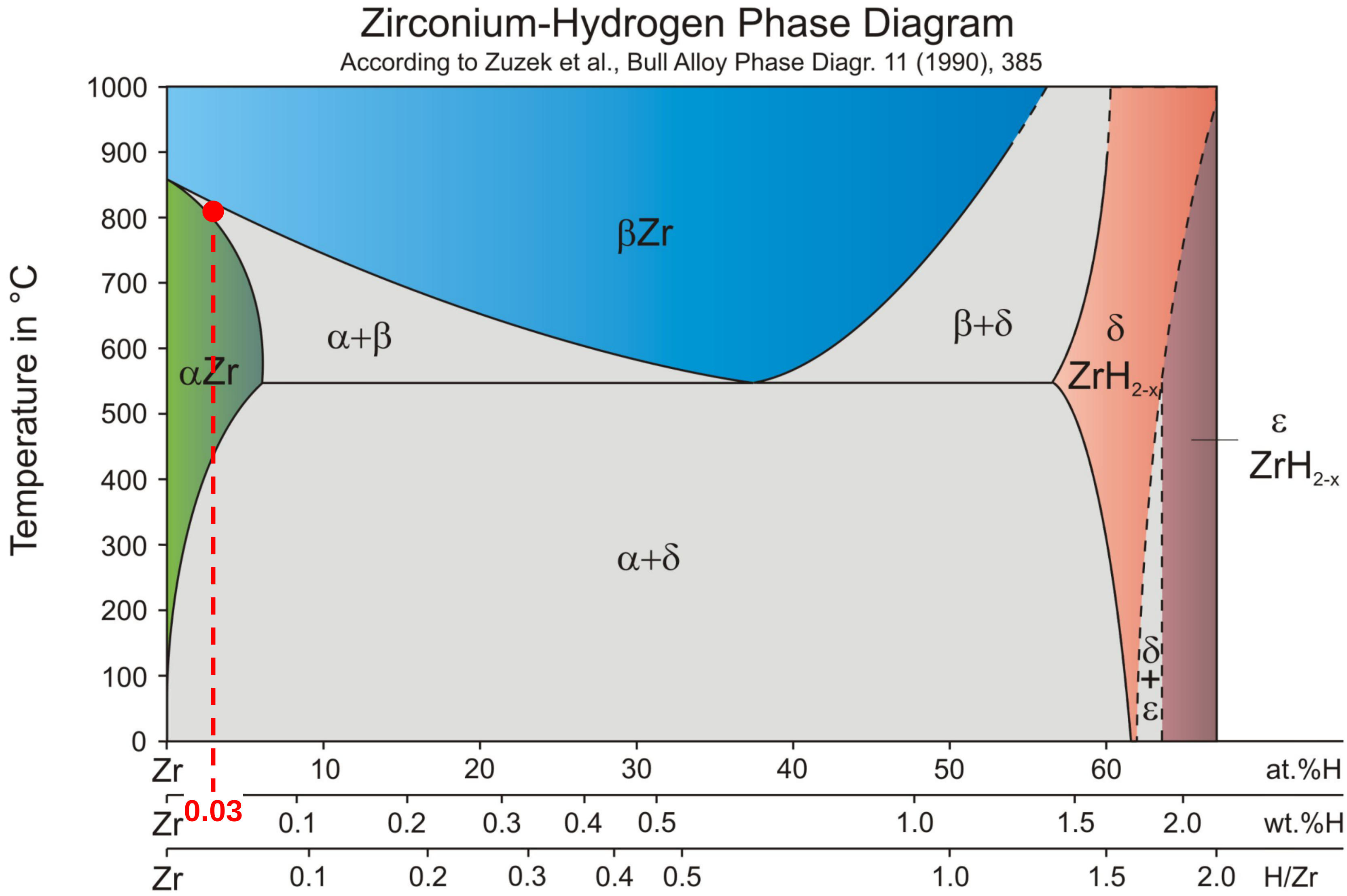
Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	1	47.8	1103
	2	51.6	1140
	3	53	1111
	4	55	1108
	5	52	1109
	6	51.8	1112
	7	53.6	1124
	8	49.6	1107
	9	53.2	1132
Outer rods	10	68	1188 (Max)
	11	65.6	1126
	12	65.8	1175
	13	61.8	1138
	14	59.4	1124
	15	*54.4*	1105
	16	62	1142
	17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

LOCA-3 average burst T: 1117 ± 30 K = 844 ± 30 °C

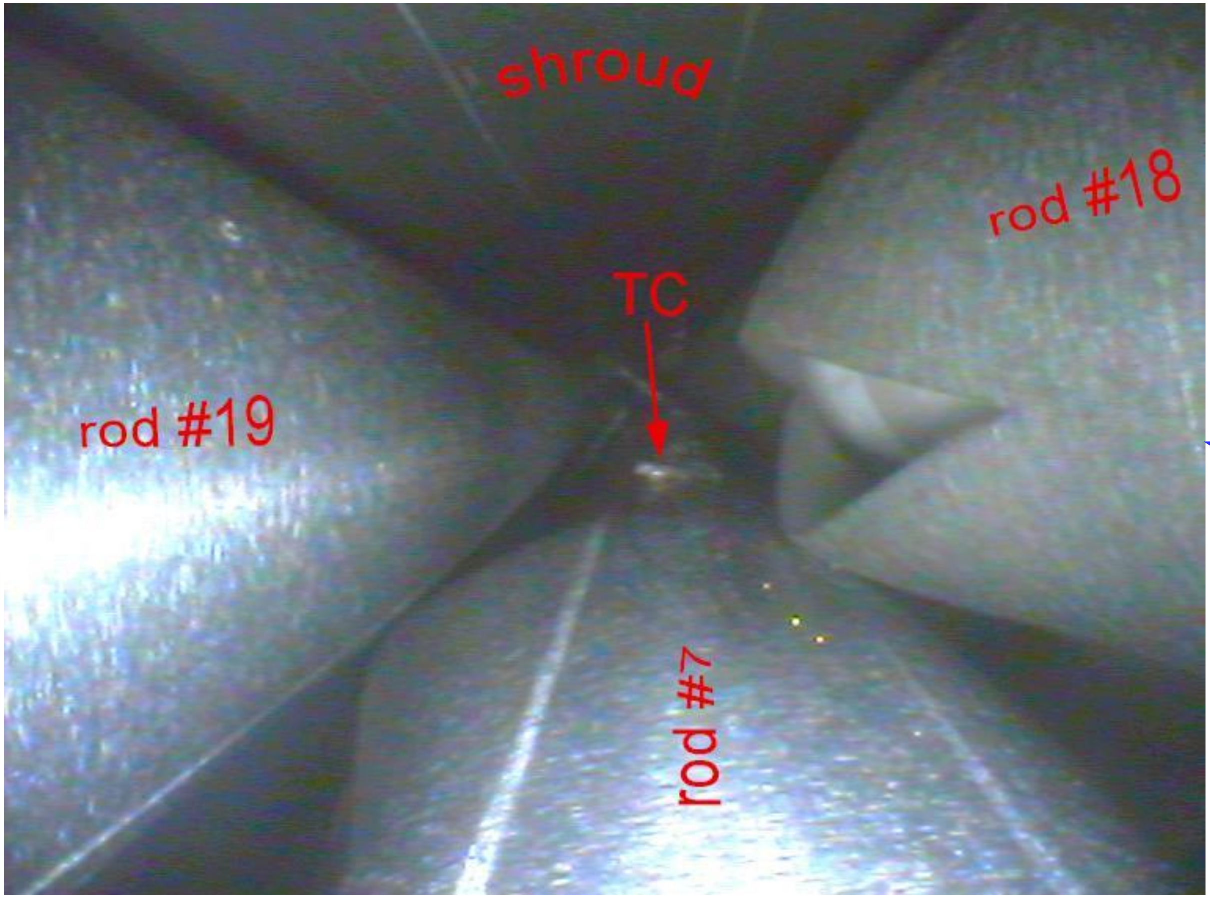
Rod group	Rod #	Burst time, s	Burst temperature, interpolated, K
Inner rods	1	50.6	1057
	2	53.4	1056
	3	54.4	1100
	4	52	1068
	5	54.2	1080
	6	52.4	1063
	7	56.2	1077
	8	52.6	1041
	9	56	1040
Outer rods	10	67.4	1121
	11	69.8	1134
	12	69	1126
	13	65.2	1106
	14	64.2	1100
	15	*58.2*	1064
	16	70.4	1151 (Max)
	17	68.6	1096
	18	73	1119
	19	68	1027 (Min)
	20	67	1047
	21	70.6	1028

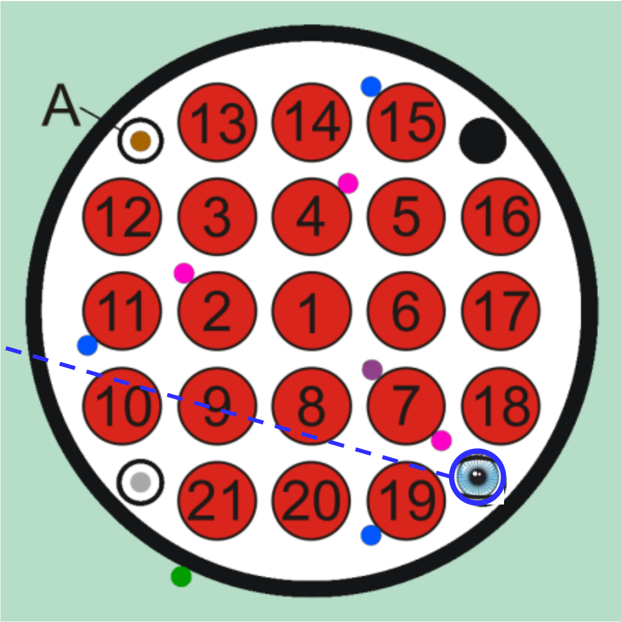
LOCA-5 average burst T: 1081 ± 36K = 808 ± 36 °C

Reason for lower burst temperature for QUENCH-L5:
Zr-H phase diagram → *decrease of α↔β phase transition temperature with increasing of hydrogen content*

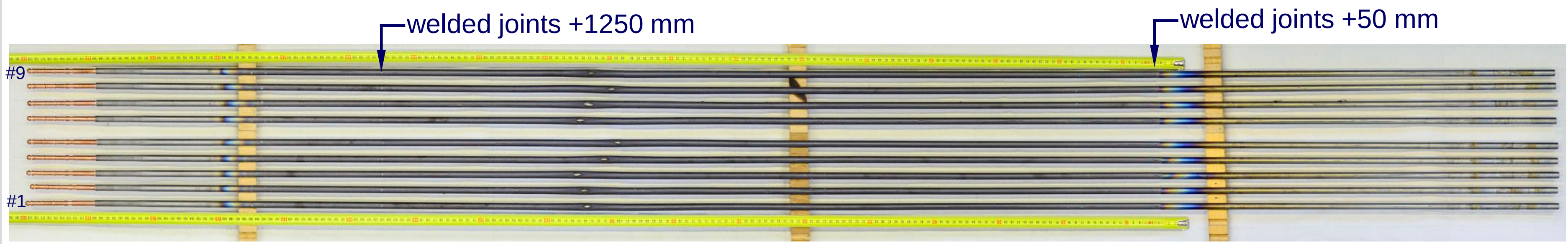


QUENCH-L5: Ballooning and burst of cladding tubes at elevation 940 mm (videoscope)

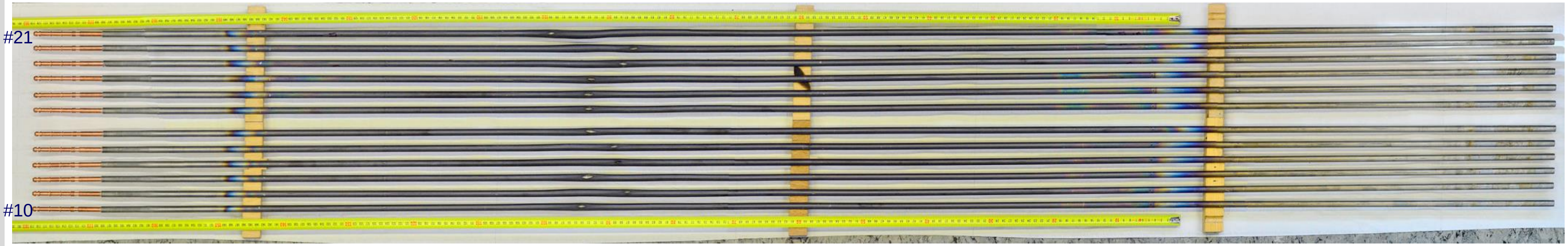




QUENCH-L5: front view of rods after bundle dismounting



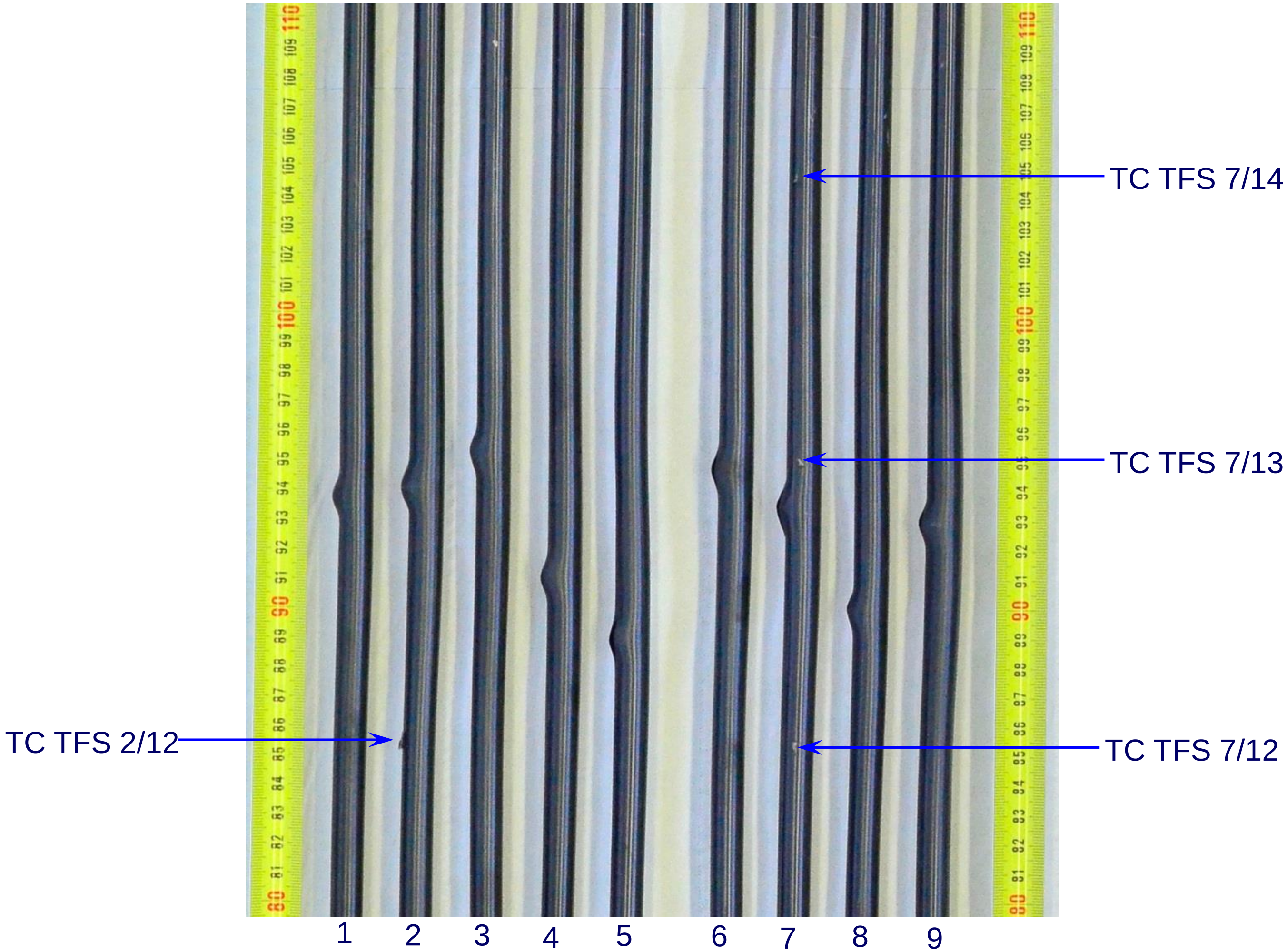
9 inner rods



12 outer rods

no rod bending in this plane

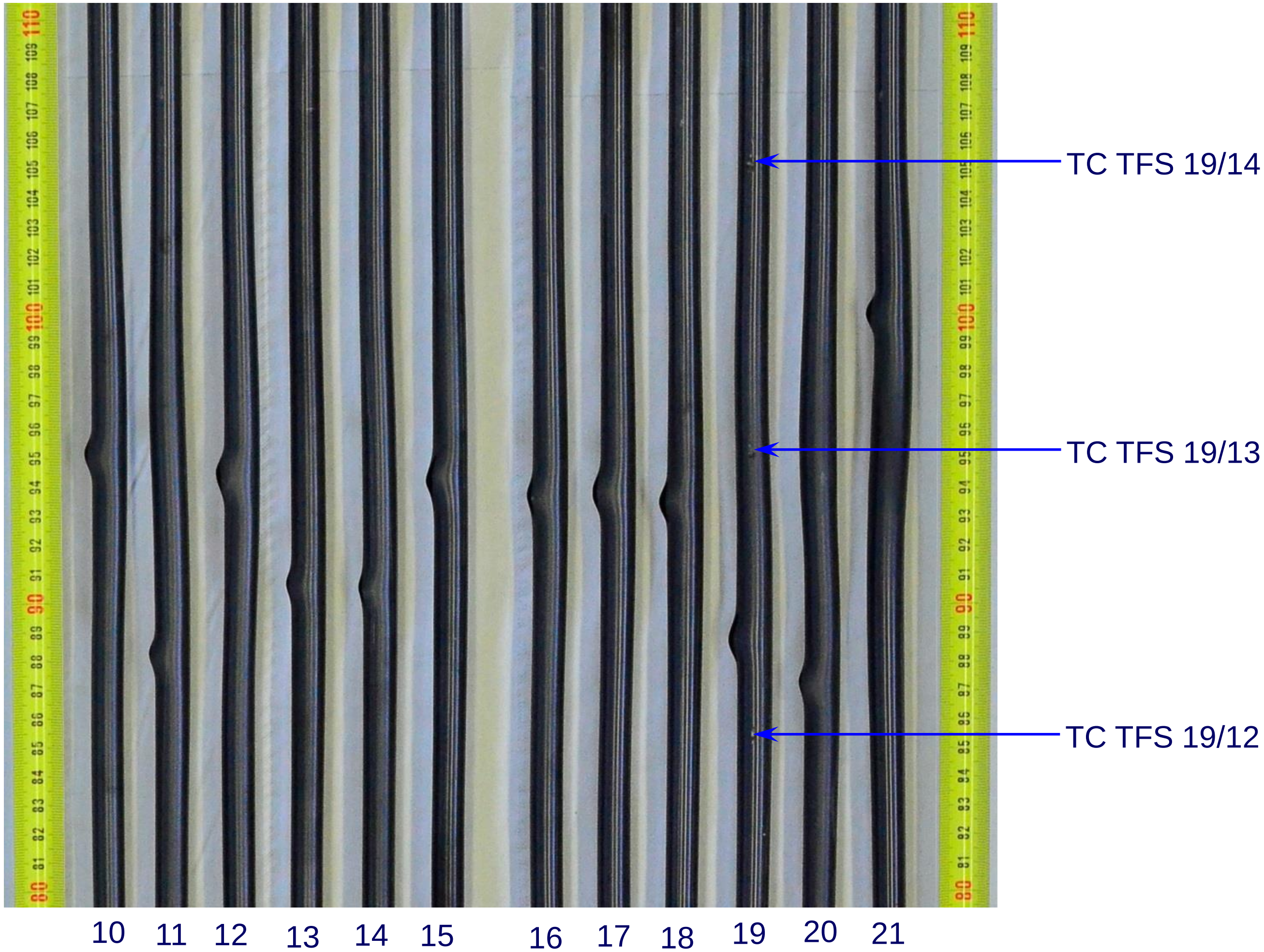
QUENCH-L5: side view of inner rods



slight rod bending in the plane going through the burst opening;

burst opening always at concave side (expected and confirmed by many former LOCA tests)

QUENCH-L5: side view of outer rods

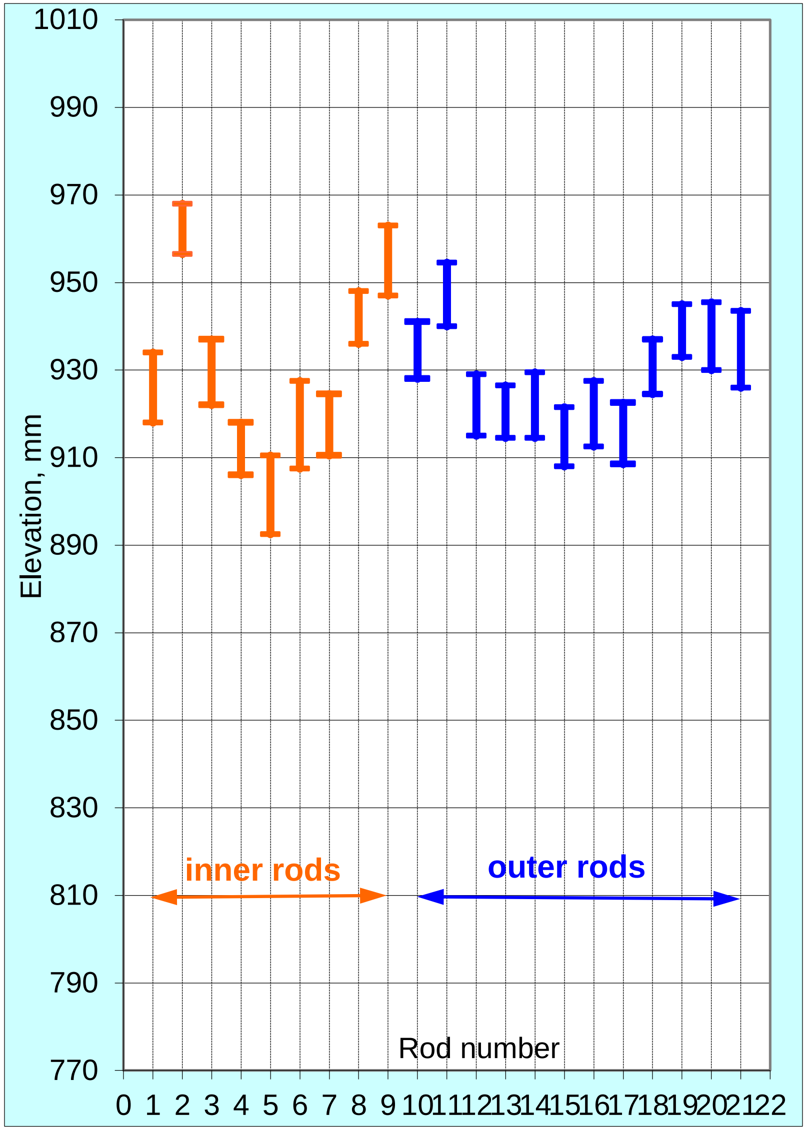


slight rod bending in the plane going through the burst opening;

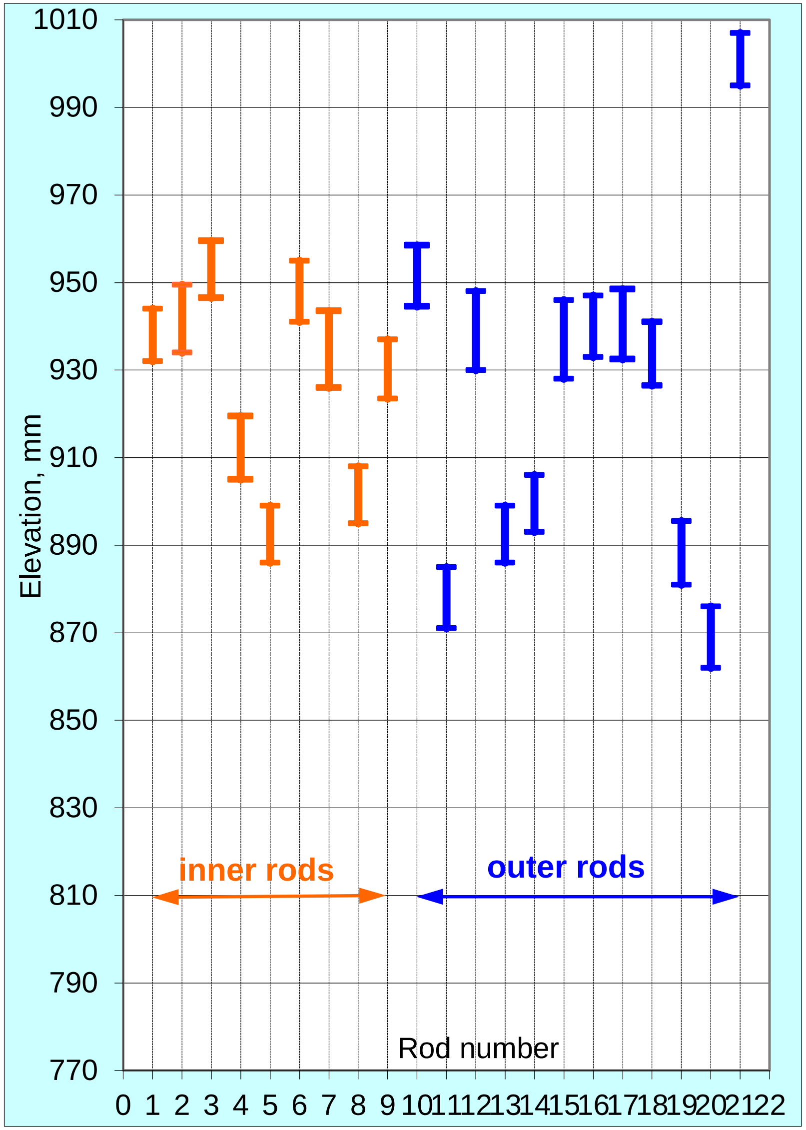
burst opening always at concave side

Length and axial position of burst openings

LOCA-3: low axial scatter



LOCA-5: moderate axial scatter



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Burst geometrical parameters: no influence of pre-hydrogenation

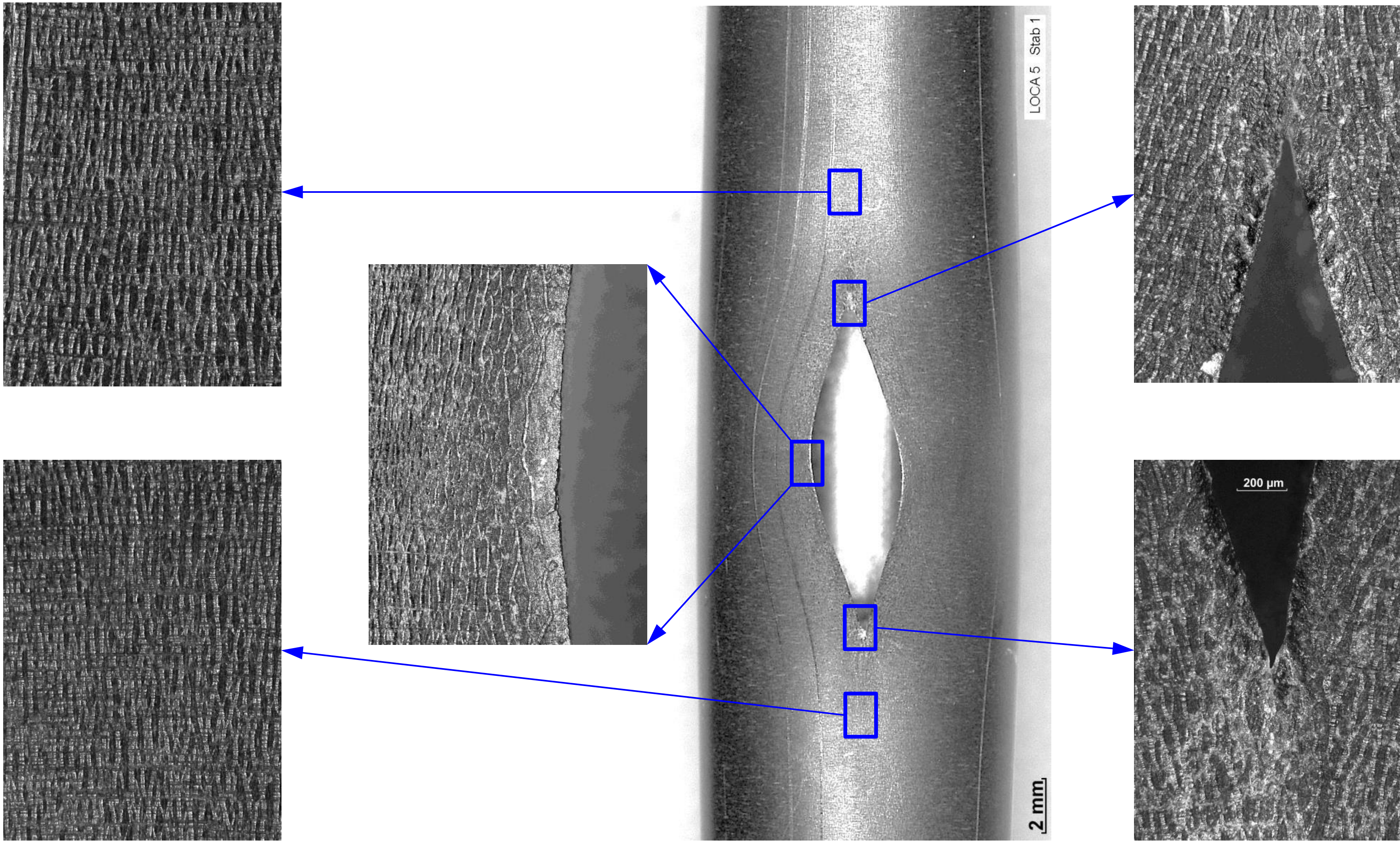
rod	max burst width, mm	burst length, mm	burst area, mm²
1	4.7	16	36
2	3.2	11.5	21
3	4.6	15	37
4	3.9	12	26
5	4.8	18	44
6	6.2	20	67
7	4.6	14	36
8	2.9	12	20
9	4.7	16	43
10	3.4	13	24
11	4.1	14.5	33
12	3.3	14	24
13	2.7	12	18
14	3.6	15	27
15	3.3	13.5	24
16	3.9	15	29
17	3.6	14	28
18	2.6	12.5	17
19	2.8	12	18
20	4.5	15.5	39
21	4.1	17.5	40

QL3; average burst opening parameters:
width 3.9 ± 0.9 mm; length 14.4 ± 2.2 mm;
area 31.0 ± 12 mm²

ro d	max burst width, mm	burst length, mm	burst area, mm²
1	3.4	12	24
2	4.4	15.5	35
3	3.3	13	23
4	3.9	14.5	29
5	3.0	13	21
6	3.6	14	27
7	4.9	17.5	46
8	3.2	13	21
9	3.9	13.5	28
10	4.0	14	31
11	3.7	14	27
12	4.9	18	52
13	2.7	13	19
14	2.8	13	20
15	4.6	18	40
16	3.1	14	24
17	4.5	16	41
18	4.1	14.5	34
19	3.5	14.5	29
20	3.6	14	29
21	3.8	12	28

QL5; average burst opening parameters:
width 3.8 ± 0.6 mm; length 14.3 ± 1.8 mm;
area 30.0 ± 8.7 mm²

QL5, burst opening region
(“tree bark” structure typical for all tested cladding materials): surface cracks formed during ballooning

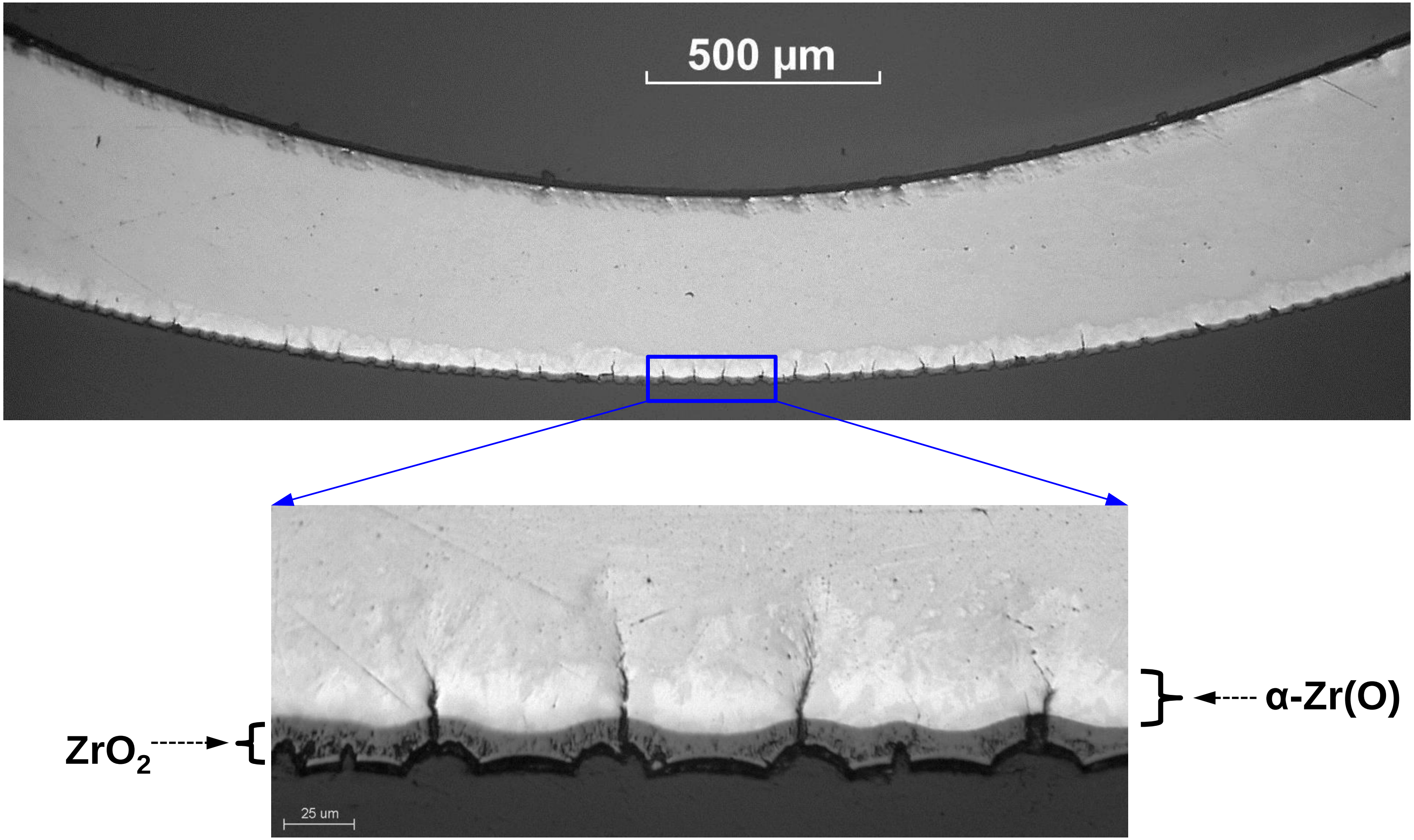


≈40 cracks/mm

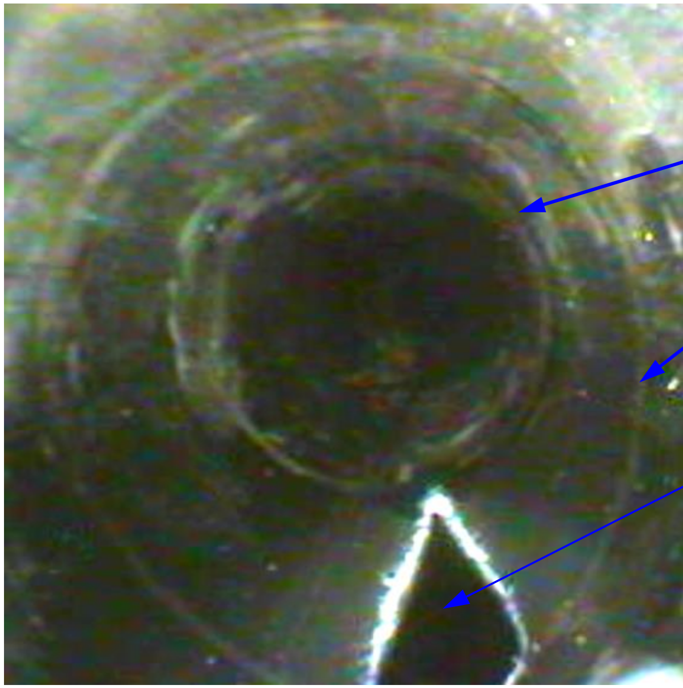
≈20 cracks/mm

Typical cross section structure for all cladding materials at elevation of about 5 mm below burst opening tip: surface cracks penetrated ZrO_2 and α-Zr(O)

(here the sample from QUENCH-L3, rod #5)

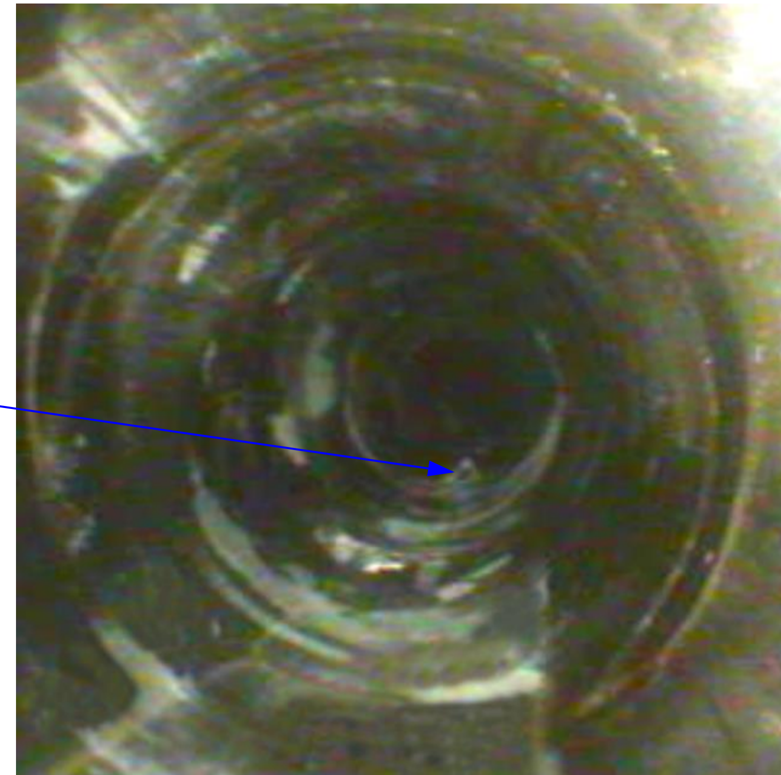


QL5, rod #3, observation of internal surface by **videoscope** (bottom view): **influence of pellet position**



traces of pellet top and bottom edges

burst opening



contact between pellet and cladding below burst opening

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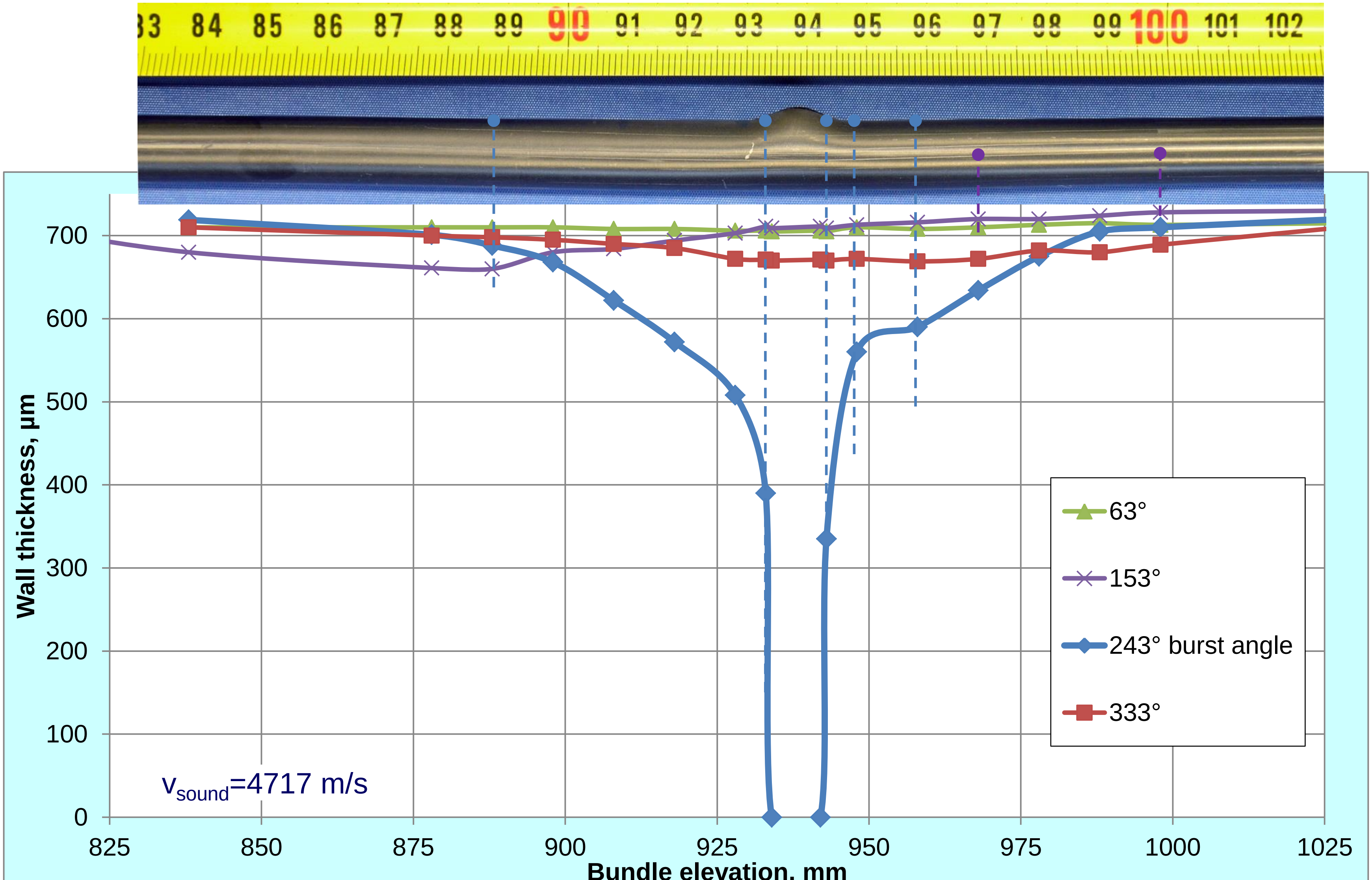
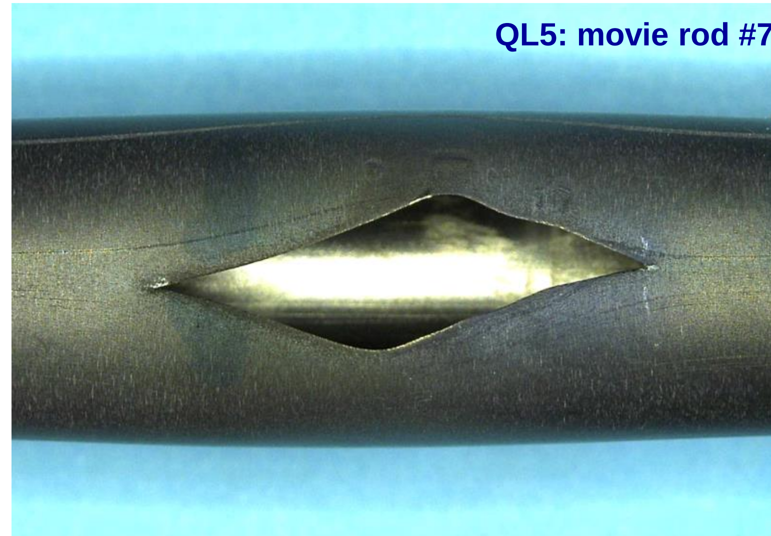
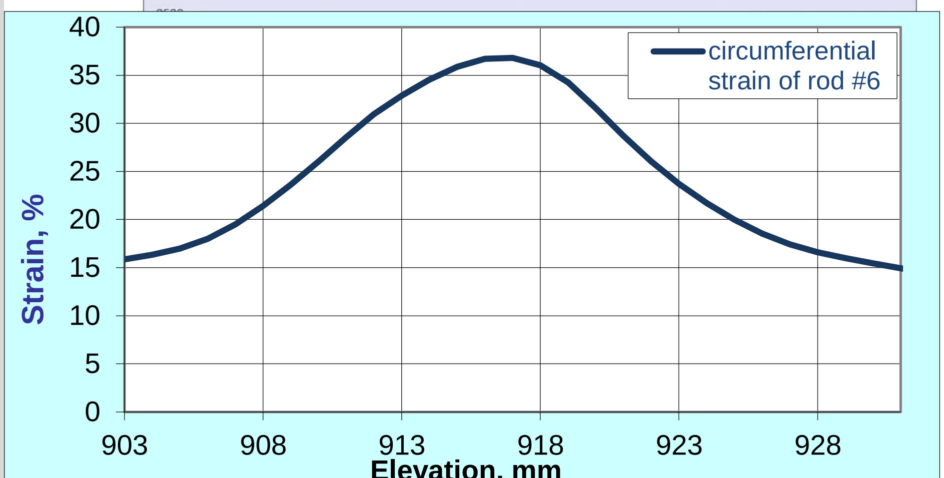
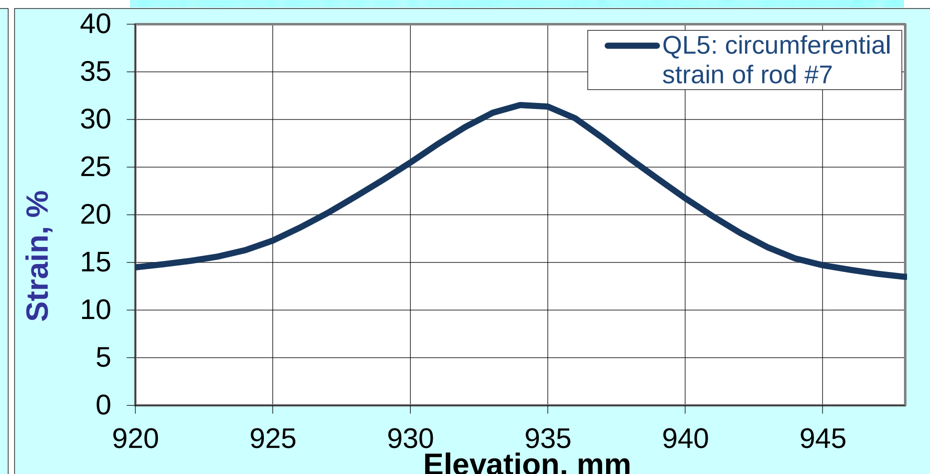
QUENCH-L5, rod #1:
cladding wall thickness (ultrasound measurement)



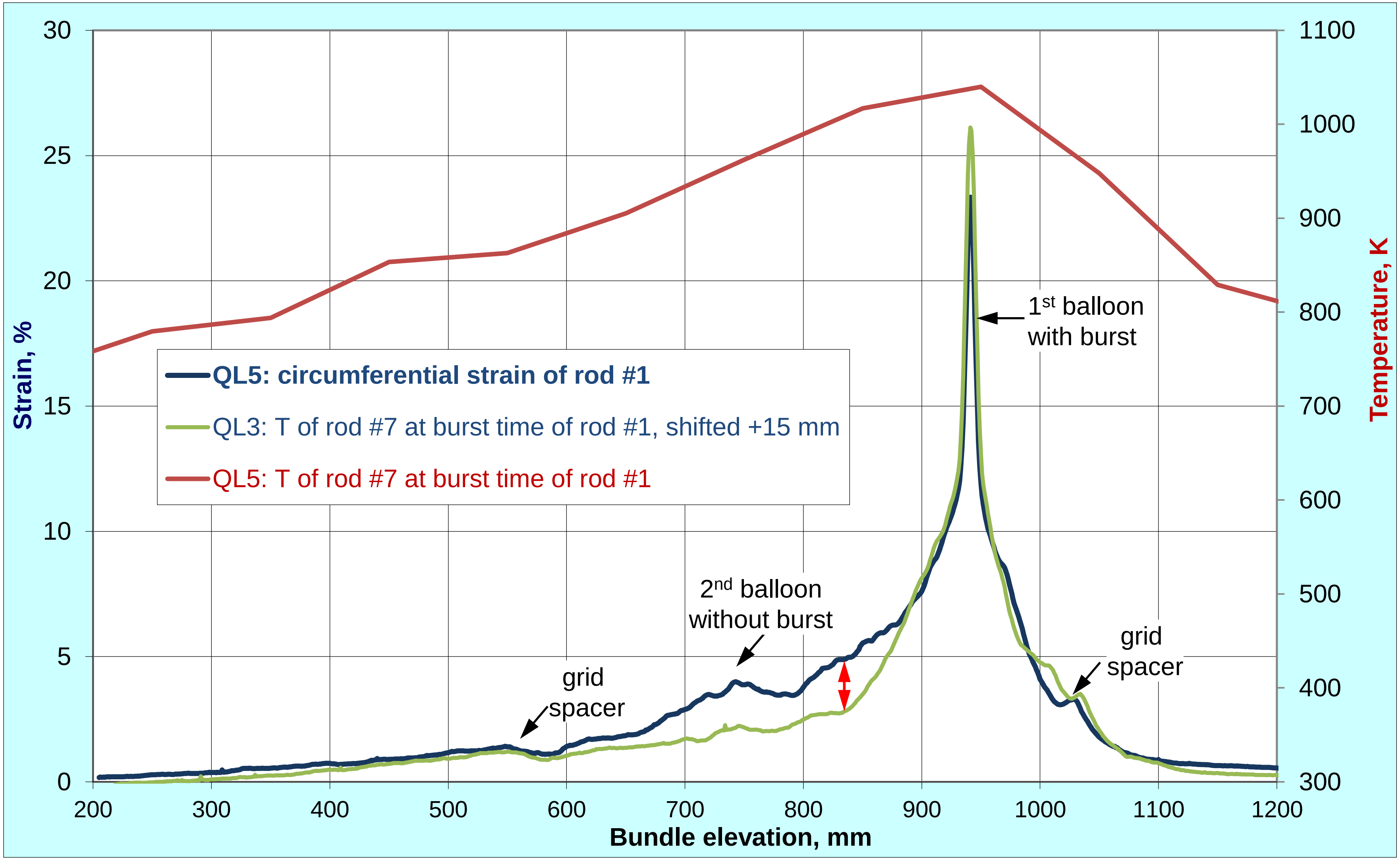
QUENCH-L3 and -L5: Circumferential strain (laser scanner) and burst position overview for largest burst opening





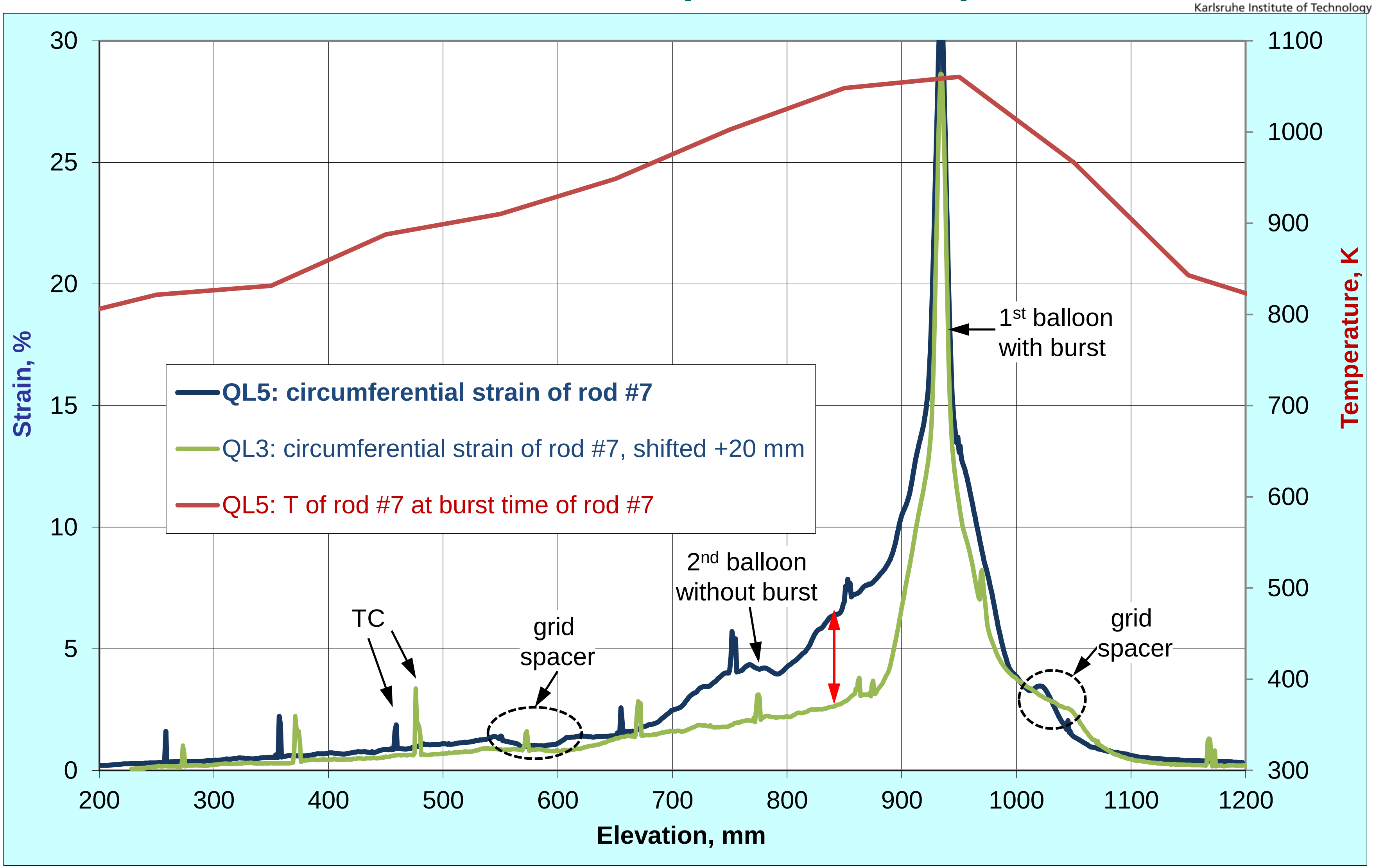


QUENCH-L5, -L3; rod #1: circumferential strain (laser scanner)



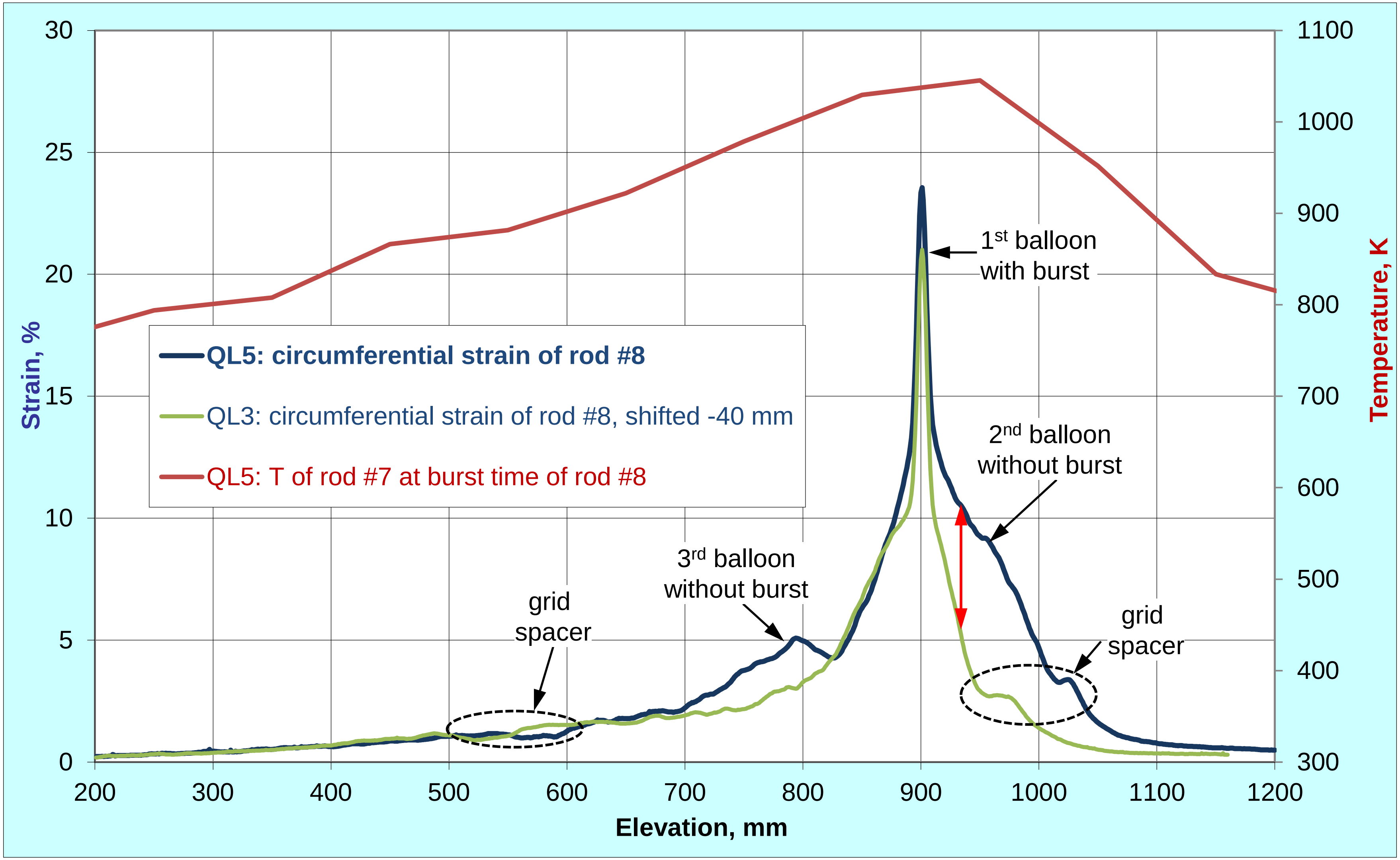
ballooning of QL5 (hydrogenated clads) is larger than ballooning of QL3 (not hydrogenated clads)

QUENCH-L5, -L3; rod #7: circumferential strain (laser scanner)



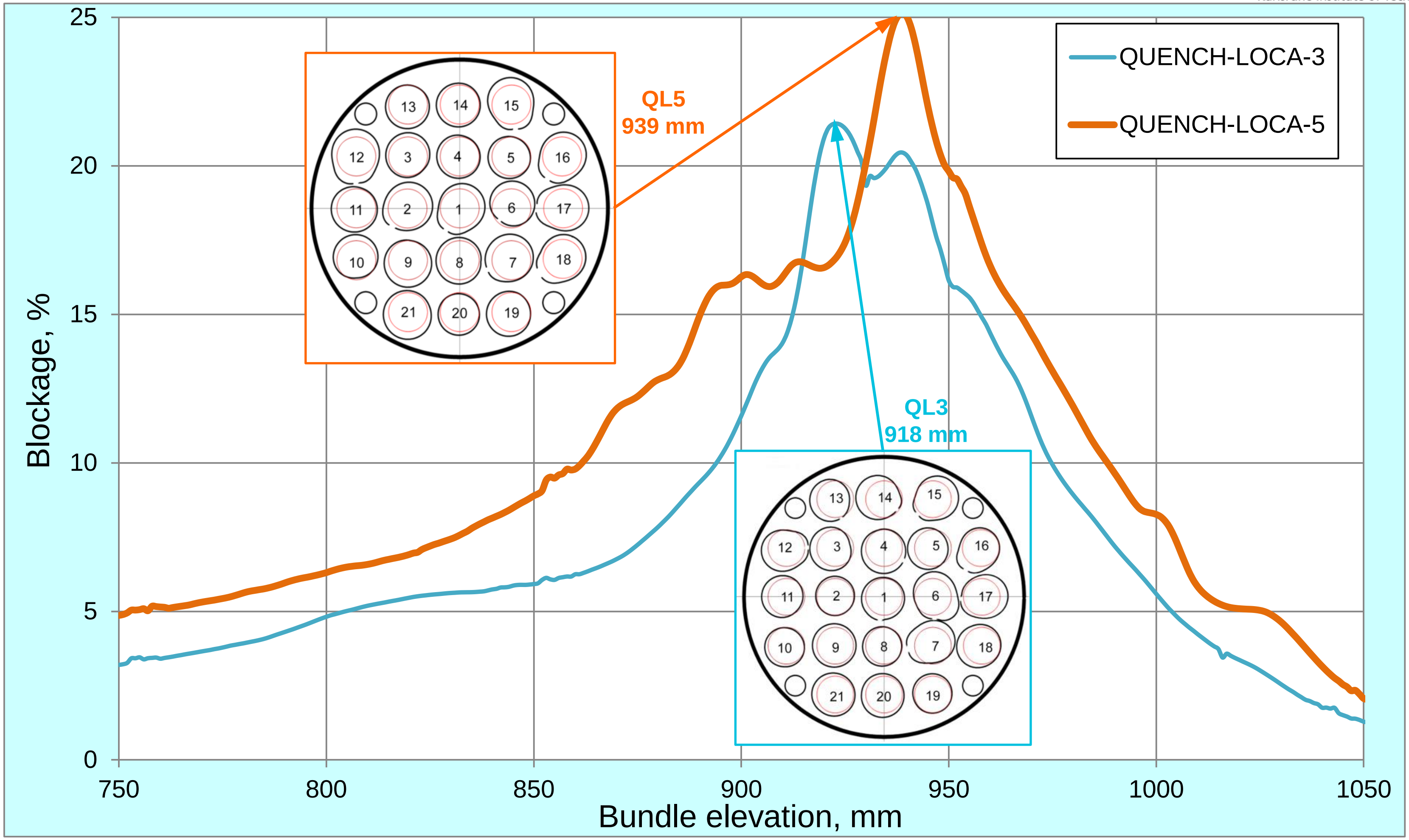
ballooning of QL5 (hydrogenated clads) is larger than ballooning of QL3 (not hydrogenated clads)

QUENCH-L5, -L3; rod #8: circumferential strain (laser scanner)



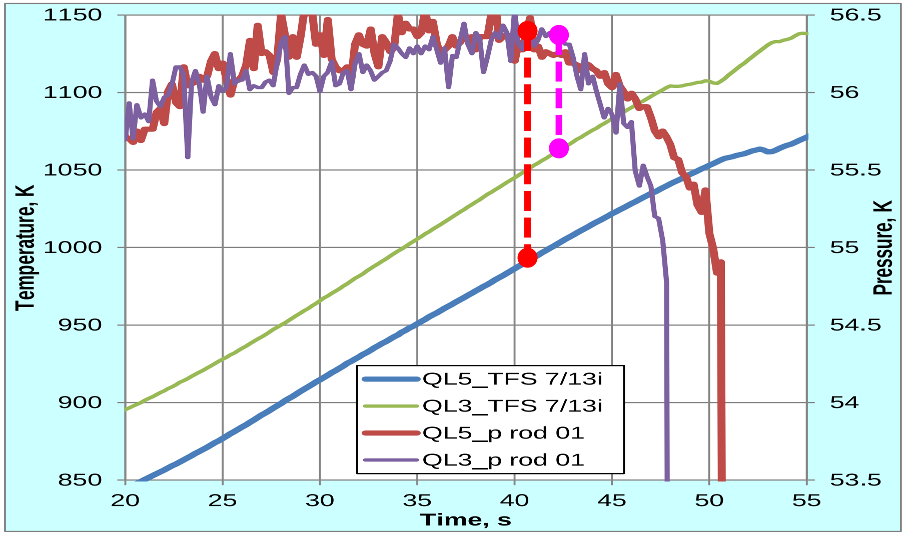
ballooning of QL5 (hydrogenated clads) is larger than ballooning of QL3 (not hydrogenated clads)

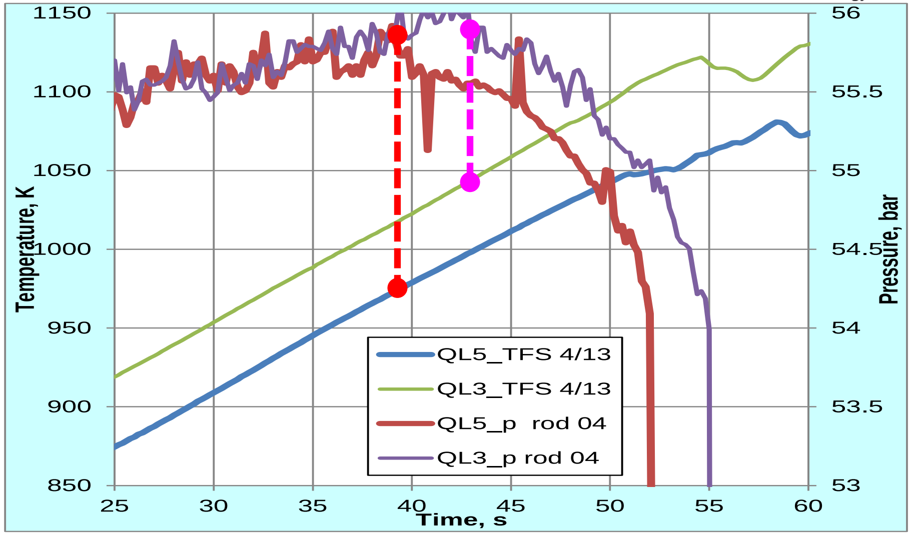
Cooling channel blockage calculated on the basis of strain measurements

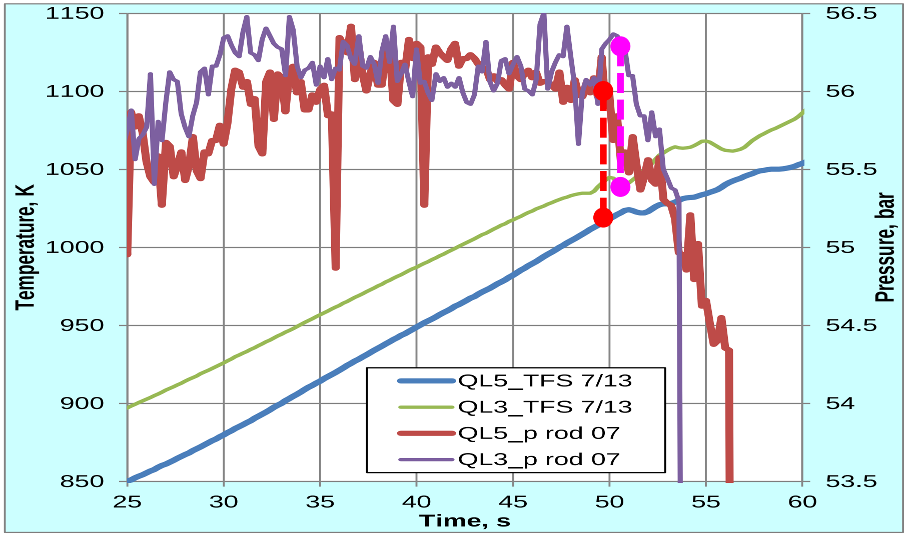


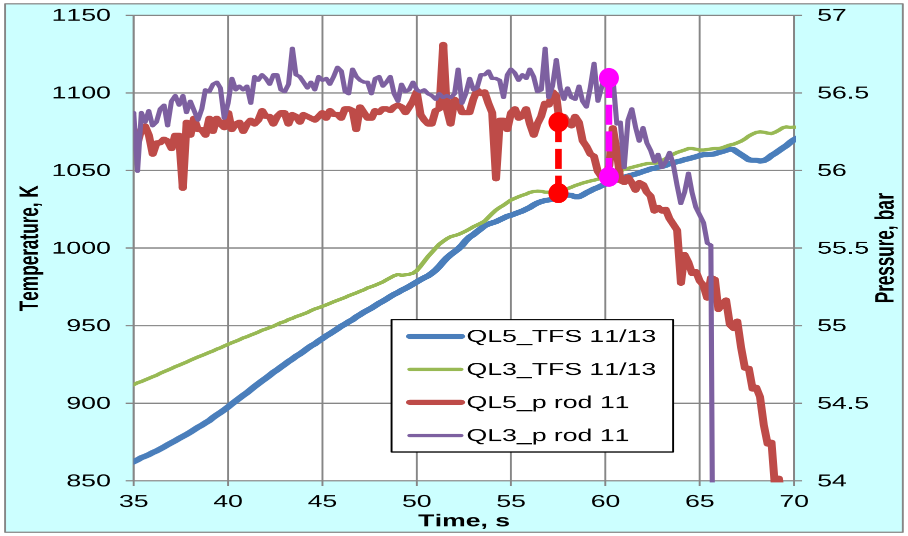
The blockage degree for the QL5 bundle at all elevations is larger than for the QL3 bundle due to increased cladding strains during ballooning

QUENCH-L5, -L3; pressure and temperature readings for different rods: onset of ballooning at lower temperatures for QL5



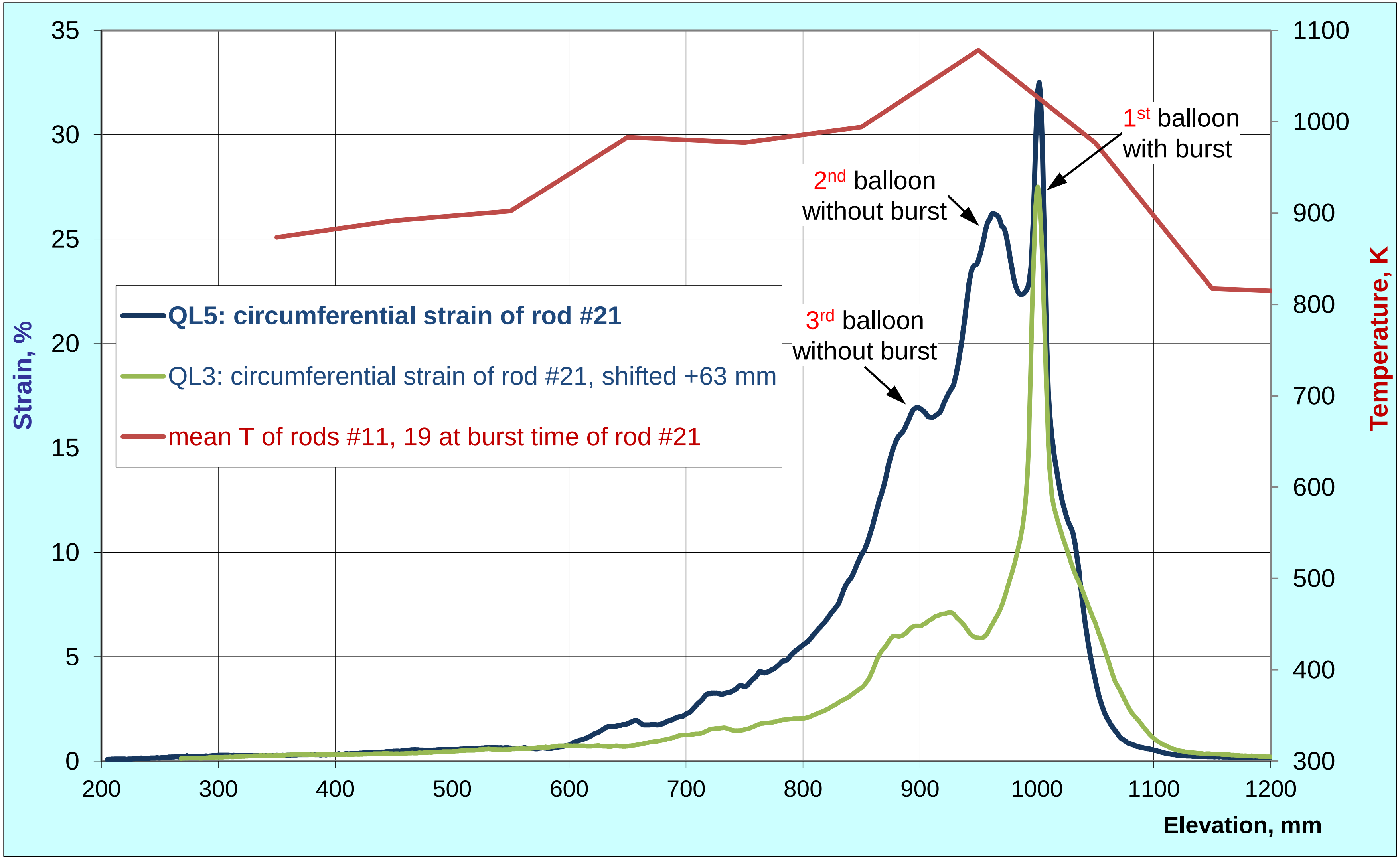






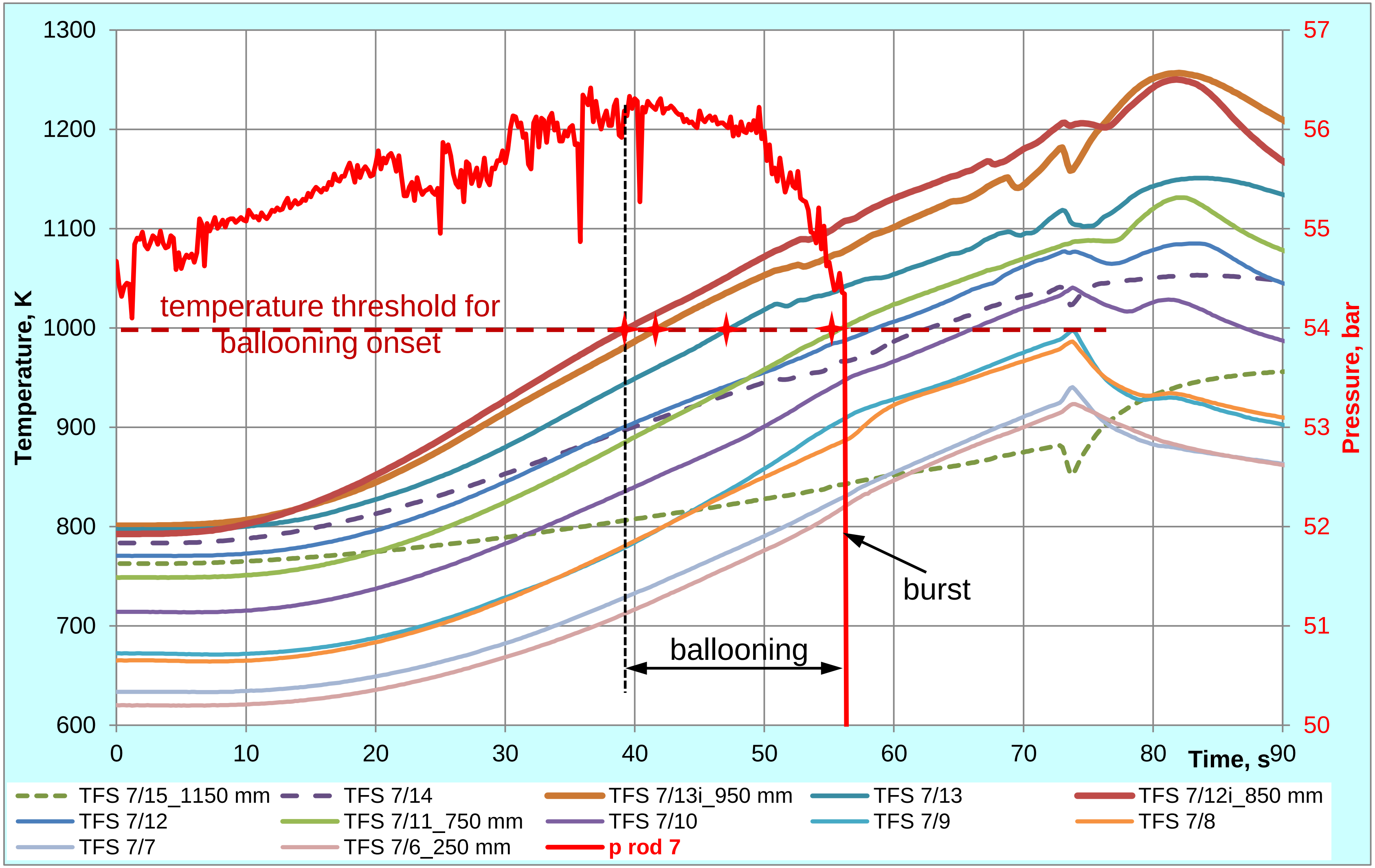
Zr alloy with dissolved hydrogen will be more ductile at lower temperatures than not hydrogenated Zr alloy

QUENCH-L5, -L3; rod #21: circumferential strain (laser scanner)

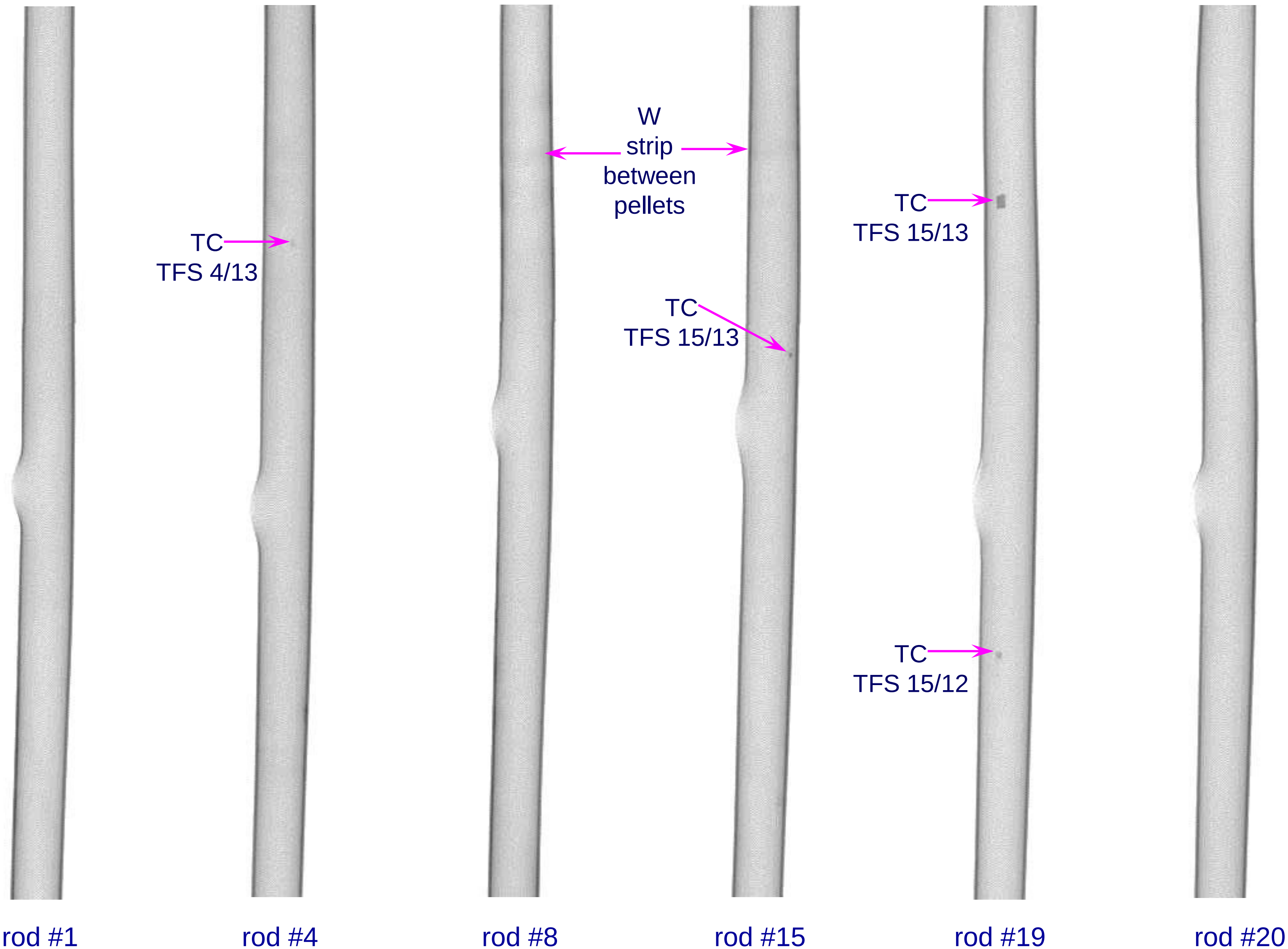


multiple ballooning regions

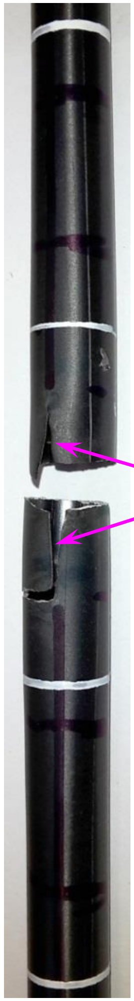
QUENCH-L5, rod #7: sequence of ballooning onsets at different bundle elevations (reason of multiple ballooning regions)



QUENCH-L5: results of neutron radiography, no indication of secondary hydrogenation (absence of hydrogen bands)



QUENCH-L5: results of tensile tests at room temperature, types of cladding fracture*



rod #7: stress concentration in the opening middle
(similar fracture: rod #1)

rod #20: stress concentration at opening tips
(similar fracture: 8 other *outer* rods)

rod #4: not prototypical fracture at TC weld
(similar fracture: rod #2)

* excepting fracture after necking in cold regions

Summary

- The QUENCH-LOCA-5 test with pre-hydrogenated 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-3 test with as-received opt. ZIRLO™ claddings: similar time schedule, maximal heat-up rate 8 K/s, cooling phase lasted 120 s and terminated with 3.3 g/s/rod water flooding.
- The maximum peak cladding temperature reached on the end of the heat-up phase at elevation 950 mm was 1250 K: lower in comparison to 1350 K for QUENCH-L3 due to lower temperature on the transient start. Due to local radial pellet shift up to contact with cladding, the circumferential temperature gradient measured across a cladding was different at different elevations (e.g. about 20 K at 950 mm and 90 K at 850 mm on the burst onset).
- The axial extension of ballooning region for each cladding is larger for QUENCH-L5 in comparison to QUENCH-L3. Some rods have up to three ballooning regions for both tests. The reason is successive onset of ductile temperature threshold at different elevations.
- The axial scatter of burst opening positions is larger for QUENCH-L5 (870 - 1000 mm) than for QUENCH-L3 (900 - 960 mm). The reason could be a not quite homogeneous axial hydrogen distribution in pre-hydrogenated claddings. The burst opening sizes are comparable for two tests: opening length is less than 20 mm, opening width is less than 6 mm.
- The cladding burst occurred at temperatures between 1027 and 1151 K (QUENCH-L3: 1064 and 1188 K). The average burst temperatures of 1081 K (808°C) for QUENCH-L5 is lower than for QUENCH-L3 (1117 K or 844°C) due to lower α-Zr→β-Zr phase transition temperature.
- No secondary hydrogenation was indicated for the QUENCH-L5 claddings due to very short high temperature period: only several seconds above 850 °C (complete transition to β-Zr phase) in comparison to more than 50 s for QUENCH-L3.
- During quenching, following the high-temperature phase, no fragmentation of claddings was observed for both QUENCH-L3 and QUENCH-L5 (residual strengths or ductility is sufficient).
- Tensile tests at room temperature showed cladding fracture mostly due to stress concentration in the region of burst opening.

Acknowledgment

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Thank you for your attention

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