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Results of the commissioning bundle test QUENCH-L0 performed under LOCA conditions

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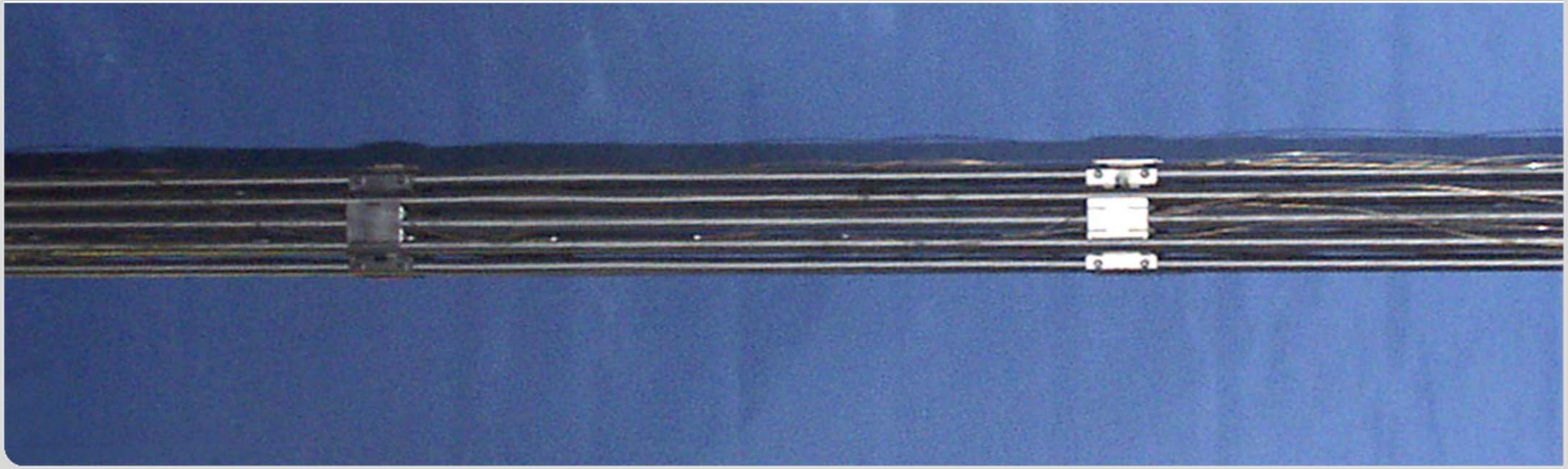
IMF3-KOR, IMF1-WT, IMF2



Objective

- **Modification of electric heated high temperature facility QUENCH at KIT for performance of bundle tests under LOCA conditions.**

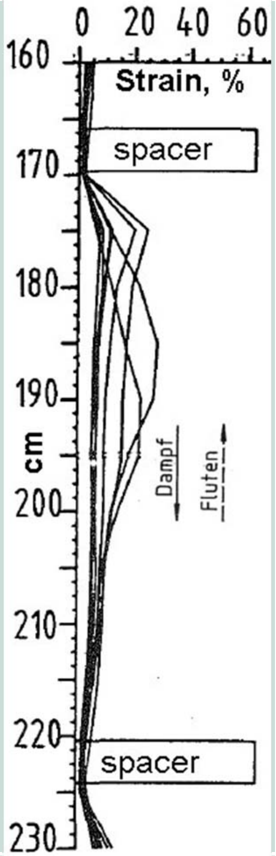
- **Bundle test with 21 rod simulators with slightly preoxidized Zircaloy-4 cladding tubes.**

- **Bringing into service two post-test methodologies: 1) laser cladding profilometry; 2) tension and ring compression tests for cladding segments.**

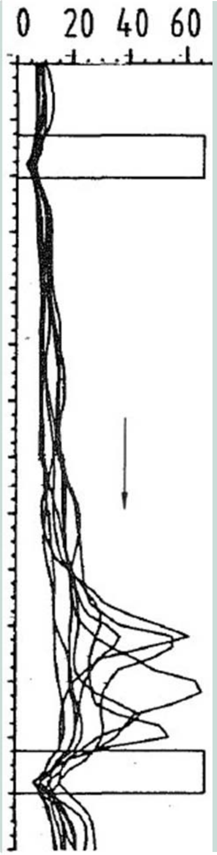
Overview of REBEKA program (1978-1987) at KfK:

electrical heated facility with 3.5 m rods

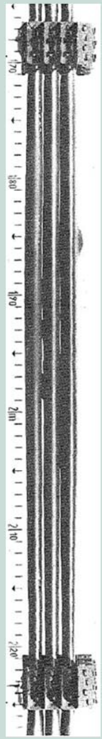
REBEKA 1



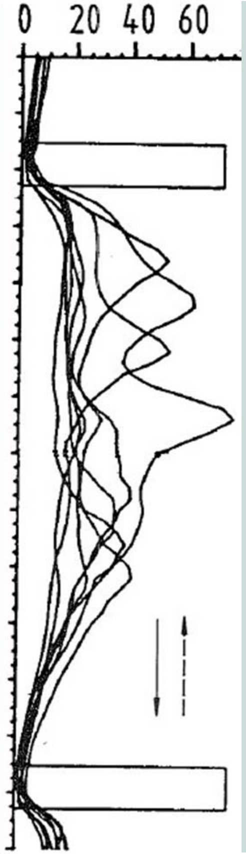
REBEKA 2



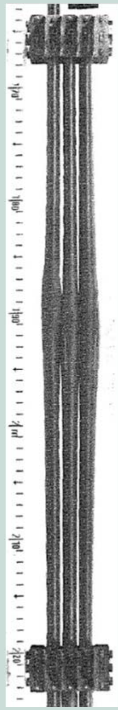
REBEKA 3



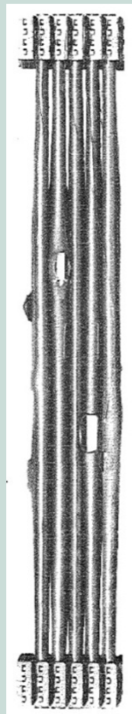
REBEKA 4



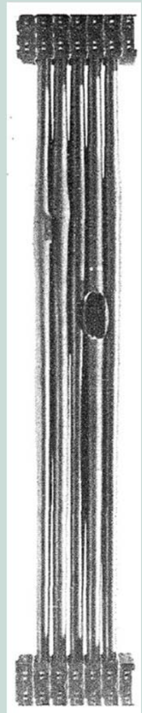
REBEKA M



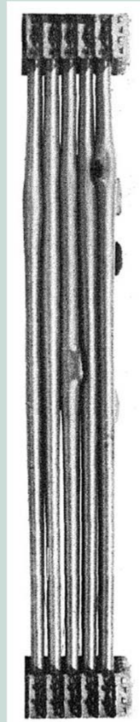
REBEKA 5



REBEKA 6

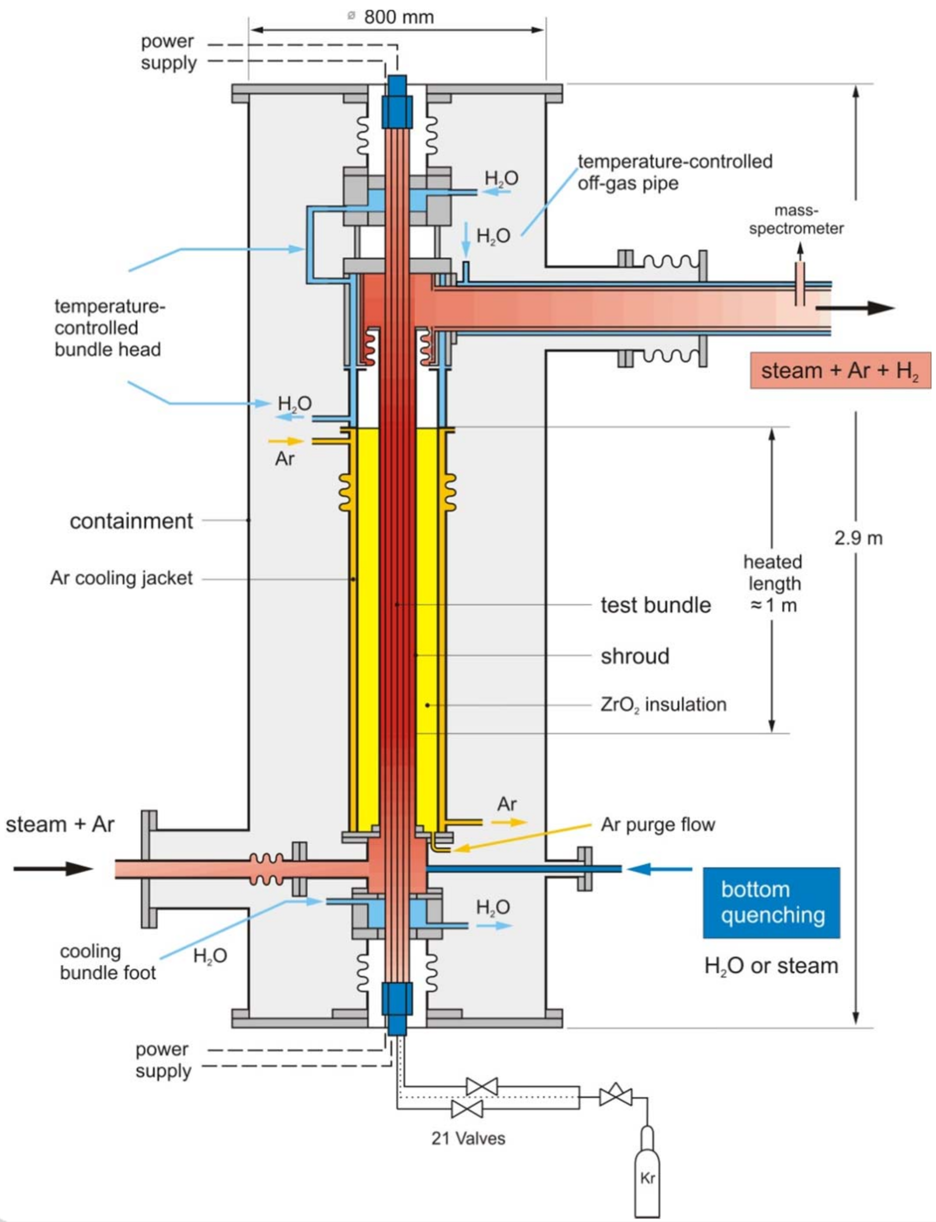


REBEKA 7



	REBEKA 1	REBEKA 2	REBEKA 3	REBEKA 4	REBEKA M	REBEKA 5	REBEKA 6	REBEKA 7
pressure, bar	60	55	51	53	70	68	62	57
burst T, °C	810	870	830	830	754	800	790	790
strain, %	28	54	44	46	63	49	42	55
blockage, %	25	60	52	55	84	52	60	66
burst region, mm		95	203	242	28	242	140	200

Features of QUENCH-facility



Scaling
  Height: 1:3 … 1:2
  Volume: 1:5000 … 1:3000

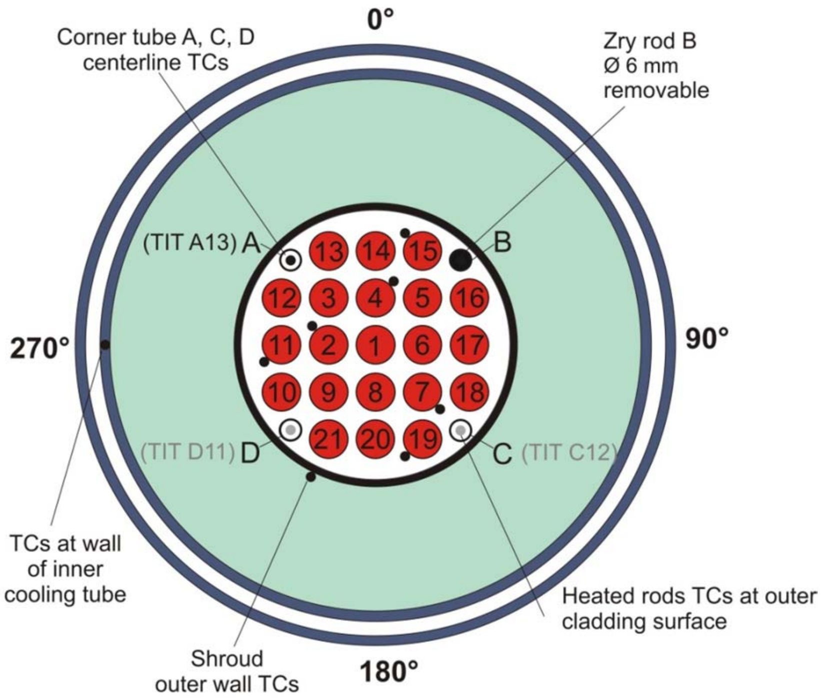
Bundle
- PWR (21 or 24 rods; Zry-4, M5, ZIRLO)
- VVER (31 Stäbe, E110)

Electrical heating with two generators
- **max: 35 + 35 kW**
- **heaters inside fuel rod simulators: 0.3 m Mo + 1 m W + 0.6 m Mo**

Instrumentation
- ~80 TCs at 17 axial levels
- Mass spectrometer (incl. steam)
- Quench water level (Δp)
- Corner rods for "online" check of oxide scale

Rod pressurisation up to 120 bar

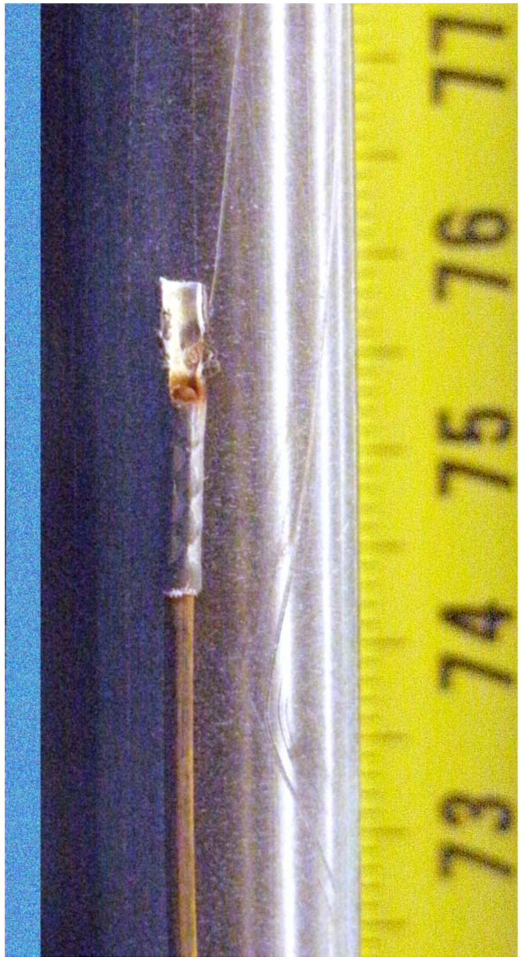
Thermocouple installation
/a total of 72 TCs/



Bundle cross section:
6 sheathed NiCr/Ni Thermocouples
at each Elevation (650, 750, 850, 950, 1050, 1150 mm)
at surface of rods # 2, 4, 7 and 11, 15, 19

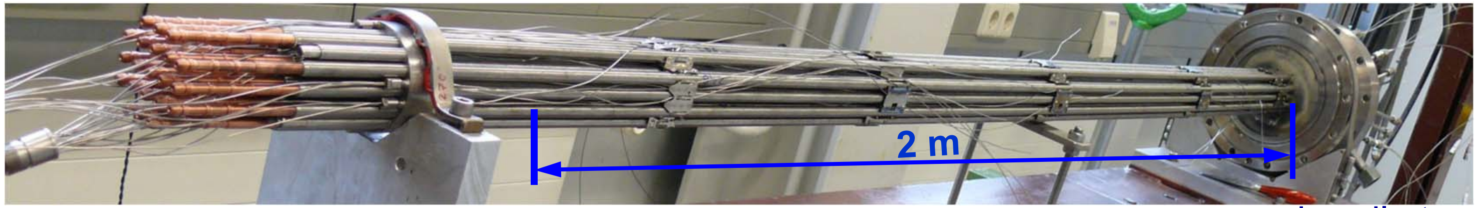
rod #7 has TCs at Elevations from -250 to 1350 mm

rod #4 before test:
TFS 4/13 at 950 mm



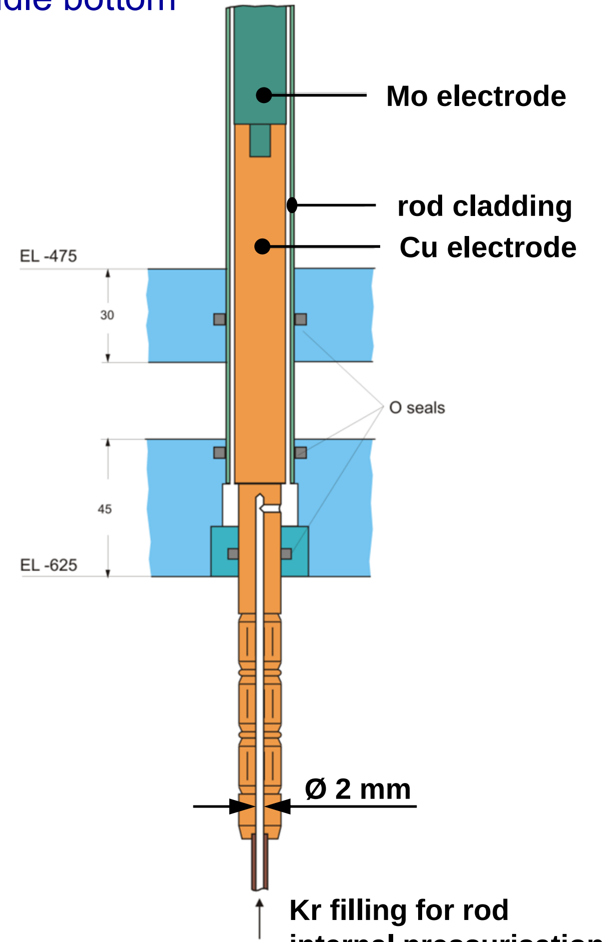
rod #7 after test:
TFS 7/11 at 750 mm

Rod pressurisation



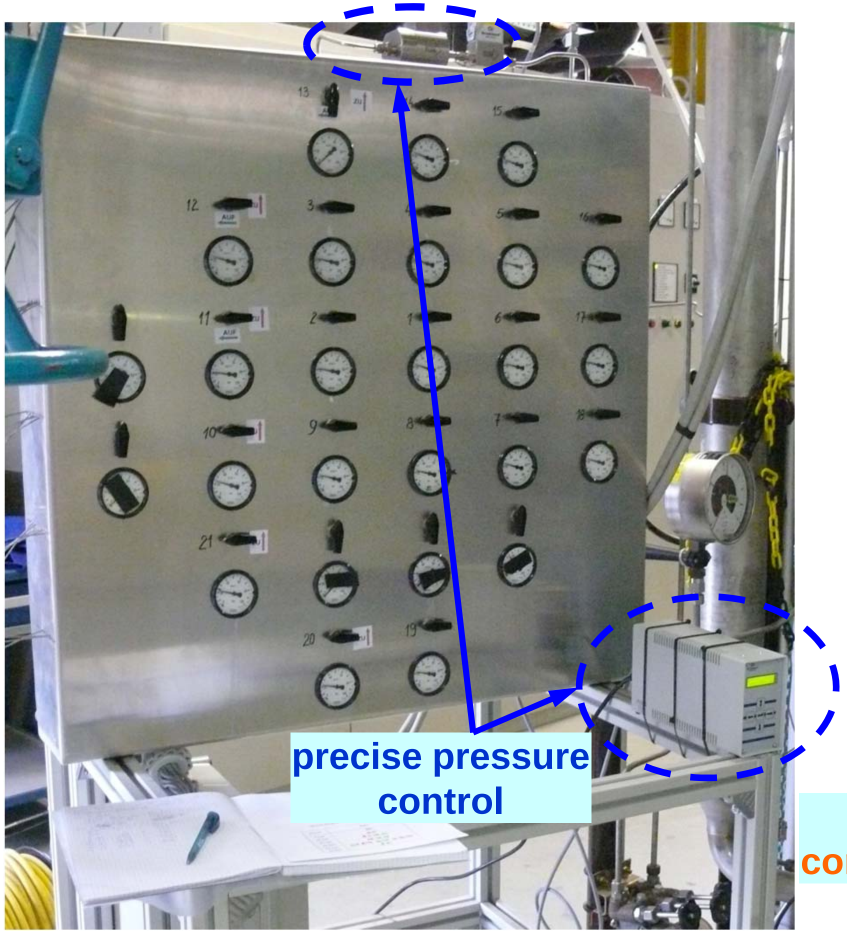
bundle bottom

bundle top

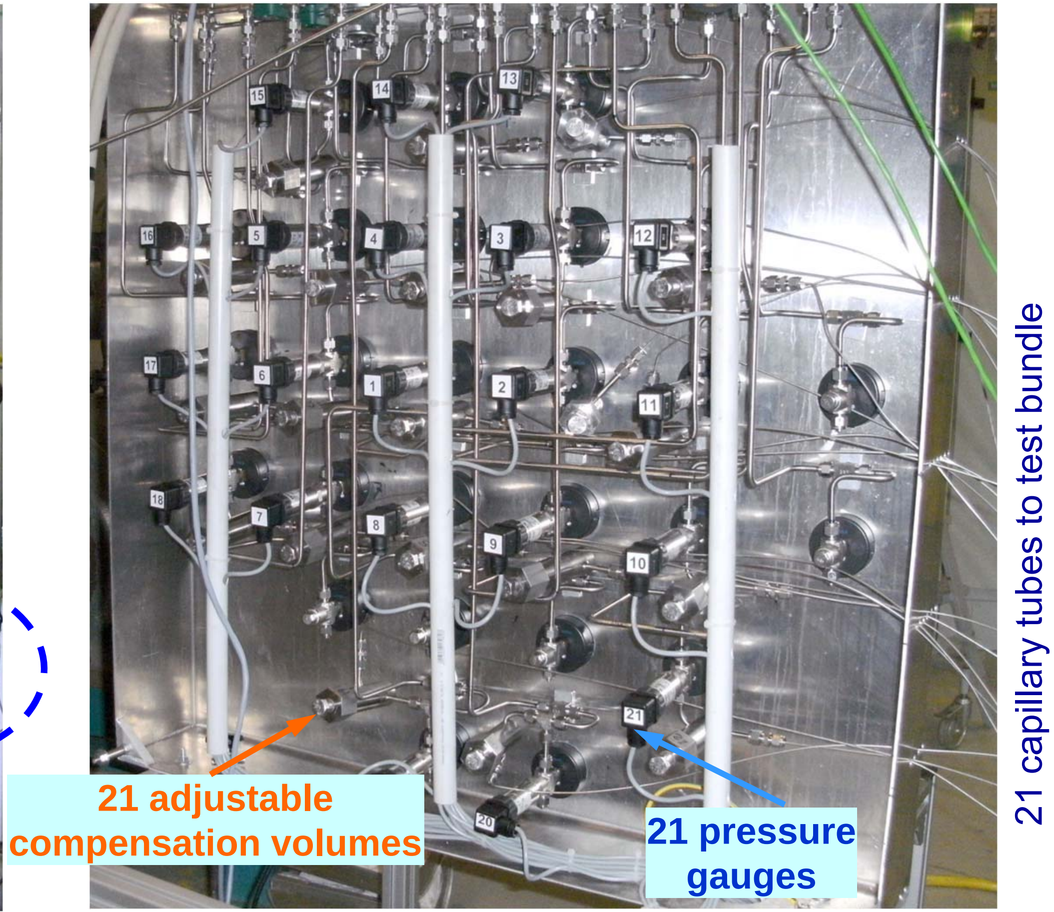


boreholes
through bottom Cu-electrodes

Pressure control and measurement panel

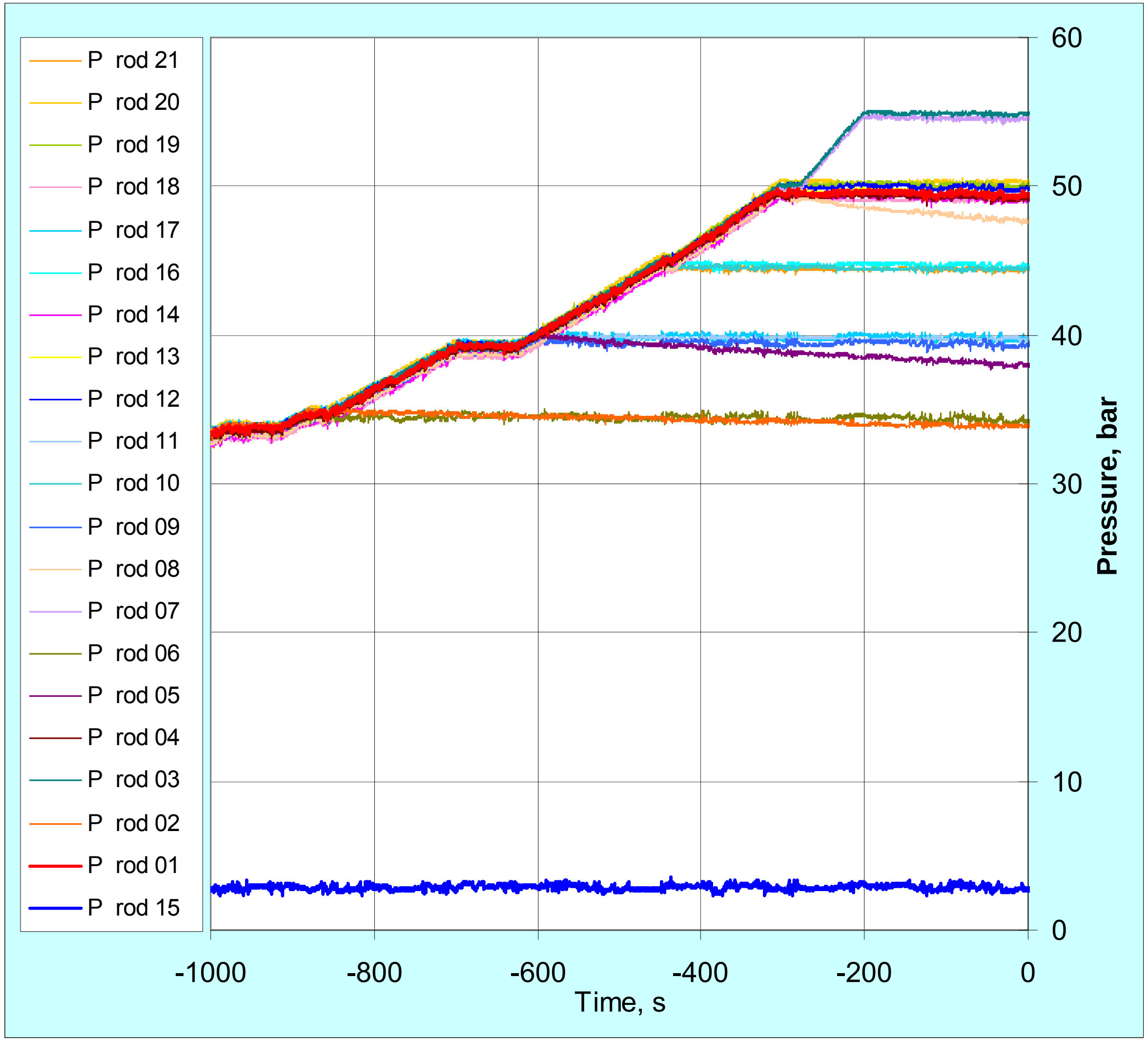


front side with 21 valves



Rear side with 21 pressure gauges and 21 compensation cylinders (to setting of original volume value of 31.5 cm³)

Rod pressurisation process

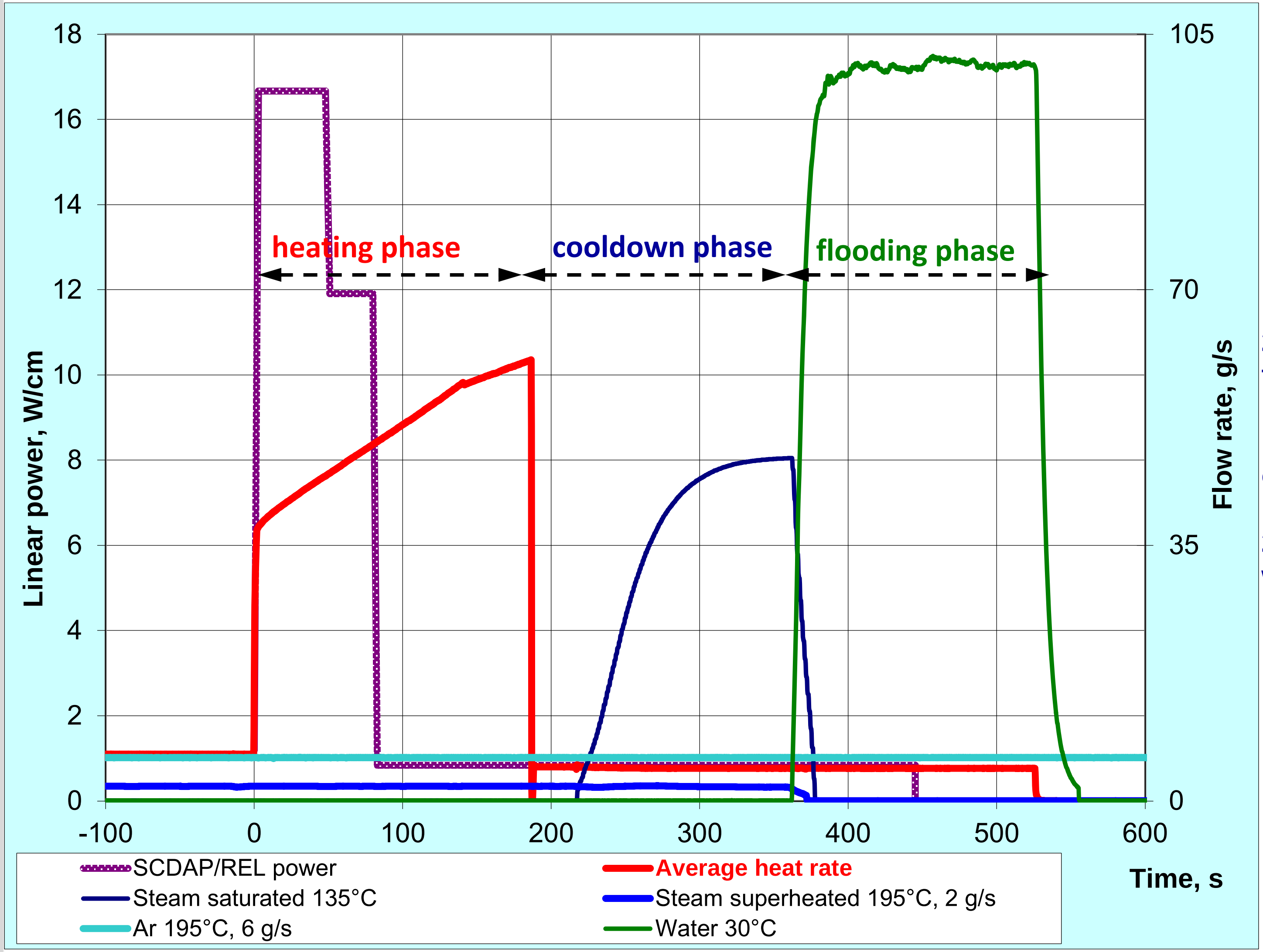


Map of bundle filling

Pressure, bar	Number of rods
3 (system p)	1
35	2
40	4
45	3
50	9
55	2

individual rod pressurisation with **Kr**
at max cladding temperature Tpct=520°C

QL0 test progression

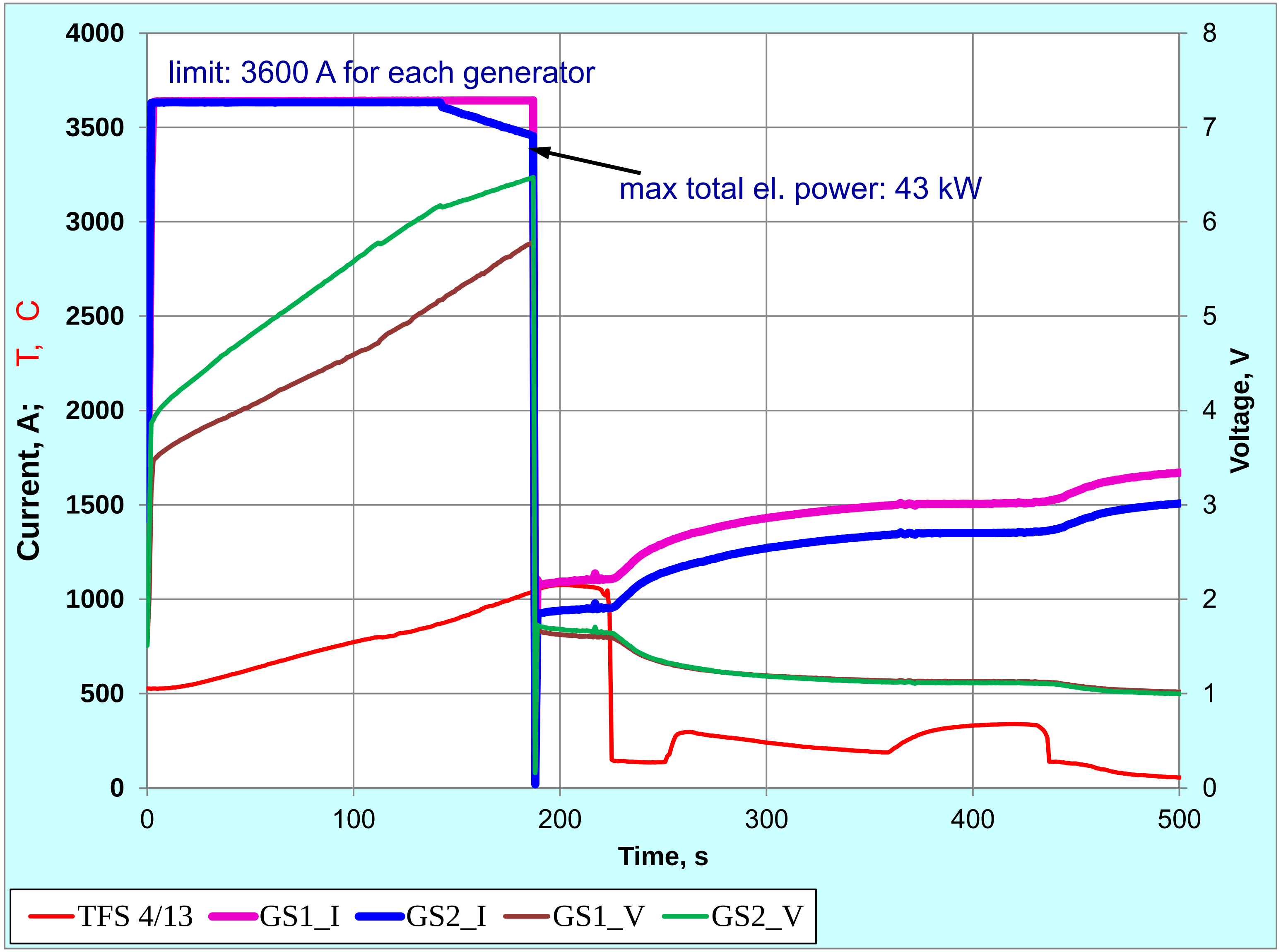


2 deviations from scenario:

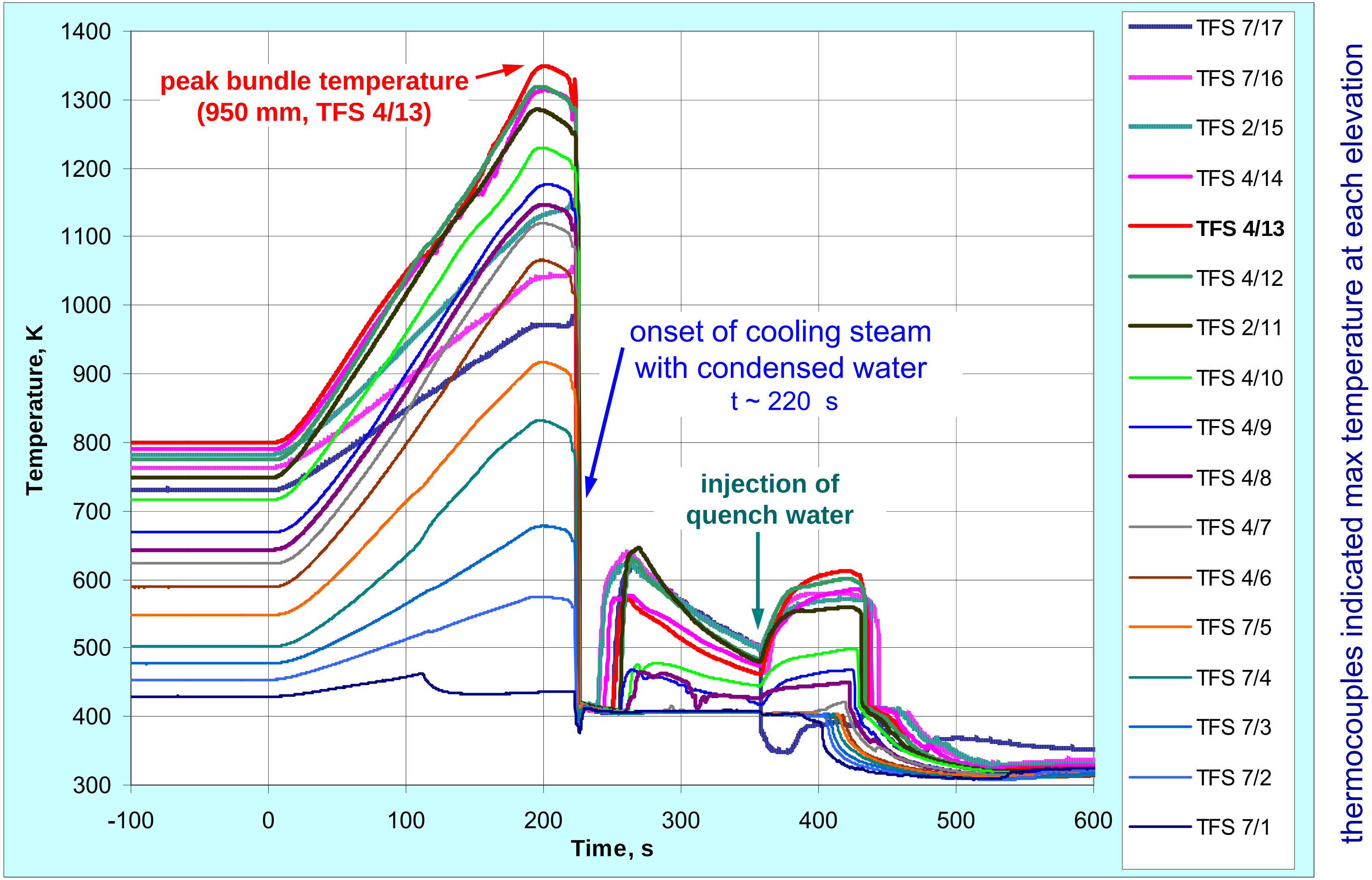
1) extended heating due to current limiting of generator

2) abrupt cooldown due to water condensed in steam pipe line

Generator current limitation

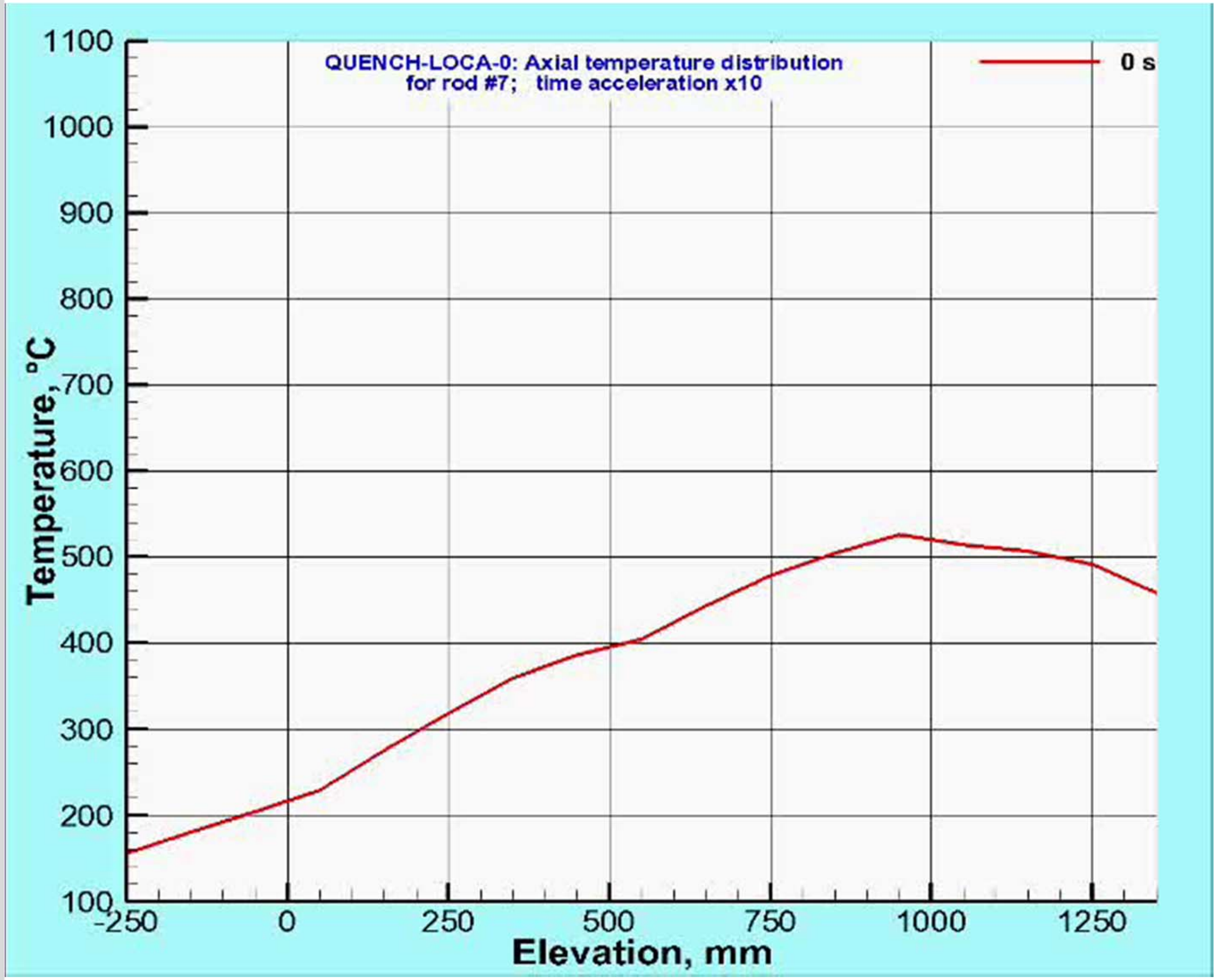


Surface thermocouple readings:
17 elevations between -250 und 1350 mm



Axial temperature development during the test *(movie):*

surface thermocouples of rod #7

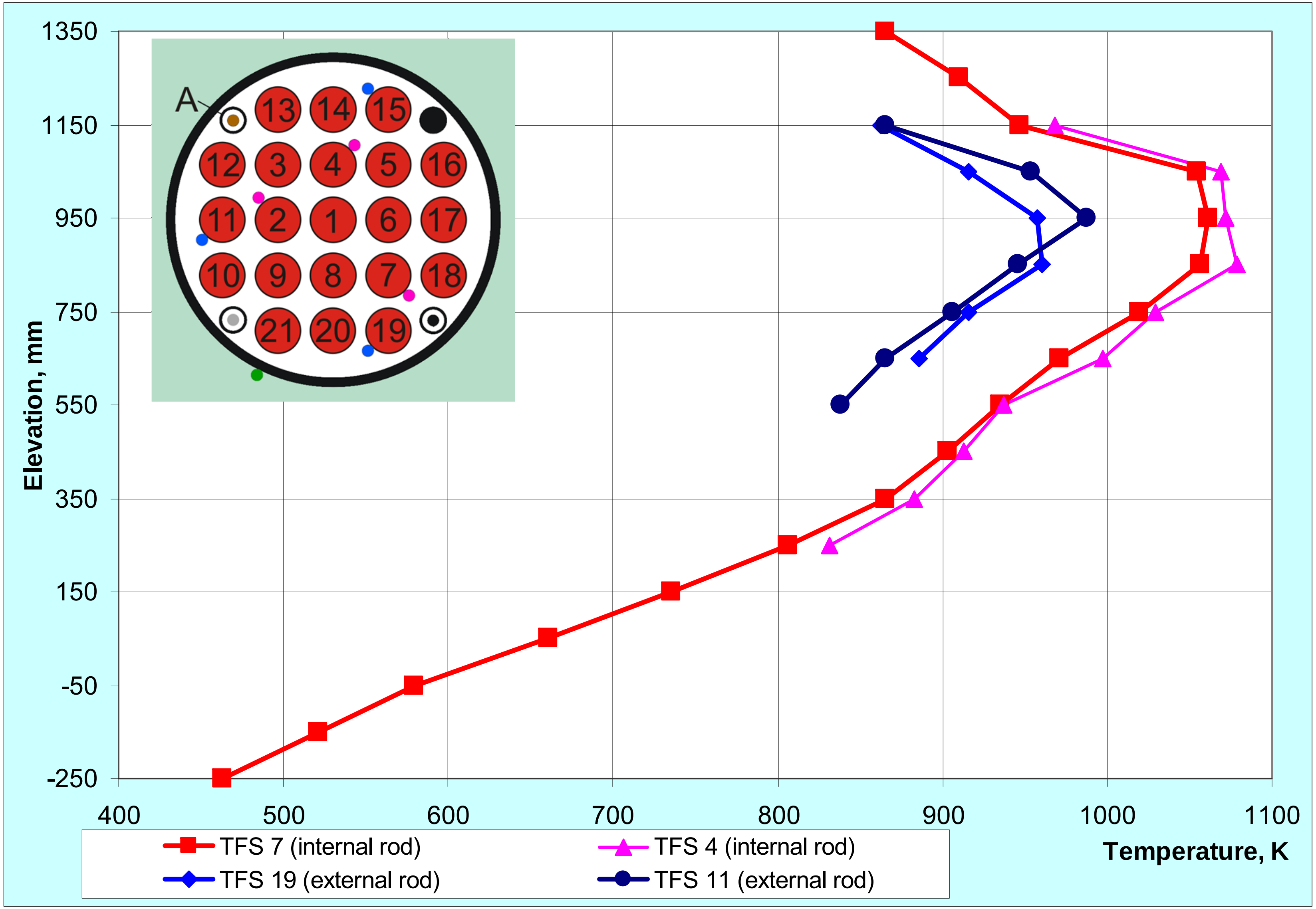


t = 200 s:
cladding surface temperature maximum reached: Tmax = TFS 4/13 = 1349 K = 1076°C

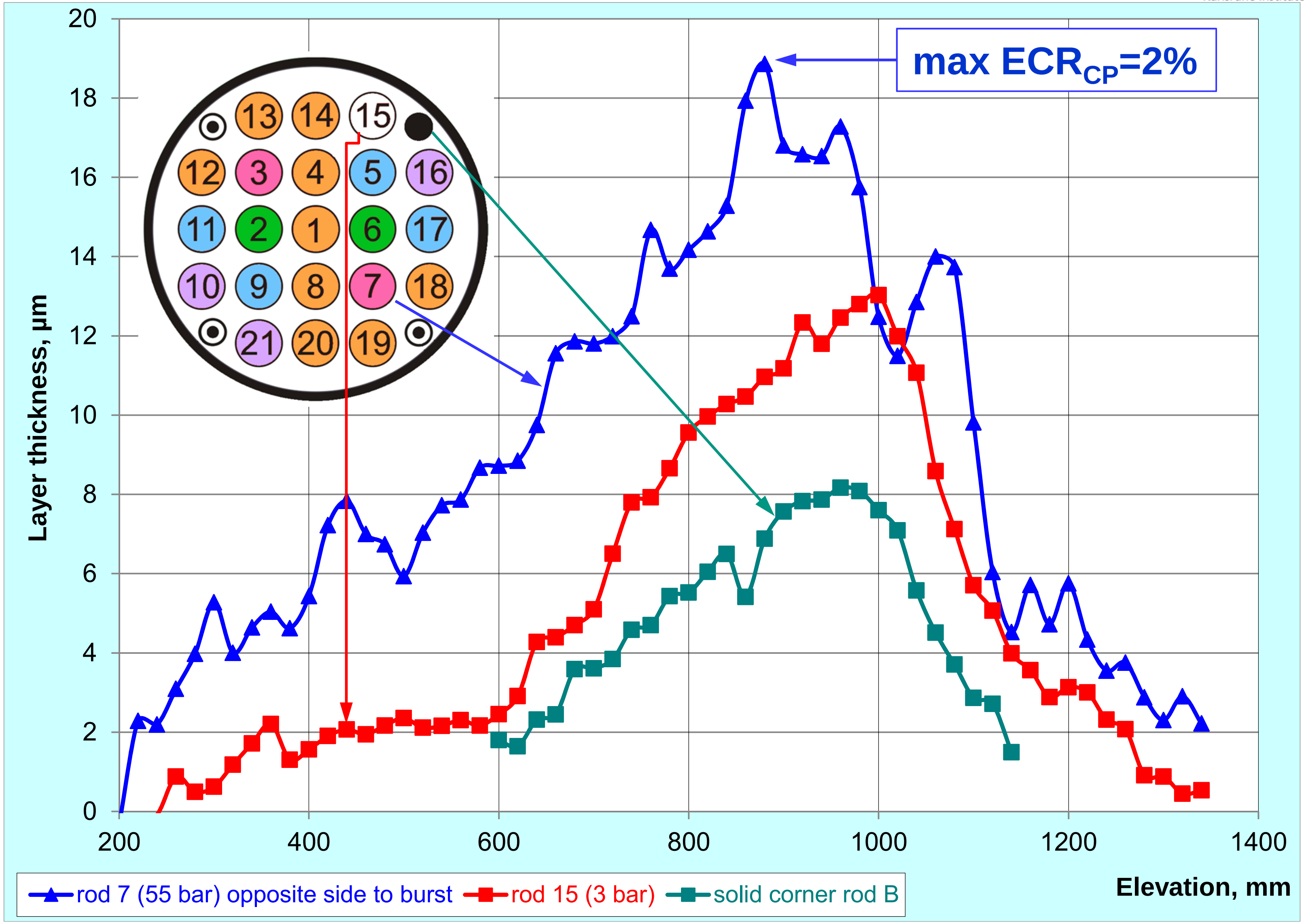
t ~ 224 s:
beginning of abrupt cladding cooling to ~ 400 K by entrainment of water condensed in steam supply tubes

t =362 s (not showed):
initiation of quench water supply

Axial and radial temperature distribution on first burst case (111 s, rod #1)



Post-test axial thickness distribution for oxide+α-Zr(O) : eddy current measurement



Pressure changing during heating phase (0-187 s) , <u>ballooning</u> and <u>burst</u>

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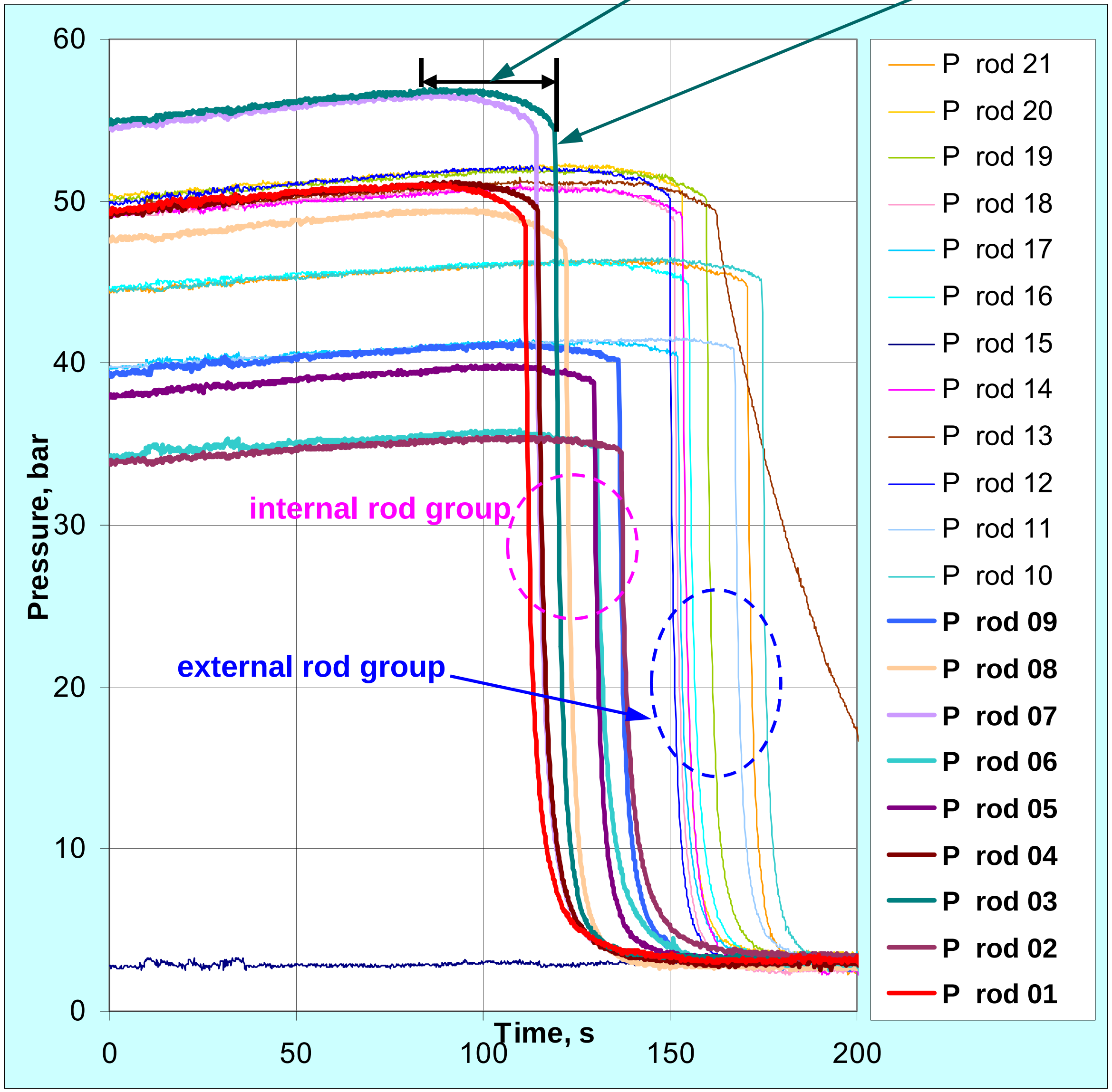
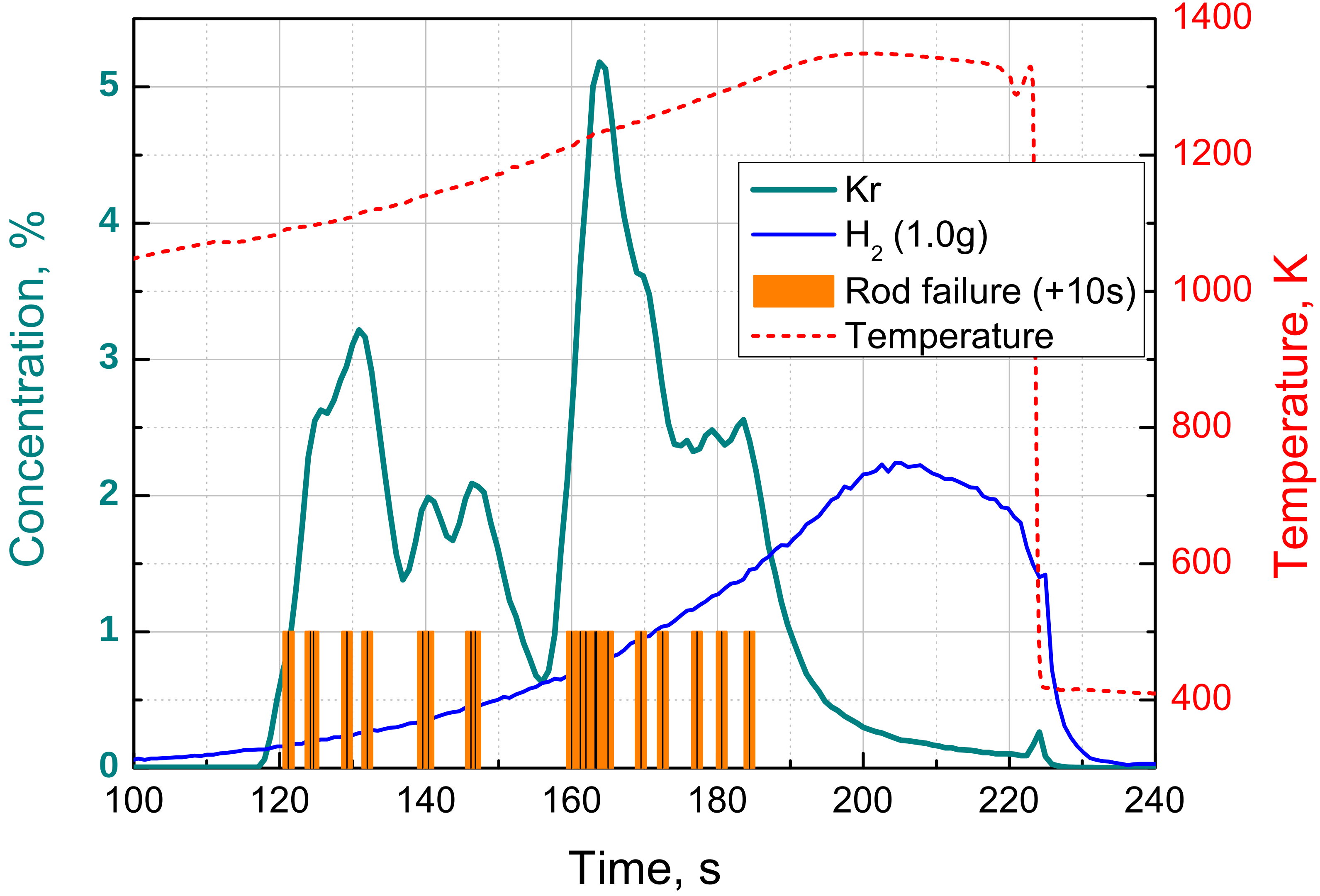
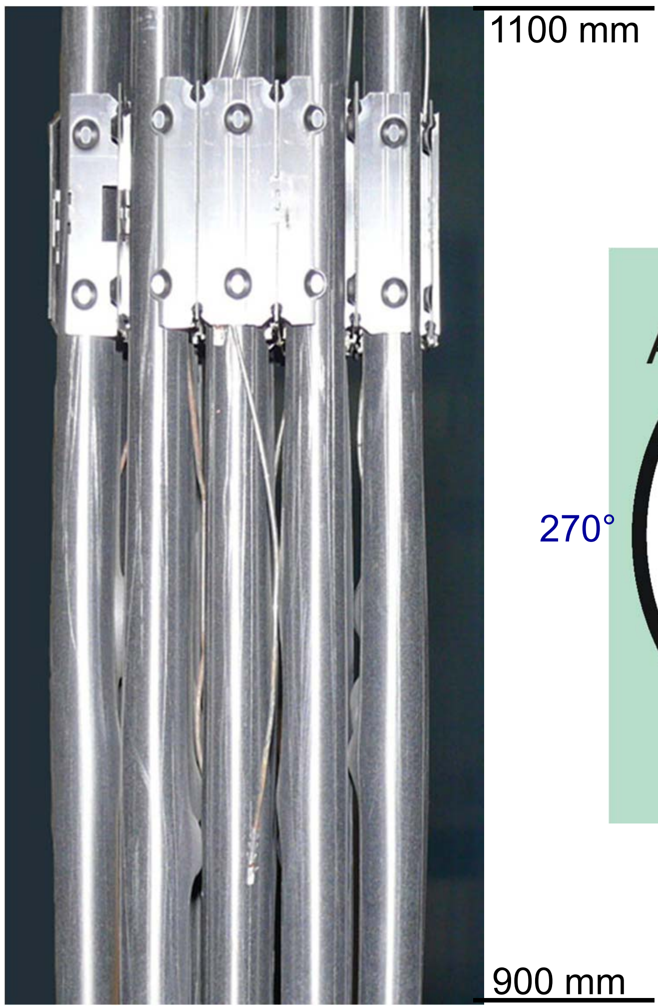


rod	start p, bar	burst p, bar	burst time, s	T@950 mm, C
1	49,3	48,5	111,2	796
7	54,6	54,1	114,2	793
4	49,2	49,5	114,6	800
3	55	54,4	119,2	816
8	47,7	46,8	122,0	813
5	38	38,9	129,6	835
6	34,2	34,7	130,4	833
9	39,2	40,1	136,2	860
2	33,8	34,5	136,8	**861 max T**
12	49,9	50,2	150,0	815
18	49	48,7	151,2	830
17	39,6	40,4	152,0	854
20	50,3	50,4	153,2	**776 min T**
14	49	49,0	153,4	821
16	44,6	44,9	155,0	818
19	50	50,0	159,6	850
13	49,4	49,0	162,5	805
11	39,8	40,8	167,2	868
21	44,4	44,8	170,6	795
10	44,5	45,2	174,4	791

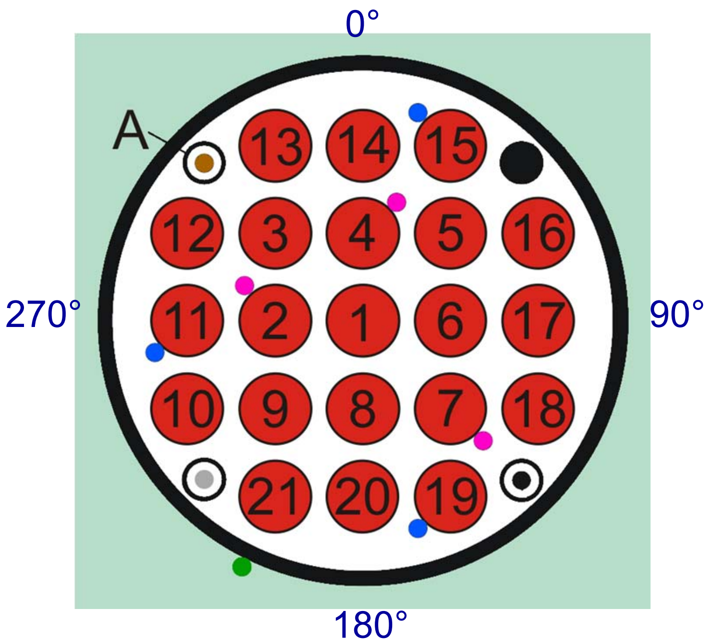
Mass spectrometer: Krypton as burst indicator and H_2 as product of Zr oxidation



Consequences of ballooning

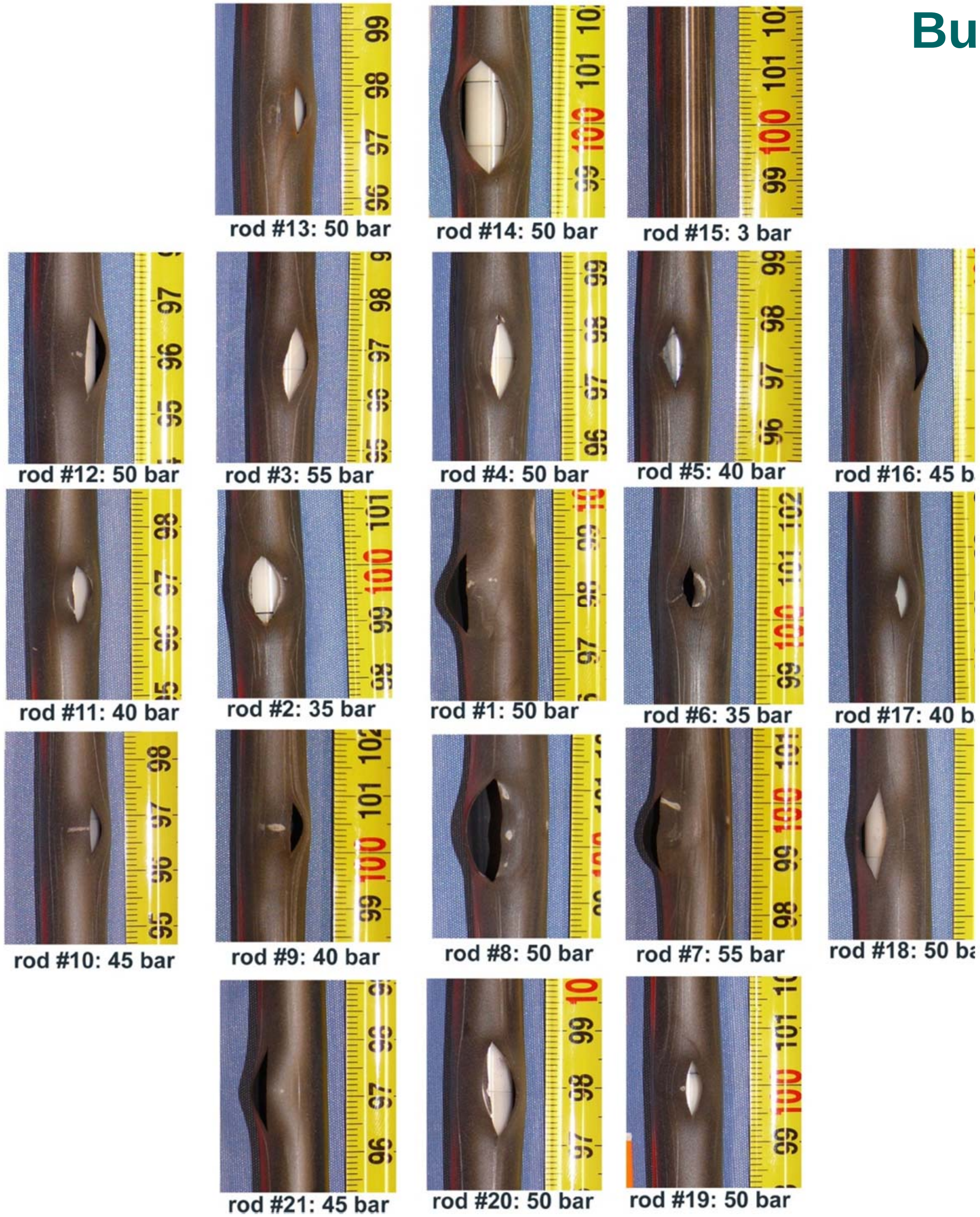


side view at 270°:
no cooling blockage

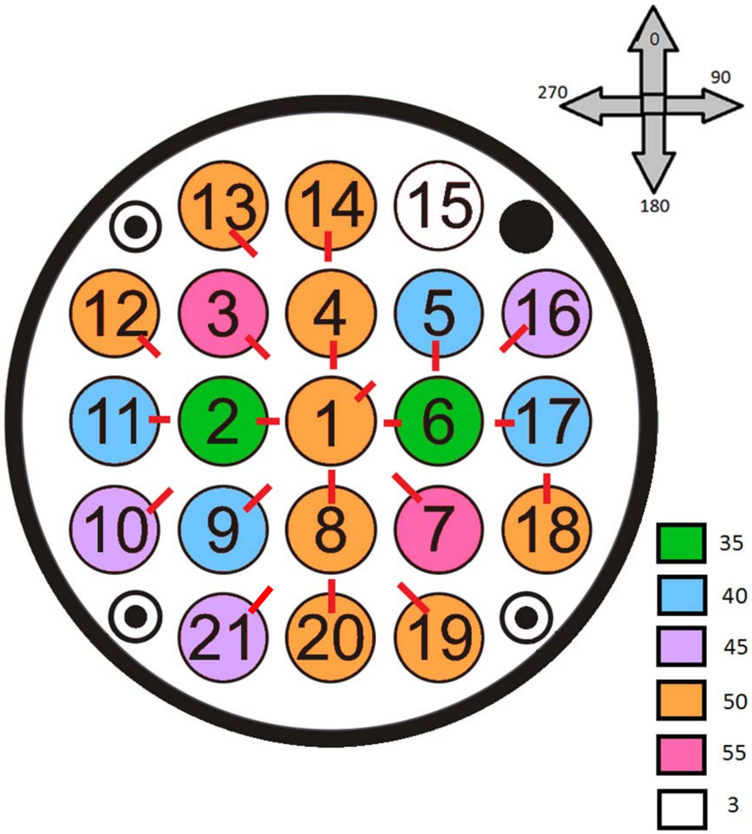


side view at 30°:
axial shrinkage of claddings
due to Zry anisotropy

Burst positions



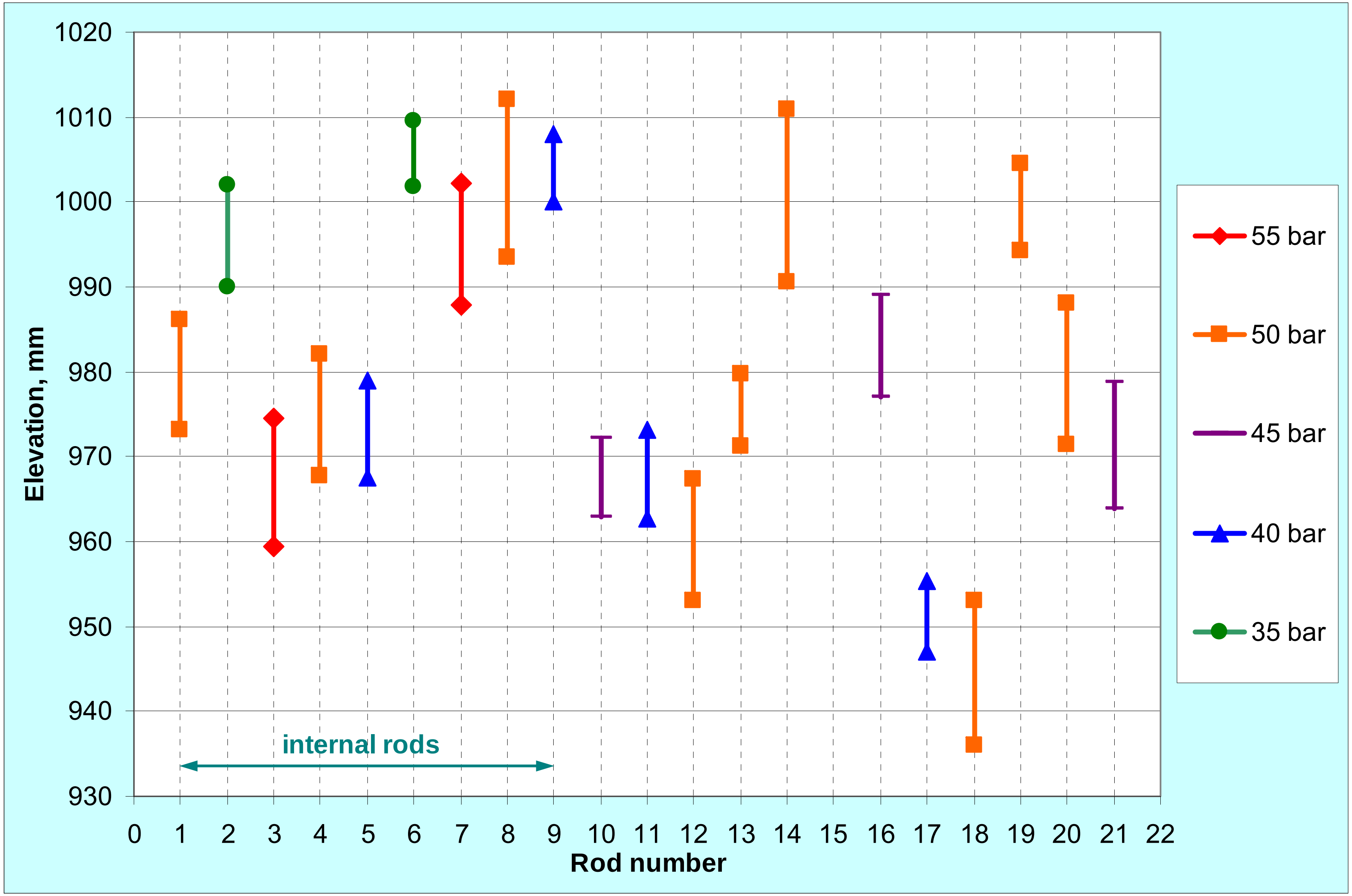
axial positions



circumferential positions

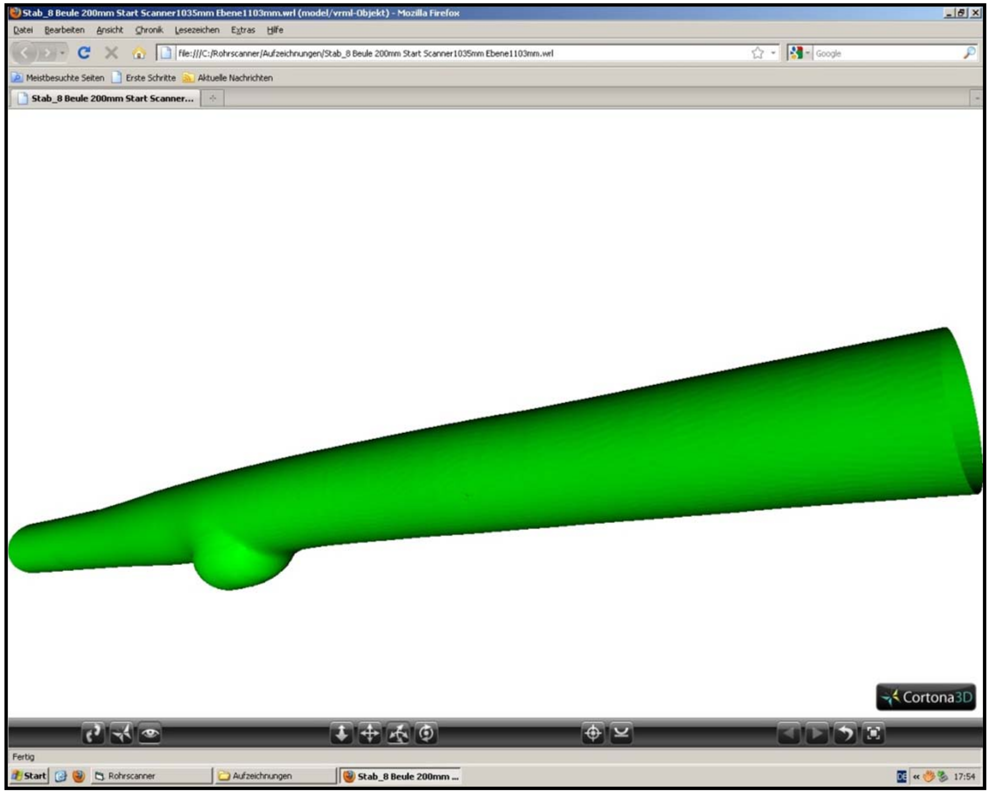
Axial burst positions;

burst length: no clear dependence on pressure



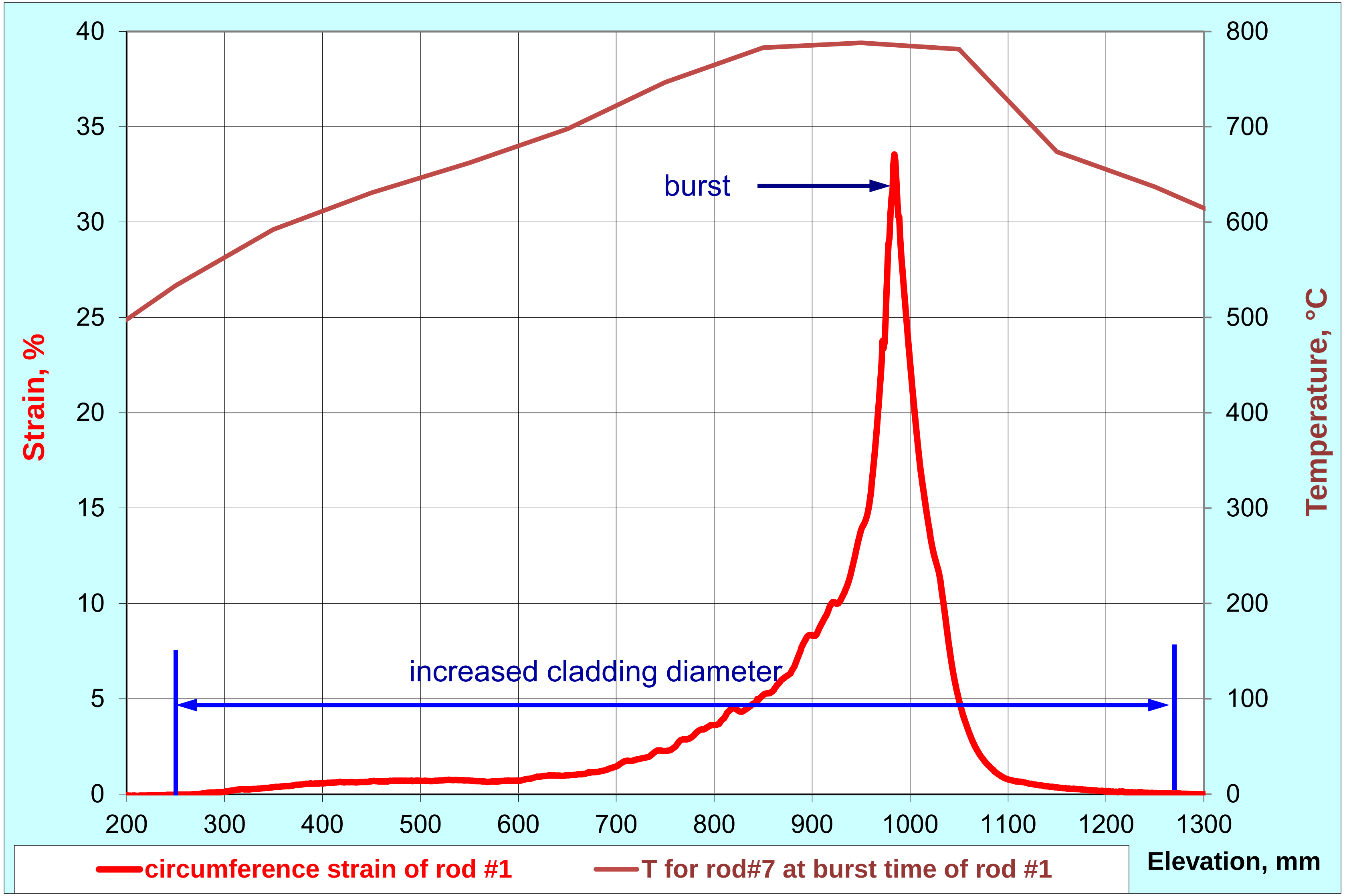
Tube scanner: laser profilometry

scanner facility

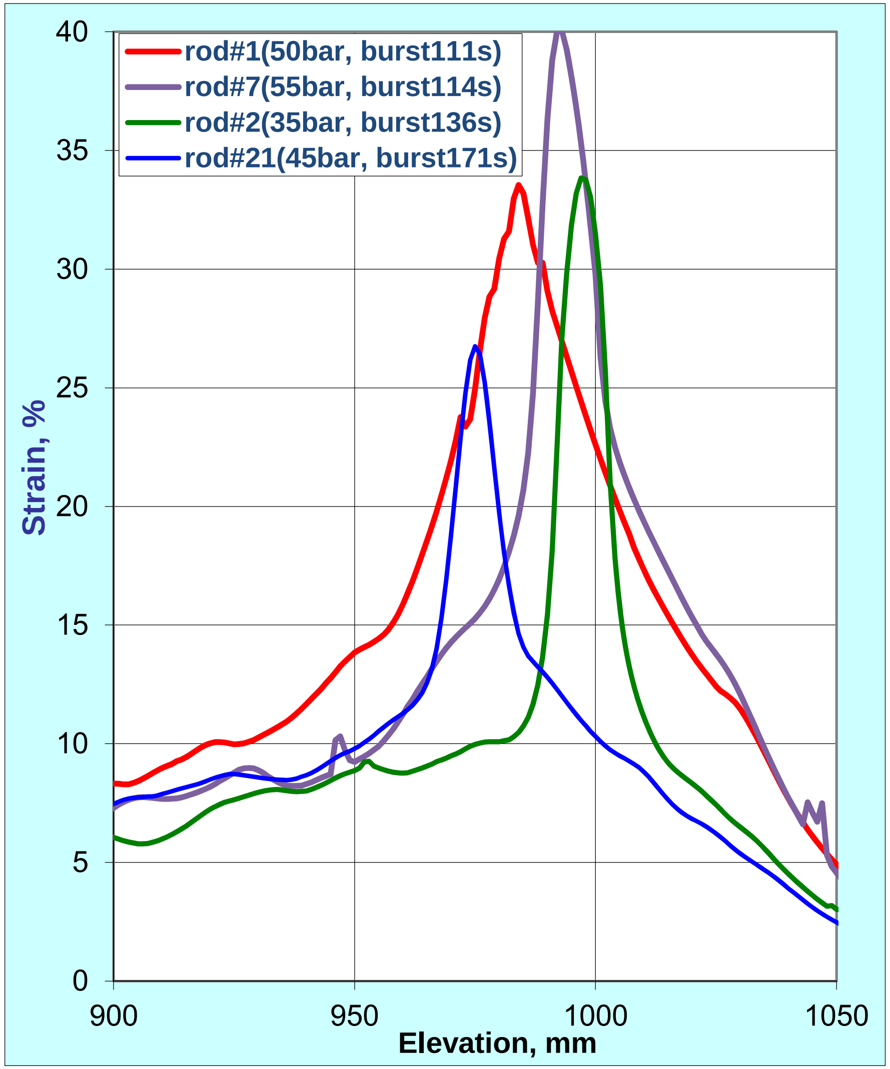


reconstructed scanned surface of rod #8:
angle step 1°; axial step 0.5 mm; scanned length 200 mm

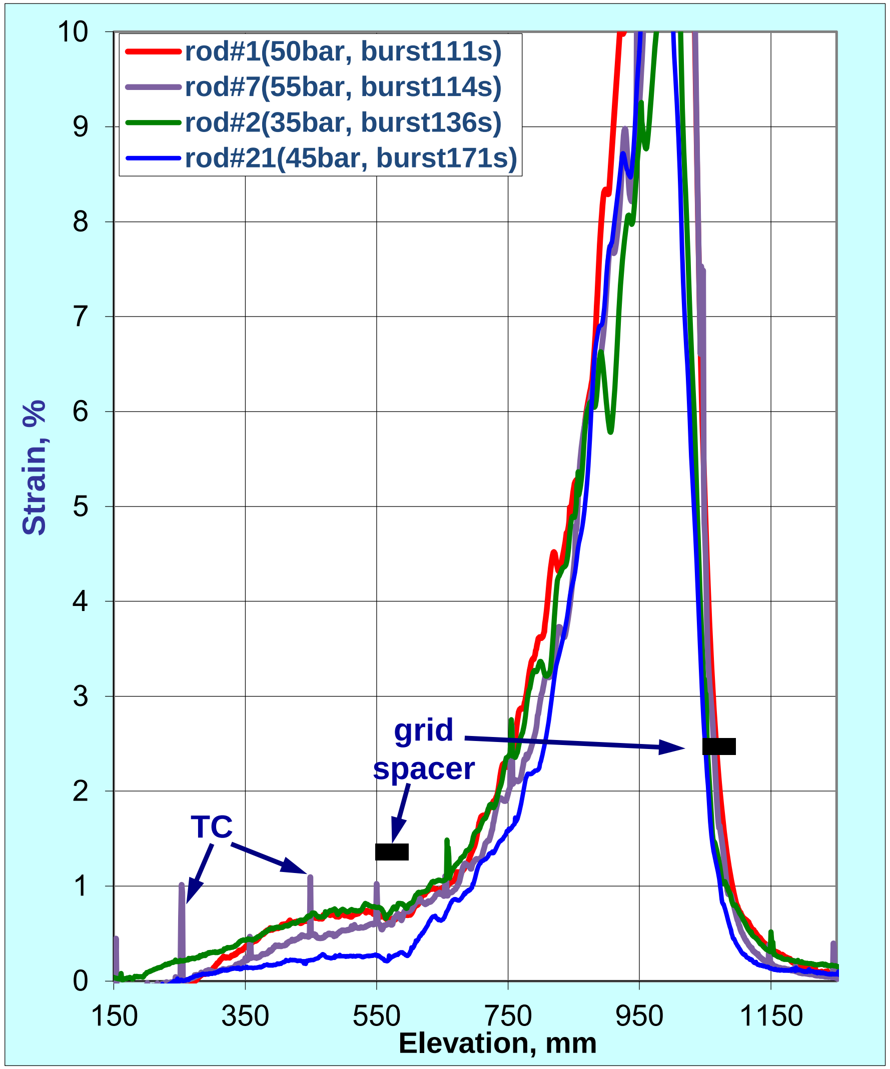
Axial changing of circumference strain (central rod)



Strain comparison for different rods

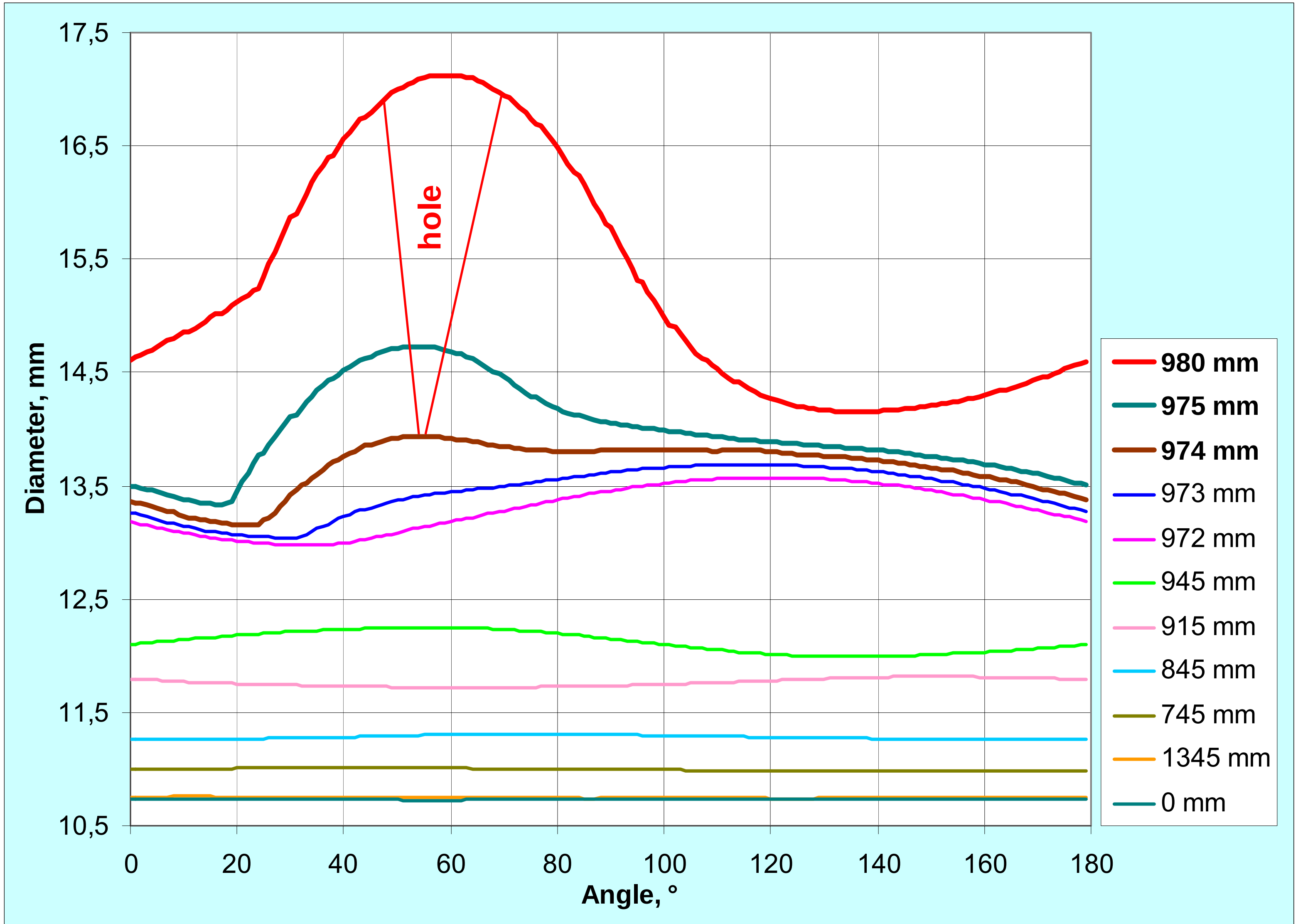


ballooning region:
extended ballooning for central rod (#1)



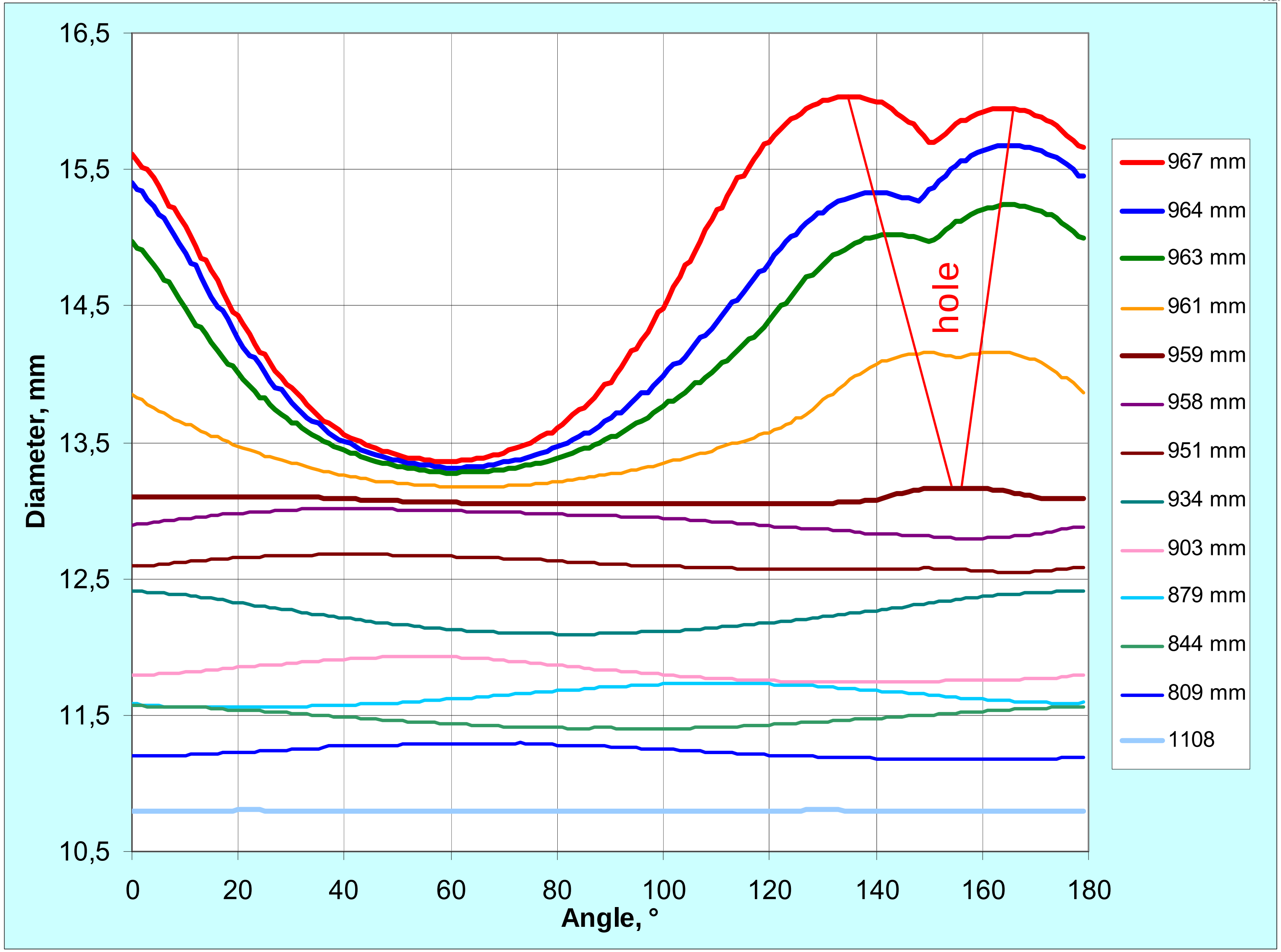
total strain region between 150 and 1300 mm

Diameter change
(rod #1, pressurised to 50 bar)



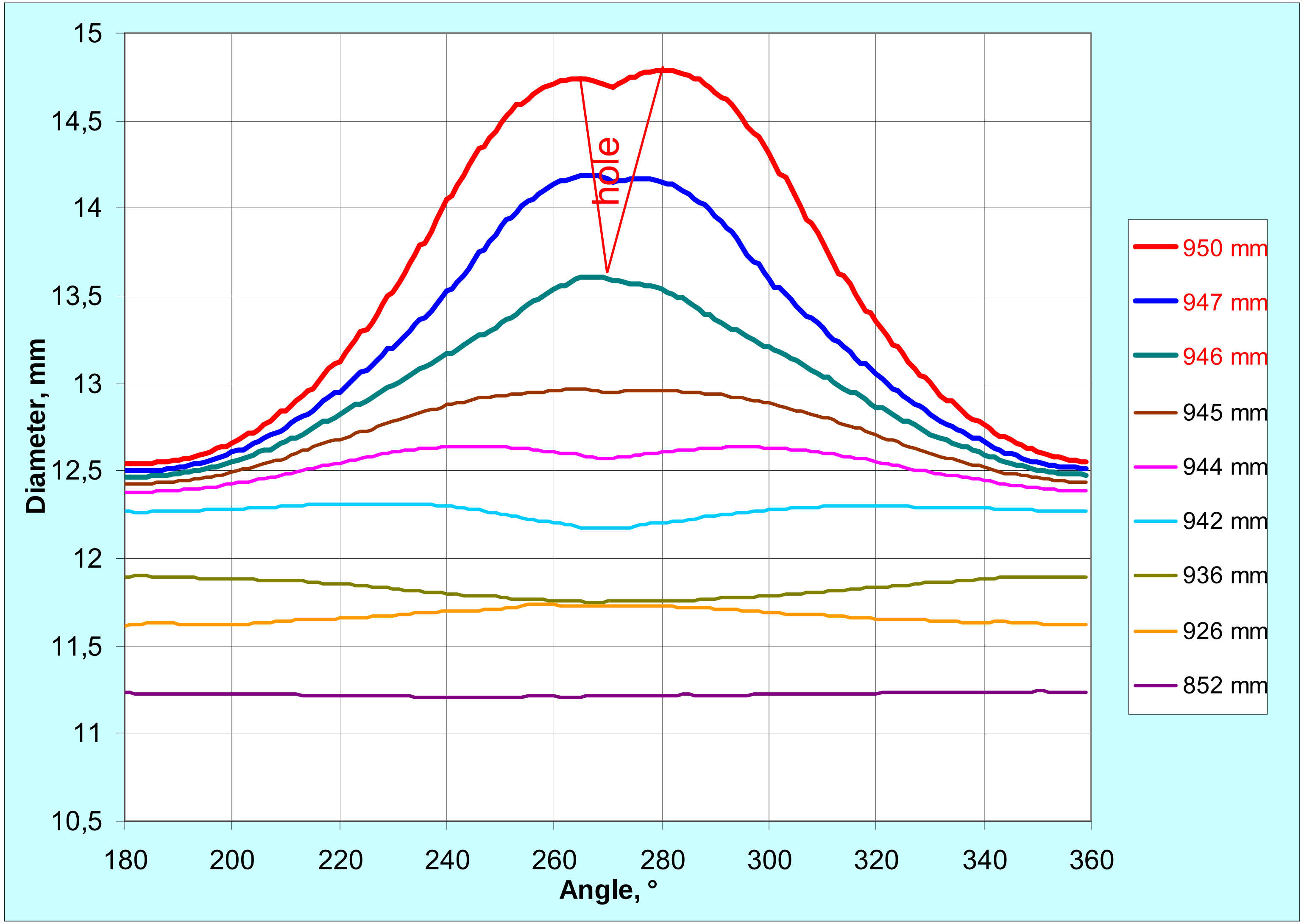
max strain: 30%

Diameter change
(rod #3, pressurised to 55 bar)



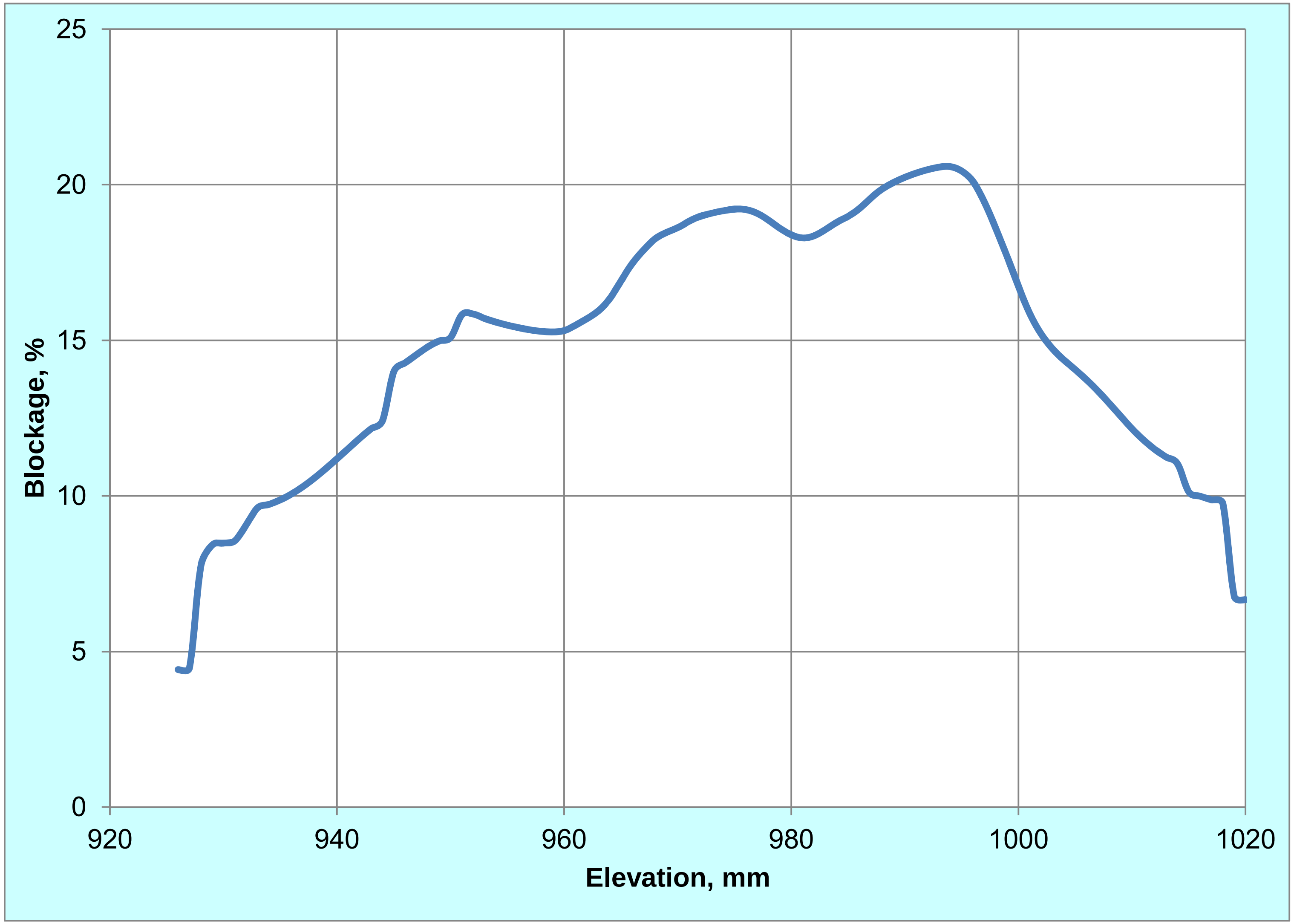
max strain: 25%

Diameter change
(rod #17, pressurised to 40 bar)



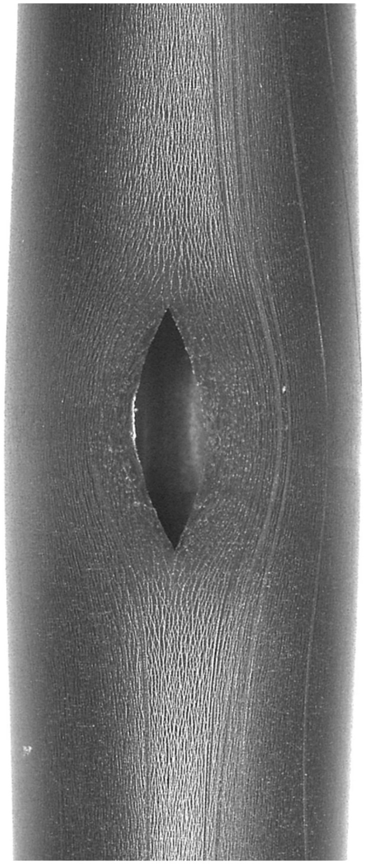
max strain: 20%

Blockage of coolant channel

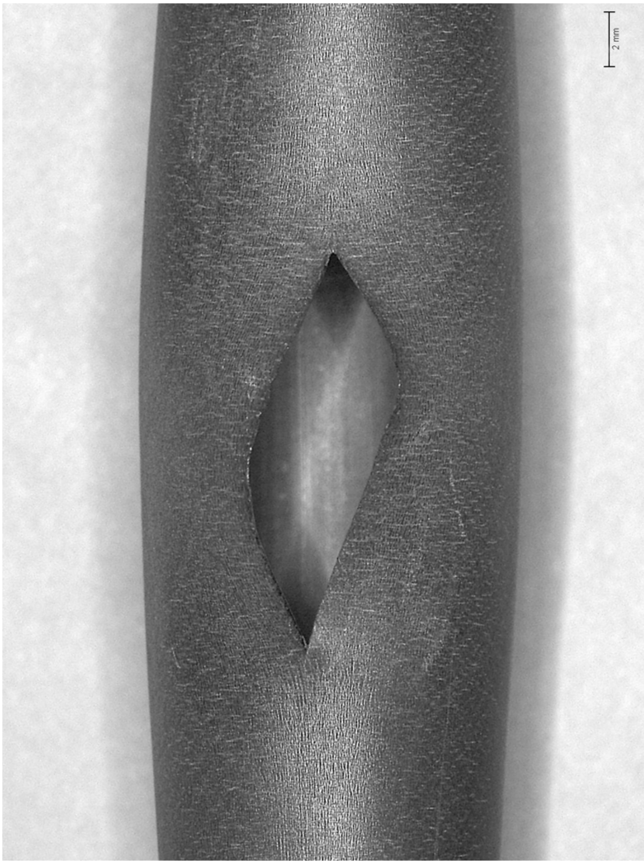


Burst examples: 360° movies

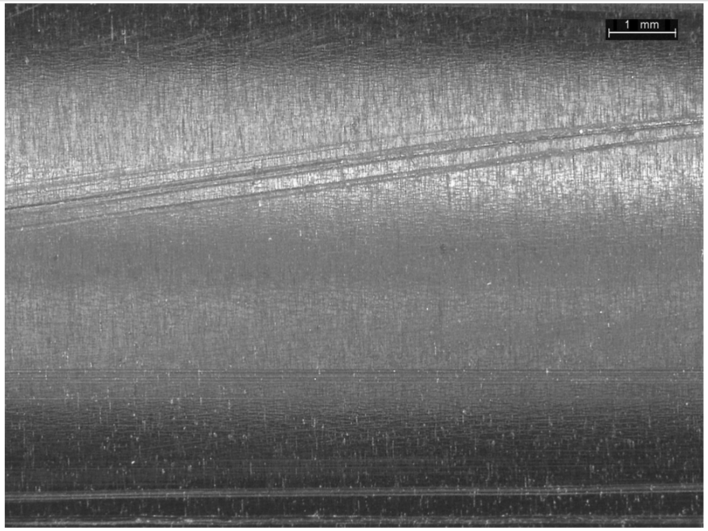
Ballooning view of rod #17 (pressurised to 40 bar)



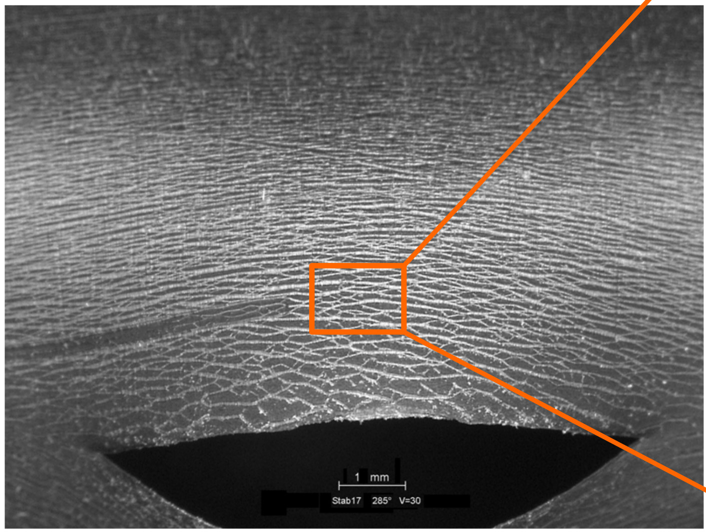
Ballooning view of rod #1 (pressurised to 50 bar)



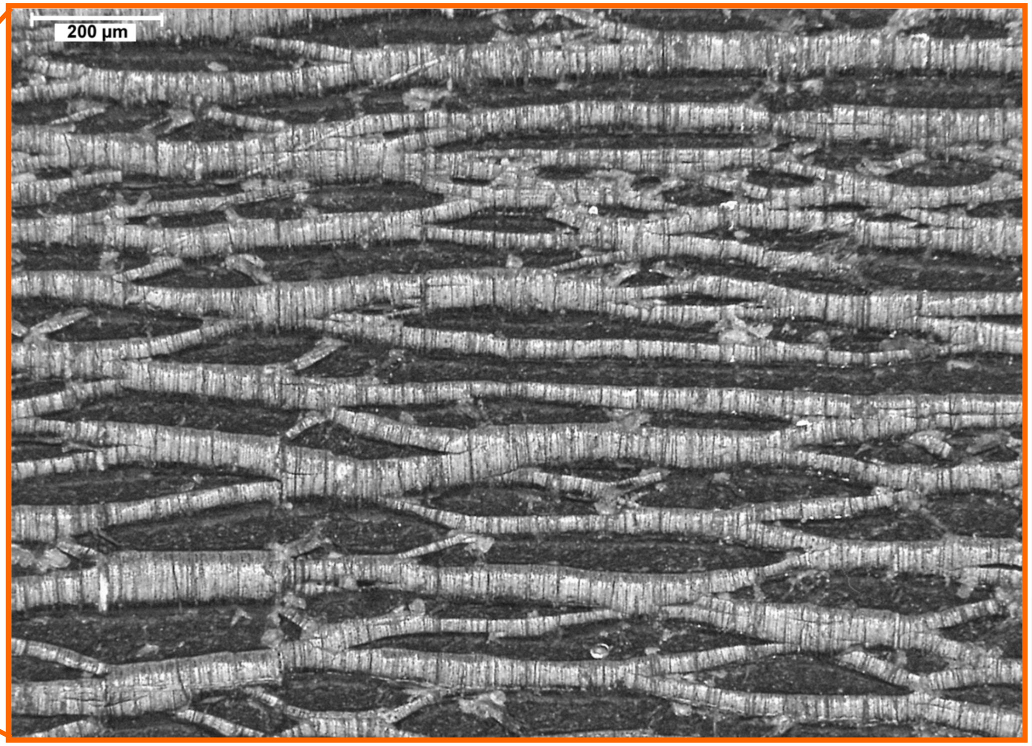
Cladding surface structure: formation of axial surface cracks during ballooning



rod #17: opposite site to burst position



rod #17 (40 bar): **„oxide cells“ near to burst**



network of surface cracks

Axial changing of surface crack structure downwards and upwards from burst;

rod #16 (45 bar), angle 215°

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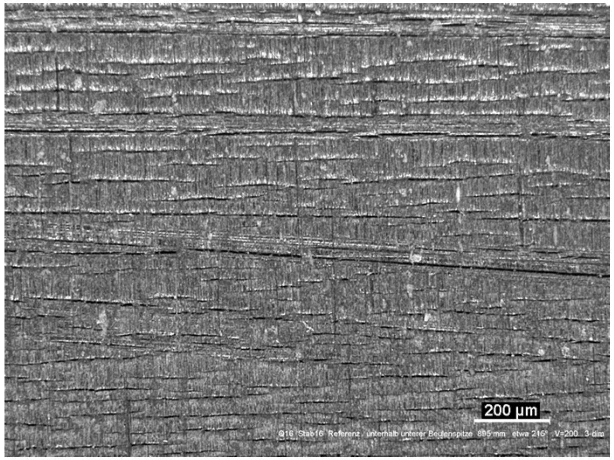
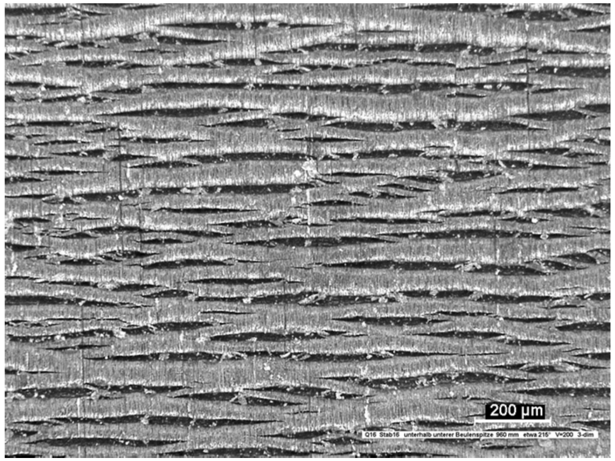
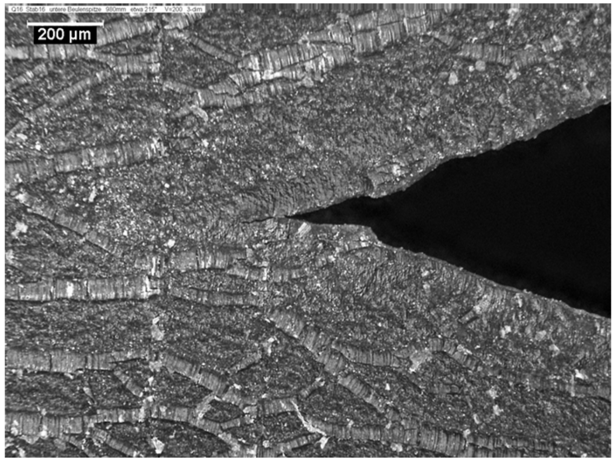


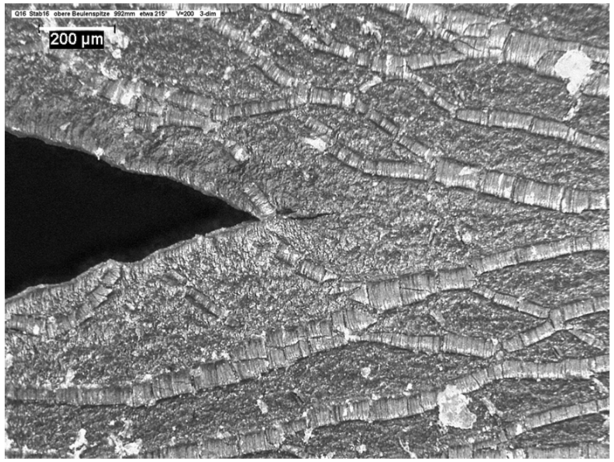
Elevation 895 mm: thin axial cracks



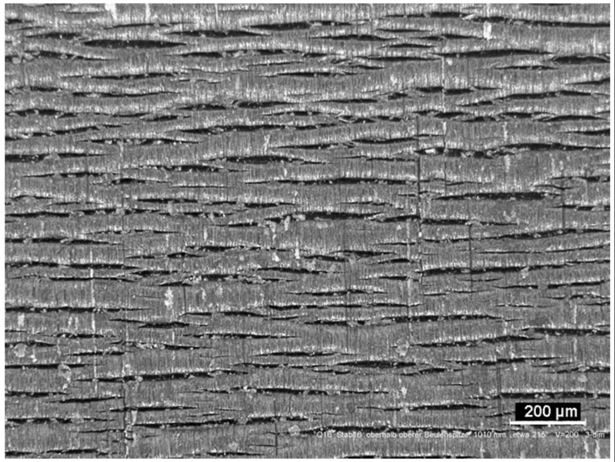
Elevation 960 mm: thick axial cracks



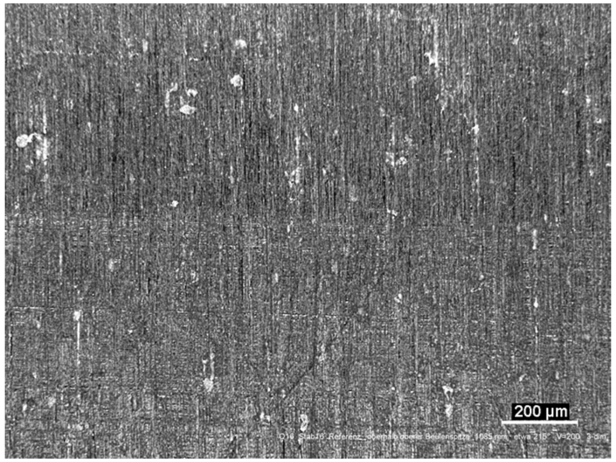
Elevation 980 mm: large cells



Elevation 992 mm: large cells



Elevation 1010 mm: thick axial cracks

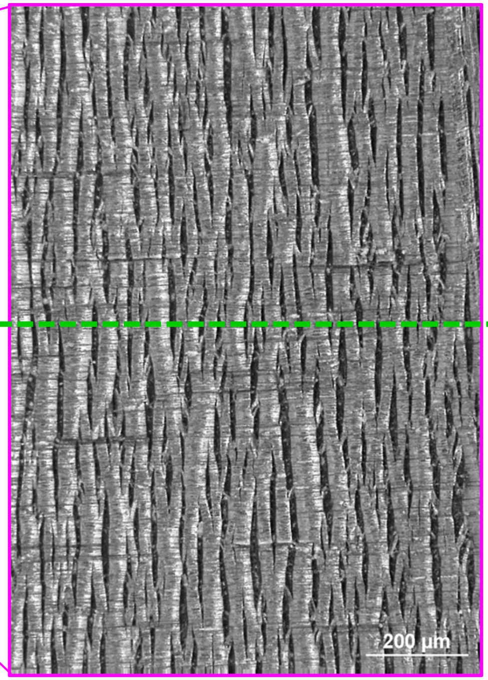


Elevation 1085 mm: absence of axial cracks

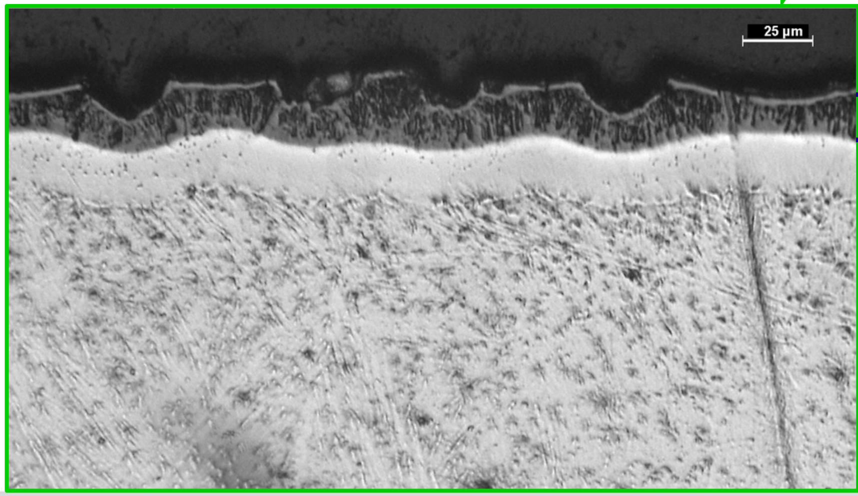
“Self-healing” surface cracks developed during ballooning

rod #3 (55 bar), angle 140°

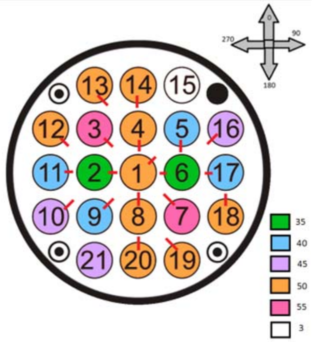
surface structure:
network of
longitudinal cracks
(“tree bark”)



cross-
section

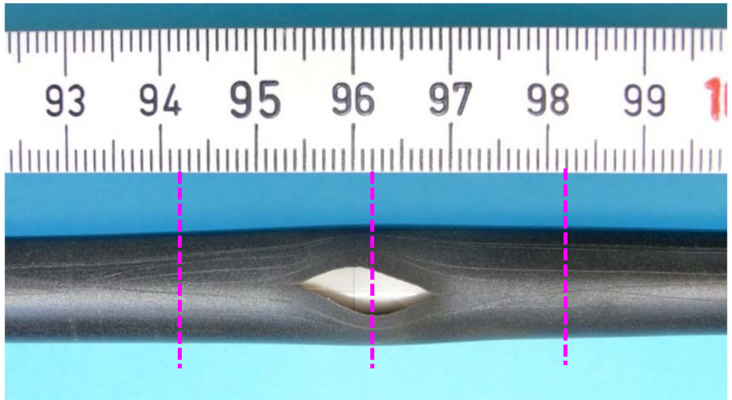


ZrO_2 with “healed” cracks

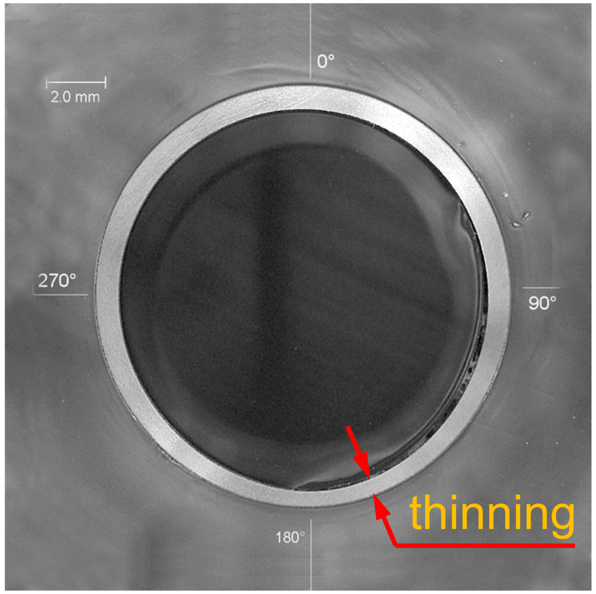
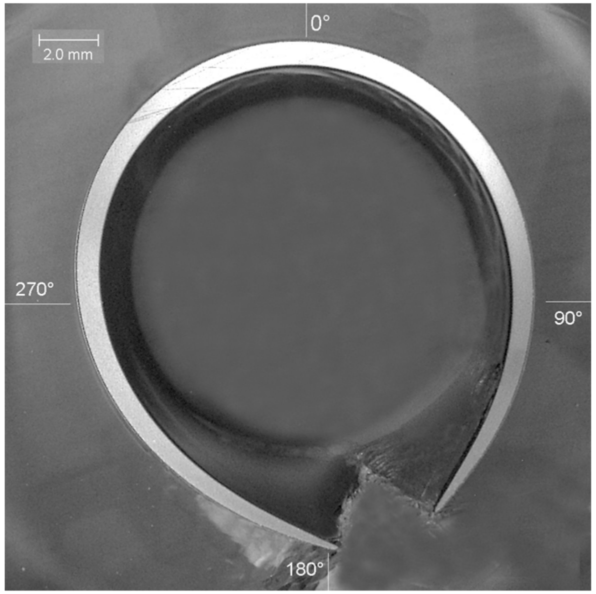
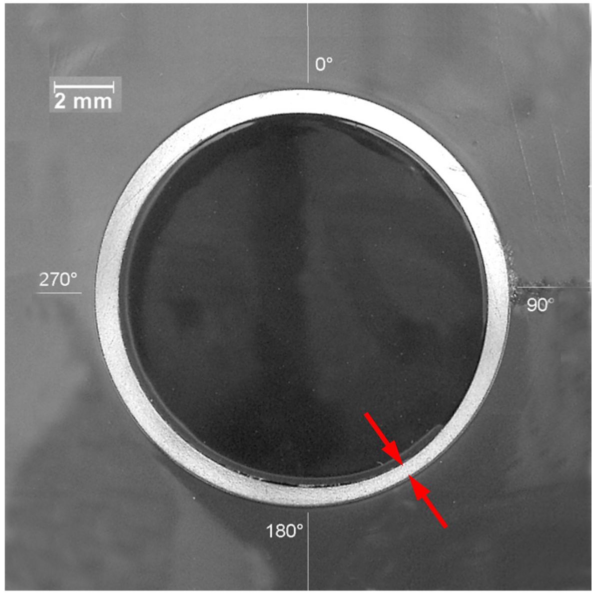


Ballooning and burst effects

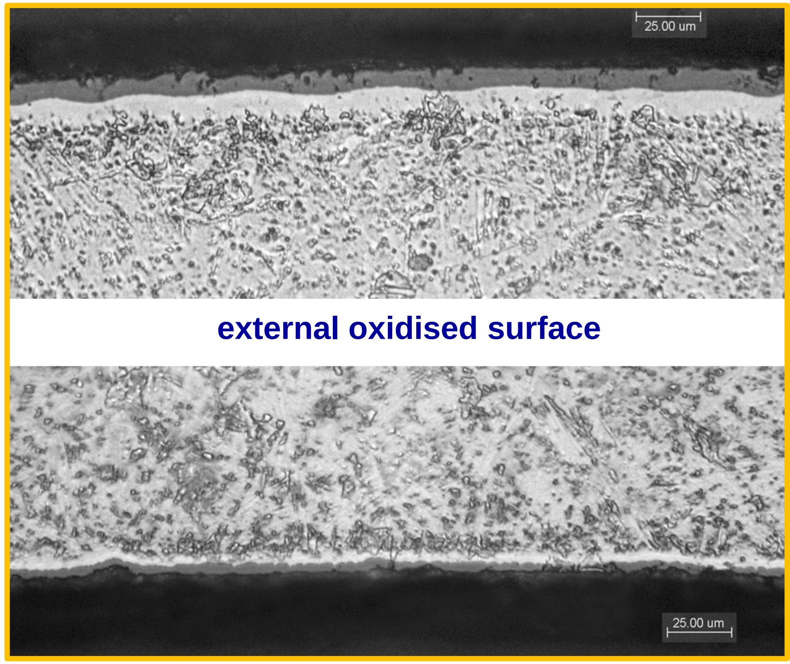
cross sections of rod #3 (55 bar)



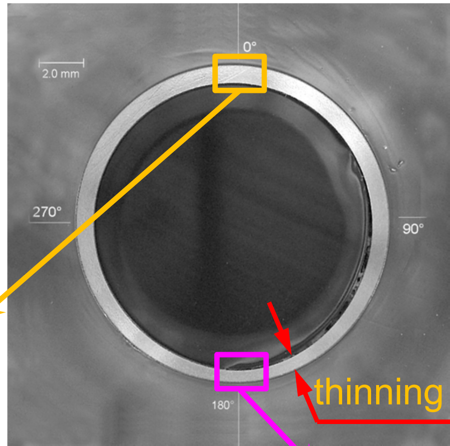
- thinning at hottest circumferential cladding position

elevation 942 mm	elevation 962 mm	elevation 982 mm
		
strain 16%	**strain 36%**	**strain 16%**

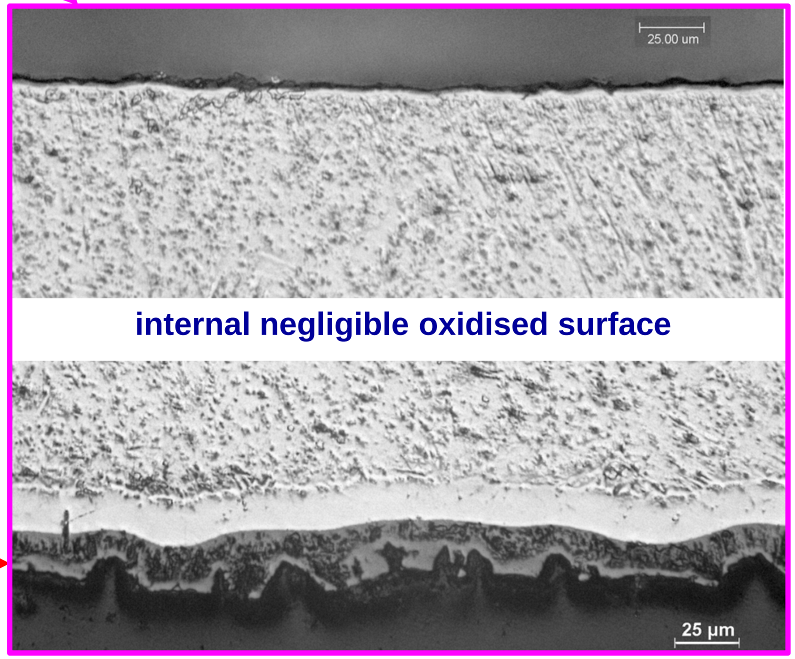
Different internal and external oxidation degree outside burst elevation /rod #3 (55 bar)/



internal oxidised surface



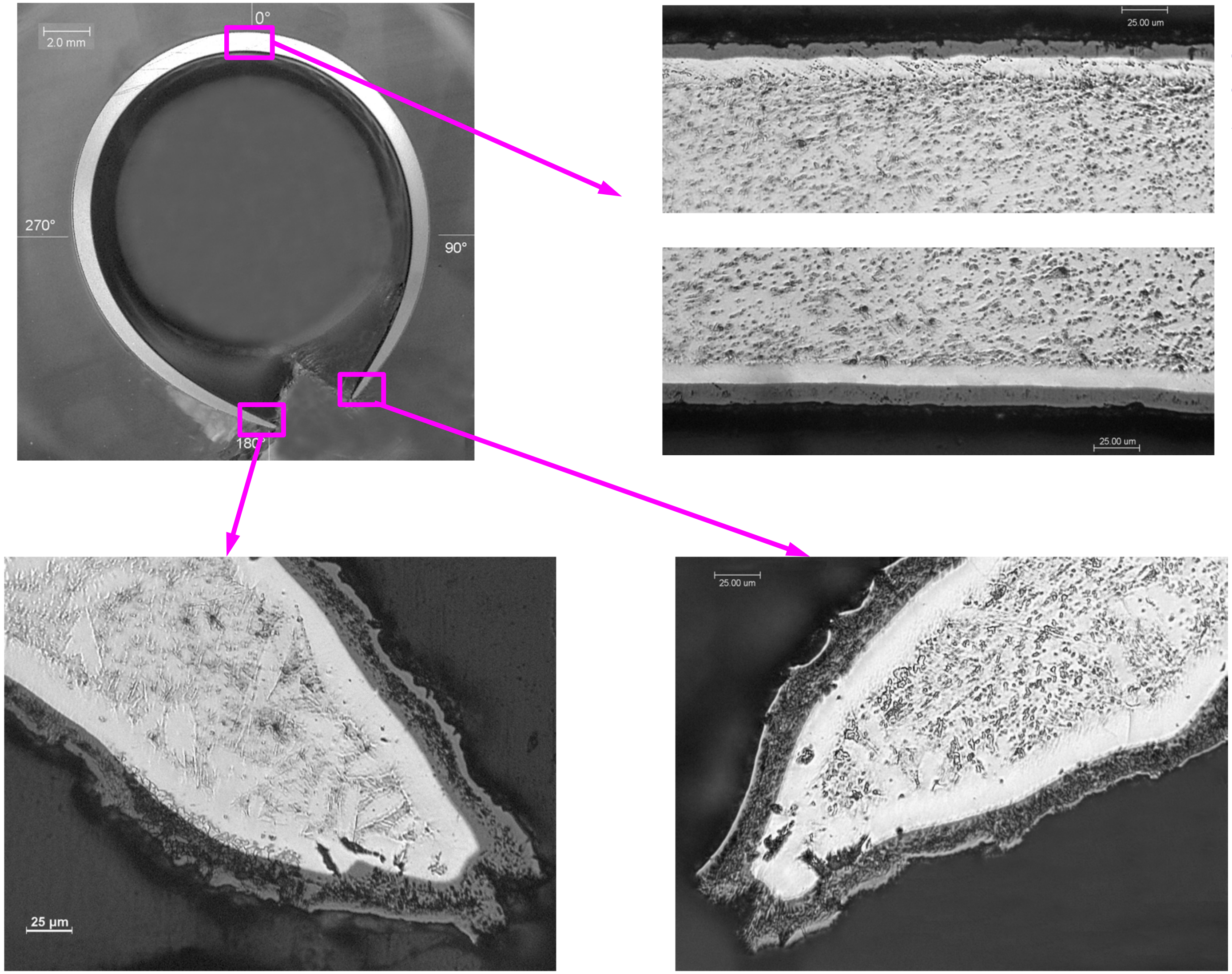
crack development during circumferential extension



external oxidised cracked surface

Similar internal and external oxidation degree at burst elevation

rod #3 (55 bar)

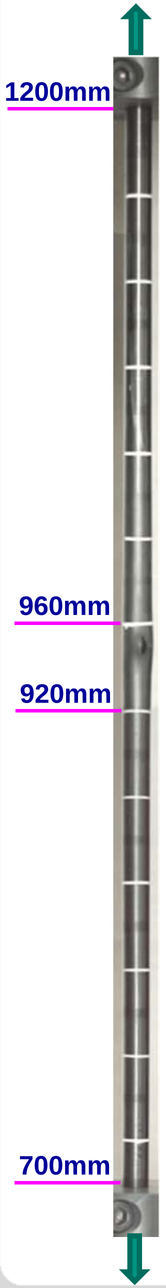


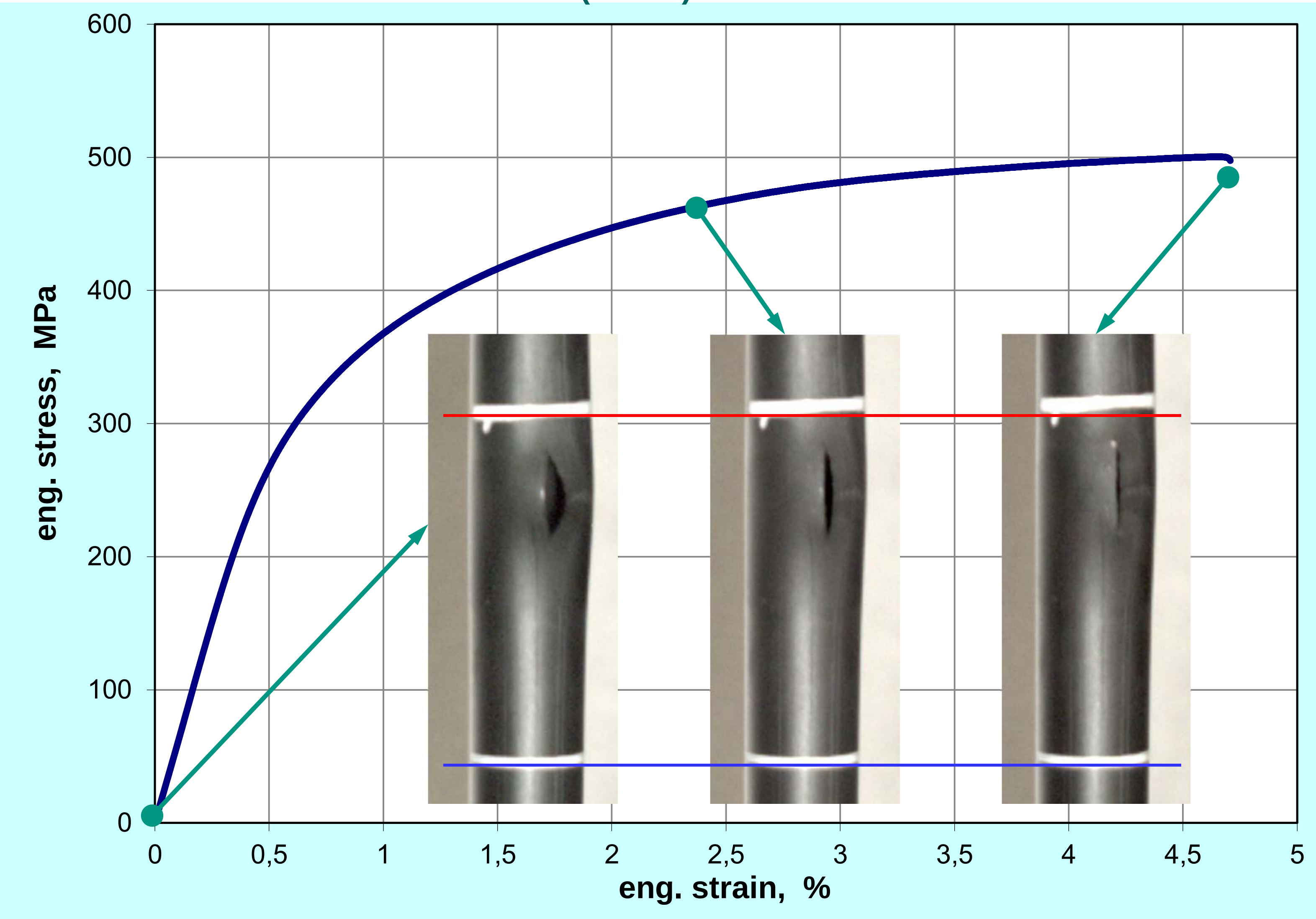
external oxidised surface

internal oxidised surface

Cladding deformation during tension test: axial extension and radial contraction with burst closing

rod #17 (40 bar)

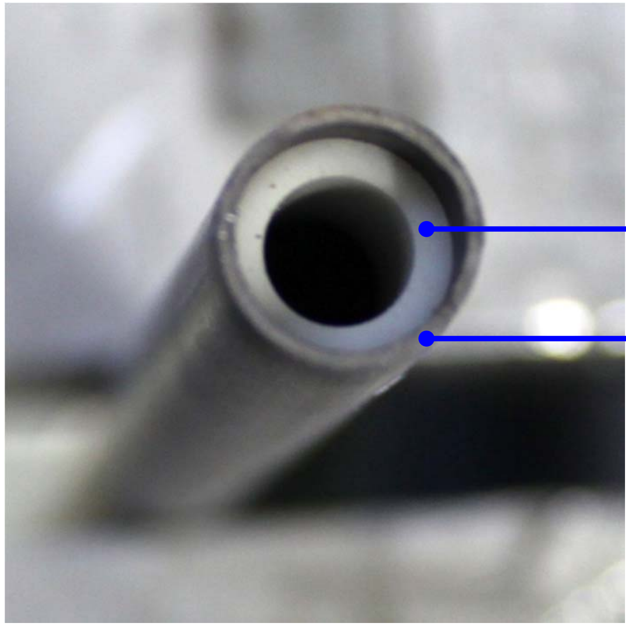




Rupture position outside ballooning

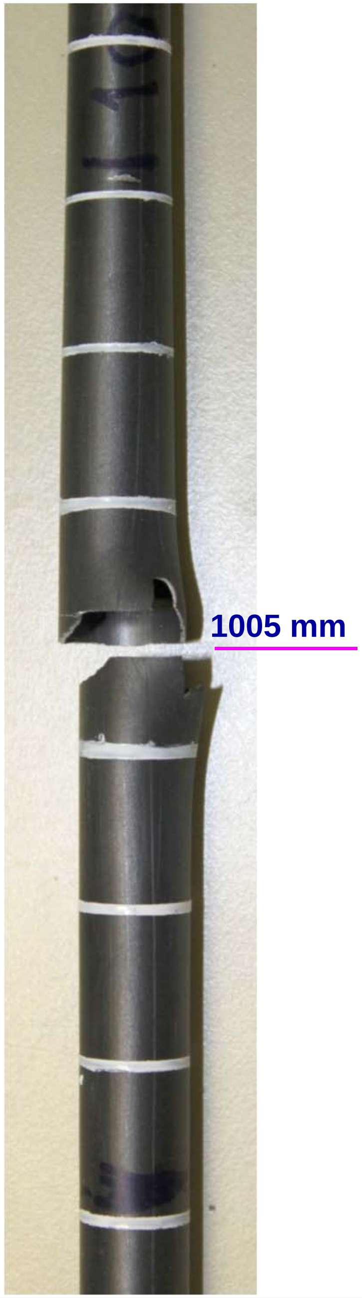
rod #17 (40 bar)

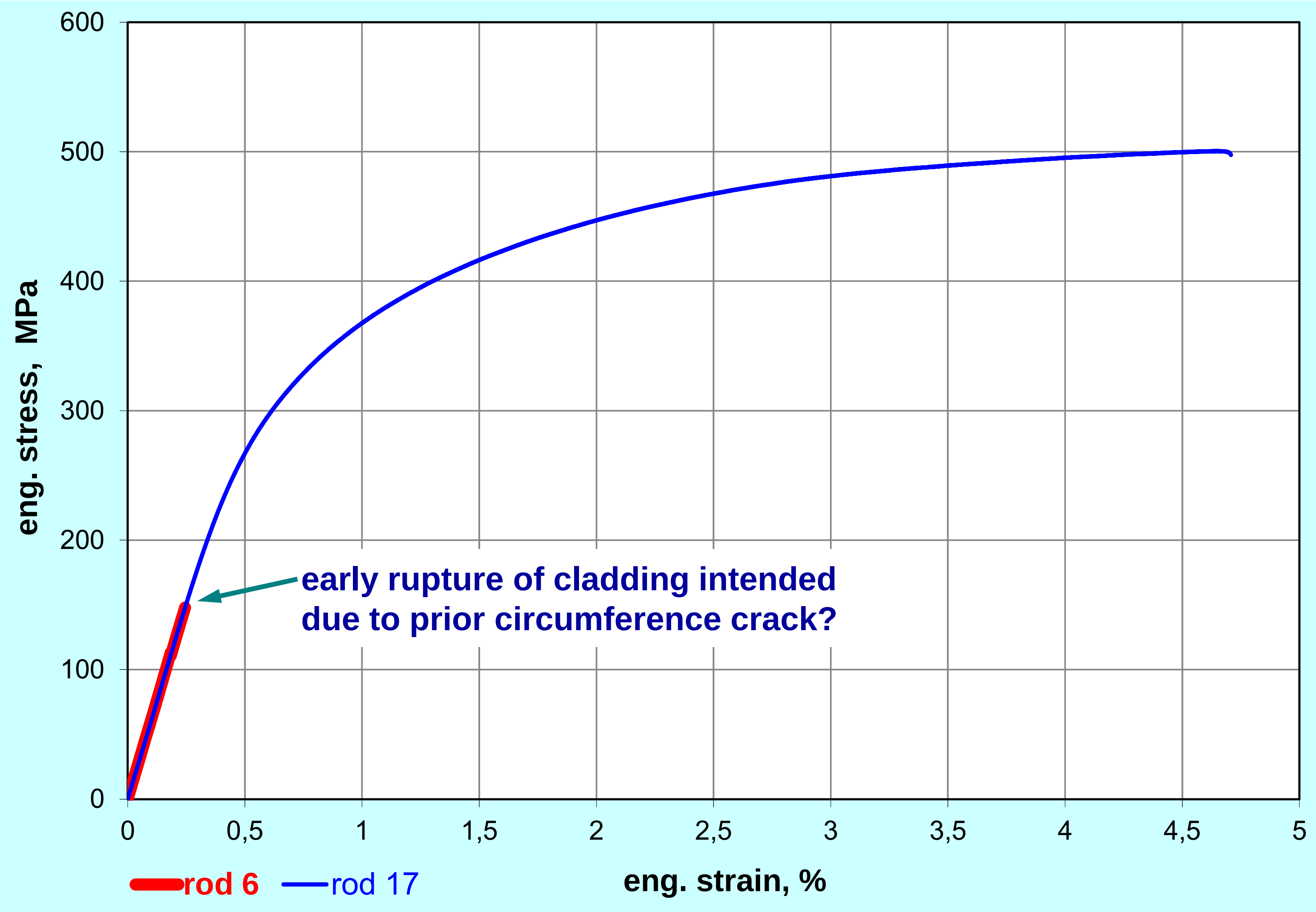
elevation with max hydrogen content (<1300 wppm: neutron radiography by M. Große)



Rupture because stuck pellet?

Tension test at rod #6: early rupture at burst position

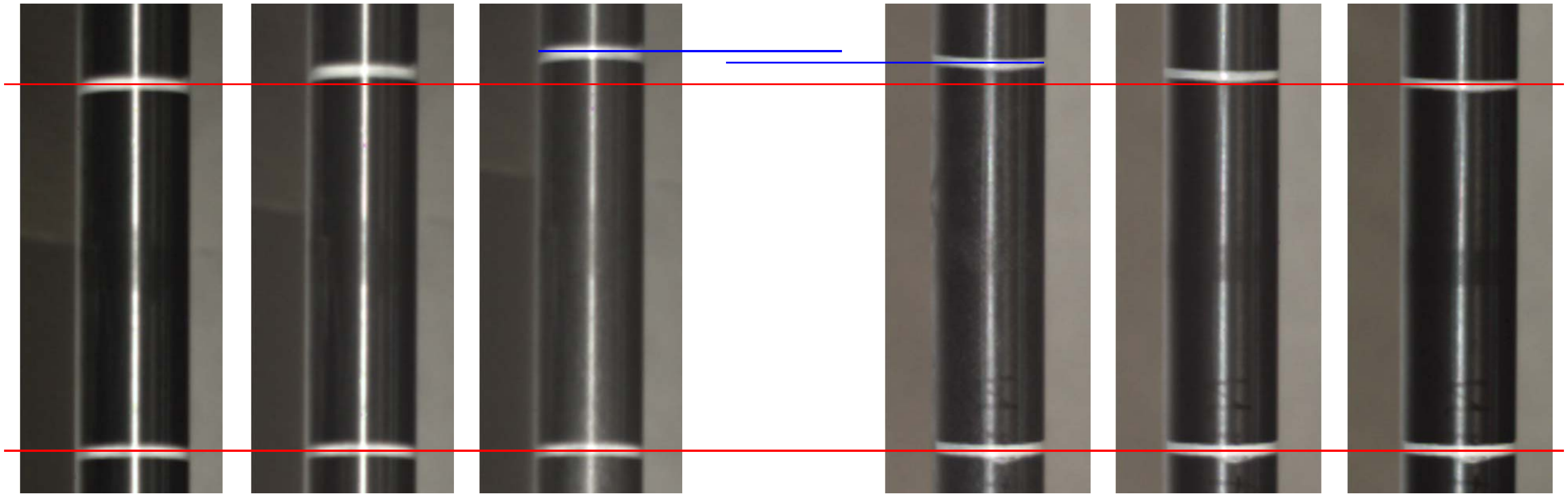




Tension test at rod #17: dependence of tube segment ductility from oxidation degree

elev. ~1200 mm
(fewer oxidised cladding)

elev. ~700 mm
(more oxidised cladding)

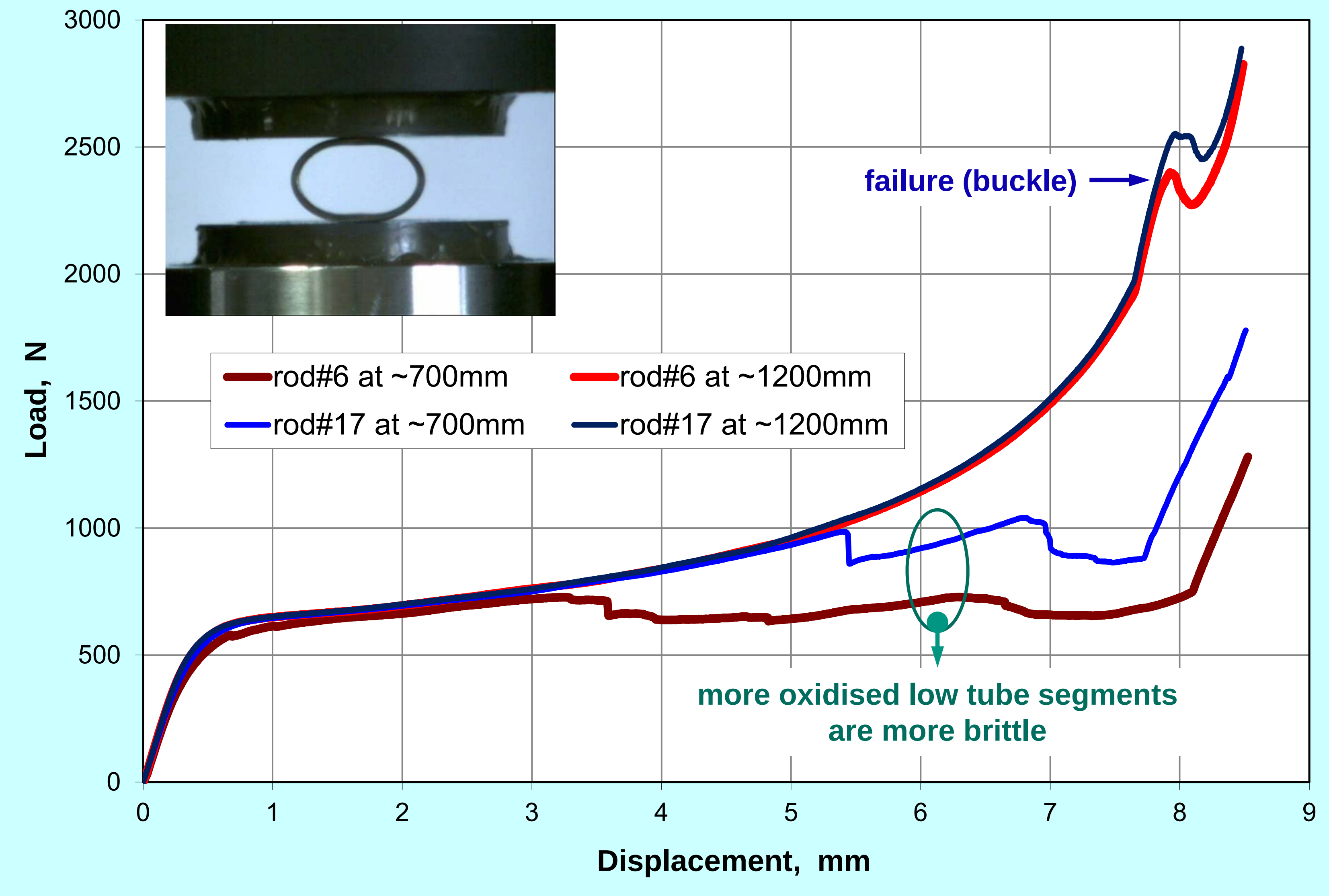


strain 0% (unloaded)	strain 2.4%	strain 4.6% (at failure)	strain 4.6% (at failure)	strain 2.4%	strain 0% (unloaded)

more ductile segment

fewer ductile segment

Results of ring compression tests:
rings with h~10 mm from two elevations



Summary

- Conduction of the QUENCH-L0 test at KIT showed principal possibility of usage of the QUENCH facility for LOCA bundle tests. Currently two improvements will be realized: 1) upgrade of DC generators for faster power increase; 2) installation of trace heating along steam feeder line.

- Data evaluation showed typical ballooning and burst processes for all 20 pressurised rods (pressure values 35, 40, 45, 50 und 55 bar). All burst cases took place during transient heating phase at temperatures between 780 und 860 C. Burst opening lengths between 10 and 20 mm were measured.

- New installed laser profilometer allowed very precise und detailed measurement of cladding strain. Measured circumferential strains are between 20 und 40%. Maximal blockage of cooling channel is 21%.

Summary (cont.)

- Metallographic observations showed development of longitudinal oxidised surface cracks in ballooning region of cladding, which were formed during ductile extension of metallic substrate. Oxide layer was developed on external and internal cladding surface at burst elevations. Only external oxide layer was observed outside of burst positions. Maximal oxide layer thickness δ_{ox}~15 µm (ECR~2%) was measured.

- Two tension tests with cladding segments (length of ~600 mm) from two rods showed different rupture positions: 1) at burst middle - probably intended with prior circumference crack; 2) at position of stuck pellet.

- Ring compression tests showed sensitivity of methods to slightly different oxidation degree.

Outlook

Five following bundle tests are planed to be performed:

- 1 test with pre-oxidised (oxide ~50 µm) Zircaloy-4 claddings
- 1 test with the DUPLEX claddings
- 2 tests with the M5® claddings
- 1 test wit the ZIRLO™ claddings

Thanks
the QUENCH-LOCA0 test and post-test investigations are sponsored by **VGB**

Thank you for your attention

http://www.imf3.kit.edu/26.php
http://quench.forschung.kit.edu/