Karlsruhe Institute of Technology

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QUENCH-LOCA Program at KIT and Results of the QUENCH L0 Bundle Test

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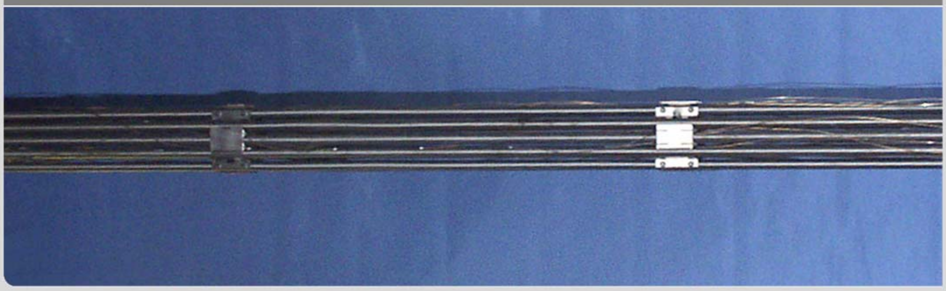
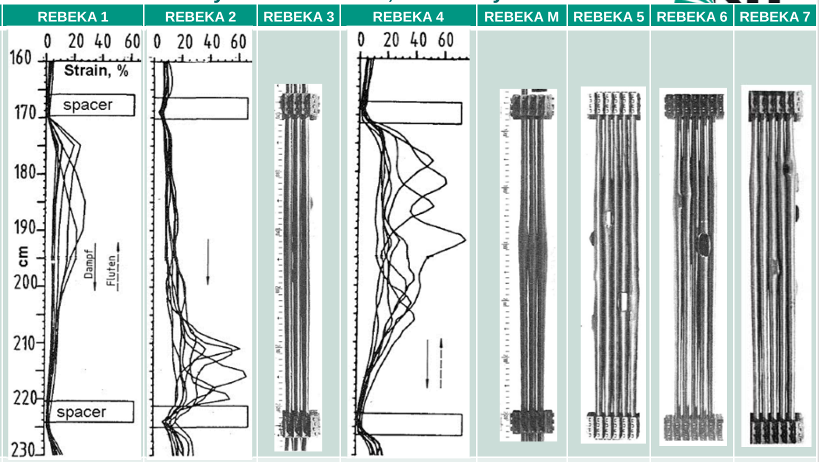


Overview of REBEKA program (1978-1987) at KfK:

electrical heated facility with 3.5 m rods; thermo-hydraulic tests



	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

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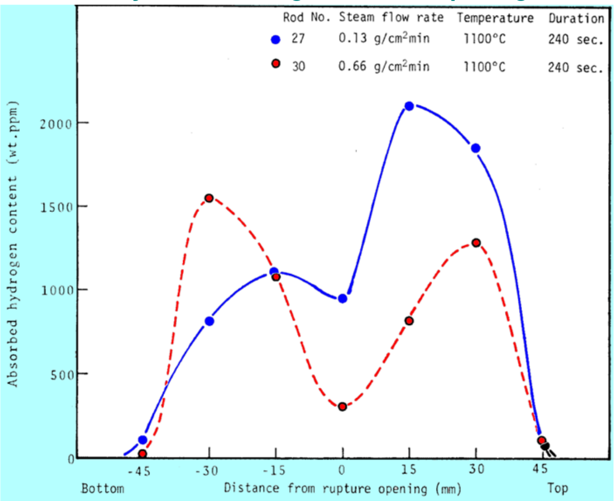
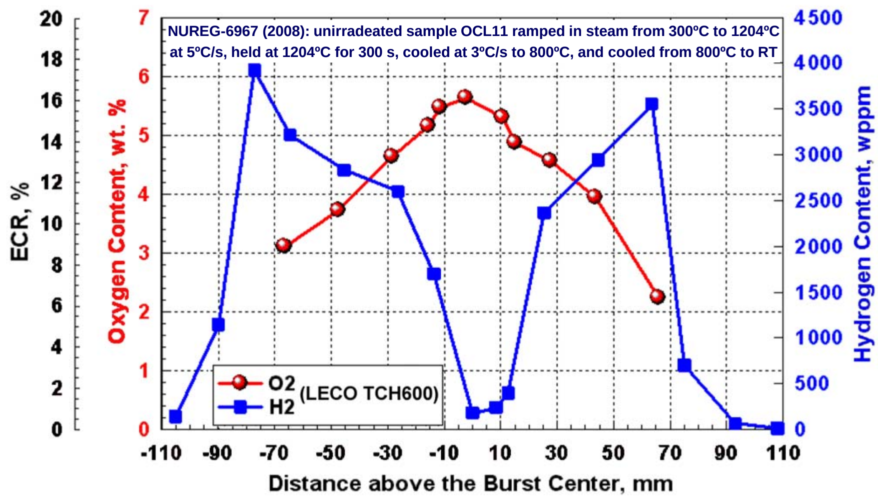
1981, Uetsuka* et al.: first observation of cladding hydriding by steam through the burst opening



Distributions of absorbed hydrogen along Zircaloy-4 claddings isothermally oxidised after rupture, with rate of steam flow as parameter

*Journal of NUCLEAR SCIENCE and TECHNOLOGY, 18[9], pp. 705~717 (September 1981).

Short term secondary hydrogenation after ballooning and burst: hydrogen uptake increased rapidly up to 4000 ppm *(significant higher than ductility limit of 500 ppm)*



sample OCL11 (Zircaloy-2):

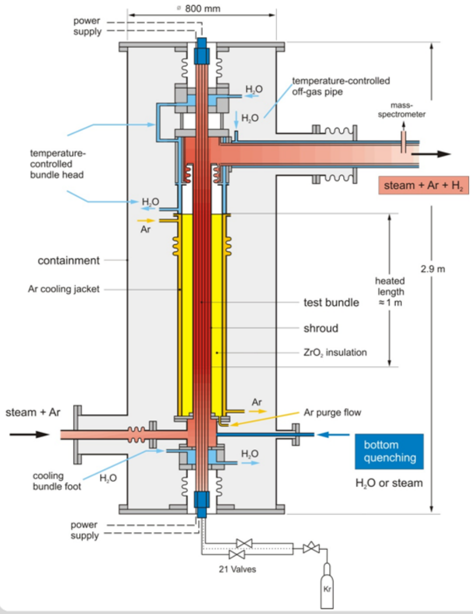
Objective of new LOCA bundle tests

- To investigate the influence of the secondary hydriding phenomenon on the applicability of the embrittlement criteria for the German nuclear reactors it was decided to perform the QUENCH-LOCA bundle test series in the QUENCH facility at KIT.

- Additionally, the QUENCH-LOCA bundle tests could support experiments performed in-pile and in-cell, respectively, e.g. single-rod tests as those planned in the OECD SCIP-2 project.

- Compared to single-rod experiments, bundle tests have the advantage of studying the mutual interference of rod ballooning among fuel rod simulators as well as the local coolant channel blockages in a more realistic arrangement.

Features of QUENCH-facility



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

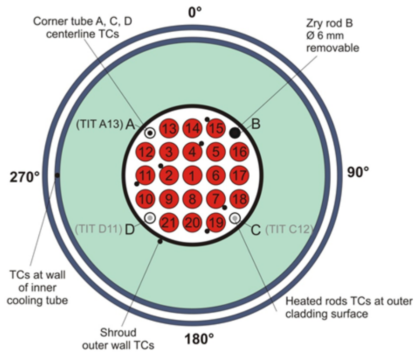
Bundle
- PWR (21 or 24 rods; Zry-4, M5, ZIRLO)
- VVER (31 Stäbe, E110)

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

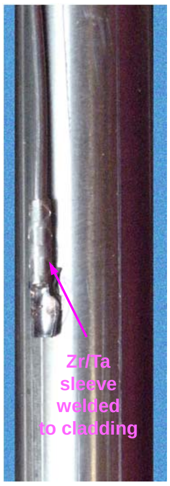
Rod pressurisation up to 120 bar

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

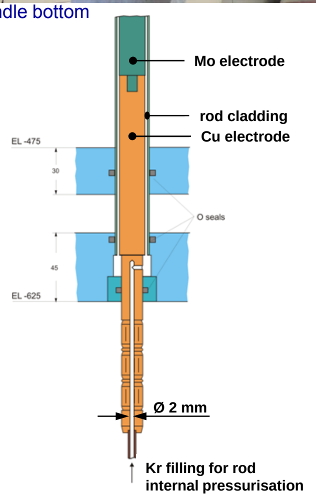


rod #4 before test:
TFS 4/13 at 950 mm

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

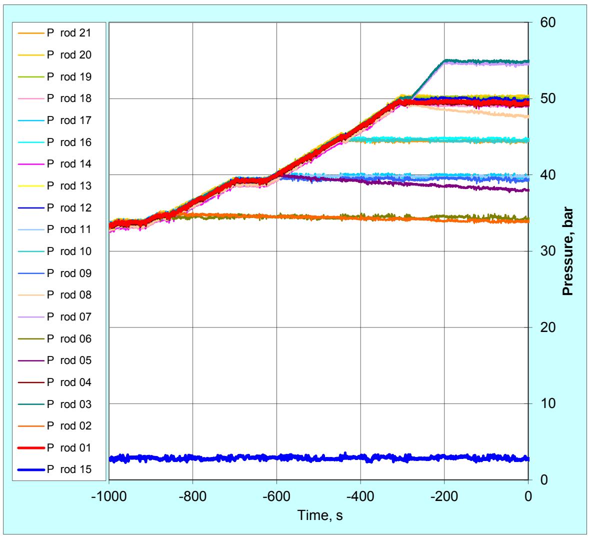
Rod pressurisation

bundle bottom bundle top



boreholes
through bottom Cu-electrodes

Rod pressurisation process

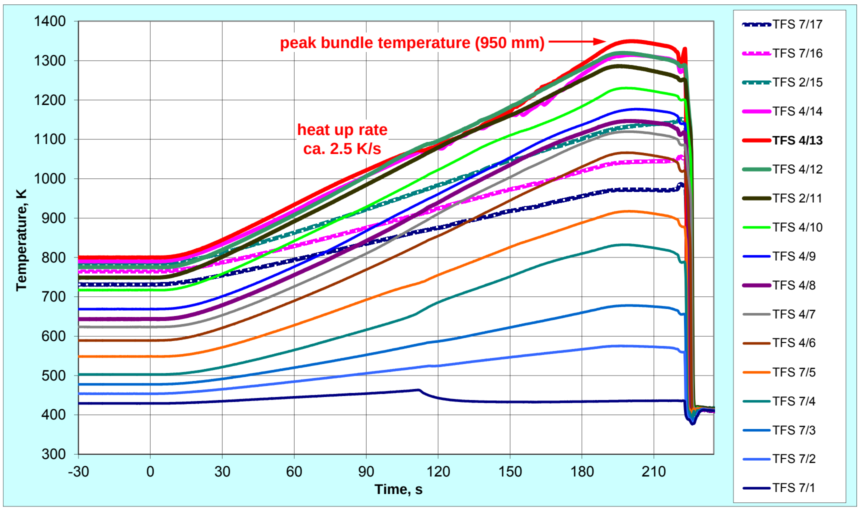


individual rod pressurisation with **Kr**
at max cladding temperature Tpct=520°C

Map of bundle filling

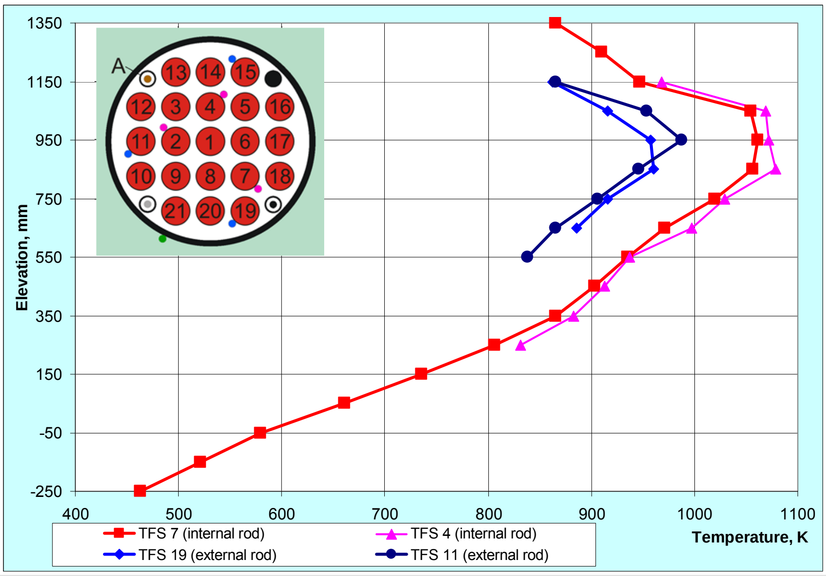
Pressure, bar	Number of rods
3 (system p)	1
35	2
40	4
45	3
50	9
55	2

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

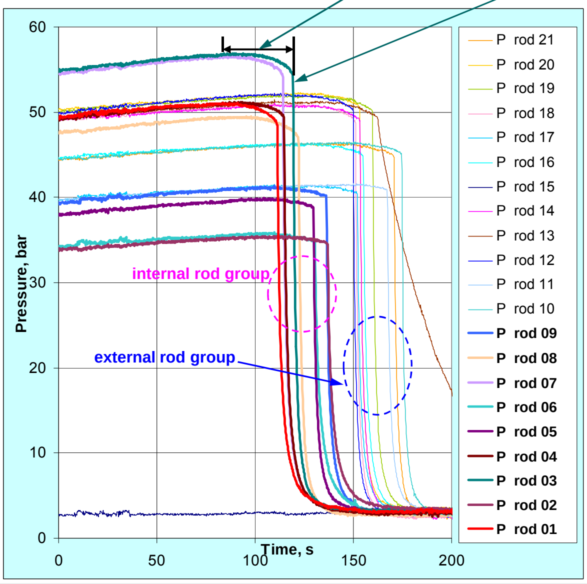


bundle quenching with mixture of saturated steam and water

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

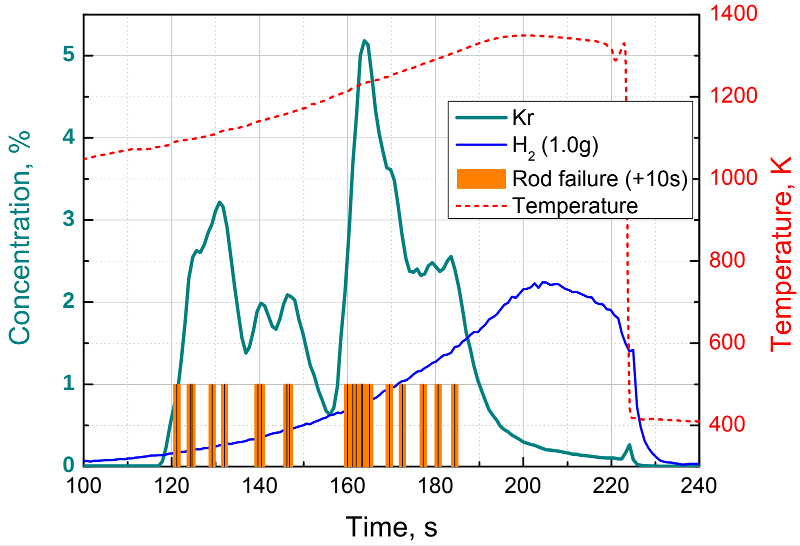


Pressure changing during heating phase (0-187 s), ballooning and burst

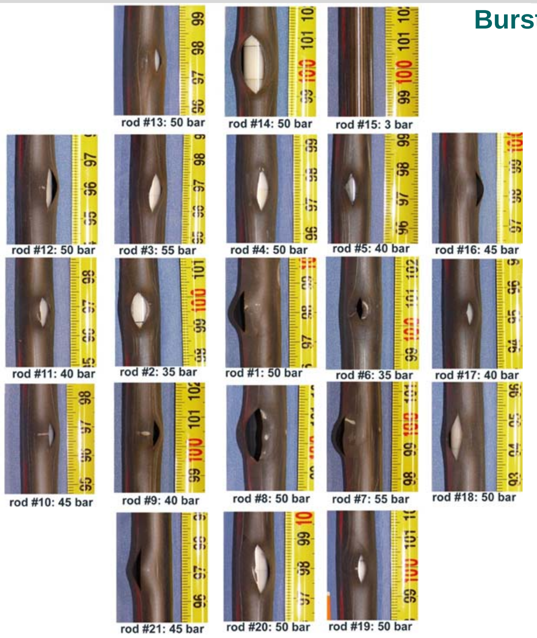


rod	start p, bar	burst p, bar	burst time, s	T@950 mm, °C
1	49,3	48,5	111,2	796
7	54,6	54,1	114,2	793
4	49,2	49,5	114,6	800
3	55	54,4	119,2	816
8	47,7	46,8	122,0	813
5	38	38,9	129,6	835
6	34,2	34,7	130,4	833
9	39,2	40,1	136,2	860
2	33,8	34,5	136,8	**861 max T**
12	49,9	50,2	150,0	815
18	49	48,7	151,2	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

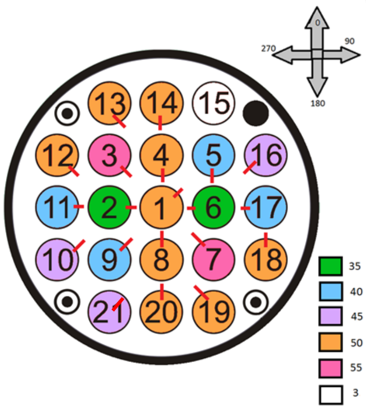
Mass spectrometer: Krypton as burst indicator and H_2 as product of Zr oxidation



Burst positions



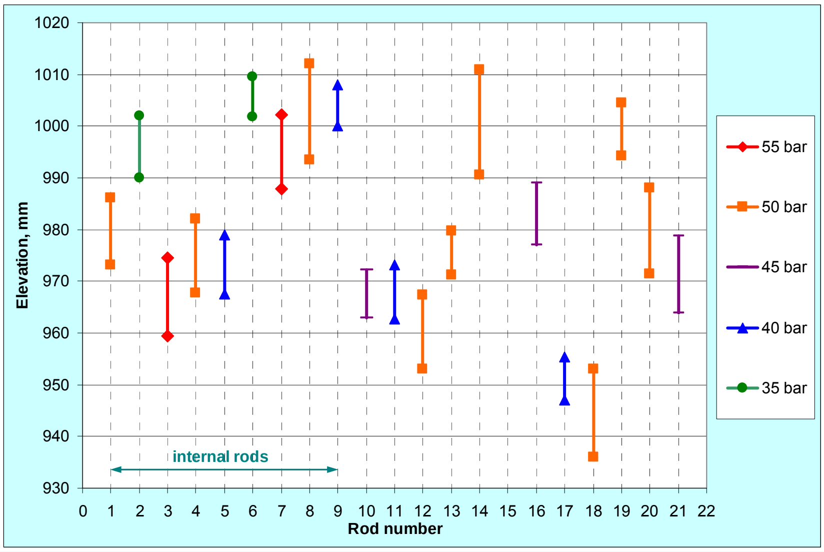
axial positions



circumferential positions

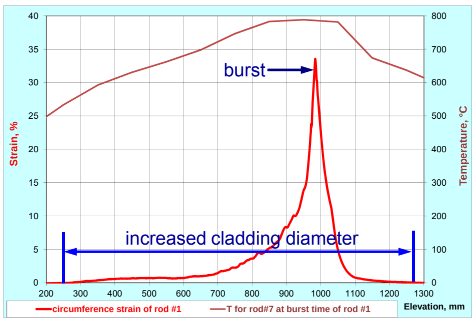
Axial burst positions;

burst length: no clear dependence on pressure

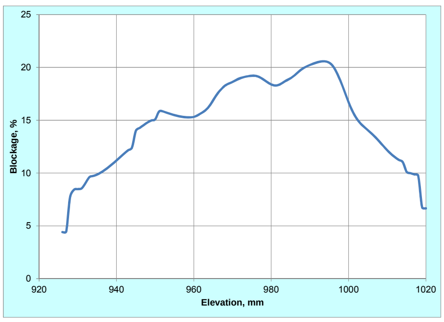


Tube scanner: laser profilometry

Axial changing of circumference strain (central rod)



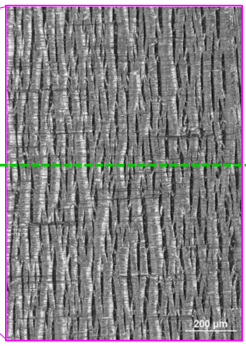
Blockage of coolant channel



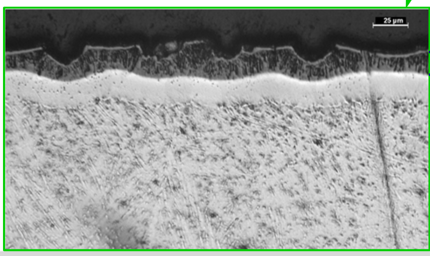
“Self-healing” surface cracks developed during ballooning

rod #3 (55 bar), angle 140°

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



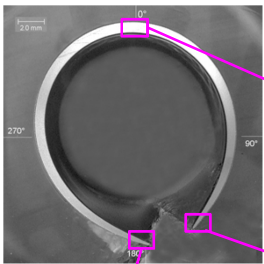
cross-
section

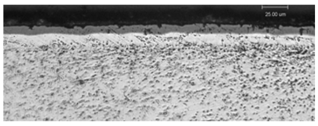


ZrO_2 with “healed” cracks developed during circumferential extension

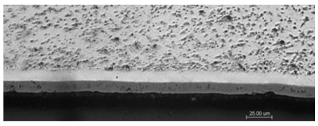
Similar internal and external oxidation degree at burst elevation

rod #3 (55 bar)

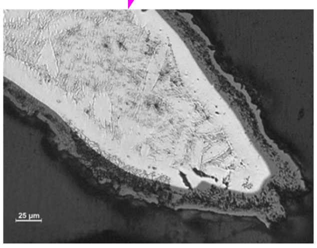


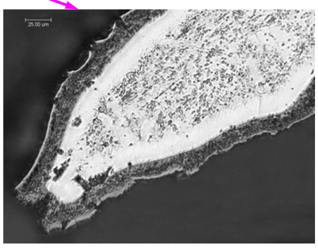


external oxidised surface

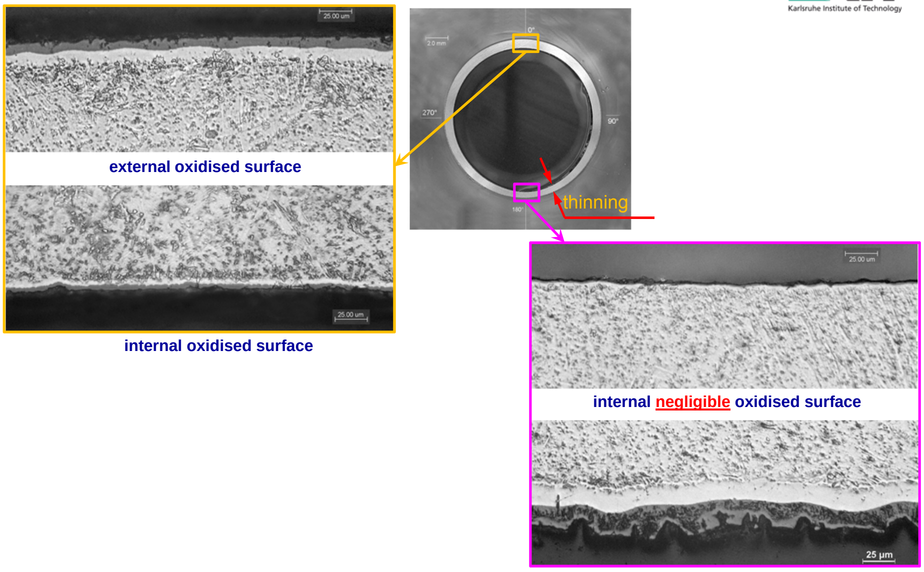


internal oxidised surface

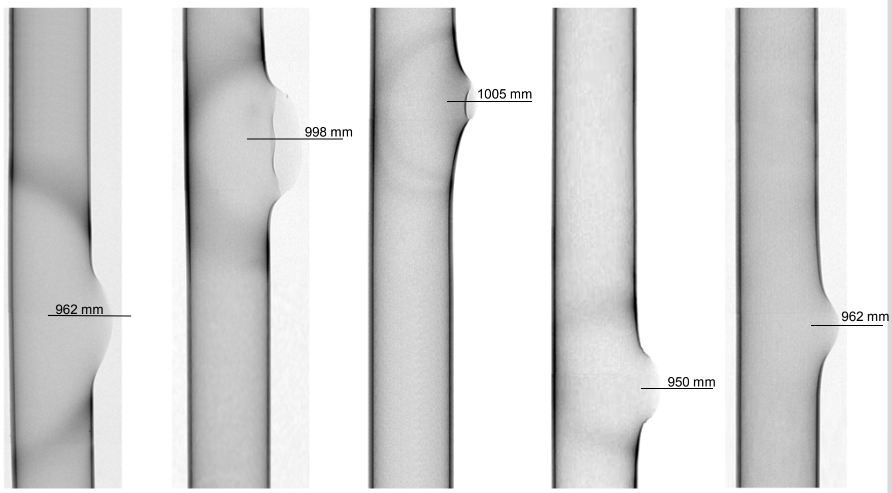




Different internal and external oxidation degree in the vicinity burst opening /rod #3 (55 bar)/

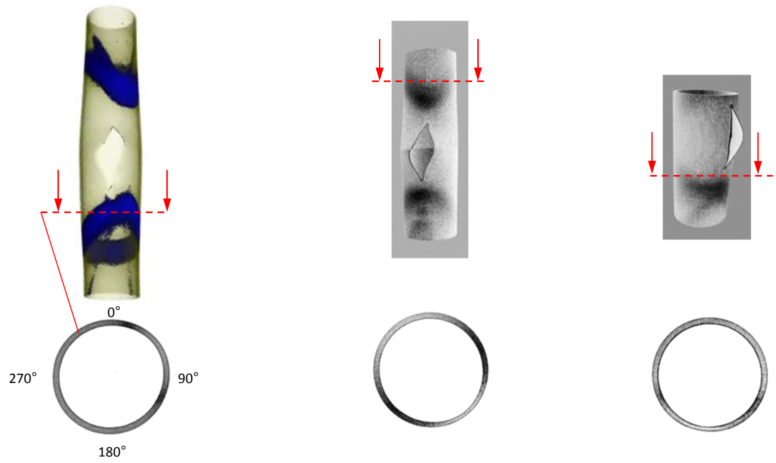


Hydrogen bands around burst location: dependence on burst temperature T_b and duration τ_Q between burst and reflood



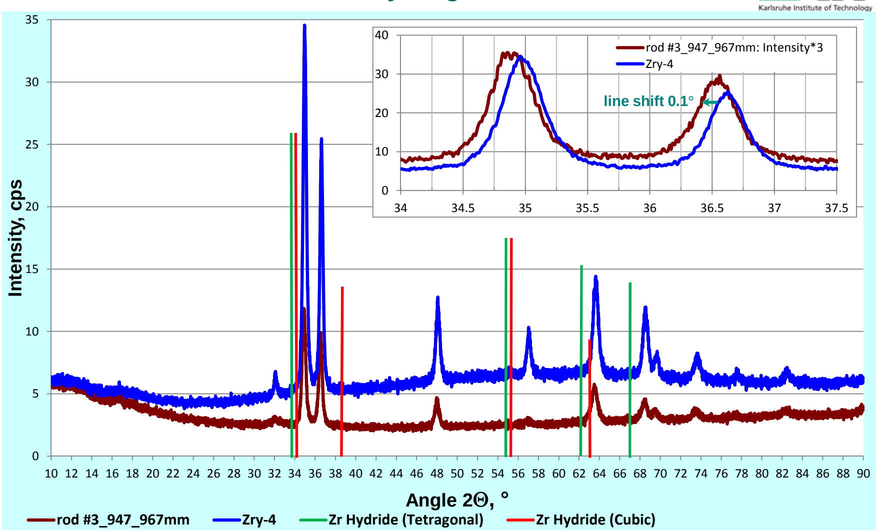
rod #3	rod #8	rod #6	rod #17	rod #10
τ_Q=104 s	τ_Q=101 s	τ_Q=93 s	τ_Q= 71 s	τ_Q=49 s
T_b=1090 K	T_b=1090K	T_b=1105 K	T_b=1130K	T_b=1065 K

Secondary hydriding: hydrogen bands around burst location (results of n^0-tomography for rod#1 with 1330wppm H)



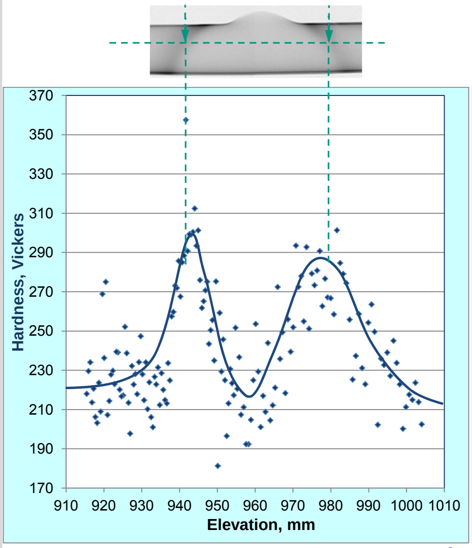
rod #1	rod #3	rod #5
C_H=1330 wppm	C_H=1330 wppm	C_H=1060 wppm

Results of X-ray diffractometry for the rod #3 at the hydrogen band

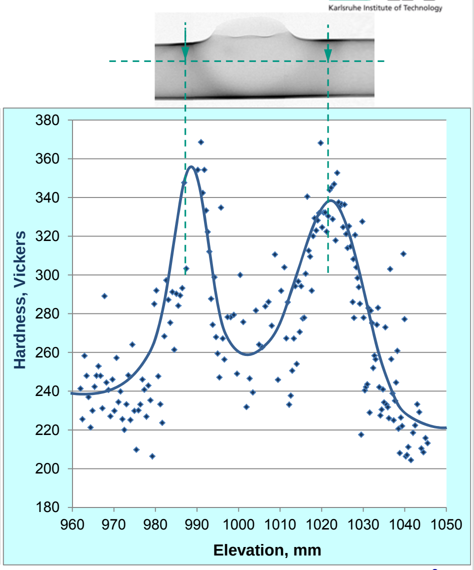


hydrogen is at least partially dissolved in the α-Zr lattice

Microhardness peaks at hydrogen bands



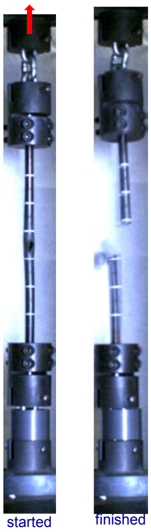
rod #3; t_{burst}=119 s; T_{burst}=1090 K; A_{burst}=40 mm^2



rod #8; t_{burst}=122 s; T_{burst}=1090 K; A_{burst}=60 mm^2

Tensile tests

INSTRON testing machine



Three types of cladding failure

Ruptures near to burst opening due to hydrogen embrittlement (7 from 9 internal rods)	Rupture across the burst opening middle due to stress concentration (external rod)	Rupture near end plugs after plastic deformation (external rods)

Summary

- Conduct of the QUENCH-L0 test at KIT with non-preoxidised Zry-4 bundle showed qualification of the QUENCH facility for LOCA bundle tests.
- Typical ballooning and burst processes for all 20 pressurized rods were observed. All burst cases took place during the transient heating phase (2.5 K/s) at temperatures between 1053 und 1133 K. Burst opening lengths between 8 and 20 mm were measured.
- Measured circumferential strains are between 20 und 40%. Maximal blockage of cooling channel is 21%.
- Neutron radiography showed formation of hydrogen bands with a width of ca. 10 mm at the boundary of cladding inner oxidized area. The hydrogen content up to 1330 wppm at band locations was measured by means of neutron tomography. No hydrides were detected by means of optical microscopy and XRD. Hydrogen is at least partially dissolved in the α-Zr lattice.
- Tension tests with cladding segments (lengths of 500-700 mm) showed different rupture positions: 1) at burst center (intended with prior tangential crack); 2) at a distance of about 200 mm from the burst position for rods without hydrogen band; 3) simultaneous ruptures below and above burst opening for rods with hydrogen bands.

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 PowerTech**

Thank you for your attention

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