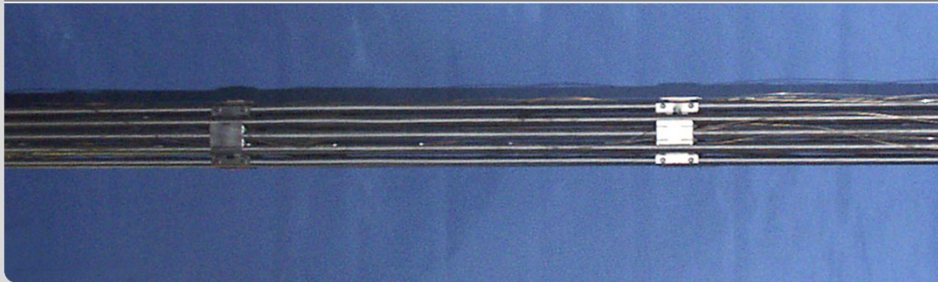


QUENCH-LOCA Program at KIT and Results of the QUENCH-L0 Bundle Test

J. Stuckert, M. Große, C. Rössger, M. Steinbrück, M. Walter

JT KTG 2012, Stuttgart

Institute for Applied Materials; Program NUKLEAR

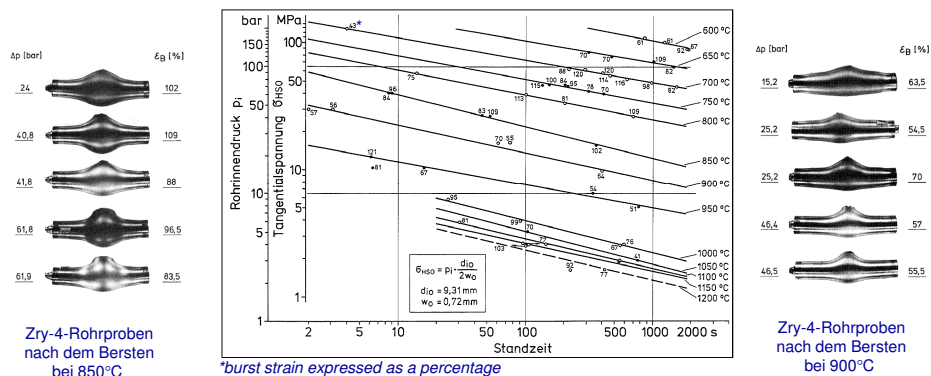


KIT – University of the State of Baden-Württemberg and
National Large-scale Research Center of the Helmholtz Association

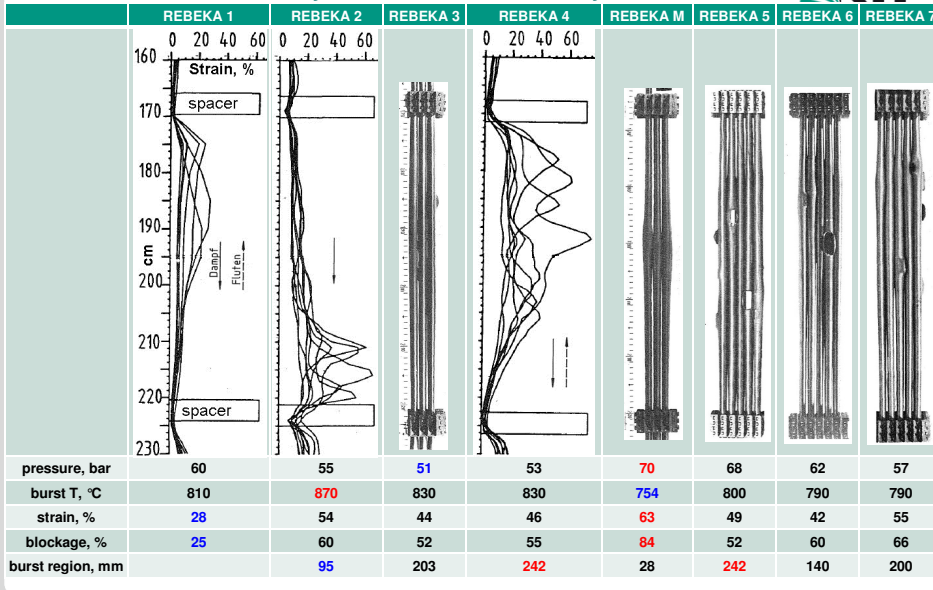
www.kit.edu

Results of early KfK single rod tests between 600 °C and 1200 °C: investigation of creep rupture time

P. Hofmann, S. Raff. KfK 3168, Juli 1981

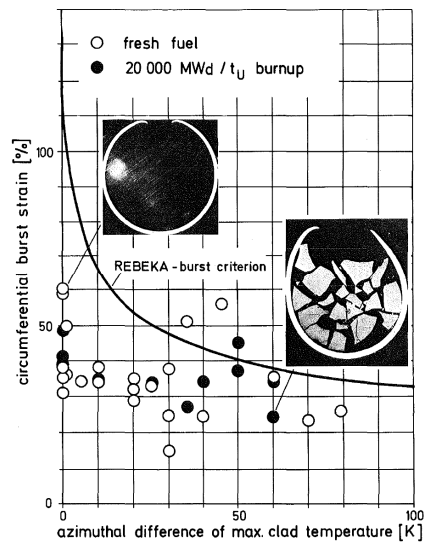


Overview of REBEKA/LOCA program (1978-1987) at KfK (now KIT):
electrical heated facility with 3.5 m rods; thermo-hydraulic tests



Comparison of in-pile- (FR2) und out-of-pile (REBEKA) tests.

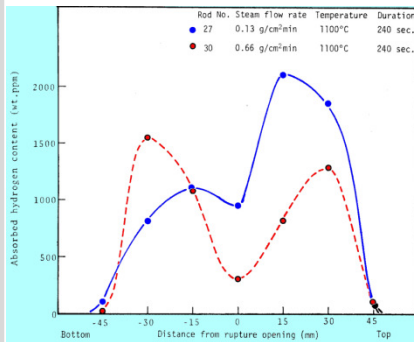
F. J. Erbacher, S. Leistikow. KfK 3973, September 1985



Secondary hydriding

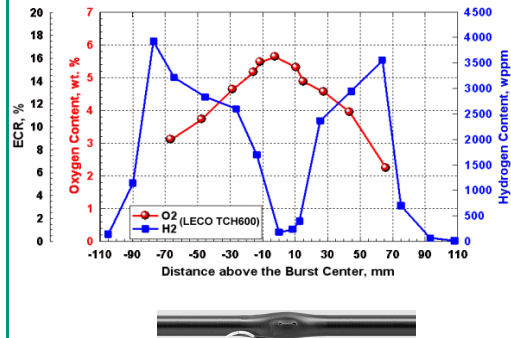
1981, JAERI: first observation of cladding hydriding by steam ingress through the burst opening

Uetsuka et al., Journal of NUCLEAR SCIENCE and TECHNOLOGY, 18[9], pp. 705-717 (September 1981).



2008, ANL: starke Hydrierung bis 4000 ppm (erheblich höher als Duktilitätsgrenze von 500 ppm)

NUREG-6967 (Billone et al.): unirradiated sample OCL11 (Zry-2) ramped in steam from 300°C to 1204°C at 5 K/s, held at 1204°C for 300 s, cooled at 3 K/s to 800°C, and cooled from 800°C to RT

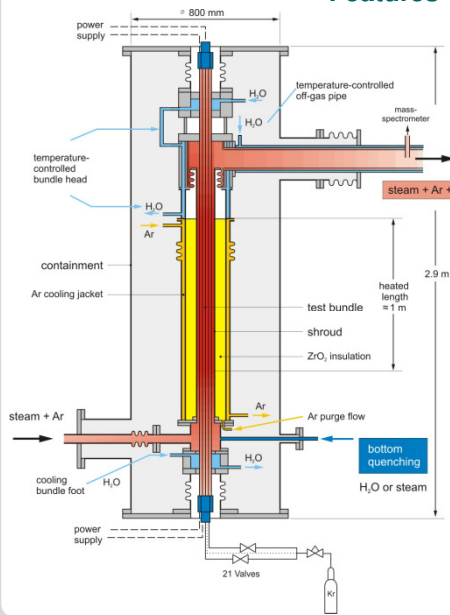


Hydrogen peaks above and underneath of burst position

Objective for new LOCA bundle tests

- Higher burn-up: increased oxidation and hydrogen uptake
- Secondary hydriding of cladding after it burst
- Application of new cladding alloys
- Evidence of core coolability
- Modification of the LOCA embrittlement criteria (1200°C, 17% ECR) with consideration of cladding hydrogenation

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

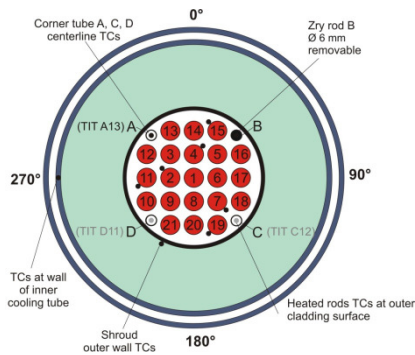
- max: 35 + 35 kW
- heaters inside fuel rod simulators: 0.3 m Mo + 1 m W + 0.6 m Mo

Instrumentation

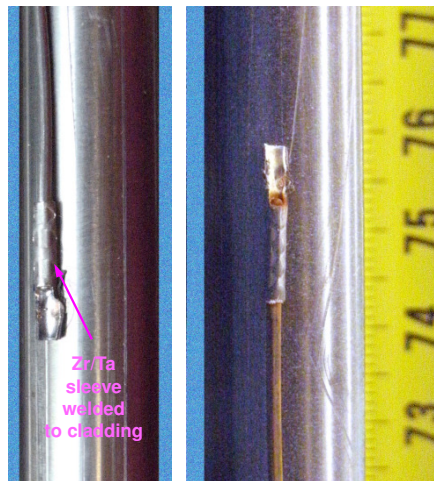
- ~80 TCs at 17 axial levels
- Mass spectrometer (incl. steam)
- Quench water level (Δp)
- Corner rods for "online" check of oxide scale

Rod pressurisation up to 120 bar

Thermocouple installation /a total of 72 TCs/



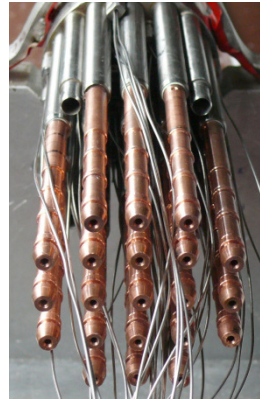
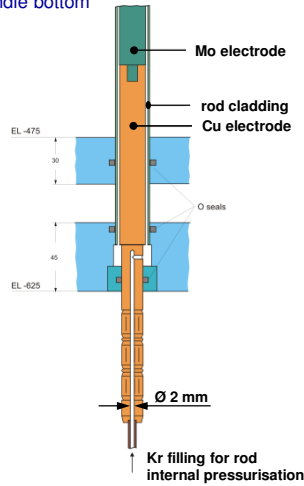
Bundle cross section:
6 sheathed NiCr/Ni Thermocouples
at each Elevation (650, 750, 850, 950, 1050, 1150 mm)
at surface of rods # 2, 4, 7 and 11, 15, 19
rod #7 has TCs at Elevations from -250 to 1350 mm



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

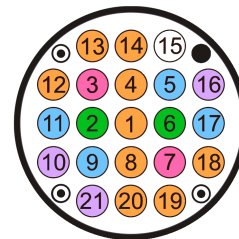
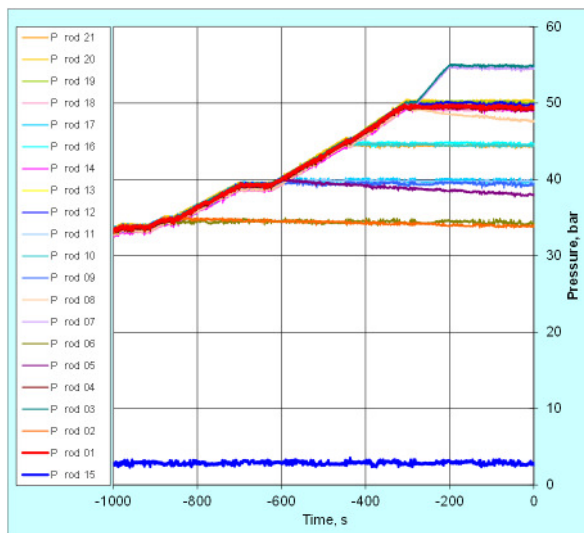
rod #7 after test:
TFS 7/11 at 750 mm

Rod pressurisation



boreholes through bottom Cu-electrodes

Rod pressurisation process

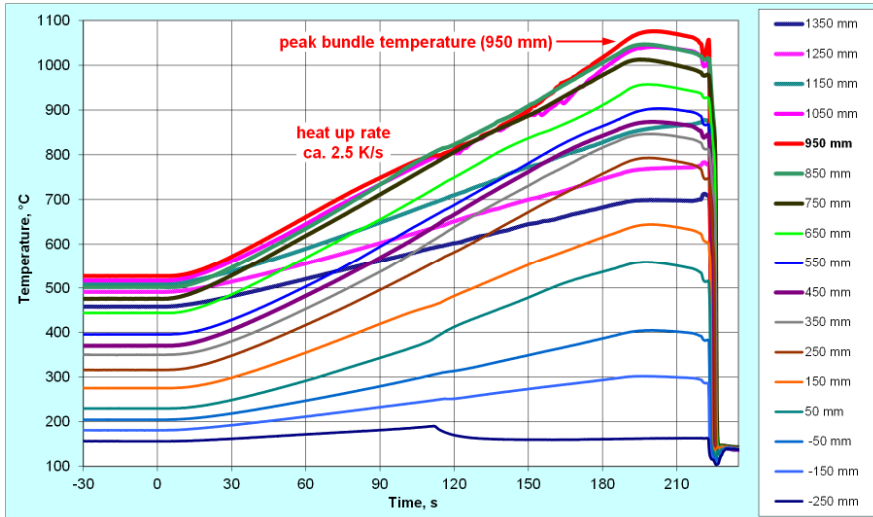


Map of bundle filling

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

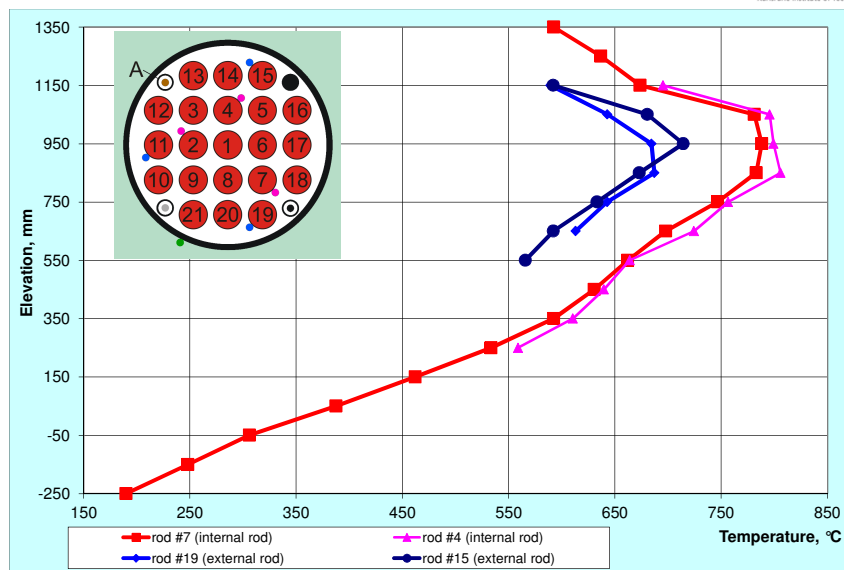
individual rod pressurisation with Kr
at peak cladding temperature $T_{pct}=520\text{ }^{\circ}\text{C}$

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

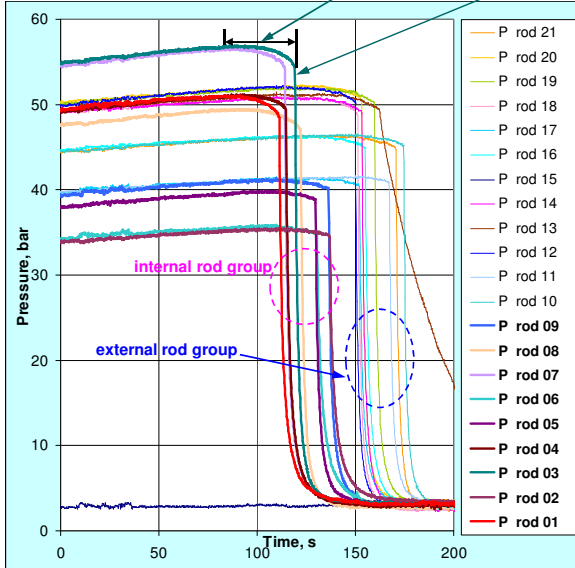


bundle quenching with mixture of saturated steam and water

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

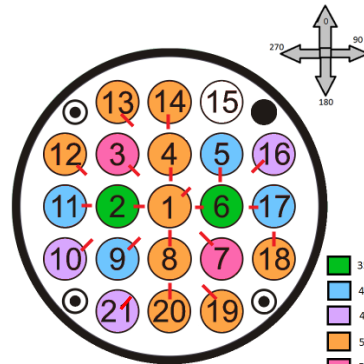
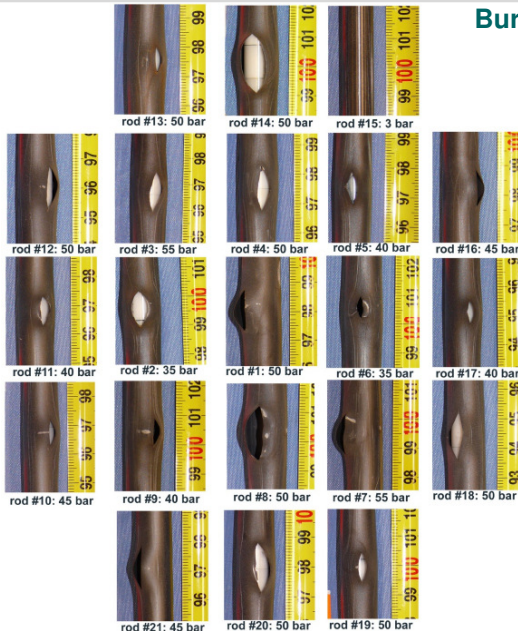


Pressure changing during heating phase (0-187 s), ballooning and burst



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

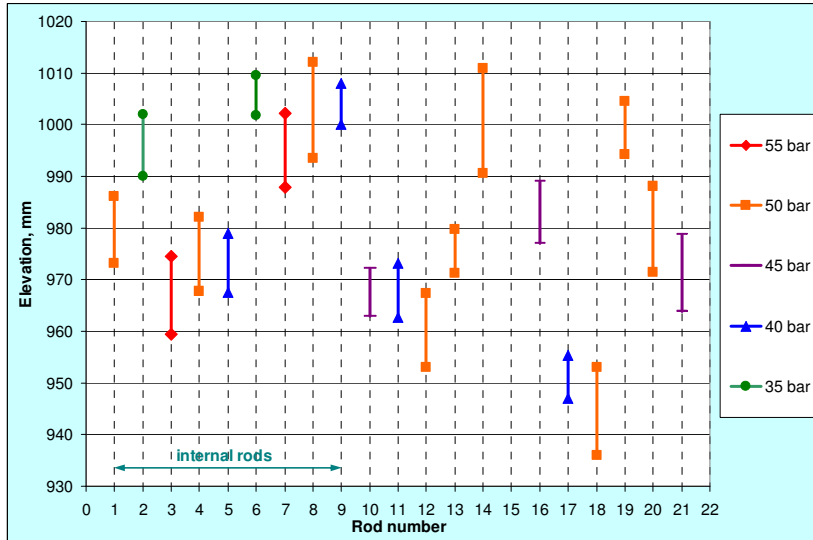
Burst positions



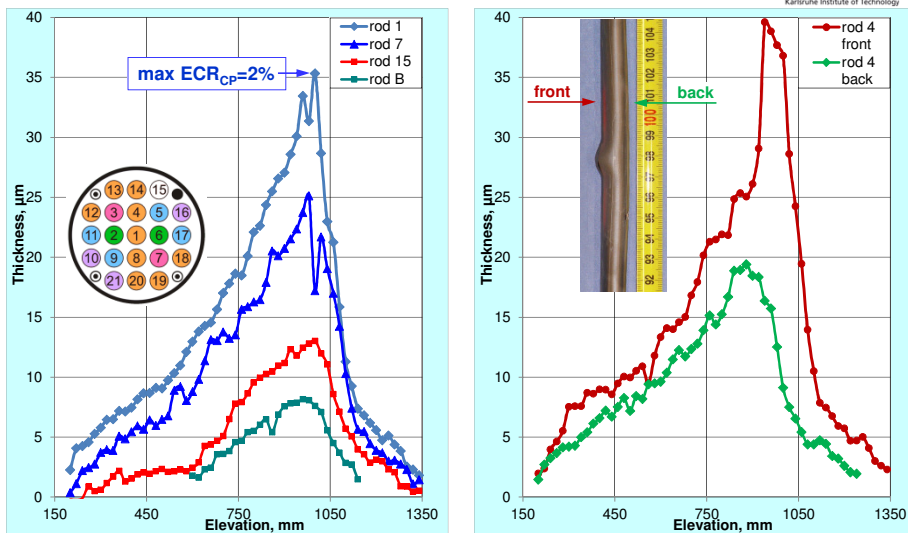
circumferential positions

axial positions

Axial burst positions; burst length: no clear dependence on pressure



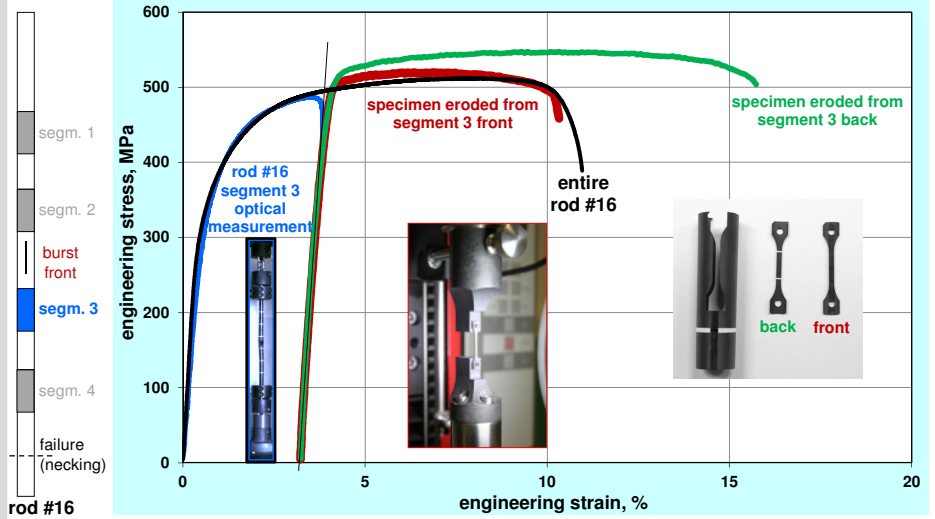
Post-test axial thickness distribution for $\text{oxide} + \alpha\text{-Zr(O)}$: eddy current measurement



circumferential averaging

along burst line and opposite line for rod #4:
burst occurs at more oxidised position

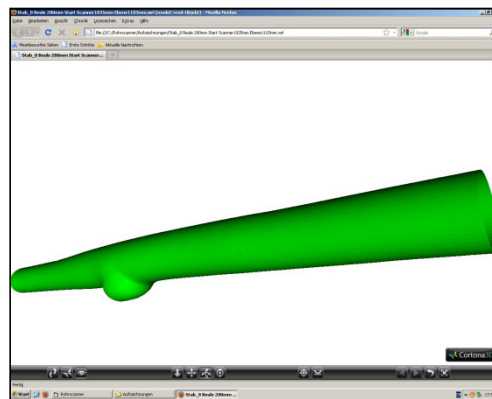
Tensile tests with cladding parts eroded from cladding



Tube scanner: laser profilometry



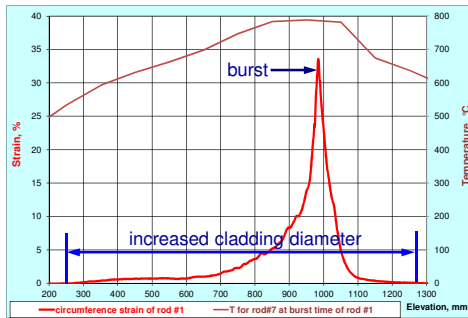
scanner facility



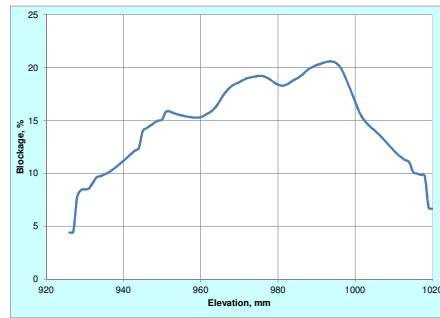
reconstructed scanned surface of rod #8:
angle step 1°; axial step 0.5 mm; scanned length 200 mm

Tube scanner: laser profilometry

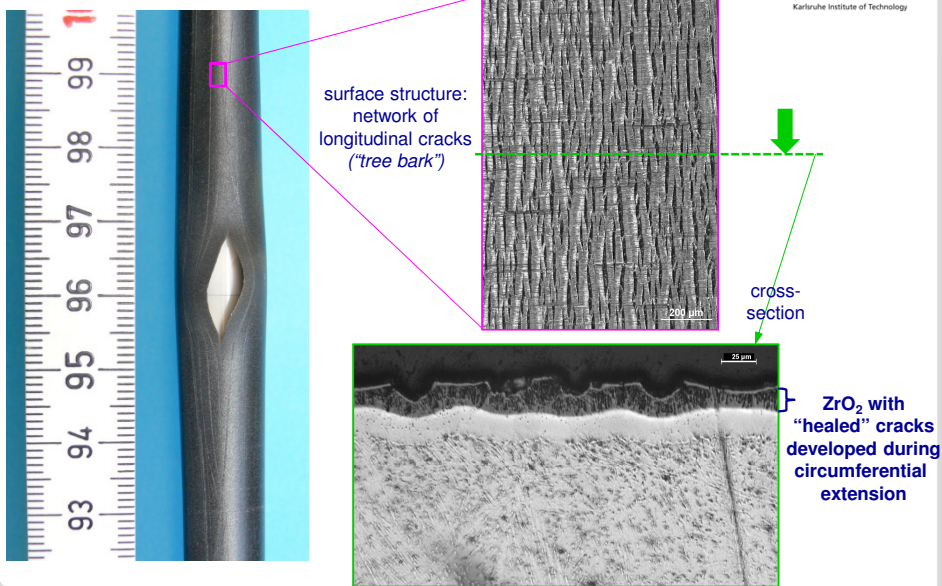
Axial changing of circumference strain (central rod)



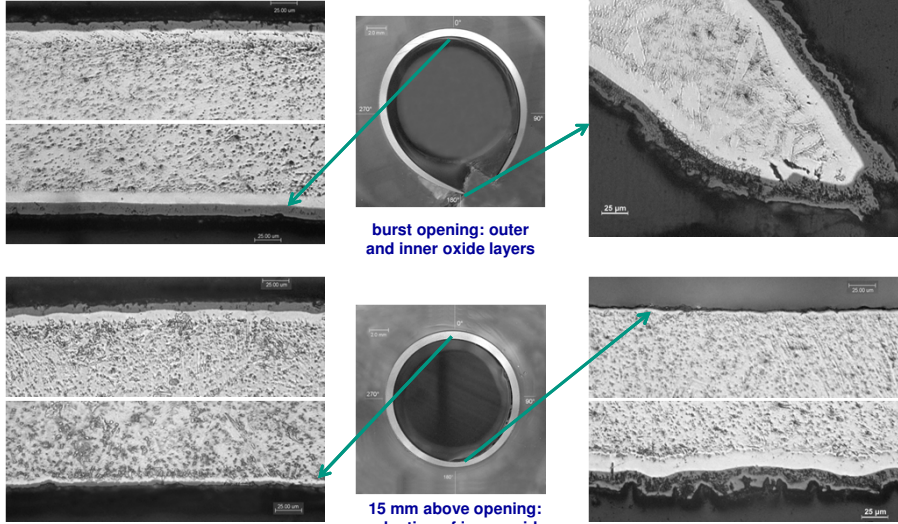
Blockage of coolant channel



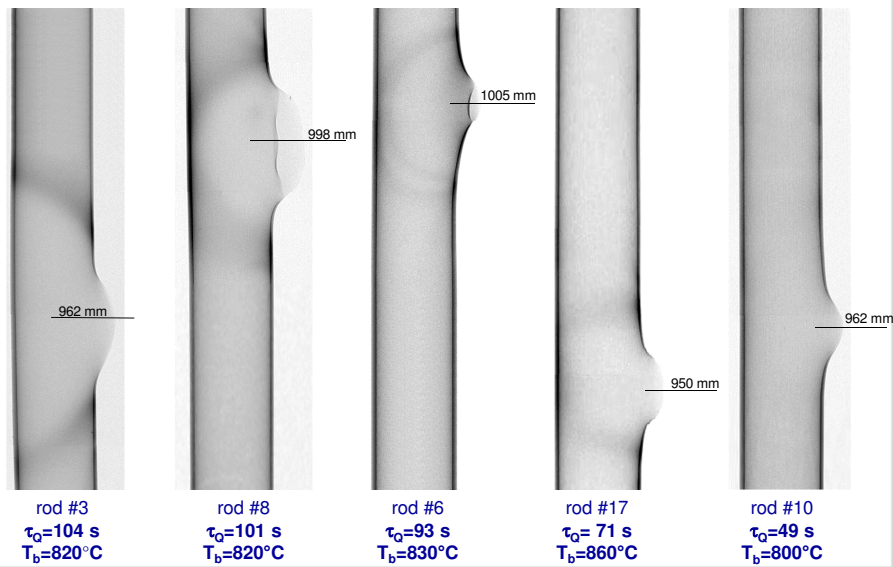
“Self-healing” surface cracks developed during ballooning rod #3 (55 bar), angle 140°



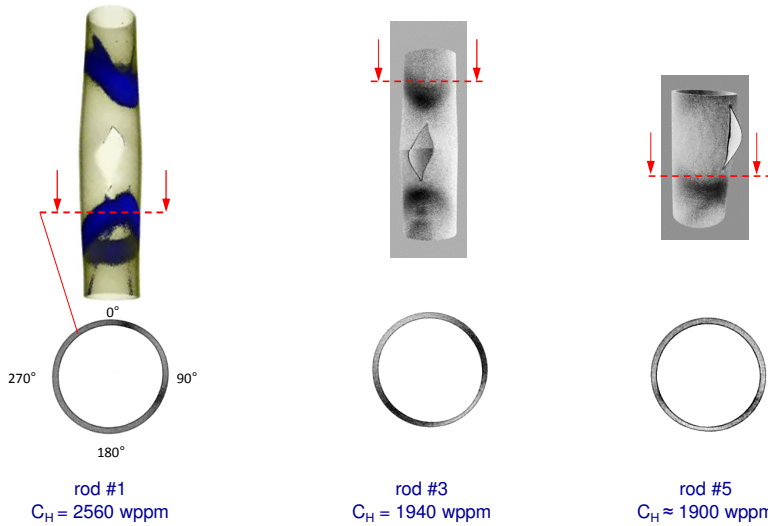
Different internal and external oxidation degree
in the vicinity burst opening /rod #3 (55 bar)/



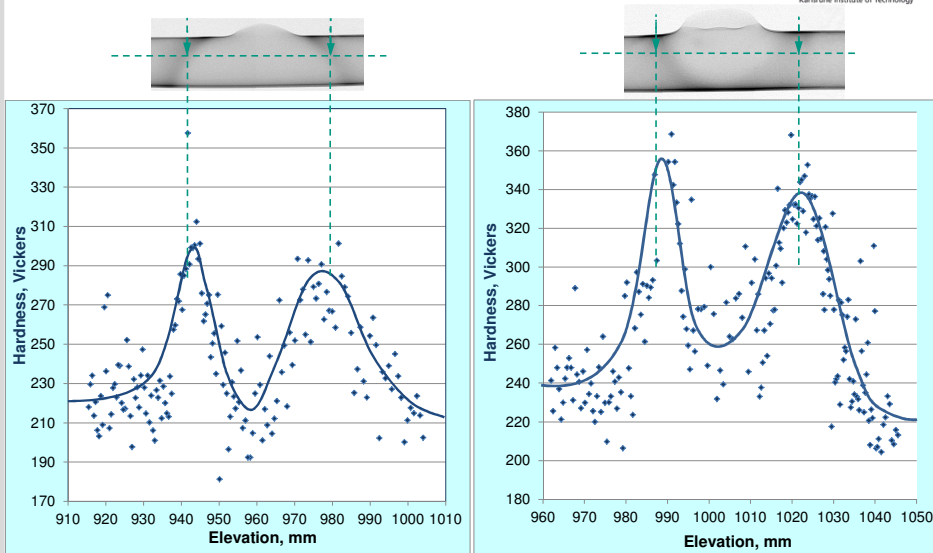
Hydrogen bands around inner oxidized burst area: dependence on
burst temperature T_b and duration τ_Q between burst and reflow



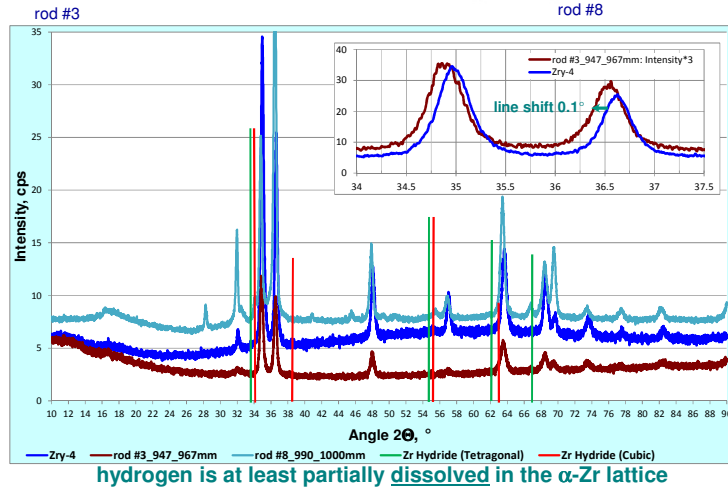
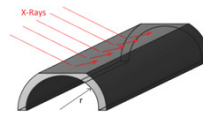
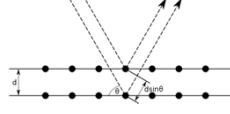
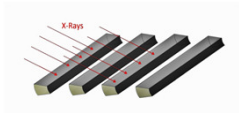
Secondary hydriding: hydrogen bands around burst location (results of n⁰-tomography)



Microhardness peaks at hydrogen bands

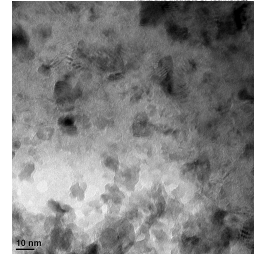
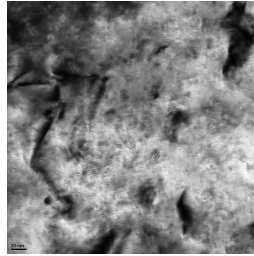
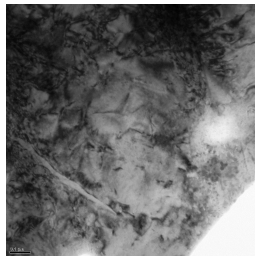


Results of X-ray diffractometry at the hydrogen band

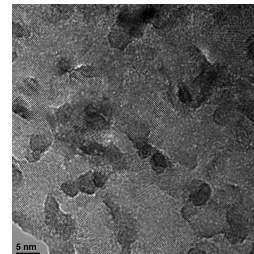
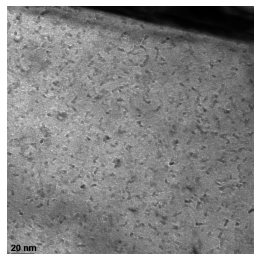
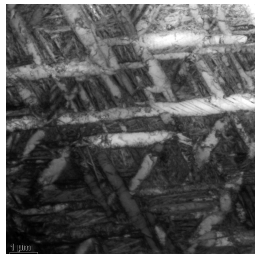


TEM results: analysis of hydrogen bands. No certain evidence of hydrides formation.

rod #3:

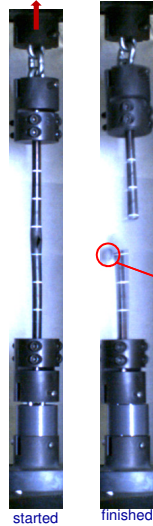


rod #8:



Tensile tests

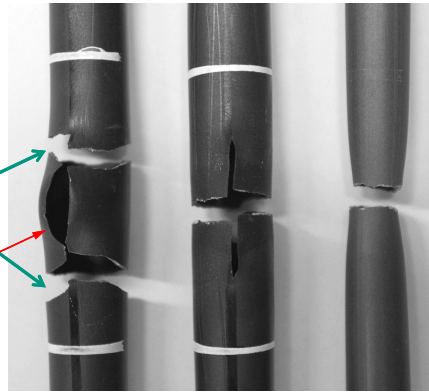
INSTRON testing machine



Double rupture of cladding along hydrogen bands

loose ring

Three types of cladding failure

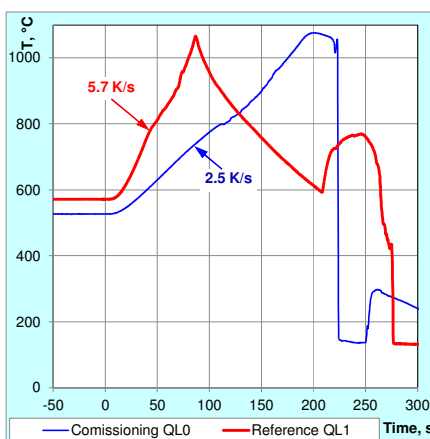


Ruptures near to burst opening due to hydrogen embrittlement (7 from 9 internal rods)

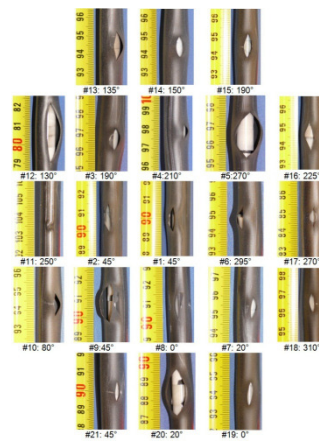
Rupture across the burst opening middle due to stress concentration (external rod)

Rupture near end plugs after plastic deformation (external rods)

First results of reference test QL1 with Zry-4 claddings performed in February 2012



Comparison of temperatures at hottest bundle elevation of 950 mm for bundles QL0 (commissioning test, 2010) and QL1 (reference test, 2012)



Axial (in mm) and circumferential (in °) burst positions for bundle test QL1. All bursts occurred during the heating-up (i.e. similar to the QL0 test)

Summary

- Two bundle tests with not pre-oxidized Zircaloy-4 claddings were performed up to now in framework of the QUENCH-LOCA program: commissioning test QL0 (2010)with heating-up rate 2.5 K/s and reference test QL1 (2012) with 5.7 K/s. *(All data below are for QL0).*
- Typical ballooning and burst processes for all pressurized rods were observed. All burst cases took place during the transient heating phase at temperatures between 800 and 900°C (estimated at bursts). 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%.
- Metallographic investigations showed formation of oxide layer at inner cladding surface around burst opening. The axial expansion of oxidized area is between 10 and 20 mm from the burst center.
- 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 2500 wppm at band locations was measured by means of neutron tomography. No hydrides were detected by means of optical microscopy, XRD and TEM. 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 the DUPLEX claddings
- 2 tests with the M5[®] claddings
- 1 test wit the ZIRLO[™] claddings

Acknowledgements

The QUENCH-LOCA0 test and post-test investigations are sponsored by VGB PowerTech.

XRD measurements were performed by Dr. H. Leiste

TEM investigations were performed by Dr. M. Klimenkov

Thank you for your attention

<http://www.iam.kit.edu/wpt/english/471.php/>

<http://quench.forschung.kit.edu/>