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

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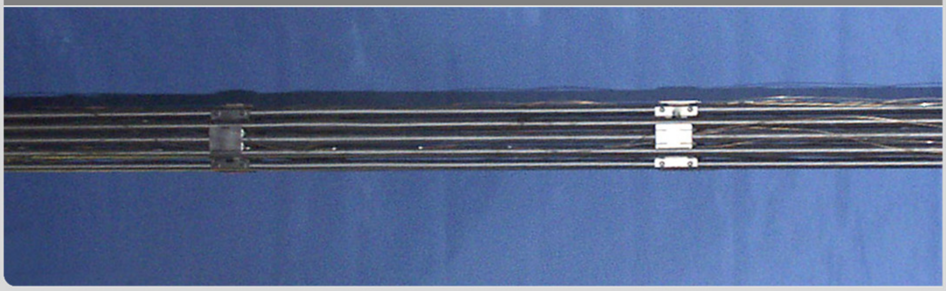
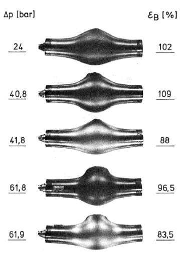
Institute for Applied Materials; Program NUKLEAR

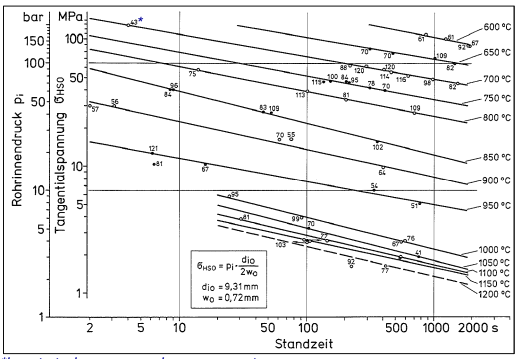


Results of early KfK single rod tests between 600°C and 1200°C: investigation of creep rupture time

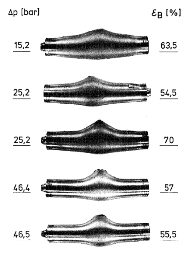
P. Hofmann, S. Raff. KfK 3168, Juli 1981



Zry-4-Rohrproben nach dem Bersten bei 850°C

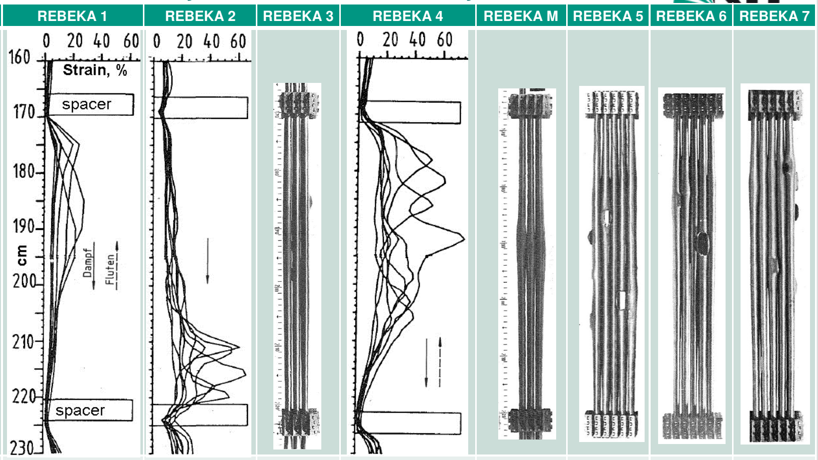


**burst strain expressed as a percentage*



Zry-4-Rohrproben nach dem Bersten bei 900°C

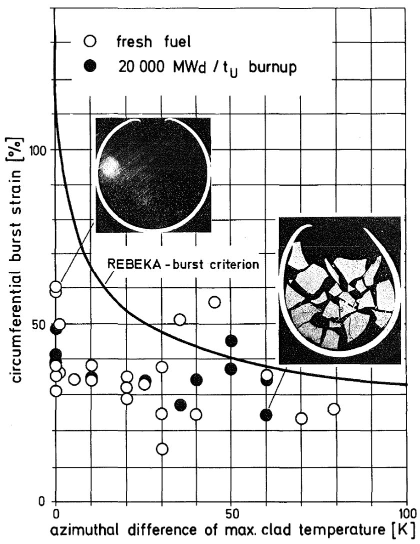
Overview of REBEKA/LOCA program (1978-1987) at KfK (now KIT): electrical heated facility with 3.5 m rods; thermo-hydraulic tests



	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

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

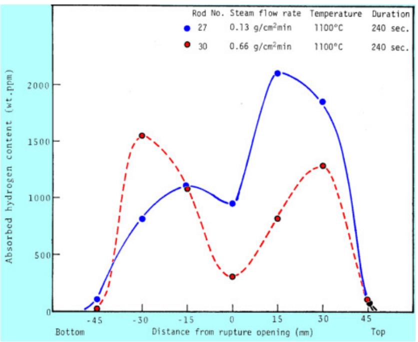
F. J. Erbacher, S. Leistikow. KfK 3973, September 1985



Secondary hydriding: hydrogen peaks above and underneath of burst position

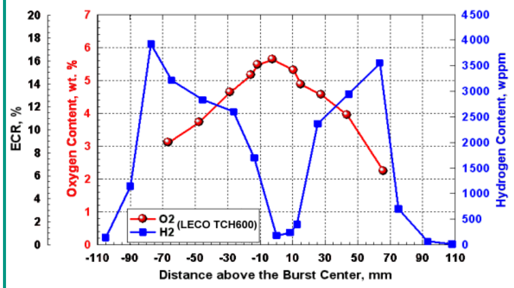
1981, JAERI*: first observation of cladding hydriding by steam ingress through the burst opening

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



2008, ANL: strong hydriding up to 4000 wppm (significantly higher than ductility limit of 500 wppm)

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

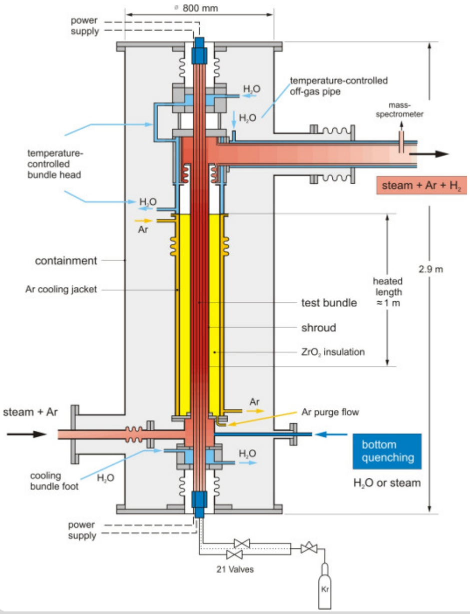


Hydrogen peaks above and underneath of burst position

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

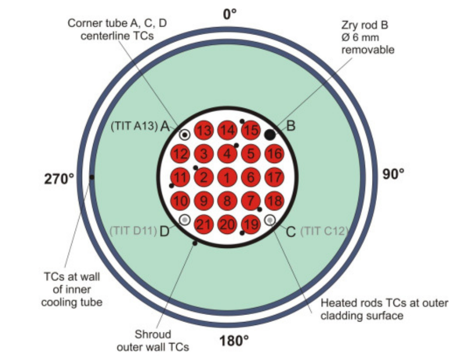
Bundle
- PWR (21 or 24 rods; Zry-4, M5, ZIRLO)
- VVER (31 Stäbe, E110)

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

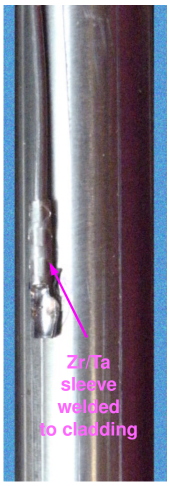
Rod pressurisation up to 120 bar

Thermocouple installation
/a total of 72 TCs/

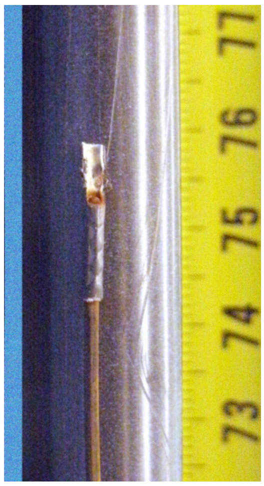


Bundle cross section:
6 sheathed NiCr/Ni Thermocouples
at each Elevation (650, 750, 850, 950, 1050, 1150 mm)
at surface of rods # 2, 4, 7 and 11, 15, 19

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

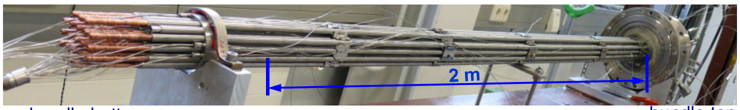


rod #4 before test:
TFS 4/13 at 950 mm

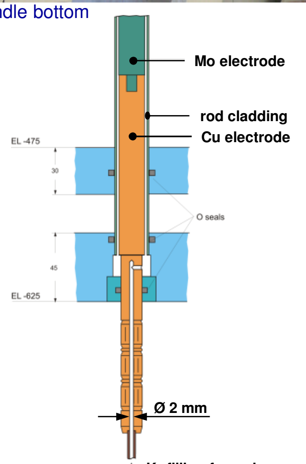


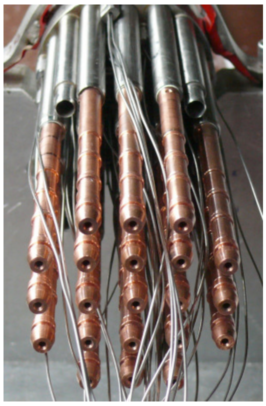
rod #7 after test:
TFS 7/11 at 750 mm

Rod pressurisation



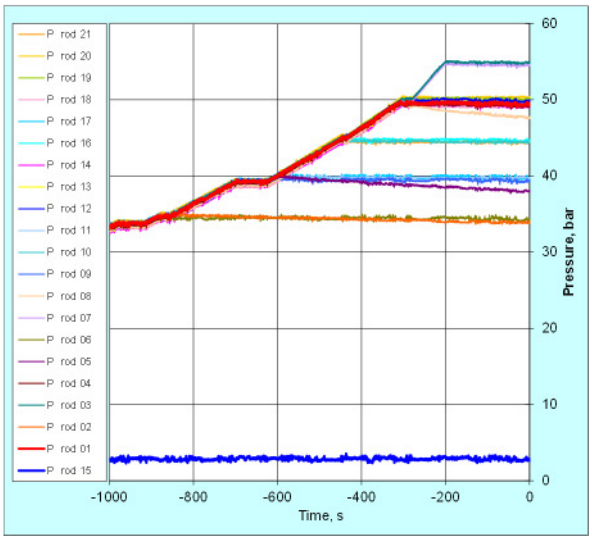
bundle bottom bundle top



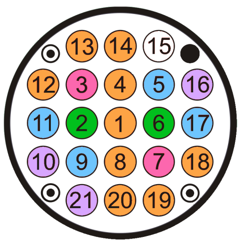


boreholes
through bottom Cu-electrodes

Rod pressurisation process



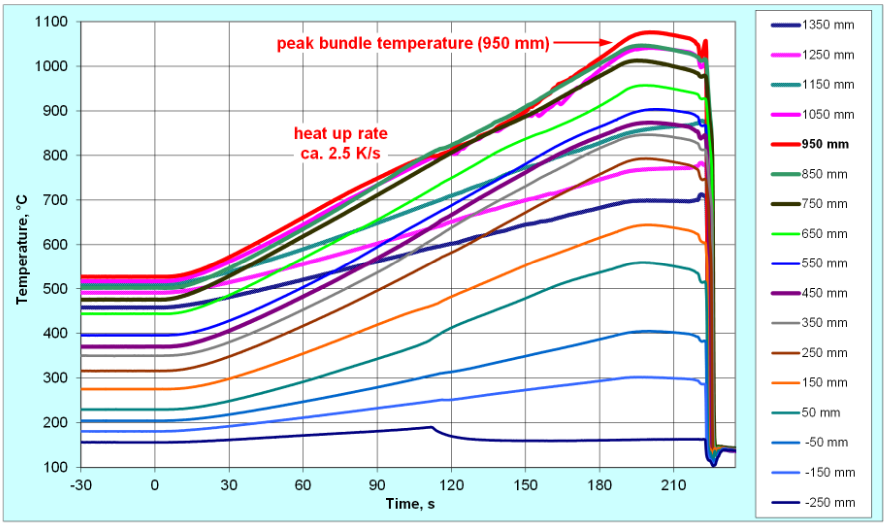
individual rod pressurisation with **Kr**
at peak cladding temperature Tpct=520°C



Map of bundle filling

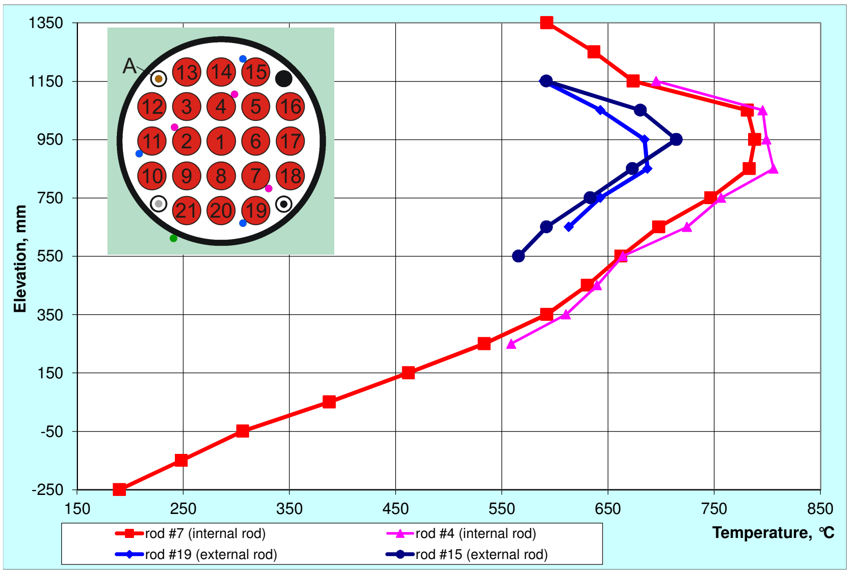
Pressure, bar	Number of rods
3 (system p)	1
35	2
40	4
45	3
50	9
55	2

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

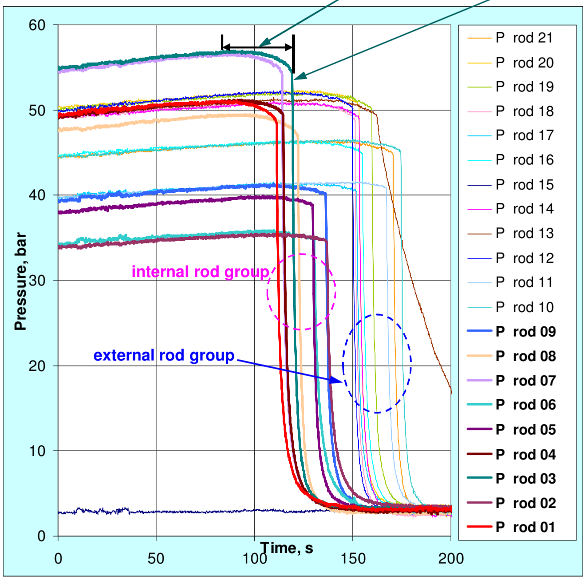


bundle quenching with mixture of saturated steam and water

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

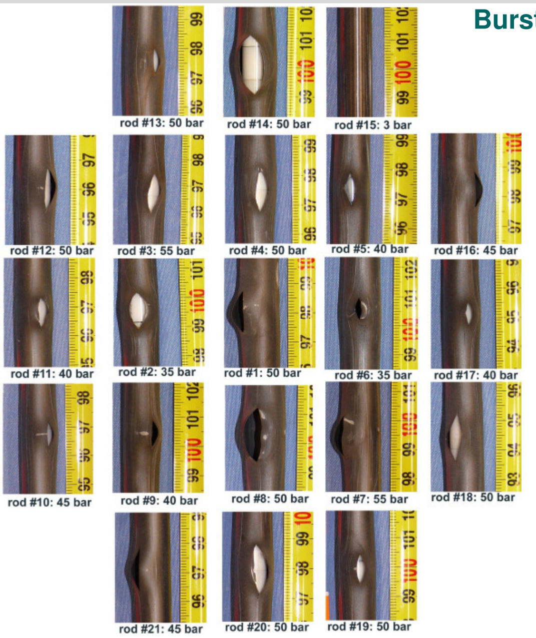


Pressure changing during heating phase (0-187 s), ballooning and burst

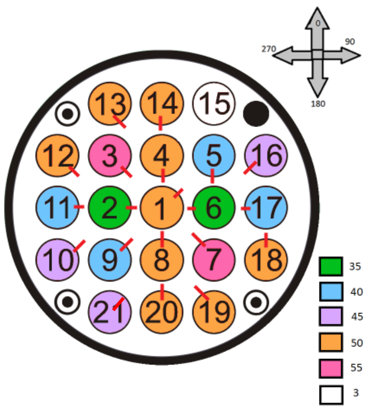


rod	burst middle, mm	burst length, mm	burst time, s	T_burst, K
1	980	13	111,2	1187
7	996	14	114,2	1161
4	975	14	114,6	1140
3	962	15	119,2	1154
8	998	17	122,0	1153
5	969	11	129,6	1184
6	1005	8	130,4	1183
9	1000	9	136,2	1212
2	996	12	136,8	1213
12	955	15	150,0	1164
18	946	17	151,2	1180
17	951	8	152,0	1206
20	975	16	153,2	1122
14	991	19	153,4	1171
16	983	12	155,0	1167
19	999	10	159,6	1202
13	976	9	162,5	1153
11	963	10	167,2	1221
21	976	15	170,6	1143
10	963	10	174,4	1138

Burst positions

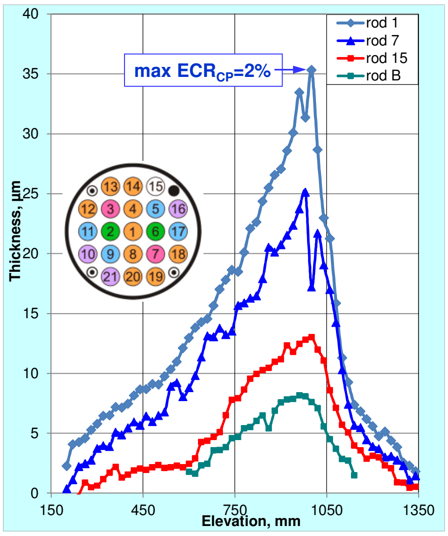


axial positions

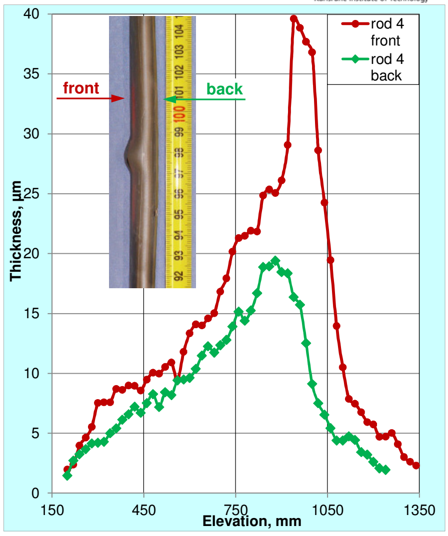


circumferential positions

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



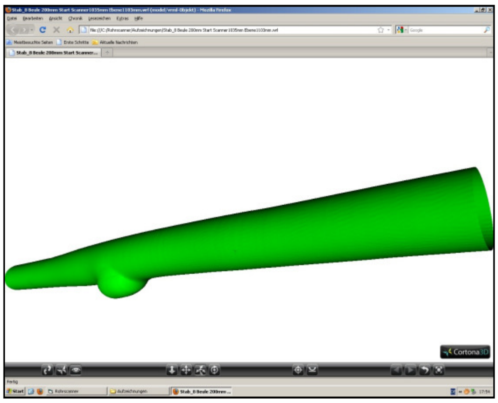
circumferential averaging



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

Tube scanner: laser profilometry

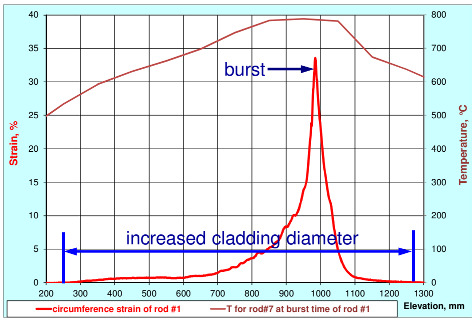
scanner facility



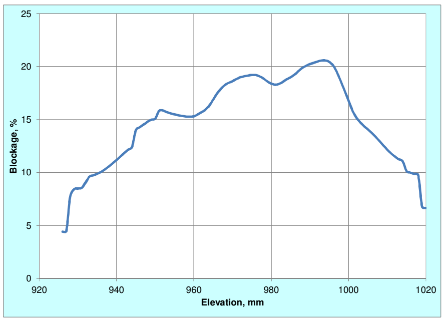
reconstructed scanned surface of rod #8:
angle step 1°; axial step 0.5 mm; scanned length 200 mm

Tube scanner: laser profilometry

Axial changing of circumference strain (central rod)



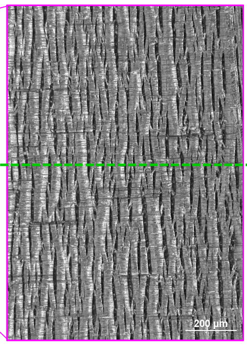
Blockage of coolant channel



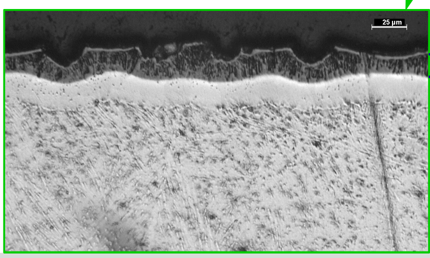
"Self-healing" surface cracks developed during ballooning

rod #3 (55 bar), angle 140°

surface structure: network of longitudinal cracks (*"tree bark"*)

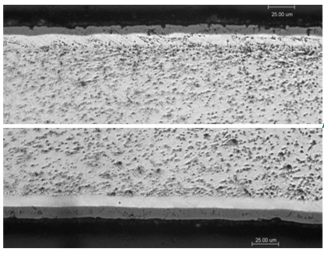


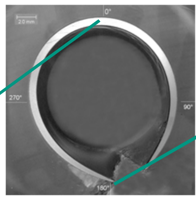
cross-section

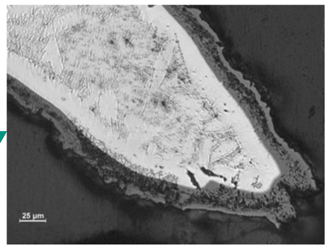


ZrO_2 with "healed" cracks developed during circumferential extension

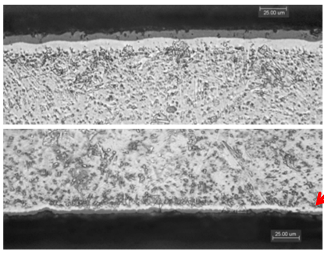
Different external and internal oxidation degree in the vicinity burst opening /rod #3 (55 bar)/

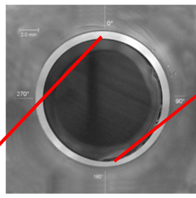


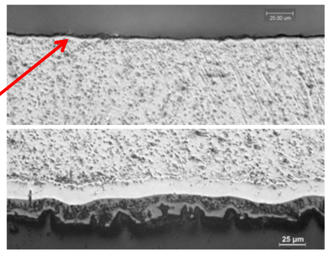




burst opening: outer and inner oxide layers

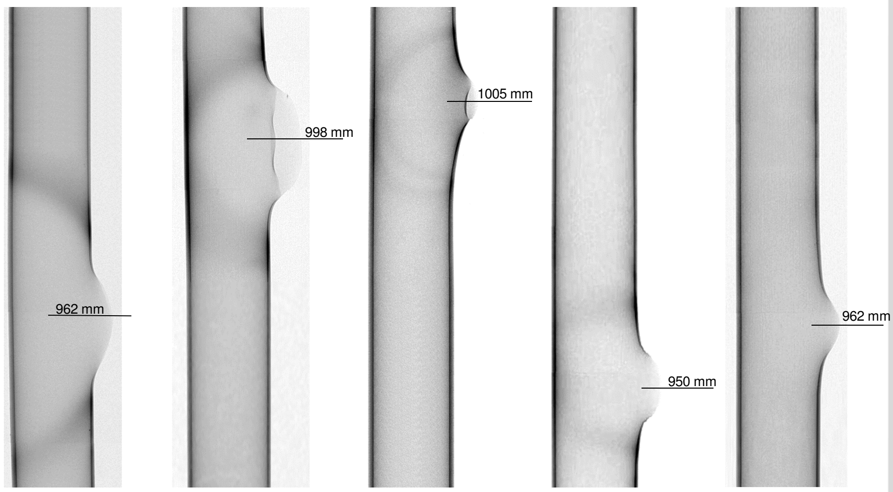






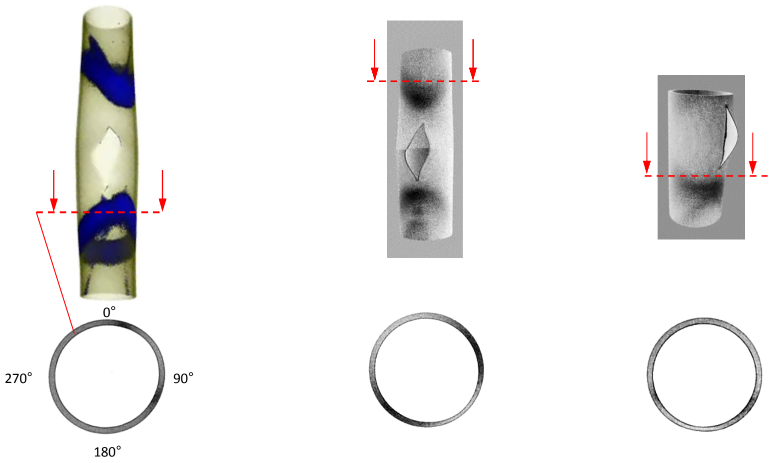
15 mm above opening: reduction or <u>absence</u> of inner oxide

Hydrogen bands around inner oxidized burst area observed by n^0-radiography: 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=820°C	T_b=820°C	T_b=830°C	T_b=860°C	T_b=800°C

Secondary hydriding: hydrogen bands around burst location (results of n^0-tomography)

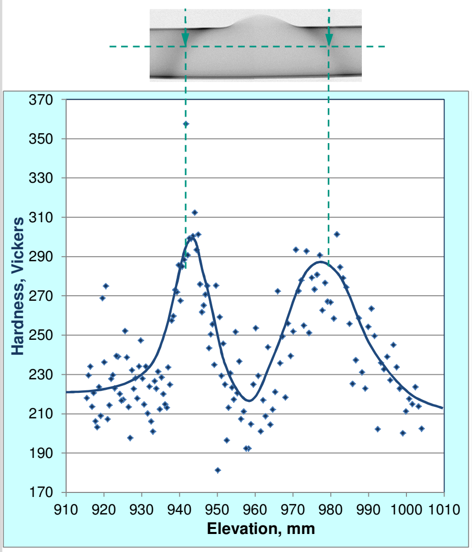


rod #1
C_H = 2560 wppm

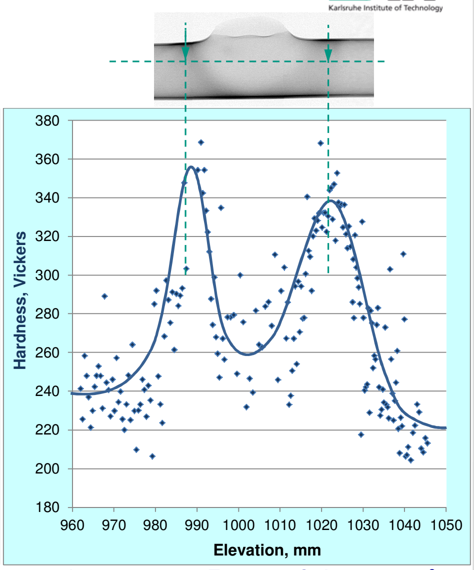
rod #3
C_H = 1940 wppm

rod #5
$C_H \approx$ 1900 wppm

Microhardness peaks at hydrogen bands

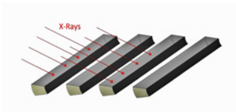


rod #3; t_{burst}=119 s; T_{burst}=820°C; A_{burst}=40 mm²

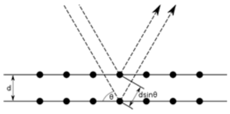


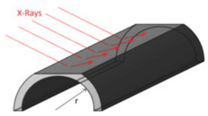
rod #8; t_{burst}=122 s; T_{burst}=820°C; A_{burst}=60 mm²

Results of X-ray diffractometry at the hydrogen band

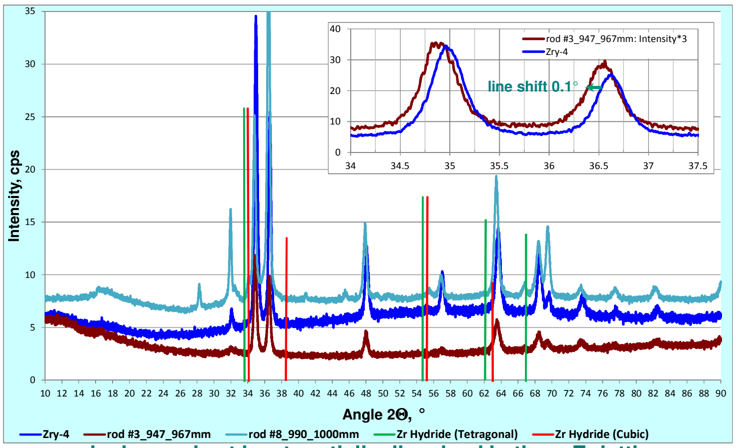


rod #3



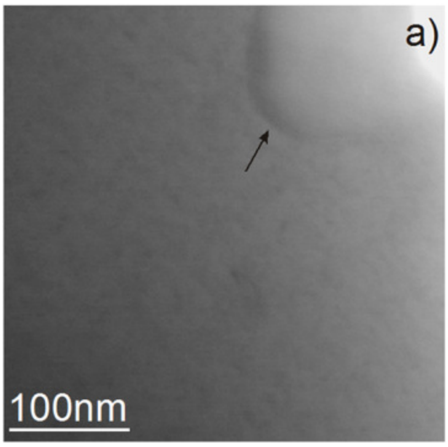


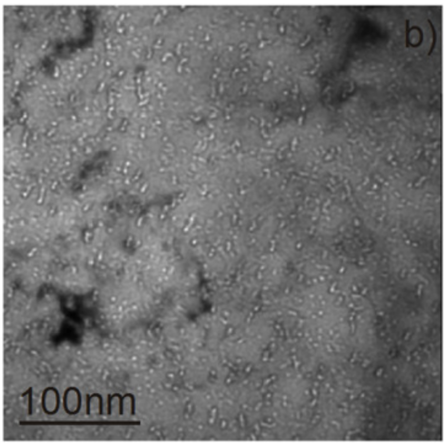
rod #8



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

TEM: comparison of as-received Zry-4 and post-test QUENCH-L0 cladding. No certain evidence of hydrides formation.

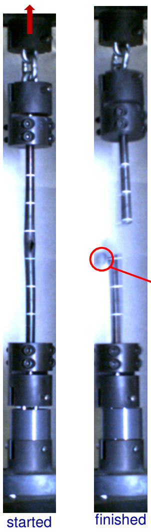




TEM image of SPP in fresh Zry-4 (a) and inhomogeneities in the hydrogen enriched band of rod #08 (b)

Tensile tests

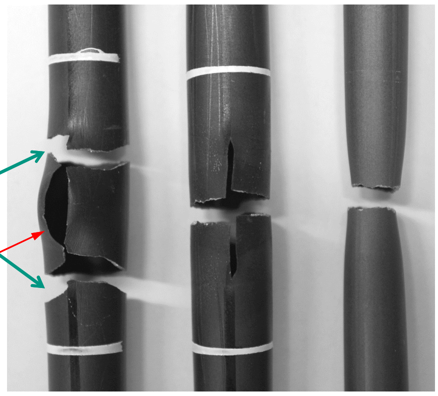
INSTRON testing machine



Double rupture of cladding along hydrogen bands

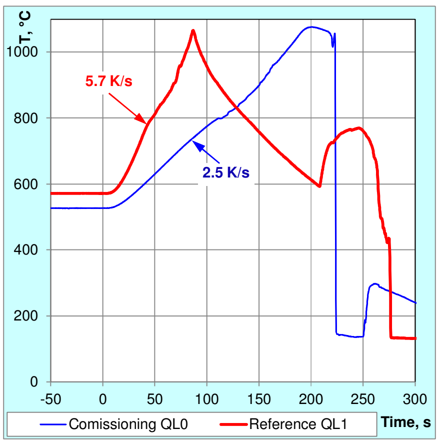
loose ring

Three types of cladding failure

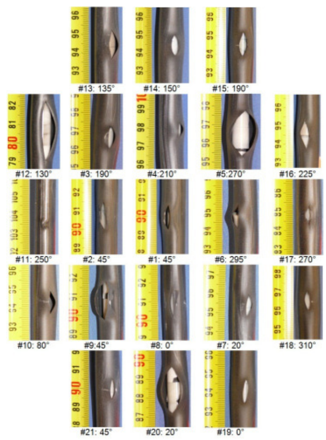


Ruptures near to burst opening due to hydrogen embrittlement (7 from 9 internal rods)	Rupture across the burst opening middle due to stress concentration (external rod)	Rupture near end plugs after plastic deformation (external rods)

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

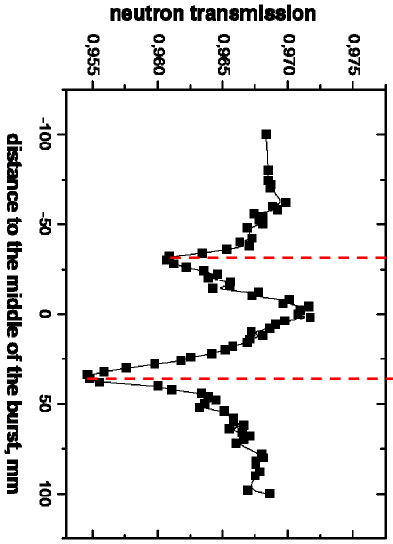


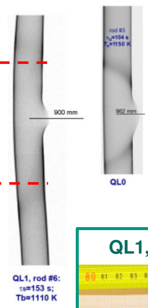
Comparison of temperatures at hottest bundle elevation of 950 mm for bundles QL0 (commissioning test, 2010) and QL1 (reference test, 2012)



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)

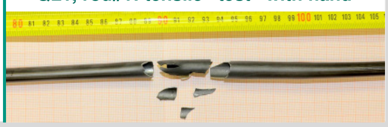
First results of n^0-radiography for reference test QL1





Hydrogenated bands of the QL1 claddings are more blurred in comparison to the QL0 test due to other temperature history

QL1, rod#1: tensile "test" with hand



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

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Thank you for your attention

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

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