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

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

<table>
<thead>
<tr>
<th></th>
<th>REBEKA 1</th>
<th>REBEKA 2</th>
<th>REBEKA 3</th>
<th>REBEKA 4</th>
<th>REBEKA M</th>
<th>REBEKA 5</th>
<th>REBEKA 6</th>
<th>REBEKA 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure, bar</td>
<td>60</td>
<td>55</td>
<td>51</td>
<td>53</td>
<td>70</td>
<td>68</td>
<td>62</td>
<td>57</td>
</tr>
<tr>
<td>burst T, °C</td>
<td>810</td>
<td>870</td>
<td>830</td>
<td>830</td>
<td>754</td>
<td>800</td>
<td>790</td>
<td>790</td>
</tr>
<tr>
<td>strain, %</td>
<td>28</td>
<td>54</td>
<td>44</td>
<td>46</td>
<td>63</td>
<td>49</td>
<td>42</td>
<td>55</td>
</tr>
<tr>
<td>blockage, %</td>
<td>25</td>
<td>60</td>
<td>52</td>
<td>55</td>
<td>84</td>
<td>52</td>
<td>60</td>
<td>66</td>
</tr>
<tr>
<td>burst region, mm</td>
<td>95</td>
<td>203</td>
<td>242</td>
<td>28</td>
<td>242</td>
<td>140</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>
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 ($\Delta p$)
- 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

rod cladding
Cu electrode

Mo electrode

Kr filling for rod internal pressurisation

bundle bottom

boreholes through bottom Cu-electrodes

bundle top

Ø 2 mm
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

individual rod pressurisation with $\text{Kr}$

at max cladding temperature $T_{\text{pct}}=520^\circ\text{C}$
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

- Limit: 3600 A for each generator
- Max total el. power: 43 kW

Graph showing current, voltage, and temperature over time.
Surface thermocouple readings:
17 elevations between -250 und 1350 mm

- Peak bundle temperature (950 mm, TFS 4/13)
- Onset of cooling steam with condensed water t ~ 220 s
- Injection of quench water

thermocouples indicated max temperature at each elevation
Axial temperature development during the test (movie): surface thermocouples of rod #7

- $t = 200 \text{ s}$: cladding surface temperature maximum reached: $T_{\text{max}} = T_{\text{FS 4/13}} = 1349 \text{ K} = 1076^{\circ}\text{C}$
- $t \sim 224 \text{ s}$: beginning of abrupt cladding cooling to $\sim 400 \text{ K}$ by entrainment of water condensed in steam supply tubes
- $t = 362 \text{ s (not showed)}$: 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+\(\alpha\)-Zr(O) : eddy current measurement

max ECR\(_{CP}\)=2%
### Pressure changing during heating phase (0-187 s), ballooning and burst

**Diagram:**
- **Internal rod group**
- **External rod group**

**Table:**
<table>
<thead>
<tr>
<th>Rod</th>
<th>Start p, bar</th>
<th>Burst p, bar</th>
<th>Burst time, s</th>
<th>T@950 mm, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.3</td>
<td>48.5</td>
<td>111.2</td>
<td>796</td>
</tr>
<tr>
<td>7</td>
<td>54.6</td>
<td>54.1</td>
<td>114.2</td>
<td>793</td>
</tr>
<tr>
<td>4</td>
<td>49.2</td>
<td>49.5</td>
<td>114.6</td>
<td>800</td>
</tr>
<tr>
<td>3</td>
<td>55</td>
<td>54.4</td>
<td>119.2</td>
<td>816</td>
</tr>
<tr>
<td>8</td>
<td>47.7</td>
<td>46.8</td>
<td>122.0</td>
<td>813</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>38.9</td>
<td>129.6</td>
<td>835</td>
</tr>
<tr>
<td>6</td>
<td>34.2</td>
<td>34.7</td>
<td>130.4</td>
<td>833</td>
</tr>
<tr>
<td>9</td>
<td>39.2</td>
<td>40.1</td>
<td>136.2</td>
<td>860</td>
</tr>
<tr>
<td>2</td>
<td>33.8</td>
<td>34.5</td>
<td>136.8</td>
<td>861</td>
</tr>
<tr>
<td>12</td>
<td>49.9</td>
<td>50.2</td>
<td>150.0</td>
<td>815</td>
</tr>
<tr>
<td>18</td>
<td>49</td>
<td>48.7</td>
<td>151.2</td>
<td>830</td>
</tr>
<tr>
<td>17</td>
<td>39.6</td>
<td>40.4</td>
<td>152.0</td>
<td>854</td>
</tr>
<tr>
<td>20</td>
<td>50.3</td>
<td>50.4</td>
<td>153.2</td>
<td>776</td>
</tr>
<tr>
<td>14</td>
<td>49</td>
<td>49.0</td>
<td>153.4</td>
<td>821</td>
</tr>
<tr>
<td>16</td>
<td>44.6</td>
<td>44.9</td>
<td>155.0</td>
<td>818</td>
</tr>
<tr>
<td>19</td>
<td>50</td>
<td>50.0</td>
<td>159.6</td>
<td>850</td>
</tr>
<tr>
<td>13</td>
<td>49.4</td>
<td>49.0</td>
<td>162.5</td>
<td>805</td>
</tr>
<tr>
<td>11</td>
<td>39.8</td>
<td>40.8</td>
<td>167.2</td>
<td>868</td>
</tr>
<tr>
<td>21</td>
<td>44.4</td>
<td>44.8</td>
<td>170.6</td>
<td>795</td>
</tr>
<tr>
<td>10</td>
<td>44.5</td>
<td>45.2</td>
<td>174.4</td>
<td>791</td>
</tr>
</tbody>
</table>
Mass spectrometer:
Krypton as burst indicator
and H$_2$ as product of Zr oxidation

![Graph showing concentration and temperature over time](image-url)
Consequences of ballooning

Side view at 270°:
No cooling blockage

Side view at 30°:
Axial shrinkage of claddings due to Zry anisotropy

900 mm

1100 mm

Consequences of ballooning

Side view at 270°:
No cooling blockage

Side view at 30°:
Axial shrinkage of claddings due to Zry anisotropy

900 mm

1100 mm
Burst positions

axial positions

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

The graph shows the axial burst positions for different rod numbers and elevations at various pressures (35 bar, 40 bar, 45 bar, 50 bar, 55 bar). The elevations are marked at 930, 940, 950, 960, 970, 980, 990, and 1000 mm. The rod numbers range from 0 to 22. The graph indicates that there is no clear dependence of burst length 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)

- Circumference strain of rod #1
- Increased cladding diameter
- Burst
- Temperature, °C
- Elevation, mm

16.11.2010 J. Stuckert – QUENCH-LOCA0
QWS-16, Karlsruhe
Strain comparison for different rods

- Rod #1 (50 bar, burst 111s)
- Rod #7 (55 bar, burst 114s)
- Rod #2 (35 bar, burst 136s)
- Rod #21 (45 bar, burst 171s)

**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

Elevation, mm

Blockage, %
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°
“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

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>942 mm</td>
<td>16%</td>
</tr>
<tr>
<td>962 mm</td>
<td>36%</td>
</tr>
<tr>
<td>982 mm</td>
<td>16%</td>
</tr>
</tbody>
</table>
Different internal and external oxidation degree outside burst elevation /rod #3 (55 bar)/

- **external oxidised surface**
- **internal oxidised surface**
- **internal negligible oxidised surface**
- **external oxidised cracked surface**

Crack development during circumferential extension
Similar internal and external oxidation degree at burst elevation
rod #3 (55 bar)
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)

Rupture because stuck pellet?

elevation with max hydrogen content (<1300 wppm: neutron radiography by M. Große)
Tension test at rod #6: early rupture at burst position

early rupture of cladding intended due to prior circumference crack?
Tension test at rod #17: dependence of tube segment ductility from oxidation degree

elev. ~1200 mm
(fewer oxidised cladding)

strain 0%
(unloaded)

strain 2.4%
(at failure)

strain 4.6%
(at failure)

more ductile segment

elev. ~700 mm
(more oxidised cladding)

strain 4.6%
(at failure)

strain 2.4%
(unloaded)

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

Displacement, mm

Load, N

- rod#6 at ~700mm
- rod#6 at ~1200mm
- rod#17 at ~700mm
- rod#17 at ~1200mm

failure (buckle)

more oxidised low tube segments are more brittle
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%.
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 \( \delta_{ox} \approx 15 \, \mu \text{m} \) (ECR\( \approx 2\% \)) was measured.

Two tension tests with cladding segments (length of \( \sim 600 \, \text{mm} \)) 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 planned 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 with the ZIRLO™ claddings

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

Thank you for your attention

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