Results of the reference bundle test QUENCH-L1 with Zircaloy-4 claddings and future planning of the QUENCH-LOCA program


QWS18, Karlsruhe 2012
LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement

Sequence of phenomena:

- cladding ballooning and burst, relief of inner rod pressure
- steam penetration through the burst opening, steam propagation in decreasing gap between cladding and pellet
- oxidation of inner cladding surface with hydrogen release
- absorption of hydrogen by cladding at the boundary of inner oxidised area
- local embrittlement of cladding near to burst opening

20.11.2012 J. Stuckert – QUENCH-LOCA-1
QWS-18, Karlsruhe
Cross-section of the QUENCH-L1 bundle

all rods filled with Kr with $p=55$ bar at $T_{pct}=800$ K
Comparison of cladding temperatures at hottest bundle elevation of 950 mm for QUENCH-L0 and -L1

Enhancements for QUENCH-L1:
1) prototypical high heating rate; 2) prototypical cool-down phase
Scenario of the QUENCH-L1 test

maximal reached power:
QUENCH-L1 (Ta-heaters, Ø 6 mm): 58.5 kW,
QUENCH-L0 (W-heaters; Ø 6 mm): 43 kW

steam 190°C, 2 g/s
steam 150°C, 20 g/s
water 20°C, 100 g/s
Ar 190°C, 6 g/s
Comparison of maximal cladding temperatures at different elevations for QUENCH-L0 and L1

LOCA-0

LOCA-1
Axial and radial temperature distribution on first burst case for QUENCH-L0 (111 s, rod #1) and -L1 (55 s, rod #4)
Rod pressure evolution during heating phase for QUENCH-L0 and -L1: burst time indication (coincided with MS results on Kr release)

duration of decrease of the inner pressure to the system pressure: $\tau_0 \approx 38$ s
Post-test QL1 bundle view between GS3 and GS4
QL1: Bending of central rods

#1: 13 mm
#2: 12 mm
#3: 17 mm
#4: 20 mm
#5: 23 mm
#6: 16 mm
#7: 18 mm
#8: 14 mm
#9: 12 mm

GS3
GS4

820 mm
QL1: Bending of periphery rods

#10 #11 #12: 5 mm #13 #14 #15 #16 #17: 17 mm #18: 22 mm #19 #20: 16 mm #21: 15 mm

20.11.2012 J. Stuckert – QUENCH-LOCA-1
QWS-18, Karlsruhe
QL1: estimation of rod position near to middle position between two spacer grids according to measured rod bending and videoscope observations

QL1: 850 mm
- thermocouples

850 mm: touched rods # 3, 4, 5

950 mm: touched rods # 5, 6, 17

intersections of blue lines correspond to original rod centres
Overview of burst openings

LOCA-0

- Rod #10: 45 bar
- Rod #9: 40 bar
- Rod #8: 50 bar
- Rod #7: 55 bar
- Rod #18: 50 bar
- Rod #19: 50 bar

LOCA-1

- Rod #13: 50 bar
- Rod #14: 50 bar
- Rod #15: 3 bar
- Rod #12: 50 bar
- Rod #3: 55 bar
- Rod #4: 50 bar
- Rod #5: 40 bar
- Rod #16: 45 bar

- Rod #17: 40 bar
- Rod #11: 40 bar
- Rod #2: 35 bar
- Rod #1: 50 bar
- Rod #6: 35 bar
- Rod #17: 40 bar

- Rod #18: 50 bar
- Rod #20: 50 bar
- Rod #21: 45 bar

- Rod #13: 135°
- Rod #14: 150°
- Rod #15: 190°
- Rod #12: 130°
- Rod #3: 190°
- Rod #4: 210°

- Rod #5: 270°
- Rod #6: 295°
- Rod #11: 250°
- Rod #2: 45°
- Rod #17: 270°

- Rod #18: 310°
- Rod #19: 0°
- Rod #20: 20°
- Rod #21: 45°
Circumferential position of burst openings

**LOCA-0:**
openings oriented
to bundle center
due to strong radial T gradient

**LOCA-1:**
not strong orientation
to bundle center
Length and axial position of burst openings

LOCA-0

LOCA-1
### Burst-Parameters

#### LOCA-0

<table>
<thead>
<tr>
<th>Rod group</th>
<th>Rod #</th>
<th>Burst time, s</th>
<th>Burst temperature, interpolated, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1</td>
<td>111.2</td>
<td>914</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>114.2</td>
<td>888</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>114.6</td>
<td>867</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>119.2</td>
<td>881</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>122.0</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>129.6</td>
<td>911</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>130.4</td>
<td>910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>136.2</td>
<td>939</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>136.8</td>
<td>940</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>150.0</td>
<td>891</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>151.2</td>
<td>907</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>152.0</td>
<td>933</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>153.2</td>
<td>849 (Min)</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>153.4</td>
<td>898</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>155.0</td>
<td>894</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>159.6</td>
<td>929</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>162.5</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>167.2</td>
<td>948 (Max)</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>170.6</td>
<td>870</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>174.4</td>
<td>865</td>
</tr>
</tbody>
</table>

#### LOCA-1

<table>
<thead>
<tr>
<th>Rod group</th>
<th>Rod #</th>
<th>Burst time, s</th>
<th>Burst temperature, interpolated, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zentralstäbe</td>
<td>4</td>
<td>55.2</td>
<td>881</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>55.2</td>
<td>837</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>55.6</td>
<td>896 (Max)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>57.2</td>
<td>831</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>57.2</td>
<td>859</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>58.6</td>
<td>859</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>59.0</td>
<td>845</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>59.8</td>
<td>801 (Min)</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>62.6</td>
<td>889</td>
</tr>
<tr>
<td>Peripherstäbe</td>
<td>15</td>
<td>64.4</td>
<td>886</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>67.6</td>
<td>831</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>67.6</td>
<td>783</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>68.6</td>
<td>881</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>68.8</td>
<td>883</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>72.6</td>
<td>808</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>73.6</td>
<td>874</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>76.0</td>
<td>832</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>76.8</td>
<td>819</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>80.6</td>
<td>867</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>83.6</td>
<td>890</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>87.6</td>
<td>870</td>
</tr>
</tbody>
</table>
Cooling channel blockage for LOCA-0 and LOCA-1

- LOCA 1
- LOCA 0

Elevation, mm

Blockage, %

- rod #12
- rod #20
- rod #5

800 850 900 950 1000 1050
LOCA-1, oxidised outer surface of ballooning region (rod #19): typical tree bark structure with micro cracks formed due to strain during ballooning
Outer and inner cladding oxidation at 900 mm for LOCA-1, rod #1

Inner and outer oxide: 20 µm

Inner oxide: 20 µm
Outer and inner cladding oxidation at 920 mm of LOCA-1, rod #1

Outer oxide: 12 µm

Inner oxide: 4 µm
QL1, rod #6: axial distribution of inner oxidation in region of secondary hydrogenation

metallographic measurements along longitudinal cut:

- ZrO2
- a-Zr(O)

QL1, rod #6: axial distribution of inner oxidation in region of secondary hydrogenation
QL1, results of X-ray ($\lambda=154$ pm) diffractometry: no evidence of hydrides with sizes more 10 nm
QL1, shift of XRD peaks: increase of lattice parameters due to dissolved hydrogen

\[ \Delta \Theta = -0.07^\circ \rightarrow C_H \approx 260 \text{ wppm} \]

\[ \Delta \Theta = -0.02^\circ \rightarrow C_H \approx 75 \text{ wppm} \]

\[ \Delta \Theta = -0.04^\circ \rightarrow C_H \approx 150 \text{ wppm} \]

\[ \Delta \Theta = -0.05^\circ \rightarrow C_H \approx 190 \text{ wppm} \]
QL1 rod #5, micro hardness and Young’s module of cladding measured at longitudinal section: hydrogen bands not detected
QL1 rod #1, micro hardness and Young’s module of cladding measured at longitudinal section: hydrogen bands detected
QL1, central rod #1: brittle rupture during handling

**n°-radiography:** hydrogenated bands
*secondary hydrogenation* during oxidation of the inner cladding surface through the burst opening

Max hydrogen concentration in hydrogenated bands (according to estimation derived for QL0):

\[
C_H(t) \approx 2 \cdot 10^3 \cdot \frac{k_{H_2} \bar{P}_{H_2}}{\rho_{Zry} LRT^4} t \approx 1500 \text{ wppm}
\]

for \( \bar{T}=1173 \text{ K} \) and \( t=150\text{s}, \bar{p}=6000\text{Pa} \)
Failure behavior during tensile tests

**QL0: 3 types**
- hydrogen embrittlement (inner rods with $C_H \approx 2000$ wppm)
- stress concentration (outer rods with $C_H \approx 1000$ wppm)
- necking (outer rods)

**QL1: only stress concentration**
(excepted rod #1 brittle ruptured during handling)

- rod #4
- rod #6
- rod #9
Tensile tests for inner rods

QL0 sample length 500 mm or 250 mm*

QL1 sample length 1000 mm or 250 mm*

01* - failure: H-band
02 - failure: H-band
04* - failure: H-band
05* - failure: H-band
06 - failure: pre-crack
07* - failure: H-band
09 - failure: necking

all failures: pre-crack

straightening of the samples
Tensile tests for outer rods

**QL0 sample length 500 mm**

- 0 - straightening of the samples
- 10 - failure: necking
- 11 - failure: necking
- 12 - failure: pre-crack
- 13 - failure: pre-crack
- 14 - failure: pre-crack
- 15 - failure: necking
- 16 - failure: necking
- 17 - failure: necking
- 18 - failure: necking
- 19 - failure: necking
- 20 - failure: pre-crack
- 21 - failure: pre-crack

**QL1 sample length 1000 mm or 250 mm**

- 12
- 13
- 14
- 16
- 17
- 18
- 20

eng. strain, %

eng. stress, MPa

eng. strain, MPa

eng. strain, MPa
QL1: tensile test with bended rod #09 with detected secondary hydrogenation
QL1: tensile test with not bended rod #16 without detected secondary hydrogenation

\[ E = 89 \text{ GPa} \]
## Results of tensile tests

### QL0

<table>
<thead>
<tr>
<th>Rod</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Fracture stress [MPa]</th>
<th>Elongation at fracture [%]</th>
<th>Rupture based on:</th>
</tr>
</thead>
<tbody>
<tr>
<td>01*</td>
<td>254</td>
<td>254</td>
<td>0.38</td>
<td>Hydrogen embrittlement</td>
</tr>
<tr>
<td>02</td>
<td>408</td>
<td>408</td>
<td>0.99</td>
<td>Hydrogen embrittlement</td>
</tr>
<tr>
<td>04*</td>
<td>276</td>
<td>276</td>
<td>0.40</td>
<td>Hydrogen embrittlement</td>
</tr>
<tr>
<td>05*</td>
<td>274</td>
<td>274</td>
<td>0.37</td>
<td>Hydrogen embrittlement</td>
</tr>
<tr>
<td>06</td>
<td>148</td>
<td>148</td>
<td>0.16</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>07*</td>
<td>222</td>
<td>222</td>
<td>0.29</td>
<td>Hydrogen embrittlement</td>
</tr>
<tr>
<td>09</td>
<td>518</td>
<td>433</td>
<td>8.10</td>
<td>Necking</td>
</tr>
<tr>
<td>10</td>
<td>512</td>
<td>507</td>
<td>10.12</td>
<td>Necking</td>
</tr>
<tr>
<td>11</td>
<td>509</td>
<td>391</td>
<td>11.67</td>
<td>Necking</td>
</tr>
<tr>
<td>12</td>
<td>502</td>
<td>499</td>
<td>6.44</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>13</td>
<td>504</td>
<td>504</td>
<td>9.18</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>14</td>
<td>430</td>
<td>430</td>
<td>1.97</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>15</td>
<td>505</td>
<td>450</td>
<td>11.70</td>
<td>Necking</td>
</tr>
<tr>
<td>16</td>
<td>512</td>
<td>389</td>
<td>10.95</td>
<td>Necking</td>
</tr>
<tr>
<td>17</td>
<td>501</td>
<td>497</td>
<td>3.83</td>
<td>Failure at stuck pellet</td>
</tr>
<tr>
<td>18</td>
<td>513</td>
<td>458</td>
<td>10.19</td>
<td>Necking</td>
</tr>
<tr>
<td>19</td>
<td>489</td>
<td>368</td>
<td>11.80</td>
<td>Necking</td>
</tr>
<tr>
<td>20</td>
<td>452</td>
<td>447</td>
<td>2.20</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>21</td>
<td>506</td>
<td>498</td>
<td>8.11</td>
<td>Stress concentration</td>
</tr>
</tbody>
</table>

### QL1

<table>
<thead>
<tr>
<th>Rod</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Fracture stress [MPa]</th>
<th>Elongation at fracture (graded) [%]</th>
<th>Rupture based on:</th>
</tr>
</thead>
<tbody>
<tr>
<td>04*</td>
<td>416</td>
<td>414</td>
<td>0.75 (0.68)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>06*</td>
<td>499</td>
<td>481</td>
<td>1.70 (1.68)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>07*</td>
<td>436</td>
<td>425</td>
<td>1.03 (0.81)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>09</td>
<td>307</td>
<td>307</td>
<td>0.59 (0.09)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>12</td>
<td>464</td>
<td>464</td>
<td>5.50 (5.27)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>13</td>
<td>518</td>
<td>515</td>
<td>5.13 (5.03)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>14</td>
<td>471</td>
<td>471</td>
<td>3.96 (3.80)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>16</td>
<td>462</td>
<td>456</td>
<td>4.31 (4.10)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>17*</td>
<td>333</td>
<td>327</td>
<td>0.33 (0.33)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>18*</td>
<td>270</td>
<td>263</td>
<td>0.19 (0.19)</td>
<td>Stress concentration</td>
</tr>
<tr>
<td>20*</td>
<td>367</td>
<td>356</td>
<td>1.13 (1.06)</td>
<td>Stress concentration</td>
</tr>
</tbody>
</table>
Tensile tests with different as-delivered claddings:
different ultimate tensile strengths and ductile elongations

Tensile test: material comparison (as delivered state)

- **M5:**
  - $E = 95$ GPa
  - $R_m = 512$ MPa
  - $R_{p0.2} = 336$ MPa

- **Zr4:**
  - $E = 97$ GPa
  - $R_m = 691$ MPa
  - $R_{p0.2} = 507$ MPa

- **Duplex DXD4:**
  - $E = 95$ GPa
  - $R_m = 696$ MPa
  - $R_{p0.2} = 532$ MPa

- **E110:**
  - $E = 98$ GPa
  - $R_m = 396$ MPa
  - $R_{p0.2} = 230$ MPa
What is prototypical rod bending rate?

Results of the FR2 in-pile single rod tests: out-of-pile results [Chung], showing significant bending below 840°C (α-Zr(O)) and negligible values above 840°C, were not confirmed by the in-pile tests. However, the orientation of the rod bend was consistent with out-of-pile results, i.e., the rupture was on the inside of the bend.

NRU MT-4 (1982) in-pile bundle test: no noticeable bending

High temperature PHEBUS-FPT1 in-pile test
Choice of heaters: ductile Ta (→ significant rod bending) or rigid W (→ negligible rod bending)

Two locations of friction during the thermal expansion:

1. (prototypical) friction between oxidised grid spacers and ballooned claddings

2. (not prototypical) friction inside the electrode group
Summary

- Test QUENCH-LOCA-1 test was performed according to prototypical scenario with heat-up rate 5.7 K/s and cooling phase lasted 120 s and terminated with 3.3 g/s/rod water flooding.

- The maximum temperature of 1373 K was reached on the end of the heat-up phase at elevation 850 mm (for QUENCH-L0 at 950 mm).

- Strong rod bending up to 23 mm was observed - significantly more in comparison to results of the QUENCH-L0 test.

- The maximum blockage ratio of cooling channel (24%) was observed at elevation 950 mm (similar blockage of QUENCH-L0 was observed at 990 mm).

- The cladding burst occurred at temperatures between 1073 and 1173 K (for QUENCH-L0 between 1123 K and 1223 K). The inner rod pressure relief to the system pressure during about 40 s (similar to QUENCH-L0).
Summary (cont.)

- Similar to QUENCH-L0, the oxide layer thickness on the inner cladding surface was measured up to 25 µm at burst elevations and less 2 µm at hydrogenated bands.

- No zirconium hydrides with sizes more 10 nm were detected. Concentration of hydrogen dissolved in matrix estimated as < 300 wppm.

- All claddings (excluding central rod #1) were fractured due to stress concentration (strengthened due to bending?) at the burst position – similar to inner rods of QL0 with hydrogen concentration about 1000 wpmm. Rod #1 was destroyed brittle during pulling out of heater with hand.

- Future bundle tests supposed to perform with tungsten heaters to avoid significant rod bending caused partially by electrodes friction.
Acknowledgment

The QUENCH-LOCA experiments are supported and partly sponsored by the association of the German utilities (VGB)

The authors would like to thank Mr. J. Moch, Dr. H. Leiste, Mrs. J. Laier and Mrs. U. Peters for intensive work during test preparation and post-test investigations

Thank you for your attention

https://www.iam.kit.edu/wpt/loca/
http://quench.forschung.kit.edu/