25 years QUENCH program

Main results of the QUENCH bundle tests

J. Stuckert, M. Große, M. Steinbrück

Abstract

In the framework of the QUENCH program at KIT, over the past 22 years, 21 bundle tests were performed under severe accident conditions with different cladding materials. Additionally, 7 QUENCH-LOCA bundle tests with fresh and pre-hydrogenated different cladding materials (Zry-4, M5®, opt. ZIRLO™) were performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR.

Main purposes of severe accident tests were hydrogen source term, as well as investigation of phenomena on melt relocation, debris, and aerosol formation. Concerning the hydrogen source term, six parameters, enhancing hydrogen production during reflood, have been identified: 1) low reflood flow rates < 1 g/s/rod; 2) breakaway effect with weakness and spallation of protective oxide layer; 3) steam starvation; 4) nitride formation by air ingress with formation of very porous oxide layer during following reflood; 5) high temperatures with melt relocation outside claddings and intensive melt oxidation; 6) eutectic interactions between B₄C, stainless steel and Zircaloy-4 leading to low melting point.

Post-test tensile experiments performed in the framework of the QUENCH-LOCA program evidenced fracture at hydrogen bands (formed during secondary hydriding) for claddings with local hydrogen concentrations >1500 wppm.
25 years QUENCH program
Main results of the QUENCH bundle tests

J. Stuckert, M. Große, M. Steinbrück
Investigations to core degradation:

**TMI-2-Accident**

- 28 March 1979:
  - 50% reactor core fragmented or melted, $H_2$ generation

**CORA**

- 1986 - 1993, 19 Tests:
  - Investigation of melt formation and -relocation

**QUENCH**

- 1997 → now, 21 Tests (+7 LOCA):
  - Material behavior, Hydrogen source term

G. Schanz et al., Information on the evolution of severe LWR fuel element damage obtained in the CORA program, JNM 188 (1992) 131-145

M. Steinbrück et al., Synopsis and outcome of the QUENCH experimental program, NED 240 (2010) 1714–1727

T. Haste et al., A comparison of core degradation phenomena in the CORA, QUENCH, Phébus SFD and Phébus FP experiments, NED 283(2015) 8–20
Composition of bundles

**WWER**, pitch 12.75 mm  
claddings: **E110** - alloy  
*Fuel rod simulators:*  
18 heated, 13 not heated, 6 corner rods

**PWR**, pitch 14.3 mm  
claddings: **Zry-4** or **M5**<sup>®</sup> alloys  
*Fuel rod simulators:*  
20 heated, 1 not heated (or absorber), 4 corner rods

**PWR**, pitch 12.6 mm  
claddings: **ZIRLO™** or **M5**<sup>®</sup> alloys  
*Fuel rod simulators:*  
24 (22) heated, 0 not heated (or 2 AgInCd absorber), 8 corner rods

**BWR**, pitch 12.898 mm  
claddings: **Zry-2** alloy  
*Fuel rod simulators:*  
24 heated, 1 corner rod

*Absorber blades with B<sub>4</sub>C pins*
Typical QUENCH scenario: performance of QUENCH-14 (M5®) similar to Q-06 (Zry-4), Q-12 (E110) and Q-15 (ZIRLO™)

- **Stabilisation**: ~1.5 h
- **Heat-up**: ~1 h
- **Pre-oxidation**: ~2500 s
- **Transient**: 2100 K, ~3100 s
- **Quench**: ~1200 s

**Materials and Flow Rates**:
- **Superheated steam (783 K)**, 3 g/s (~400 s)
- **Water**, 42 g/s
- **Ar**, 3 g/s

**Electric Power**:
- **1st rod**: 10.7 kW
- **2nd rod**: 18.2 kW
- **3rd rod**: ~4 kW

**Other Parameters**:
- **H₂**: ~9.8 kW
- **Time**: 60 s before transient

**Notes**:
- 2100 K
- 1850 K
- ~3100 s
- ~9.8 kW
- ~1200 s
- ~4 kW
## QUENCH test matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>Quench medium / Injection rate</th>
<th>Temp. at onset of flooding</th>
<th>Max. oxide before transient</th>
<th>Max. oxide before flooding</th>
<th>Max. oxide after test</th>
<th>H₂ production before / during cooldown</th>
<th>Remarks, objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUENCH-00</td>
<td>Oct. 9 - 16, 97</td>
<td>Water 80 g/s</td>
<td>≈ 1800 K</td>
<td></td>
<td>completely oxidized</td>
<td></td>
<td>commissioning test</td>
</tr>
<tr>
<td>QUENCH-01</td>
<td>February 26, 98</td>
<td>Water 52 g/s</td>
<td>≈ 1830 K</td>
<td>312 µm</td>
<td>completely oxidized</td>
<td>36 / 3</td>
<td>pre-oxidized cladding</td>
</tr>
<tr>
<td>QUENCH-02</td>
<td>July 7, 98</td>
<td>Water 47 g/s</td>
<td>≈ 2400 K</td>
<td></td>
<td>completely oxidized</td>
<td>20 / 140</td>
<td>no additional pre-oxidation, melt</td>
</tr>
<tr>
<td>QUENCH-03</td>
<td>January 20, 99</td>
<td>Water 40 g/s</td>
<td>≈ 2350 K</td>
<td></td>
<td>completely oxidized</td>
<td>18 / 120</td>
<td>no additional pre-oxidation, melt</td>
</tr>
<tr>
<td>QUENCH-04</td>
<td>June 30, 99</td>
<td>Steam 50 g/s</td>
<td>≈ 2160 K</td>
<td>82 µm</td>
<td>280 µm</td>
<td>10 / 2</td>
<td>slightly pre-oxidized cladding</td>
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<tr>
<td>QUENCH-05</td>
<td>March 29, 2000</td>
<td>Steam 48 g/s</td>
<td>≈ 2020 K</td>
<td>160 µm</td>
<td>≈ 420 µm</td>
<td>25 / 2</td>
<td>pre-oxidized cladding</td>
</tr>
<tr>
<td>QUENCH-06</td>
<td>Dec. 13 2000</td>
<td>Water 42 g/s</td>
<td>≈ 2060 K</td>
<td>207 µm, 300 µm</td>
<td>630 µm</td>
<td>32 / 4</td>
<td>OECD-ISP 45</td>
</tr>
<tr>
<td>QUENCH-07</td>
<td>July 25, 2001</td>
<td>Steam 15 g/s</td>
<td>≈ 2100 K</td>
<td>230 µm</td>
<td>completely oxidized</td>
<td>66 / 120</td>
<td>EU COLOSS B₄C, eutectic melt</td>
</tr>
<tr>
<td>QUENCH-08</td>
<td>July 3, 2002</td>
<td>Steam 49 g/s</td>
<td>≈ 2100 K</td>
<td>274 µm</td>
<td>completely oxidized</td>
<td>60 / 400</td>
<td>EU COLOSS B₄C, eutectic melt</td>
</tr>
<tr>
<td>QUENCH-09</td>
<td>July 24, 2003</td>
<td>Steam 15 g/s</td>
<td>≈ 2090 K</td>
<td></td>
<td>completely oxidized</td>
<td>46 / 38</td>
<td>EU COLOSS: reference for QUENCH-07, melt</td>
</tr>
<tr>
<td>QUENCH-10</td>
<td>July 21, 2004</td>
<td>Water 50 g/s</td>
<td>≈ 2200 K</td>
<td>514 µm, 613 µm (at 850 mm)</td>
<td>completely oxidized</td>
<td>48 / 5</td>
<td>EU LACOMERA; air ingress</td>
</tr>
<tr>
<td>QUENCH-11</td>
<td>Dec 08, 2005</td>
<td>Water 18 g/s</td>
<td>≈ 2040 K</td>
<td>170 µm</td>
<td>completely oxidized</td>
<td>9 / 132</td>
<td>EU LACOMERA; boil-off, melt; benchmark</td>
</tr>
<tr>
<td>QUENCH-12</td>
<td>Sept 27, 2006</td>
<td>Water 48 g/s</td>
<td>≈ 2100 K</td>
<td>160 µm, breakaway</td>
<td>completely oxidized</td>
<td>34 / 24</td>
<td>ISTC; WWER, melt</td>
</tr>
<tr>
<td>QUENCH-13</td>
<td>Nov. 7, 2007</td>
<td>Water 52 g/s</td>
<td>≈ 1820 K</td>
<td>400 µm, 750 µm</td>
<td></td>
<td>42 / 1</td>
<td>EU SARNET; Ag/In/Cd (aerosol)</td>
</tr>
<tr>
<td>QUENCH-14</td>
<td>Sept 27, 2006</td>
<td>Water 41 g/s</td>
<td>≈ 2100 K</td>
<td>170 µm, 470 µm</td>
<td>900 µm</td>
<td>34 / 6</td>
<td>M5® cladding</td>
</tr>
<tr>
<td>QUENCH-15</td>
<td>Nov. 7, 2007</td>
<td>Water 41 g/s</td>
<td>≈ 2100 K</td>
<td>145 µm, 320 µm</td>
<td>620 µm</td>
<td>41 / 7</td>
<td>ZIRLO™ cladding</td>
</tr>
<tr>
<td>QUENCH-16</td>
<td>July 27, 2012</td>
<td>Water 50 g/s</td>
<td>≈ 1870 K</td>
<td>135 µm, 140 µm</td>
<td>850 µm: outer porous, inner dense</td>
<td>16 / 128</td>
<td>EU LACOMECO; air ingress, melt; benchmark</td>
</tr>
<tr>
<td>QUENCH-17</td>
<td>Jan. 31, 2013</td>
<td>Water 10 g/s</td>
<td>≈ 1800 K</td>
<td></td>
<td>completely oxidized</td>
<td>110 / 1</td>
<td>EU SARNET-2; DEBRIS formation</td>
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<tr>
<td>QUENCH-18</td>
<td>Sept. 27, 2017</td>
<td>Water 53 g/s</td>
<td>≈ 2000 K</td>
<td>90 µm</td>
<td>completely oxidized</td>
<td>56 / 238</td>
<td>EU ALISA; AgInCd absorber (melt and aerosols); air ingress</td>
</tr>
<tr>
<td>QUENCH-19</td>
<td>August 29, 2018</td>
<td>Water 41 g/s</td>
<td>≈ 1740 K</td>
<td></td>
<td>completely oxidized</td>
<td>8.8 / 0.5</td>
<td>ATF (FeCrAl) clads; cooperation with ORNL</td>
</tr>
<tr>
<td>QUENCH-20</td>
<td>October 9, 2019</td>
<td>Water 50 g/s</td>
<td>≈ 2000 K</td>
<td>100 µm</td>
<td>t.b.d.</td>
<td>25.4 / 32</td>
<td>EU SAFEST; BWR bundle with B₄C absorber</td>
</tr>
</tbody>
</table>
Development of cracks in the cladding with thick oxide layer (>150 µm) and cooled down with steam. Crack density ~ 4 cm/cm².

Negligible oxidation of crack edges gives only some percent of generated hydrogen.

Oxidation of cracks developed during flooding: low contribution to hydrogen production.

**QUENCH-17: Debris formation after degradation of strongly oxidized cladding and release of pre-segmented pellet simulators**

**Test Scenario**

- **Debris:** 1) separated parts of fuel pellets simulator; 2) large segments of failed Zry claddings.

**Bundle Composition**

- 9 unheated rods with Zry-4 cladding
- 12 heated rods with Hf cladding

**Cross-section at 400 mm:**
- Metallography; debris bed porosity 50%
- Tomography; blockage 85%

**X-ray Tomography**

J. Stuckert et al., *Results of the QUENCH-DEBRIS test*, ICAPP 2014, Paper 14150
Weakening of protective oxide layer by breakaway oxidation: QUENCH-12 (WWER, electrolytic E110) vs. QUENCH-06 (Zry-4)

Q12 cladding: spalling of oxide scales due to breakaway effect

Q06 oxidized cladding

Increased hydrogen production during reflood after breakaway: QUENCH-12 (electrolytic E110) vs. QUENCH-14 (M5®)

Consequences of breakaway enhanced hydrogen release: 1) new metallic surfaces, 2) melt release outside cladding, 3) release of hydrogen absorbed in metal.

Post-test calculations: need for improvement of model for quench phase
Influence of pre-reflood steam or oxygen starvation conditions (QUENCH-09, -11, -16, -18)

Steam starvation at 1700K

ZrO$_2$, 134 µm
$\alpha$-Zr(O), 182 µm
$\beta$-Zr, 431 µm

Steam starvation at 1700K

ZrO$_2$, 228 µm
$\alpha$-Zr(O), 397 µm
$\beta$-Zr, 177 µm

J. Stuckert and M. Veshchunov
Behaviour of Oxide Layer of Zirconium-Based Fuel Rod Cladding under Steam Starvation Conditions, FZKA-7373 (2008)

Development of metallic precipitations inside oxide layer. Precipitates will expose to intensive oxidation during following flooding

ZrO$_2$: 186 µm, Metallic precipitations 24%
$\alpha$-Zr(O), 646 µm
Air ingress after moderate pre-oxidation (QUENCH-10, -16): massive nitride formation during oxygen starvation and their intensive re-oxidation during quench.

Endoscope observation at ~850 mm

prior nitrided scale re-oxidised during quench and spalled

from internal ZrO$_2$ layer growing during quench

J. Stuckert and M. Steinbrück
Experimental results of the QUENCH-16 bundle test on air ingress, PNE 71 (2014) 134-141
Typical layer structure of strong oxidised cladding at hottest bundle elevation of 1000 mm after reflood

- **outer ZrO$_2$** formed during pre-oxidation and reflood
- **melt** formed at ~2030 K and partially oxidised due to dissolution of ZrO$_2$
- **inner ZrO$_2$** formed during reflood (due to interaction with steam penetrated under breached cladding; no interaction with pellet)

**QUENCH-15 (ZIRLO™)**
- rod #17
  - J. Stuckert et al., Experimental and calculation results of the integral reflood test QUENCH-15 with ZIRLO™ cladding tubes in comparison with results of previous QUENCH tests, NED 241 (2011) 3224–3233

**QUENCH-14 (M5®)**
- rod #11
  - J. Stuckert et al., Experimental and calculation results of the integral reflood test QUENCH-14 with M5® cladding tubes, ANE 37 (2010) 1036–1047

**QUENCH-06 (Zry-4)**
- rod #12
Eutectic melt induced upper 1200°C by absorber rod: 
complementary tests Q-07 (B₄C rod) and Q-08 (without absorber)

QUENCH-07: formation of significant melt amount and melt relocation
B₄C<->Fe eutectic at ~1150°C
Zry <-> SS eutectic at ~1300°C

QUENCH-08: moderate melt formation; no noticeable melt relocation

hydrogen productions for different test phases with indication of temperature evolution during the phase:

J. Stuckert et al., Experimental and Computational Results of the QUENCH-08 Experiment (Reference to QUENCH-07), FZKA-6970 (2005)
QUENCH-11, elev. 837 mm: melt relocated outside fuel rods and oxidised in steam.
Molten pools frozen at middle and upper elevations of the PWR QUENCH-03 bundle flooded from the bundle bottom at $T_{pct} \approx 2350$ K by water with flow rate $F_q \approx 1$ g/s/rod

| 650 mm | 950 mm | 1150 mm |

P. Hofmann et al., *Experimental and calculation results of the experiments QUENCH-02 and QUENCH-03*, FZKA-6295 (2000)
Analysis of the melt composition formed in the PWR QUENCH-02 bundle flooded from bottom at $T_{pct} \approx 2400$ K with flow rate $F_q \approx 1$ g/s/rod

Post-test image of cross section of the QUENCH-02 bundle at elevation of 850 mm showing an oxidized molten pool surrounded by oxide

Ceramic precipitates inside QUENCH-02 molten pool, oxygen concentration 53 at% (image analysis): above saturation limit of 46%

SVECHA simulation of Zr melt oxidation at 2473 K for two temperature drops in the boundary oxide layer $\Delta T = 10$ K and 50 K for cylindrical molten pool with radius of 6 mm; solid and dotted curves: radial positions of internal (red) and external (green) oxide layer boundaries; dashed curves: volume fraction of precipitates

M. Veshchunov et al., Modelling of Zr-O and U-Zr-O melts oxidation and new crucible tests, FZKA-6792 (2002)
Hydrogen release
with (Q-02, Q-11) and without (Q-14) melt oxidation in steam

Temperature histories:
- Q02_TSH13/90
- Q11_TSH13/90
- Q14_TSH13/90

Hydrogen releases:
- Q-02_H2_rate
- Q11_H2_rate
- Q14_H2_rate

Reflood temperature histories hydrogen releases
QUENCH-13: aerosol release after failure of AgInCd absorber rod

Sample PSI BI1/6 (D_{ae}=0.4-0.7 \, \mu m): collected after control rod failure

Sample PSI BI3/6 (D_{ae}=0.4-0.7 \, \mu m): collected before reflood

<table>
<thead>
<tr>
<th>Element</th>
<th>Cd</th>
<th>In</th>
<th>Ag</th>
<th>W</th>
</tr>
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<tbody>
<tr>
<td>wt%</td>
<td>42</td>
<td>41</td>
<td>2.5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Cd</th>
<th>In</th>
<th>Ag</th>
<th>W</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>33</td>
<td>31</td>
<td>8</td>
<td>27</td>
<td>1</td>
</tr>
</tbody>
</table>

T. Lind et al., Aerosol behavior during SIC control rod failure in QUENCH-13 test, JNM 397 (2010) 92–100
QUENCH-18 test on air ingress and aerosol release

fuel assembly 17x17

- fuel rod (264)
- guide tube for AgInCd control rod (24)
- instrument thimble

proposed QUENCH test bundle

- pressurised, unheated rod
- heated rod
- corner rod C
- absorber rod (Ag/In/Cd)
- shroud

Outlet gas behaviour during air ingress in QUENCH-18: starvation phenomena

consumed oxygen: 100 g; consumed nitrogen: 120 g;
consumed steam: 450 g; released hydrogen: 45 g

$t \approx 10600 \text{ s}: \text{oxygen starvation, } H_2 \text{ increase}
steam and nitrogen consumption
Failure of absorber rods and aerosol release in QUENCH-18

- T at 550 mm (TIT G/9)
- He off-gas
- aerosol

Temperature, K

Time, s

He, %*1000 ; aerosol, g/m³

Failure of absorber rods and aerosol release in QUENCH-18

$t=10530$ s: helium and aerosol release
### Aerosols in QUENCH-18: release of Cd, Ag, In

<table>
<thead>
<tr>
<th>Element</th>
<th>Released, g</th>
<th>fraction of total mass in control rods, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>9.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Silver</td>
<td>6.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Indium</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16.8</strong></td>
<td><strong>1.3</strong></td>
</tr>
</tbody>
</table>

J. Kalilainen et al., *The measurement of Ag/In/Cd release under air-ingress conditions in the QUENCH-18 bundle test*. JNM 517 (2019), pp. 315-327
Composition of the test bundle QUENCH-19 (FeCrAl)

24 heated rods (FeCrAl(Y) clad, ZrO₂ pellet, W heater)
8 corner rods (FeCrAl Kanthal APM)

ZrO₂ fiber insulation

cooling jacket (Inconel)

cross section (arrangement the same as for QUENCH-15)

ORNL Kanthal AF spacer grids:
height 22 mm, sheet thickness 0.5 mm

AREVA Inconel spacer grid:
height 45 mm, sheet thickness 0.5 mm

J. Stuckert et al., First results of the bundle test QUENCH-19 with FeCrAl claddings. QWS-24 (2018), Karlsruhe
Test performance: comparison of QUENCH-15 (ZIRLO) and -19 (FeCrAl)

Energy release during Q15 pre-oxidation (i.e. until 6000 s):
- Electrical $E_e = 63.7$ MJ
- Chemical $E_ch = 3.5$ MJ

$E_ch < E_e$
Hydrogen release in QUENCH-15 (ZIRLO) and -19 (FeCrAl)

QUENCH-15: max rate 1830 mg/s; totally 47.6 g H₂

QUENCH-19: max rate 280 mg/s; totally 9.2 g H₂

max $T_{\text{clad}} \approx 1400 \, ^\circ\text{C}$
QUENCH-19 bundle at elevations between 900 and 1100 mm: cladding damages by molten thermocouple steel (AISI 304) sheaths

- the melting range of 304 steel is 1400...1450°C
- the melting range of FeCrAl alloys is 1500...1520°C

Positions of TC (•) at elevations 13 (950 mm) and 14 (1050 mm)
QUENCH-19, 950 mm, rod 2: molten claddings of central rods

frozen cladding melt
melt-interacting ZrO$_2$ pellet

0°

270°

90°

180°
QUENCH-19, 950 mm: penetration of FeO melt into pellet

ZrO$_2$-x grain

FeO melt

(Fe, Cr, Al) oxides
QUENCH-19, 950 mm: oxide precipitates inside molten FeO formed already at 1370 °C.
QUENCH-20: test bundle composition
¼ SVEA-96 OPTIMA2 assembly (BWR)

Geometrical parameters:
- bundle pitch 12.898 mm;
- outer diameter of claddings 9.84 mm;
- thickness of claddings 0.605 mm;
- absorber blades: thickness 8.05 mm

- cladding length 2500 mm
- absorber and cannel box lengths 1600 mm
- water gap between channel box and absorber blade 2.5 mm (nominal inter-assembly gap in BWR-PROTEUS core is 13.8 mm -> water gap 2.875 mm)

- heater rods (24):
  cladding Zy-2 with inner ZrSn-liner (10% of clad),
  ZrO₂ pellet OD 8.48±0.05 ID 5.45±0.1 mm, length 11 mm,
  W heater OD 5.25±0.025 mm

- advanced low tin ZIRLO fuel channel box, wall thickness 1.4 mm
- water channel box (ZIRLO), side length 27.4 mm, wall thickness 0.8 mm
- corner rod (Zry-4, OD 6 mm)
- water cross wing (ZIRLO), wall thickness 3 mm
- Zr shroud □ 86 mm, wall thickness 3 mm
- ZrO₂ porous thermal insulation

Inconel cooling jacket, inner tube ID=158.3 mm
Strong degradation of absorber blades, channel box and shroud between elevations 650 and 950 mm at angle positions 0° and 270°.
QUENCH-20: reaction of $\text{B}_4\text{C}$ with steam, integral gas release

According to $\text{CO}_x$ and $\text{CH}_4$ release: corresponding mass of $\text{B}_2\text{O}_3$ is 96.8 g; $\text{H}_2$ is 10.0 g
**QUENCH-20: hydrogen release**

**H₂ release during the whole test:** 57.4 g; before quench – interaction of steam with Zry, during quench – steam interaction with Zry and absorber

**H₂ release during quench:**
- 22 g (from Zry and molten steel) + 10 g (from B₄C)

**H₂ release during quench:**
- 32 g

**Before quench:** 25.4 g
Database: contents

- Core damage state and evolution
- Temperatures, Heat-up rates Steam starvation prior to reflood(?)
- Reflood medium and mass flow rate
- Hydrogen data
- Fraction of Zry consumed for H₂ production
- PARAMETER: top, top + bottom flooding

| Core damage evolution in reflood experiments | Reactor type | Pressure at reflood | Intact/loc. ballooning | Absorber damaged | Fuel rod damaged | Metallic melt relocated | Local debris | Local debris/Pool | Global debris/Pool | Material relocation >LH | K | Kᵢ | g | g | g | a | % | % |
|--------------------------------------------|--------------|-------------------|-----------------------|----------------|-------------------|------------------------|-------------|------------------|-----------------|------------------------|---|----|---|---|---|---|---|---|---|
| Data source                                |              |                   |                       |                |                  |                        |             |                  |                 |                        |   |    |   |   |   |   |   |   |   |
| CODEX 3/2                                  | V            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1773 / 1923 | 0,6 | W | 0,9 | 1 | 0 | ? | 1 | <5 | <5 |
| PARAMETER 2                                | V            | L                 | B                     | Tiny           |                  |                        |             |                  |                 |                        | 1700 /~1700 | ?   | No| W  | 5 |   |   |   |   |   |
| PARAMETER SF1 (top)                        | V            | L                 |                       |                |                  |                        |             |                  |                 |                        | 2123 / 2300 | 2   | No| W  | 1,4 | 20 | 54 | 17 | 91 | 73 | 78 | 60 |
| PARAMETER SF2 (t+b)                        | V            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1770 / 1850 | 0,2 | No| W  | 5 | 23,5 | 1,5 | 0 | 25 | 6 | 6 |
| PARAMETER SF3 (top)                        | V            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1870 / 1900 | 0,3 | No| W  | 1,4 | 31 | 4,5 | 0 | 35,5 | 13 | 13 |
| PARAMETER SF4 (air)                        | V            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1900 / 2300 | "   | Air| W  | 3,2 | 21 | 66 | 20 | 107 | 76 | 80 |
| QUENCH IBS05                                | P            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1700 / 1750 | ?   |   | W  | 2,6 | 20 | 33 | 5 | 58 | 62 | 66 | 34 |
| QUENCH-01                                  | "            | L                 |                       |                |                  |                        |             |                  |                 |                        | 1830 / 1900 | 0,7 | No| W  | 1,8 | 36 | 1  | 2 | 39 | 3  | 8  | 24 |
| QUENCH-02                                  | "            | L                 |                       |                |                  |                        |             |                  |                 |                        | 2470 / 2500 | "   | No| W  | 1,7 | 20 | 109 | 31 | 160 | 84 | 88 | 83 |

W. Hering et al., Integration of New Experiments into the Reflood Map, ICAPP 2015 Paper 15465
Database: (cont.)

- ZIRLO™ and M5® claddings
- QUENCH-12: WWER
- QUENCH-17: DEBRIS

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- ZIRLO™ and M5® claddings
- QUENCH-12: WWER
- QUENCH-17: DEBRIS
## QUENCH-LOCA test matrix

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QUENCH-LOCA program at KIT (2010-2016): Influence of hydrogen uptake after LOCA-burst on mechanical properties of claddings

ballooning and burst of claddings in comparison to pre-test fuel rod positions in the QUENCH-LOCA bundle: 25% blockage of cooling channel

axial burst positions after bundle QUENCH-LOCA test with Zry-4 claddings

hydrogen bands inside cladding detected with n°-radiography: >2000 wppm hydrogen content

double rupture of cladding along hydrogen bands during tensile tests for CH>1500 wppm

J. Stuckert et al., QUENCH-LOCA program at KIT on secondary hydriding, NED 255 (2013), 185-201.

J. Stuckert et al., Lessons learned from the QUENCH-LOCA experiments, QWS-23 (2017).

M. Grosse et al., Secondary hydriding during LOCA – Results from the QUENCH-L0 test, JNM 420 (2012), 575-582.
SUMMARY

- 21 bundle tests were performed under severe accident conditions with different cladding materials.
- Six parameters, enhancing hydrogen production during reflood, have been identified:
  1) Low reflood flow rates < 1 g/s/rod (QUENCH-07, -08, -11);
  2) Breakaway effect with weakness and spallation of protective oxide layer (QUENCH-12);
  3) Steam starvation (QUENCH-09, -11, -16);
  4) Nitride formation by air ingress with formation of very porous oxide layer during following reflood (QUENCH-10, -16);
  5) High temperatures with melt relocation outside claddings and intensive melt oxidation (QUENCH-02, -03, -09, -11, -16, -18);
  6) Eutectic interactions between B₄C, stainless steel and Zircaloy-4 leading to low melting point (QUENCH-07, -09, -20).
- Additionally to hydrogen source term, other phenomena on melt relocation, debris, and aerosol formation were investigated.
- 7 QUENCH-LOCA bundle tests with fresh and pre-hydrogenated different cladding materials (Zry-4, M5®, opt. ZIRLO™) were performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR. Post-test tensile experiments evidenced fracture at hydrogen bands (formed during secondary hydriding) for claddings with local hydrogen concentrations >1500 wppm.
Thank you for the fruitful cooperation and attention

http://quench.forschung.kit.edu/
http://www.iam.kit.edu/awp/666.php