Experimental program QUENCH at KIT on core degradation during reflooding under LOCA conditions and in the early phase of a severe accident

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IAEA TM on DBA and SA

Istitute for Applied Materials, IAM-WPT, IAM-AWP; Program NUKLEAR
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, 17 Tests:
  - Hydrogen source term
  - Material behaviour
### CORA test matrix: 19 bundle tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date of Test</th>
<th>Max Cladding Temperature</th>
<th>Absorber Material</th>
<th>Other Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Aug. 6, 1987</td>
<td>≈ 2000°C</td>
<td>U0₂ refer. Inconel spacer</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Dec. 3, 1987</td>
<td>≈ 2400°C</td>
<td>U0₂ refer. high temperature</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Feb. 26, 1988</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>PWR-absorber</td>
</tr>
<tr>
<td>12</td>
<td>June 9, 1988</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>quenching</td>
</tr>
<tr>
<td>16</td>
<td>Nov. 14, 1988</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>BWR-absorber</td>
</tr>
<tr>
<td>15</td>
<td>March 2, 1989</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>rods with internal pressure</td>
</tr>
<tr>
<td>17</td>
<td>June 29, 1989</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>quenching</td>
</tr>
<tr>
<td>9</td>
<td>Nov. 9, 1989</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>10 bar system pressure</td>
</tr>
<tr>
<td>7</td>
<td>Feb. 22, 1990</td>
<td>&lt; 2000°C</td>
<td>AgInCd</td>
<td>57-rod bundle, slow cooling</td>
</tr>
<tr>
<td>18</td>
<td>June 21, 1990</td>
<td>&lt; 2000°C</td>
<td>B₄C</td>
<td>59-rod bundle, slow cooling</td>
</tr>
<tr>
<td>13</td>
<td>Nov. 15, 1990</td>
<td>≈ 2200°C</td>
<td>AgInCd</td>
<td>quench initiation at higher temperature; OECD/ISP</td>
</tr>
<tr>
<td>29</td>
<td>Apr. 11, 1991</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>pre-oxidized</td>
</tr>
<tr>
<td>31</td>
<td>July 25, 1991</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>slow initial heat-up (≈ 0.3 K/s)</td>
</tr>
<tr>
<td>30</td>
<td>Oct. 30, 1991</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>slow initial heat-up (≈ 0.2 K/s)</td>
</tr>
<tr>
<td>28</td>
<td>Feb. 25, 1992</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>pre-oxidized</td>
</tr>
<tr>
<td>10</td>
<td>July 16, 1992</td>
<td>≈ 2000°C</td>
<td>AgInCd</td>
<td>cold lower end; 2 g/s steam flow rate</td>
</tr>
<tr>
<td>33</td>
<td>Oct. 1, 1992</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>dry core conditions, no extra steam input</td>
</tr>
<tr>
<td>W1</td>
<td>Feb. 18, 1993</td>
<td>≈ 2000°C</td>
<td></td>
<td>WWER-test</td>
</tr>
<tr>
<td>W2</td>
<td>Apr. 21, 1993</td>
<td>≈ 2000°C</td>
<td>B₄C</td>
<td>WWER-test with absorber</td>
</tr>
</tbody>
</table>

Initial heat-up rate ≈ 1.0 K/s. Steam flow rate, PWR: 6 g/s, BWR: 2 g/s.

**Quench rate (from the bottom) ≈ 1 cm/s.**
CORA-18: large BWR bundle

874 mm: remnants of B₄C-SS eutectic melt formed at T>1200°C

560 mm: 1) remnants of B₄C-SS eutectic melt; 2) strong degraded fuel rods (U-Zr-SS-O melt)

269 mm: 1) melt relocated from upper elevations; 2) degraded absorber
Hydrogen production during CORA tests without/with reflood (quenching)

**without quench**

**with quench: T escalation; H$_2$ peak**

![Graphs showing temperature and hydrogen production over time for CORA-13 and CORA-17 with and without quenching.](image)
Motivation

- Reflood is a prime accident management measure to terminate a nuclear accident.
- Reflood may cause temperature excursion connected with increased hydrogen and FP release.
- Simulation of core behaviour at high temperatures and during quenching is still a matter of improvement.
- QUENCH experiments (bundle+SET) provide data for development of models and validation of SFD code systems.
QUENCH Programme

Separate-effects tests

Modelling → CODES → Application

Validation

Bundle experiments
### Composition of bundles

#### QUENCH-12 VVER
- **Claddings:** E110 - alloy
- **Fuel rod simulators:**
  - 18 heated
  - 13 not heated
  - 6 corner rods
- **Metallic surface ratio:** Q12/Q14 = 1.22

#### QUENCH-14 (typical geometry)
- **Claddings:** M5® - alloy
- **Fuel rod simulators:**
  - 20 heated
  - 1 not heated
  - 4 corner rods

#### QUENCH-15
- **Claddings:** ZIRLO™ - alloy
- **Fuel rod simulators:**
  - 24 heated
  - 0 not heated
  - 8 corner rods
- **Metallic surface ratio:** Q15/Q14 = 1.09
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: ~3100 s
quench: ~1200 s

Water, 42 g/s (~400 s)
Superheated steam (783 K), 3 g/s
Ar, 3 g/s

Pe: ~9.8 kW
~3.8 kW
10.7 kW
18.2 kW
~ 4 kW

Tm: 873 K
1473 K
2100 K
1850 K

H2: ~9.8 kW
### QUENCH test matrix: different test series

<table>
<thead>
<tr>
<th>Test</th>
<th>Quench medium / Injection rate</th>
<th>Temp. at onset of flooding</th>
<th>Max. ZrO$_2$ before transient</th>
<th>Max. ZrO$_2$ before flooding</th>
<th>Max. ZrO$_2$ after test</th>
<th>H$_2$ production before / during cooldown</th>
<th>Remarks, objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUENCH-00</td>
<td>Water 80 g/s</td>
<td>≈ 1800 K</td>
<td></td>
<td></td>
<td>completely oxidized</td>
<td></td>
<td>commissioning test</td>
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<tr>
<td>Oct. 9 - 16, 97</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>QUENCH-01</td>
<td>Water 52 g/s</td>
<td>≈ 1830 K</td>
<td>312 µm</td>
<td></td>
<td>500 µm at 913 mm</td>
<td>36 / 3</td>
<td>pre-oxidized cladding</td>
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<td>February 26, 98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-02</td>
<td>Water 47 g/s</td>
<td>≈ 2400 K</td>
<td></td>
<td></td>
<td>completely oxidized</td>
<td>20 / 140</td>
<td>no additional pre-oxidation, melt</td>
</tr>
<tr>
<td>July 7, 98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>QUENCH-03</td>
<td>Water 40 g/s</td>
<td>≈ 2350 K</td>
<td></td>
<td></td>
<td>completely oxidized</td>
<td>18 / 120</td>
<td>no additional pre-oxidation, melt</td>
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<td>January 20, 99</td>
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<tr>
<td>QUENCH-04</td>
<td>Steam 50 g/s</td>
<td>≈ 2160 K</td>
<td>82 µm</td>
<td></td>
<td>280 µm</td>
<td>10 / 2</td>
<td>slightly pre-oxidized cladding</td>
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<td>June 30, 99</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>QUENCH-05</td>
<td>Steam 48 g/s</td>
<td>≈ 2020 K</td>
<td>160 µm</td>
<td></td>
<td>≈ 420 µm</td>
<td>25 / 2</td>
<td>pre-oxidized cladding</td>
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<tr>
<td>March 29, 2000</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-06</td>
<td>Water 42 g/s</td>
<td>≈ 2060 K</td>
<td>207 µm</td>
<td>300 µm</td>
<td>≈ 630 µm</td>
<td>32 / 4</td>
<td>OECD-ISP 45</td>
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<td>Dec. 13 2000</td>
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<td></td>
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<tr>
<td>QUENCH-07</td>
<td>Steam 15 g/s</td>
<td>≈ 2100 K</td>
<td>230 µm</td>
<td></td>
<td>completely oxidized</td>
<td>66 / 120</td>
<td>B$_4$C, eutectic melt</td>
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<tr>
<td>July 25, 2001</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-09</td>
<td>Steam 49 g/s</td>
<td>≈ 2100 K</td>
<td></td>
<td></td>
<td>completely oxidized</td>
<td>60 / 400</td>
<td>B$_4$C, eutectic melt</td>
</tr>
<tr>
<td>July 3, 2002</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>QUENCH-08</td>
<td>Steam 15 g/s</td>
<td>≈ 2090 K</td>
<td>274 µm</td>
<td></td>
<td>completely oxidized</td>
<td>46 / 38</td>
<td>reference for QUENCH-07, melt</td>
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<tr>
<td>July 24, 2003</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-10</td>
<td>Water 50 g/s</td>
<td>≈ 2200 K</td>
<td>514 µm (at 850 mm)</td>
<td></td>
<td>completely oxidized</td>
<td>48 / 5</td>
<td>air ingress</td>
</tr>
<tr>
<td>July 21, 2004</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-11</td>
<td>Water 18 g/s</td>
<td>≈ 2040 K</td>
<td>170 µm</td>
<td></td>
<td>completely oxidized</td>
<td>9 / 132</td>
<td>boil-off, melt; benchmark</td>
</tr>
<tr>
<td>Dec 08, 2005</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-12</td>
<td>Water 48 g/s</td>
<td>≈ 2100 K</td>
<td>160 µm, breakaway</td>
<td>300 µm, breakaway</td>
<td>completely oxidized</td>
<td>34 / 24</td>
<td>VVER, melt</td>
</tr>
<tr>
<td>Sept 27, 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-13</td>
<td>Water 52 g/s</td>
<td>≈ 1820 K</td>
<td></td>
<td></td>
<td>400 µm</td>
<td>750 µm</td>
<td>Ag/In/Cd (aerosol)</td>
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<tr>
<td>Nov. 7, 2007</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUENCH-14</td>
<td>Water 41 g/s</td>
<td>≈ 2100 K</td>
<td>170 µm</td>
<td></td>
<td>470 µm</td>
<td>900 µm</td>
<td>M5® cladding</td>
</tr>
<tr>
<td>Sept 27, 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUENCH-15</td>
<td>Water 41 g/s</td>
<td>≈ 2100 K</td>
<td>145 µm</td>
<td></td>
<td>320 µm</td>
<td>620 µm</td>
<td>ZIRLO™ cladding</td>
</tr>
<tr>
<td>Nov. 7, 2007</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>QUENCH-16</td>
<td>Water 50 g/s</td>
<td>≈ 1870 K</td>
<td>135 µm</td>
<td></td>
<td>140 µm</td>
<td>850 µm: outer porous, inner dense</td>
<td>air ingress, melt; benchmark</td>
</tr>
<tr>
<td>July 27, 2012</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>QUENCH-17</td>
<td>Water 10 g/s</td>
<td>≈ 1800 K</td>
<td></td>
<td></td>
<td>completely oxidized</td>
<td>110 / 1</td>
<td>DEBRIS formation</td>
</tr>
<tr>
<td>Jan. 31, 2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Quenching with emergency cooling water

- Fuel rod, $\Phi \sim 10\,\text{mm}$
- $1000^\circ\text{C} < T < 2000^\circ\text{C}$
- Saturated 2 phase fluid
- Film boiling
- Nucleate boiling
- Collapsed water front
- Steam + Hydrogen
- Water

$>200\,\text{mm}$
Crack development in the cladding, cooled down with steam. Crack density ~ 4 cm/cm²

Negligible oxidation of crack edges gives only some percent of generated hydrogen
Weakening of protective oxide layer by breakaway oxidation: QUENCH-12 (VVER, old E110) vs. QUENCH-06 (Zry-4)

Q12: rubble on spacer grid consists of spalled cladding scales and fragments of partially oxidized cladding

Q12 cladding: spalling of oxide scales due to breakaway effect

Q06 cross-section

Q06 oxidized cladding
Increased hydrogen production during reflood after breakaway:
QUENCH-12 (old 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 starvation conditions

Steam starvation at 1700K

„Thin“ oxide layer

Steam starvation at 1700K

„Thick“ oxide layer

Development of metallic precipitations inside oxide layer. Precipitates will expose to intensive oxidation during following flooding
Oxidation of Zircaloy-4 in O$_2$, N$_2$, and air /thermogravimetric measurements/

Significant nitride formation in air but not in pure nitrogen
Air ingress after strong cladding pre-oxidation (QUENCH-10): local nitride formation with formation of reoxidised “pockets” during reflood

pre-oxidation: thick ZrO₂

post-air-ingress: nitrided “pockets”

post-reflood: re-oxidised “pockets”
Air ingress after moderate pre-oxidation (QUENCH-16): massive nitride formation with their intensive re-oxidation during quench

pre-reflood

post-reflood

Endoscope observation at ~850 mm

prior nitrided scale re-oxidised during quench and spalled

thick internal $\text{ZrO}_2$ sub-layer growing during flooding

nitride formation inside oxide layer
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

**QUENCH-14 (M5)**
- rod #11

**QUENCH-06 (Zry-4)**
- rod #12
Eutectic melt induced upper 1200°C by absorber rod: complementary tests Q-07 (B$_4$C rod) and Q-08 (without absorber)

QUENCH-07: formation of significant melt amount and melt relocation
B$_4$C$\leftrightarrow$Fe eutectic at $\sim$1150°C
Zry $\leftrightarrow$ SS eutectic at $\sim$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:

![Graph showing hydrogen production for different test phases](image-url)
QUENCH-11, elev. 837 mm: melt relocated outside fuel rods and oxidised in steam.
Hydrogen release
with (Q-02, Q-11) and without (Q-14) melt oxidation in steam
SUMMARY of the QUENCH program

Six parameters, enhancing hydrogen production, have been identified:

• Low reflood flow rates < 1 g/s/rod (QUENCH-07, -08, -11)

• Breakaway effect with weakness and spallation of protective oxide layer (QUENCH-12)

• Steam starvation (QUENCH-09)

• Nitride formation by air ingress with formation of very porous oxide layer during following reflood (QUENCH-10, -16)

• High temperatures with melt relocation outside claddings and intensive melt oxidation (QUENCH-02, -03, -11)

• Eutectic interactions between B₄C, stainless steel and Zircaloy-4 leading to low melting point (QUENCH-07, -09)
LOCA program at KIT on secondary hydrogenation of cladding and its influence on cladding embrittlement

Sequence of phenomena:

- cladding ballooning and burst at T>700°C, 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
QUENCH-LOCA program at KIT (2010-2015): 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

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

hydrogen bands inside cladding detected with n°-radiography:
max 2500 wppm hydrogen content
double rupture of cladding along hydrogen bands during tensile tests (UTS $R_m \approx 300$ MPa)

secondary hydriding

Outlook: Four bundle tests with non- and pre-hydrogenated M5® and ZIRLO™ claddings will be performed up to 2015
Thank you for your attention


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