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 (very) 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
Main topics during the last year

- ACM bundle tests
  - QUENCH-14 with M5® cladding
  - QUENCH-15 with ZIRLO™ cladding

- Separate-effects tests (SET)
  - Oxidation of advanced Zr cladding alloys in various atmospheres
  - Neutron radiography for determination of absorbed hydrogen in SET samples and bundle rods
  - Single-rod experiments on failure of AgInCd control rods
  - High-temperature oxidation of hafnium
QUENCH bundle facility

- Bundle with 21-31 fuel rod simulators of ~2.5 m length
- Electrically heated: ~1 m; max 70 kW
- Fuel simulator: ZrO₂ pellets
- Quenching (from bottom) with water or saturated steam
- Off-gas analysis by mass spectrometer (H₂, steam …)
- Extensive instrumentation for T, p, flow rates, level, etc.
- Removable corner rods during test

QUENCH-14 and QUENCH-15

- Bundle tests with M₅® and ZIRLO™ claddings in the frame of QUENCH-ACM
- Test protocol identical to reference test QUENCH-06 with Zry-4 cladding (OECD ISP-45)
- Conducted at 2 July 2008 and 27 May 2009
- First analyses of results indicate a similar global bundle behaviour of QUENCH-14/-15 and QUENCH-06
QUENCH-14: Power profile and temperature

QUENCH-14: Temperature at reflood
**QUENCH-ACM: Hydrogen release**

![Bar chart showing hydrogen release for different materials](image1)

- **Zry-4**
- **E110**
- **M5**
- **ZIRLO**

**QUENCH test**
- Q-06
- Q-12
- Q-14
- Q-15

**Hydrogen release, g**

**before reflood**

**during reflood**

**Post-test hydrogen content in corner rods and cladding**

**QUENCH-14: Hydrogen absorption**

![Graph showing hydrogen concentration vs bundle elevation](image2)

- **rod A, Zry-4**
- **rod C, E110**
- **rod 16, M5**

**H concentration, at.%**

**Bundle elevation, mm**

- 500
- 600
- 700
- 800
- 900
- 1000
- 1100
- 1200
- 1300

**E110**

**Zry-4**

**M5**

**1300**

**1100**

**900**

**700**
Separate-effects tests

- New furnace for in-situ neutron radiography commissioned at PSI

- Oxidation tests of advanced cladding alloys
  - Zircaloy-4, Duplex, M5, Zirlo, E110
  - Steam and air atmosphere
  - 600-1200 °C in TG
  - Higher temperatures in tube furnace (BOX)

- High-temperature oxidation of hafnium (preparation for QUENCH-Debris)

- Single-rod tests on degradation of AgInCd absorber rods

INRRO furnace for in-situ hydrogen analysis

In-situ Neutron Radiography Reaction Oven

\[ T_{\text{max}} = 1600 \, ^\circ\text{C} \]

Time- and space-resolved in-situ determination of hydrogen uptake by Zr alloys
INRRO furnace for in-situ hydrogen analysis

Zircaloy-4, 6 h at 1000 °C in steam

TG with steam furnace

- Online mass gain during oxidation
- Max. temperature 1250°C
- Steam supply to the specimen from the top
- Ar as protective gas for the balance
⇒ Almost pure steam atmosphere at specimen
Specimens

- 2-cm cladding segments
- Both side oxidation allowed

Composition (main alloying elements)

<table>
<thead>
<tr>
<th>Element</th>
<th>Zry-4</th>
<th>D4</th>
<th>M5</th>
<th>E110</th>
<th>ZIRLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sn</td>
<td>1.5</td>
<td>0.5</td>
<td>0.01</td>
<td>&lt; 0.01</td>
<td>1</td>
</tr>
<tr>
<td>Fe</td>
<td>0.2</td>
<td>0.5</td>
<td>0.05</td>
<td>0.008</td>
<td>~0.11</td>
</tr>
</tbody>
</table>

Isothermal tests – TG results
Isothermal tests – Post-test appearance (1)

- 600 °C
- Zircaloy-4
- Duplex
- M5
- E110
- ZIRLO

- 700 °C

- 800 °C

Isothermal tests – Post-test appearance (2)

- 900 °C

- 1000 °C

- 1100 °C

- Zircaloy-4
- Duplex
- M5
- E110
- ZIRLO
Isothermal tests – Metallographic images

3 h, 1000 °C

3 h, 1100 °C

Zry-4

M5

ZIRLO

Typical oxide structures at 1000 and 1100 °C

Determination of H in Zry samples by NR

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Zry-4</th>
<th>Duplex</th>
<th>M5</th>
<th>E110</th>
<th>ZIRLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>900</td>
<td></td>
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</tr>
</tbody>
</table>
Transition to breakaway

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Time at transition h</th>
<th>Oxide at transition µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>6-8</td>
<td>3-8</td>
</tr>
<tr>
<td>700</td>
<td>1-10</td>
<td>7-17</td>
</tr>
<tr>
<td>800</td>
<td>1-7</td>
<td>11-37</td>
</tr>
<tr>
<td>900</td>
<td>0.6-1.5</td>
<td>18-33</td>
</tr>
<tr>
<td>1000</td>
<td>0.3-0.7</td>
<td>43-85</td>
</tr>
</tbody>
</table>

AgInCd control rod tests in the QUENCH-SR rig

- Four tests retracing temperature history of 950 mm elevation in QUENCH-13
  - with and w/o inner oxidation of Zry-4 guide tube
  - with and w/o initial contact between Zry-4 and SS tubes
- One test retracing temperature history of 750 mm elevation in QUENCH-13
  - asymmetric, with holes
- One test without Zry-4 guide tube
Post-test appearance and failure temperatures

1450°C

SIC-11
w/o Zry-4 guide tube

QUENCH program 2010-2014

QUENCH-DEBRIS
• In the frame of EC-SARNET-2
• Investigation of formation and coolability of debris and melt in the core
• Two tests planned, final boundary conditions tbd.

QUENCH-LOCA
• In cooperation with German industry and GRS
• Investigation of ballooning and (secondary) hydrogen uptake of advanced cladding alloys in realistic bundle geometry
• Critical review of embrittlement criterion
• Complementary to various single-rod-tests worldwide (Halden, Studsvik, JHR (2015))
Finally…

You are invited to the

15th International QUENCH Workshop

Forschungszentrum Karlsruhe (FZK)
November 3-5, 2009

www.fzk.de/quench

Thank you for your attention