Is Spent Nuclear Fuel Immune from Delayed Hydride Cracking (DHC) during Dry Storage? – An IAEA Coordinated Research Project

Contribute information on DHC for Zircaloy-4 fuel cladding

The objective:

to evaluate the temperature dependence of the loading threshold for DHC in Zircaloy-4 cladding and apply the results to the conditions for dry storage. The results are based on an international, interlaboratory experimental programme.
Outline

• Limits of DHC
• Conditions during dry storage of spent nuclear fuel
• Measurement of limits of DHC leading to immunity
• Application to dry storage
Limits of DHC

- Hydrogen concentration
- Heating
- Stress intensity factor – $K_{IH}$
- Temperature
Temperature dependence of DHC

\[ v_c = v_0 \exp(-Q/RT) \]
Limits of DHC

- Hydrogen concentration
- Heating
- Stress intensity factor – $K_{IH}$
- Temperature
$K_I = f(\sigma \sqrt{a})$

**Diagram:**

- **Stress intensity factor (K$_I$)**
  - **No crack growth**
  - **Stable crack growth**
  - **Unstable crack growth**
  - **V$_C$**

**Graph:**

- Log Crack velocity

**Equation:**

$K_{IH} = \text{Something}$
Limits of DHC

- Hydrogen concentration
- Heating
- Stress intensity factor – $K_{IH}$
- Temperature
Conditions during dry storage

• High temperature from radioactive decay that declines with time:
  USNRC requires $\leq 400 \, ^\circ\text{C}$

• Hoop stress from internal gas pressure that declines with temperature through Gas Law:
  USNRC requires $\leq 90 \, \text{MPa}$
Potential failure mechanisms

- Oxidation: inert atmosphere
- I-SCC: no stress ramp and temperatures too low for I migration
- Creep rupture: predicted strains < 1%
- DHC: subject of this paper
Cladding materials – Zircaloy-4

- **LWR**
  - PWR Stress-relieved, 480 °C, 3.5 h (CWSR)

- **CANDU**
  - Stress-relieved, 500 °C, 8 h
## Cladding materials - dimensions

<table>
<thead>
<tr>
<th></th>
<th>Outside diameter</th>
<th>Wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>9.5</td>
<td>0.57</td>
</tr>
<tr>
<td>CANDU</td>
<td>13.1</td>
<td>0.39</td>
</tr>
</tbody>
</table>
## Microstructure

<table>
<thead>
<tr>
<th></th>
<th>Grain width (µm)</th>
<th>Grain shape</th>
<th>Texture $F_R$</th>
<th>Strength at 250°C (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>&lt;1</td>
<td>Elongated</td>
<td>0.58</td>
<td>419</td>
</tr>
<tr>
<td>CANDU</td>
<td>4</td>
<td>Elongated/Equiaxed</td>
<td>0.66</td>
<td>256</td>
</tr>
</tbody>
</table>
Pin-Loading Tension Specimen, Fixture and Assembly (Studsvik Nuclear)

\[ K_I = \left[ \frac{P}{2t\sqrt{W}} \right] f \left(\frac{a}{W}\right) \]
Specimen preparation & testing

- 120 to 180 ppm hydrogen added
- Circumferential hydrides
- 13 mm long section
- Two notches extended 1.5 mm by fatigue
- Crack detection by potential drop, crack opening or microscopy
- Testing in temperature range 227 to 315 °C
Test temperature history

Peak temperature, 60 min

$1,5^\circ\text{C/min}$

$5^\circ\text{C/min}$

$30\text{ min}$

Test temperature

Loading
Methods to test for $K_{IH}$

- Multiple specimen method
  - Based on ASTM E1681
- Constant displacement
  - Based on ASTM E1681
- Stepped uploading
- Stepped downloading
Multiple separate specimens

CANDU
250°C
7 MPa√m
Constant displacement

PWR
267°C
7.6 MPa√m
Stepped downloading

PWR
250°C
5.2 MPa√m
Crack surfaces after test on PWR cladding at 267°C

Top: 6.16 mm, bottom: 6.55 mm; difference 6.1%

\[ K_{IH} = 7.6 \text{ MPa}\sqrt{m} \]
\[ K_{IH} = \sqrt{C/(1/(1-2\nu)-\sigma_f/\sigma_y}) \]

where
\[ C = E^2 \epsilon_T t/8\pi(1-\nu^2)^2 \]
High temperature limit for DHC in PWR cladding, $T_0$

![Graph showing crack growth rate and test temperature relationship for PWR KIH, V Ref [28], and PWR V.](image)
Immunity from DHC during dry storage of spent nuclear fuel

![Graph showing immunity from DHC at different temperatures and hoop stress over time.]

- Immune at 360°C
- Immune at 320°C
- Hoop stress

Temperature (°C) vs. Time (Years)
Critical flaw depth at US NRC limit

- \( a = \left( \frac{K_{IH}}{\sigma} \right)^2 \cdot \frac{Q}{1.2 \pi} \)
- \( Q \), shape factor varies between 1.0 and 1.5
- Limiting stress, \( \sigma \), is 90 MPa
- \( K_{IH} = 5.2 \text{ MPa} \sqrt{\text{m}} \)
- Flaw depth, \( a \), 1.5 to 2.3 times cladding thickness: through-wall
- No cracks observed up to 20 years storage
Summary

- $K_{IH}$ in Zircaloy fuel cladding measured by four techniques.
- At 250°C value was 5.2 MPa$\sqrt{m}$ for PWR cladding.
- $K_{IH}$ increased with temperature to a high value with corresponding drop in crack growth rate.
- Represents immunity from DHC.
Summary (continued)

• For DHC, flaws have to be very large to grow.
• The temperature immunity and large critical flaw size imply DHC unlikely during dry storage of spent fuel; conclusion supported by surveillance.
• Recommend more surveillance and testing of irradiated material to increase confidence in this conclusion.