Supplement of

Hydride reorientation in fuel cladding under interim storage conditions with low hoop stress

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KEK-Initiative – „Kompetenzerhalt in der Kerntechnik“

Funded by: Federal Ministry for Economic Affairs and Climate Action

Lead partner: GRS – global research for safety

14 September 2023
Regulatory framework

Interim storage:
Licensed for 40 years as of first packaging / storage of cask, e.g. 1994 in Gorleben

StandAG:
Final depository found by 2031
Without permits or construction!

BGE estimation:
Reasonable until 2068

Guideline by ESK
Need verification of cask and inventory safety after licensed timeframe, including:
- Physical framework
- Material behaviour
- Aging
- Inspection of not accessible components like cladding tubes, spacers etc.
Unknnowns and uncertainties with the unresolved final storage situation

Main considerations for extended interim storage:

- Castor storage containers likely not suitable for final storage
  - Opening of containers
  - Unknown load limits for fuel handling

- Mechanical properties of the stored fuel assemblies are in question
  - Quantity, type and orientation of hydrides
  - Changes due to creep by swelling and gas emission
  - Combination of these factors with changes by neutron flux, hardening, embrittlement

Source:
Research field hydrides

Stress induced hydride redistribution/-orientation

- Load switch from compressive to tensile stress in cladding
- Hydrogen solved interstitially (partially with T)
- Pressure from the inside causes tensile stresses in cladding
  - Tensile stresses lead to decrease of distance between circumferential lattice planes – less energy available
  - Decrease promotes precipitation in radial direction
    – becomes favourable direction
- Hydrogen diffuses along stress and temperature gradients
  ➢ Diffusion might lead to prolonged hydride chains across wall
Previous investigations: high hydrogen content

Source:

Source:

Reorientation parameters

- **Kim**:
  - Hydride content: ~ 300 ppmw
  - Stress: 50 - 90 MPa
  - Cooling rate: ~ 0.5 K/min

- **Chu**:
  - Hydride content: ~ 320 ppmw
  - Stress: 160 MPa
  - Cooling rate: ~ 1 K/min
  - Cycling 400 °C – 170 °C
    0 / 1 / 4 / 12 Cycles
Previous investigations: low hydrogen content

Reorientation parameters

- Kim:
  - Hydride content: ~ 137 ppmw
  - Stress: 150 MPa
  - Cooling rate: ~ 0.5 K/min

- Chu:
  - Hydride content: ~ 130 ppmw
  - Stress: 160 MPa
  - Cooling rate: ~ 1 K/min
    - Cycling 400 °C – 170 °C
Hypothesis

- **Rapid cooling:**
  - Supersaturation -> precipitation
  - Growth of hydrides

- **Slow cooling with hydrides:**
  - Migration to existing hydrides
  - Nucleation at existing hydrides
    - Growth of circumferential hydrides

- **Slow cooling without hydrides:**
  - Migration of hydrogen
  - Nucleation at lattice anomalies
  - Hydride growth

Source:
### Current approach

<table>
<thead>
<tr>
<th>$\sigma_{\text{hoop}}$ in MPa</th>
<th>$\text{H}_2$-content in wppm</th>
<th>Cooling rate</th>
<th>$90$</th>
<th>$100$</th>
<th>$110$</th>
<th>$130$</th>
<th>$150$</th>
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<td>4 K/h</td>
<td>200</td>
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</tbody>
</table>
High hydrogen content

Hydride redistribution/-orientation
- Primarily circumf. hydrides
- Small amount of radial hydrides
- Interconnection between radial and circumf.

From Literature
- Primarily circumferential hydrides
- Small amount of radial hydrides
- Origin of radial hydrides at circumf. hydrides

Low hydrogen content

Findings for low hydrogen:

- Stress between 70 - 90 MPa has low influence on reorientation
- Very high reorientation factors even with “high” cooling rates
- Overall high influence of H-content on reorientation factor
- Threshold for reorientation way below 70 MPa (solubility hysteresis)
Solution corrected precipitation

Isochore conditions:

\[
\frac{p_1}{p_2} = \frac{T_1}{T_2}
\]

- \( p_1 \): Pressure before cooling (90.4 bar)
- \( p_2 \): Pressure after cooling (72.3 bar)
- \( T_1 \): Starting temperature (673.15 K)
- \( T_2 \): End temperature (538.8 K)

\[
\sigma_t = \frac{p \cdot r}{s}
\]

- \( \sigma_t \): Hoop stress
- \( \sigma_a \): Axial stress
- \( s \): Wall thickness
- \( r \): Radius
- \( p \): Pressure

\[
\sigma_t = \frac{7.23 \text{ MPa} \cdot 4.13 \text{ mm}}{0.57 \text{ mm}} = 52.4 \text{ MPa}
\]

**Graphical representation:**

- Temperatures: 400 °C, 266 °C
- Concentration vs. temperature

**Equations:**

\[
T_{TSSD} = \frac{36540}{R \ln \frac{1.28 \cdot 10^5}{c_H}}
\]

\[
T_{TSSP} = \frac{28068}{R \ln \frac{5.26 \cdot 10^4}{c_H}}
\]

\( c_H = 100 \text{ ppmw} \)

Conclusions & consequences

Conclusions:
- Cooling rate has low influence on reorientation
- Reorientation is highly dependent on H-content
- Hypothesis by Kaufholz et al. validated
- Low contents lead to low precipitation temperatures
- Threshold for reorientation way below 70 MPa
- Calculated around 52 MPa
- Hydrides through the wall are possible

For handling:
- Mechanical properties are to be tested
- New alloys which are designed for low H-content need to be tested for similar behaviour
- Low burnup rods are prone to this behaviour
  - Older fuels and VVER

For conditioning:
- Multi barrier system should be stabilised
  - Integrity of fuel rods
- Planning of conditioning and decommission needs reliable information for fuel properties
  - for western designs as well as VVER

Ramifications:
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