Mechanical properties of pre-hydrogenated (600 – 5000 wppm) cladding segments

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Objectives

• Preparation of hydrogenated probes for mechanical tests

• Hydrogen uptake under hydrogen starvation conditions to achieve axial hydrogen gradient in the cladding

• Tension and ring compression tests with hydrogenated probes
Short term secondary hydrogenation after ballooning and burst: hydrogen uptake increased rapidly up to 4000 ppm (significant higher than ductility limit of 500 ppm)

NUREG-6967 (2008): unirradiated sample OCL11 ramped in steam from 300°C to 1204°C at 5°C/s, held at 1204°C for 300 s, cooled at 3°C/s to 800°C, and cooled from 800°C to RT

sample OCL11 (Zircaloy-2):
Hydrogenation facility

vertical 3-zones tube furnace LORA (height 60 cm)

H2 and Ar supply

sample extraction at furnace top

steel rod

flame (burning of H2)

sample

sample 15 cm

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### Test matrix

<table>
<thead>
<tr>
<th>probe</th>
<th>temperature</th>
<th>H2 partial pressure</th>
<th>hydrogenation duration</th>
<th>dissolved hydrogen (weight gain)</th>
<th>hydrogen solubility limit</th>
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</thead>
<tbody>
<tr>
<td>H11Z4</td>
<td>700</td>
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<td>16770</td>
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<td>2</td>
<td>681</td>
<td>10820</td>
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<tr>
<td>H14 Z4</td>
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<td>4</td>
<td>1819</td>
<td>10820</td>
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<td>10820</td>
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<tr>
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<td>8</td>
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<tr>
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<tr>
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<td>900</td>
<td>37</td>
<td>8</td>
<td>1689</td>
<td>2770</td>
</tr>
</tbody>
</table>
Post-test probe appearance:
probe bending at T<800°C due to phase transition $\alpha$-Zr to $\beta$-Zr

H14Z4: annealed at 700 °C with H2 (37 mbar); $\Delta t=240$ s $\Delta m_H=1800$ wppm

H19Z4: annealed at 800 °C with H2 (37 mbar); $\Delta t=240$ s $\Delta m_H=1600$ wppm

H33Z4: annealed at 900 °C with H2 (37 mbar); $\Delta t=480$ s $\Delta m_H=1700$ wppm
Axial distribution of hydrogen content measured by neutron radiography

Hydrogenation duration @ T:
- 60 s @ 900°C
- 240 s @ 900°C
- 480 s @ 900°C
- 480 s @ 700°C

Hydrogen content, wppm vs. Elevation, mm

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Tension tests with probes hydrogenated at 700 and 800°C: rupture with negligible contraction

700°C: significant hydrogen gradient

- 5400 wppm
- 4800 wppm
- 2700 wppm

- 2500 wppm
- 1800 wppm
- 680 wppm

800°C: moderate hydrogen gradient

- 2800 wppm
- 1600 wppm
- 800 wppm

ductile not hydrogenated probe with pronounced contraction
Tension tests with probes hydrogenated at 800°C (moderate H gradient) and 900°C (small gradient)

- Ductile not hydrogenated probe with pronounced contraction
- Negligible contraction
Compression tests with rings from bottom of probes hydrogenated at 700 and 800°C

- 700°C
- 800°C

Graphs showing load vs. displacement for different hydrogenation levels at 700°C and 800°C.
Compression tests with rings from bottom of probes hydrogenated at 700 and 900°C: hardening and embrittlement increase at higher annealing temperature
Summary

- Twelve Zry-4 cladding specimens with length of 150 mm were hydrogenated in Ar + H₂ atmosphere at temperatures 700, 800 and 900 °C.

- Average hydrogen content was measured with probe weighing between 600 and 5000 wppm. Axial hydrogen distribution was measured by neutron radiography.

- No macroscopic hydrides were observed by means of optical microscopy.

- Tension and ring compression tests showed clear hardening and embrittlement increase with increased hydrogen content and annealing temperature.
The authors would like to thank Ms Peters, Ms Baudin, Ms C. Goulet and Ms Wozniak

Thank you for your attention