Effects of Pre-Irradiation on Irradiation Growth & Creep of Re-Crystallized Zircaloy-4

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Background & Motivation for this Study

- Excessive creep and growth of Zr alloy components can cause problems in service
  - For example in PWRs guide tube bowing can lead to incomplete control rod insertion (IRI)
  - Several factors known/suspected to influence irradiation creep and growth but a complete understanding is lacking

- Nuclear Fuel Industry Research (NFIR) program commissioned in-pile creep & growth test at Halden
  - Irradiated guide tube material supplied by program members for testing with an innovative in-pile technique
  - To obtain guide tube axial creep and growth rates - providing data for comparison with existing models
  - To reveal any influence of hydrogen (suspected to affect growth) on creep and growth behaviour
Materials used in the Study

- Several sections recrystallized Zry-4 guide tube from 3 fuel assemblies from 2 commercial PWRs (USA & France)
  - High hydrogen (W2): 600 - 800 ppm [H]; 321°C; 1.00 E+22 ncm⁻²
  - Medium hydrogen (W1): 225 - 250 ppm [H]; 307°C; 1.05 E+22 ncm⁻²
  - Low hydrogen (F): 135 - 142 ppm [H]; 295-300°C; 0.96 E+22 ncm⁻²

- Material characterisation: oxide thickness (blue) and hydrogen content (red) determined before and after Halden irradiation
Test Rig & Specimen Matrix

- Test rig uses a pressure flask connected to a PWR test loop in the Halden reactor (320°C, 16 MPa, B/LiOH)
- Extensometer (LVDT) attached to each specimen for on-line length change measurement
- Booster fuel rods surround bottom 2 specimen clusters to create region of fast flux (3 E+13 n/cm²/s)
- High, medium, low [H] specimens placed in each cluster:
  - Cluster 4: axial compression, no fast flux - (thermal creep)
  - Cluster 3: no axial compression, no fast flux - controls
  - Cluster 2: no axial compression, fast flux - growth
  - Cluster 1: axial compression, fast flux - creep & growth
No Axial Compression: Growth or Controls
Axial Compression Specimen: Creep & Growth

- Loop pressure squeezes a sealed bellows which applies a compressive axial force on guide tube via a “nut and bolt” arrangement

Bellows upper end -plug inserted into GT and clipped into rig structure

Guide tube with welded on end -sleeves

Connecting bolt

Transformer support tube Allen bolted to bellows upper end -plug

Transformer screwed onto support tube

End -sleeves welded to GT

Nut

Mobile armature screwed into connecting bolt

Loop pressure squeezes a sealed bellows which applies a compressive axial force on guide tube via a “nut and bolt” arrangement.
Cluster 2: In-Pile Growth Results (no load)

- Data from Cycle 1 perturbed by LVDT movement ~50 µm over ½ cycle 😞
- Data from Cycle 0 missing due to LVDT failures (bad cables) 😞
- Growth appears linear (fluence increment is small in 457 power days) ☺️
Cluster 1: In-Pile Creep & Growth Results

- Data from Cycle 1 perturbed by LVDT movement ~50 µm over ½ cycle 😞
- Data from Cycle 0 missing due to LVDT failures (bad cables) 😞
- Growth behaviour countered by compressive load – lower elongation rates 😊

Cluster 1 Fast Neutron Fluence Accumulated in Halden (E+20 n/cm²)

Specimen Elongation (µm)
Images from Metallography: medium [H]

A) Overview showing the hydride precipitates

After base irradiation
225 ppm

After Halden irradiation
340 ppm
## Summary of In-Pile Creep and Growth Rates

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Base Hydrogen (ppm)</th>
<th>[H] Uptake (ppm)</th>
<th>Base Temperature (°C)</th>
<th>Stable Creep &amp; Growth Rate (%/dpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>growth</td>
<td>135</td>
<td>104</td>
<td>295-300</td>
<td>0.045</td>
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<tr>
<td></td>
<td>225</td>
<td>115</td>
<td>307</td>
<td>0.080</td>
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<tr>
<td></td>
<td>800</td>
<td>88</td>
<td>321</td>
<td>0.123</td>
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<tr>
<td>creep &amp; growth</td>
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<td>84</td>
<td>295-300</td>
<td>0.008</td>
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<tr>
<td></td>
<td>250</td>
<td>112</td>
<td>307</td>
<td>0.056</td>
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<tr>
<td></td>
<td>600</td>
<td>250</td>
<td>321</td>
<td>0.094</td>
</tr>
</tbody>
</table>

- Ratio growth rates low: medium: high = 1: 1.86: 2.86
- Each creep & growth rate less than growth without load by similar amounts
Main Summary

- Three guide tube specimens with three slightly different base irradiations exhibited three distinct growth rates during a re-irradiation in the Halden reactor
  - Irradiation conditions in Halden the same
  - Differential oxidation / hydrogen uptake during the re-irradiation ruled out as the cause of the difference in growth rate
  - Main difference between the materials was hydrogen content (from base irradiation) – higher growth rate for higher [H]
  - However, higher growth rate also correlated with higher base irradiation temperature
  - Substantiating a cause for either of these correlations is not considered in this paper, but is the subject of a further analysis and assessment carried within the NFIR program
Thank you for your attention