
S. K. Yagnik¹, J-H Chen², and R-C Kuo²

¹ EPRI (USA), ² INER Taiwan

17th International Symposium on Zirconium in the Nuclear Industry
Hyderabad (India)
February 3-7, 2013
Presentation outline

• Introduction
• Experimental
  – Hydride Distributions and Materials Tested
  – Specimen Geometry/Feasibility Study/Bending Effects
  – Validation of Test Procedure
• Results
  – Scope of Testing
• Data and Discussion
  – Elongation/Strength/Fractography/Effect of Material processing
• Conclusions
Introduction (1)

- Effects of hydrides on the mechanical integrity of Zr-alloy fuel assembly components depend on three main characteristics:
  - Concentration (ppm of H);
  - Morphology (orientation and spacing of hydride platelets);
  - Distribution/Localization

Re: hydride Distribution in fuel cladding, typically,
  - Hydride rim (e.g., H migration down the temperature gradient);
  - Blisters/Lens (e.g., due to oxide spallation)
Introduction (2)

- Typically, at comparable hydrogen contents, hydride localization is more detrimental

Hydride Rim

Present Study

Hydride Lens

15th Symposium (2007); STP-1505
Hydride Distributions in Materials Tested

- **Unirradiated SRA Zr-4 Cladding:**
  - Uniform
  - Rimmed
  - Layered

- **Irradiated RXA Zr-4 Guide Tube:**
  - Uniform hydrides
  - $7 \times 10^{25} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$)
Hydriding Procedures

- Uniform: Gas phase charging; including temperature cycling
- Rimmed: Uniform (~ 200 ppm) or rim hydriding followed by a cathodic charging step
- Layered: Uniform samples imposed with temperature gradient
Test Samples and Loading Configuration

• Uniaxial tension Test (UTT)
  – Plane stress
  – Circumferential hydrides normal to loading direction

• Slotted-Arc Test (SAT)
  – Plane strain
  – Circumferential hydrides along loading direction
  – Considerations for specimen geometry and bending effects

14th Symposium (2005); STP-1467
Illustration of hydride distribution in UTT and ISATP

UTT

Fracture Surface

View of Longitudinal Fractograph

Circumferential Hydride

View of Cross-section

ISATP

Circumferential Hydride

Fracture Surface

View of Cross-sectional Fractograph
Bending Effects: Defined and FEM Analysis

\[
\text{Bending Effect} = \frac{\Delta \sigma_{i-o}}{\sigma_{\text{mean}}} = \frac{\sigma_i - \sigma_o}{(\sigma_i + \sigma_o)/2}
\]

ISATP: Best choice for avoiding bending effects while retaining interesting high [H] OD region

© 2013 Electric Power Research Institute, Inc. All rights reserved.
Strain and Stress Distributions in one Quadrant of ISATP
ISATP Sample Fabrication

Unit: mm

Hydrogen Determination

Metallographic Examination

ISATP Specimens
Validation of Test Procedure

![Diagram with labeled components: Guiding Rail, Non-contact Strain Measuring System, Grip, Anti-bending Mechanism, and a graph showing Stress (MPa) vs. Strain (mm/mm).]
Results: Ductility Data Obtained

- For the three types of hydride distributions and two types of loading configurations at RT and 300°C:
  - Uniform (UE) and Total Elongation (TE) as a function of $[H]$
    - 3 distributions x 2 test type x 2 temps x 2 elongations = 24 data sets
  - Plotted in this format (by linear regression)
    - Elongation = Constant − Slope * $[H]$
- Ultimate Tensile Strength (UTS) and Yield Strength (YS)
  - Compared for the three distributions
  - Compared for irradiated RXA GT vs irradiated SRA cladding
- Fractography (comparative fracture modes)
TE and UE at RT for UTT Geometry

- Total Elongation %
  - Hydrogen Concentration (ppm)

- Uniform Elongation %
  - Hydrogen Concentration (ppm)
TE and UE at 300°C for UTT Geometry

Graph showing the relationship between total elongation and uniform elongation with hydrogen concentration in ppm for different geometries: Uniformly Hydrided, Hydride-Rimmed, and Hydride-Layered.
TE and UE at RT for ISATP Geometry
TE and UE at 300°C for ISATP Geometry
### Summary Elongation Data (by Linear Regression)

<table>
<thead>
<tr>
<th>Linear Regression</th>
<th>UTT</th>
<th>ISATP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>300°C</td>
</tr>
<tr>
<td>Uniformly Hydrided</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Elongation</td>
<td>TE(%) = 18.525 - 9.091*10^{-3} *C_H</td>
<td>TE(%) = 15.876 - 1.378*10^{-3} *C_H</td>
</tr>
<tr>
<td>Uniform Elongation</td>
<td>UE(%) = 7.983 - 1.692*10^{-3} *C_H</td>
<td>UE(%) = 5.283 - 2.988*10^{-4} *C_H</td>
</tr>
<tr>
<td>Hydride-Rimmed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Elongation</td>
<td>TE(%) = 19.502 - 1.498*10^{-2} *C_H</td>
<td>TE(%) = 16.268 - 4.686*10^{-3} *C_H</td>
</tr>
<tr>
<td>Uniform Elongation</td>
<td>UE(%) = 8.040 - 2.909*10^{-3} *C_H</td>
<td>UE(%) = 5.139 - 5.624*10^{-4} *C_H</td>
</tr>
<tr>
<td>Hydride-Layered</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Elongation</td>
<td>TE(%) = 18.173 - 1.609*10^{-2} *C_H</td>
<td>TE(%) = 17.358 - 7.589*10^{-3} *C_H</td>
</tr>
<tr>
<td>Uniform Elongation</td>
<td>UE(%) = 8.062 - 4.808*10^{-3} *C_H</td>
<td>UE(%) = 6.118 - 1.650*10^{-3} *C_H</td>
</tr>
</tbody>
</table>
UTS and YS at 300°C

UTT at 300°C
- Uniformly Hydrided: UTS
- Hydride-Rimmed: UTS
- Hydride-Layered: UTS
- Uniformly Hydrided: YS
- Hydride-Rimmed: YS
- Hydride-Layered: YS

ISATP at 300°C
- Uniformly Hydrided: UTS
- Hydride-Rimmed: UTS
- Hydride-Layered: UTS
- Uniformly Hydrided: YS
- Hydride-Rimmed: YS
- Hydride-Layered: YS

Not affected by hydride distribution
Fractography Compared Uniform vs Layered (following RT ISATP)

Uniform; \([H] = 719 \text{ ppm}\)

Layered; \([H] = 849 \text{ ppm}\)

Fewer microcracks

Many microcracks
Fractography Compared Uniform vs Layered (following 300°C ISATP)

Uniform; [H] = 842 ppm

Layered; [H] = 778 ppm

Ductile dimples

Brittle microcracks

Ductile dimples and Brittle microcracks
Fractography Compared Rim vs Layered (following RT UTT; longitudinal section)

Rim = 60 μm

Rim = 60 μm + hydride layering

A combination of tensile separation and shear fracturing
Fractography Compared Rim vs Layered (following RT ISATP; cross-section)

Rim = 40 μm  Total [H] = 2363 ppm  Rim = 40 μm + hydride layering  Total [H] = 1020 ppm

The width of tensile separation increased
TE and UE Compared at 300°C between Irradiated RXA and SRA Materials (from UTT)

Limited SRA Cladding data (ESAT)
Conclusions (1)

- Extensive mechanical testing has been performed on small miniature specimens (cut-outs), emphasizing hydride localization, reaching the following conclusions:

1. Elongations decrease with increase in bulk [H] and hydride rim and layer thickness

2. Uniformly hydrided material sustains the largest deformation. At comparable [H], the ductility ranks (from good to best):

   \[ \text{hydride layered} < \text{hydride rimmed} < \text{uniformly hydrided} \]

3. Effective tensile strengths show little dependence on [H] and hydride rim thickness

4. Depending on [H], the fracture of uniformly hydrided material occurs by a shear process.
Conclusions (2)

5. Hydride rimmed and hydride-layered specimens fail by a combined process of tensile separation (rim and dense hydrides region) and shear fracture (alloy matrix region)

6. Combination of [H] and hydride distribution governs the ductility
   - Elongations quantified by linear regression;
   - RXA and SRA Zr-4 compared (within limited [H])
Together...Shaping the Future of Electricity