Effect of Hydrogen on Mechanical Properties and Failure Morphology of LWR Fuel Cladding under Rapid Deformation

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Background

- Analysis on RIA, cask-drop accidents: Mechanical response,
- Data under high strain rates: very limited, tube axial tensile data.

Objectives

- Obtain basic mechanical properties:
  - Stress-strain relationship, ductility, critical strain energy density
  - under uniaxial hoop stress condition
  - with various hydride morphologies at high deformation rate.
1. Experimental
   1.1 Test Method and Apparatus
   1.2 Materials
   1.3 Specimen Description

2. Burst test results
   (stress-strain curve)
   2.1 Unirradiated Cladding Tubes
   2.2 Irradiated Cladding Tubes

3. Discussion
   (effect of major factors)

4. Conclusions
1.1 Test Method and Apparatus

Loading Method (Open end burst test)

- Stress state: uni-axial tension to circumferential direction.
- Pressurization ends within 10-20 ms.
- Strain rates; $10^3$-$10^4$ higher than conventional data
1.1 Test Method and Apparatus

Rapid burst tester installed in the hot cell.

High temperature test assembly with heater, strain detector, and specimen.
### 1.2 Materials

#### Unirradiated tube: As-cold worked Zry-2 (ASC)

#### Irradiated tube: Irradiated in BWR (ZYF, ZYS)

<table>
<thead>
<tr>
<th>Fuel Cladding Tube</th>
<th>ZYF</th>
<th>ZYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding O.D., and Thickness</td>
<td>12.3 mm, 0.86 mm</td>
<td>12.5 mm, 0.86 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Zircaloy-2</td>
<td>Zircaloy-2</td>
</tr>
<tr>
<td>Pellet</td>
<td>UO₂</td>
<td>UO₂</td>
</tr>
<tr>
<td>Reactor</td>
<td>BWR</td>
<td>BWR</td>
</tr>
<tr>
<td>Irradiation Period</td>
<td>1 cycle</td>
<td>5 cycles</td>
</tr>
<tr>
<td>Rod average B.U.</td>
<td>7.1 GWD/t</td>
<td>31.4 GWD/t</td>
</tr>
<tr>
<td>Rod average fast neutron fluence</td>
<td>1.0 (x10^{25} m^{-2}) E&gt;1 MeV</td>
<td>5.4 (x10^{25} m^{-2}) E&gt;1 MeV</td>
</tr>
</tbody>
</table>

Hydrogen charged (High BU fuel)
1.3 Specimen Description

- **High BU fuel rod:** higher H content

- H. charged by autoclave in LiOH

- Characterization of hydride by image analyzer

- **Hydride orientation (Fn):** Not changed for irradiated material.

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Specimen: **ZYS686**, 
As irradiated, 
62 ppm H, Fn=0.22

ZYS687, 
Hydrogen charged, 
115 ppm H, Fn=0.21

ZYS689, 
Hydrogen charged, 
212 ppm H, Fn=0.20
1.3 Specimen Description

- Typical hydride obtained by in-cell H. charging:
  (Specimen: ZYS689, 212 ppm H)

- Zry-2 grains and corresponding hydrides

**Hydrides:**
(1) Transgranular,
(2) connected together at grain boundaries.
2.1 Unirradiated Cladding Tubes (5)

- Typical hydrides morphologies in three dimensional representation for the specimens with circumferential and radial hydrides.

(Specimen: ASC-17 Circumferential Hydrides)

(Hoop stress)

20 μm

Radial

Longitudinal

Tangential

(Specimen: ASC-R23 Radial Hydrides)

(Hoop stress)

20 μm

Radial

Longitudinal

Tangential
2. Burst test results

2.1 Unirradiated Cladding Tubes (1)

**Typical response**

Typical response of lapse time, hoop stress, hoop strain curve during pressurization.

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By plotting stress and strain at given lapse time: stress-strain curve. (ASC-40, 15 ppmH)

![Graph showing hoop stress-strain curve](image)
2.1 Unirradiated Cladding Tubes (2)

- **Effect of radial hydride (R.H.)**
  - Reduced ductility even at low H. concentration.

![Graphs showing stress-strain relationship for unirradiated cladding tubes with different hydride concentrations.](image)

**ASC-32, \( \varepsilon_f : 0.8\% \), 335 ppmH, (Circumferential Hydride at RT)**

**ASC-R52, \( \varepsilon_f : 0.5\% \), 30 ppmH (Radial Hydride at RT)**
2.1 Unirradiated Cladding Tubes (3)

- **Effect of radial hydride**
  Cross section metallograph with, without R.H.

  - Brittle failure;
    30 ppmH with R. H.
    equivalent to 335ppmH with circum. H.

  - Reduce ductility

- ASC-40, 15ppmH, \( \varepsilon \); 6.4%
- ASC-R52, 30ppmH, \( \varepsilon \); 0.5%
- ASC-32, 335ppmH, \( \varepsilon \); 0.8%

- Effect of radial hydride
  - 30 ppmH with R. H. equivalent to 335ppmH with circum. H.
2.1 Unirradiated Cladding Tubes (4)

Temperature dependence (Specimen: as-CW)

- Stress-strain curves are similar except strength.
- No clear temperature dependence in hardening exponent, $n \approx -0.05$.

ASC-106, tested at 25°C
ASC-120, tested at 250°C
ASC-119, tested at 350°C
2.2 Irradiated Cladding Tubes (1)

- **Effect of fuel BU(1)**
  - Low hardening exponent, n, close to zero
  - Affect from 1 cycle irradiation,
  - No clear BU dependence in n and ductility.

**Nippon Nuclear Fuel Development Co., Ltd.**

- Constant: 1061 MPa
  - Strain hardening ex. : 0.001
- **σ = K ( ε p)^n**
  - K : Constant: 1061 MPa
  - n : Strain hardening ex. : 0.001

- Constant: 1099 MPa
  - Strain hardening ex. : 0.002
- **σ = K ( ε p)^n**
  - K : Constant: 1099 MPa
  - n : Strain hardening ex. : 0.002
2.2 Irradiated Cladding Tubes (3)

- Effect of fuel BU(2)
  - Difference in neutron fluence
  - Generally ductile for lower fluence, but almost same.

- Due to the difference in failure mode.
  (spiral and axial opening)

- Spiral deformation cause low strain hardening, low ductility.

(ZYF681, 8.1x10^{24}m^{-2}, E>1MeV, 30ppm H, failure strain 2.3%)
(ZYS685, 6.2x10^{25}m^{-2}, E>1MeV, 69ppm H, failure strain 2.4%)
2.2 Irradiated Cladding Tubes (2)

**Combined effect of hydrogen & irradiation**

- True stress - true strain curve
- Engineering stress - engineering strain curve

Results: Engineering (Nominal) values
\[ \sigma_{\text{yield}} : 948 \text{ MPa}, \quad \sigma_{\text{UTS}} : 964 \text{ MPa} \]
\[ \varepsilon_{\text{uniform}} : 0.4 \text{ (plastic), } 1.4 \% \text{ (total)} \]
\[ \varepsilon_{\text{total}} : 0.4 \text{ (plastic), } 1.4 \% \text{ (total)} \]
Max. Strain Energy Density: 16.2 (MN-m/m^3)

- Failed before plastic deformation

Nominal Stress, Nominal Strain
\[ \sigma_{\text{yield}} : 0 \text{ MPa}, \quad \sigma_{\text{UTS}} : 701 \text{ MPa} \]
\[ \varepsilon_{\text{uniform}} : -0.0 \text{ (plastic), } 0.7 \% \text{ (total)} \]
\[ \varepsilon_{\text{total}} : -0.0 \text{ (plastic), } 0.7 \% \text{ (total)} \]
Max. Strain Energy Density: 4.0 (MN-m/m^3)

**Importance of combined effect of neutron irradiation and hydrides on mechanical properties.**
3. Discussion

Effect of temperature and hydrogen concentration on strength


 Almost the same temperature dependence, No effect of hydrogen concentration above 150°C
Effect of temperature and hydrogen concentration on ductility

- Ductility: Reduces
  - above 200 - 400 ppm H (Unirradiated),
  - above around 100 ppm H (Irradiated)

**n values:**
- used in plastic instability theory
- smaller than that of MATPRO under the rapid strain rate,
- No clear temperature dependence (relatively large scatter).

**Note:** Ref.[6] MATPRO-Version 11, Rev.2 (1981).
**Effect of neutron fluence on n:**

1. Significantly affected,
2. Saturate after one cycle irradiation.

**Effect of hydrogen:**

3. Slightly accelerate the loss of strain hardening ability.
Effect of temperature and H concentration on SED

- SED:
  - Literature data increased with temperature.
  - Relatively large scatter

- This study:
  - Good agreement with previous data at RT.

- Low SED over 300ppm, no tem. dependence.

4. Conclusions (1/2)

1. Open end rapid burst tests to impose a high strain rate in hoop direction: well-suited for separate effects RIA tests.

2. Hydride morphology after H. charging by LiOH autoclave:
   - Hydride orientation (Fn) was not changed by hydrogenation,
   - Hydrides are dominantly transgranular, which led to the fracture surface with transgranular cleavage facets.

3. Mechanical properties of unirradiated cladding:
   - Failure elongation was nearly unchanged or increased slightly up to ~200 ppm, but decreased drastically at ~400 ppm.
   - Radial distribution of hydrides had a pronounced effect on ductility. A drastic reduction occurred in failure strain and the strain energy density at a much lower hydrogen concentration of less than ~100 ppm.
4. Mechanical properties of irradiated cladding:

- At room temperature the failure strain for the low fluence material was nearly the same as that for the intermediate fluence material. This was interpreted to be due to the different failure mode; a spiral mode for the low fluence material whereas an axial split for the intermediate fluence.

- Strain energy density data obtained agreed reasonably well with those reported in the literature.

- Values of the strain hardening exponent were extremely small indicating that plastic instability theory simply can not be used to evaluate failure strain under RIA conditions.
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Effect of radial hydride (RH)

Definition of Accumulated Hydride Length (AHL)

Accumulated Hydride Length, AHL

AHL/Thickness = 0.64

AHL/Thickness = 0.12

Fracture model based on hydride failure

Typical specimen

For reference
Effect of radial hydride (RH)

- Radially projected hydride length to specimen thickness (AHL) control the mechanical properties.
- RH affects ductility than strength.
2.1 Unirradiated Cladding Tubes (3)

Effect of radial hydride
Change the fracture surfaces

For reference

(ASC-17, Circumferential hydrides, 115 ppm H)  (ASC-R23, Radial hydrides, 253 ppm H)

Without R.H.  With R.H.