Simulation of Outside-in Cracking in BWR Fuel Cladding Tubes under Power Ramp

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Background (1)

• The **outside-in failure** was observed in Japanese power ramp tests of high burnup BWR fuels.

• The **delayed hydride cracking (DHC)** would be the mechanism of crack propagation.

BWR Segment Rod Failed in Power Ramp Test (5cy. irradiated, RTP: 44.6kW/m, failed after 22min hold)

*H. Hayashi et al., 2005WRFPM, PaperID1080*
Important characteristic of radial DHC during outside-in failure is that crack grows in radial direction of fuel cladding tube with thermal gradient.

- Increase of Thermal Gradient by Power Ramp
- Increase of Thermal Diffusion of Hydrogen
- Effect on DHC?*

*Sagat et al. has indicated thermal gradient enhanced DHC

Important characteristics of Radial DHC during outside-in failure

- Cracking in Radial direction (Previous study)
  - Development of making method of “Outer-surface Incipient Crack (ORIC)”
  - Isothermal radial DHC test(→)

- Cracking with Thermal gradient → “power ramp simulator”

K. Sakamoto et al., WRFP2008
Objective

To assess fuel integrity during power ramp, threshold condition for crack growth and time to penetrate cladding wall thickness are required.

In the present study we performed the radial DHC test with radial thermal gradient to clarify the effect of thermal gradient on

• Threshold condition for crack growth $\rightarrow K_{IH}$
• Time to penetrate cladding wall thickness $\rightarrow V_{DHC}$
Experimental (1)

CW Zry2 fuel cladding tubes
110 mm long

Hydrogen Charging
LiOH solution
approximately 100-350 ppm

Making of ORIC
\( \text{I}_2/\text{CH}_3\text{OH} \) solution
0.05 – 0.15 mm depth

Radial DHC test with thermal gradient
Power Ramp Simulator

Fractography
SEM, OM

Radial DHC with Thermal Gradient

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( T_\text{DHC} ) (K)</th>
<th>( t_\text{DHC} ) (h)</th>
<th>Hoop Stress (MPa)</th>
<th>LHGR (kW/m)</th>
<th>Hydrogen Conc. (ppm)</th>
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<tbody>
<tr>
<td>TG01</td>
<td>561</td>
<td>0</td>
<td>300</td>
<td>40</td>
<td>236</td>
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<tr>
<td>TG02</td>
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<td>300</td>
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<td>40</td>
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<td>561</td>
<td>1</td>
<td>300</td>
<td>40</td>
<td>352</td>
</tr>
</tbody>
</table>

ORIC (Outer Surface Incipient Crack)

OM (Optical Microscope) Image of ORIC

Flow Chart
Experimental (2)

Power Ramp Simulator

Temperature and Pressure Conditions

No Overshooting of Temp.

Temperature at Outer Surface

Hoop Stress

Time

\( t_{DHC} \)

0 - 1 h

300 MPa

\( T_{DHC} \)

561 K

\( \text{LHGR} = 40 \text{ kW/m} \)

\(< 50 \text{ MPa} \)

\( 40 \text{ kW/m} \rightarrow dT \sim 60 \text{ K} \)

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Experimental (3)

Radial DHC test with radial thermal gradient (Present study)

Radial DHC test under isothermal condition (Previous study)

Overshooting of Temp. \( T_{max} = T_{DHC} + 50K \)

Temperature at Outer Surface

Hoop Stress

No Overshooting of Temp.

\( T_{DHC} = 561 \text{ K} \)

\( t_{DHC} = 0 \text{ - } 1 \text{ h} \)

\( LHGR = 40 \text{ kW/m} \)

\( <50 \text{ MPa} \)

\( 300 \text{ MPa} \)

\( 200 \text{ - } 300 \text{ MPa} \)

Time
Typical micrographs of crack after radial DHC test with radial thermal gradient (LHGR = 40kW/m, $T_{\text{DHC}} = 561\text{K}$, $t_{\text{DHC}} = 0.25\text{h}$, hydrogen content = 187ppm)
Results (1)

No radial DHC was observed without radial thermal gradient

→ Radial DHC required thermal gradient
Results (2) - $K_{IH}$

Threshold Condition for Crack Growth with Thermal Gradient

$K_{IH} \sim 5 \text{ MPa m}^{0.5}$

Predicted Relationship between $D_I$ and hoop stress required for radial DHC

($\rightarrow$ Under isothermal cond.: $3.5 \text{ MPa m}^{0.5}$)
Results (3) - $V_{DHC}$

With thermal grad.
No suppression
 (> 561 K)

Under isothermal cond.
Strong suppression
 (548 K - 561 K)
Discussion (1)

Mechanism of Outside-in Cracking with Thermal Gradient

Thermal Gradient

→ Thermal Diffusion of H

→ Generation of Supersaturated H at Crack Tip

→ Acceleration of Radial DHC

Result of Calculation of Hydrogen Redistribution during Radial DHC Test

\( t_{\text{DHC}} = 0.5h, \text{Heat-Generating Part} \)
Effect of Supersaturated Hydrogen on Radial DHC

Concentration of supersaturated hydrogen was changed by varying $T_{\text{max}}$ of isothermal radial DHC test.

**Experimental conditions of radial DHC tests under isothermal condition**

<table>
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<tr>
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<th>$T_{\text{max}}$ (K)</th>
<th>$dT$ (K)</th>
<th>$t_{\text{DHC}}$ (h)</th>
<th>Hoop Stress (MPa)</th>
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Threshold Concentration of Supersaturated Hydrogen $\rightarrow 20 – 30$ ppm
Discussion (3)

Effect of Supersaturated Hydrogen on Radial DHC

→ Crack tip was surrounded by enough supersaturated hydrogen

Range where radial cracking was observed

Threshold concentration of supersaturated hydrogen by isothermal DHC tests

Crack tip was surrounded by enough supersaturated hydrogen

Range where radial cracking was observed

Zr
Zry-2

Threshold concentration of supersaturated hydrogen by isothermal DHC tests

Range where radial cracking was observed
Discussion (3)

Mechanism of Outside-in Cracking with Thermal Gradient

Requirements:

• Enough supply of supersaturated H to crack tip

• Hydrogen flow towards crack tip? (as Sagat et al. indicated)
Conclusions

By using unirradiated Zry-2 fuel cladding tubes, outside-in cracking was examined both with and without the thermal gradient.

• Without radial thermal gradient, there was no radial DHC. On the other hand, with the radial thermal gradient, the velocity of the outside-in cracking was significantly higher than that expected from the data obtained under the isothermal condition.

• The threshold depth of the incipient crack was found to be approximately 0.1 mm at the hoop stress of 300 MPa.

• It was suggested that the outside-in cracking during the power ramp is strongly dependent on the distribution of dissolved hydrogen as a result of the thermal diffusion.