Friction Stir Welding as a Solution to Canister Stress Corrosion Cracking

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PNNL

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The canister seismic modeling and Friction Stir Welding crack repair test data discussed in this presentation was performed under a PNNL Laboratory Directed Research and Development (LDRD) project in FY2017. The LDRD was titled: “Modeling of Used Nuclear Fuel Canister Mitigation and Repair Techniques.”
Key Premise: Stress corrosion cracking (SCC) of dry storage and transportation canisters is a problem that needs to be addressed.
- Repair is assumed to be necessary.

This presentation is focused on the application of friction stir welding (FSW) as a solution to the problem.
- PNNL FSW test data looks promising.
- What does the solution look like?
- What additional R&D is needed to make FSW canister repair a reality?

Related cumulative effects issues are also noted.
- Transient loads, residual stresses, crack advancement.
Consequences of Canister Cracks

Through-wall cracks:
- Violate confinement boundary.
- Are not consistent with design basis/safety basis/licensing basis.

Partial-wall cracks:
- Can potentially grow to become through-wall cracks.
- Are not consistent with design basis/safety basis/licensing basis.

“Not consistent with design basis/safety basis/licensing basis” is a potentially serious structural problem for someone in the chain:
- Utility
- Shutdown site
- Interim storage facility
- Repository
Canister Storage and Transportation Structural Loading Conditions

- **Dry Storage**
  - Normal Handling
  - Seismic
  - Tip Over

- **Transportation**
  - Normal Handling
  - NCT Shock & Vibration
  - NCT Package Drop
  - HAC Package Drop

- What threshold of transient loading will advance a CISCC?
- Consider cumulative crack propagation under canister mechanical loads:
  - Store, transport, store, transport, repackage, disposal.
- This is a Cumulative Effects topic that could use more analysis/R&D.
  - Canister structural loads.
  - Canister structural loads with partial-wall cracks.
  - Canister structural loads with significant residual stress.
Historical ground motion data from the USGS is applied to models of dry cask storage systems to calculate peak canister wall stress.

- The storage system design influences canister response.
- Stress is based on nominal canister wall thickness.
- Potential tensile stress at CISCC (near weld) locations, which could advance through the canister wall.
- More analysis recommended to quantify loads.
## Canister Load Summary, Storage and Transportation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Load Case</th>
<th>Stress Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Stress¹</td>
<td>All</td>
<td>Weld HAZ: ~50-250 MPa (hoop, axial)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weld Repair HAZ: ~200-400 MPa (hoop, axial)</td>
</tr>
<tr>
<td>Storage</td>
<td>1ft Handling Drop</td>
<td>~70 MPa Peak von Mises Stress (Regions of 30, 50, 70 MPa)</td>
</tr>
<tr>
<td>Storage</td>
<td>Seismic</td>
<td>~30 MPa Circumferential Stress, Design &amp; Earthquake Dependent</td>
</tr>
<tr>
<td>Storage</td>
<td>Tip Over</td>
<td>~200 MPa Peak von Mises Stress (Regions of 150, 170, 200 MPa)</td>
</tr>
<tr>
<td>Transportation</td>
<td>Handling</td>
<td>TBD – ENSA/DOE Test Campaign</td>
</tr>
<tr>
<td>Transportation</td>
<td>NCT S&amp;V Rail</td>
<td>TBD – ENSA/DOE Test Campaign</td>
</tr>
<tr>
<td>Transportation</td>
<td>NCT S&amp;V Truck</td>
<td>TBD – ENSA/DOE Test Campaign</td>
</tr>
<tr>
<td>Transportation</td>
<td>NCT 30cm Drop</td>
<td>TBD – ENSA/DOE Test Campaign</td>
</tr>
<tr>
<td>Transportation</td>
<td>HAC 9m Drop</td>
<td>*No current plans for quantifying HAC loads</td>
</tr>
</tbody>
</table>

¹ Enos and Bryan, Final Report: Characterization of Canister Mockup Weld Residual Stresses, FCRD-UFD-2016-000064
FSW Repair of Simulated Crack in Stainless Steel Plate: A wire EDM cut was made in the plate to depths of 4 mm and 8 mm. FSW with a tool depth of 6 mm was applied to repair the simulated crack. A number of tension samples were cut from the repaired plate.
Simulated Crack Tension Test Examples

Simulated 4mm Crack without Repair

Simulated 4mm Crack Repaired with Friction Stir Weld
Tension Test with Digital Image Correlation
Load Displacement curves for five different sample types of 9.5mm thickness. Unrepaired samples have 4mm and 8mm deep cracks perpendicular to the pull direction. The partial depth FSW repair is an 8mm crack depth sample repaired to slightly less than 8mm depth (leaving a flaw/void in the middle of the material). The full depth FSW had a 4mm crack that was fully repaired with FSW, and nearly matches the base metal strength.
Example Nuclear Power Plant: North Anna, Mineral VA

Images from Google Maps

ISFSI: Independent Spent Fuel Storage Installation
Example Crawler and Transfer Cask

http://www.lift-systems.com/nuclear-fuel-transportation.html

Estimated Cost of Crawler: $3m/buy, $100k-200k/lease
Estimated cost of transfer cask: $3m/buy*
*Cost estimated as something between a canister and package cost.
Transfer Cask Illustrations

HOLTEC Design

http://docplayer.net/docs-images/24/2306524/images/16-0.png

Patent Illustration

https://patents.google.com/patent/US6853697

Fig. 12

https://patents.google.com/patent/US6853697
Note: All cost estimates are “ballpark estimates” based on conversations with industry.

- **Radworker Labor**
  - 15 workers per work crew
  - Practice days, procedure writing, revision, approval
  - $30k per work day

- **Analysis/licensing activity**
  - $500k+

- **Crawler**
  - $3m/buy, $100k-200k/lease

- **New Canister or Outer Canister**
  - $1m

- **Transfer Cask**
  - $3m (somewhere between a canister $1m and package $7m)

- **New dual purpose cask design, fabrication, licensing**
  - $7m ($5m to $9m)
## Commercially Available Solution #1: “Russian Nesting Doll”

### Operating Plant Site

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase new (larger) outer canister</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Larger canister fits in old overpack, but licensing analysis needed</td>
<td>500,000</td>
</tr>
<tr>
<td>Labor to transfer/seal/replace in overpack (2 days)</td>
<td>60,000</td>
</tr>
<tr>
<td>Larger canister needs new transportation package</td>
<td>7,000,000</td>
</tr>
</tbody>
</table>

**Subtotal** 8,560,000

### Decommissioned Site Potential Additional Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawler</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Transfer Cask</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Temporary Hot Cell or Shielding Solution</td>
<td>?</td>
</tr>
</tbody>
</table>

**Subtotal** 6,000,000 + ?
## Commercially Available Solution #2: Repackaging

### Operating Plant Site

<table>
<thead>
<tr>
<th>Item</th>
<th>Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase new replacement canister</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Labor to transfer/repackage (7 days)</td>
<td>210,000</td>
</tr>
<tr>
<td>Risk of Fuel Assembly Damage</td>
<td>?</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>1,210,000 + ?</strong></td>
</tr>
</tbody>
</table>

### Decommissioned Site Potential Additional Cost

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<th>Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawler</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Transfer Cask</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Temporary Hot Cell for repackaging</td>
<td>?</td>
</tr>
<tr>
<td>Risk of Fuel Assembly Damage</td>
<td>?</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>6,000,000 + ? + ?</strong></td>
</tr>
</tbody>
</table>
# FSW Repair Solution

## Operating Plant Site

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design/Purchase/Install/Operate FSW system</td>
<td>X</td>
</tr>
<tr>
<td>Labor to FSW (4 days)</td>
<td>120,000</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>120,000 + X</td>
</tr>
</tbody>
</table>

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<td>3,000,000</td>
</tr>
<tr>
<td>Temporary Hot Cell for FSW</td>
<td>?</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>6,000,000 + ?</td>
</tr>
</tbody>
</table>

**Conclusion:** FSW has the potential to be a cost effective solution compared to current commercially available options.
Recommended R&D

**FSW Repair:**
- Identify and resolve remaining technical concerns about FSW application:
  - Practical tool depth/repair depth assessment
  - Pressure/force requirements, structural loads on canisters, analysis
  - Tool design for low force welding to avoid canister buckling
  - Partial wall thickness repair analyses
  - Post FSW residual stress evaluation
  - Thermal energy study
  - Licensing basis technical material
  - System design prep (e.g., radiation hardening requirements, etc.)
- Analyze repaired canister loads under HAC.

**Cumulative Effects:**
- Canister storage and transportation load evaluation.
- Evaluate CISCC crack advancement under dynamic loads.
- Expand canister seismic loading estimates.
- Revise structural dynamic analyses to include residual stress state.