Chloride-Induced Stress Corrosion Cracking Tests and Example Aging Management Program

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NRC/NMSS/SFST

Public Meeting with Nuclear Energy Institute on Chloride Induced Stress Corrosion Cracking Regulatory Issue Resolution Protocol

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Outline

• NRC sponsored testing
• Power plant operating experience
• Potential for chloride-induced stress corrosion cracking (CISCC) of stainless steel dry storage canisters (DSCs)
• Example aging management program (AMP) for CISCC
  – Regulatory basis
  – Description of AMP elements
NRC Sponsored Testing  
NUREG/CR-7170

• Test objectives:
  – Limit absolute humidity (AH) to about 30 g/m³
  – Vary test temperature, surface salt concentration and material condition

• Test methods:
  – ASTM G30 U-bend specimens with 0.1, 1, or 10 g/m² of sea salt
    – Expose to salt fog for various times
    – Quantity determined by control specimen weight gain
    – As-received or sensitized (2 hours at 650 °C) Type 304
    – Exposed in test chamber to cyclic AH (15 and 30 g/m³)
  – ASTM G38-01 C-ring specimens at ~0.4% or 1.5% strain
    – Tested with 1 or 10 g/m² of simulated sea salt 35, 45, and 52°C
  – ASTM G30 U-bend specimens with non chloride salts (No SCC)
  – ASTM G30 U-bend specimens at elevated temperatures (SCC observed)
## Surface Chloride Concentration

<table>
<thead>
<tr>
<th>Specimen Temp. (°C)</th>
<th>Relative Humidity (RH) (%)</th>
<th>Exposure Time</th>
<th>SCC Observed?</th>
<th>Lowest salt concentration at which SCC was observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>56-100</td>
<td>8 months</td>
<td>No</td>
<td>N/A – salt deliquesced and drained off</td>
</tr>
<tr>
<td>35</td>
<td>38-76</td>
<td>4 – 12 months</td>
<td>Yes</td>
<td>0.1</td>
</tr>
<tr>
<td>45</td>
<td>23-46</td>
<td>4 – 12 months</td>
<td>Yes</td>
<td>0.1</td>
</tr>
<tr>
<td>52</td>
<td>16-33</td>
<td>2.5 – 8 months</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>12-23</td>
<td>6.5 months</td>
<td>Yes</td>
<td>10</td>
</tr>
</tbody>
</table>

Pitting on specimens at 10 g/m² (top), 1 g/m² (middle), and 0.1 g/m² (bottom)

Cross section of sensitized, 0.1 g/m² specimen at 45°C after 4 months

Top view of sensitized specimen with 10 g/m² tested at 60°C for 6.5 months
U-bend Testing Summary

- CISCC observed at temperatures up to 60 °C with absolute humidity values less than or equal to 30 g/m³
- No observed CISCC at 25 °C is believed to be a result of salt solution draining from the specimens
- CISCC observed with salt concentration of 0.1 g/m², lower than previous reports
- CISCC at 80 °C required absolute humidity values above 30 g/m³
C-ring Specimen Tests

- ASTM G38-01 C-ring specimens used to evaluate lower strain condition relative to U-bend specimens
- Specimens strained to slightly above yield stress (~0.4% strain) or 1.5% strain, as measured by strain gage
- Specimens tested with 1 or 10 g/m² of simulated sea salt
- Specimens exposed at conditions of 35°C and 72% RH, 45°C and 44% RH, and 52°C and 32% RH (AH ~ 30 g/m³)
## C-ring Specimen Tests

<table>
<thead>
<tr>
<th>Specimen Temp. (°C)</th>
<th>RH (%)</th>
<th>AH (g/m³)</th>
<th>Salt Conc. (g/m²)</th>
<th>Strain (%)</th>
<th>Exposure Time (months)</th>
<th>Crack Initiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>72</td>
<td>29</td>
<td>1</td>
<td>0.4</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>0.4</td>
<td>3</td>
<td>Sensitized</td>
</tr>
<tr>
<td>45</td>
<td>44</td>
<td>29</td>
<td>1</td>
<td>0.4</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>0.4</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>52</td>
<td>32</td>
<td>29</td>
<td>1</td>
<td>0.4</td>
<td>2</td>
<td>As-received and sensitized</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>0.4</td>
<td>3</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>1.5</td>
<td>2</td>
<td>As-received and sensitized</td>
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</tr>
</tbody>
</table>
Conclusions from NRC Sponsored SCC testing

- CISCC observed on specimens with deposited sea salt at temperatures from 35 to 60°C with absolute humidity values less than or equal to 30 g/m³
- CISCC initiation is observed at salt quantity as low as 0.1 g/m² (U-bend specimens) or strain as low as 0.4 % (C-ring specimens) but the extent of cracking increased with increasing salt quantity or strain
- Sensitized material was more susceptible to CISCC than material in as-received (mill-annealed) condition
- No SCC was observed for specimens exposed to simulated atmospheric deposits that did not contain chloride salts
- CISCC observed at temperatures of 80°C when RH was sufficiently high for deliquescence of deposited sea salts (AH > 30 g/m³)
Power Plant Operating Experience with SCC of Stainless Steels

<table>
<thead>
<tr>
<th>Plant</th>
<th>Distance to water, m</th>
<th>Body of water</th>
<th>Material/Component</th>
<th>Thickness, or crack depth, mm</th>
<th>Time in Service, years</th>
<th>Est. Crack growth rate, m/s</th>
<th>Est. Crack growth rate, mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koeberg</td>
<td>100</td>
<td>South Atlantic</td>
<td>304L/RWST</td>
<td>5.0 to 15.5</td>
<td>17</td>
<td>$9.3 \times 10^{12}$ to $2.9 \times 10^{11}$</td>
<td>0.29 to 0.91</td>
</tr>
<tr>
<td>Ohi</td>
<td>200</td>
<td>Wakasa Bay, Sea of Japan</td>
<td>304L/RWST</td>
<td>1.5 to 7.5</td>
<td>30</td>
<td>$5.5 \times 10^{12}$ to $7.9 \times 10^{12}$</td>
<td>0.17 to 0.25</td>
</tr>
<tr>
<td>St Lucie</td>
<td>800</td>
<td>Atlantic</td>
<td>304/RWST pipe</td>
<td>6.2</td>
<td>16</td>
<td>$1.2 \times 10^{11}$</td>
<td>0.39</td>
</tr>
<tr>
<td>Turkey Point</td>
<td>400</td>
<td>Biscayne Bay, Atlantic</td>
<td>304/pipe</td>
<td>3.7</td>
<td>33</td>
<td>$3.6 \times 10^{12}$</td>
<td>0.11</td>
</tr>
<tr>
<td>San Onofre</td>
<td>150</td>
<td>Pacific Ocean</td>
<td>304/pipe</td>
<td>3.4 to 6.2</td>
<td>25</td>
<td>$4.3 \times 10^{12}$ to $7.8 \times 10^{12}$</td>
<td>0.14 to 0.25</td>
</tr>
</tbody>
</table>

- CISCC growth rates of 0.11 to 0.91 mm/yr for components in service
  - Median rate of $9.6 \times 10^{-12}$ m/s (0.30 mm/yr) reported by Kosaki (2008)
- Activation energy for CISCC propagation needs to be considered
  - 5.6 to 9.4 kcal/mol (23 to 39 kJ/mol) reported by Hayashibara et al. (2008)
Potential for SCC of Welded Stainless Steel DSCs

- 304 and 316 Stainless steels are susceptible to CISCC
  - Sensitization from welding increases susceptibility to CISCC
  - CISCC has been observed with low surface chloride concentrations
  - Crevice and pitting corrosion can be precursors to CISCC
  - Residual stresses from welding likely sufficient for CISCC
- Atmospheric CISCC of welded stainless steels has been observed
  - Component failures in 16-33 years
  - Estimated crack growth rates of 0.11 to 0.91 mm/yr
- Limited data on the atmospheric deposits on welded stainless steel canisters

2/3 of the requirements for CISCC are present in welded stainless steel dry storage canisters (DSCs)
Potential for SCC of Welded Stainless Steel DSCs

- Cl salts could be deposited by air flow from passive cooling.
- Relative humidity increase as canister cools may lead to deliquescence of deposited Cl salts and CISCC.
- Reactor operating experience indicates CISCC is a potential aging effect that requires management.
Regulatory Basis for Aging Management Programs

- **10 CFR 72.42(a), 72.240(c):**
  - Time limited aging analysis (TLAA) that demonstrate that important to safety (ITS) structures systems and components (SSCs) will continue to perform their intended function for the period of extended operation.
  - A description of the aging management program (AMP) for management of issues associated with aging that could adversely affect ITS SSCs.

- **Guidance: NUREG-1927 AMP Elements:**
  1. Scope of the Program
  2. Preventive Actions
  3. Parameters Monitored/Inspected
  4. Detection of Aging Effects
  5. Monitoring and Trending
  6. Acceptance Criteria
  7. Corrective Actions
  8. Confirmation Process
  9. Administrative Controls
  10. Operating Experience
AMP Element 1
Scope of the Program

NUREG-1927: The scope of the program should include the specific structures and components subject to an aging management review (AMR)

- Welded stainless steel dry storage canisters
  - Fabrication and closure welds
  - Weld heat affected zones
  - Locations where temporary supports or fixtures were attached by welding
  - Crevice locations
  - Surface areas where atmospheric deposits preferentially occurs
  - Surface areas with a lower than average temperature
AMP Element 2
Preventative Actions

NUREG-1927: Preventive actions should mitigate or prevent the applicable aging effects

- Aging Management Program is for condition monitoring.
  - Preventative actions are not presently incorporated into existing dry storage canister designs
- Future designs or amendments could include
  - Surface modification to impart compressive residual stresses on welds and weld heat affected zones
  - Materials with improved localized corrosion and SCC resistance
AMP Element 3
Parameters Monitored/Inspected

NUREG-1927: Parameters monitored or inspected should be linked to the effects of aging on the intended functions of the particular structure and component

- Canister surfaces, welds, and weld heat affected zones for discontinuities and imperfections
- Size and location of localized corrosion (e.g., pitting and crevice corrosion) and stress corrosion cracks
- Appearance and location of atmospheric deposits on the canister surfaces
AMP Element 4
Detection of Aging Effects (1/2)

NUREG-1927: Define method or technique, frequency, sample size, data collection, and timing to ensure timely detection of aging effects

• Qualified and demonstrated technique to detect evidence of localized corrosion and SCC:
  – Remote visual inspection, e.g. EVT-1, VT-1, VT-3, or Eddy Current Testing (ET) may be appropriate

• Pending detection findings, sizing SCC would require volumetric methods
AMP Element 4
Detection of Aging Effects (2/2)

• Sample size
  – Minimum of one canister at each site
  – Canisters with the greatest susceptibility

• Data Collection
  – Documentation of the examination of the canister
  – Location and appearance of deposits

• Frequency
  – Every 5 years

• Timing of Inspections
  – Within 25 years of initial loading
AMP Element 5
Monitoring and Trending

NUREG-1927: Should provide for prediction of the extent of the effects of aging and timely corrective or mitigative actions

- Document canister condition particularly at welds and crevice locations using images and video that will allow comparison in subsequent examinations
- Changes to the size and number of any corrosion product accumulations
- Location and sizing of localized corrosion and stress corrosion cracking
AMP Element 6
Acceptance Criteria (1/2)

NUREG-1927: Acceptance criteria, against which the need for corrective action will be evaluated; should ensure that SSC functions are maintained

- No indications of:
  - Pitting or crevice corrosion
  - Stress corrosion cracking
  - Corrosion products near crevices
  - Corrosion products on or adjacent to fabrication welds, closure welds, and welds for temporary supports or attachments
AMP Element 6
Acceptance Criteria (2/2)

- Locations with corrosion products require additional examination for localized corrosion and/or SCC
- Size of the area affected and the depth of penetration if localized corrosion and/or SCC is identified
- Canisters with localized corrosion and/or SCC must be evaluated for continued service in accordance with ASME B&PV Code Section XI IWB-3514.1 and IWB-3640
AMP Element 7
Corrective Actions

NUREG-1927: Corrective actions, including root cause determination and prevention of recurrence, should be timely

• Supplemental inspections to determine the extent of condition at the site
• Subsequent inspections of canisters with indications
• Canisters that do not meet the prescribed evaluation criteria must be repaired or removed from service
AMP Element 8
Confirmation Process

NUREG-1927: Confirmation process should ensure that preventive actions are adequate & appropriate corrective actions have been completed & are effective

• Licensee Quality Assurance Program consistent with 10 CFR 72 Subpart G, or 10 CFR 50 Appendix B

• Ensure that inspections, evaluations, and corrective actions are completed in accordance with the Site Specific or General Licensees Corrective Action Program (CAP)
  – Extent of condition
  – Evaluation for continued service
  – Repair, replace, mitigation actions
AMP Element 9
Administrative Controls

NUREG-1927: Administrative controls should provide a formal review and approval process

- Licensee Quality Assurance Program consistent with 10 CFR 72 Subpart G, or 10 CFR 50 Appendix B
- Training requirements for inspectors
- Records retention requirements
AMP Element 10
Operational Experience

NUREG-1927: Include past corrective actions; provide objective evidence to support a determination that the effects of aging will be adequately managed so that the SSC intended functions will be maintained during the period of extended operation.

- Current operating experience limited to a few inspections
  - Deposits and corrosion products on surfaces
  - Evidence of water contacting DSC
- Reactor operating experience
- Similar DSC designs and canister materials at other ISFSI locations
Summary

• Conditions necessary for chloride induced SCC have been evaluated in well controlled laboratory tests

• CISCC growth rates for welded stainless steels available from both laboratory and field testing are comparable to rates derived from reactor operating experience

• CISCC is a potential aging mechanism for welded stainless steel DSCs that requires an Aging Management Program
  • Several reported cases of CISCC from atmospheric deposits observed in operating reactors (NRC Information Notice 2012-20)
  • Limited data available from DSC inspections

• Analysis of the potential for CISCC needs to consider both the range of available test data and operating experience with welded stainless steel components
Acronyms

AH: Absolute Humidity
AMP: Aging management program
AMR: Aging management review
ASME B&PV code: American Society of Mechanical Engineers Boiler and Pressure Vessel code
CAP: Corrective action program
CISCC: Chloride induced stress corrosion cracking
CFR: Code of Federal Regulations
DSC: Dry storage canister
EVT-1: Enhanced visual testing-1 (Boiling water reactor vessels and internals project, BWRVIP-03)
ISFSI: Independent spent fuel storage installation
ITS: Important to safety
RH: Relative humidity
SCC: Stress corrosion cracking
SSC: Structures systems and components
TLAA: time limiting aging analysis
VT-1: Visual Testing-1 (ASME B&PV code Section XI, Article IWA-2200)
VT-3: Visual Testing-3 (ASME B&PV code Section XI, Article IWA-2200)