Progress on Inspection and Evaluation of CISCC at Canister of Dry Storage Cask
Q1) What can happened to the canister if brine (salt spray) will be deposited on the canister surface at various locations for ISFSIs?
Q2) How long it will take until the canister integrity is damaged?
Q3) What is the safety and economic consequences, if the canister is damaged?
Q4) What is the uncertainty in the answering to these three initial questions?

The main goal of IRP/NEUP is to perform a systematic analysis assessment that answers to the two initial questions with an input
Objective

Develop Physics–Based Probabilistic (Deterministic) Computational Model and Tool for routine assessments of UNF canister degradation to prevent or reduce the consequences of failure, by optimized the inspection time interval and repair if required, and the impact of repair on the canister reliability. Including the option of extend the operation of ISFSIs beyond the design lifetime, approved by NRC.

- Note: CISCC is complex nonlinear phenomena, coupled physics and stochastic behavior, and need spatial and time scale from laboratory experiments.
Canister structural deterioration is a random process as it is a function of random variables. The uncertainty and variability of data obtained by laboratory experiments and inspection sampling of a canisters population are best modeled by stochastic models.
Project Status

Paul Plante, Cask Relicensing Project Manager
Connecticut Yankee/Maine Yankee/Yankee Rowe

Laboratory Exposures
Field Exposures at Maine Yankee

Figure 1: Schematic representation of the full scale mock storage container manufactured at Ramo
31 large 4-pb specimens (32x1.65x1.59 cm), with various residual stress landscape (250MPa Max.). 8 were placed at Maine Yankee.

Two large 4-pb samples were sent to Sandia, including one 304 L polished, and one 304 H polished for electrochemical Analysis.

9 samples were placed in the CSM humidity chamber at 50°C, 35%RH in early August, 2017. One 304 L polished samples was taken out on Oct. 30, 2017 and sent to Sandia for pit morphology characterization. Another 12 samples were newly placed in CSM humidity chamber in late March, 2018.

24 small 4-pb specimens (10x0.6x0.8 cm) with different surface and load conditions but all the same material, 304 L, were placed at Maine Yankee. Another 8 small 4-pb specimens were place in CSM Second HM chamber in late March, 2018.
# General factors affecting CISCC

<table>
<thead>
<tr>
<th>Susceptible Material</th>
<th>composition, microstructure, heat treatment, inclusions (size, composition, orientation), grain size, grain boundary composition, grain orientation, amount of hot or cold work, sensitization, welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Stress</td>
<td>HEZ, Base materials, Weldment (Axial and Radial) – Mockup. Mockup stress replication into the specimens.</td>
</tr>
<tr>
<td>Surface</td>
<td>surface finish (Polish and Rough), surface treatment, electrochemical potential and Current.</td>
</tr>
<tr>
<td>Environment</td>
<td>temperature, composition, oxygen concentration, pH, Cl⁻, concentration of other anions, (concentration of adsorbing organic molecules, radiation effects, presence of microbial films, the impact of dust), mass transfer limitations on oxygen (diffusion coefficients, flow patterns in ventilation channel)</td>
</tr>
</tbody>
</table>
Modified Implant Test for atmospheric marine conditions is being developed to test materials for CISCC – 304L/304H/Mockup

**Goal** – Determine the most susceptible microstructure to the atmospheric marine environment – Location and Time

**HEZ** Characterizations quantification

Replication of Microstructure into the distributed specimens for pitting and crack testing (304/304H)
• Canister Mockup Stress Analysis Comparison with the Measured Data.

• Replication Methodology of Canister Mockup to 4-points Bend Specimens for
Pitting – Experiments

Data Distribution as a Function of Exposure Time at Humidity Chamber (SNL and CSM):

- Nucleation – Preliminary information on base polish specimen and weldment under analysis (After 90 days of exposure (T=50 C, RH= 35%))
- Growth Rate as a Function of Exposure Time – Data in the near future
- Transition-to-Crack ? (ABAQUS Simulation)
Correlations between different types of environment? Four modes of Environment:

- Ambient at Site – Measured at different site (i.e. Main Yankee)
- Inside the Ventilation Channel – Flow Rate and Temperature Distribution (Can be calculated in reasonable precision with MC and CFD)

Cracks Propgration Rate (NCSU)

The impact of the Environment on Initiations and Growth Rate of Crack – Macro and Micro Scale (APS) Experiments:

Data on $K_{ISCC}$ and $J_{ISCC}$, the effect of atmospheric marine environment

On Macro Scale – Calibration and Fixture Setup Completed
On Micro Scale – In-situ and Ex-Situ Fixtures are completed, with some improvement: Preliminary Results.
- Fix heating problem
- Run stress corrosion cracking experiments on 304, 304H, and 304L samples to see how changes in certain parameters changes the stress corrosion cracking rate
  - Will allow us to optimize time at APS to get data of cracks propagating through the material
Canister Inspection and Reliability (LANL&BYU)
(three independent methods)

- Fast Screening (hit/miss) of a Existing of Damage – Started with Nonlinear Resonant Ultrasound Spectroscopy (NRUS), in the last year we shifted to Vibro-thermography.
- Slower Inspection – Variation of Pit/Crack Dimension as a function of Time – Time Reversed Elastic Nonlinearity Diagnostic (TREND)
- Chloride Detection on Canister at Dry Storage Casks Using PGAA and NAA Techniques – The Monte Carlo Simulation is Completed.
- Bibliographic Review – Is Conducted
- Systematic Experimental Plan – Need to be outlined
Vibro-Thermography

- Vibrate the sample
- Damaged areas dissipate more heat as a result of friction

Wide range of applications:
- Crack detection (open as well as closed cracks, independent of their orientation in the material)
- Testing of adhesive, rivet, and welding joints
- Characterization of multi-material compounds
Example—Shows Applications Potential to Canisters


Figure 13. Crack spacing comparison of column A. ● Thermography ■ Microscope.

Figure 14. Crack spacing comparison of column B. ● Thermography ■ Microscope.

Figure 5. Four-point-bending specification.

Figure 6. Gradiom profile (Temperature versus time). Pulse duration: 25, 50, 100, 200, 300, 400, and 500 ms.
Nonlinear ultrasound (LANL/BYU) is more sensitive to damage than linear ultrasound (commercial products).

Nonlinear ultrasound can image closed cracks and open cracks, whereas linear ultrasound only detects open cracks.

SCC has closed crack portion, meaning the crack is penetrating deeper than standard technology can determine.

Resonance inspection determines if structure is damaged. Focused ultrasound images damage.
Inspection Efficiency (type, size, depth, orientation, location)

Probability of Crack Detection


Recommendation: 60 # of specimens for hit/miss, 40 for size

Defect Size = F(signal Strength) + random and systematic errors

Vibro-thermography

Ultrasonic

X-ray radiography

Extreme Value Statistical Analysis

Typical POD function: Step or Continuously increasing

ASNT, NDE handbook, Ultrasonic Testing, 2006
Stochastic Modeling for a Canister Life Degradation

Integrated Software Tool for Canister Life Prediction.

(Laboratory Experiments and Field Data, with Inspection Reliability, POD)

Verification and Validation:
1) Predication of Laboratory Data
2) Predication of Field Data
3) Probability of Detection (POD)
Extreme Value Analysis to Predict the Maximum Pit\Crack Depth

In classical statistics:
focus on AVERAGE behavior of stochastic process
central limit theorem

In extreme value theory:
focus on extreme and rare events
Fisher-Tippett theorem
The distribution of \( M_n = \max \{ X_1, \ldots, X_n \} \) converges to (\( n \to \infty \))

\[
\xi \neq 0 \quad G(y) = \exp \left( - \left[ 1 + \xi \left( \frac{y-\mu}{\sigma} \right) \right]^{-1/\xi} \right)
\]

\[
\xi = 0 \quad G(y) = \exp \left( - \exp \left( - \frac{y-\mu}{\sigma} \right) \right)
\]

which is called the **Generalized Extreme Value (GEV)** distribution.

It has three parameters

- \( \mu \) location parameter
- \( \sigma \) scale parameter
- \( \xi \) shape parameter
Generalized Extreme Value (GEV)

GEV has 3 types depending on shape parameter $\xi$

**Gumbel** $\xi = 0$

$G(x) = \exp(-\exp(-x))$

**Fréchet** $\xi = 1/\alpha > 0$

$G(x) = \exp\left(-\left[1 + \frac{x}{\alpha}\right]^{-\alpha}\right)$

**Weibull** $\xi = -1/\alpha < 0$

$G(x) = \exp\left(-\left[1 - \frac{x}{\alpha}\right]^\alpha\right)$

$x = \frac{y - \mu}{\sigma}$
On The Stochastic Risk Bases Inspection Methodology

Time Dependent Markov Chain Monte Carlo (MCMC) Simulation with Confidence Interval. Why?

Probability distribution of interest: $f(D_{\text{max}})$

$f(D_{\text{max}})$ is a high dimensional, complex distribution
Analytical calculations on $f(D_{\text{max}})$ is not possible with multivariable
Direct sampling from $f(D_{\text{max}})$ is very problematic.
Benchmarking \ Application of Methodology

- Laboratory Experiments
- Data from Field Experiments

The data extracted from the open literature

Comments from Literature Review:
- Lack of Information on Uncertainty \ Sensitivity Analysis
- Not include a wide-ranging of statistical analysis and correlations between the environment, material microstructure, and stress.

- The correlation between accelerate experimental and
<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature (°C)</th>
<th>[Cl(^-)] (µg·g(^{-1}))</th>
<th>Other</th>
<th>(E_p) or (E_{RP}) (mV(_{SCE}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>80</td>
<td>19,000</td>
<td>Synthetic seawater</td>
<td>+50 ((E_p))</td>
<td>Haruki et al. 1991</td>
</tr>
</tbody>
</table>
| 304   | 20               | 34,500                      | With additions of Na\(_2\)S\(_2\)O\(_3\)  
0 mol·dm\(^{-3}\)  
4 \times 10\(^{-3}\) mol·dm\(^{-3}\)  
1 \times 10\(^{-3}\) mol·dm\(^{-3}\)  
2 \times 10\(^{-3}\) mol·dm\(^{-3}\)  
4 \times 10\(^{-3}\) mol·dm\(^{-3}\)  
0.01 mol·dm\(^{-3}\)  
0.1 mol·dm\(^{-3}\)  
0.4 mol·dm\(^{-3}\)  
1.0 mol·dm\(^{-3}\) | (\(E_p\))  
+30\(^*\)  
-20  
+40  
-130  
-205  
-195  
-135  
-95  
-65  | Szklarska-Smialowska 2005 (Fig 7.15) |
| 304   | 80               | 34,500                      | With additions of Na\(_2\)S\(_2\)O\(_3\)  
0 mol·dm\(^{-3}\)  
1 \times 10\(^{-4}\) mol·dm\(^{-3}\)  
4 \times 10\(^{-4}\) mol·dm\(^{-3}\)  
1 \times 10\(^{-3}\) mol·dm\(^{-3}\)  
0.01 mol·dm\(^{-3}\)  
0.1 mol·dm\(^{-3}\) | (\(E_p\))  
-65\(^*\)  
-65  
-255  
-265  
-260  
-190  | Szklarska-Smialowska 2005 (Fig 7.15) |
| 304   | 25  
40  
60  
90  | 17,000                      | With addition of 0.1 mol·dm\(^{-3}\) NaHCO\(_3\), pH 8 | +415 (\(E_p\))  
+320  
+155  
+65  | Szklarska-Smialowska 2005 (Fig 12.2) |
| 304   | 100  
150   | 345                         | Sensitized 304                  | -55 (\(E_p\))  
-240  | Szklarska-Smialowska 2005 (Fig 12.5) |
### Literature Data on Pitting of Type 304/304L Stainless Steels

QRS-1384J-1 v2.1 Appendix F Corrosion of Stainless Steels

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature (°C)</th>
<th>[Cl⁻] (µg.g⁻¹)</th>
<th>Other</th>
<th>E_p or E_rf (mV SCE)</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>304</td>
<td>20</td>
<td>Range 100-20,000</td>
<td></td>
<td></td>
<td>Szklarska-Smialowska 2005 (Fig 12.6)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>60</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>Ambient</td>
<td>34,500</td>
<td></td>
<td>+232 (E_p)</td>
<td>Szklarska-Smialowska 2005 (Fig 18.4)</td>
</tr>
<tr>
<td>304</td>
<td>30</td>
<td>3,450</td>
<td>With addition of 0.1 mol·dm⁻³ NaHCO₃</td>
<td>-70 (E_p)</td>
<td>Sedriks 1996 (Table 4.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+50 µg·g⁻¹ SO₄²⁻, 2 µg·g⁻¹ Cu²⁺</td>
<td>(E_p)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Base metal, Weld HAZ, 60% cold work</td>
<td>+390</td>
<td>Sedriks 1996 (Table 4.10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+190</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>+210</td>
<td></td>
</tr>
<tr>
<td>304L</td>
<td>30</td>
<td>142,000</td>
<td>pH 9.3</td>
<td>-51 (E_p)</td>
<td>Sridhar et al. 1993</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>-216 (E_rf)</td>
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<tr>
<td>304</td>
<td></td>
<td>18,400</td>
<td>pH 3</td>
<td>-5 (E_p)</td>
<td>Sedriks 1996 (Fig. 4.38)</td>
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<tr>
<td></td>
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<td></td>
<td>pH 4</td>
<td>+10</td>
<td></td>
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<td></td>
<td></td>
<td>pH 5</td>
<td>+15</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>pH 6</td>
<td>+25</td>
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<td>pH 7</td>
<td>+40</td>
<td></td>
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<td></td>
<td>pH 8</td>
<td>+50</td>
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<td></td>
<td></td>
<td></td>
<td>pH 9</td>
<td>+60</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>pH 10</td>
<td>+70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pH 11</td>
<td>+80</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pH 12</td>
<td>+400</td>
<td></td>
</tr>
<tr>
<td>Alloy</td>
<td>pH</td>
<td>Temperature (°C)</td>
<td>[Cl\textsuperscript{-}] (µg·g\textsuperscript{-1})</td>
<td>Redox conditions</td>
<td>Other</td>
</tr>
<tr>
<td>--------</td>
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<td>---------------------------------</td>
<td>------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>304</td>
<td>12.8-10.5</td>
<td>30, 45</td>
<td></td>
<td></td>
<td>200 days, 60 days</td>
</tr>
<tr>
<td>304</td>
<td>13.3</td>
<td>Ambient</td>
<td>18,400</td>
<td>Aerated</td>
<td>28 days</td>
</tr>
<tr>
<td>304</td>
<td>13</td>
<td>30, 50, 80</td>
<td></td>
<td>Deaerated</td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>10, 12.5, 13.5</td>
<td>50</td>
<td></td>
<td>Deaerated</td>
<td>230 days</td>
</tr>
<tr>
<td>304</td>
<td>Ambient</td>
<td>90</td>
<td>7,000-43,000</td>
<td>Aerated</td>
<td>10 hrs</td>
</tr>
<tr>
<td>304L</td>
<td>Ambient</td>
<td>25-100</td>
<td>“Freshwater”</td>
<td>Aerated</td>
<td></td>
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<tr>
<td>304L</td>
<td>Ambient</td>
<td>27, 90</td>
<td>“Saltwater”</td>
<td>Aerated</td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>Ambient</td>
<td>25, 50, 75</td>
<td>Interstitial clay water</td>
<td>Aerated</td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>Ambient</td>
<td>-</td>
<td>Aerated</td>
<td>Urban, 5-15 yr</td>
<td></td>
</tr>
</tbody>
</table>
| 304    | Ambient | -                | Aerated                         | Industrial/urban, 5-15 y |               | <0.03, 0.022, 0.05-2, 0.01  | Kears et al. 1984
Summary and Conclusion

- Project Extension – Submitted for Approval
- More Resources Required to Cover the Entire Scope of the Experiments, Modeling, Reliability of NDT Efforts, to Improve the aging management of The canister at ISFSIs at different locations.

- **Finally Quotation from:** ATMOSPHERIC-INDUCED STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEELS UNDER LIMITED CHLORIDE SUPPLY (304L and 316L, RH 30%, T= 80 °C, U-bends, pieces taken from an intermediate level waste canister, contact sea water and MgCl₂.

- **Conclusions:** Initial results from the field exposures indicate that pitting occurs within 5 months of exposure and after 11 months of exposure only pits, **no evidence of AISCC??**, have been found in the U-bend specimens. Wetness sensors and SEM examination indicate that both MgCl₂ and NaCl build up on the surfaces (pitting).

- By Anthony Cook et. al. 18th International Corrosion Congress, 2011