Regulatory Issue Resolution Protocol (RIRP) Pilot: Marine Atmosphere Stress Corrosion Cracking (SCC)

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Overview

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- RIRP Background
- Regulatory Background
- Technical Information
- Path Forward

RIRP BACKGROUND

RIRP Background

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- Identified by the NRC
  - Austenitic stainless steel (SS) is susceptible to SCC in chloride environments, near salt water bodies
  - Insufficient data available to determine extent of spent fuel storage canisters susceptibility to SCC
    - Specific environmental conditions
    - Associated time scales
  - NUREG-7030 demonstrated SCC for relevant environments

RIRP Background

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- Screening and Planning Phases
  - February 2010: Initial proposal
  - March 2011: Drafted problem and success criteria
  - February 2012:
    - Discussed progress
    - Need to update schedule, considering parallel efforts
- Implementation Phase (Ongoing)
  - Research existing data (complete)
  - Field Testing
  - Develop Screening Criteria
- Closure Phase (Pending)

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REGULATORY BACKGROUND

Deployed Canisters

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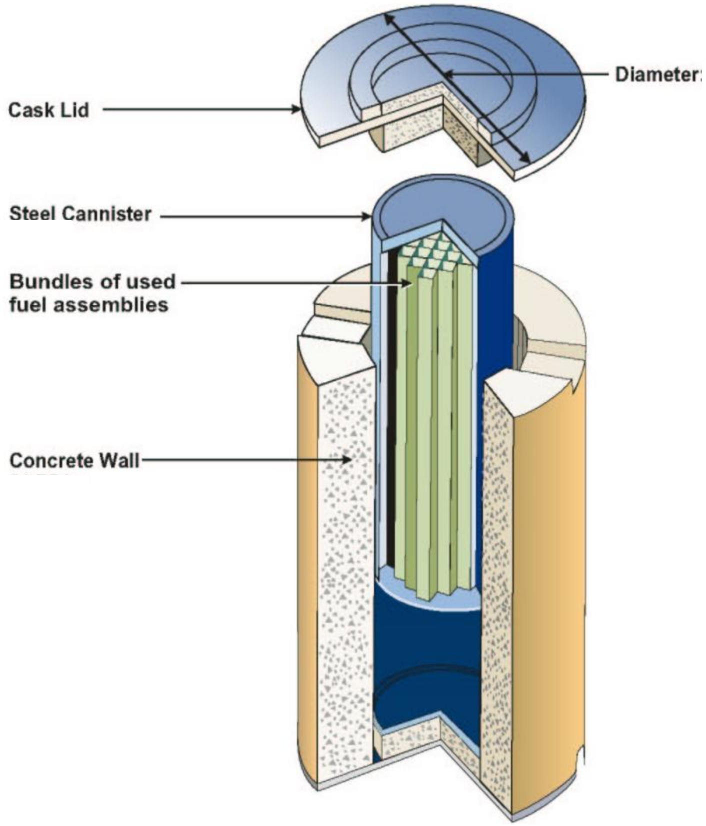
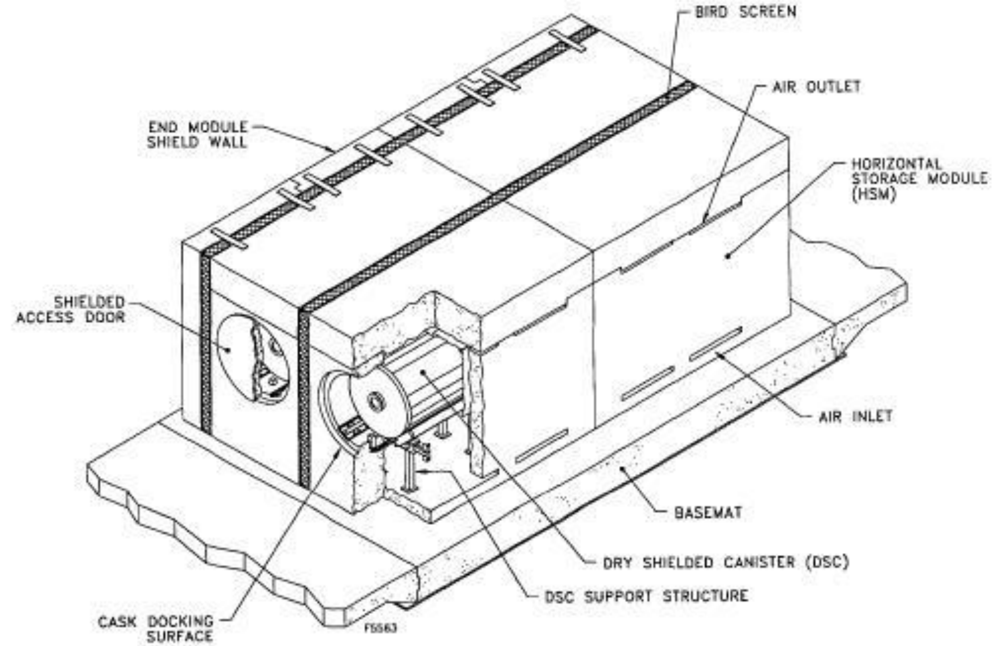
U.S. CANISTER DESIGN TECHNOLOGIES	
BFS/ES	66
GNB	26
Holtec	446
NAC	269
Transnuclear	603
TOTAL	**1410**

Source: Compiled from StoreFuel, Vol. 13, Num. 164, April 3, 2012

Example Canister Designs





NRC Regulatory Focus

- Initial License Terms (0-20 years)
  - No immediate safety issue identified
  - NRC continues to monitor and evaluate data; expects same from licensees
  - Unexpected, premature weathering damage of other cask components has been detected and mitigated
- Renewal Terms (20-60 years)
  - Renewal terms may be more conducive to initiation of undetected SCC
  - SRP-LR for reactors recommends external surface monitoring of stainless steel in chloride environments
- Extended Storage (60+ years)
  - Addressed through NRC EST and EPRI ESCP

Reference: NUREG-1800; NUREG-1801

Governing Regulations

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- Confinement Integrity
  - Designed to accommodate environmental conditions
  - No significant chemical, galvanic, or other reactions
  - Inspected to ensure no defects
  - Maintain confinement (normal, off-normal, and accident conditions)
  - Periodic monitoring to determine when corrective action is needed
- Dose Limits
  - Confinement features must be sufficient to meet 10 CFR 72.104, 106
- Ready-Retrieval
  - Cladding must be protected such that degradation will not pose operational safety problems upon removal
  - Storage systems must be designed to allow ready retrieval

Note: List is not comprehensive; most pertinent governing regulations are noted.

Source: 10 CFR 72.24(l)(1); 72.120(d); 72.122(b),(h)(1),(h)(4),(l); 72.236(d),(j),(l)

Governing Regulations

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- License renewal
  - Assessment based on initial licensing basis
  - AMP describes management of issues associated with aging that could adversely affect SSCs important to safety
    - Prevention
    - Mitigation
    - Condition Monitoring
    - Performance Monitoring
  - Demonstrate SSCs important to safety have not been adversely affected

Source: 10 CFR 72.3, 72.42(a)(2), 72.240(c)(3),(d)

Safety Issues

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- Loss of confinement integrity
  - Potential radiological exposure
    - Loss of helium and radionuclides
    - Oxidation of fuel cladding
    - Additional concern during retrieval and transfer of fuel
  - Environmental contamination
- Failure times and likelihoods are unknown
  - No monitoring of canister integrity
  - Relevant examples of chloride-induced SCC in austenitic SS are known
  - Further assessment of canisters is needed

Safety Assessment

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- Industry should assess the significance for specific site locations and cask designs
  - Prioritize based on potential vulnerabilities
  - Consider current license terms and future renewals
- Provide to NRC for evaluation under appropriate process
- Consider significant parameters
  - Canister surface temperature
  - Local humidity
  - Salt concentration and composition
  - Stress state of canister
  - Exposure times

Aging Management

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- Welded canisters are not typically monitored and not readily accessible when in storage
- Industry should consider aging management approaches to assess phenomena
  - Performing corrosion analyses
  - Collecting data
  - Establishing preventative maintenance activities
  - Monitoring and inspecting canisters
  - Mitigating potential corrosion damage

TECHNICAL INFORMATION

Technical Information – Key Messages

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- Available operational experience (OpE) indicates events where SCC of austenitic SS components was attributed to atmospheric chloride exposure.
- The susceptibility for SCC appears to increase at lower temperatures, potentially less than 60 to 80°C.
- The DRH for sea salt appears close to that of $MgCl_2$. SCC on U-bend specimens with sea salt is observed at RH less than the DRH for NaCl and at AH less than 30 g/m^3.
- SCC is observed on U-bend specimens covered with 1 g/m^2 of sea salt at AH less than 30 g/m^3.
- Visual examination has not been demonstrated to identify the features associated with SCC of the canister.
- More information is needed concerning the actual conditions of canisters in the field.

OpE Overview

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- SCC of austenitic SS components attributed to atmospheric chloride exposure
  - Nuclear Power Plant Events
  - Other industrial and commercial components
- Events provide some indication of potential susceptibility of canisters to SCC

Examples of Plant OpE

- St. Lucie Unit 2 – April, 1999[1]
  - Leaking of 304 SS piping in refueling water storage tank (RWST) trench exposed to atmosphere
  - ~16 years in service (Unit 2 commissioned 1983)
  - Branched through-wall cracking initiated on pipe OD
  - 24” diameter, ¼” wall piping, 30 psig at 120°F (49°C)
  - Indications more severe at field welds
- Turkey Point Unit 3 – April, 2005[2]
  - Flaw in 304 SS spent fuel pool cooling line attributed to chloride-induced SCC
  - Initiated on pipe OD, at base of a pit
  - Piping housed in room with grating steel door open to outside
  - Indication ½” from flange butt weld, in HAZ

1. LER 389-1999-003: “ECCS Suction Header Leaks Result in Both ECCS Trains Inoperable and TS 3.0.3 Entry,” ADAMS Legacy Library Accession Number 9905130085.
2. L-2005-168: “10 CFR 50.55a Request for Temporary Non-Code Repair,” ADAMS Main Library Accession Number ML052780060.

Examples of Plant OpE

- Ohi Unit 1 (Japan) – July, 2004[3]
  - Cracking in the SS RWST exposed to outdoor environment (5 locations)
  - Crack noted in the vicinity of backplate weld
  - Tank was installed without coating in 1974; coated in 1981
  - ~30 years in-service

3. Japan NISA/METI News Release PRI-04-25, "Report and Its Examination Result from Kansai Electric Power Company on Cause and Countermeasures of Defect (Water Ooze from Refueling Water Storage Tank) Found During the Periodical Inspection of Ohi Power Station Unit-1, Kansai Electric Power Company," July 27, 2004.

Examples of Plant OpE

- Koeberg Units 1 and 2 (South Africa)
  - Cracking in 304L piping connected to tank exposed to outdoor environment[4]
    - Extensive crack networks initiating from surface pits
  - Cracks in 304L PTR tanks[5]
    - Primarily in areas adjacent to welds
    - Fabricated to ASME Code, Section III, Subsection NC
    - Water maintained between 7 and 40°C
    - <30 years in-service

4. M. van Dalen, C. Wicker, G. Wilson, "Non Destructive Testing of Materials Subject to Atmospheric Stress Corrosion Cracking," 17th World Conference on Nondestructive Testing, Shanghai, China, 2008.
5. RFI No. NUC110801/WB, Appendix 6.1, Ref. DSG-310-301, "Technical Specification for Replacement PTR Tanks for Koeberg Nuclear Power Station," 2001. http://mp2mas17.eskom.co.za/tenderbulletin/details.asp?id=936

Other Industrial and Commercial OpE

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- Stainless steel nuts for atmospheric test racks at Kure Beach[6]
- 304L Dished ends for outdoor pressure vessels[7,8]
- 316L Rock climbing hangers in seaside cliffs[9]

6. R. Kain, "Marine Atmospheric Stress Corrosion Cracking of Austenitic Stainless Steels," Materials Selection and Design, December 1990.
7. J.B. Gnanamoorthy, "Stress Corrosion Cracking of Unsensitized Stainless Steels in Ambient-Temperature Coastal Atmosphere," Materials Selection and Design, December 1990.
8. R. Dayal, J. Gnanamoorthy, "Failure of a Stainless Steel Tank Used for Storage of Heavy Water/Helium," Handbook of Case Histories in Failure Analysis, Vol. 2, K.A. Esakul, Ed., ASM International, 1992.
9. A. Sjong, L. Eiselstein, "Marine Atmospheric SCC of Unsensitized Stainless Steel Rock Climbing Protection," Journal of Failure Analysis and Prevention, Volume 8, pages 410-418, 2008.

Considerations for Assessing SCC Susceptibility

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- Deposition rate of salt on canister surface
- Deliquescence temperature and humidity
- Minimum salt concentration for SCC
- Tensile stresses

NRC Sponsored Research at SwRI/CNWRA

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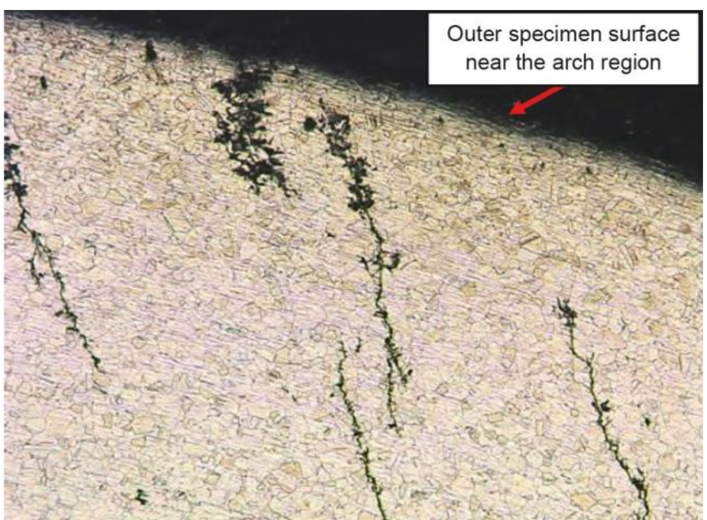
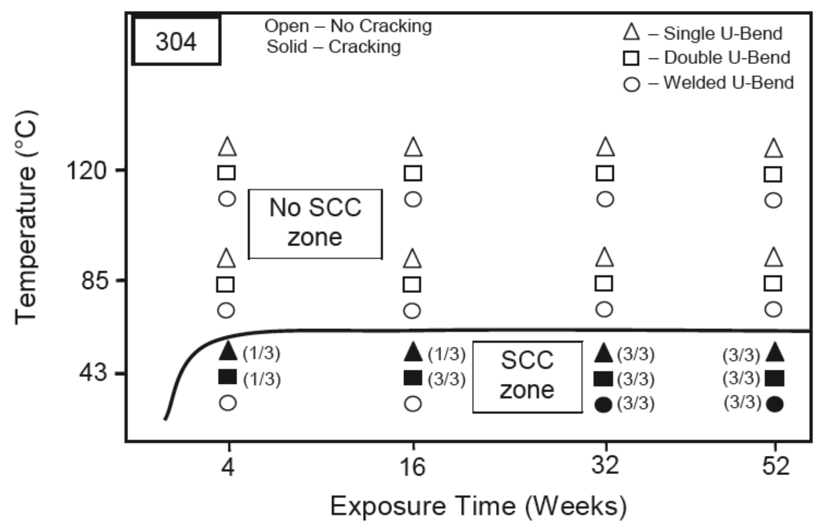
- Previous and current NRC-sponsored work primarily focused on defining:
  - Temperature and humidity requirements
  - Minimum salt concentration for SCC
- NUREG/CR-7030 work[10]
  - Salt spray and salt fog testing of U-bend specimens
  - Limited control of salt deposition
  - High absolute humidity conditions
- Ongoing EST research program[11]
  - Initiated in support of extended storage and transportation activities
  - Cyclic or static exposure of U-bend specimens
  - Known quantities of salt deposited on specimens

10. NUREG/CR-7030, "Atmospheric Stress Corrosion Cracking Susceptibility of Welded and Unwelded 304, 304L, and 316L Austenitic Stainless Steels Commonly Used for Dry Cask Storage Containers Exposed to Marine Environments, 2010.
11. T. Mintz, L. Caseres, X. He, J. Dante, G. Oberson, D. Dunn, T. Ahn, "Atmospheric Salt Fog Testing to Evaluate Chloride-Induced Stress Corrosion Cracking of Type 204 Stainless Steel," CORROSION 2012, Salt Lake City, ADAMS Main Library Accession Number ML120720549.

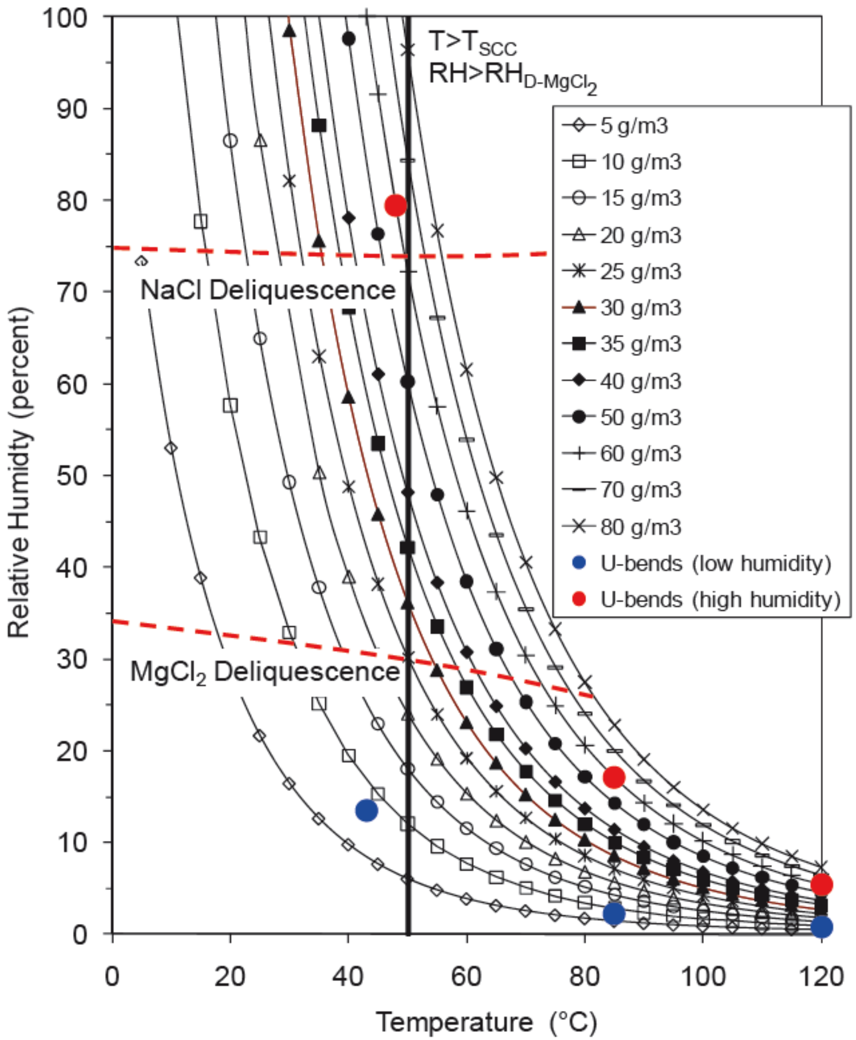
NUREG/CR-7030 – Key Findings

- For salt fog tests conducted at 43, 85, and 120°C, only U-bend specimens at 43°C exhibited SCC – 304, 304L, and 316L
- At 43°C, 304, 304L, the extent of cracking increased with time from 4 to 52 weeks exposure.
- At 43°C, 316L, cracking detected at 32 weeks





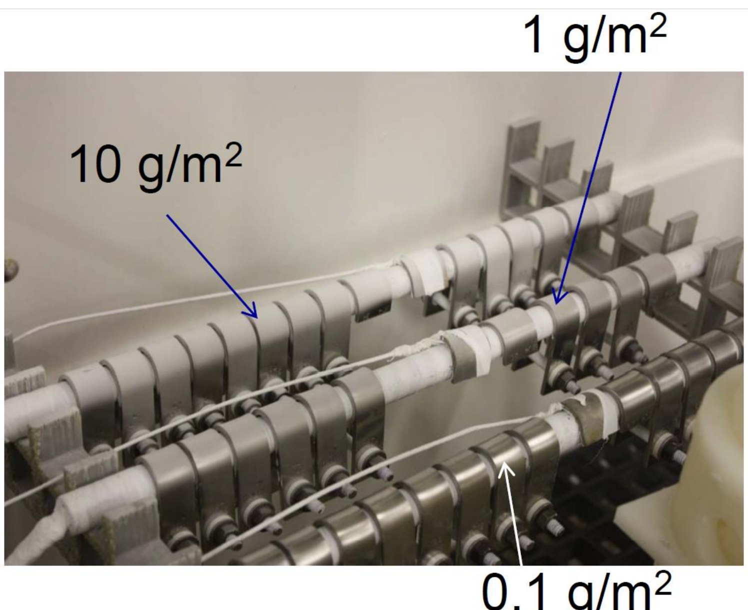
NUREG/CR-7030 Test Conditions

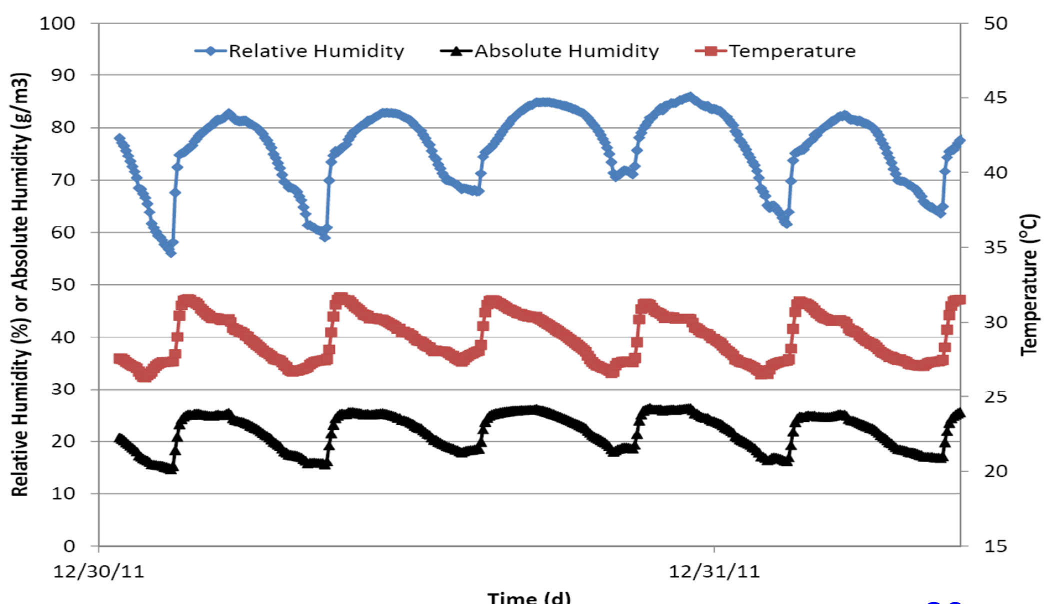


- High absolute humidity (AH) ~ 60 g/m^3
- AH limit in nature ~ 30 g/m^3
- At 43°C, relative humidity (RH) above deliquescence RH (DRH) for NaCl
- No tests between DRH for $MgCl_2$ and NaCl
- Possibility of liquid water contacting specimens from test methodology rather than deliquescence

Ongoing EST Research Program

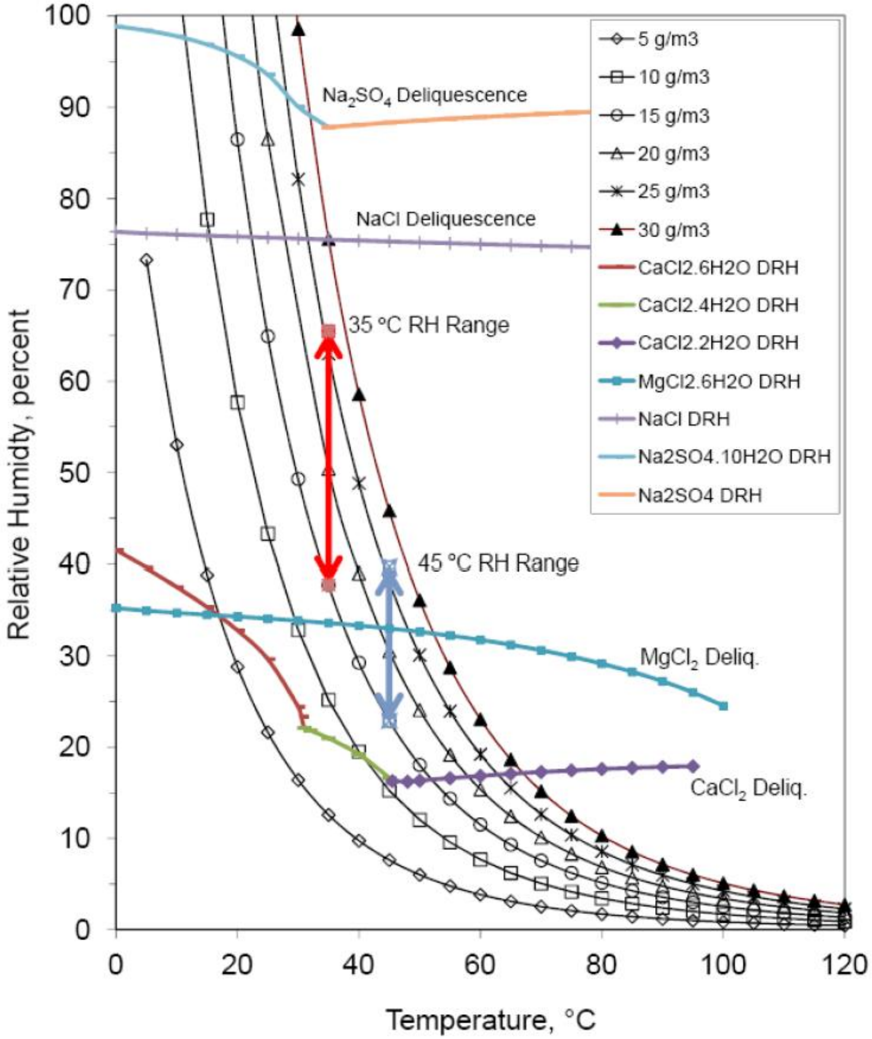
- Determine minimum salt concentration for crack initiation
- Deposit known quantities of ASTM sea salt onto type 304 U-bend specimens; as-received, sensitized, and welded
- Expose specimens at temperatures of 35 and 45°C to cyclic humidity up to AH of 30 g/m^3





Specimens coated with 0.1, 1, or 10 g/m^2 salt

Minimum Salt Concentration – Test Conditions



- At 35°C, humidity cycle (red arrow) should be above calculated DRH for $MgCl_2$ and $CaCl_2$ but below NaCl.
- At 45°C, humidity cycle (blue arrow) should cross calculated DRH line for $MgCl_2$.

Minimum Salt Concentration Preliminary Observations

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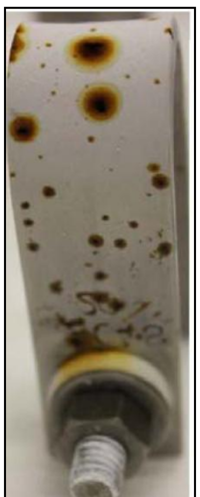
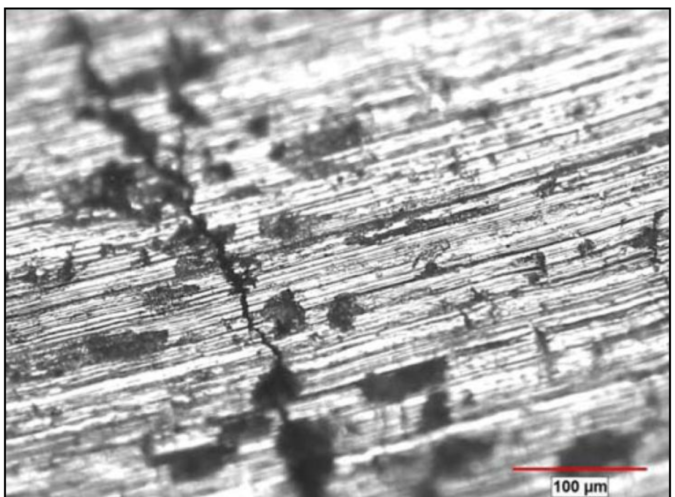
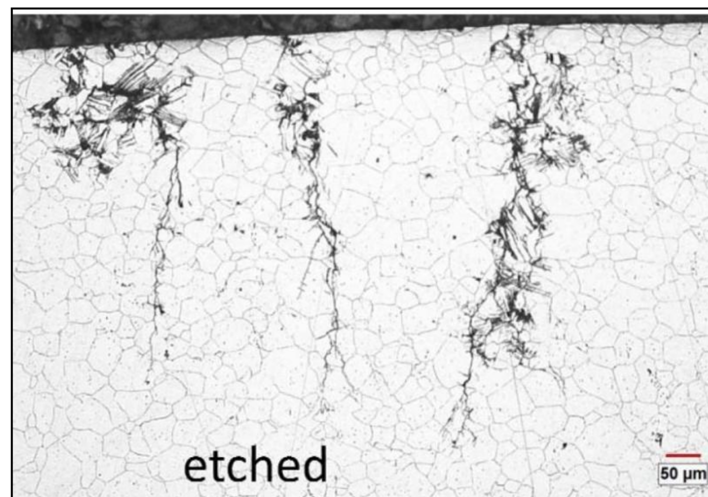
- Within 3 months, as-received and sensitized specimens with 1 or 10 g/m^2 salt showed intergranular cracking. No welded specimens have cracked yet, but there may be interdendritic attack.
- Some specimens with 0.1 g/m^2 salt at 35°C have minor pitting.
- Preliminary results are consistent with Japanese reports on threshold chloride ion concentration for SCC of 0.8 g/m^2.[12,13]







12. K. Shirai, J. Tani, H. Takeda, M. Wataru, T. Saegusa, "SCC Evaluation of Test Multi-Purpose Canister," 2011 Water Reactor Fuel Performance Meeting, Chengdu, China, September 11-14, 2011.
13. T. Saegusa, "Issues and Countermeasures for Long-Term Storage of Spent Fuel by Dry Cask," 2012 NRC Regulatory Information Conference.

Ongoing EST Research Program – Elevated Temperature Deliquescence and SCC

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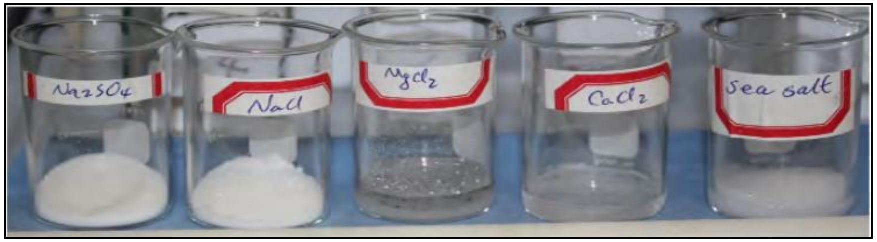
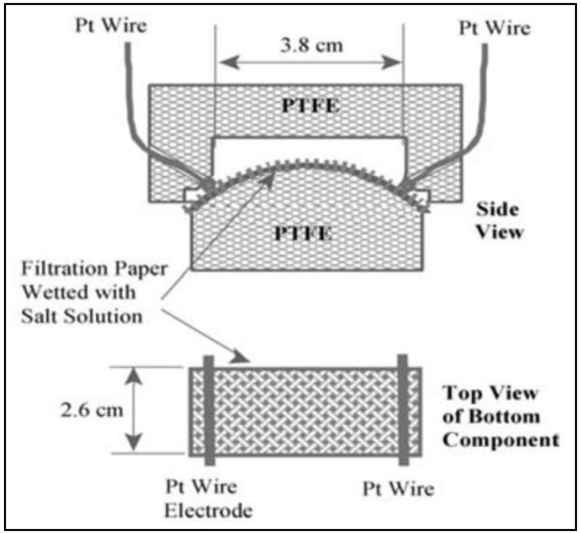
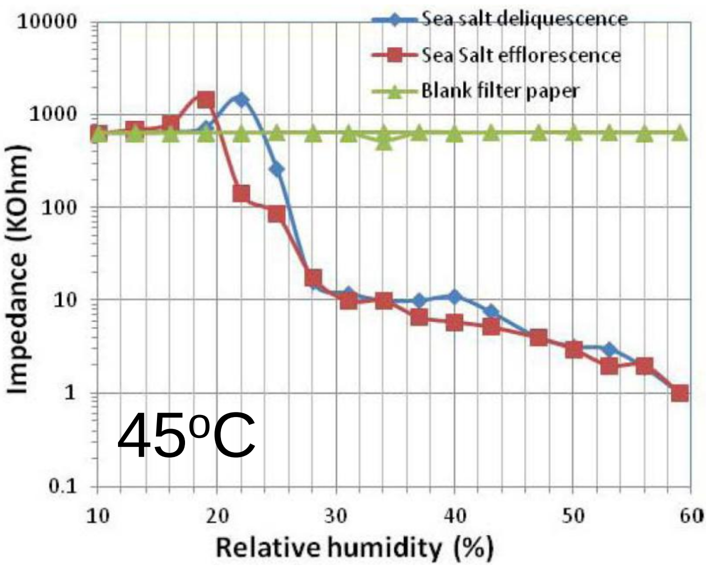
- Determine DRH for sea salt and its pure salt constituents at temperatures in the range of 45 to 80°C.
- Measure DRH by observing salts in beakers at different humidity levels or other analytical methods such as the conductivity cell.
- Expose U-bend specimens to range of humidity levels at the elevated temperatures to determine conditions where SCC could occur.

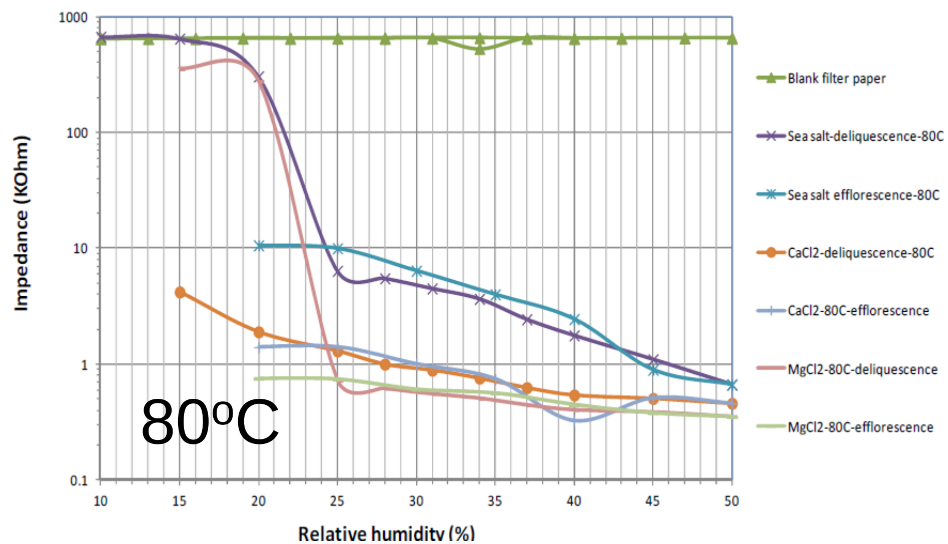




Elevated Temperature Deliquescence Preliminary Observations

- For conductivity cell measurements, deliquescence creates conductive electrolyte reducing the measured impedance.





- DRH for $CaCl_2$ is lowest of sea salt constituents, in the range of 20 to 25% RH.
- DRH is similar for $MgCl_2$ and sea salt, in the range of 30 to 35% RH.
- Deliquescence of NaCl is not observed up to 50% RH.
- Efflorescence may not occur until lower humidity than DRH.

Elevated Temperature SCC Test Plan

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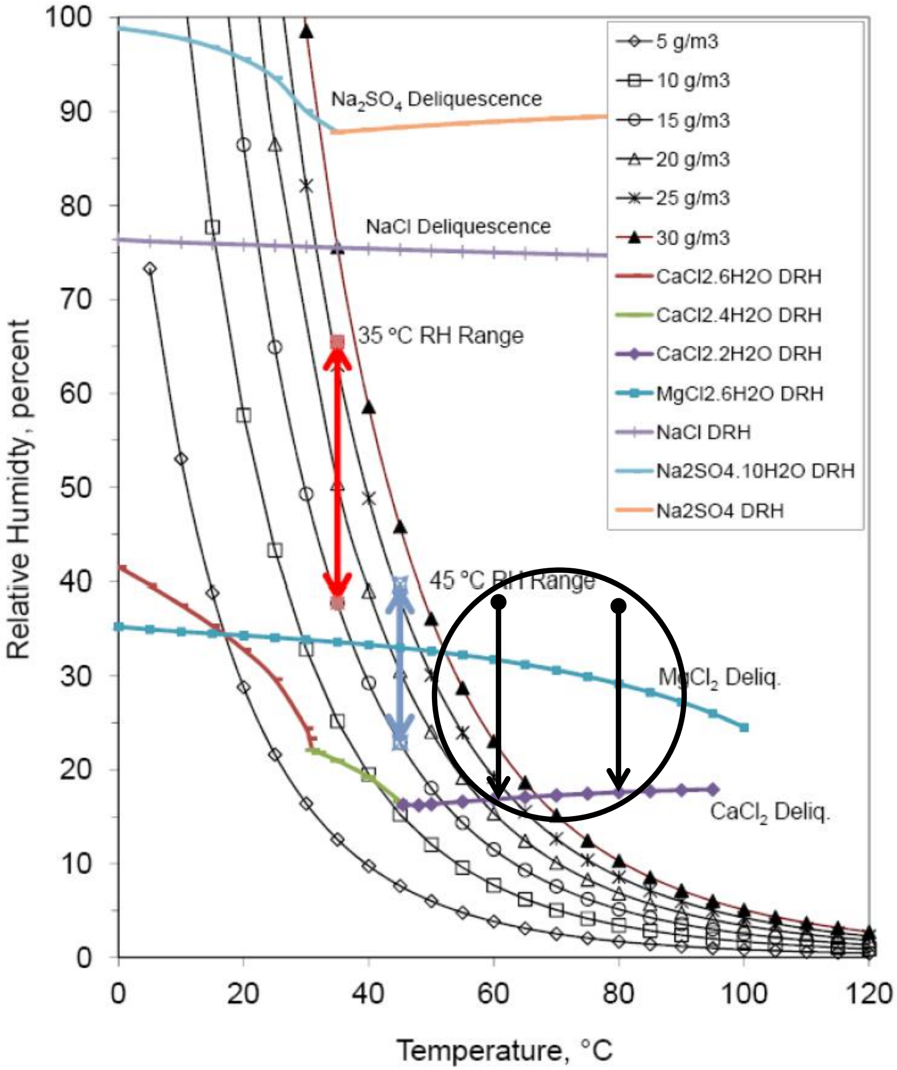

- Expose U-bend specimens coated with 10 g/m^2 salt at temperatures of 60 and 80°C and constant RH.
- Start with relatively high RH of 40%, above DRH for $MgCl_2$.
- If cracking occurs, expose new specimens at progressively lower RH to observe trend for crack initiation.
- Japanese data showed SCC at 80°C and 16% RH for $CaCl_2$.[14]

14. M. Mayuzumi, J. Tani, T. Arai, "Chloride induced stress corrosion cracking of candidate canister materials for dry storage of spent fuel," Nuclear Engineering and Design, Volume 283, pages 1227-1232, 2008.

Elevated Temperature SCC Preliminary Observations

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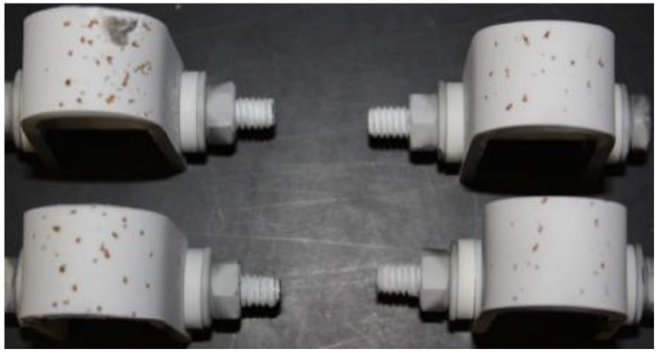
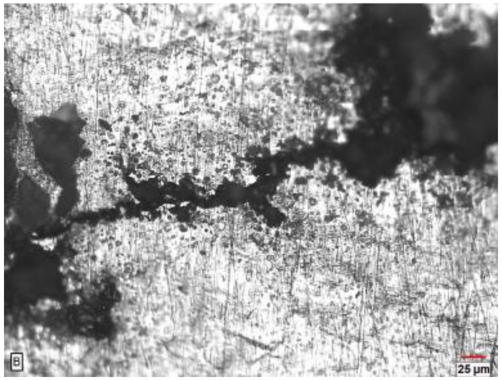
- Cracking observed for specimens tested at 60°C and 40% RH. Testing underway at 35% RH, should be near or slightly above $MgCl_2$ and sea salt DRH.
- Testing underway at 80°C and 40% RH, and appears that cracking has occurred. Test is well above expected DRH for $MgCl_2$ and sea salt. Subsequent tests planned at lower RH.





Specimens tested at 60^{o}C and 40% RH.

Considerations for Future NRC-EST Research

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- Dilution of chlorides at high RH[15,16]
- Effects of stress and strain level on crack initiation
  - Alternatives to U-bend testing, including C-ring, bent beam, notched tensile, or others
  - Japanese data showed SCC at half of the yield stress[14]
- Non-coastal atmospheric species or industrial pollutants (underway)
- Welding residual stress analyses
  - Potential for tensile stresses to propagate through wall
  - May consider lid and body welds
- Non-destructive examination methodologies
  - There is no currently qualified technique or acceptance criteria for examination of the canisters.
  - Challenges for remote visual examination include accessibility, camera resolution, lighting, and surface condition among others.
  - The ability of remote visual examination to identify features associated with SCC has not been shown by performance demonstration, mockup testing, or other means.

14. M. Mayuzumi, J. Tani, T. Arai, "Chloride induced stress corrosion cracking of candidate canister materials for dry storage of spent fuel," Nuclear Engineering and Design, Volume 283, pages 1227-1232, 2008.
15. O.E. Albores-Silva, E.A. Charles, C. Padovani, "Effect of chloride deposition on stress corrosion cracking of 316L stainless steel used for intermediate level radioactive waste containers," Corrosion Engineering, Science, and Technology, Volume 46, pages 124-128, 2011.
16. J. Prosek, A. Iversen, C. Taxén, D. Thierry, "Low-temperature stress corrosion cracking of stainless steels in the atmosphere in the presence of chloride deposits," Corrosion, Volume 65, pages 105-117, 2009.

Preliminary Weld Residual Stress Analysis

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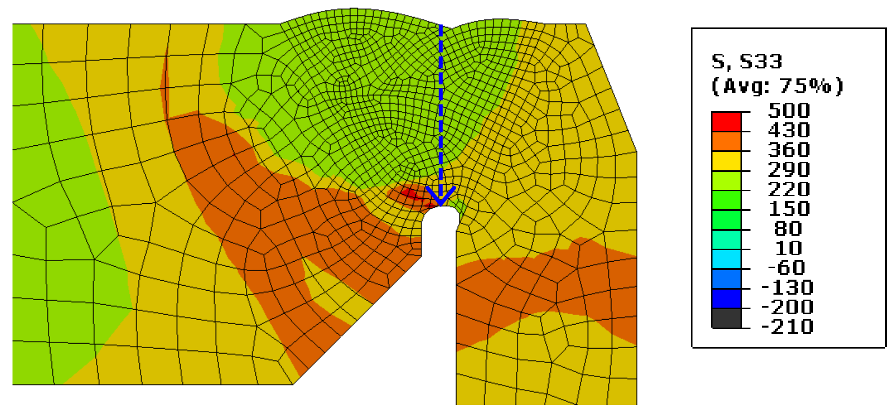
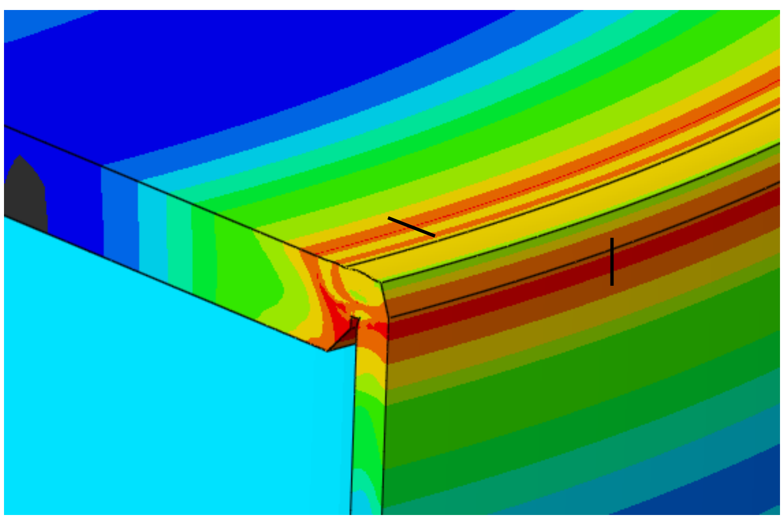
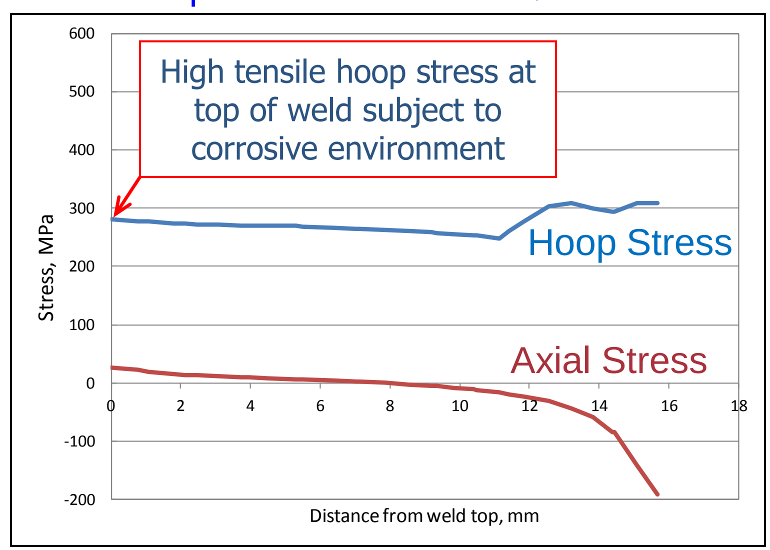
- High tensile stresses in hoop direction
- Estimated parameters – configuration, heat input, number of passes, etc.
- Potential cracks would tend to orient radially



Hoop stress distribution, MPa



Weld top -------------------> Weld bottom



Current Information Needs

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- Additional information from industry is needed to reduce the uncertainty concerning the potential for SCC of the canisters.
- Actual conditions of canisters in field
  - Temperature – Actual heat load, measured surface temperature
  - Humidity
  - Salt concentration in air
    - Japanese measured salt concentration in air at Tokai and Fukushima[13,14]
    - Similar concentration in dry storage building as outside
  - Amount and composition of salt on canister surface
- Welding design and parameters for lid and body welds
  - Joint design
  - Welding technique and parameters
  - Repairs

13. T. Saegusa, "Issues and Countermeasures for Long-Term Storage of Spent Fuel by Dry Cask," 2012 NRC Regulatory Information Conference.
14. M. Mayuzumi, J. Tani, T. Arai, "Chloride induced stress corrosion cracking of candidate canister materials for dry storage of spent fuel," Nuclear Engineering and Design, Volume 283, pages 1227-1232, 2008.

PATH FORWARD

Summary

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- RIRP Problem Statement (08/2011):

  There is insufficient data to determine the environmental conditions, and associated time scales, necessary for potential initiation of chloride-induced stress corrosion cracking (SCC) in stainless steel dry spent nuclear fuel (SNF) storage canisters deployed at ISFSI locations.

- RIRP participants should discuss whether process is working adequately for this issue

Reference: NRC letter to NEI, "Nuclear Regulatory Commission Response to Industry Regarding Coastal Marine Atmosphere Issue," dated August 4, 2011, ADAMS Accession Number ML1121700692.

Alternative Processes

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- NRC continues to consider other regulatory processes beyond RIRP
  - Generic Communications
    - RIS
    - Information Notice
    - Generic Letter
- Industry programs beyond ESCP