U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

Darrell S. Dunn

NRC/NMSS/SFST

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

August 5, 2014

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

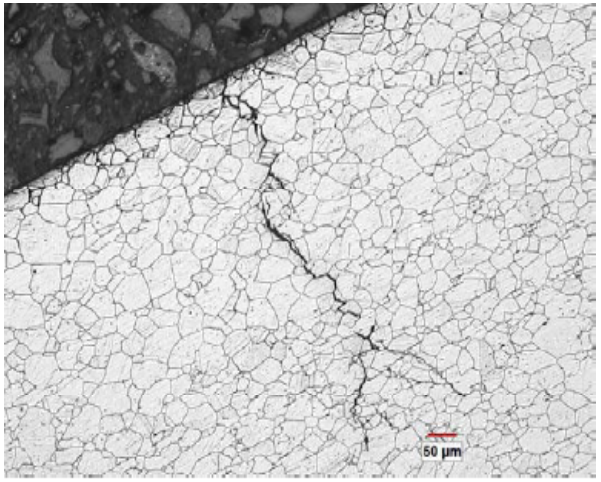
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- Test objectives:
  - Limit absolute humidity (AH) to about 30 g/m^3
  - Vary test temperature, surface salt concentration and material condition
- Test methods:
  - ASTM G30 U-bend specimens with 0.1, 1, or 10 g/m^2 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 ^{o}C) Type 304
    - Exposed in test chamber to cyclic AH (15 and 30 g/m^3)
  - ASTM G38-01 C-ring specimens at ~0.4% or 1.5% strain
    - Tested with 1 or 10 g/m^2 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)

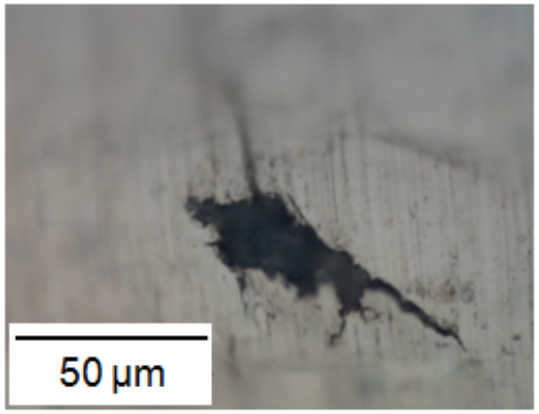
Surface Chloride Concentration

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

Pitting on specimens at 10 g/m^2 (top), 1 g/m^2 (middle), and 0.1 g/m^2 (bottom)

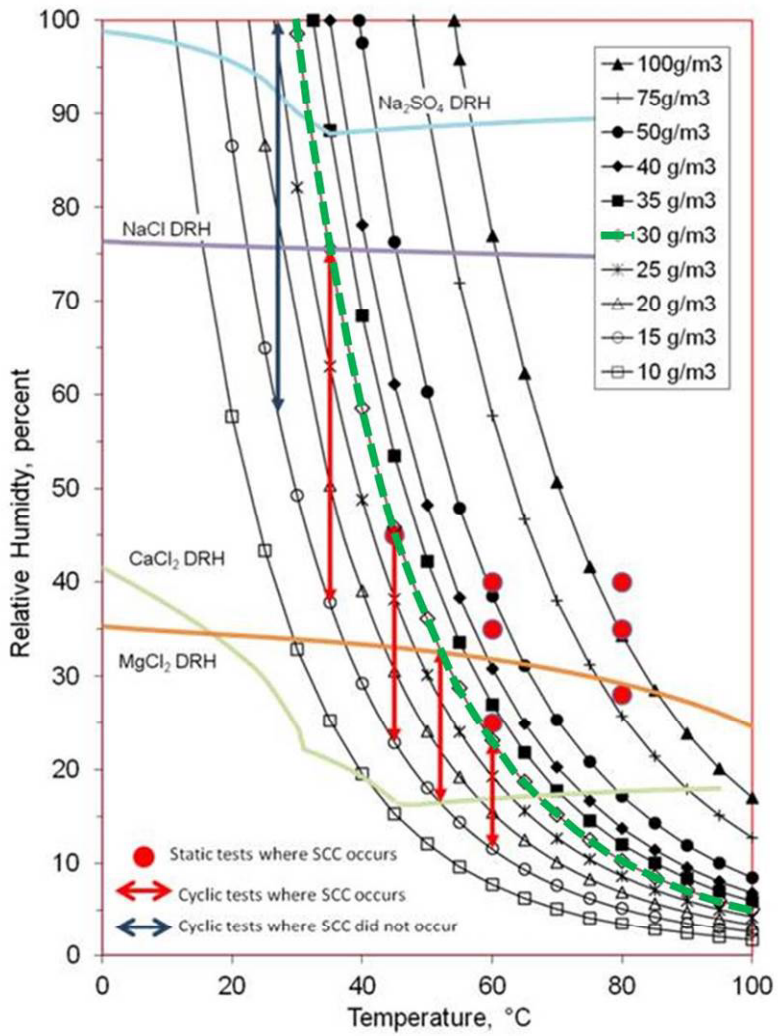


Cross section of sensitized, 0.1 g/m^2 specimen at 45°C after 4 months



Top view of sensitized specimen with 10 g/m^2 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/m^3
- 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/m^2, lower than previous reports
- CISCC at 80 °C required absolute humidity values above 30 g/m^3

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/m^2 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/m^3)

C-ring Specimen Tests

Specimen Temp. (°C)	RH (%)	AH (g/m^3)	Salt Conc. (g/m^2)	Strain (%)	Exposure Time (months)	Crack Initiation
35	72	29	1	0.4	2	No
			10	0.4	3	Sensitized
45	44	29	1	0.4	3	No
			10	0.4	3	No
				1.5	2	As-received and sensitized
52	32	29	1	0.4	2	As-received and sensitized
			10	0.4	3	Sensitized
				1.5	2	As-received and sensitized

Conclusions from NRC Sponsored SCC testing

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- 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/m^3
- CISCC initiation is observed at salt quantity as low as 0.1 g/m^2 (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/m^3)

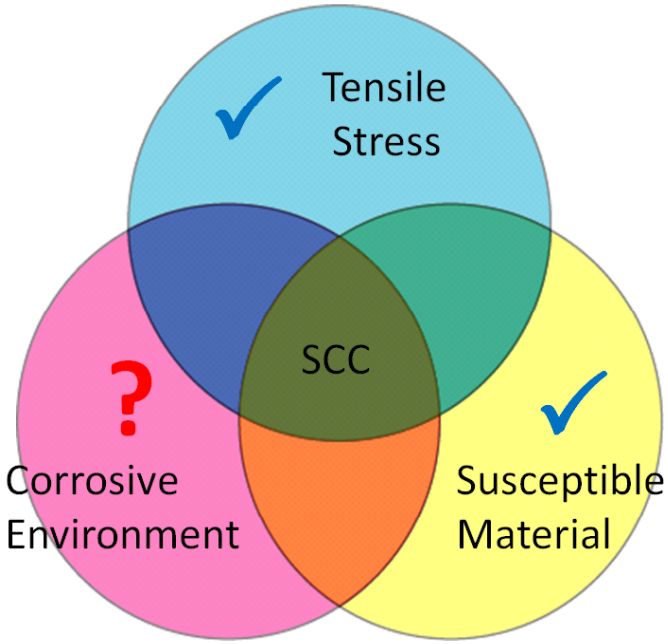
Power Plant Operating Experience with SCC of Stainless Steels

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

- CISCC growth rates of 0.11 to 0.91 mm/yr for components in service
  - Median rate of 9.6×10^{-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)

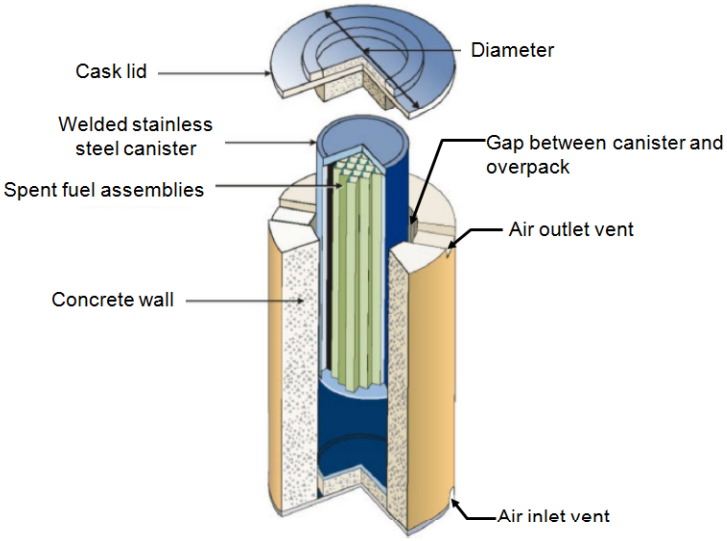
Potential for SCC of Welded Stainless Steel DSCs

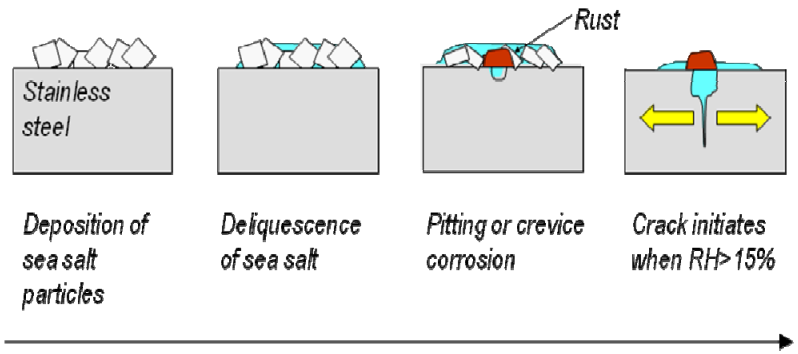


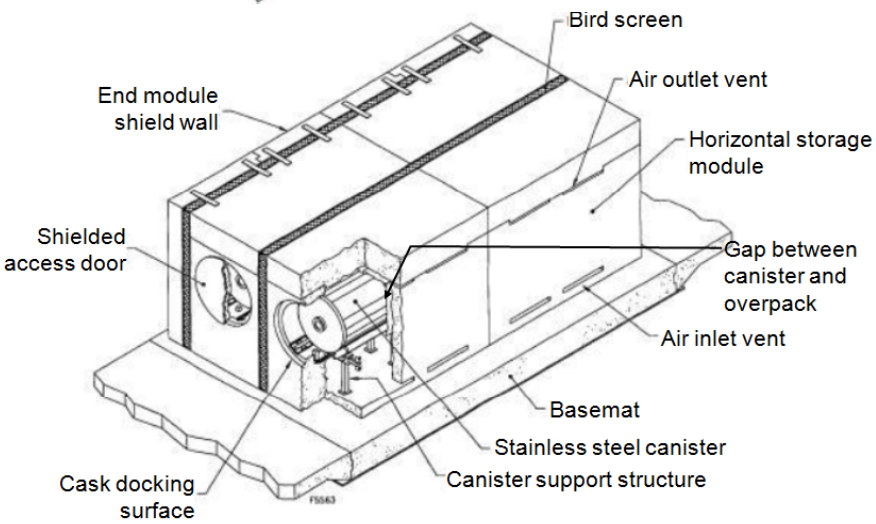
2/3 of the requirements for CISCC are present in welded stainless steel dry storage canisters (DSCs)

- 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

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- **<u>10 CFR 72.42(a), 72.240(c):</u>**
  - 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.
- **<u>Guidance: NUREG-1927 AMP Elements:</u>**

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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)