Susceptibility Assessment Criteria for Chloride-Induced Stress Corrosion Cracking (CISCC) of Welded Stainless Steel Canisters for Dry Cask Storage Systems

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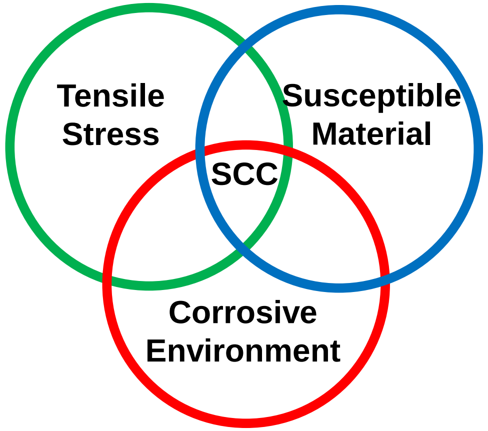
Overview

- Background
- Project Timeline
- Progression of Modeling
- Key Results
- Susceptibility Criteria Format
- Steps Beyond the RIRP

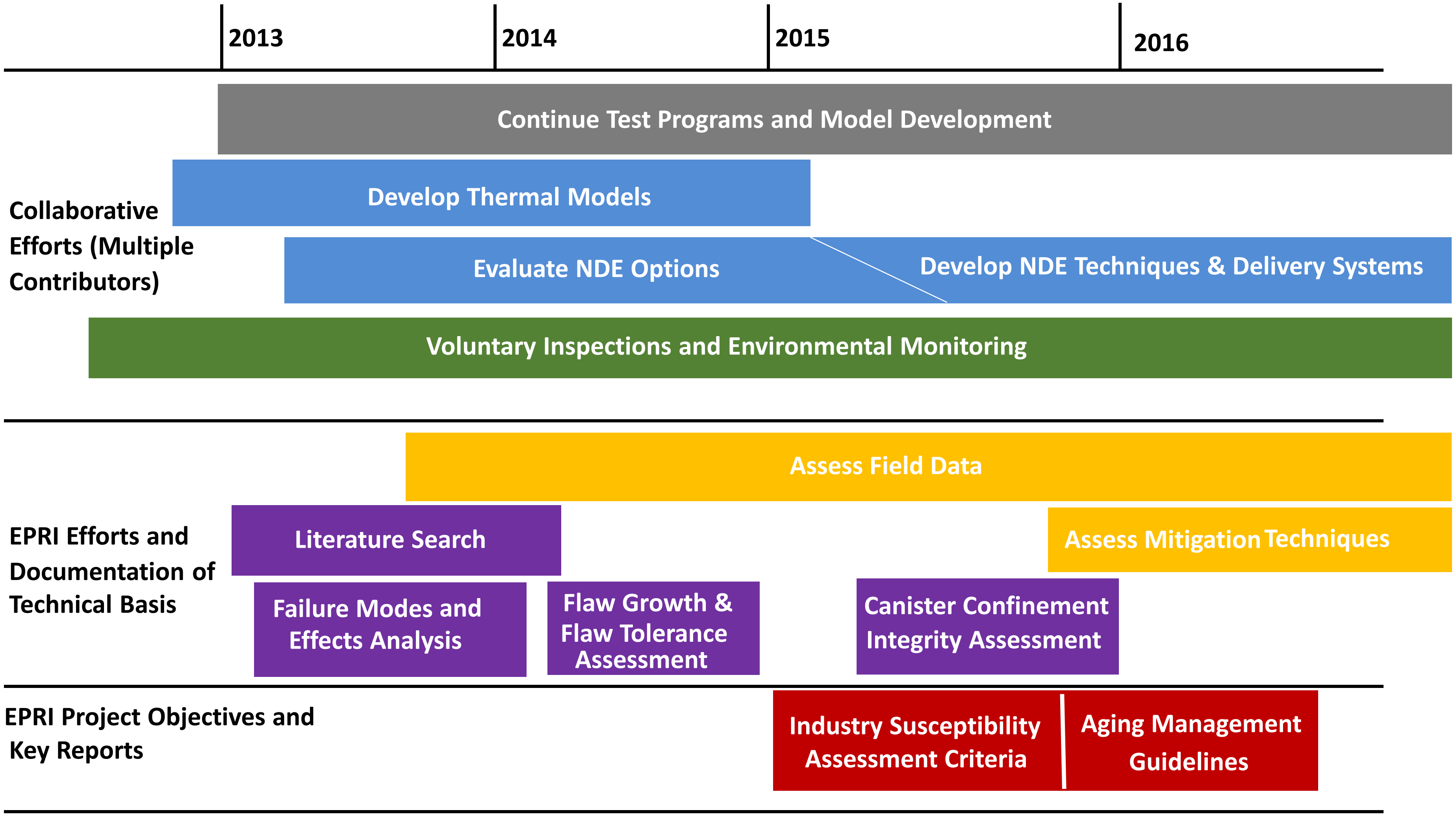
Background

- Chloride Induced Stress Corrosion Cracking (CISCC) of stainless steel reactor components has occurred when three elements are all present:
  - Elevated stress
  - Susceptible Material
  - Corrosive Environment
    - Surface contamination by atmospheric chlorides
    - Sufficient humidity



- EPRI has a multi-year project to
  - Evaluate susceptibility to CISCC for welded stainless steel used fuel canisters
  - Develop related aging management guidelines

Project Timeline



Progression of Modeling

- Failure Modes and Effects Analysis
  - Qualitative judgments of frequency/probability, detectability, & severity over time based on literature and limited calculations
  - Define boundaries of the degradation problem & guide approach to subsequent assessments
- Canister Flaw Growth and Flaw Tolerance
  - Model flaw growth to through-wall
  - Determine consequential flaw sizes
- **Susceptibility Assessment Criteria**
  - **Model the process of canister degradation based on the pathways identified in the FMEA**
- *Canister Confinement Integrity Assessment*
  - *Probabilistic analysis to determine the benefit of various monitoring, mitigation, & inspection regimes*

Susceptibility Criteria Format

- ISFSI Susceptibility Ranking (Z_{ISFSI})
  - Direct resources to locations where CISCC is more likely to occur
  - Results from sites identified as more susceptible may help to refine aging management recommendations (improve technical basis, identify bounding locations)
  - Proximity to chloride source and local absolute humidity are key variables
- Canister susceptibility ranking (H_{CAN} and V_{CAN}) intended to identify canister(s) to be inspected at a given site and to guide scope expansion if needed
  - Geometry (horizontal or vertical) affects locations of maximum chloride deposition and locations of minimum temperature
  - Canister material, storage duration, and fuel load power are key variables

ISFSI Susceptibility Ranking

$$Z_{ISFSI} = Cl_{starting} + Cl_{adj} + AH_{adj}$$

- Chloride starting value is based on proximity to a marine shore
- Chloride adjustments are made for elevation, for proximity to a cooling tower (saline/non-saline), and for proximity to salted roads
- Absolute humidity adjustment is based on local atmosphere annual average data, this affects the amount of time a surface is likely to support deliquescence

ISFSI Susceptibility Ranking

- Ranking value will range from 1 to 10
- Ranking value will be constant with time
- Ranking value will be an input to Horizontal and Vertical Canister Rankings

Canister Susceptibility Ranking

- Ranking value will range from 1 to 10
- Ranking value will increase with time
- Ranking will be different for vertical and horizontal canisters
- Within a given geometry, ranking values may be used to identify bounding canisters at different sites
  - Canister rank must be greater by at least 2
  - Z_{ISFSI} at bounding canister site must be equal or greater
- Additional considerations are provided for identification of canister(s) to be inspected

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Horizontal and Vertical Canister Ranking

$$H_{CAN}, V_{CAN} = Deposition + Material + Power$$

- Separate paths are needed because the different geometries have different specific locations of concern and different heat profiles
- Rankings cannot be used to make any comparison of the susceptibility of horizontal canisters relative to the susceptibility of vertical canisters
- Although the canister geometries have different deposition profiles, they are weighted in the same manner due to high variability and uncertainty in deposition rate

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Canister Locations of Higher Susceptibility

Factor for CISCC Susceptibility	**Locations on Horizontal Canister**	**Locations on Vertical Canister**
Tensile Stresses on OD	Regions in the vicinity of welds (e.g. within about 2 thicknesses)	Regions in the vicinity of welds (e.g. within about 2 thicknesses)
Low Surface Temperature	Lids; shell along canister underside and along ends	Lower region of canister OD
Elevated Chloride Deposition	Upward-facing surfaces of canister shell	Top lid; possibly the areas in the vicinity of the overpack inlets
Crevice-like Geometry	Support rail contact region	Areas where canister contacts the overpack channels/standoffs*
Material Condition	Areas of heavy grinding or mechanical damage (e.g. gouges)	Areas of heavy grinding or mechanical damage (e.g. gouges)
More Susceptible Location(s)	Shell welds at canister ends (top surface); support rail interface near welds	Canister sides near welds at the bottom of the canister

* These features are not present in all overpack designs for vertical canisters.

Canister Ranking Parameters - Deposition

- Deposition parameter reflects both canister age and environmental characteristics
- The parameter is established based on the value of X_{Cl}, which is calculated using:
  - The storage duration of the canister
  - The Z_{ISFSI} value for the canister site
- At higher Z_{ISFSI} values, X_{Cl} increases faster (i.e., higher X_{Cl} for a given storage duration)

Canister Ranking Parameters - Material

- The material alloy factor provides credit to canisters constructed from alloys that are more resistant to CISCC initiation.
- Different values are provided for 304, 304L(N), 316, and 316L(N).
- The primary differences among these alloys are the limitation of the carbon content to reduce the potential for sensitization during welding (–L/–LN) and the addition of molybdenum (type 316) to increase the passivity of the surface oxide layer.

Canister Ranking Parameters - Power

- Decreasing thermal power causes decreasing canister surface temperature.
- Deliquescence for a significant portion of time each year at atmospheric levels of absolute humidity tends to begin at 25^{o}C above atmospheric temperature.
- The relationship between thermal power levels and temperature at various points on the canister is different for horizontal and vertical canisters.

Qualitative Considerations for Identifying Candidate(s) for Canister Inspection Among Equally Ranked Canisters

- Canister in storage the longest
- Specific canister placement
- Pre-load storage and installation experience
- Fabrication record information

Susceptibility Assessment Criteria Schedule

- Susceptibility Assessment Criteria draft report currently in review cycle
  - EPRI staff
  - Advisory panel (comprised of vendors, DOE, NEI, utilities)
  - EPRI High Level Waste Technical Advisory Committee
- Publication anticipated in September 2015

Steps Beyond the RIRP Resolution

- Canister Confinement Integrity Assessment
  - Probabilistic assessment of flaw growth
  - Compare various inspection regimes (optimize resources, aiming for detection prior to 75% through-wall)
- Aging Management Guidelines
- Continue to follow CISCC testing, modeling and inspection results

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Example AMP for Localized Corrosion and Stress Corrosion Cracking of Welded Stainless Steel Dry Storage Canisters

Darrell S. Dunn,
NRC/NMSS/DSFM/RMB

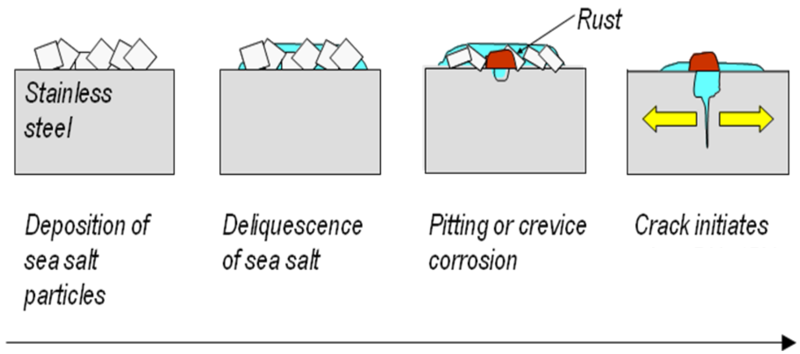
Chloride-Induced Stress Corrosion Cracking
Regulatory Issue Resolution Protocol Meeting
April 21, 2015

Outline

- Atmospheric chloride-induced stress corrosion cracking (CISCC)
- CISCC calculations:
  - Effect of temperature
  - Deliquescence of chloride salts
  - Conservative estimation of CISCC growth
  - Key points
- Example aging management program (AMP)
- Summary

Atmospheric CISCC

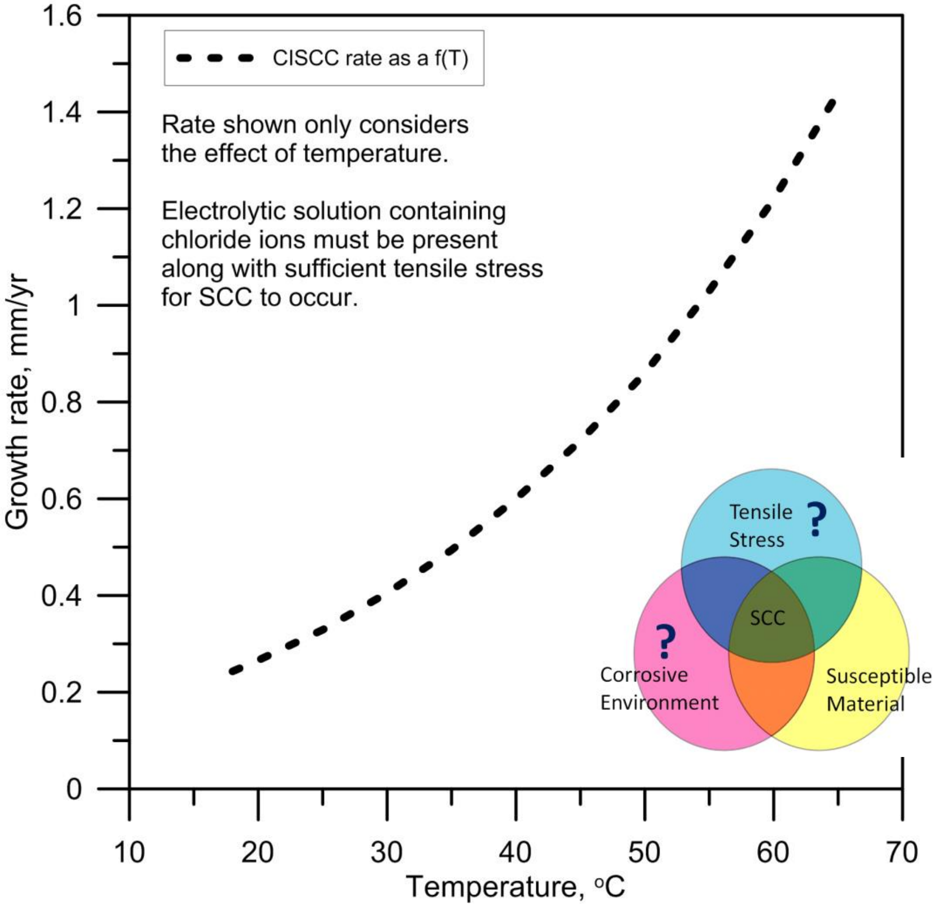
- Atmospheric CISCC of welded stainless steel components observed in operating power plants
  - Piping systems
  - Storage tanks
- CISCC complex process with multiple dependencies
  - Surface temperatures
  - Composition of deposited salts
  - Surface concentration of salts
  - Site specific environmental parameters
  - Residual stress profiles



- Cl salts transported and deposited by flow of ambient air
- Salt deliquescence dependent on composition and relative humidity
- Pitting and crevice corrosion initiation sites for CISCC

References:
NRC IN 2012-20 (ML12319A440)
NUREG/CR-7170 (ML14051A417)
NUREG/CR-7030 (ML103120081)

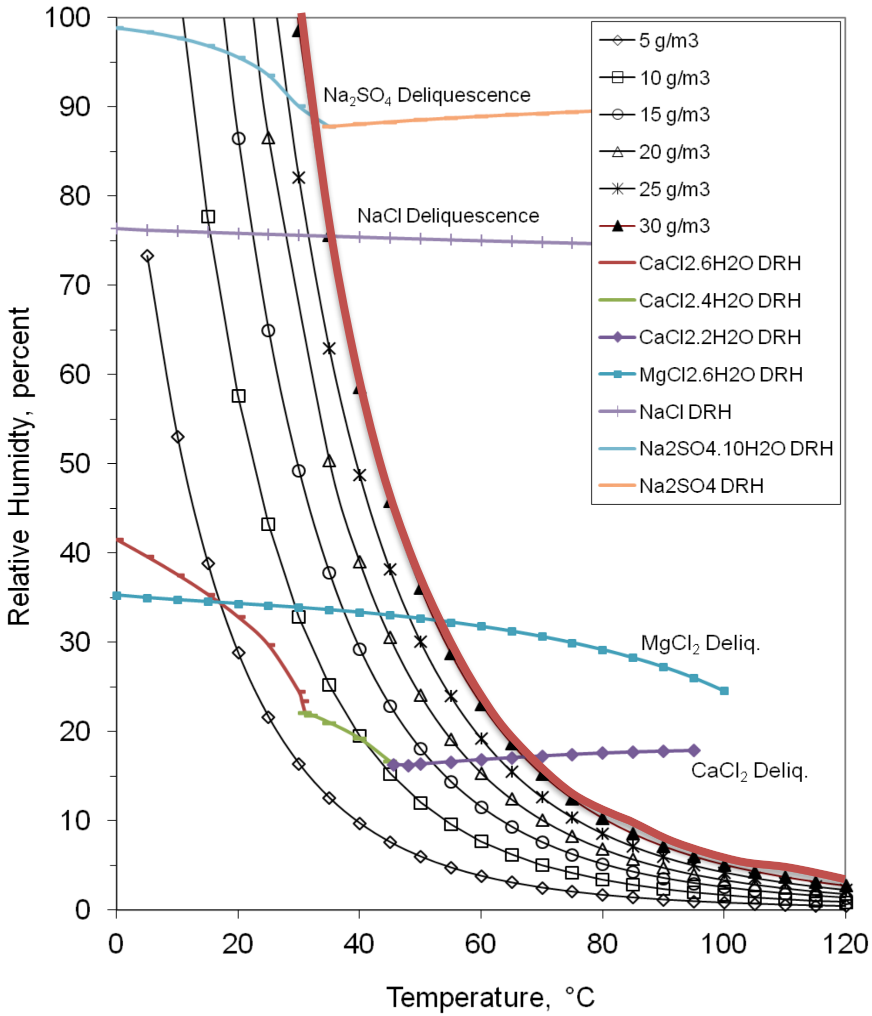
CISCC Growth Rate vs Temperature



- Baseline rate of 0.29 mm/yr at 23°C from Kosaki (2008)
- Activation energy of 31 kJ/mol from Hayashibara et al. (2008)
- DOES NOT show crack growth rates of actual components
  - Composition and deliquescence behavior of atmospheric deposits
  - Site specific environmental data
  - Residual stress profile
- Plant operating experience*
  - Turkey Point: 0.11 mm/yr
  - San Onofre: 0.25 mm/yr
  - St. Lucie: 0.39 mm/yr

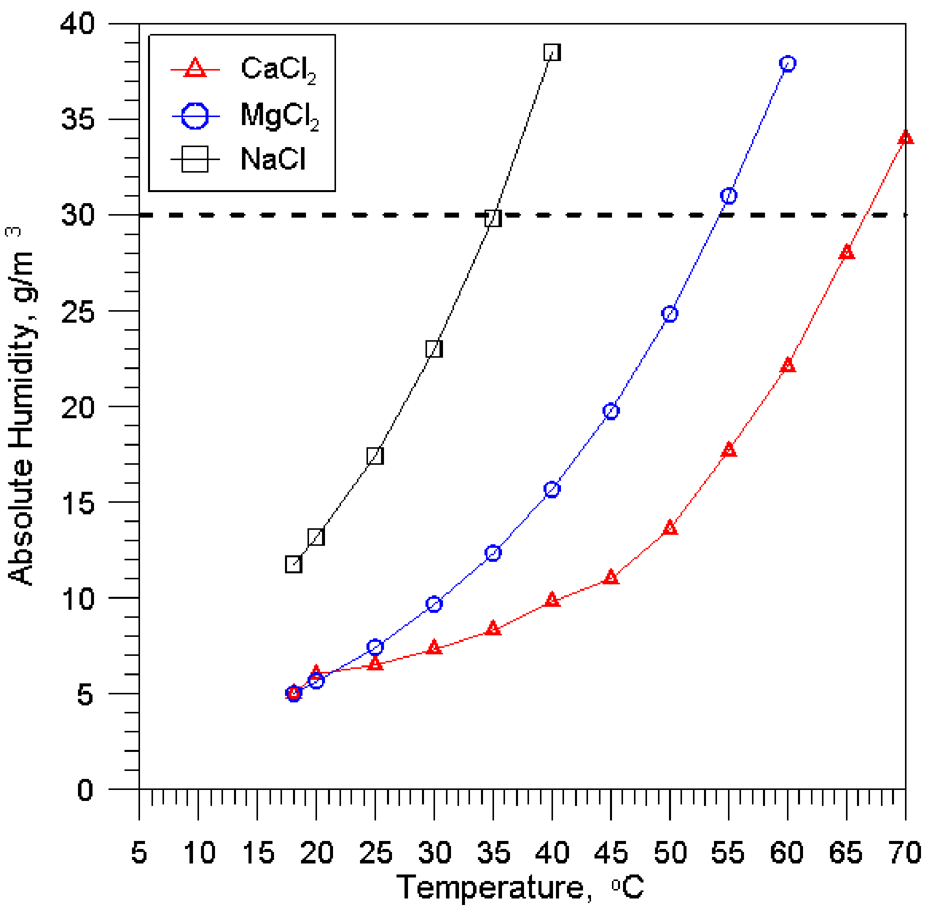
*Assuming crack initiation at the start of plant operation and continuous growth

Deliquescence of Deposited Salts



- Deliquescence of chloride salts dependent on composition of salts, relative humidity, and temperature
- NUREG/CR-7170

Deliquescence of Chloride Salts



- Minimum absolute humidity (AH) for deliquescence as a function of temperature
- AH value of 30 g/m^3 used as a maximum for natural conditions
- Maximum AH values based on 2014 National Oceanic and Atmospheric Administration (NOAA) data
  - Vandenberg AFB*, CA: 16.3 g/m^3
  - Witham Field*, FL: 24.8 g/m^3
  - Groton*, CT: 21.5 g/m^3

*None of these sites have been determined to be representative of any NRC licensed facilities

Deliquescence of Chloride Salts

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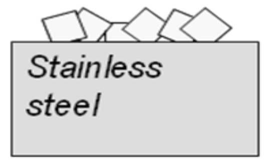
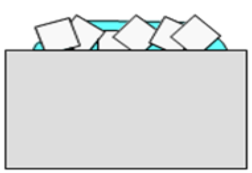
NOAA data
Ambient Air

- Temperature
- Relative Humidity
- Dew Point



Deposition of sea salt particles

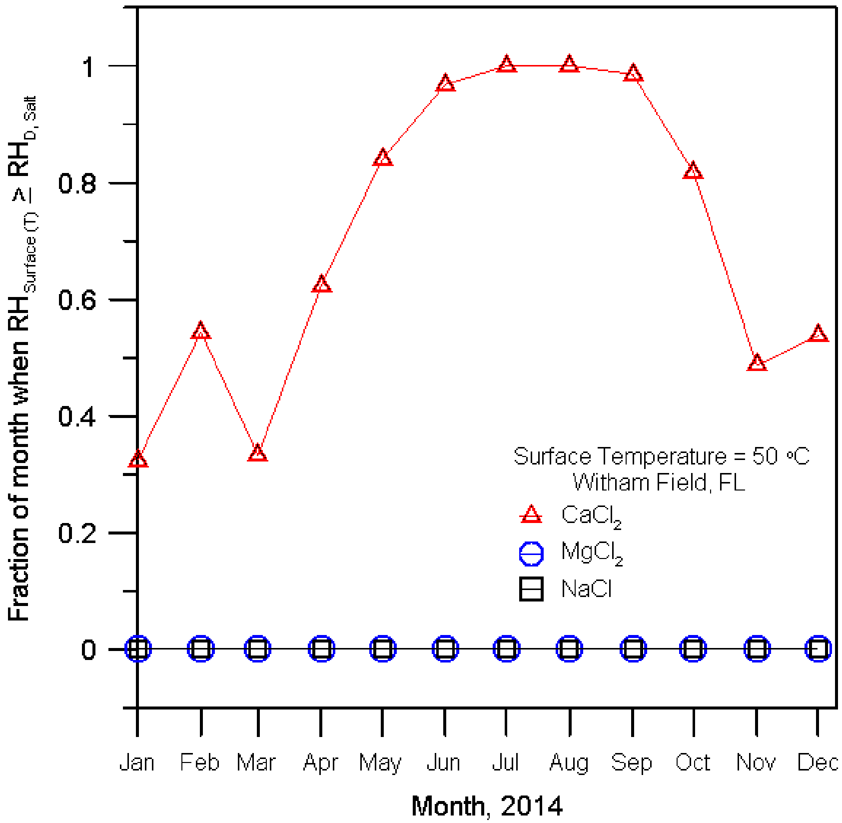


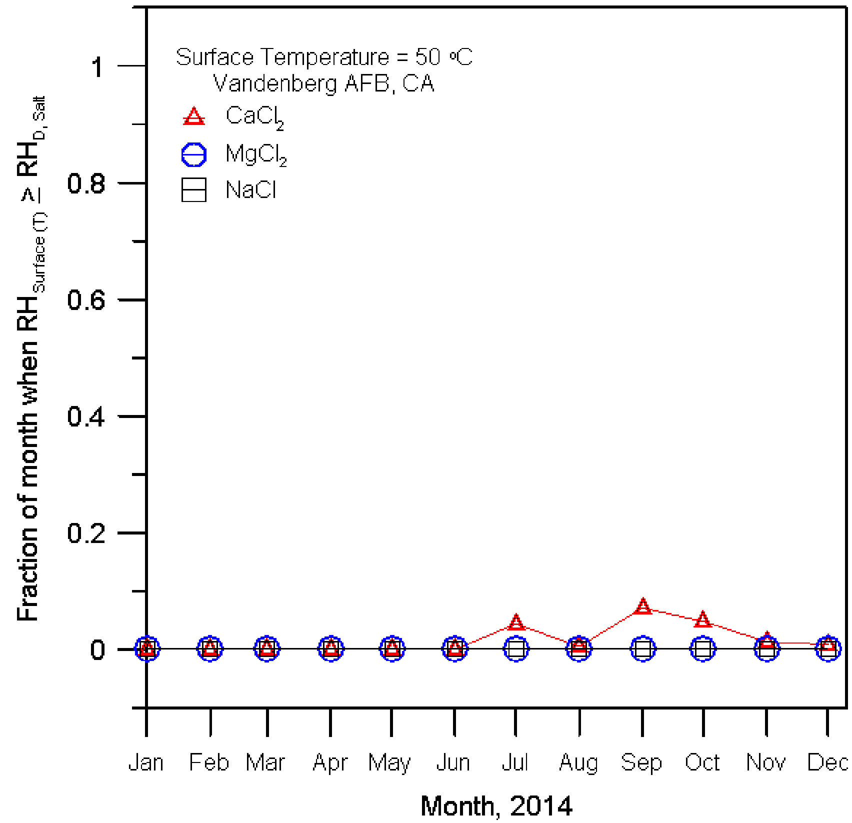
Deliquescence of sea salt

Deliquescence of deposited salts occurs if the relative humidity (RH) at a surface at temperature (T) is equal to or greater than the relative humidity necessary for salt deliquescence $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$

- Calculations for ambient air contacting a heated surface with salt deposits ($CaCl_2$, $MgCl_2$, NaCl)
- Surface temperatures range from 20 to 65^{o}C
- Determine the time that an aqueous solution with Cl^- ions may be in contact with a surface at temperature using NOAA weather station data and salt deliquescence curves
- Fraction of the month where $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$ for 2014

Deliquescence of Chloride Salts





<u>Solubility at 50°C</u>

$CaCl_2$: 132g/100g water

$CaCO_3$: 0.00077g/100g water

$Ca(OH)_2$: 0.131g/100g water

$CaSO_4$ $2H_2O$: 0.255g/100g water

Deliquescence of Chloride Salts

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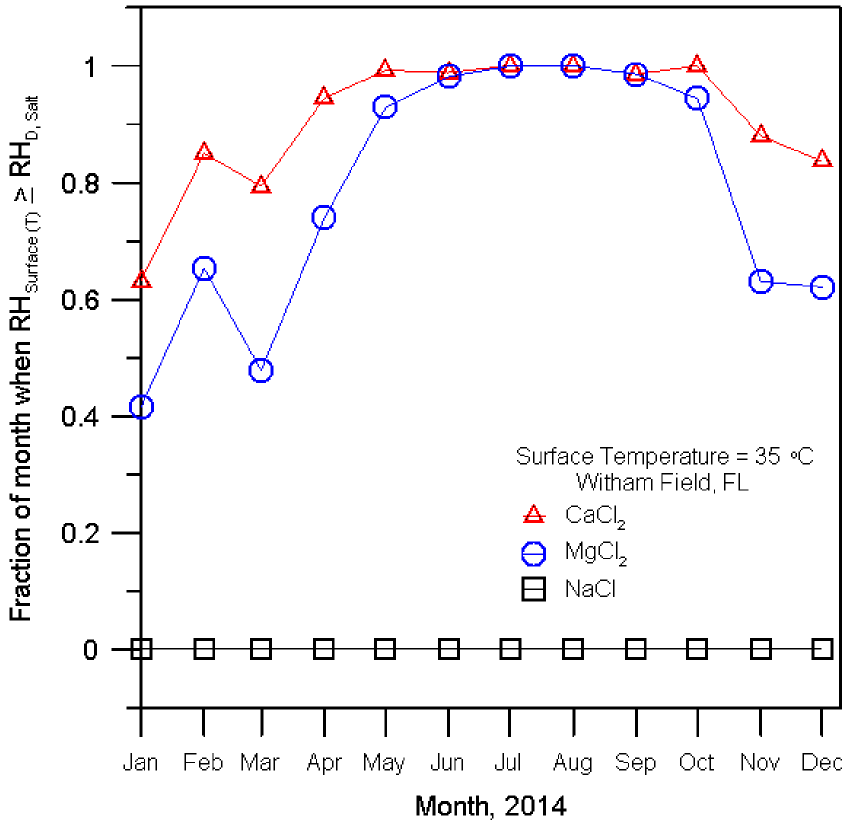
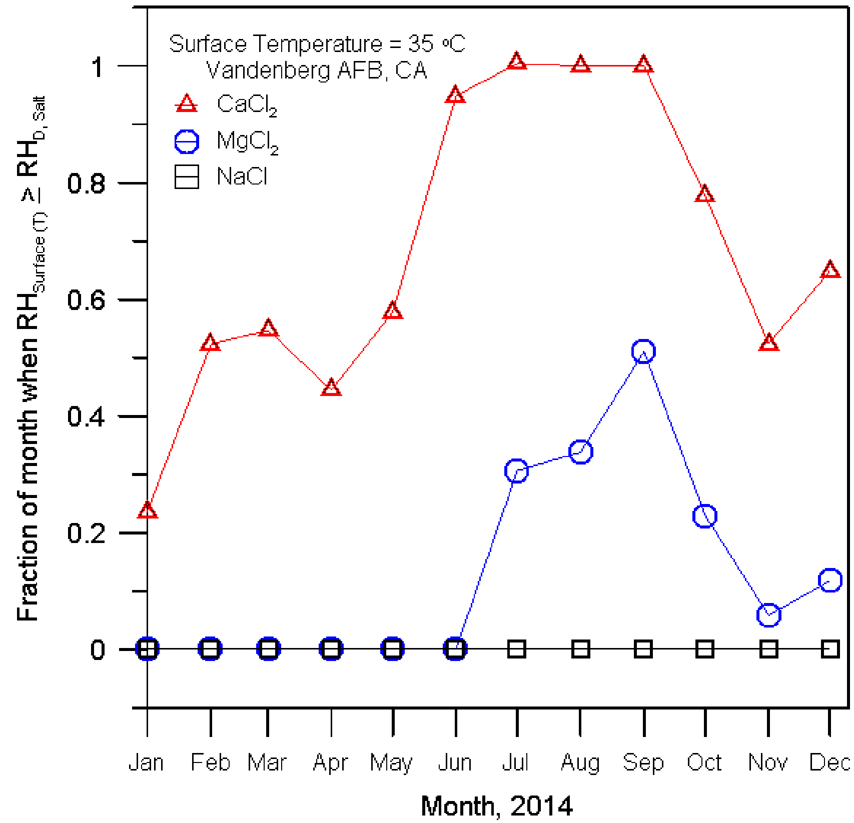




<u>Solubility at 35°C</u>

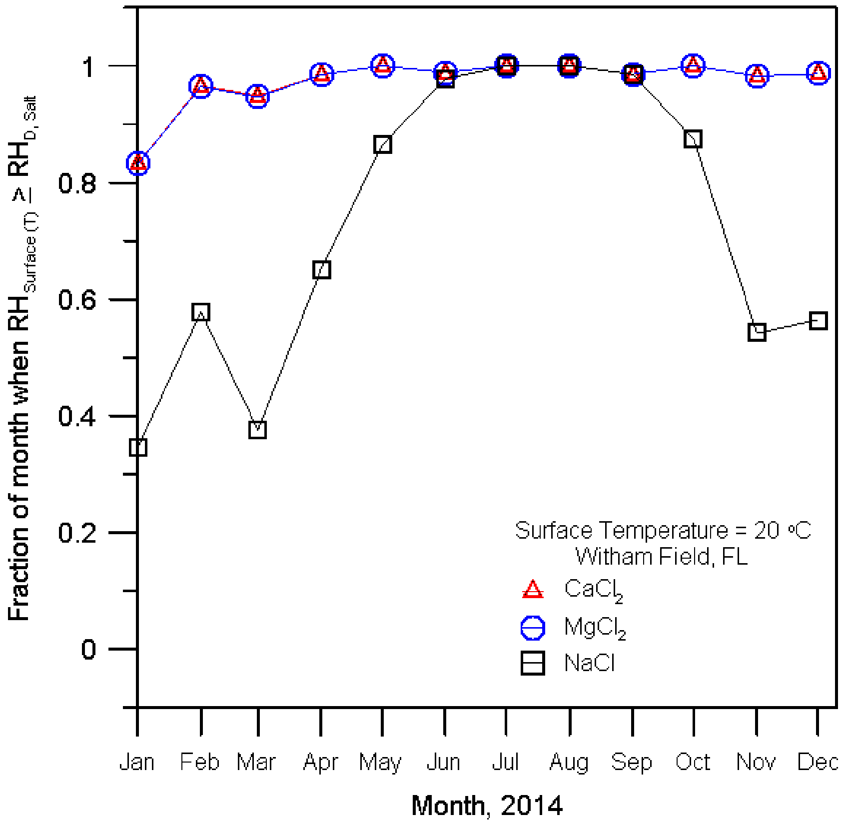
$MgCl_2$: 57g/100g water

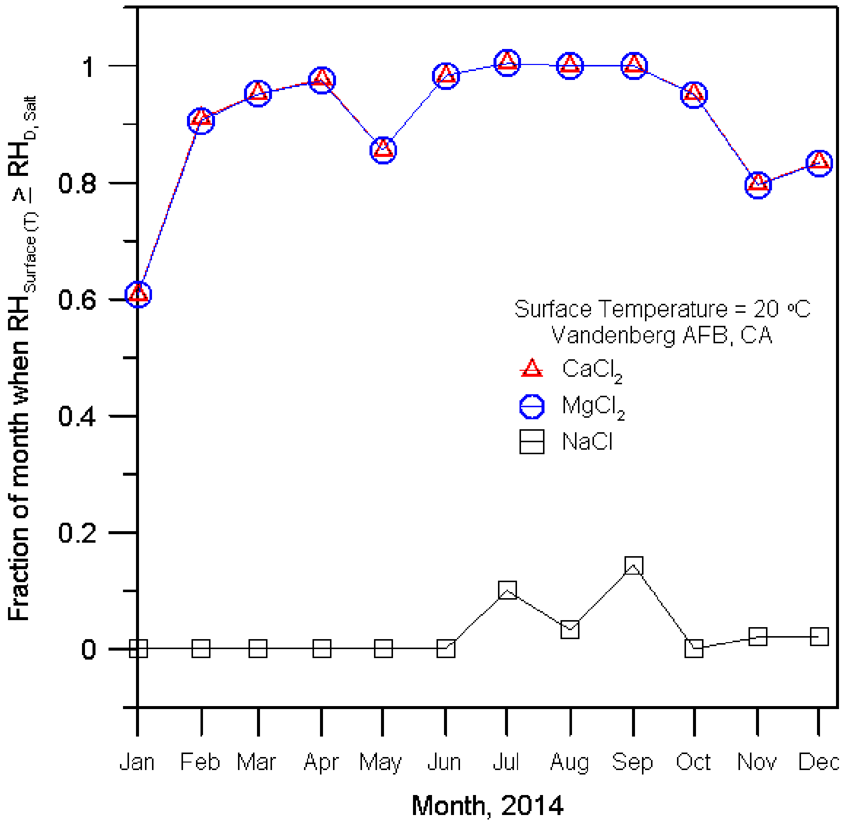
$MgCO_3$: 0.04g/100g water

$Mg(OH)_2$: 0.001g/100g water

$MgSO_4$: 42g/100g water

Deliquescence of Chloride Salts

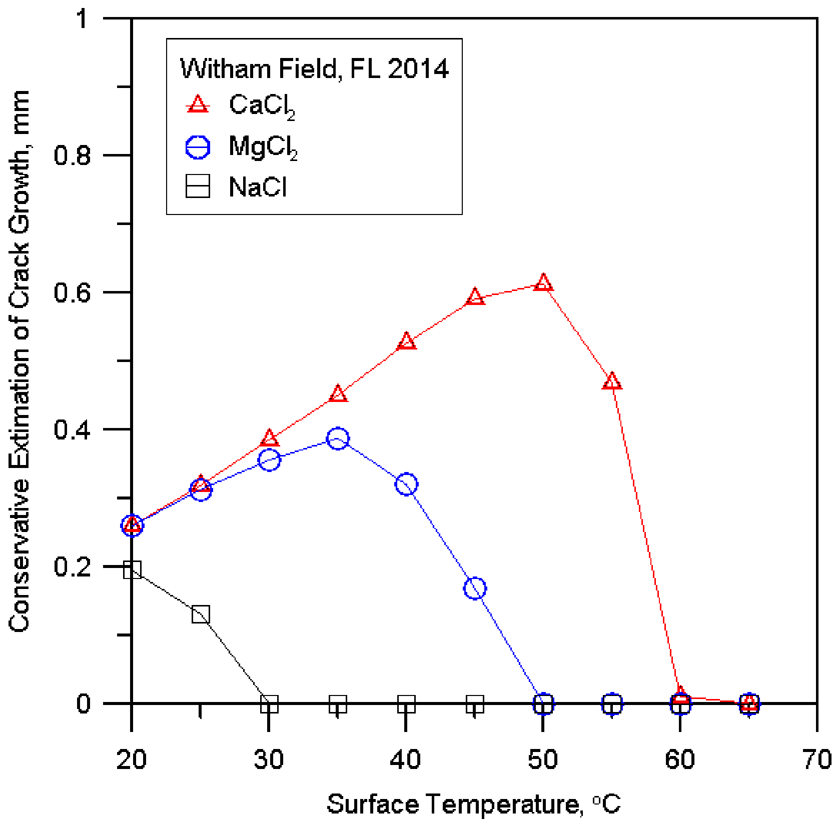


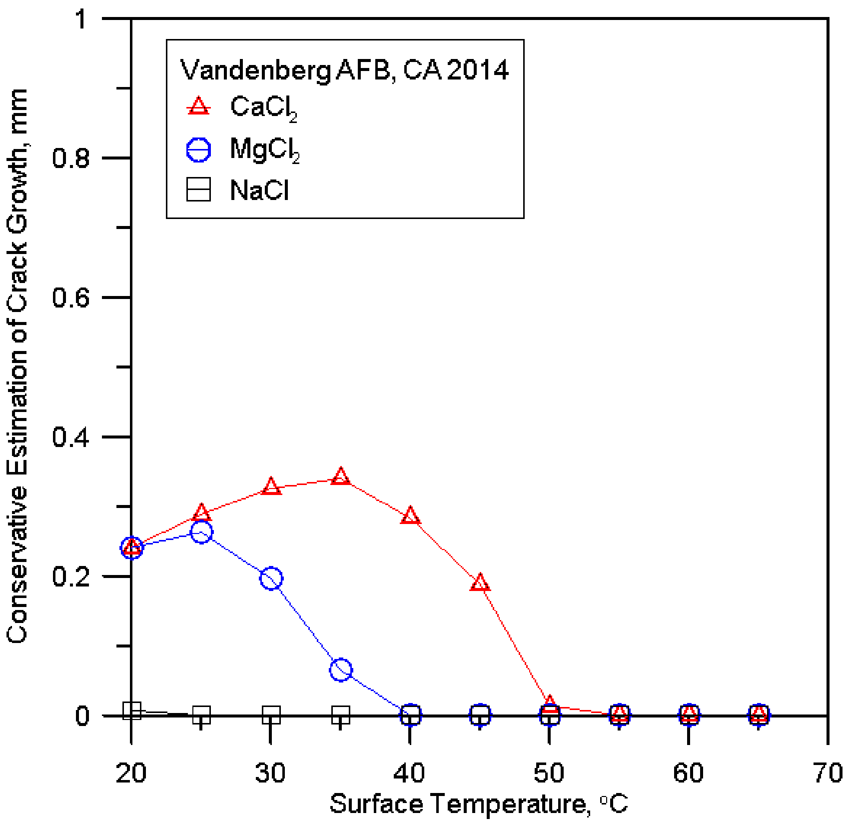


CISCC Calculation Assumptions

- Conservative Assumptions (not necessarily representative):
  - Sufficient through wall tensile residual stresses for CISCC initiation and growth
  - Sufficient surface salt concentrations for CISCC initiation and growth
  - Composition of surface deposits do not change with time
    - No changes as a result of precipitation or decomposition reactions
    - No effects of corrosion product accumulation
  - Deliquescence is instantaneous when $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$
  - CISCC initiation instantaneous when $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$
  - Crack growth at all times when $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$
  - CISCC re-initiation instantaneous when $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$
  - Maximum CISCC rate at temperature when $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$
- Assumptions under further evaluation:
  - CISCC stops when $RH_{Surface\ (T)} < RH_{D,\ Salt}$
  - CISCC growth rate is independent of surface salt concentration
  - CISCC growth rate independent of crack depth

Conservative Estimations of CISCC Crack Growth





- Evaluating seasonal/annual environmental variations with composition of actual atmospheric deposits to eliminate overly conservative assumptions for more representative CISCC growth rates

Key Points

- CISCC initiation and growth a complex aging mechanism with multiple coupled parameters including deposit compositions, site specific environmental conditions and surface temperatures
  - When and where deliquescence could occur
  - Fraction of time when cracking may occur
  - Crack growth rates
- Conservative approach for CISCC calculations
  - Conservative assumptions used for CISCC initiation and growth
  - Multiple assumptions likely overestimate CISCC growth rates
- CISCC rates limited by site specific environmental conditions
  - CISCC not expected above ~55^{o}C
- Aging Management Program appropriate for managing possible aging effects as a result of CISCC initiation and growth

Example AMP for Welded Stainless Steel Canisters

- Example AMP included in NUREG-1927 Revision 1
  - American Society of Mechanical Engineers Boiler and Pressure Vessel (ASME B&PV) Code Section XI - Rules For Inservice Inspection Of Nuclear Power Plant Components

- 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

- Inservice inspection of external surfaces of welded austenitic stainless steel canisters for localized corrosion and SCC
  - Fabrication and closure welds
  - Weld heat affected zones
  - Locations where temporary supports or fixtures were attached by welding
  - Crevice locations
  - Surfaces where atmospheric deposits tend to accumulate
  - Surface areas with a lower than average temperature

AMP Element 2
Preventative Actions

- Example AMP is for condition monitoring.
  - Preventative actions are not incorporated into the example AMP contained in NUREG-1927 Revision 1
- Preventative actions for welded stainless steel canisters may 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

- Canister surfaces, welds, and weld heat affected zones for discontinuities and imperfections
- Appearance and location of atmospheric deposits on the canister surfaces
- Size and location of localized corrosion (e.g., pitting and crevice corrosion) and stress corrosion cracks

AMP Element 4
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
- Suspected areas of localized corrosion and/or SCC require additional evaluation
- Sample size
  - Minimum of one canister at each site (greatest susceptibility)
- Data Collection
  - Documentation of the canister inspection
  - Location and appearance of deposits, localized corrosion, SCC
- Frequency
  - Every 5 years
- Alternative methods or techniques may be provided

AMP Element 5
Monitoring and Trending

- Reference plans or procedures to establish a baseline
- 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 corrosion product accumulations
- Track parameters and aging effects such as location and sizing of localized corrosion and SCC

AMP Element 6
Acceptance Criteria

- No indications of:
  - Pitting corrosion, crevice corrosion, or SCC
  - Corrosion products on or adjacent to fabrication welds, closure welds, and welds for temporary supports or attachments
- Locations with corrosion products require additional examination for localized corrosion and/or SCC
- Canisters with localized corrosion and/or SCC must be evaluated for continued service.
- Example AMP uses ASME B&PV Section XI Criteria
  - IWB-3514
  - IWB-3640
- Alternative acceptance criteria may be provided

AMP Element 7
Corrective Actions

- Applicants may reference the use of a Corrective Action Program (CAP), which is consistent with the quality assurance (QA) requirements in either 10 CFR Part 50, Appendix B, or 10 CFR Part 72, Subpart G
- Perform functionality assessments
- Perform apparent/root cause evaluations
- Address the extent of condition
- Determine actions to prevent recurrence
- Justifications for non-repairs
- Trend conditions
- Identify operating experience actions, (e.g., AMP changes)
- Determine if the condition is reportable to the NRC

AMP Element 8
Confirmation Process

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- Confirmation process should be commensurate with the specific or general licensee Quality Assurance (QA) Program and consistent with 10 CFR Part 72, Subpart G or 10 CFR Part 50, Appendix B.
- QA Program ensures that the confirmation process includes provisions to preclude repetition of significant conditions adverse to quality.
- The confirmation process describes or references procedures to:
  - Determine follow-up actions to verify effective implementation of corrective actions
  - Monitor for adverse trends due to recurring or repetitive findings

AMP Element 9
Administrative Controls

- The specific or general licensee QA Program must be commensurate with 10 CFR Part 72, Subpart G or 10 CFR Part 50, Appendix B and specifically addresses:
  - Instrument calibration and maintenance
  - Inspector requirements
  - Record retention requirements
  - Document control
- The administrative controls describes or references:
  - Frequency/methods for reporting inspection results to the NRC
  - Frequency for updating AMP based on industry-wide operational experience

AMP Element 10
Operational Experience

- References and evaluates applicable operating experience, including:
  - Internal and industry-wide condition reports,
  - Internal and industry-wide corrective action reports,
  - Vendor-issued safety bulletins,
  - NRC Information Notices, and
  - Applicable DOE or industry initiatives (e.g., EPRI or DOE sponsored inspections)
- References the methods for capturing operating experience from other ISFSIs with similar in-scope SSCs

AMP Element 10
Operational Experience

- Identifies any degradation in the referenced operating experience as either age-related or event-driven, with proper justification for that assessment
- Past operating experience supports the adequacy of the proposed AMP, including the method/technique, acceptance criteria, and frequency of inspection
- Example AMP also references past operating experience

Summary

- Atmospheric CISCC has been observed in welded austenitic stainless steel components
- Limited data on atmospheric CISCC growth rates and composition of atmospheric deposits
- Composition of deposits, operating environment and surface temperature of the canister are significant
- Example AMP for welded austenitic stainless steel canisters included in NUREG-1927 Revision 1
- Adaptation of inspection methods used for operating reactor pressure boundary components and development of inspection delivery systems for canister inspections are necessary to improve canister inspection capabilities

Acronyms

AH: Absolute Humidity (grams of water per cubic meter of air)
AMP: Aging Management Program

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

DOE: Department of Energy

EPRI: Electrical Power Research Institute

EVT-1: Enhanced Visual Testing-1 (Boiling water reactor vessels and internals project, BWRVIP-03)

ISFSI: Independent Spent fuel Storage Installation

NOAA: National Oceanic and Atmospheric Administration

QA: Quality Assurance

T: Temperature

TLAA: Time-Limited Aging Analysis

RH: Relative Humidity

SCC: Stress Corrosion Cracking

SSC: Structure, system or component

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)