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

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Chloride-Induced Stress Corrosion Cracking
Regulatory Issue Resolution Protocol Meeting
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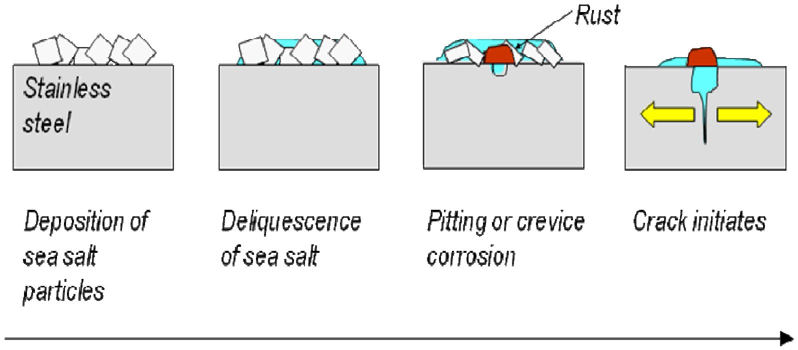
Outline

- 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

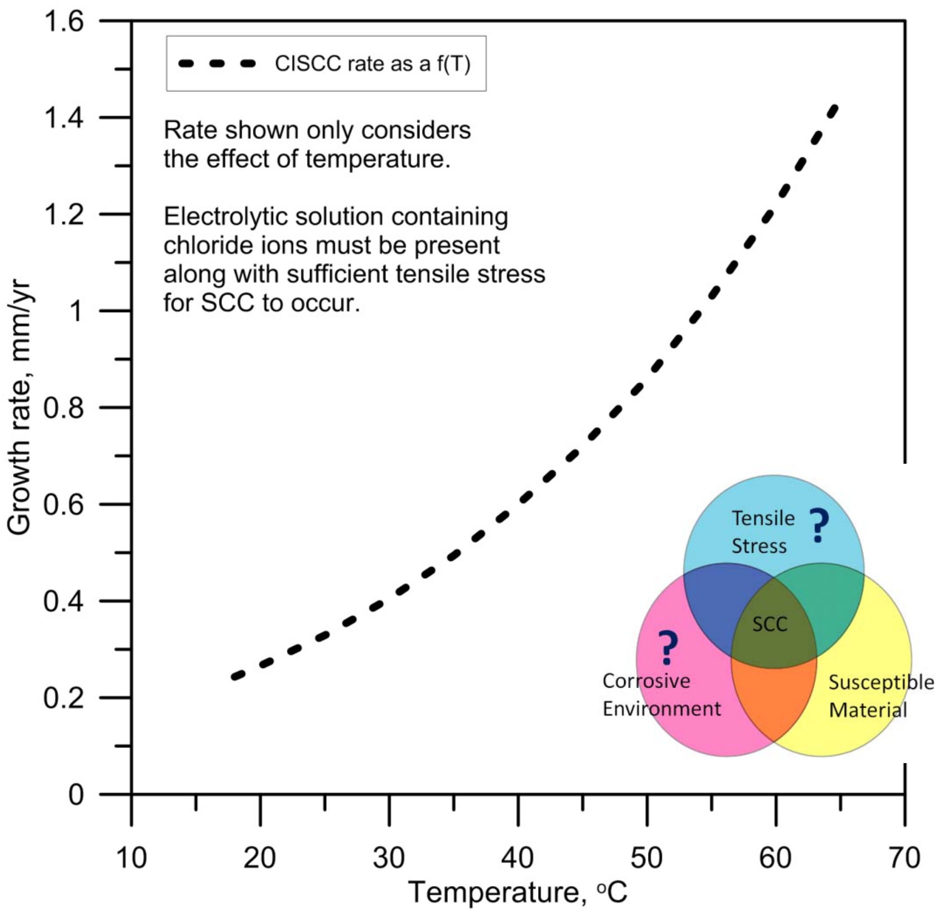
- Atmospheric CISCC of welded stainless steel components observed in operating power plants
  - Piping systems
  - Storage tanks
- CISCC complex process with multiple dependencies
  - Surface temperatures
  - Composition of deposited salts
  - Surface concentration of salts
  - Site specific environmental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

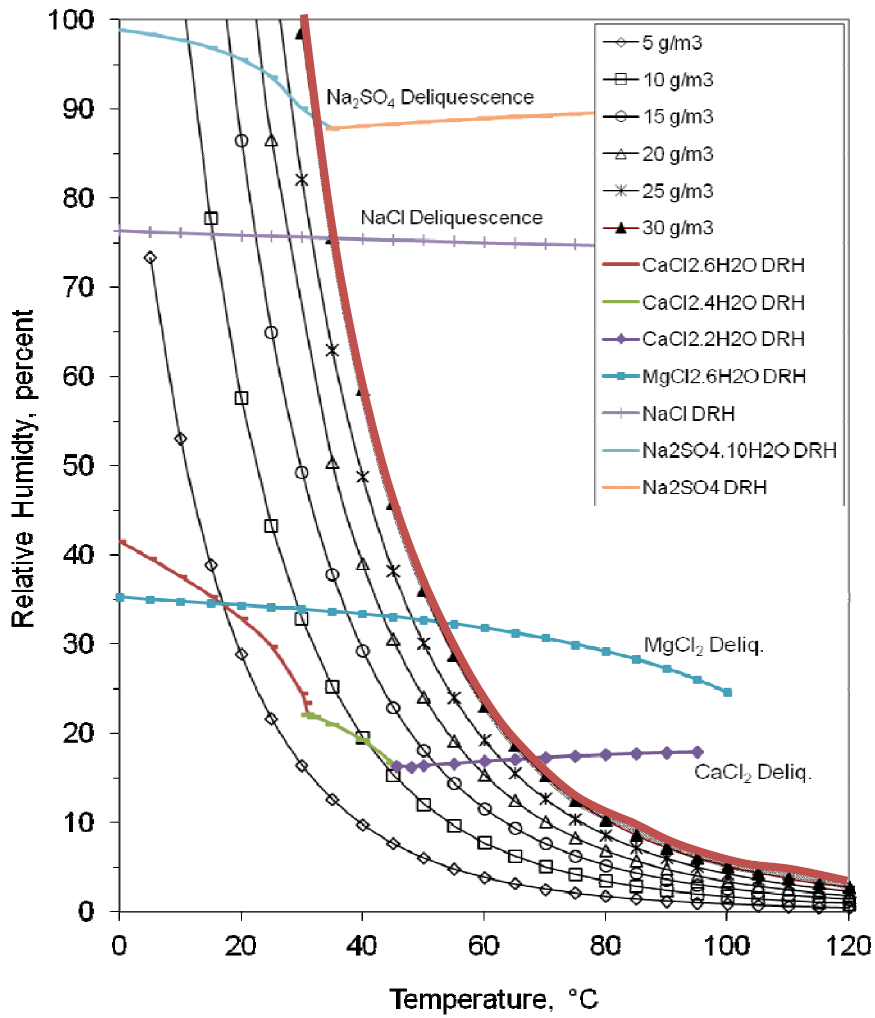
CISCC Growth Rate vs Temperature



- 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

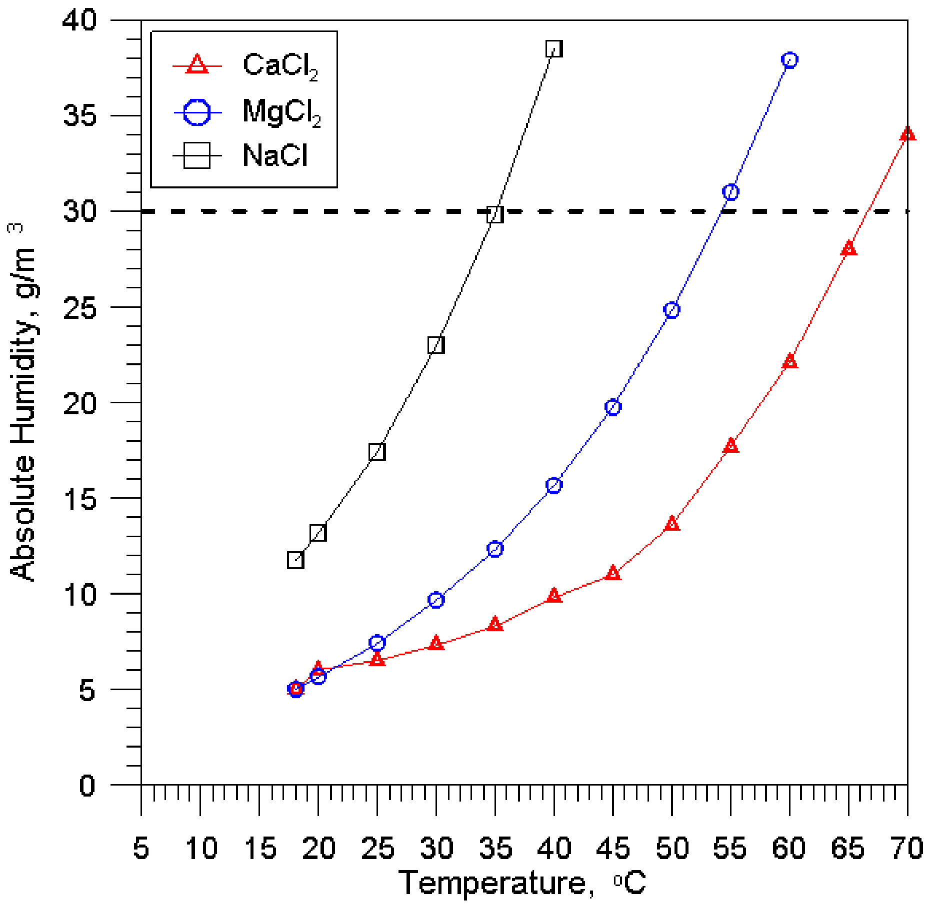
*Assuming crack initiation at the start of plant operation and continuous growth

Deliquescence of Deposited Salts



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

Deliquescence of Chloride Salts

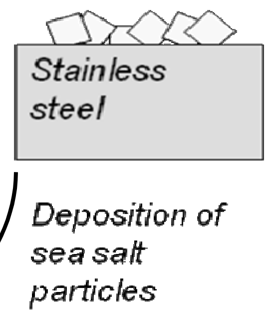


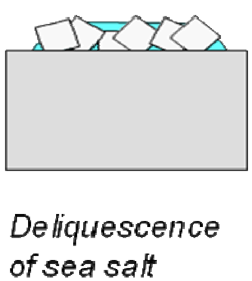
- Minimum absolute humidity (AH) for deliquescence as a function of temperature
- AH value of 30 g/m^3 used as a maximum for natural conditions
- Maximum AH values based on 2014 National Oceanic and Atmospheric Administration (NOAA) data
  - Vandenberg AFB*, CA: 16.3 g/m^3
  - Witham Field*, FL: 24.8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

NOAA data
Ambient Air
•Temperature
•Relative Humidity
•Dew Point

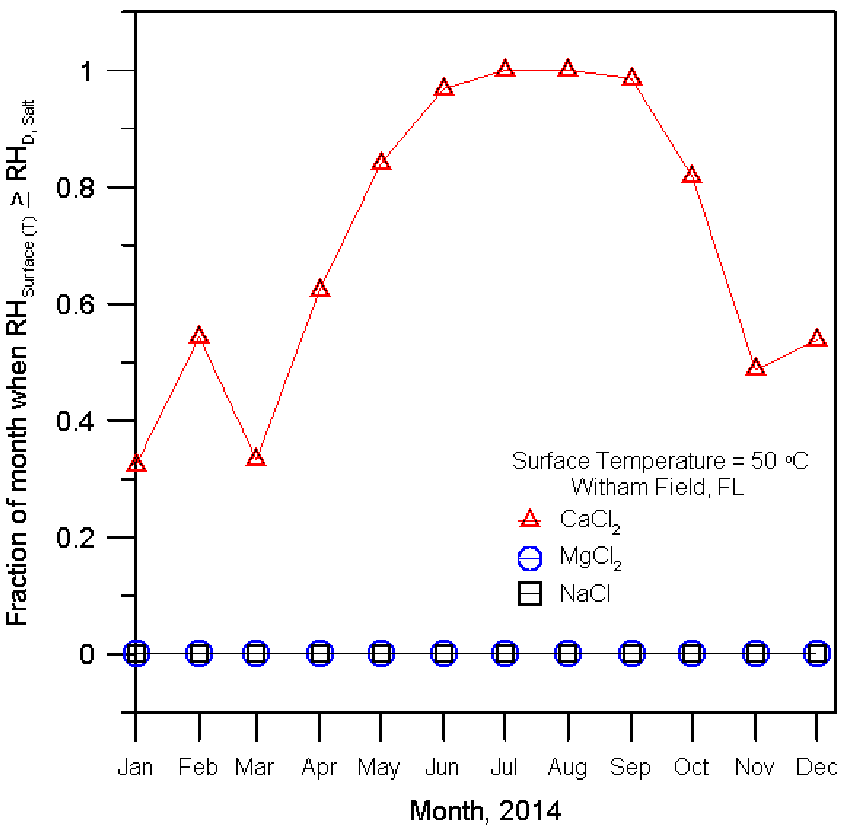


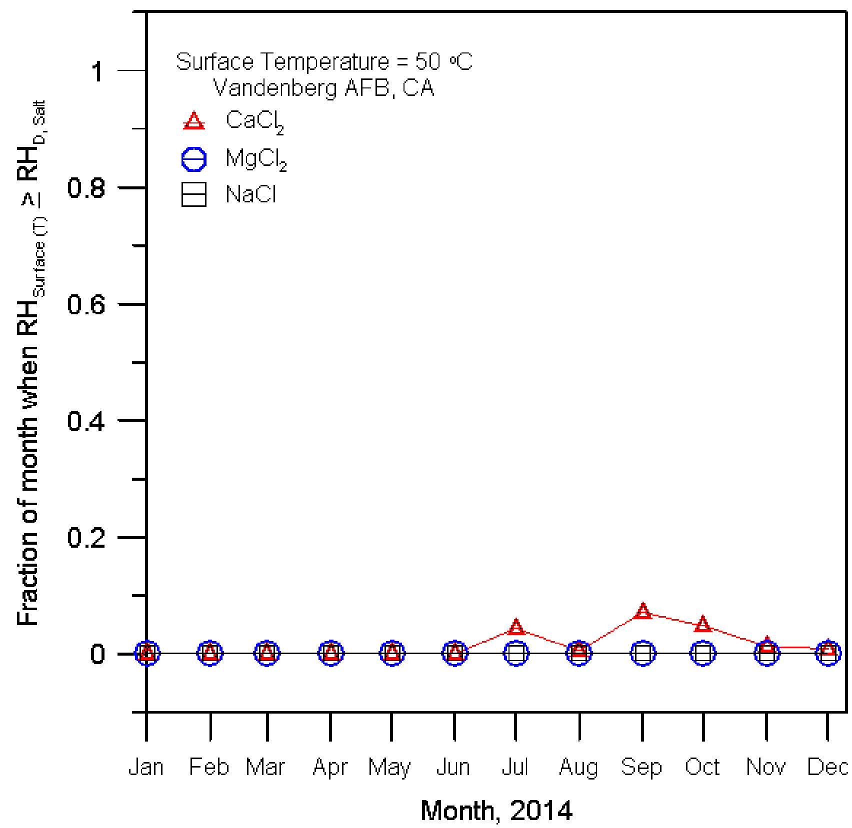


Deliquescence of deposited salts occurs if the relative humidity (RH) at a surface at temperature (T) is equal to or greater than the relative humidity necessary for salt deliquescence $RH_{Surface\ (T)} \geq RH_{D,\ Salt}$

- 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 50ºC</u>

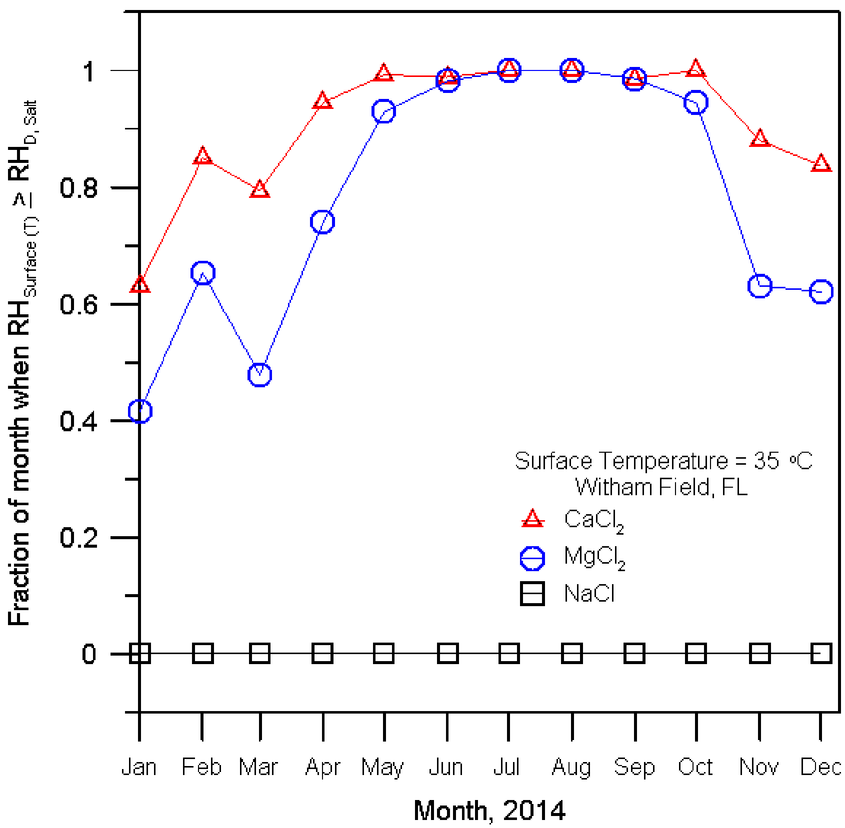
$CaCl_2$: 132g/100g water

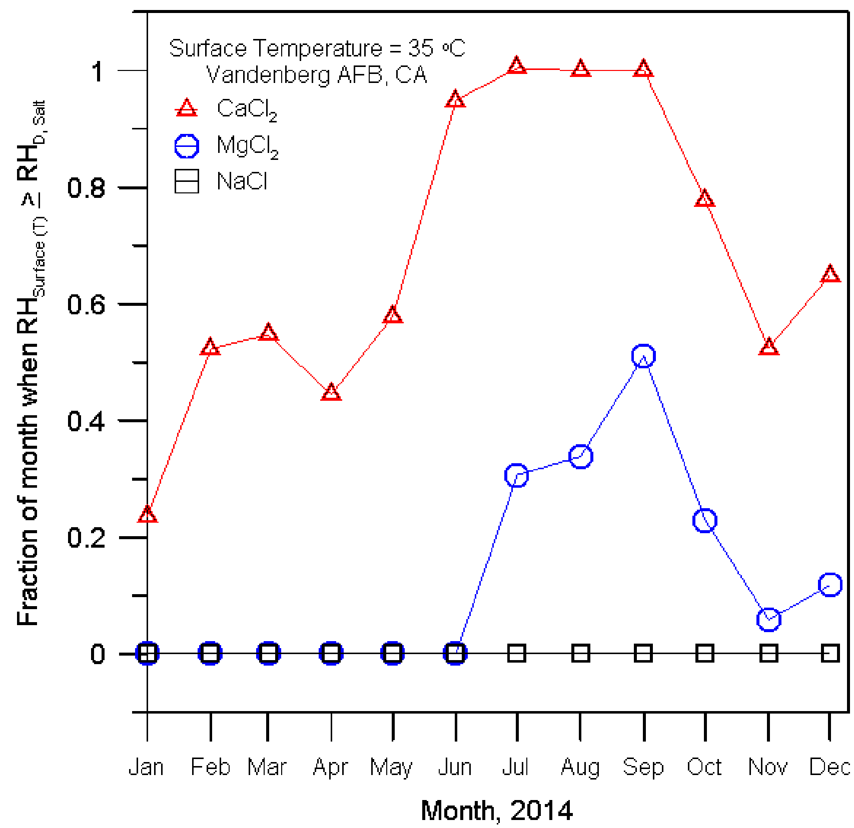
$CaCO_3$: 0.00077g/100g water

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

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

Deliquescence of Chloride Salts





<u>Solubility at 35ºC</u>

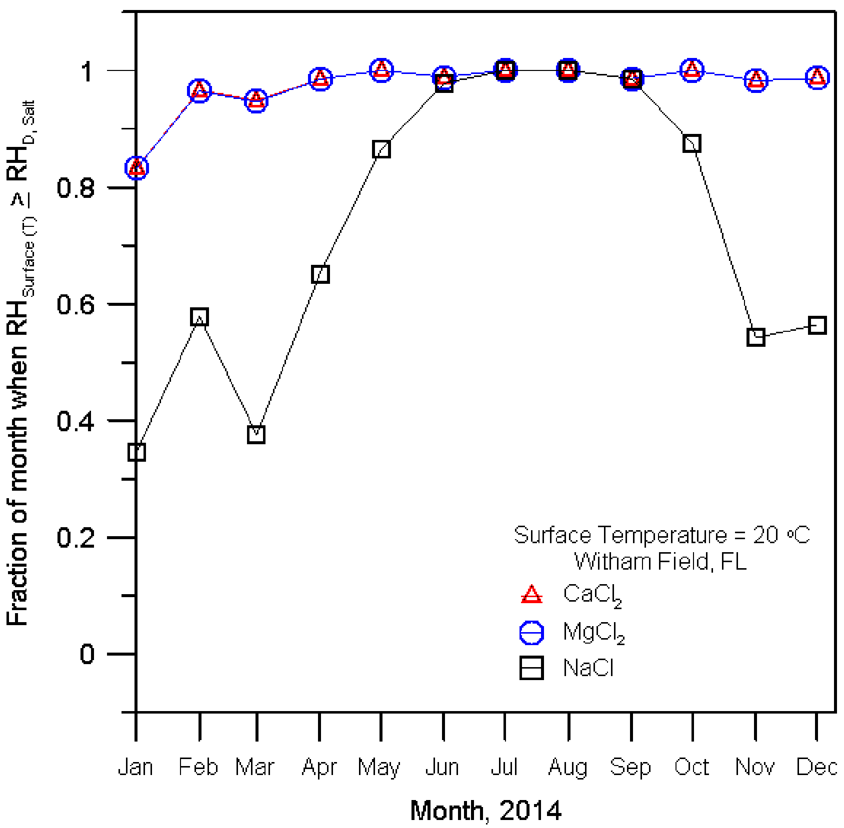
$MgCl_2$: 57g/100g water

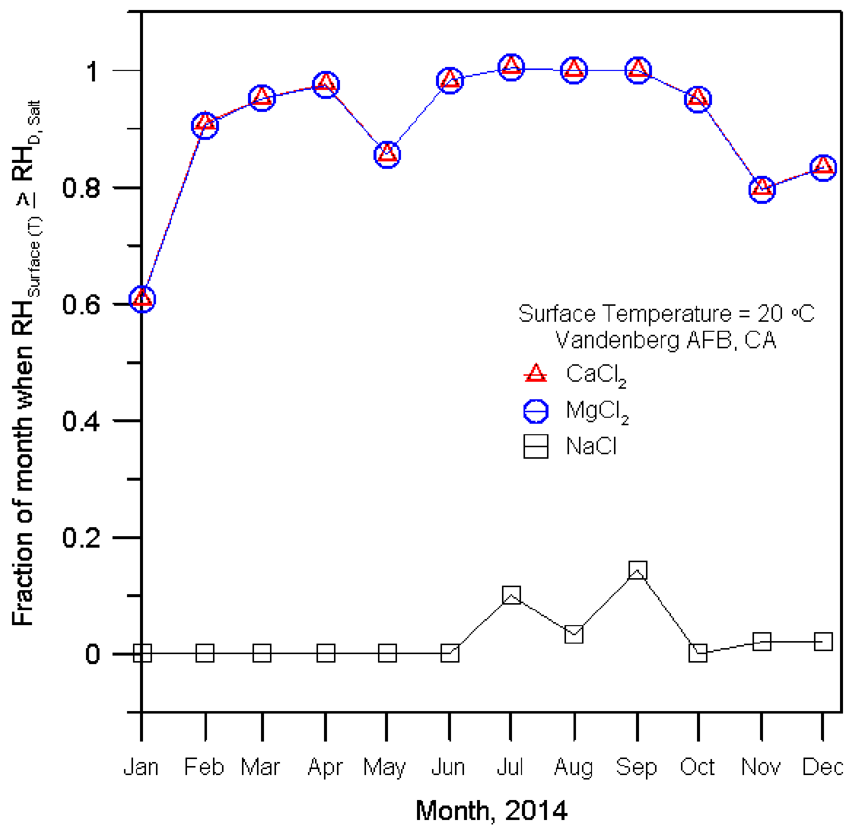
$MgCO_3$: 0.04g/100g water

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

$MgSO_4$: 42g/100g water

Deliquescence of Chloride Salts

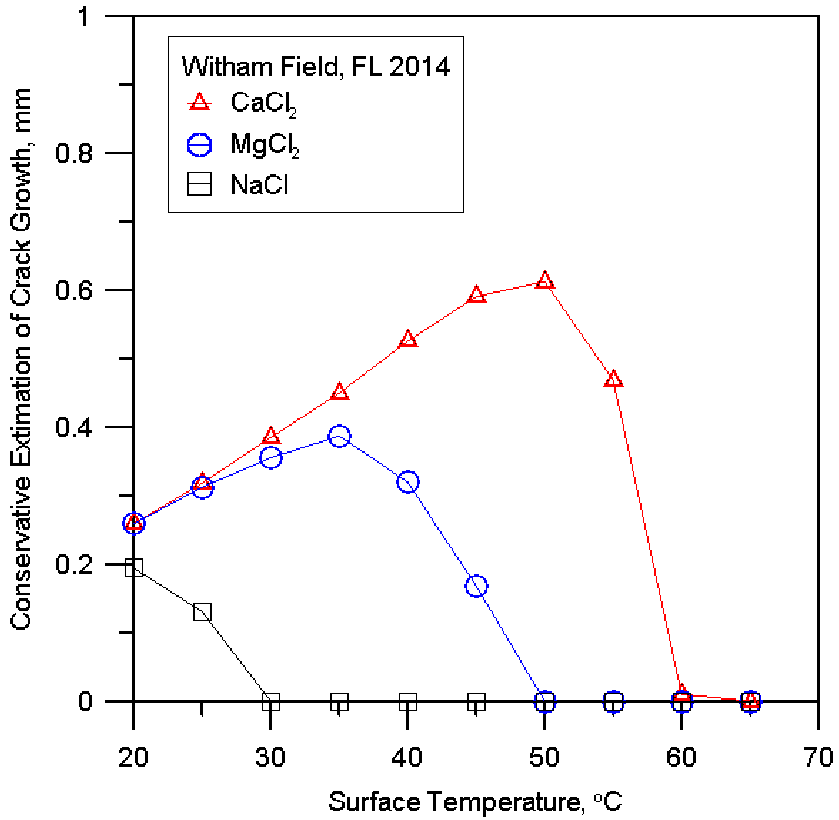


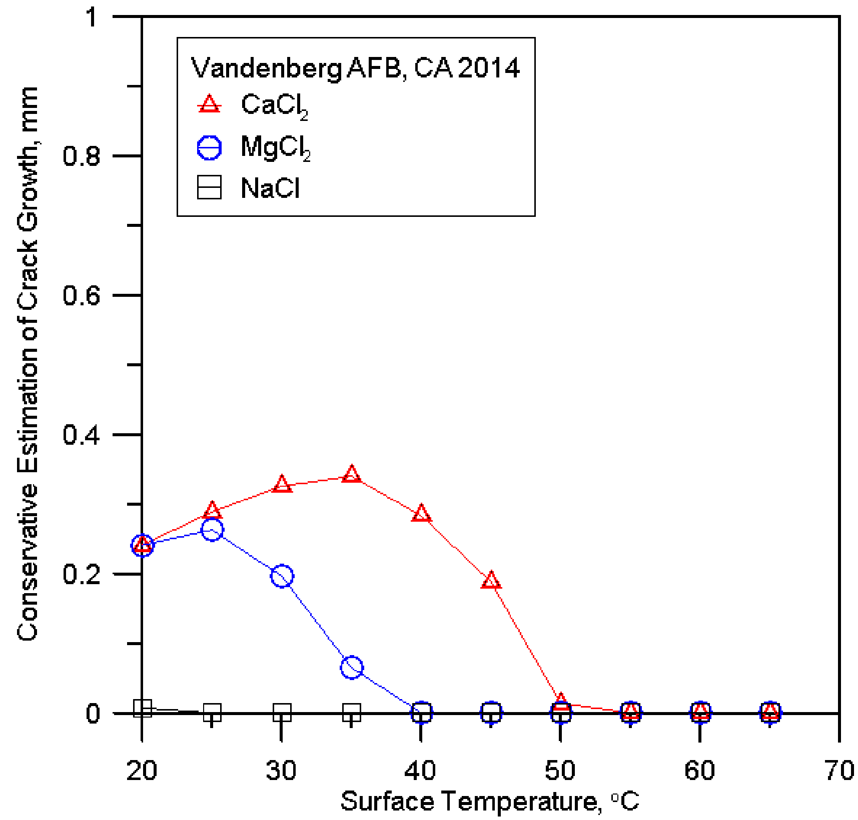


CISCC Calculation Assumptions

- 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

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- 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

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- 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

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- 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

- 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

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- 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)