U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY
Spent Fuel and Waste Science and Technology (SFWST)

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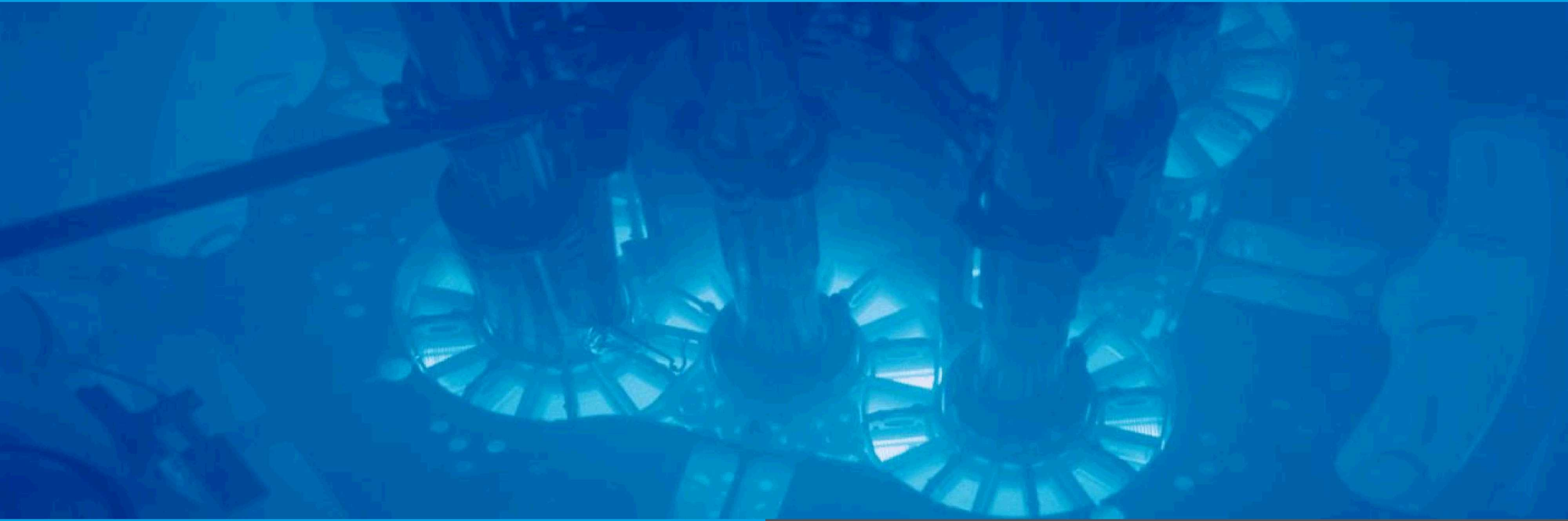


Evaluating Stress Corrosion Cracking of Spent Nuclear Fuel Storage Canisters

Charles Bryan, Rebecca Schaller, Andrew Knight

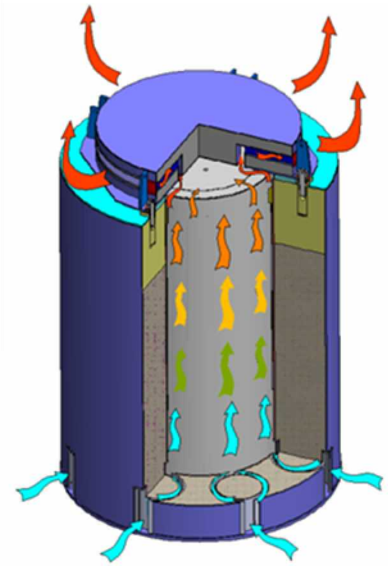
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

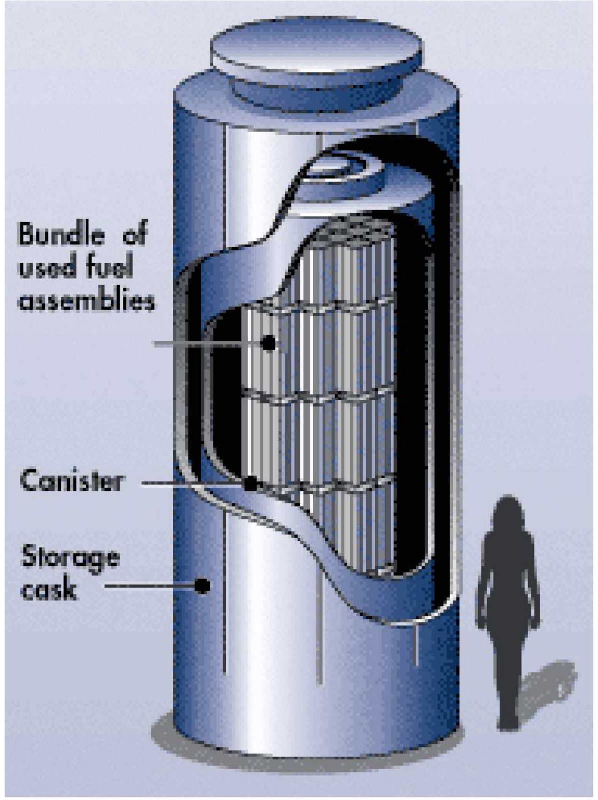
Background

- United States currently has over 80,000 metric tons of Spent Nuclear Fuel (SNF), about 30% in dry storage systems.
- The dry storage systems are intended as interim storage until a permanent disposal site is developed. Until recently, systems were licensed for 20 years with an additional 20 years upon license renewal; in 2011, CFR was modified to allow for initial 40 year license period, with an additional 40 year renewal.
- However, the United States currently does not have a disposal pathway for SNF. In any conceivable scenario, some SNF will be in storage for decades beyond the original storage system specifications.
- In most systems, SNF is stored in stainless steel (304 SS) canisters. Canisters are stored in passively-ventilated overpacks, and accumulate surface dust over time. Stress Corrosion Cracking (SCC) of stainless steel due to deliquescence of chloride-rich salts is a potential failure mechanism, especially given longer-than-intended storage times.
- Understanding SCC of interim storage containers has been determined to be a high priority data gap (EPRI 2011; DOE 2012; NRC 2012).
- Efforts to better understand the risk of canister failure by SCC, and to predict timing and conditions of occurrence are being pursued by the DOE and others.

Canistered SNF Dry Storage Systems—Two Standard Designs

Vertical—In vertical systems, the welded stainless steel canister sits upright within a steel-lined concrete overpack. The canister is passively cooled by air that enters through inlets at the bottom of the overpack and exits through vents near the top.

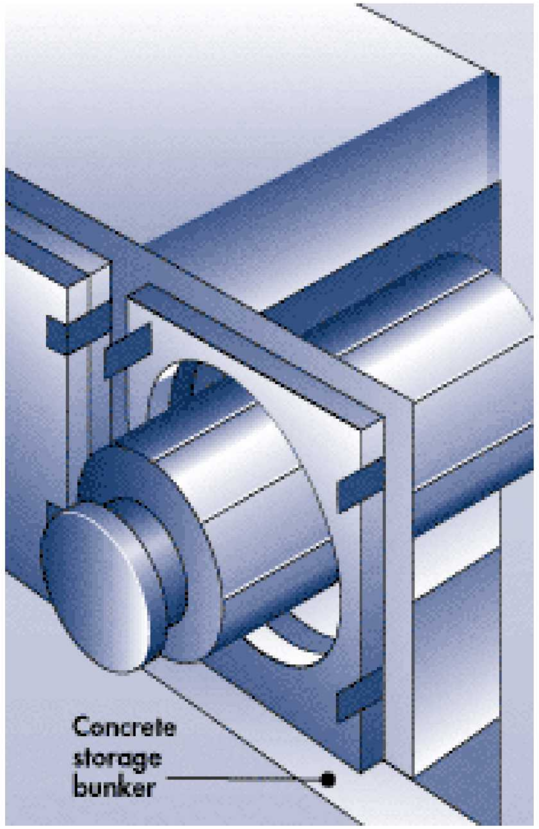




Pathway for air flow through the overpack.

Canistered SNF Dry Storage Systems—Two Standard Designs

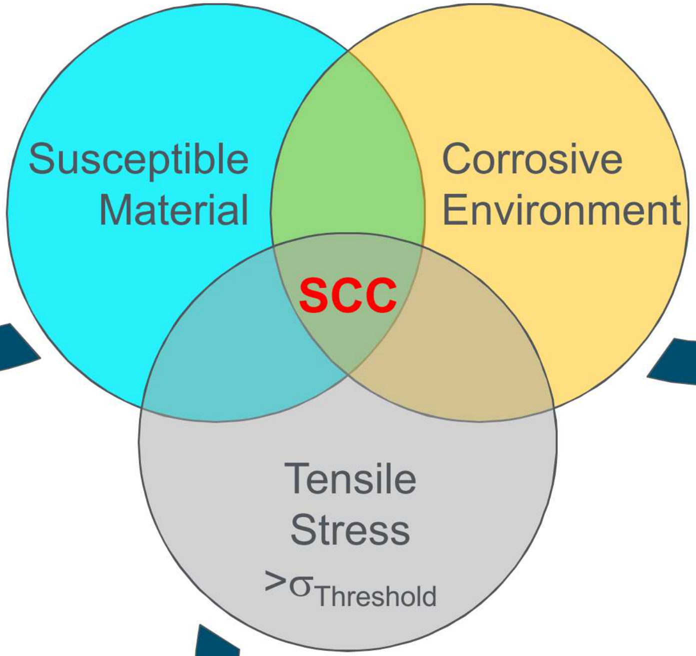
Horizontal—In horizontal systems, the welded canister rests on its side upon rails within a concrete vault. Air enters the overpack through a vent in the base, flows up and around the canister, and exits through vents on the roof.

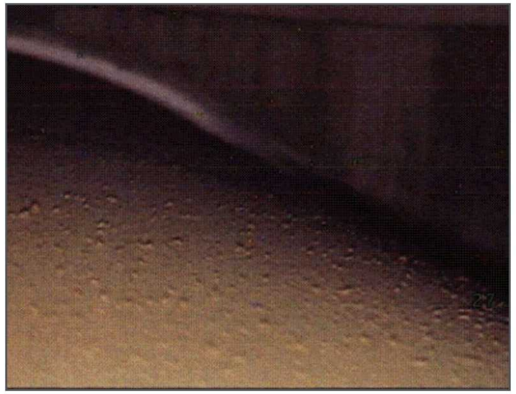


Criteria for Stress Corrosion Cracking

To evaluate the potential for occurrence of SCC, each must be considered

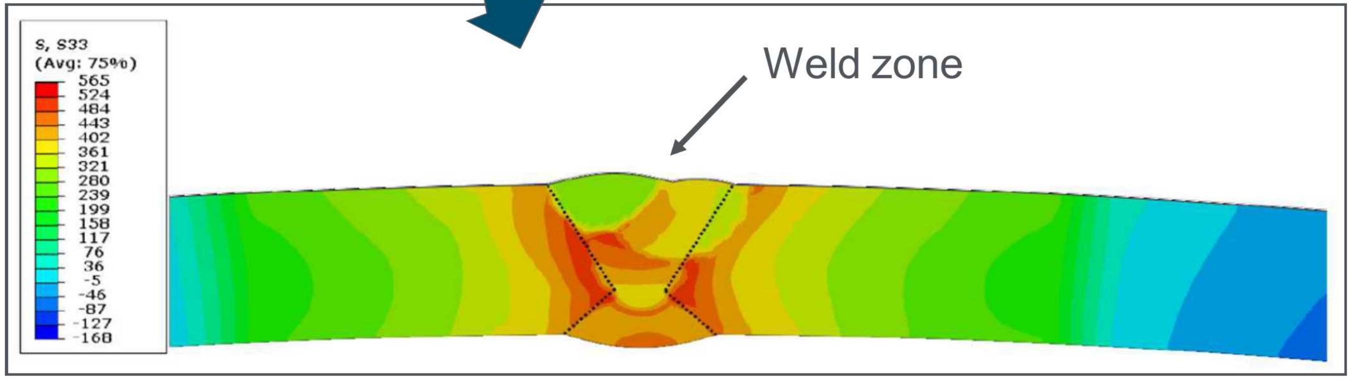
Weld zone, Ranor 304 SS plate





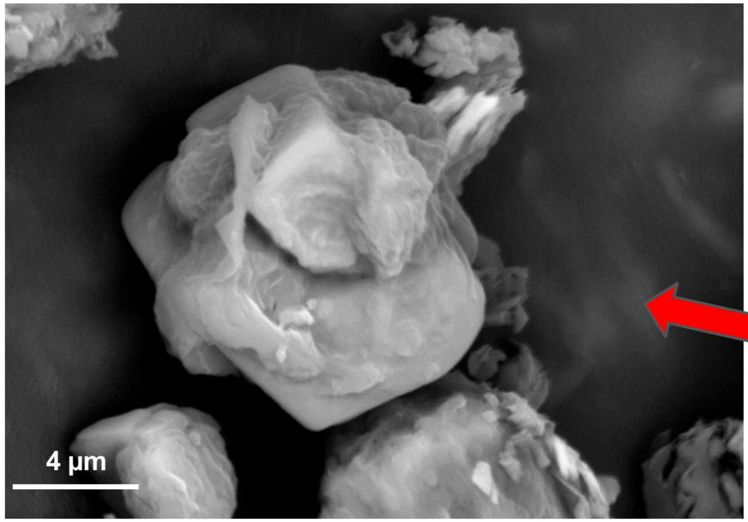
Dust on storage canister surface at Calvert Cliffs (EPRI 2014)

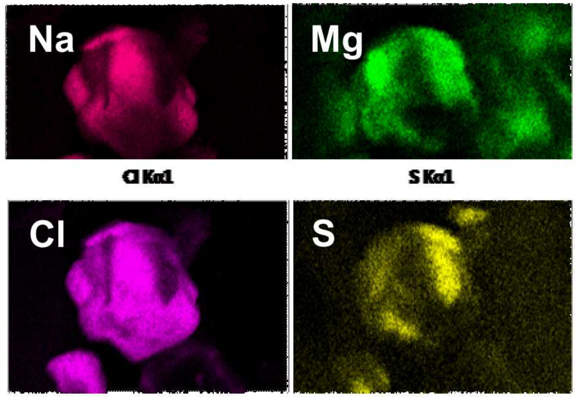
NRC (2013) modeled weld residual stresses



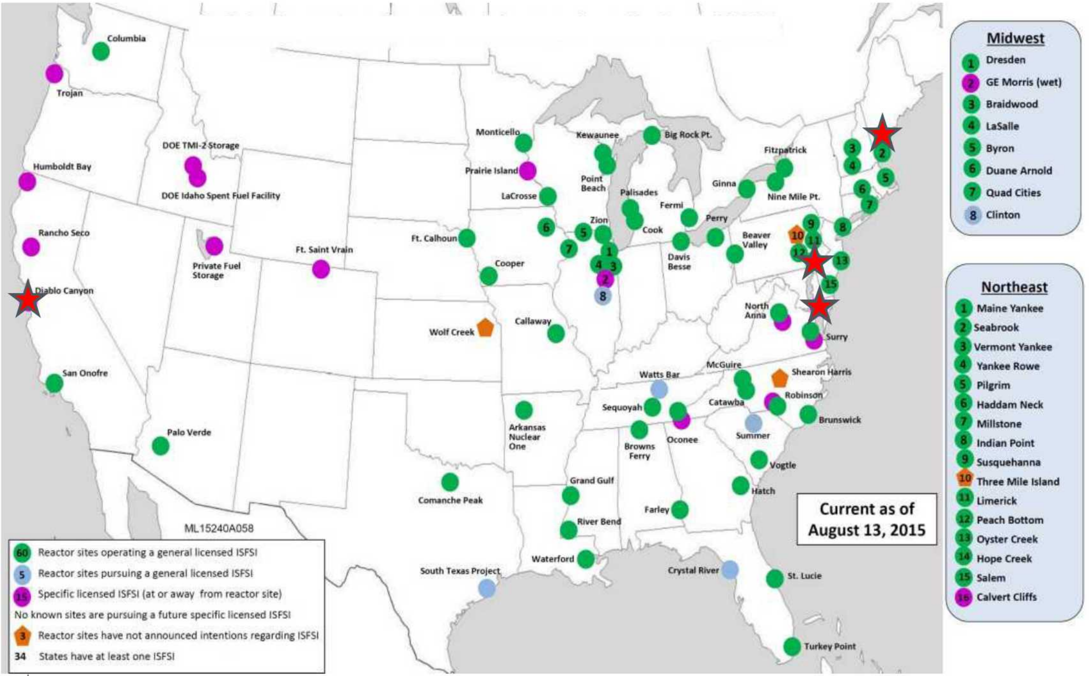
Environment

Sea-salt aggregate on Diablo Canyon ISFSI storage canister





Locations of U.S. Spent Nuclear Fuel Independent Storage Installations



★ Locations where dust and soluble salt samples have been collected

Near-marine sites are considered to especially at risk because of potentially high concentrations of chloride-rich sea-salt aerosols

Susceptible Material

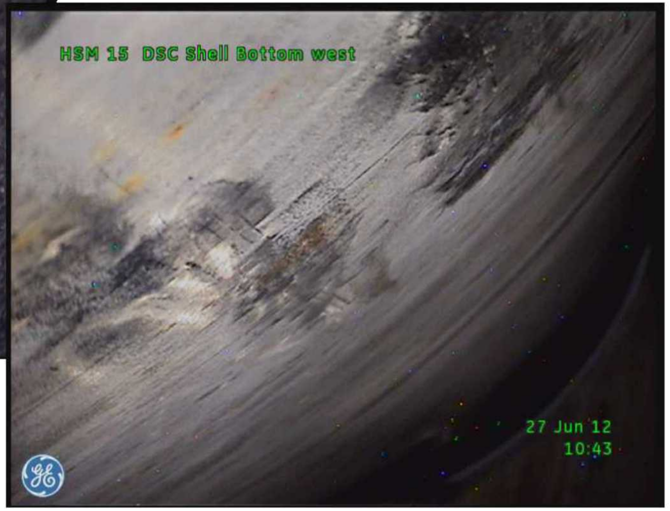
- **304 SS is known to be susceptible to atmospheric SCC**. Susceptibility is a function of many factors:
- Degree of sensitization
- Degree of cold work
- Surface finish
- Presence of iron contamination

- Experimental testing to date has shown rapid initiation of SCC under some conditions.
- Currently evaluating prototypical weld samples to determine degree of work hardening (~cold work) and microstructure (e.g., sensitization)

Weld zone, Ranor 304 SS plate

Rust spots on storage canister at Calvert Cliffs

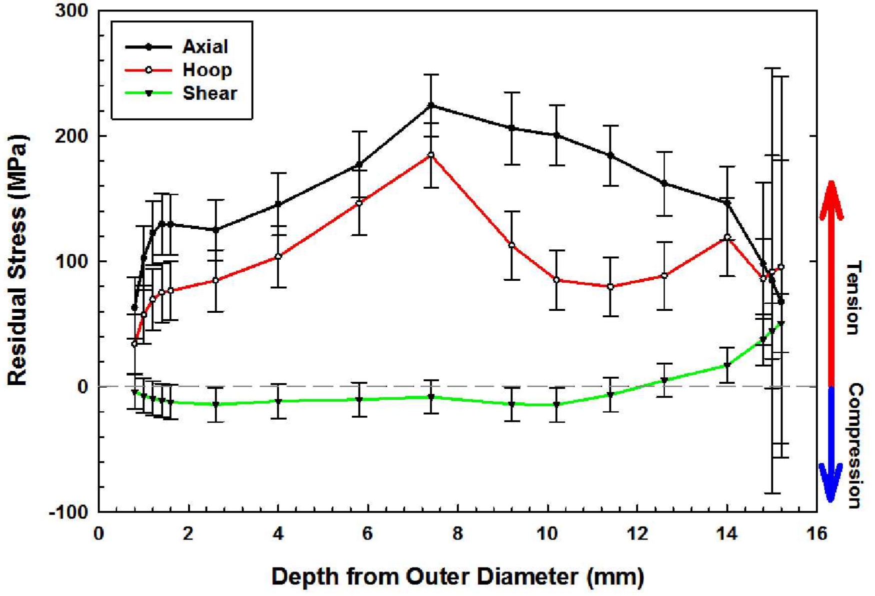
Surface finish



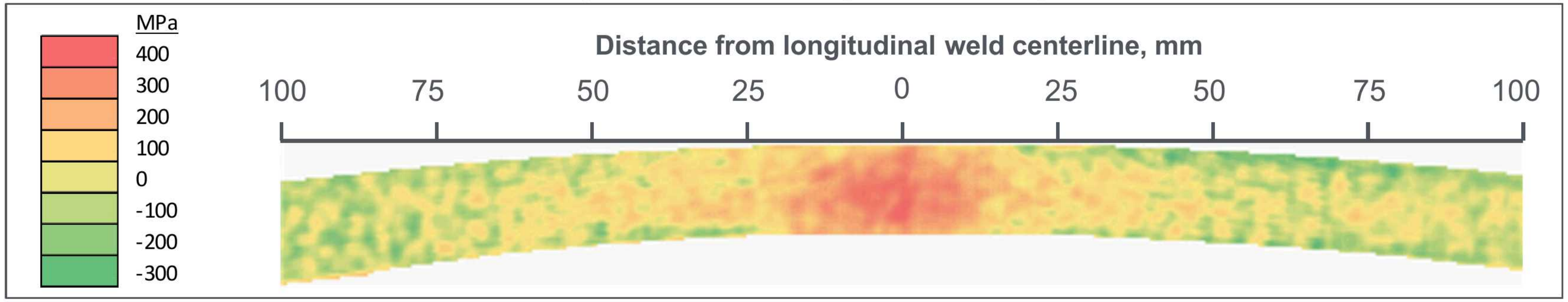
Tensile Stress

- **Sandia full-diameter cylindrical mockup**
- Made By Ranor (old supplier to Transnuclear) using identical procedures to real NUHOMS canisters
- **Weld residual stresses measured using several methods.**
- High through-wall tensile stresses measured at both longitudinal (seam) welds and circumferential welds.
- Highest tensile stresses measured at simulated weld repairs.

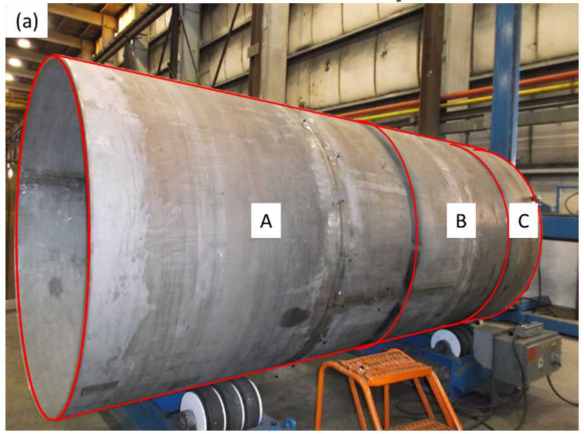
Residual stresses measured by deep-hole drilling method, longitudinal weld heat-affected zone

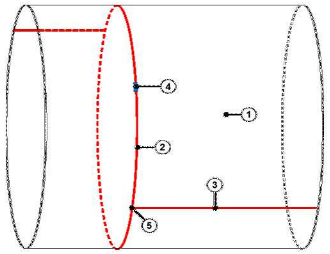


Residual stresses measured by deep-hole drilling method, longitudinal weld heat-affected zone

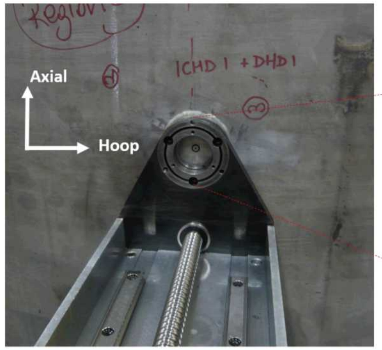


Sandia Mockup

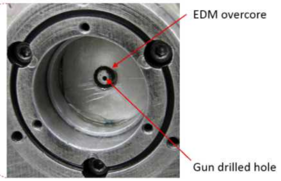




Locations for Stress Measurements



Deep-hole Drilling

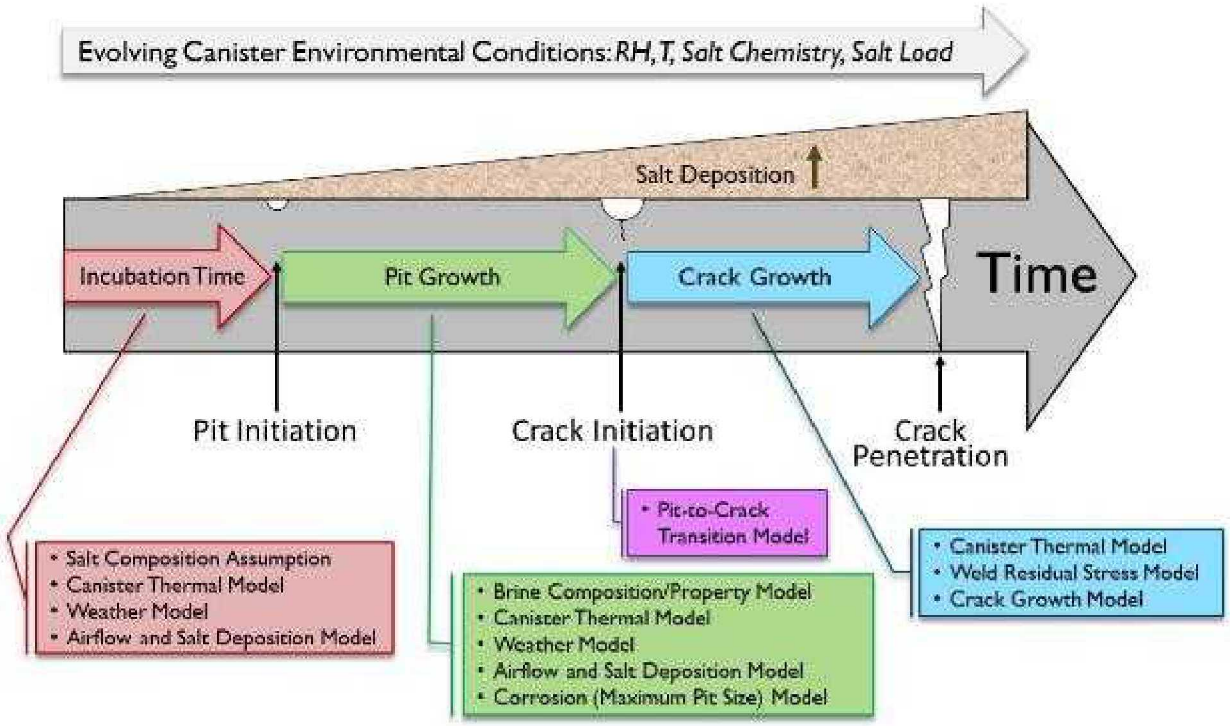


Current SNL Objectives

Overall objective: Improve the ability to predict timing and location of potential canister penetration by SCC cracks

- Improve understanding of electrolyte (deliquescent brine) physical and chemical characteristics
  - Effects of brine/atmosphere reactions
  - Effects of corrosion
- Understand the relationship between surface environment and damage (pitting/SCC) distributions and rates
  - Temperature and RH
  - Salt surface load and spatial distribution
- Develop quantitative understanding of the effects of variability in material properties and mechanical environment on corrosion.
  - Weld/HAZ/base metal material properties (sensitization, texture, mineralogy)
  - Tensile stress intensity and depth profile

SNL Stress Corrosion Cracking Studies

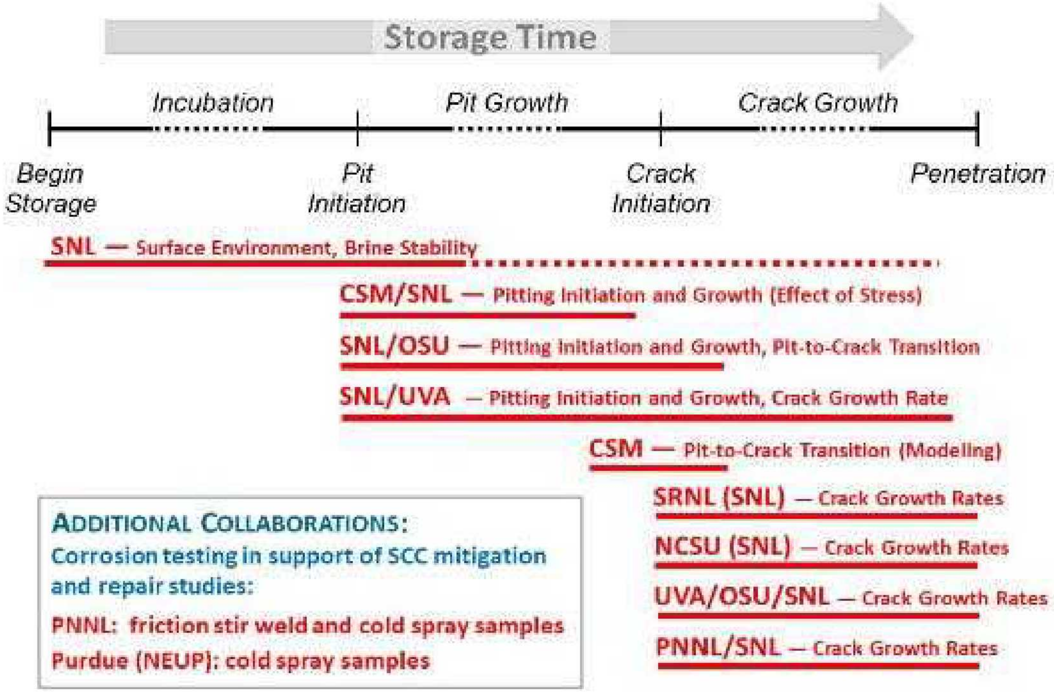


INTEGRATED MECHANISTIC/PROBABILISTIC MODEL FOR CANISTER SCC

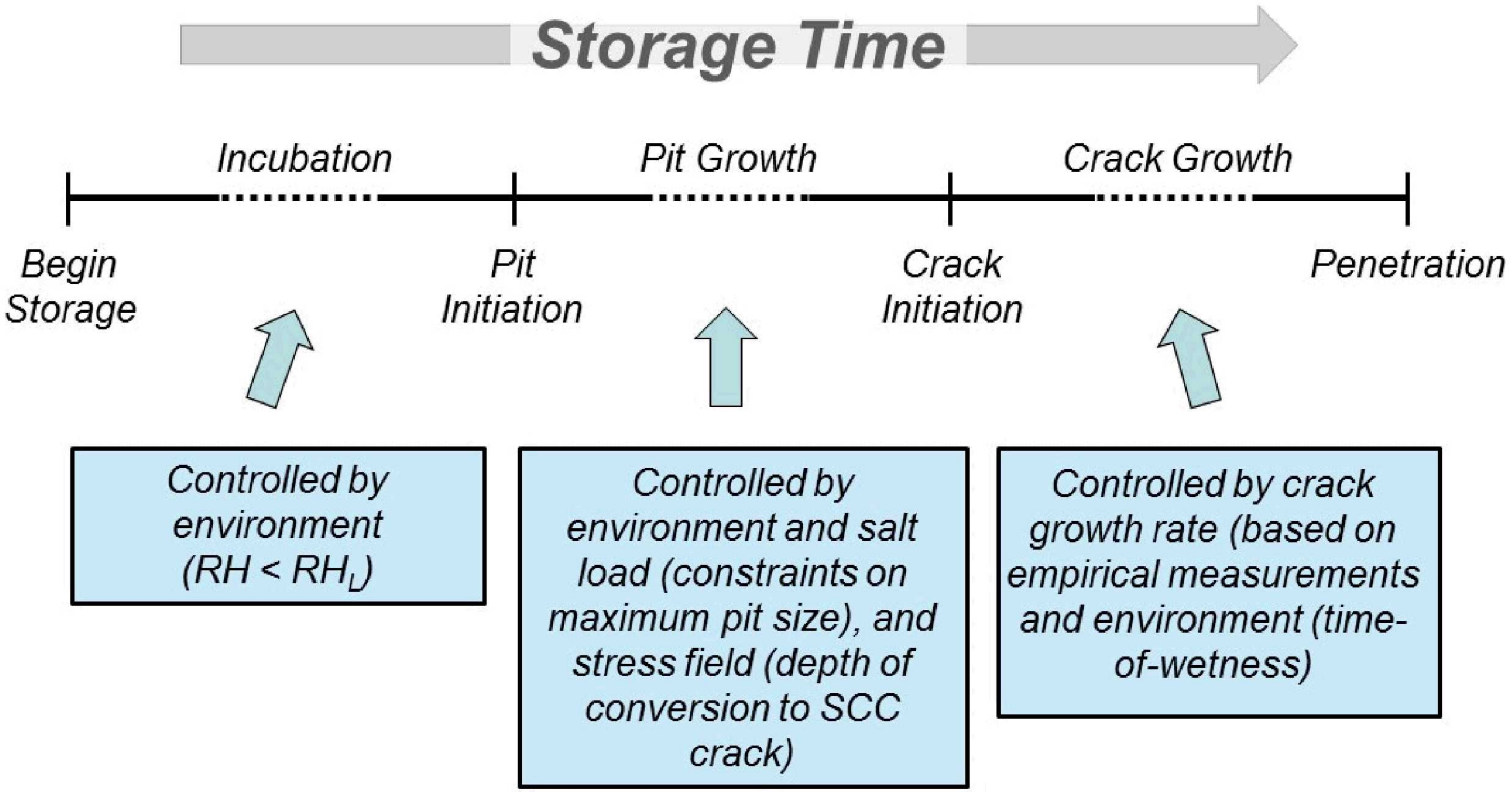
Goal: Improve the ability to predict timing and location of potential canister penetration by SCC cracks

COLLABORATIVE EFFORT

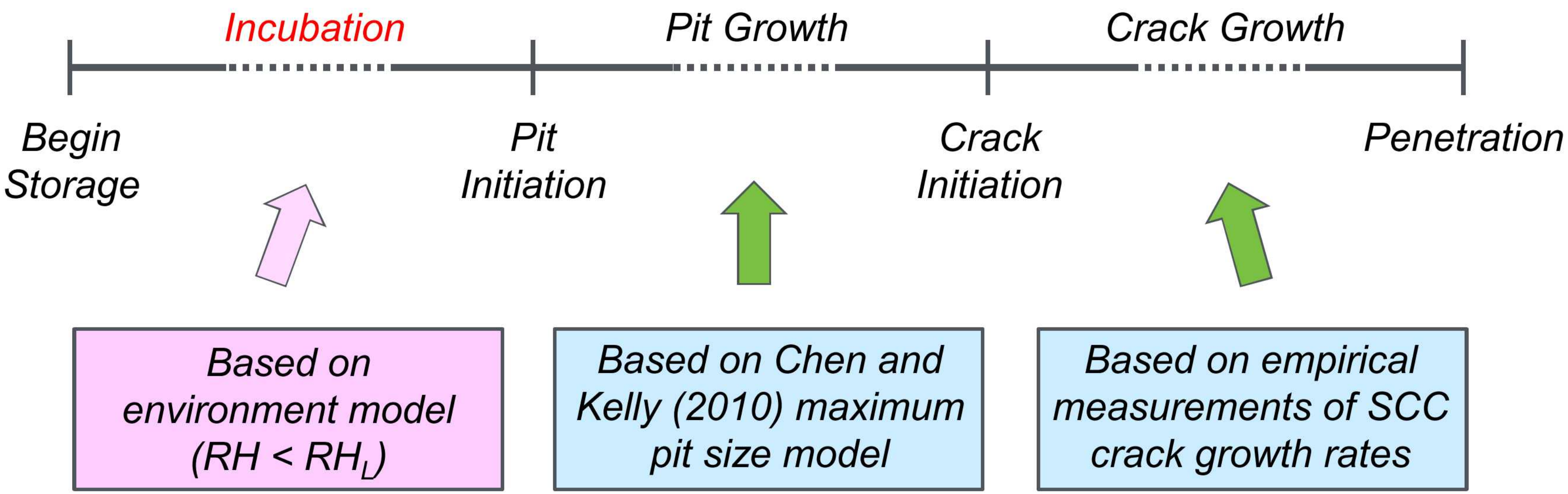
- Determine electrolyte *(deliquescent brine)* compositions and evolution with time
- Determine the relationship between surface environment *(T, RH, salt load/distribution)* and damage *(pitting/SCC)* distributions/rates
- Determine the effects of material properties *(microstructure)* and mechanical environment *(residual stress intensity and depth profile)* on corrosion distributions and rates



General Timeline for SCC Initiation and Penetration



Canister Surface Environment



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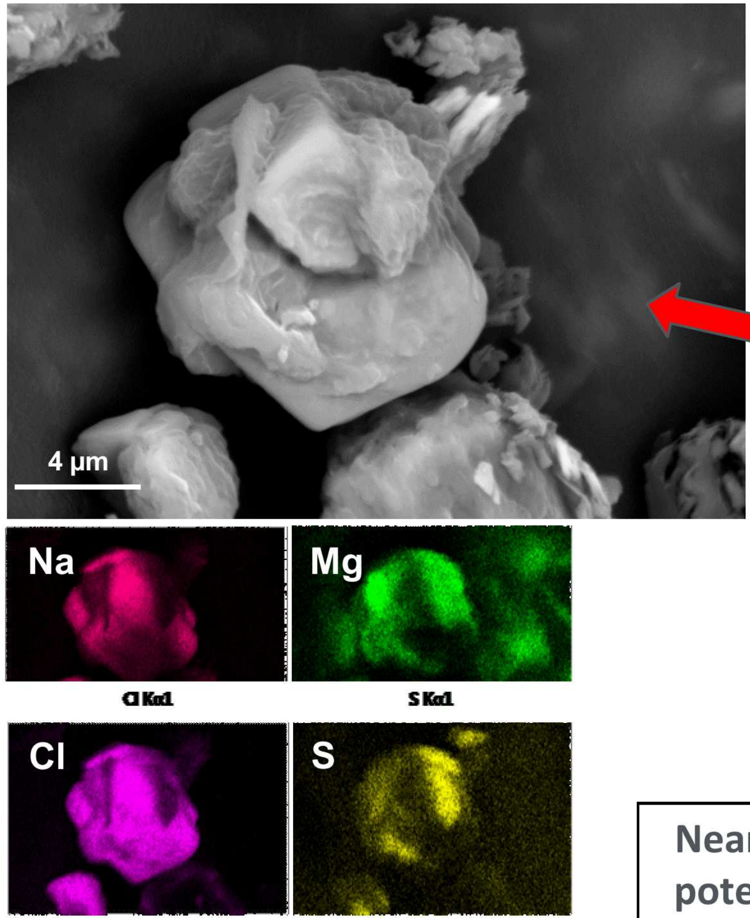

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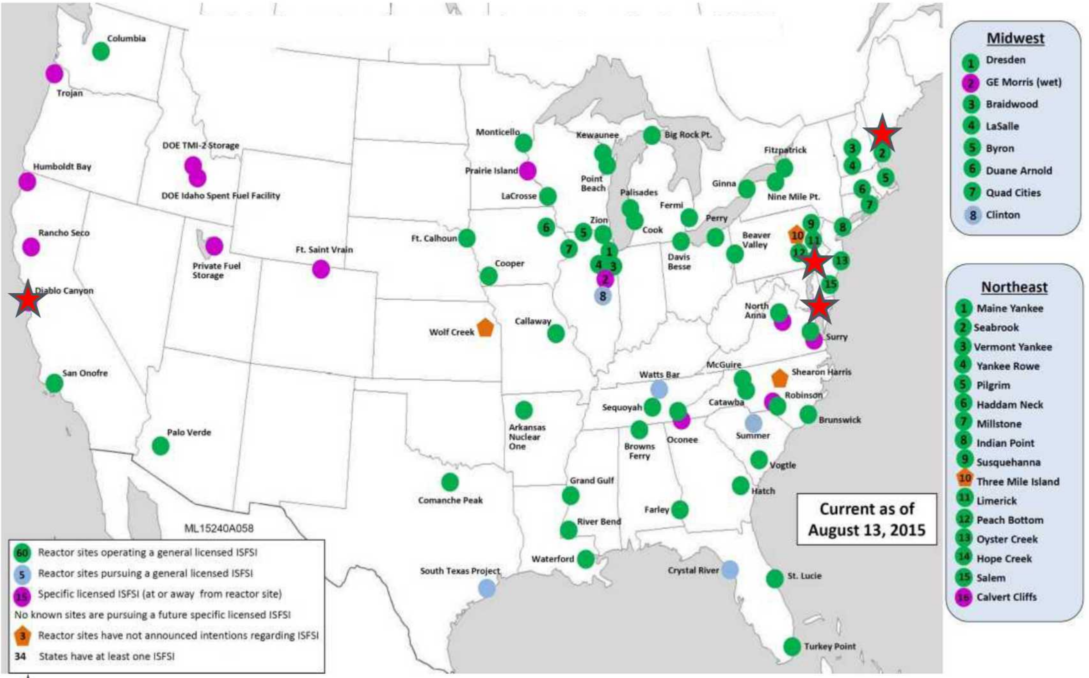
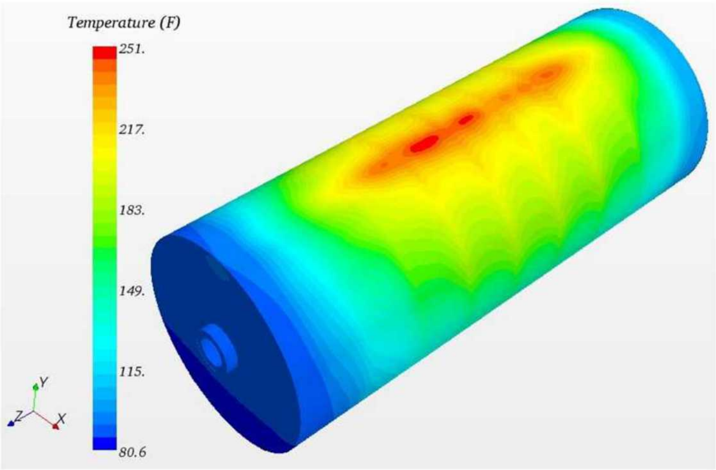


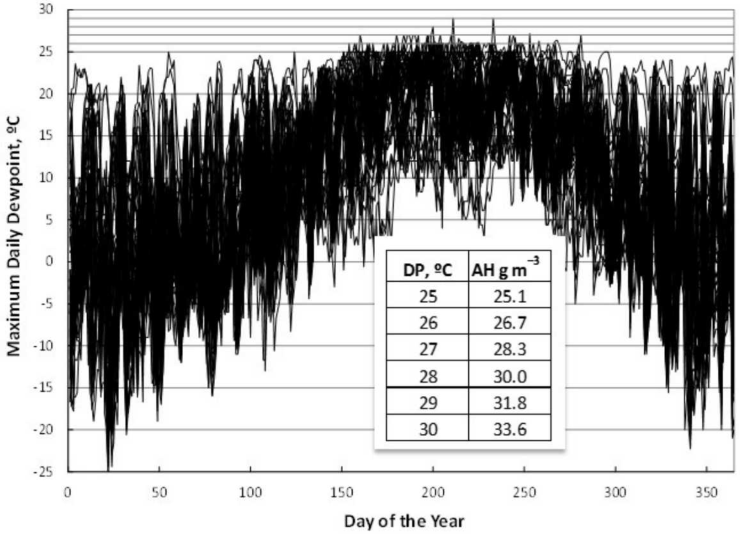
★ **Locations where dust and soluble salt samples have been collected**

Near-marine sites are considered to especially at risk because of potentially high concentrations of chloride-rich sea-salt aerosols

Incubation Period



Surface temperature estimates

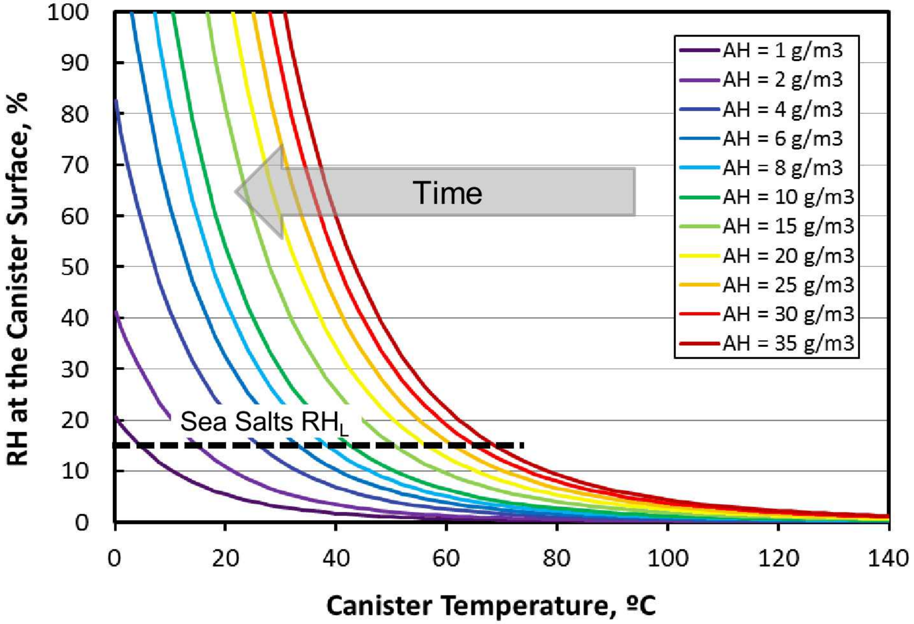


DP, ºC	AH g m^{-3}
25	25.1
26	26.7
27	28.3
28	30.0
29	31.8
30	33.6

Site-specific National Weather Service data: daily and seasonal variations in AH

Canister surface RH =
***f*(Ambient AH, canister surface T)**

Use weather data and predicted canister surface temperature to predict RH at any location and time.



Timing of corrosion initiation—point in time at which RH$_L$ is first reached.

Summing time when RH>RH$_L$ provides "time of wetness"; time when corrosion can actually occur.

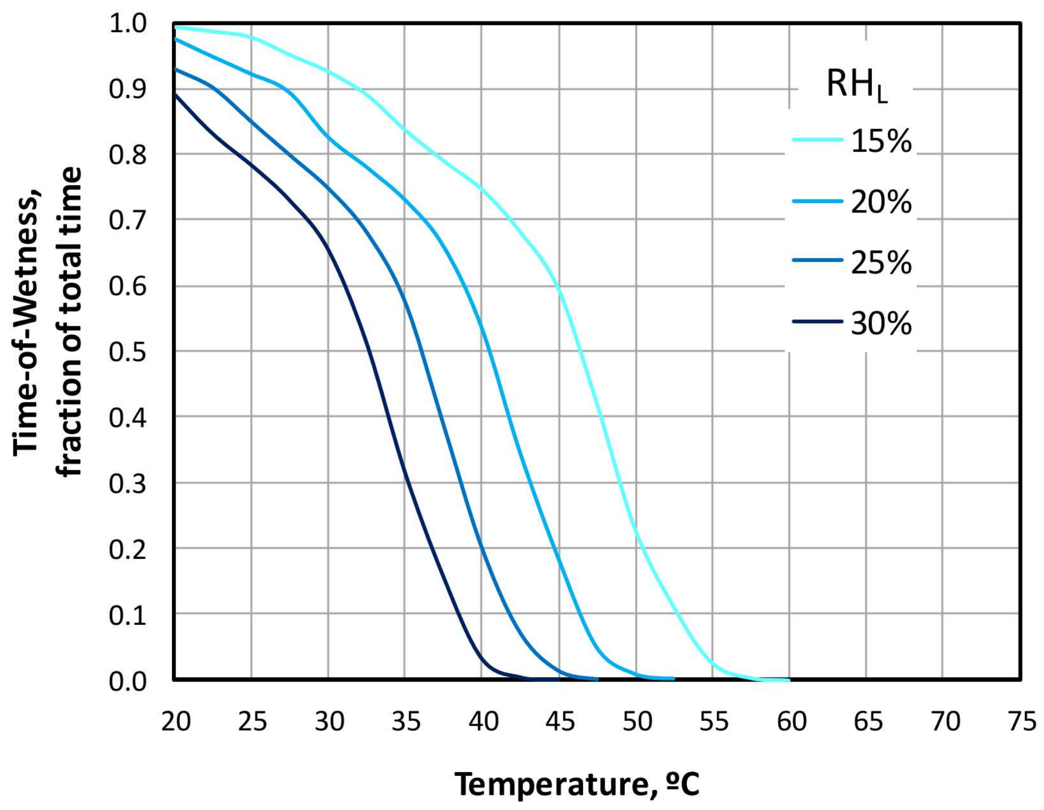
Both vary with canister surface location.

Concept of Time-of-Wetness

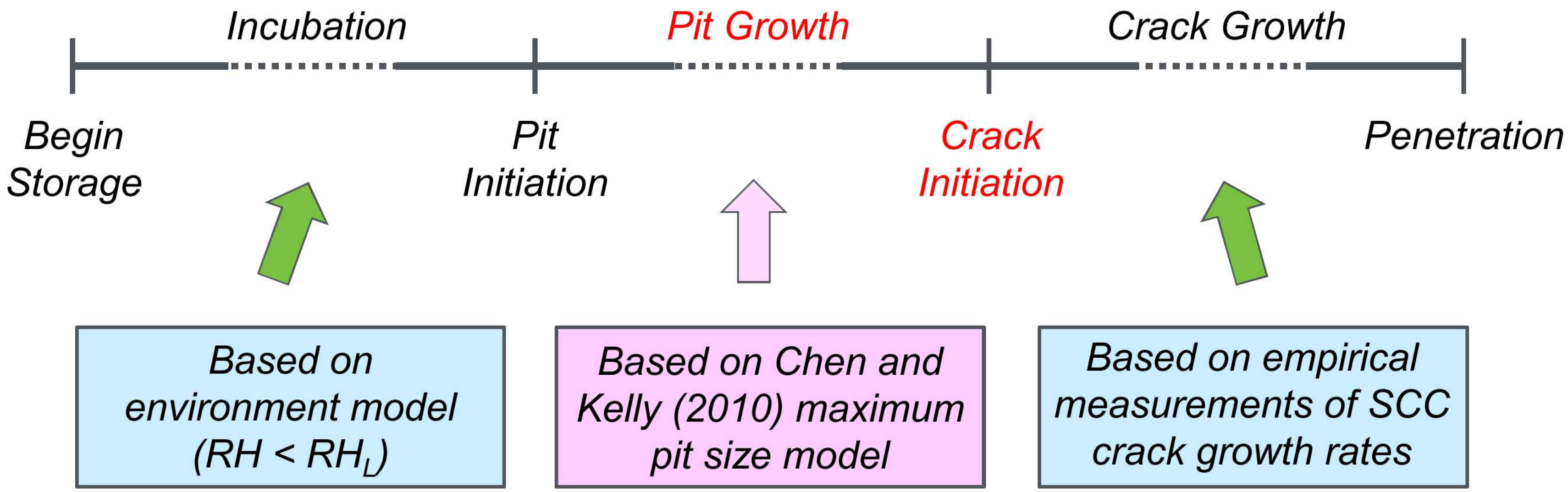
Time-of-wetness:

- Corrosion only occurs when a threshold RH (RH_L) is exceeded.
- Corrosion can start-stop on a daily or seasonal basis, as a function of changing T, AH
- Total integrated time when aqueous conditions exist is time-of-wetness
- Rationale: External cathode, required to support corrosion at the anode, is only present when aqueous conditions exist on the metal surface.
- Widely accepted approach (ASTM procedure G84-89). *However, many reasons to challenge time of wetness on a conceptual basis.* *(e.g., Schindelholz et al., 2013)*

Calculated time-of-wetness as a function of canister surface temperature and RH_L. Based on one year of weather data from the Oceanside Municipal Airport near the San Onofre ISFSI.



Pit Growth and SCC Crack Initiation



Pitting and SCC Crack Initiation

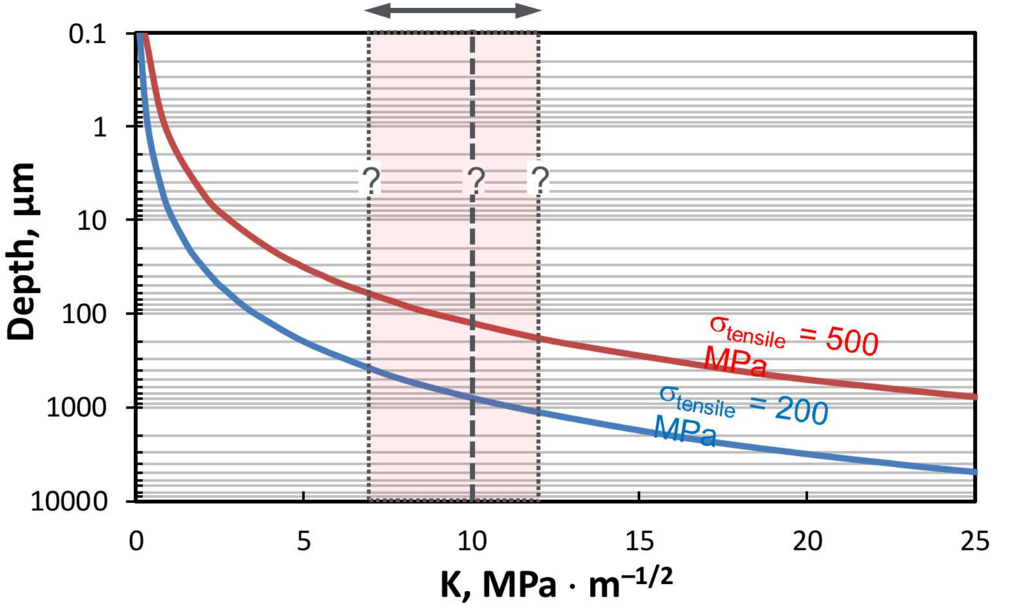
Pitting and SCC crack initiation

- Corrosion starts (pits form) once the RH_L is exceeded.
- *Pits grow over time, but for any given set of environmental conditions (T, RH, salt load), pit depths reach a limiting value.*
- Maximum pit depth model (Chen and Kelly 2010) can be used to calculate the maximum possible pit depth over time as a function of environmental parameters (temperature, RH, and deposited salt density).
- Pits generate aggressive chemistry and act as local stress focusers. SCC cracks initiate from corrosion pits on the metal surface.
- Depth of pit-to-crack transition can be estimated using the “Kondo criterion” (Kondo, 1985).

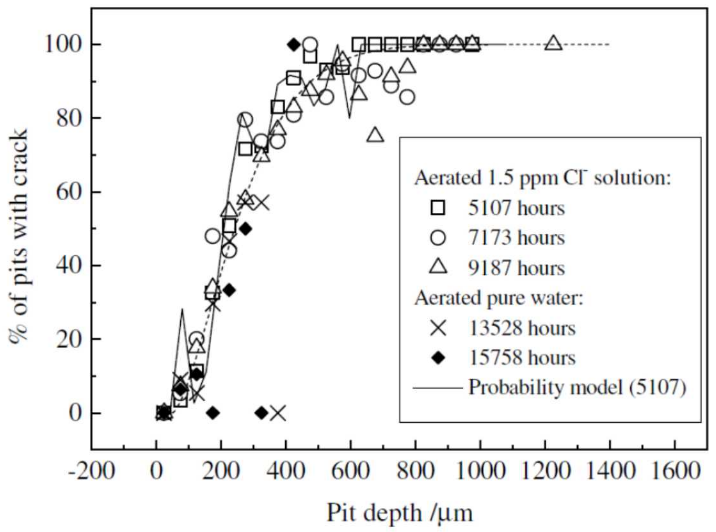
Crack Initiation: the "Kondo Criterion"

"Kondo criterion". **Pit-to-crack transition** occurs when the pit depth is equal to the depth at which an equivalent-depth SCC crack would have a crack-tip stress intensity factor (*K*) that exceeds K_{ISCC} for the metal.

- *K* is calculated as a function of crack depth using a sampled through-wall stress profile.
- K_{ISCC} is sampled from a compilation of literature values.



Experimental data from Turnbull et al. (2006)

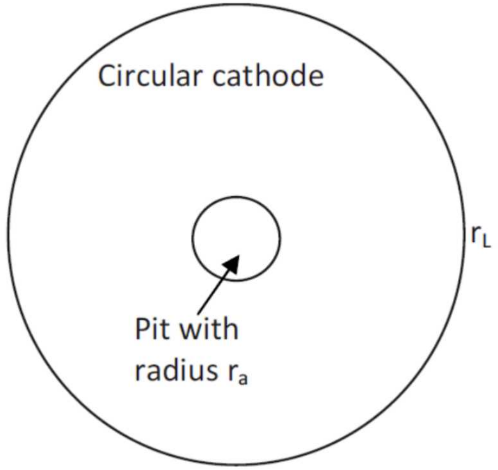


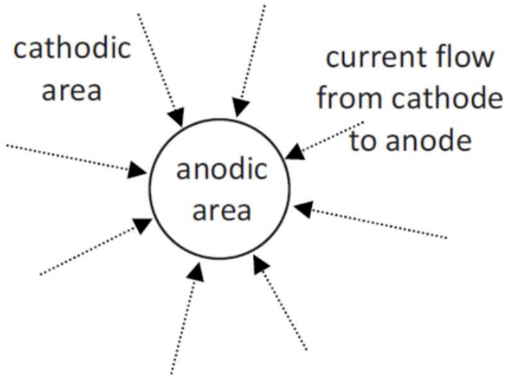
Stochastic process: As a pit deepens, the likelihood of a crack initiating increases.

Maximum Pit Size Model

Chen and Kelly (2010): Max pit size is a function of the maximum cathode current.

Pits are modeled as being hemispherical, and stifle once the pit becomes so large that the anodic current requirement exceeds the available cathode current.





Electrochemical term (from cathodic polarization curve)

Max. cathode current

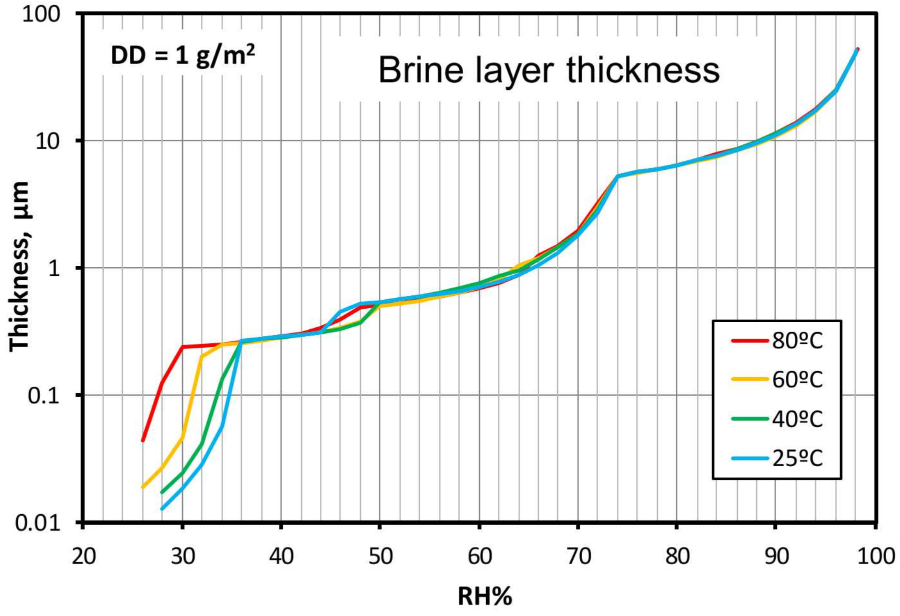
Brine conductivity

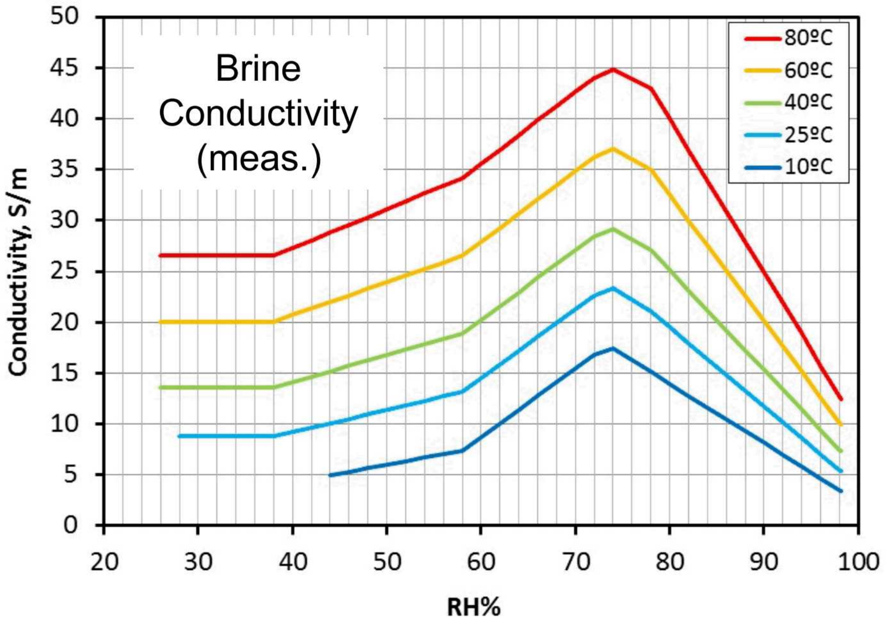
Brine layer thickness

$$\ln I_{c,max} = \frac{4\pi k W_L \Delta E_{max}}{I_{c,max}} + ln\left[\frac{\pi e r_a^2 \int_{E_{corr}}^{E_{rp}} (I_c - I_p) dE}{\Delta E_{max}}\right]$$

Parameterizing the Model for Sea-Salt Brines

Values are based on geochemical modeling, literature data, and measured data for brine densities and conductivities (7 brines, from 98-38% RH).





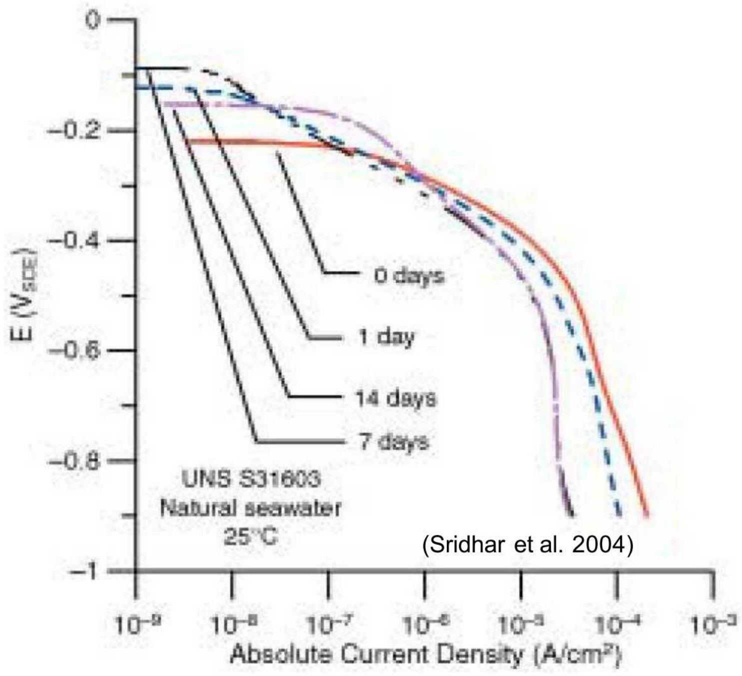
Original *Chen and Kelly* (2010) model: Based on NaCl brines (dry out at ~75% RH).

Assumption: *Brine forms a continuous brine layer.* This seems unlikely at low salt loads or low RH values. However:

- Experimental data suggest that the cathode can extend well beyond the perimeter of salt grains (Schindelholz et al., 2013).
- Insoluble dust particles will increase brine film continuity via capillary effects.

Cathodic Polarization Curves and electrochemical parameters for concentrated brines

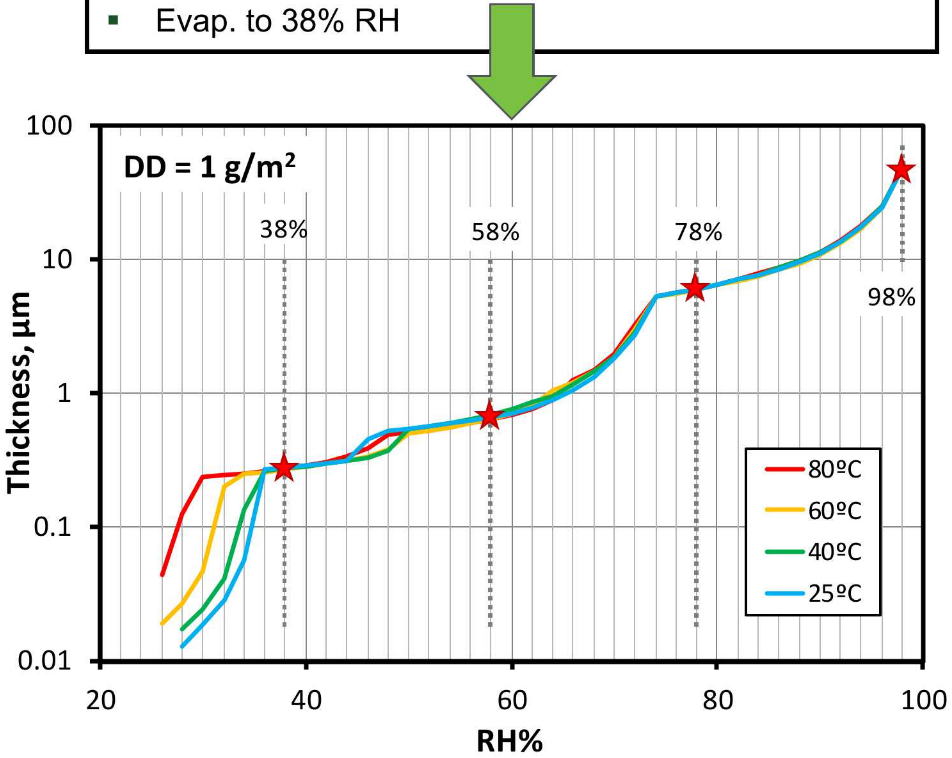
Chen and Kelly used cathodic polarization curve for seawater at 25ºC, 316 SS (Sridhar et al. 2004)



(a)

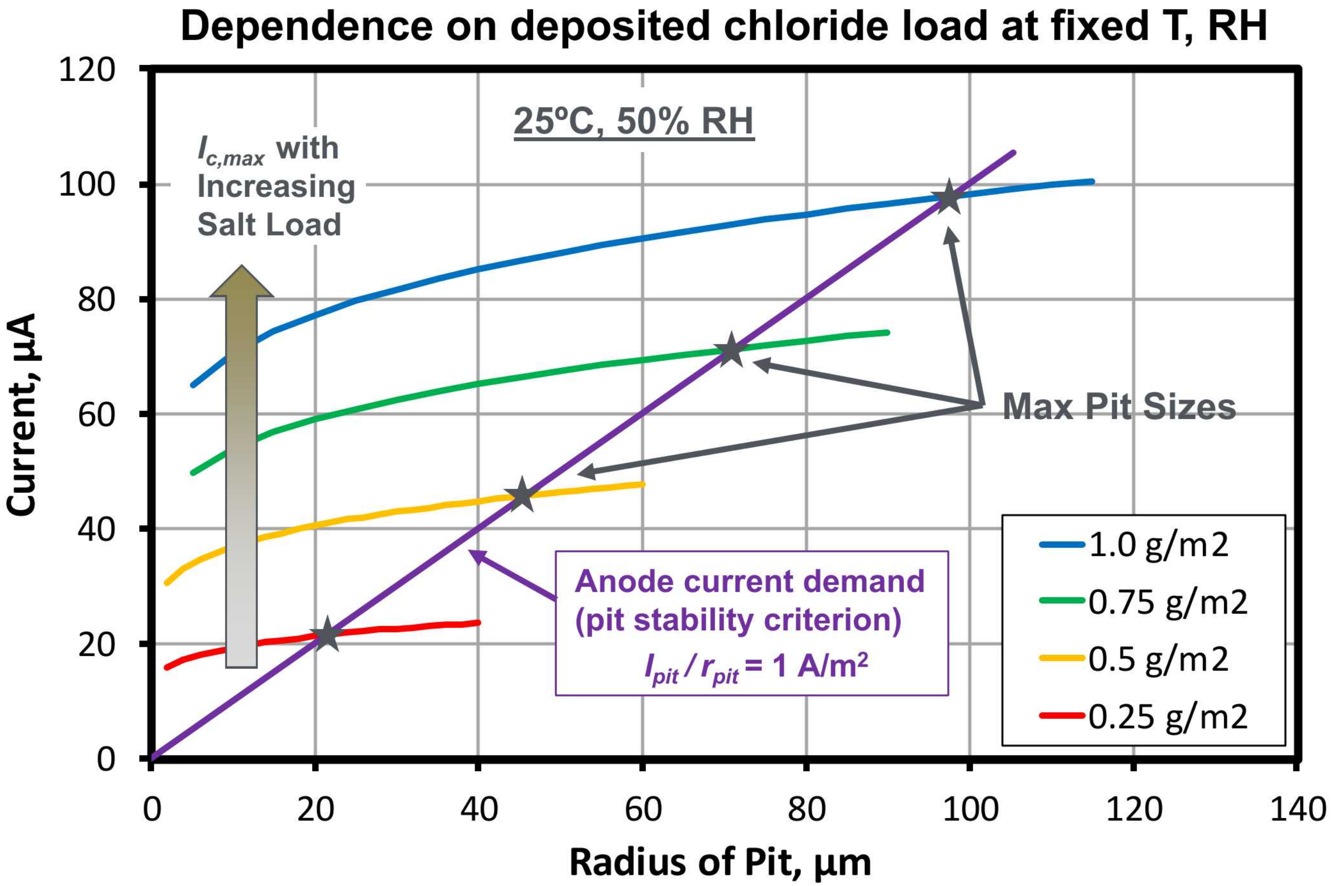
To characterize variability in cathode kinetics with brine composition, SNL has measured polarization curves and other electrochemical parameters in four brines corresponding to:

- Unevaporated Seawater (98% RH)
- Evap. to 78% RH
- Evap. to 58% RH
- Evap. to 38% RH



Determining Maximum Pit Size

Maximum pit size is determined the intersection of the anode current demand and the available cathode current.



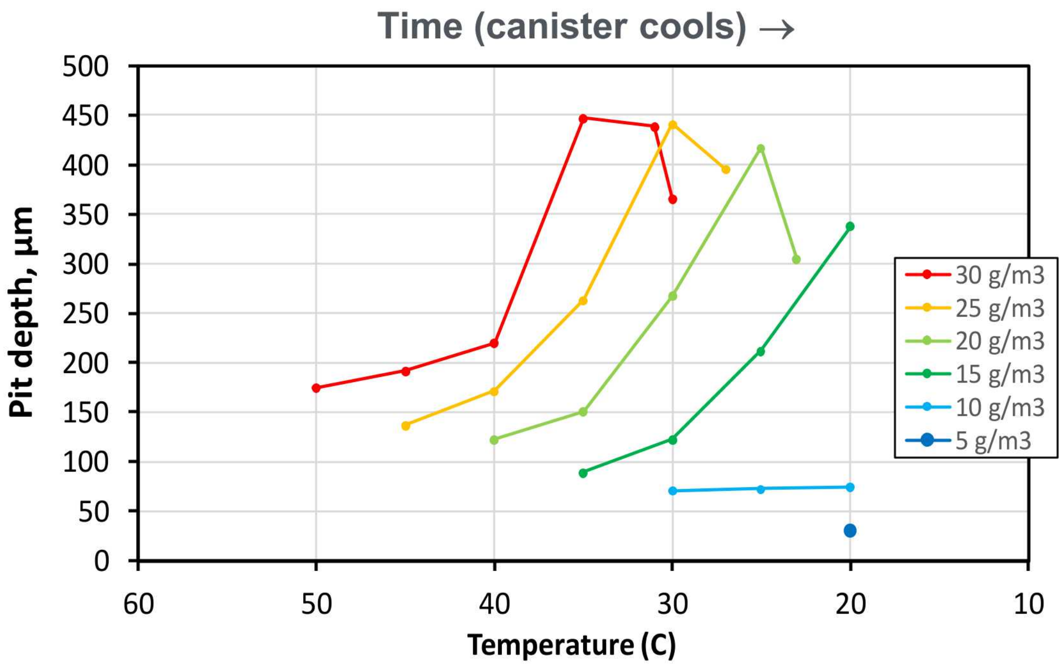
Model Results

As the canister cools, T drops, and RH increases

<u>Assume constant AH:</u> As T is varied, RH modified to hold AH constant. Salt load held constant throughout.

- **Largest pits possible at temperatures corresponding 75-85% RH**
  - *Higher T = lower RH, thinner brine films*
  - *Lower T = higher RH, more dilute solutions.*
- **Overall trends:**
  - *As the canister cools, maximum possible pit size increases*
  - *Increasing salt load with time will also result in larger pits*

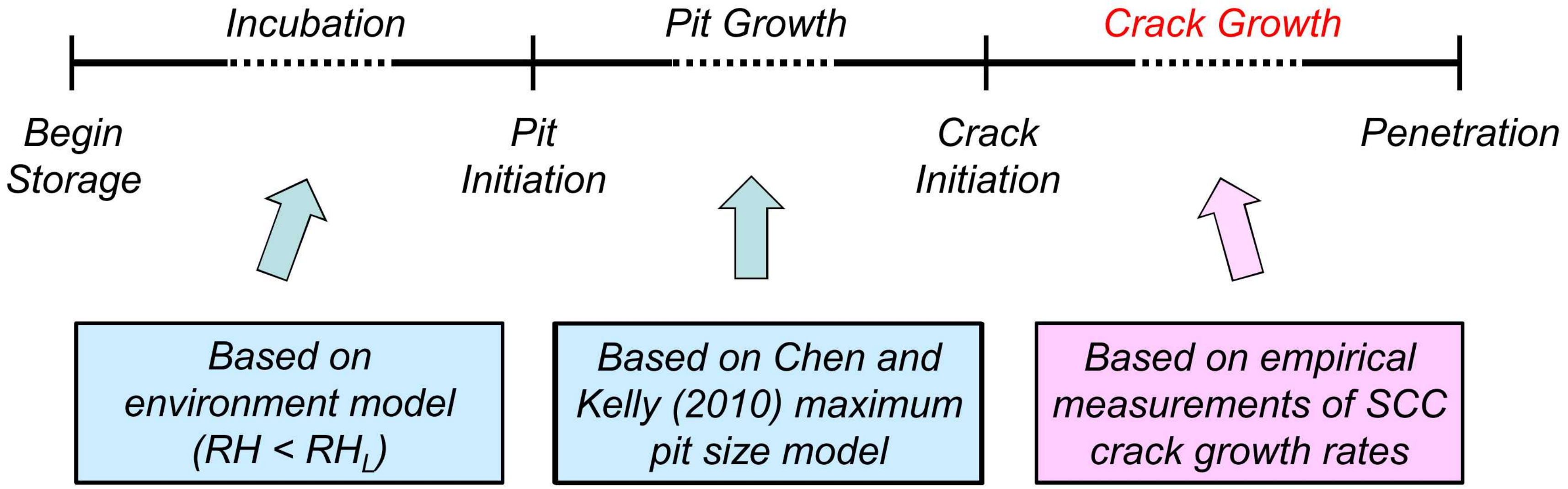
Risk of meeting Kondo Criterion and initiating SCC will increase with time.



Caveat: Electrochemical terms are held constant. Realistically, they vary with brine composition and temperature.
(Woldemedhin et al. 2014, 2015; Srinivasan et al. 2015)

SCC Crack Growth

Model for SCC Crack Growth



Stress Corrosion Cracking Model:

Crack growth

Model for crack growth:

- In general:

$$\frac{dx_{crack}}{dt} = \dot{x}_{crack} = \alpha_{crack}\, f(T)\, f(K)\, f(R_a)\, f([Cl^-])\, f(m_{Cl}) f(pH)\, f(\sigma_{ys}) \ldots$$

- Implemented a version incorporating only effect of T, K:

$$\frac{dx_{crack}}{dt} = \alpha_{crack} \cdot exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \cdot (K - K_{th})^{\beta_{crack}}$$

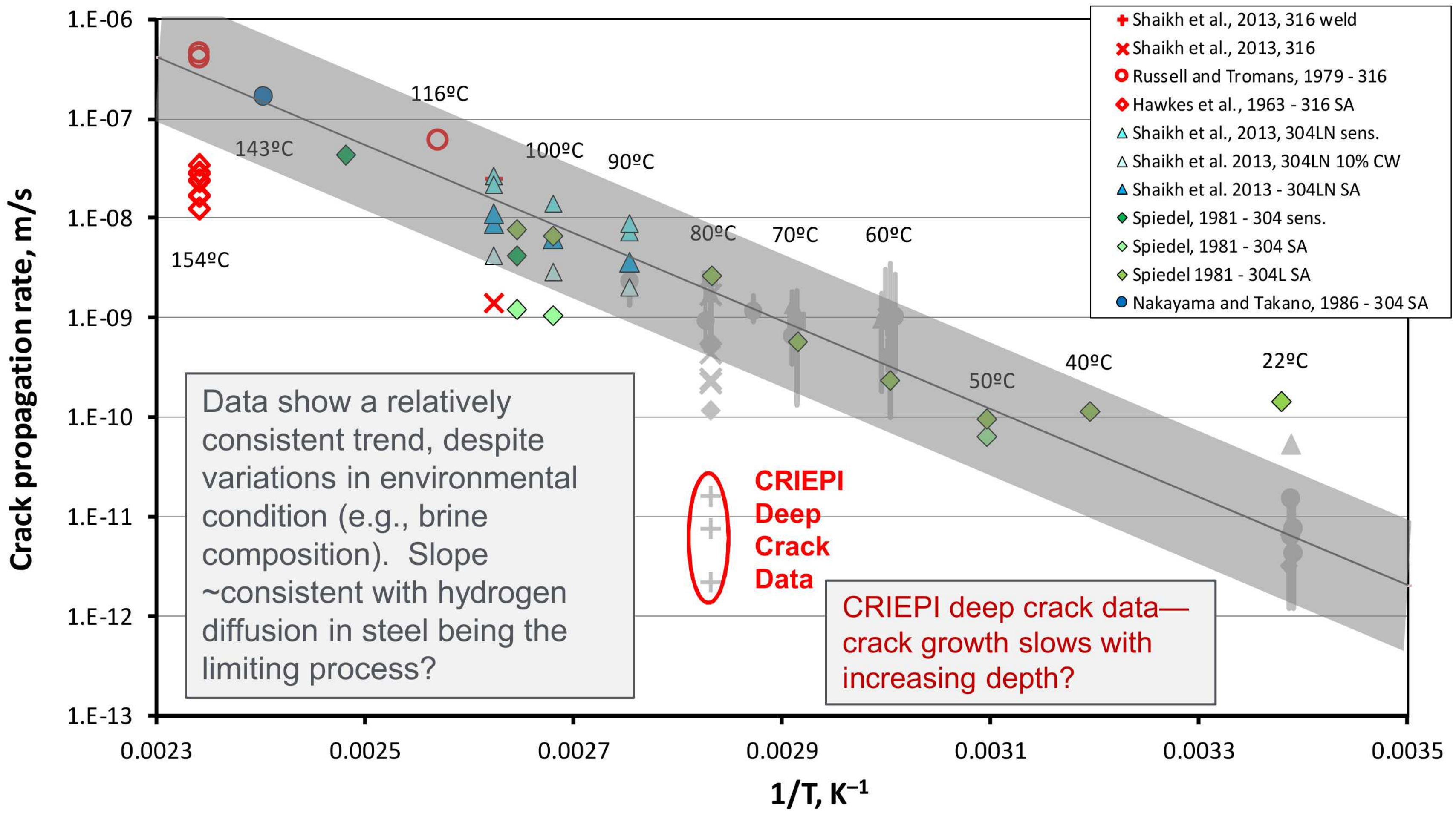
dx_{crack}/dt = crack growth rate
α_{crack} = crack growth amplitude
Q = activation energy for g=crack growth
R = universal gas constant (8.314 J mol^{-1} K^{-1})
T = temperature (K) of interest
T_{ref} = reference temperature (K) at which α was derived.
K = crack tip stress intensity factor
K_{th} = threshold stress for SCC
β_{crack} = stress intensity factor exponent.

Where $K = \sigma_{applied} Y \sqrt{\pi x_{crack}}$

$\sigma_{applied}$ = tensile stress
Y = shape factor
x_{crack} = depth

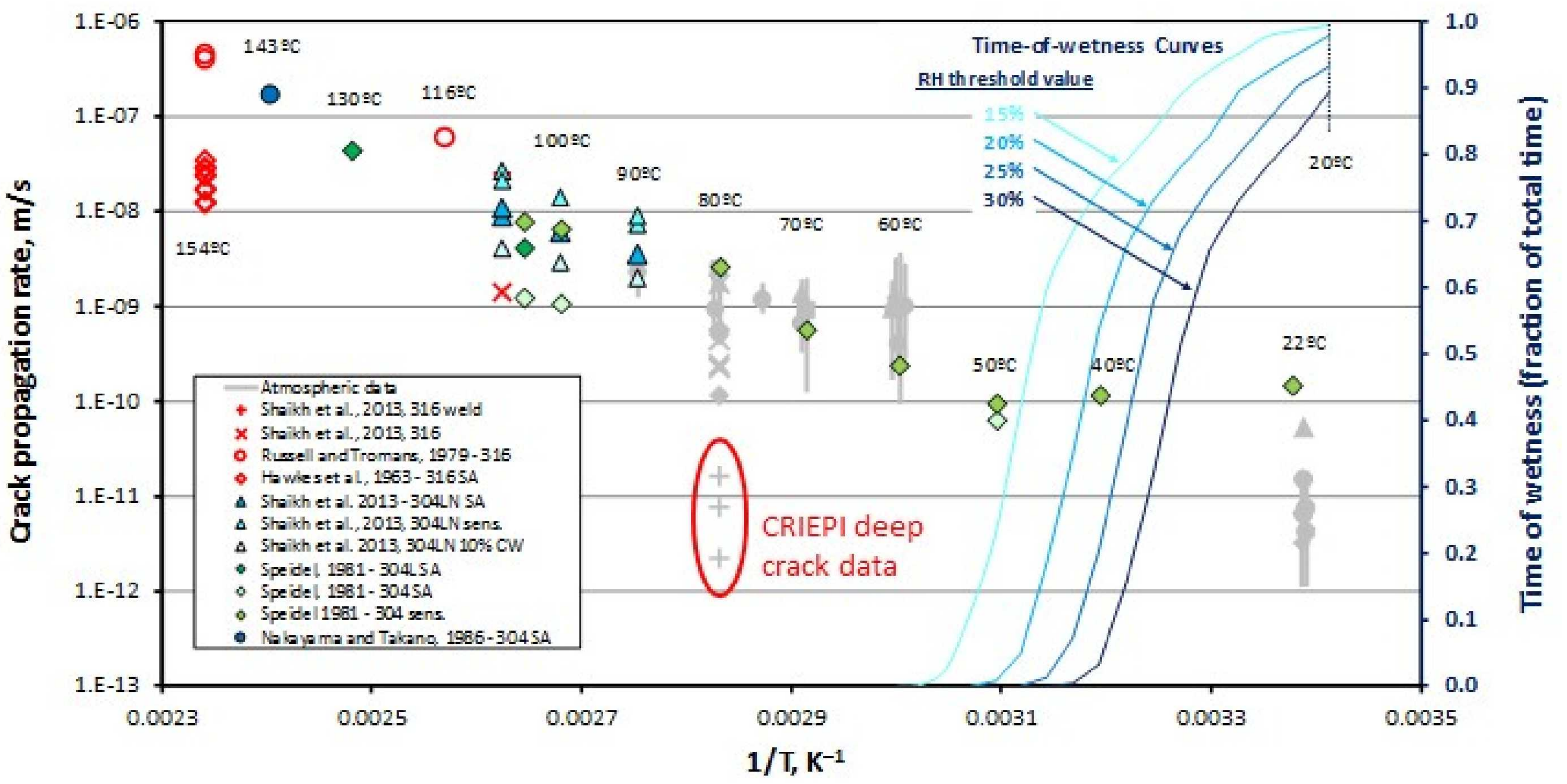
Literature Crack Growth Rates

Data for 304 SS and 316 SS

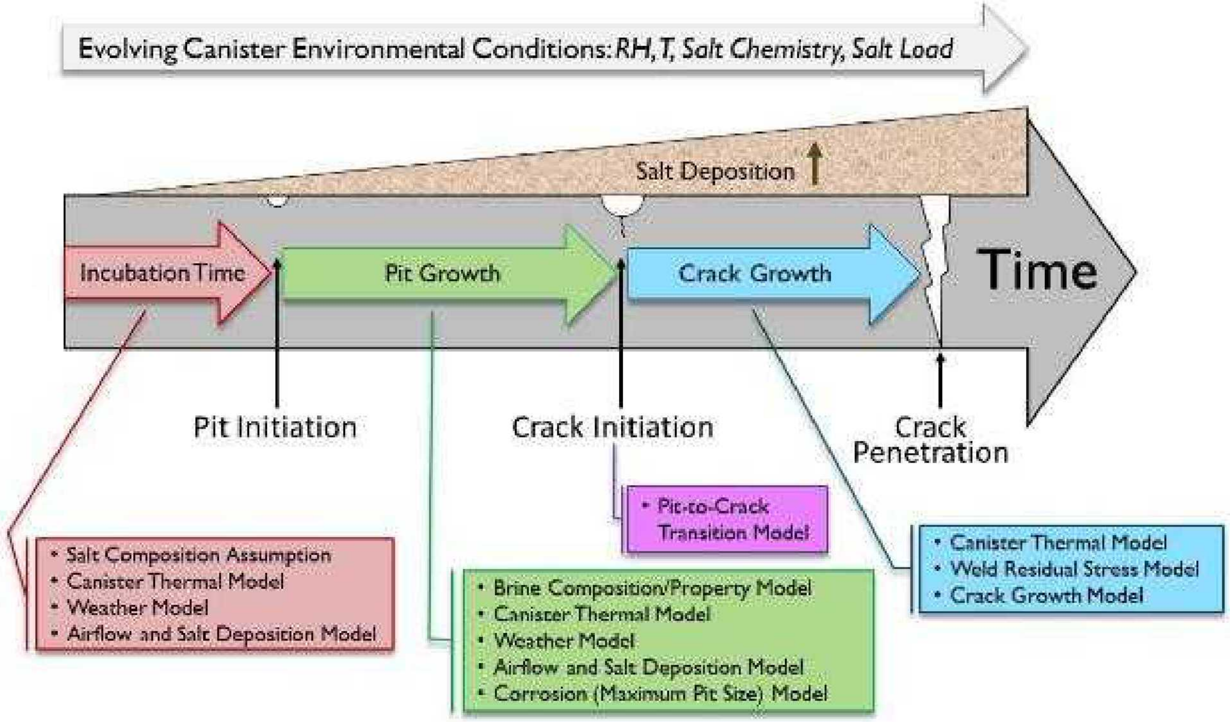


Role of Time-of-Wetness

Overall Crack Penetration Rate = Crack Growth Rate × Time-of-wetness



SNL Stress Corrosion Cracking Probabilistic Model



INTEGRATED MECHANISTIC/PROBABILISTIC MODEL FOR CANISTER SCC

Goal: Improve the ability to predict timing and location of potential canister penetration by SCC cracks

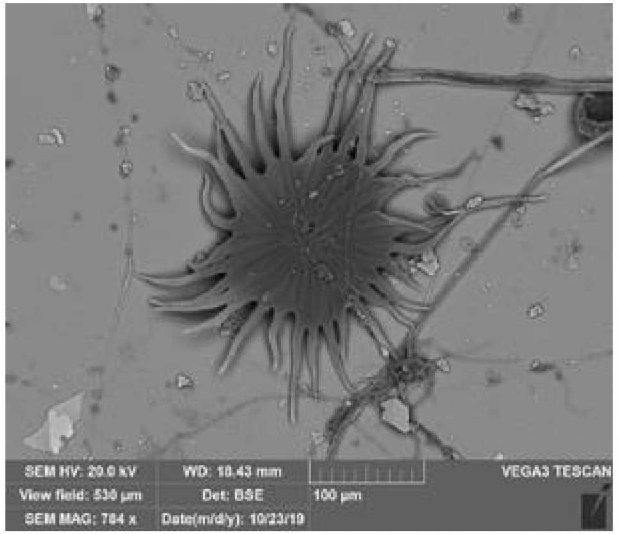
Intended model uses

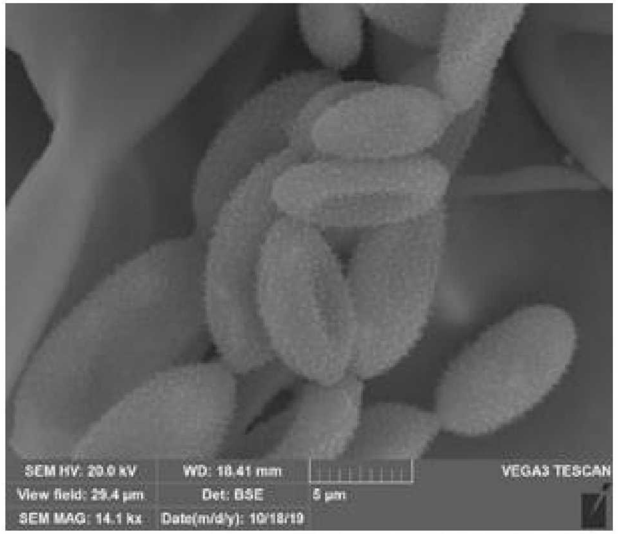
- **Assessing risk of SCC initiation and penetration as a function of:**
  - Estimated heat decay curve (canister surface temperatures)
  - ISFSI location (weather parameters, salt deposition rates)
  - Canister surface location (variation in T, salt load)
- **Support development of appropriate ISFSI Aging Management Plans: informing required canister inspections for SCC**
  - Maps of at-risk locations on the canister surfaces
  - Determination of necessary SCC inspection intervals

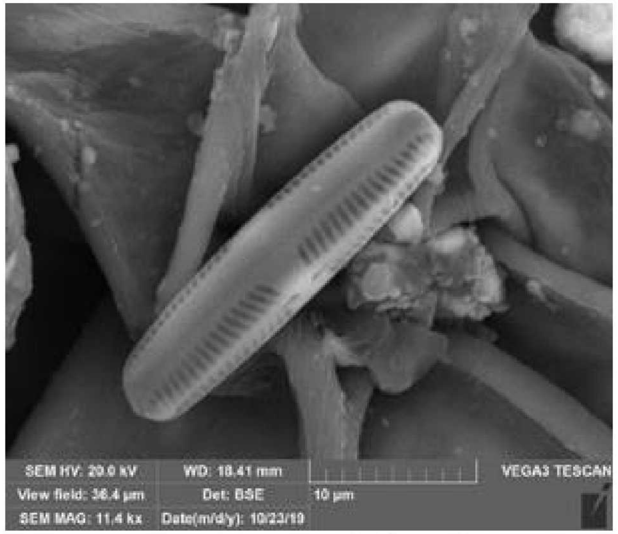
Summary and Next Steps

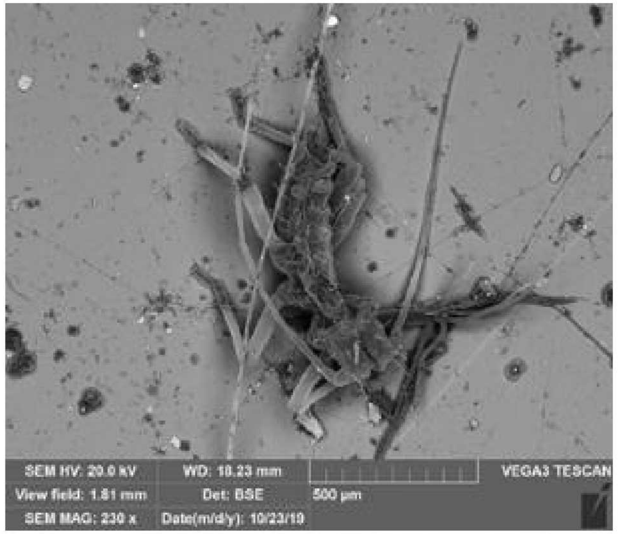
- ***Experimental Results:***
  - Large scale atmospheric exposures displayed dependence of pitting and morphology as a *f(Environment)*
  - SCC atmospheric weld exposures displayed very few detectable cracks
  - Corrosion field exposures displayed small amounts of corrosion after two year exposures
- ***Implications: SCC Model Assumptions may be challenged by:***
  - *f(environment)*
  - Material microstructure
  - Brine evolution during corrosion processes
- **Next steps:**
  - Determine validity of SCC model assumptions with respect to ***pitting, pit-to-crack, and crack growth*** as a ***f(Environment and material)***
    - *What is the primary factor that governs pit morphology?*
    - *Is pit-crack transition influenced by f(Environment) and pit morphology?*
    - *Is crack growth rate a f(Environment)?*

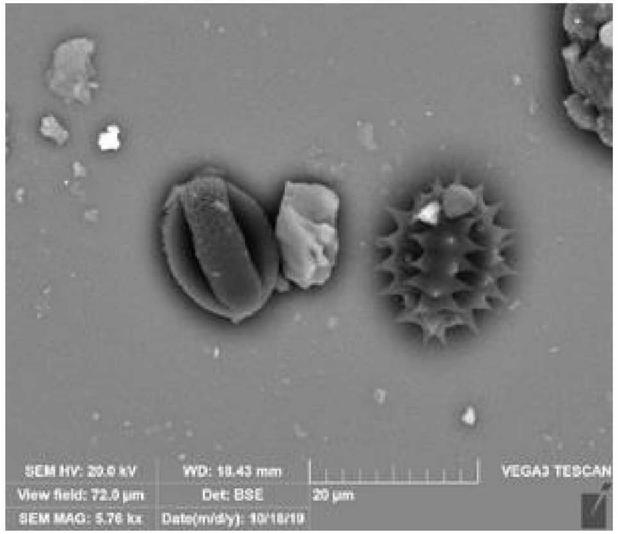
Questions?

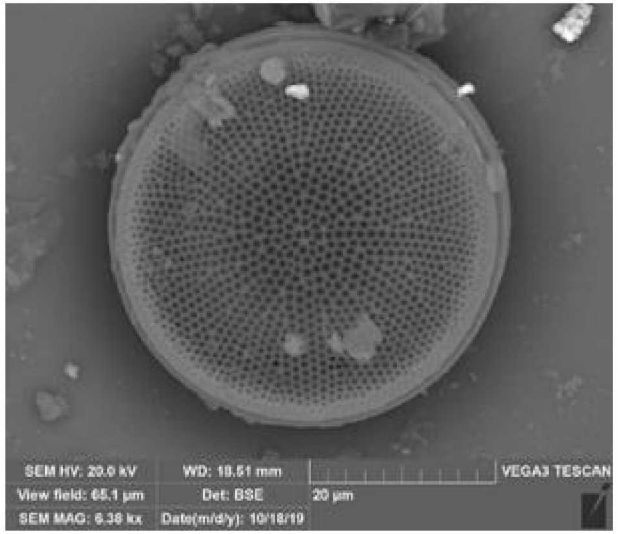

SEM HV: 20.0 kV
WD: 18.43 mm
VEGA3 TESCAN
View field: 530 µm
Det: BSE
100 µm
SEM MAG: 784 x
Date(m/d/y): 10/23/19

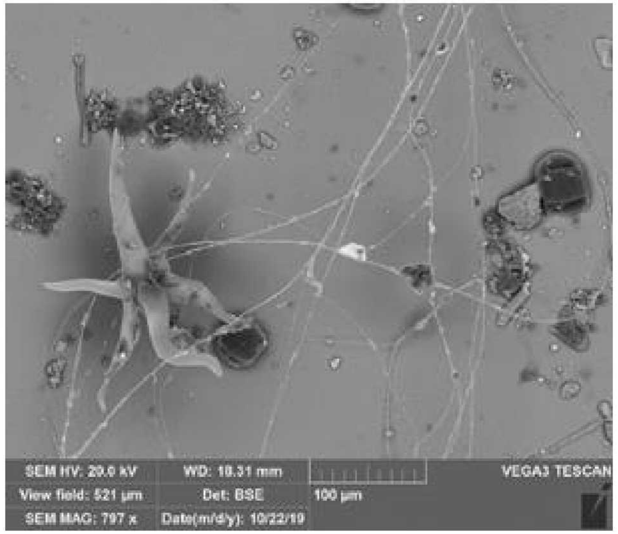

SEM HV: 20.0 kV
WD: 18.41 mm
VEGA3 TESCAN
View field: 29.4 µm
Det: BSE
5 µm
SEM MAG: 14.1 kx
Date(m/d/y): 10/18/19

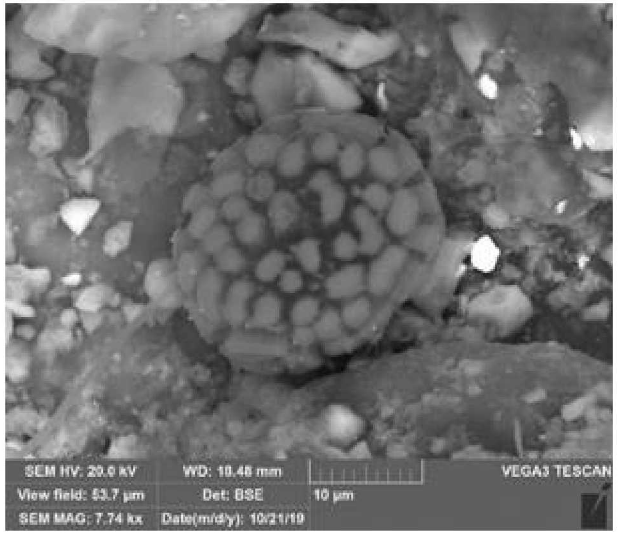

SEM HV: 20.0 kV
WD: 18.41 mm
VEGA3 TESCAN
View field: 36.4 µm
Det: BSE
10 µm
SEM MAG: 11.4 kx
Date(m/d/y): 10/23/19


SEM HV: 20.0 kV
WD: 18.23 mm
VEGA3 TESCAN
View field: 1.81 mm
Det: BSE
500 µm
SEM MAG: 230 x
Date(m/d/y): 10/23/19


SEM HV: 20.0 kV
WD: 18.43 mm
VEGA3 TESCAN
View field: 72.0 µm
Det: BSE
20 µm
SEM MAG: 5.76 kx
Date(m/d/y): 10/18/19


SEM HV: 20.0 kV
WD: 18.51 mm
VEGA3 TESCAN
View field: 65.1 µm
Det: BSE
20 µm
SEM MAG: 6.38 kx
Date(m/d/y): 10/18/19


SEM HV: 20.0 kV
WD: 18.31 mm
VEGA3 TESCAN
View field: 521 µm
Det: BSE
100 µm
SEM MAG: 797 x
Date(m/d/y): 10/22/19


SEM HV: 20.0 kV
WD: 18.48 mm
VEGA3 TESCAN
View field: 53.7 µm
Det: BSE
10 µm
SEM MAG: 7.74 kx
Date(m/d/y): 10/21/19

Backup Slides

Current Experimental work

Canister Surface Environment: Evaluation of Sea-Salt Brine Stabilities

Focus on Mg-Cl_2 brine, that strongly control deliquescence RH and potentially brine corrosiveness

Experimental Evaluation of Magnesium Chloride Brine Stability

Previous Experiments:

80°C, 35% RH test:

- Chloride loss
- Conversion to Mg-hydroxychloride

48°C, 40% RH test:

- Chloride loss
- Reaction with atmospheric CO_2; conversion to Mg-carbonate
- Degree of reaction limited by low air flow, limited duration

Current Experiment (in progress)

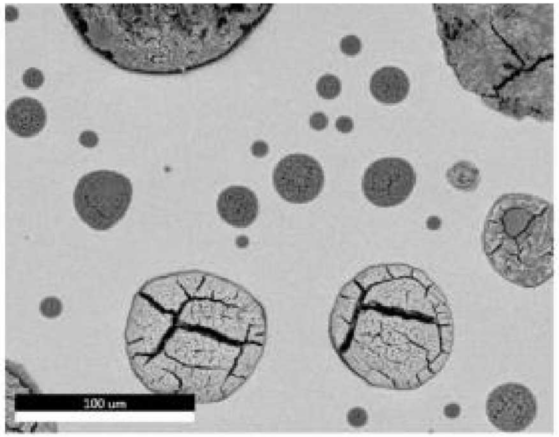
48°C, 40% RH test:

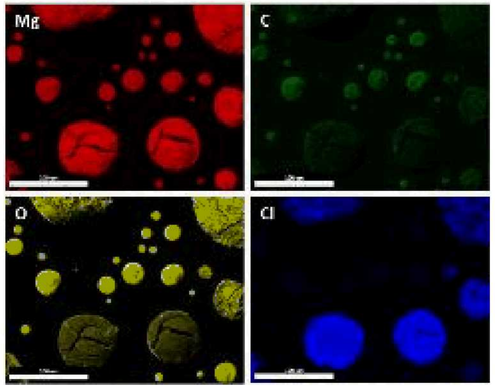
- High air flow, longer duration

Future work: Reactions with other atmospheric gases

- SO_x, NO_x

SEM Image of $MgCl_2$ droplets on wafer surface

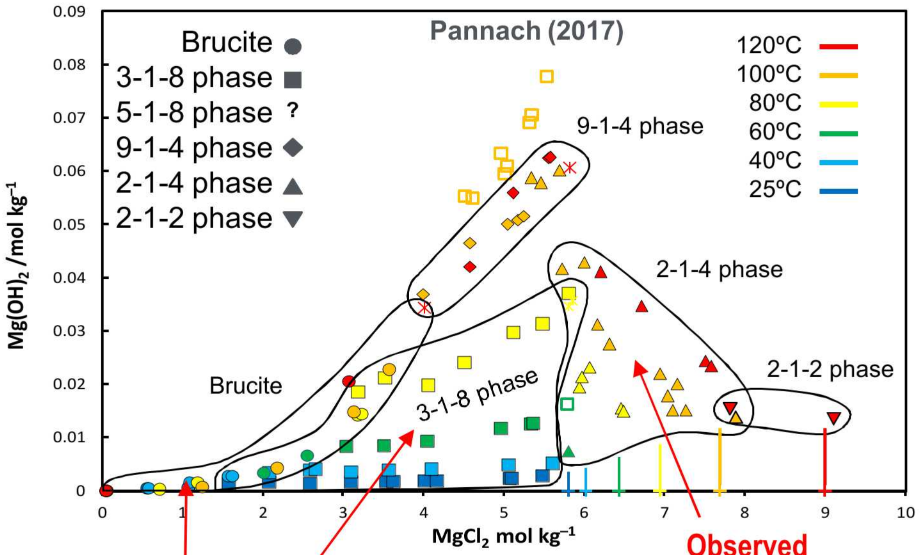




EDS element maps showing depletion of chloride in small droplets of $MgCl_2$. due to chloride degassing.

Characterization of Mg-hydroxychloride Hydrates:

- Observed in several experiments
- Controls on deliquescence RH, brine composition and properties



Canister Surface Environment: Dust Sampling and Analysis

Maine Yankee Sampling

MAINE YANKEE SAMPLING, OCTOBER, 2019

- Samples placed in inlet and outlet vents of four storage systems (SNF canisters) by CSM in 2017; transferred to SNL ownership with end of CSM IRP.
- Locations (8 total): high and low heat flow, sheltered and exposed inlet and outlet vent locations
- At each location:
  - 1 large 4-pt bend specimen, with attached dust collection coupons.
  - 3 small 4-pt bend specimens (varying surface finishes and stress levels)

Specimens examined, all 8 dust collection coupons collected and replaced, two small 4-pt bend samples collected.

Samples characterized by SEM/EDS and chemical analysis.

Sampling at Maine Yankee ISFSI, October, 2017

Maine Yankee Sampling

<u>General Impressions</u>

- Samples tethered to vent screens, close to the screens
- Samples dirty with wind-blown dust and plant debris, and spider webs and other insect debris; inlet samples much dirtier (in general) than outlet samples
- Much lower deposition on vertical surfaces *(tension surface of large 4-point bend)*
- Many samples show evidence of wetting—rain spatter, condensation(?), or accumulation of wet fog(?) (rings or droplet patterns in the dust; rust under dust collector)

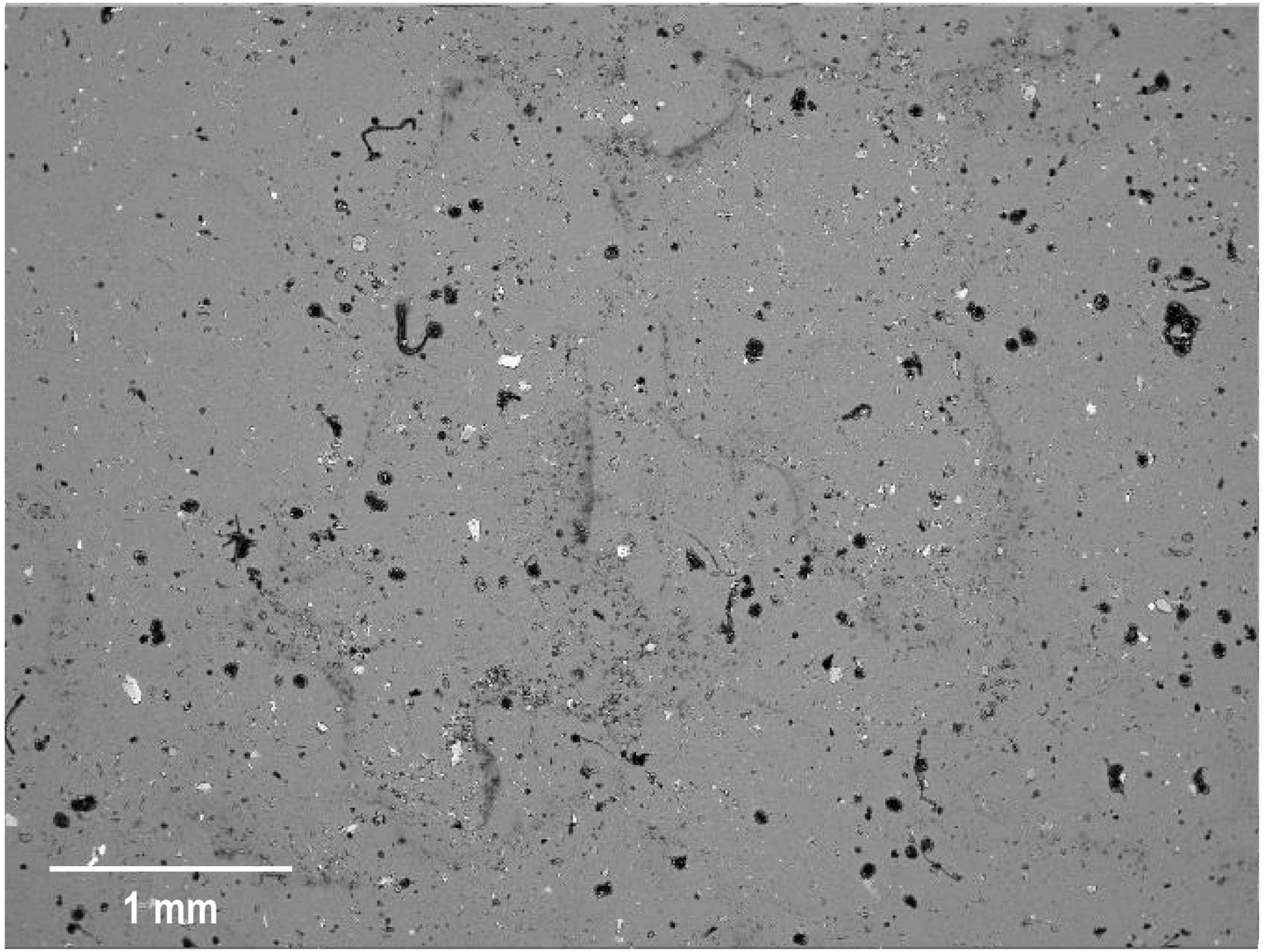
Important to note that these samples are **not representative** of the canister surface environment (exposure to wetting, ambient T and RH, horizontal orientation leads to heavy dust loads). But they do provide some information on salt compositions, and potentially, on salt corrosiveness.

Maine Yankee Sampling

SEM/EDS Analysis

Dust analyzed as deposited, on silica wafer dust collectors:

- Organic materials
  - Pollen
  - Stellate trichomes, plant fibers
  - Cobwebs, insect parts
- Mineral Phases
  - Dominantly silicate minerals—mica, quartz, feldspars (Si-Al-silicates)
  - Salt phases

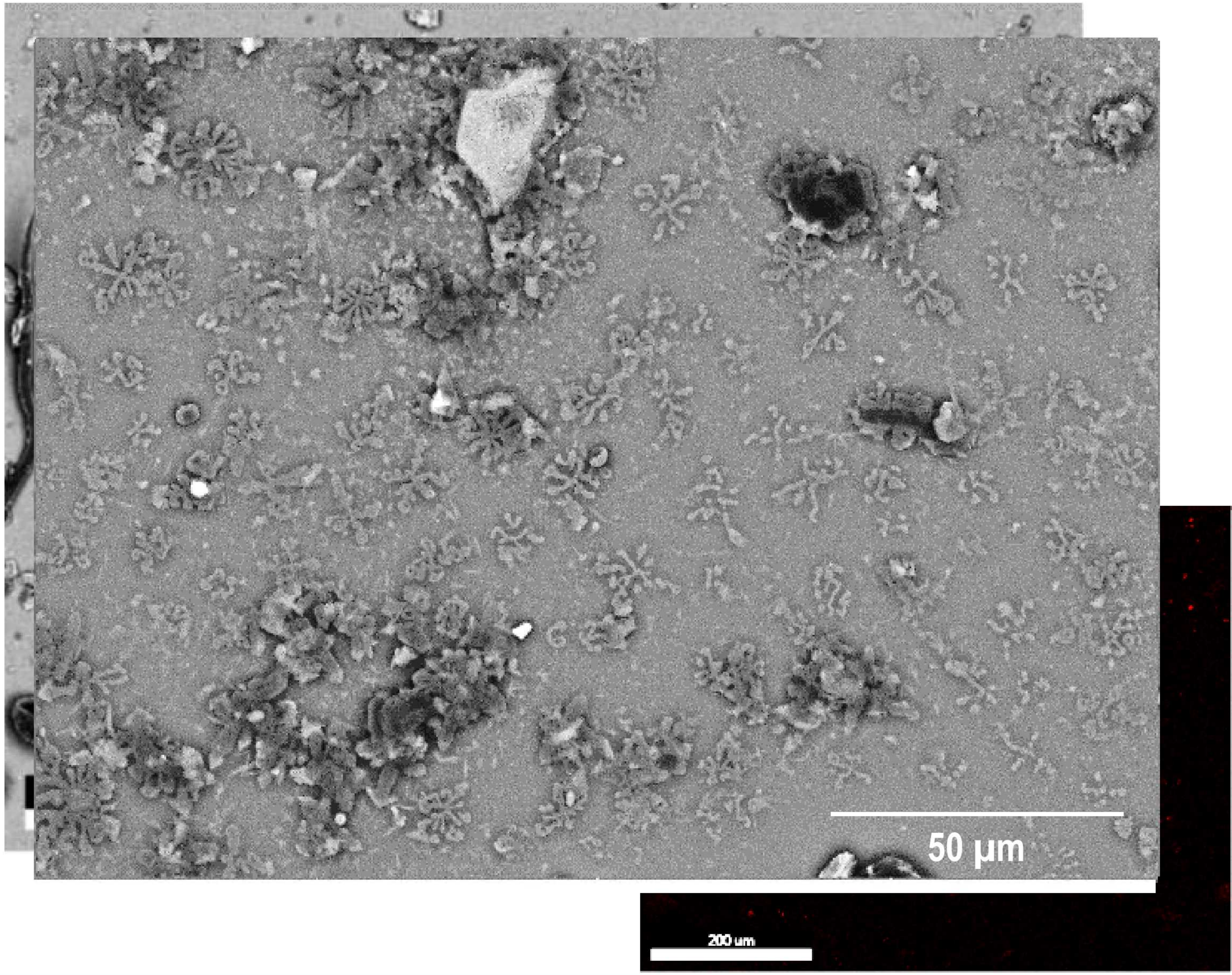


Maine Yankee Sampling

SEM/EDS Analysis

<u>Salt phases: Composition and distribution</u>

- Individual salt aerosols—generally tiny particles of NaCl, associated with mineral, pollen grains
- Sea-salts? Dried sea-fog droplets?
- Salts associated with pollen and plant matter
- Redistributed salts due to wafer wetting



Maine Yankee Sampling

SEM/EDS Analysis

Chemical Analyses: Soluble Salts

Salts consist of a mixture of marine (Na, Cl, Mg, SO_4) and continental (Ca, K, NO_3, SO_4) salts

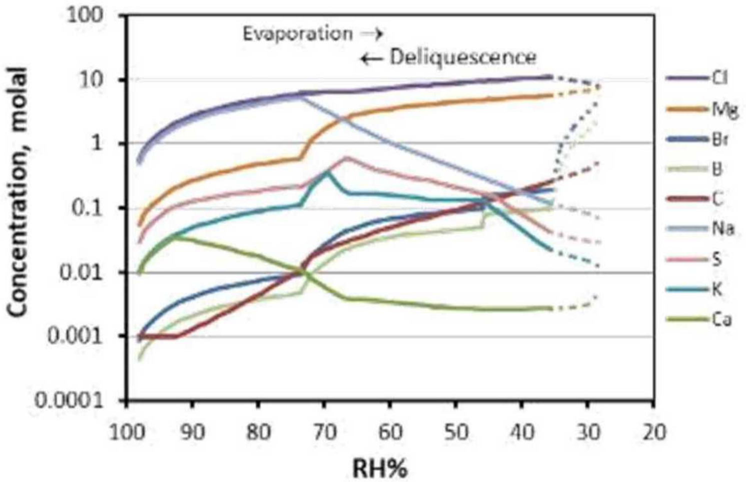
Salts are somewhat more chloride-rich than salts previously recovered from the Maine Yankee canister surfaces

μmoles/sample

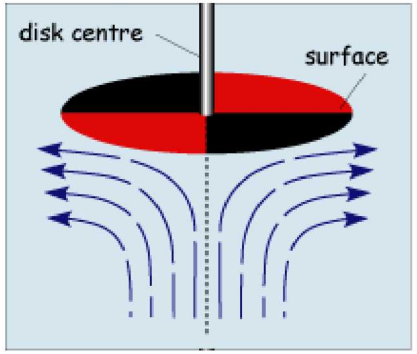
Sample #	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	F^-	Cl^-	NO_2^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
VCC-18 inlet	1.853	0.021	0.500	0.190	0.478	–	0.675	0.027	0.273	0.020	0.120
VCC-18 outlet	0.350	0.026	0.080	0.041	0.120	–	0.969	0.033	0.879	0.007	0.221
VCC-37 inlet	2.368	0.016	0.398	0.232	0.494	0.019	0.989	–	0.364	0.033	0.208
VCC-37 outlet	0.152	0.019	0.029	0.012	0.039	–	0.178	0.017	0.168	–	0.065
VCC-42 inlet	0.963	0.016	0.479	0.089	0.263	–	0.373	0.017	0.128	–	0.085
VCC-42 outlet	2.339	0.018	1.109	0.183	0.981	–	0.872	0.033	1.528	–	0.292
VCC-56 inlet	0.669	0.012	0.500	0.063	0.285	–	0.272	0.017	0.111	–	0.077
VCC-56 outlet	0.373	0.018	0.358	0.045	0.334	–	0.139	–	0.053	–	0.027

Prediction of Maximum Pit Size from Brine Characteristics and Electrochemical Kinetics

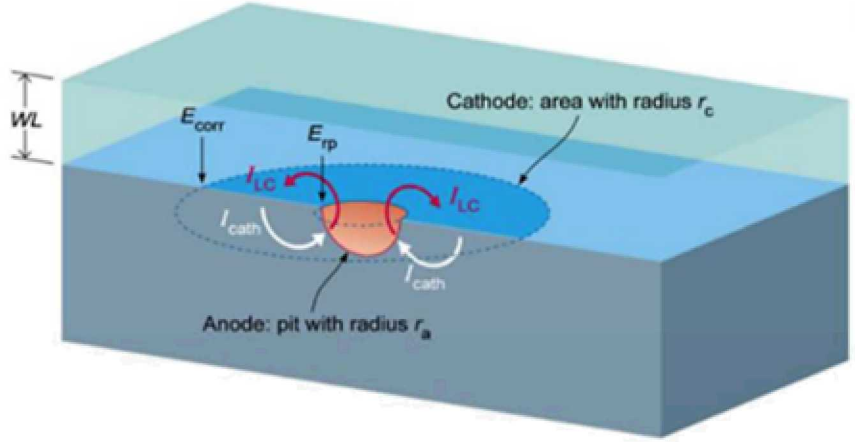
Challenge: Information on ***electrochemical parameters lacking*** for expected canister brine conditions (W_L and chemistry)

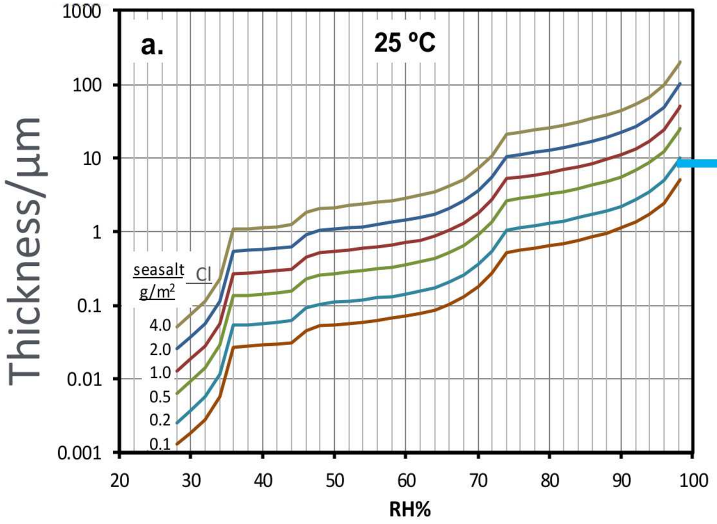


Rotating disc electrode



Simulate $W_L > 1$ µm





Cathodic polarization curves

Anodic polarization curves

$$\ln I_{c,max} = \frac{4\pi k W_L \Delta E_{max}}{I_{c,max}} + ln\left[\frac{\pi e r_a^2 \int_{E_{corr}}^{E_{rp}} \left(I_c - I_p\right) dE}{\Delta E_{max}}\right]$$

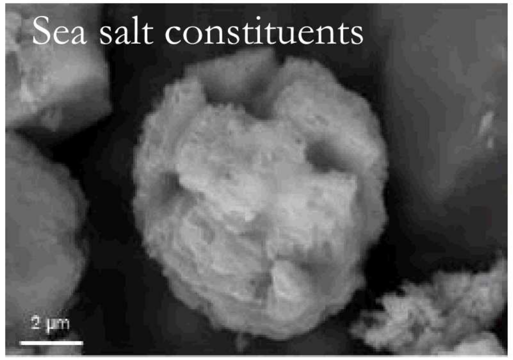
$$d = \frac{A}{nF\rho}\int_0^t i\,dt$$

Role of Surface Environment on Pitting Damage and Pit-to-Crack Transition

Samples

SS304H

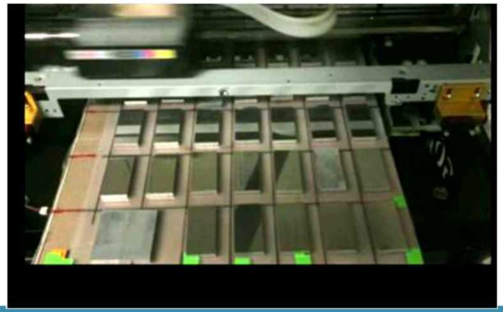
Mirror, R_a = 0.05 µm
Ground, R_a = 2.83 µm

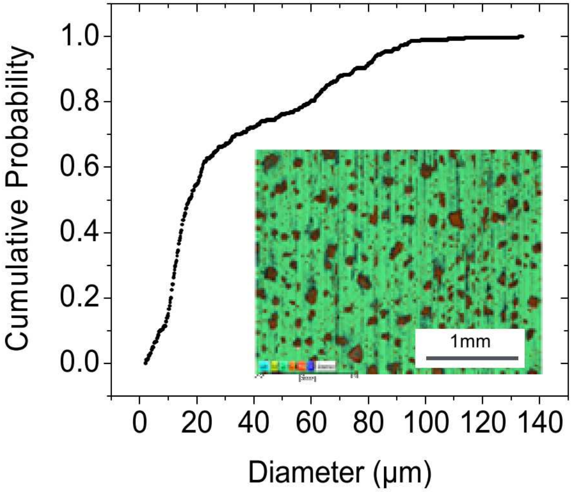


Salt	g/L	DRH
NaCl	24.53	75%
$MgCl_2$	5.2	32%

Salt Load

Inkjet Deposition





Exposure Conditions

%RH	Temperature (°C)			
76	35			
70	35			
65	35			
60	35			
55	35	40		
50	35	40		
45	35	40	45	
40	35	40	45	
35	35	40	45	50
30	35	40	45	50

Time

1 week to 2 years

Sandia National Laboratories

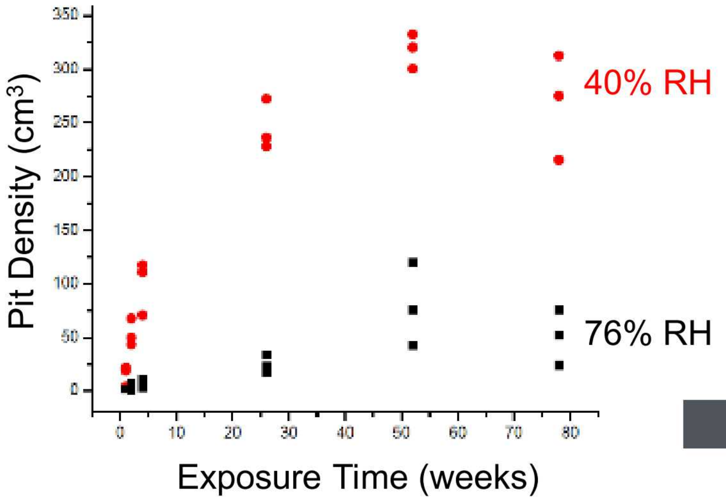
WASTEPD Performance and Design

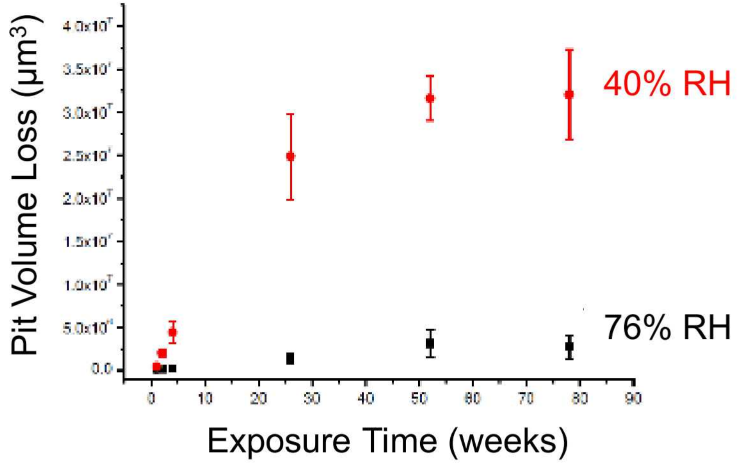
Effect of Humidity on Pitting and Cracking

ENVIRONMENT, F(t)
RH, T, seasalt, 10 µg/cm^2 and 300 µg/cm^2

MATERIAL
304H (unsensitized)

MATERIAL CONDITION
ground



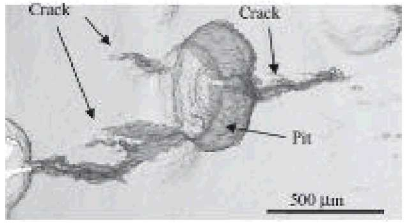


K = f(pit depth, σ), assuming hemispherical pits

Turnbull, 2010

$K > K_{ISCC}$?

Crack initiation?



Horner, 2011

Current Status:

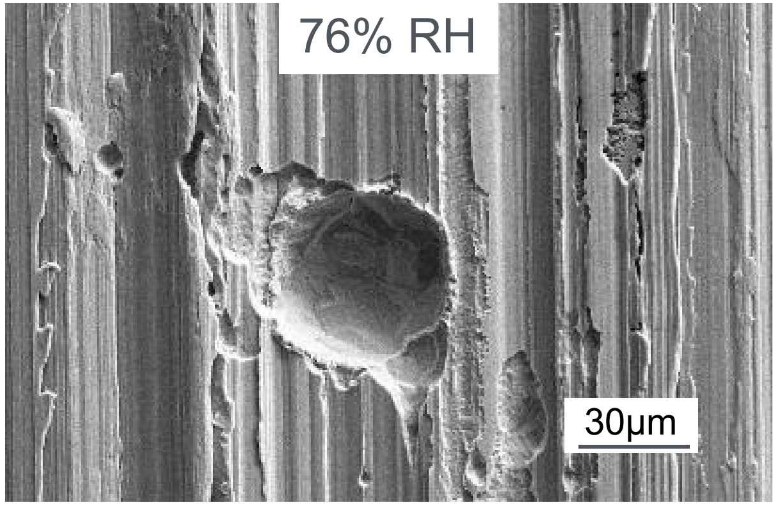
- ***Similar depth distribution, but diameters and shape RH dependent***
- **Maximum pit size model validated by atmospheric exposure with critical assumptions**
- **JECS 2019 paper**

Important results

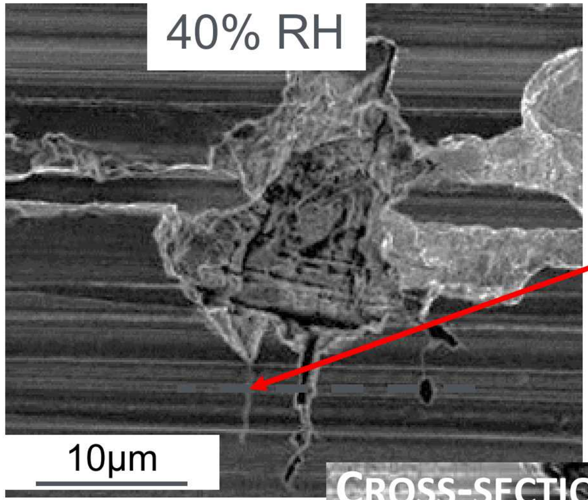
- ***Maximum pit size model bounds results at 76% RH, but when/where is it valid?***

Humidity Controls Pit Morphology and Cracking

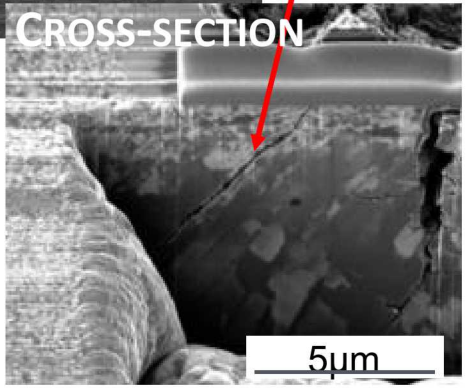
HIGH RH: NaCl RICH BRINE

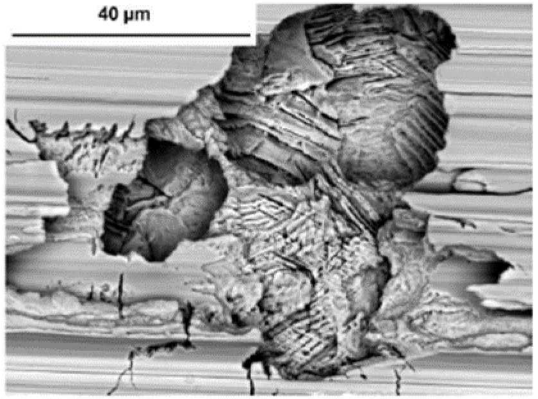


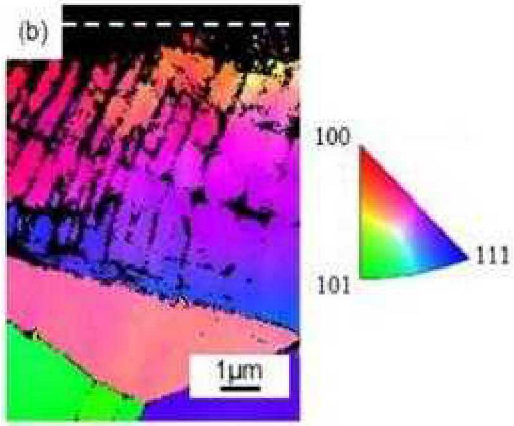
LOW RH: $MgCl_2$ RICH BRINE



Crack





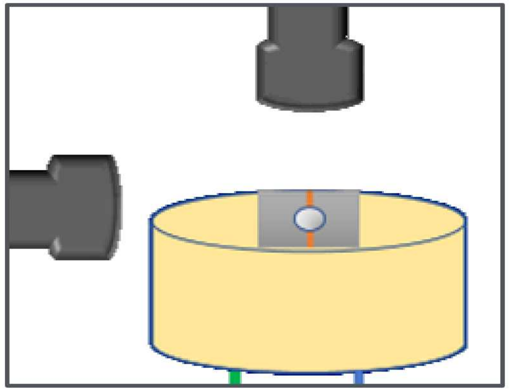


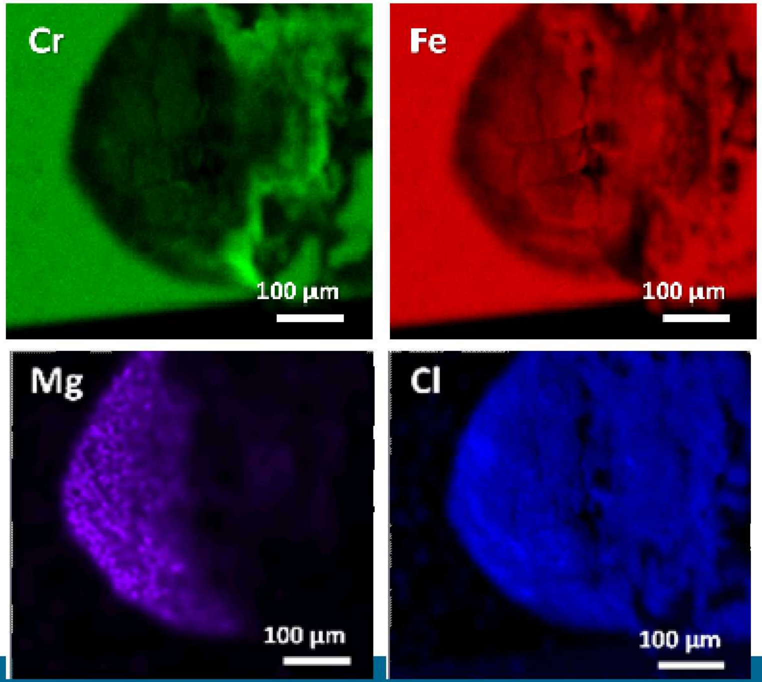
CURRENT MODEL ASSUMPTION: *HEMISPHERICAL PITS*

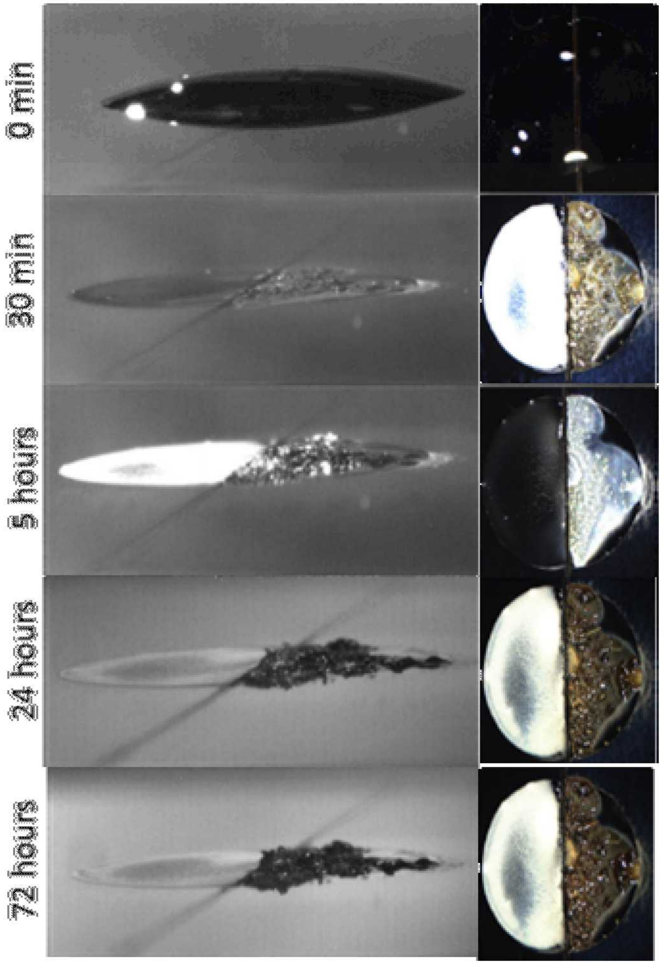
- DEFORMATION FROM GRINDING MAY BE RESPONSIBLE FOR *MORPHOLOGY AT LOW RH* AND *SUSCEPTIBILITY TO CRACKING*

Brine Interaction with Corrosive Environment
f (T, RH, Salt Load, Chemistry) ?

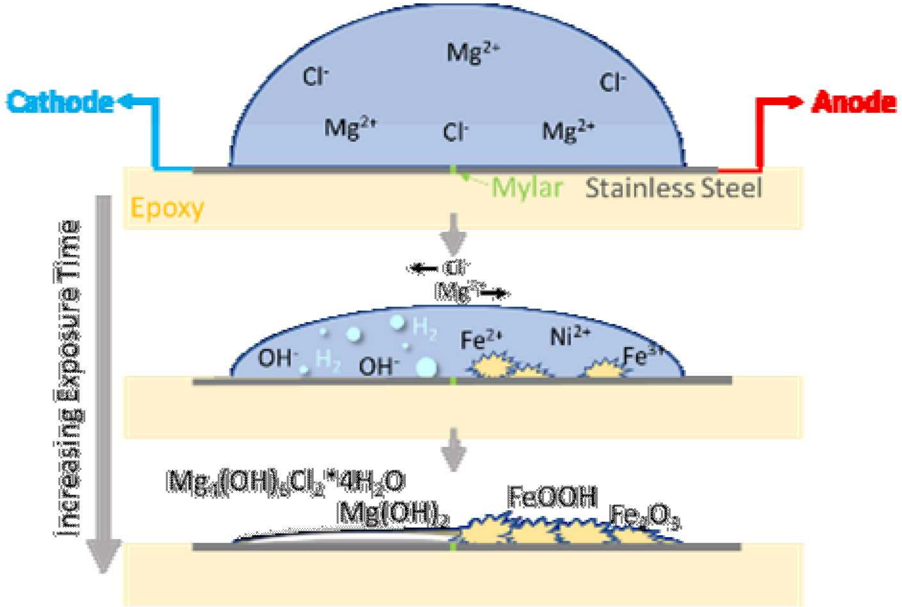
Dual Electrode Exposure







← EDS maps Post-corrosion



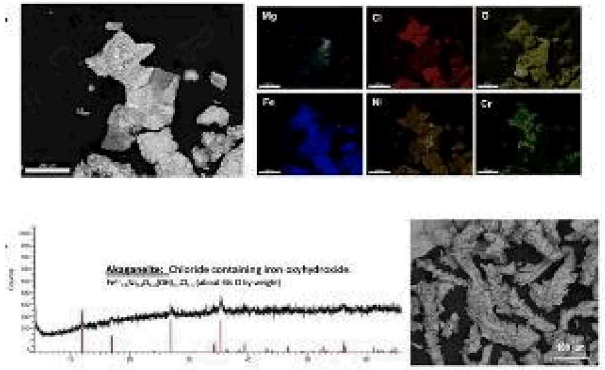
Current Status:

- Brine evolution during corrosion
- Correlate extent of corrosion with brine conditions?

Characterization of SCC in Canister-Relevant Weld Regions

“Big Plate” Sandia Mockup Exposure Samples

- 8 g/m^2 $MgCl_2$
  - Exposure: 80ºC, 35 % RH, 12 months
  - 3 % Potassium Tetrathionate, pH =1, 6 mo. (3 mo. 40ºC)
- Analysis
  - Composition of brine and corrosion products
  - NDE inspections for SCC
    - Fluorescent Dye Penetrant
    - UT Phased Array & Eddy Current Array
- Goals
  - Determine orientation and location of SCC around canister welds
  - Evaluate brine evolution under corrosion



SEM/EDS and XRD of Corrosion products

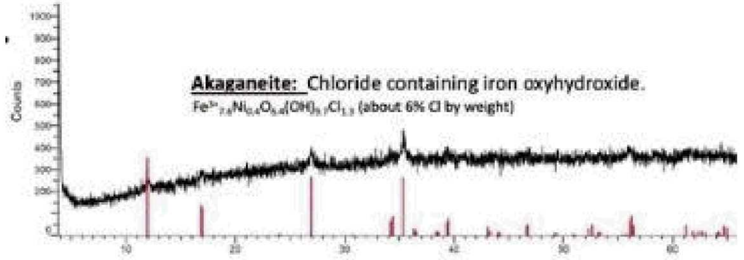

Fluorescent Dye Penetrant

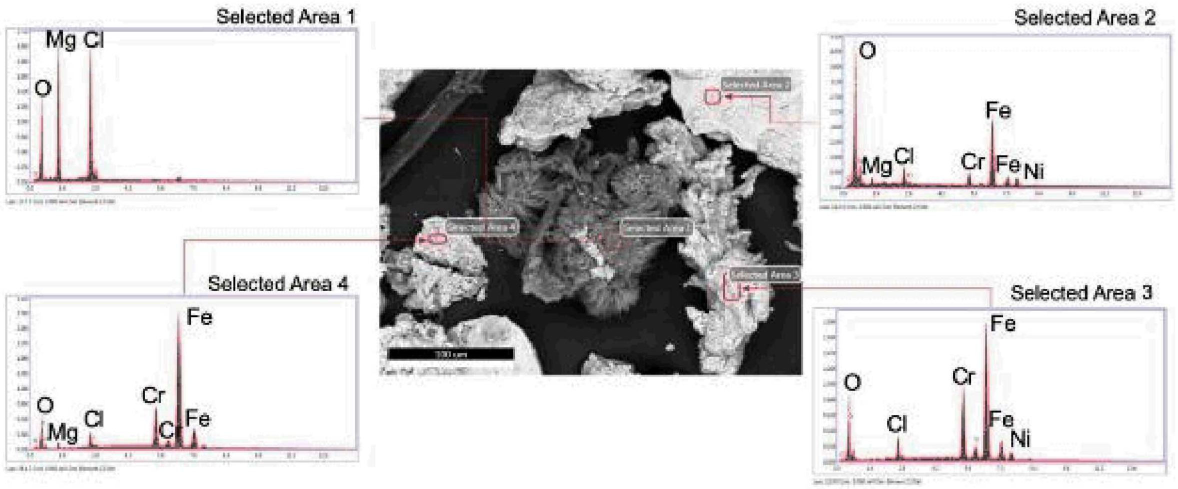

Eddy Current Array


UT Phased Array

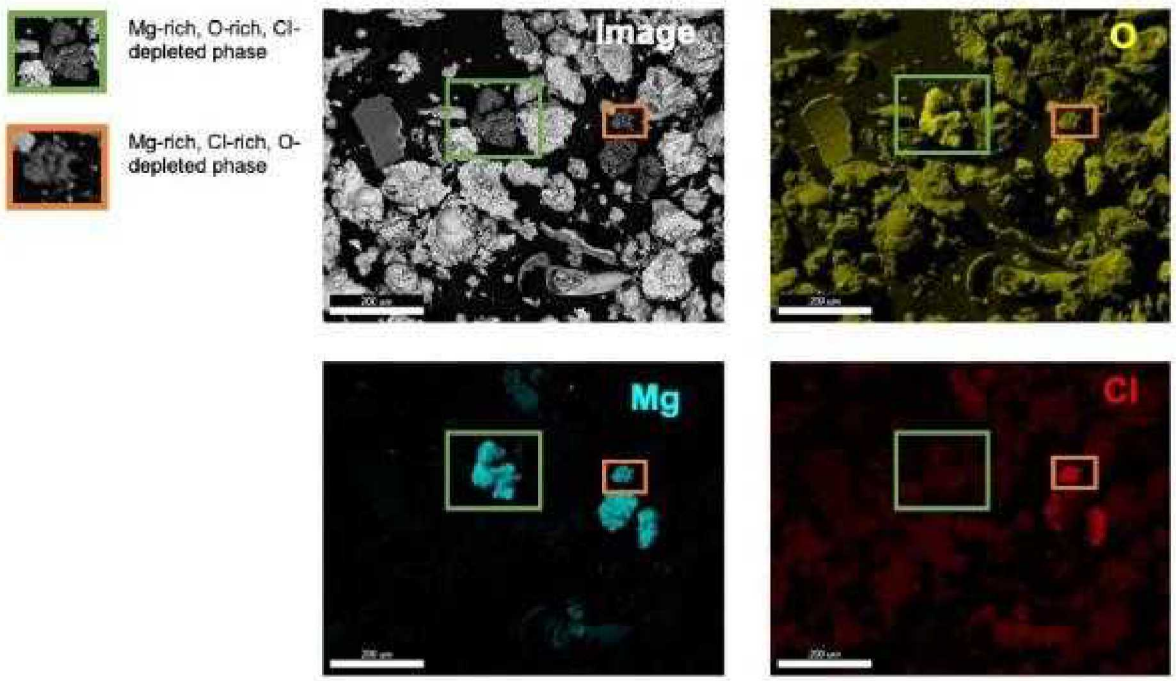
Chemical Composition of Brine and Corrosion Products

- Corrosion Products
  - Iron containing corrosion products were largely amorphous
    - Akageneite was identified by XRD





- Brine Evolution
  - Distinct Mg containing phases were found
    - O-rich/Cl-depleted: Likely mg-hydroxychloride (2-1-4 phase)
    - Cl-rich: Likely bischofite



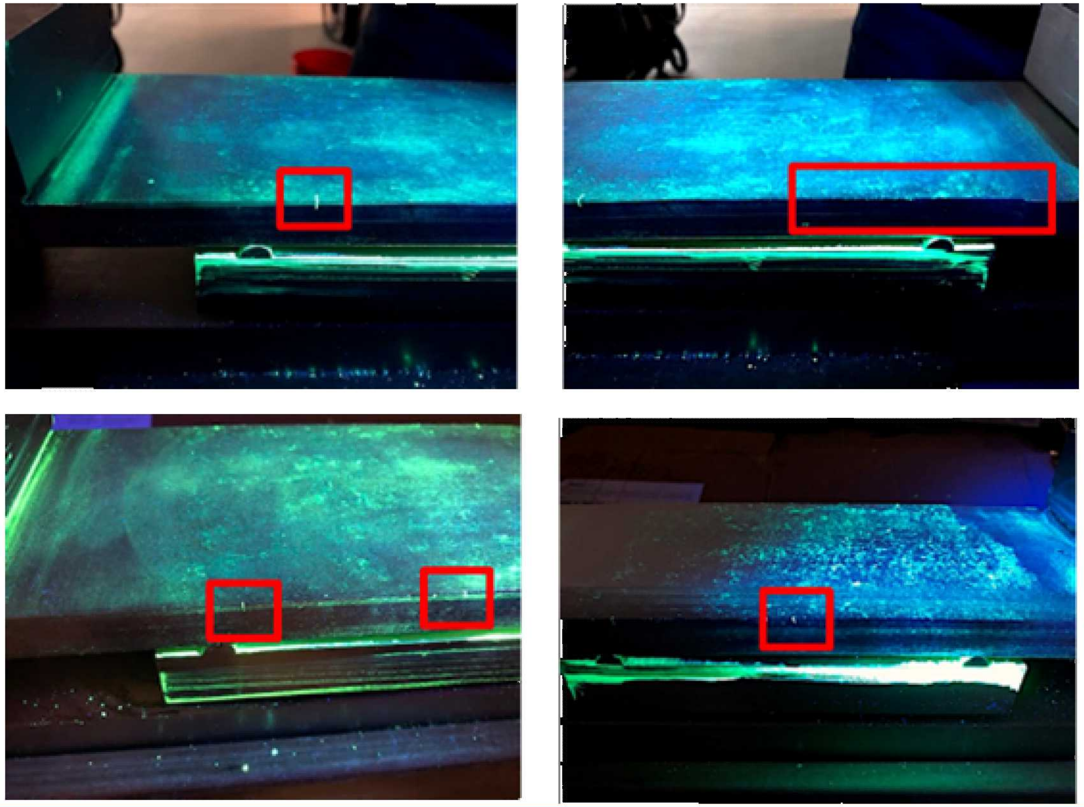
Dye Penetrant Analysis

- Presence of cracks on the edge of the 4-point bend specimen
- No crack indications found in mock up welded plates

→ Mockup plate samples were subsequently analyzed by *Eddy current & Phased Array*

Part Inspected	Exposure	Crack Indications	Notes
Circumferential Weld	80 C, 35% RH	No	
Longitudinal Weld	80 C, 35% RH	No	High background due to corroded surface
Circumferential Weld	Potassium Tetrathionate	No	
4 Point Bend Specimen	80 C, 35% RH	Yes	

4-point bend specimen



Eddy Current and Phased Array

– Flaws were identified
  - Most likely caused from manufacturing

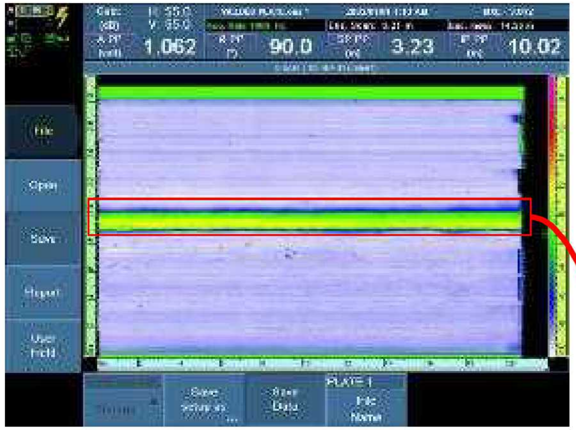
– No crack indications detected in any mockup plate sample

Current Status:

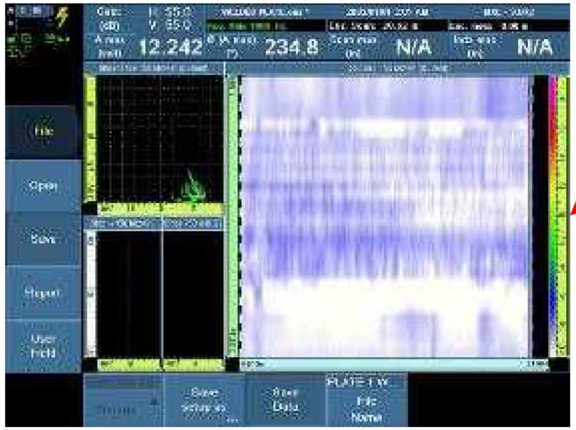
- Further analysis through SEM/EBSD to inspect corrosion damage/ identify if microcracks formed

Circumferential weld, 80 C, 35 % RH

Eddy Current



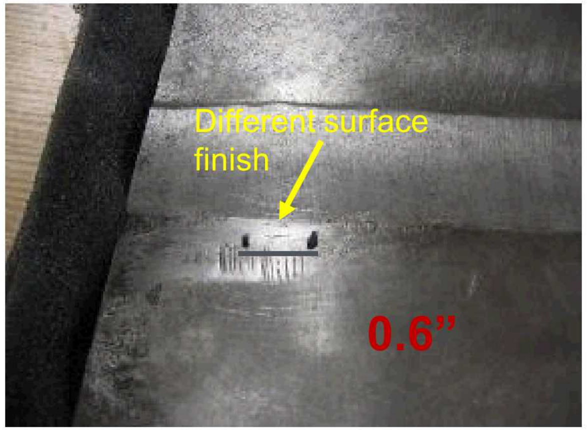
Top: No flaw indications.



Top scan of weld: No flaw indications.

Phased Array

Indication seen



Indication marked on surface of plate to

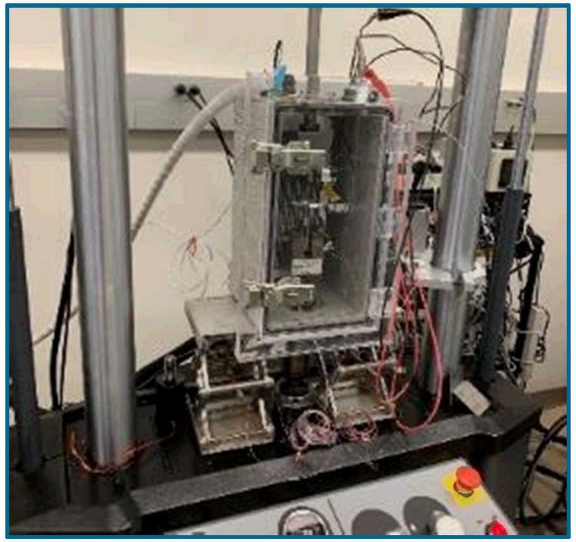
Initial SCC Crack Growth Testing for Canister-Relevant Conditions

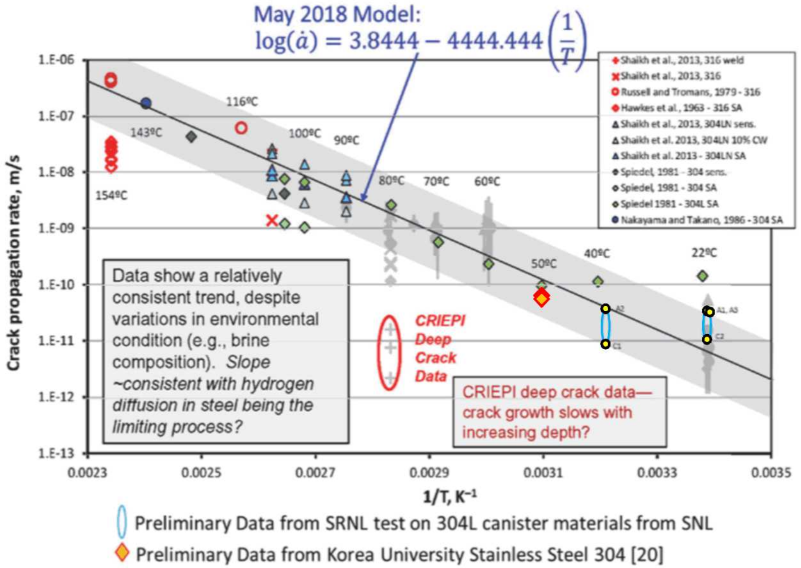
Knowledge Gaps

CGR data for austenitic SS in relevant atmospheric environments is lacking

Goals

1) Quantify SCC behavior of SS via CGR vs. K in atmospheric conditions
2) Validation and development of SCC models





<u>Current Status:</u>

<u>Pit to crack-</u>

- With OSU, developed a method for periodic loading
- FY19, generated data for sample under atmospheric salt load
- Characterization of features controlling pit-to-crack transition underway.

<u>SCC-</u>

- 4 new load frames procured
- Load frame and sample development for atmospheric SCC testing underway: SENT vs. CT sample, pre-cracked and ground