SAND2014-4910C

Used Fuel Disposition Campaign

Uncertainty Quantification of a Stress Corrosion Cracking Model for SNF Interim Storage Canisters

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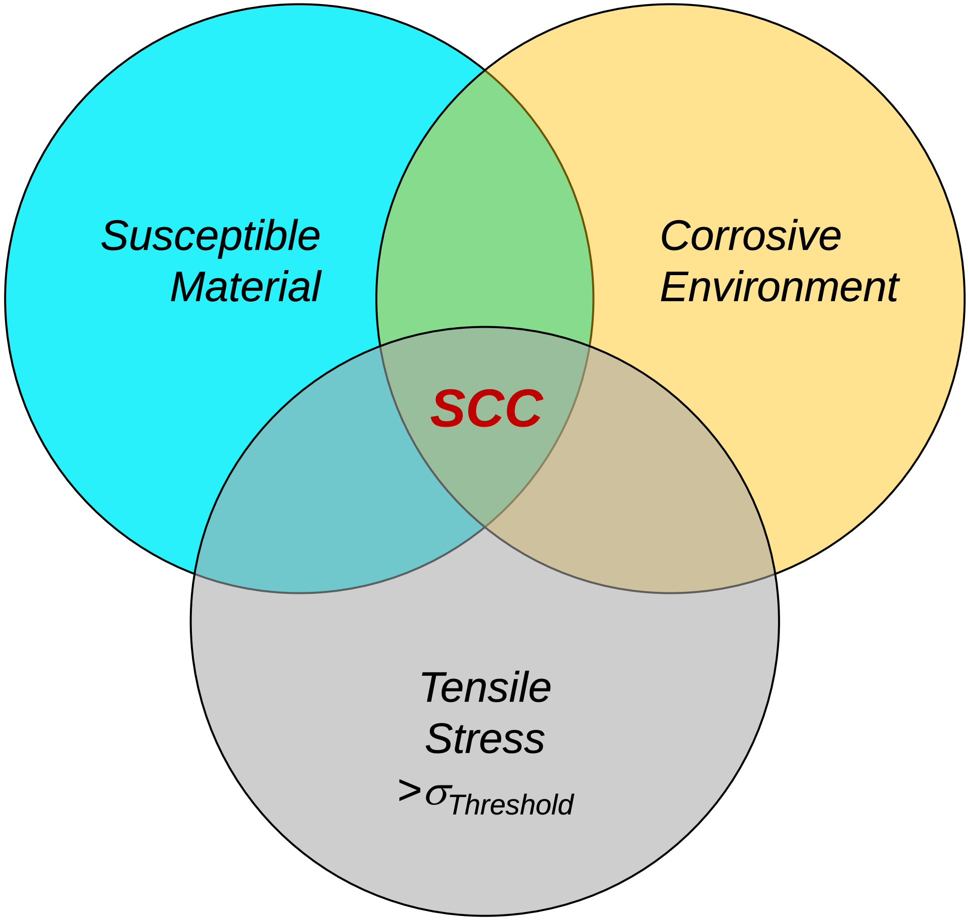
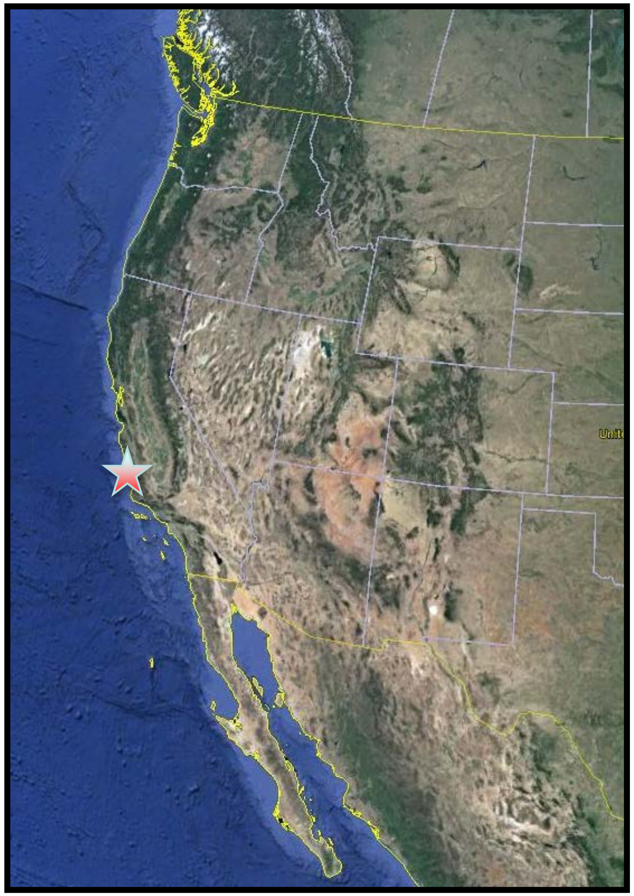
Overview

- Criteria for occurrence of stress corrosion cracking
- Models and parameters for each criterion
- SCC model development; crack initiation and growth

Criteria for Stress Corrosion Cracking



Corrosive Environment: Near-Marine Settings



For example, Diablo Canyon Site: ISFSI is ~1/3 mile from the shoreline, on a hill above the plant.

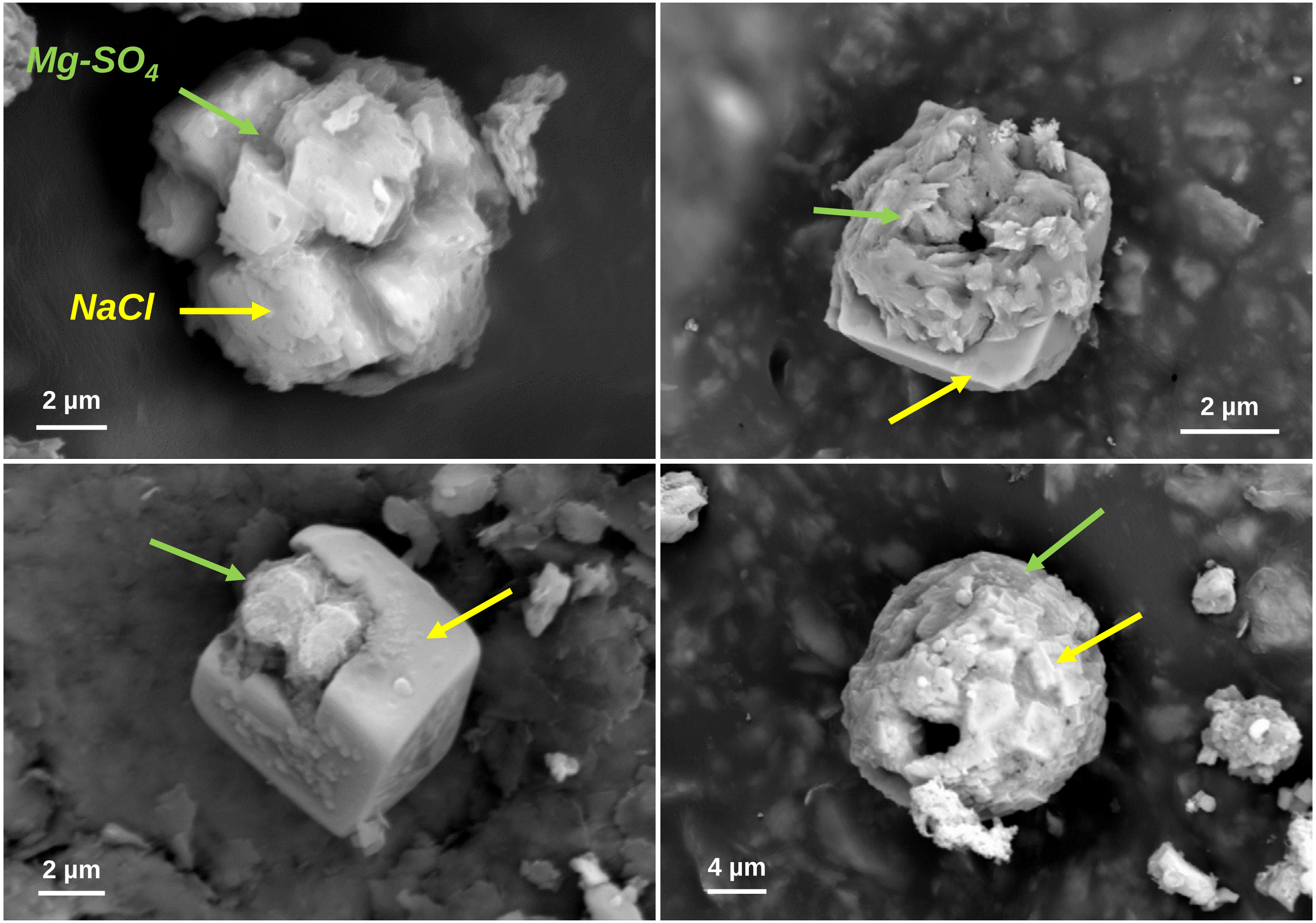
SEM/EDS Analysis

Diablo Canyon Sample # 170-003: Top center

Clusters of sea salts. Dominant minerals are NaCl (cubic crystals), and Mg-sulfate (sheaf-like crystals and masses between cubes)

Common morphologies:

- ***Spherical aggregates (hollow)***
- ***Skeletal and hopper crystals***



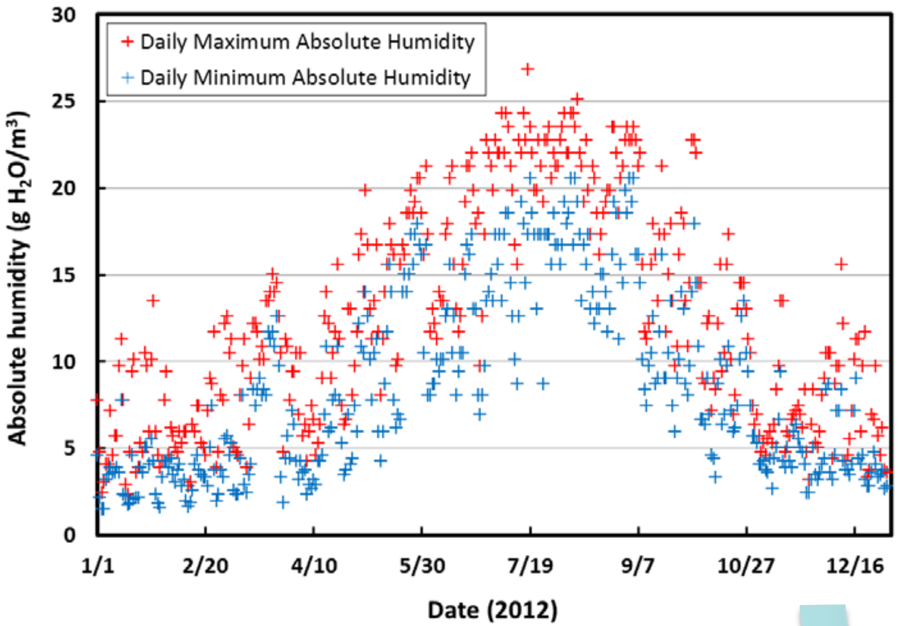
Modeling the Environment

Corrosive environment

- **Aqueous conditions**
  - To model, need the following data:
    - Outside environment: Absolute humidity, or dewpoint, or (temperature + RH).
    - Temperature on the waste package surface at any given location
    - Composition of deliquescent salts
- **Corrosive (chloride-rich) brine (CISCC).**
  - Need models for:

- Composition of deposited aerosols
- Effect of particle-gas conversion reactions
- Amount of chloride on surface?
  - *Threshold chloride concentration for initiation of pitting or SCC?*
  - *Threshold chloride concentration to support through-going SCC?*

Modeling the Environment: RH at the Canister Surface

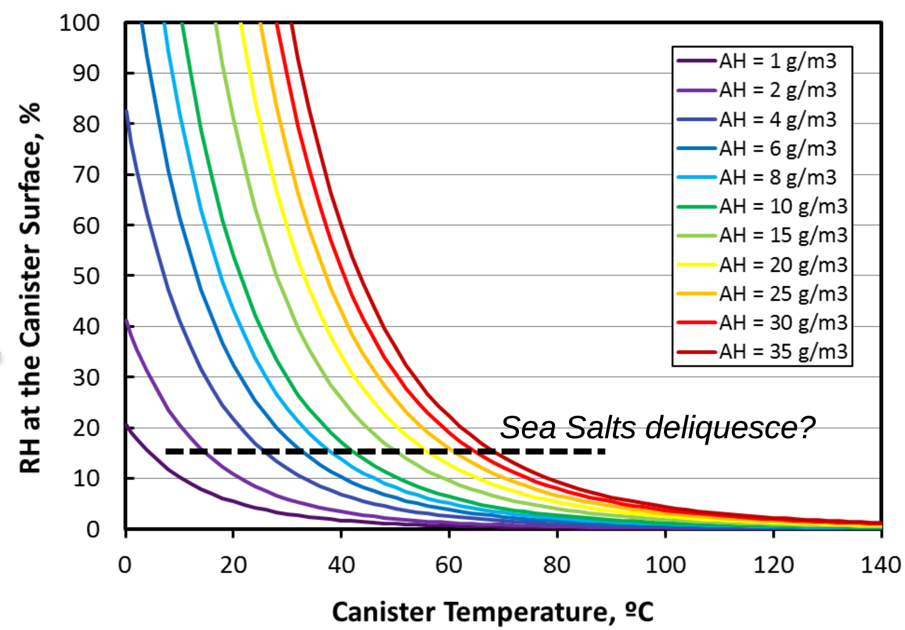


Daily maximum and minimum absolute humidities (atmospheric water contents) from a National Weather Service site near Calvert Cliffs

How to sample? Daily, seasonally? Use daily mean, or conservatively use max AH?

Use weather data and predicted canister surface temperature to predict local RH and the occurrence of deliquescence.

Implement as a lookup table.
Vary deliquescence RH?



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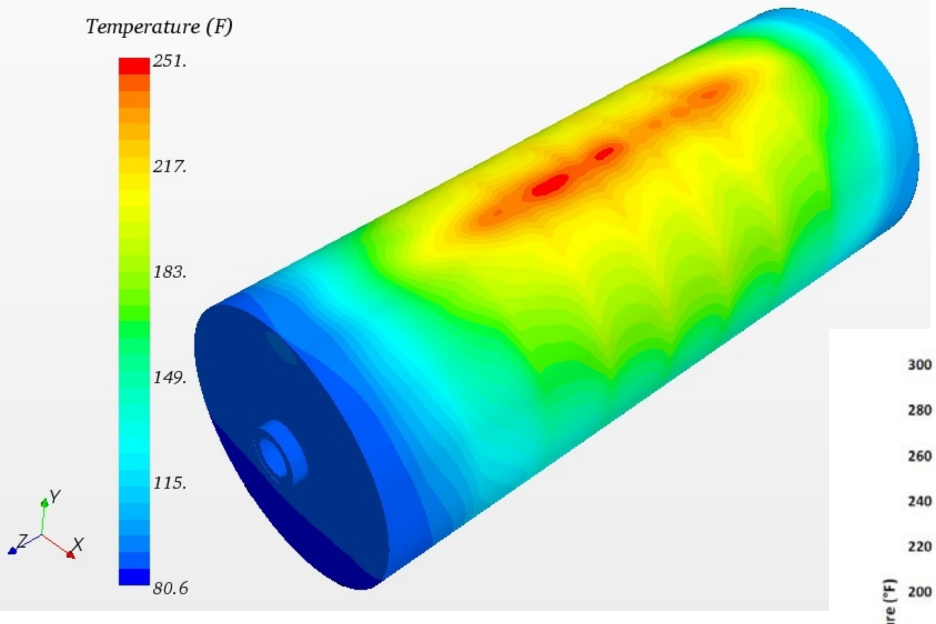
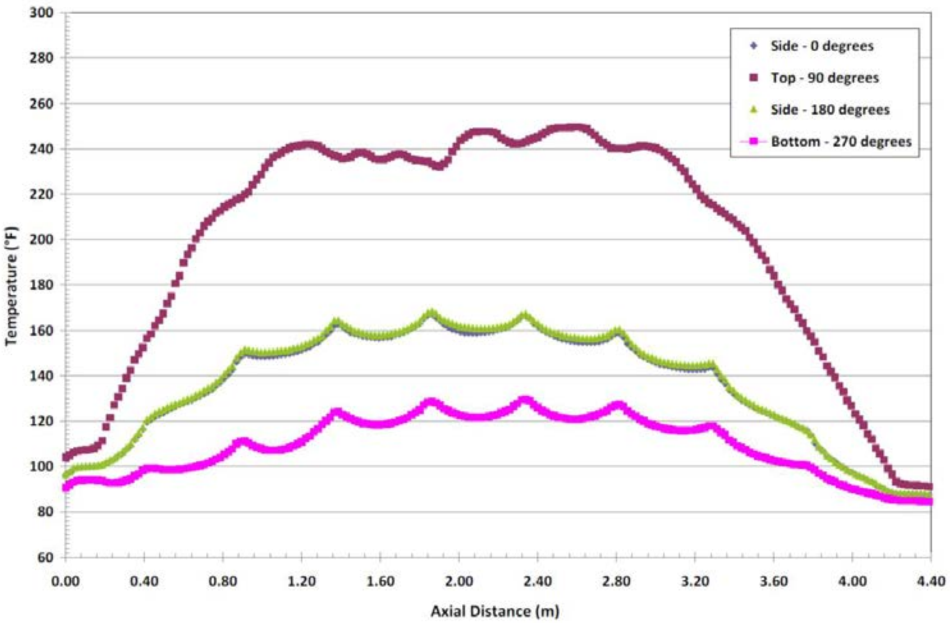
Modeling the Environment: Waste Package temperature



Changes in location-specific surface temperature is important to determine:

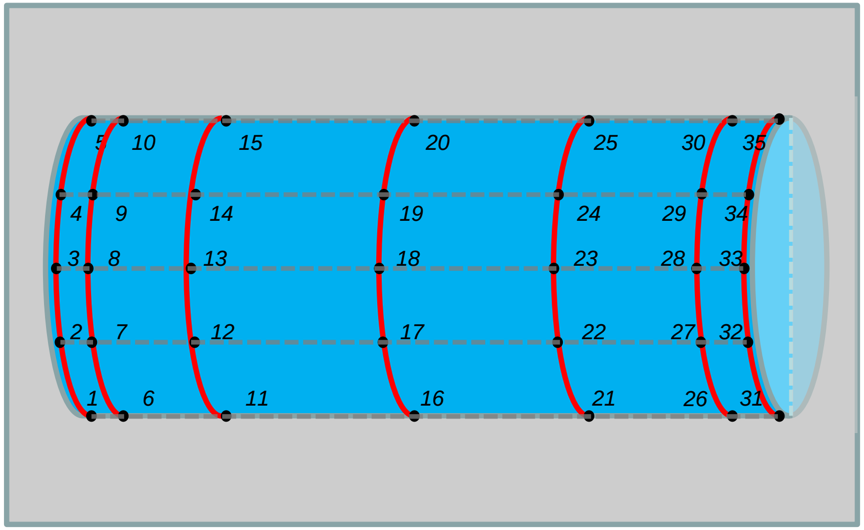
- *Timing of deliquescence and potential corrosion initiation*
- *Temperature-dependent corrosion parameters (e.g. crack growth rate)*



PNNL modeling of NUHOMS package

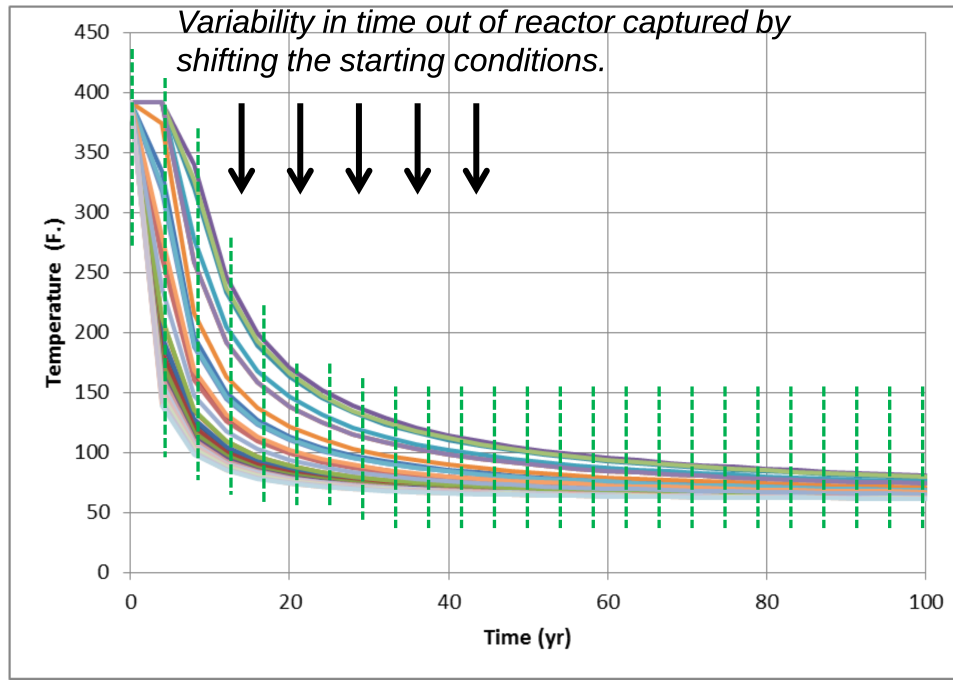
- *Surface temperature map*
- *Surface profiles*

Modeling the Environment: Waste Package temperature



PNNL will provide

- *Five longitudinal profiles at 0º, 45º, 90º, 135º, and 180º*
- *25 points in time, from 0-100 yrs out of the reactor.*



For the model, interpolate in time and space, to get the temperature at any point on the canister surface, at any point in time.

Variability in time out of reactor captured by shifting the starting conditions.

Assume surface T varies linearly with ambient T

Cannot capture variability in burnup.

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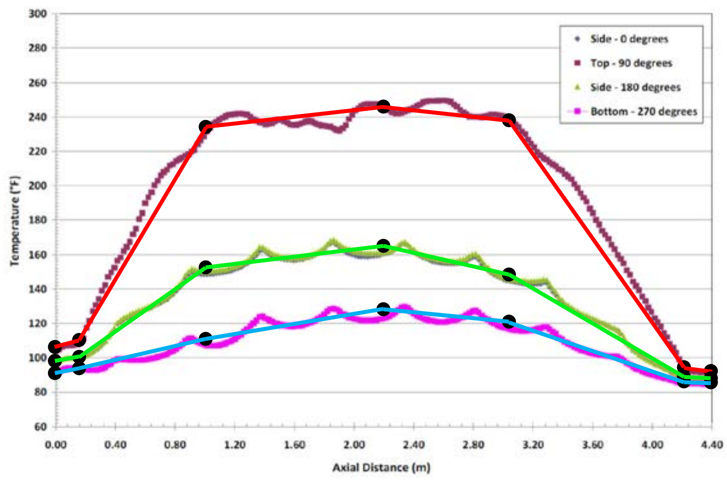
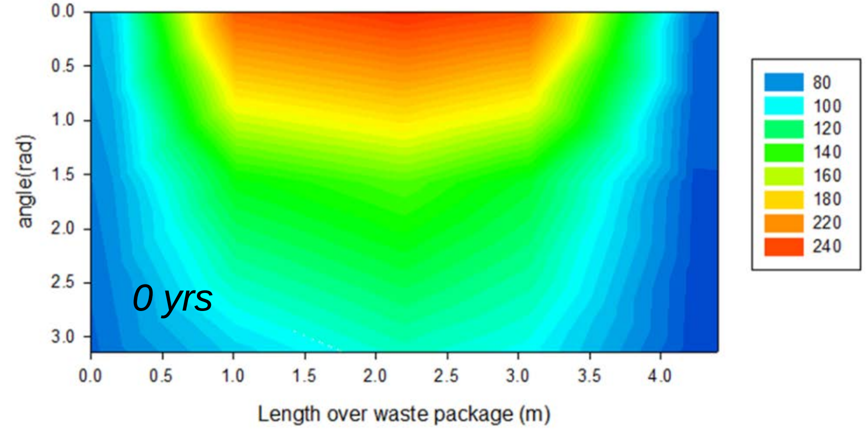
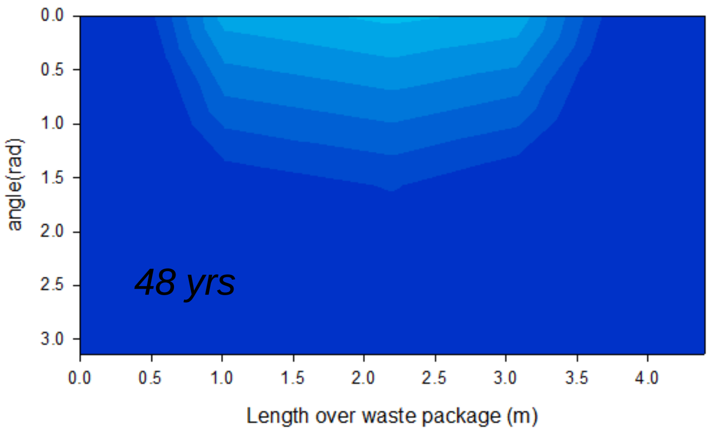
Modeling the Environment: Waste Package Temperature

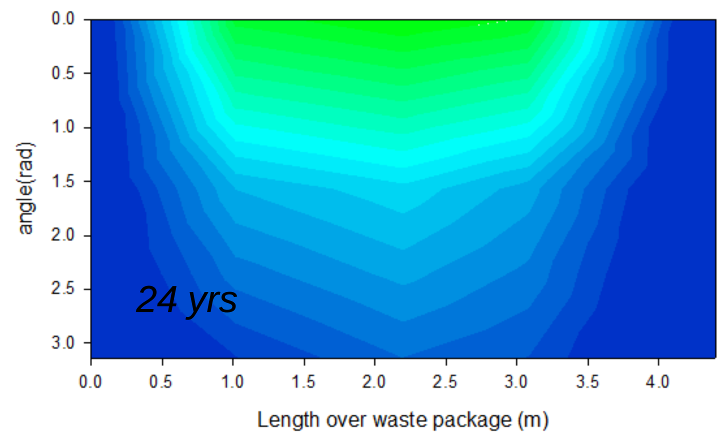
Results of interpolation



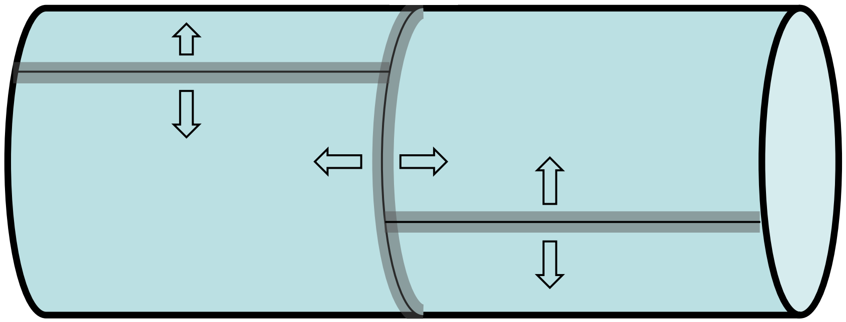
Flattened canister map







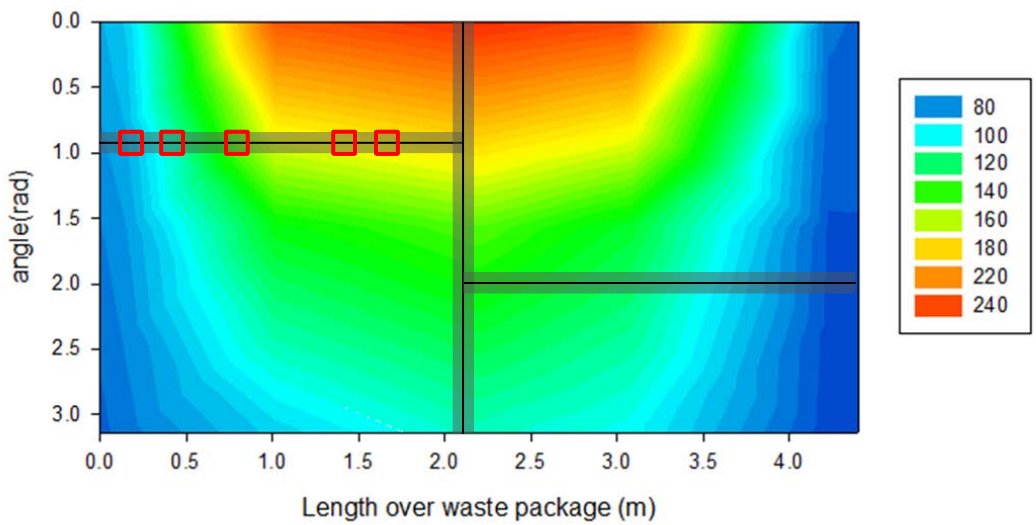
Modeling the Environment: Weld Location



Welds:
- 1 circumferential
- 2 longitudinal
- Location unknown

To implement:

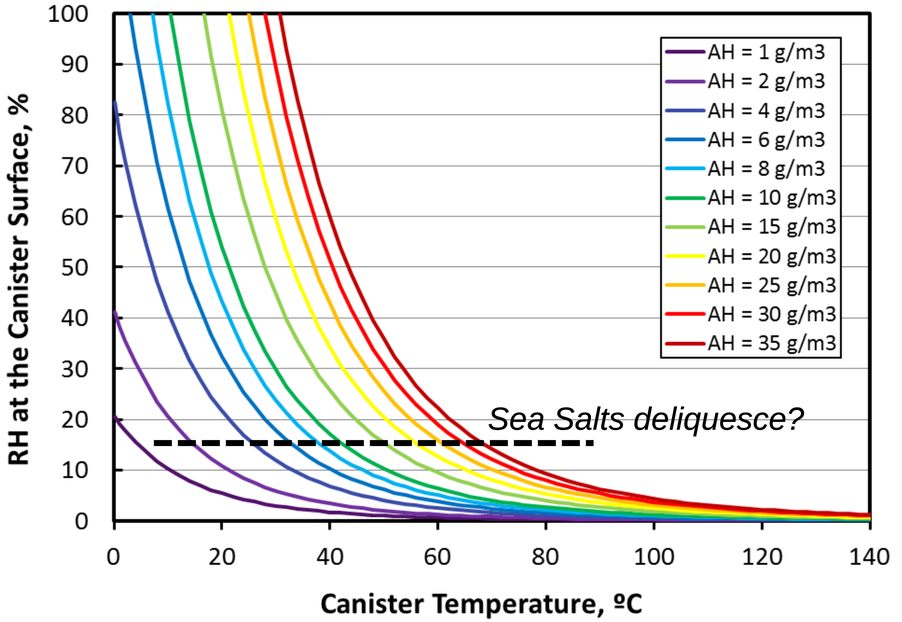
Aleatory sampling of the weld locations on the package surface. Divide welds into segments and calculate a temperature history for each segment.



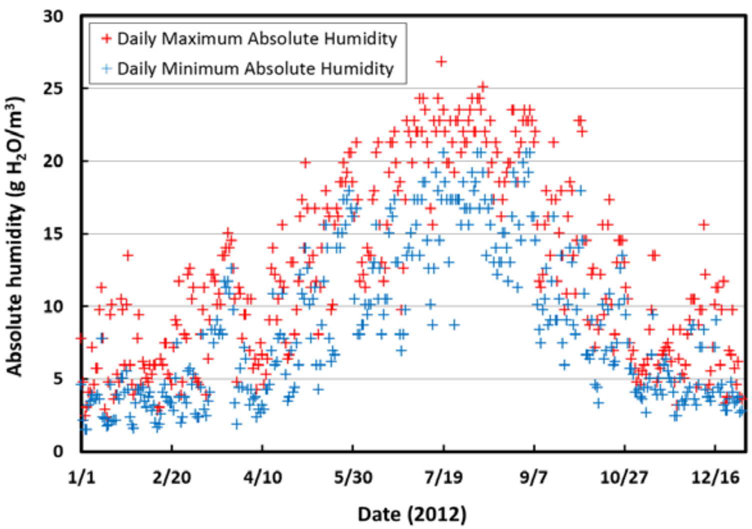
Modeling the Environment: Chemistry

Assumption:

- Will only evaluate for a near-marine environment (assume deposited salts are sea-salts). Do not consider geographical variations in salt composition. We are eliminating uncertainty in deposited salt composition.
- Therefore, deposited salts are potentially corrosive.
- Sea salts will deliquesce ~30% RH, but corrosion observed at a lower RH (RH_L); assume RH_L = 15%. Sample this?



Modeling the Environment: Chemistry

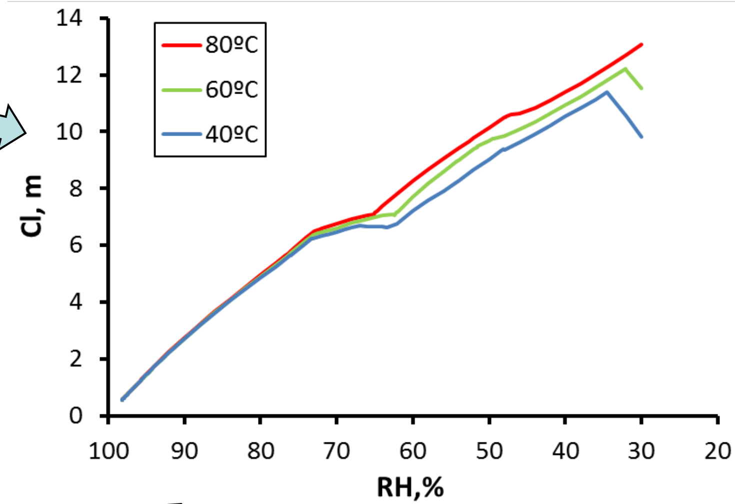


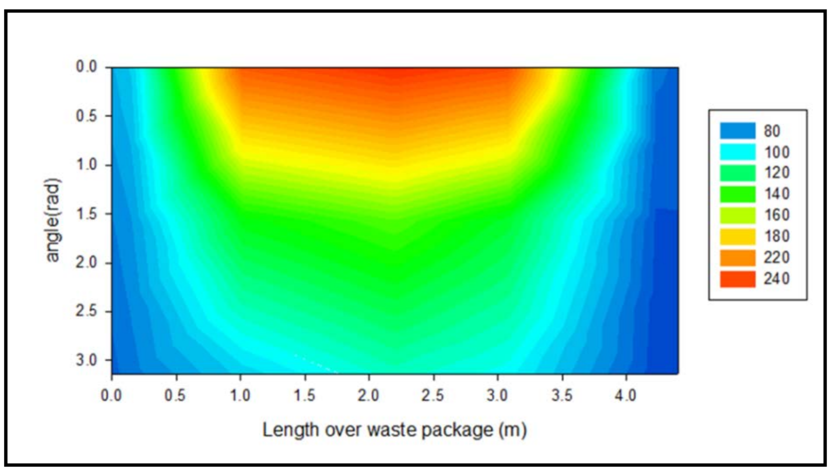
Chloride concentration:

- **Affects rate of initiation and propagation of corrosion**
- **Combine Absolute Humidity and WP Temperature to determine RH, and use that to determine location-specific Cl^- concentration.**

Location -specific RH

Evaporation of sea water





Location-specific [Cl^-]

Sample daily, weekly, seasonally?

Modeling the Environment: Amount of Chloride Present

Chloride deposition model: Necessary to determine when SCC can occur, if there is a threshold chloride concentration for corrosion (e.g., Shirai et al., 2011). This is a point of contention.

In some studies, rate of SCC initiation and/or corrosion rate is a function of the amount of chloride present (e.g., Cook et al., 2011. Implemented in some models (Nakayama and Sakakibara, 2013).

Almost no data available (measurements from three ISFSI sites). EPRI is currently working on a chloride deposition model.

Implementation—evaluate parametrically of those models which require it.

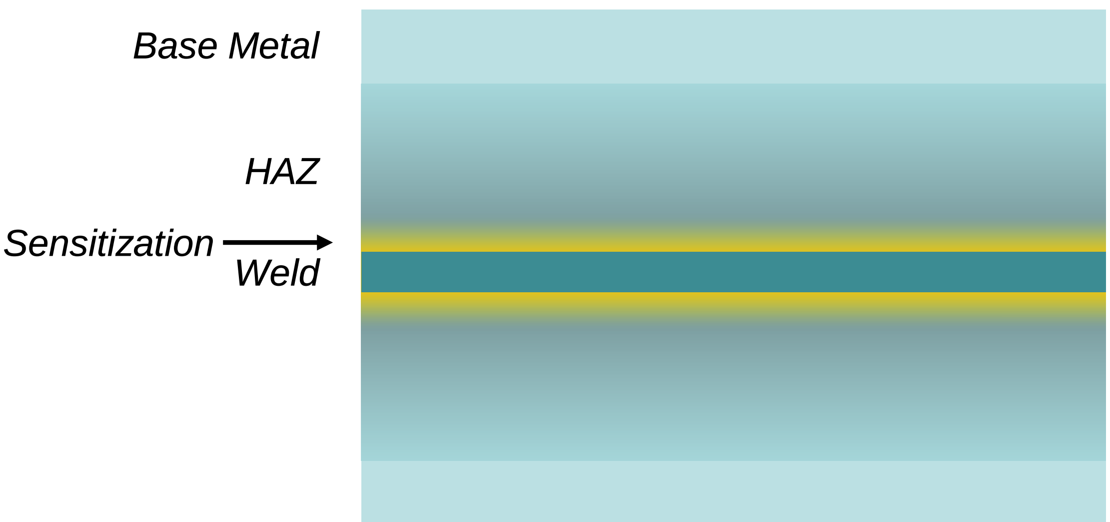
Susceptible Material

- **"304 stainless steel is susceptible to SCC" (given the appropriate stress conditions)**
- **But several factors affect susceptibility**
  - Sensitization—in the HAZ near the weld, segregation of Cr and C as chromium carbides along the grain boundaries results in chrome-depleted zones along grain boundaries, creates a region more susceptible to corrosion near the weld
  - Degree of cold working—more cold working results in more susceptibility (as milled corresponds to ~10% cold working)
  - Surface finish
  - Presence of iron or steel contamination on the stainless steel surface

Susceptible Material—Sensitization

Sensitization is a function of exposure to elevated temperatures, and time of exposure.

- Occurs in HAZ near the weld
- Segregation of Cr-carbides along the grain boundaries results in chrome-depleted zones in grains
- Increases susceptibility to both pitting corrosion and SCC
- Possible change in mechanism from transgranular to intergranular SCC. Different mechanism, possibly different dependence on temperature or environment); sensitization considered a major factor in low temperature SCC. Intergranular SCC generally modeled using percolation theory (fraction of grain boundaries with depleted zones)



Implementation:

Adjust pitting density (pit initiation model), pit and SCC growth rates? Use degree of sensitization to assign a delta to these parameters? Use width of the sensitized zone as variable?

Consider sensitization in assessing literature data for use?

Put in a placeholder and assess degree of sensitization in mockup samples for later implementation.

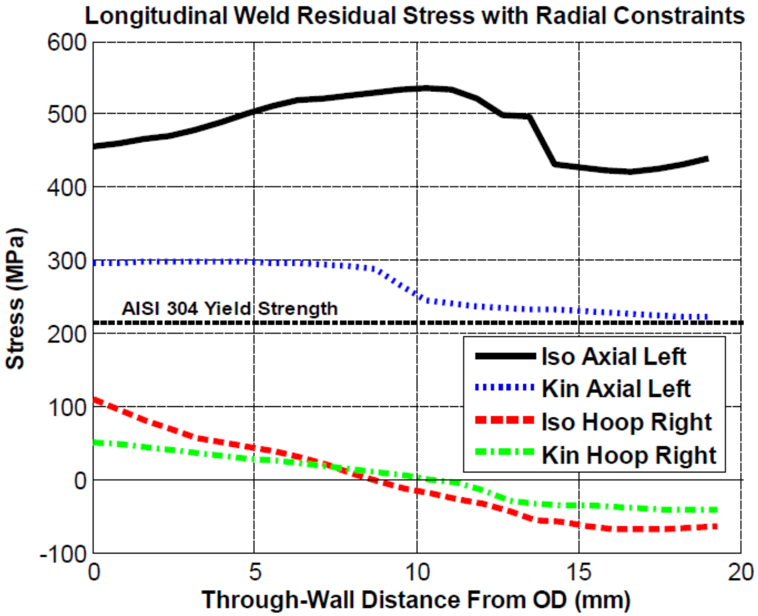
Susceptible Material—Other Factors

- **Iron contamination. Embedded particles of a less corrosion-resistant metal create a galvanic couple, and initiate pitting corrosion and SCC**
  - Corrosion of the embedded metal helps maintain the aggressive chemistry at the anode promoting corrosion
  - Considered one of the dominant causes of low-temperature (<60ºC) SCC.
  - Relevant? During the Calvert Cliffs inspection, corrosion was observed on the canister surface, and attributed to corrosion of embedded steel fragments in the stainless steel
  - Implement as a delta on the pit or SCC initiation rate?
- **Degree of cold-working? Consider when evaluating literature data for parameter values/ranges (as-received is ~10% cold worked, and is NOT the same as solution annealed)**

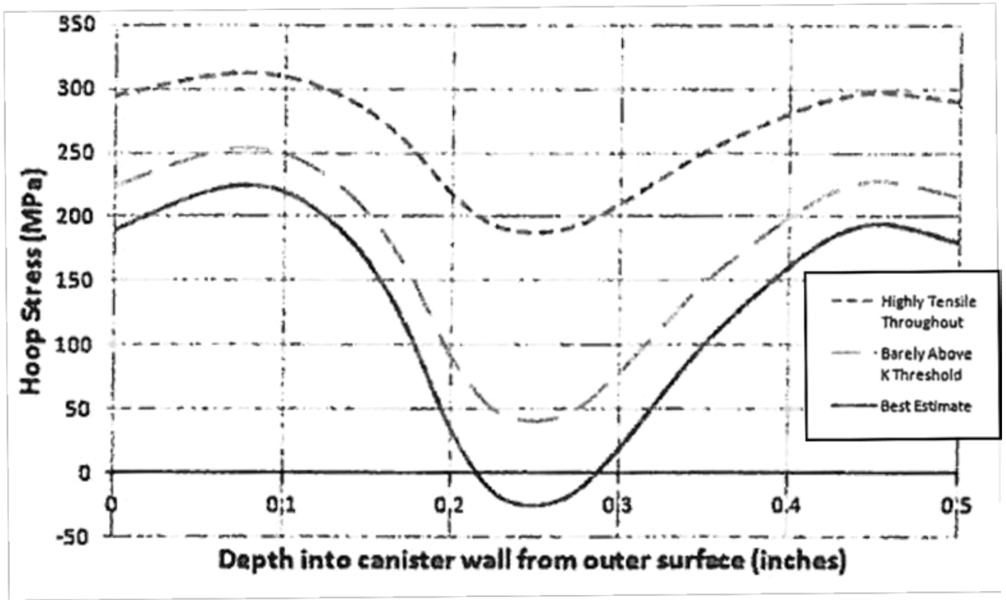
Tensile Stress

- Tensile stresses in weld HAZs approach the yield stress for the metal, more than sufficient to support initiation and propagation of SCC.
- However, 3D stress distribution in canister welds is unknown. Possible profiles are below
- Implementation: parametrically vary stress profile until relevant weld-specific information available (MIT weld characterization, SNL mockup).

Through-wall tensile stress in at least one direction (NRC 2013)



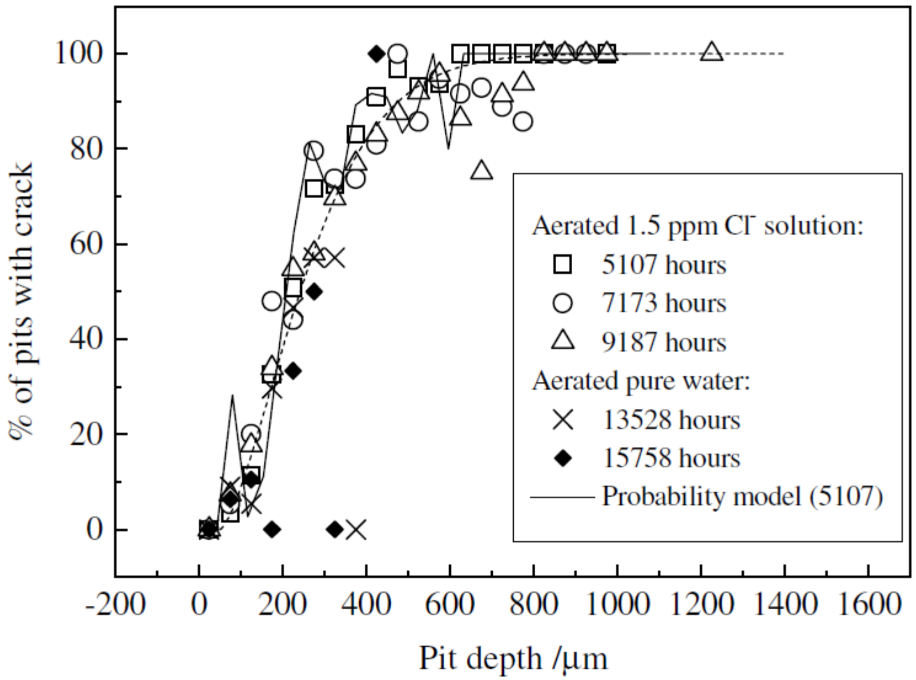
Stress profile with possible compressive zone in the middle of the sample (Ferry et al., 2013)



SCC Initiation and Propagation Models

SCC initiation from corrosion pits

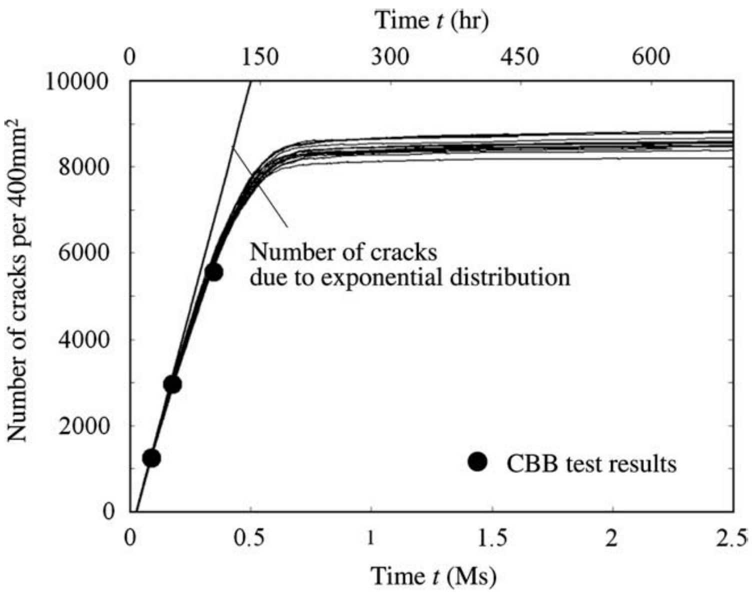
- Described in Turnbull et al. 2006, 2006b, and 2009, and others. Implemented by MI group (Ferry et al. 2014)
- Pits provide the aggressive solution chemistry and a stress concentrating effec
- Supported by experimental data that show that SCC nearly always initiates from a pit.
- Important features: threshold pit depth for crack initiation; crack growth rate must exceed pit growth rate (to avoid being over run by the pit)
- Statistical model, uses distributions for initi pit depth distribution, evolution of pit depth distributions, and pit and crack growth rate equations with normally distributed parameters. Parameters can be adjusted to fit experimental data.
- Does not include a pitting initiation or pitting density model



Turnbull et al. 2006

SCC Initiation and Propagation Models

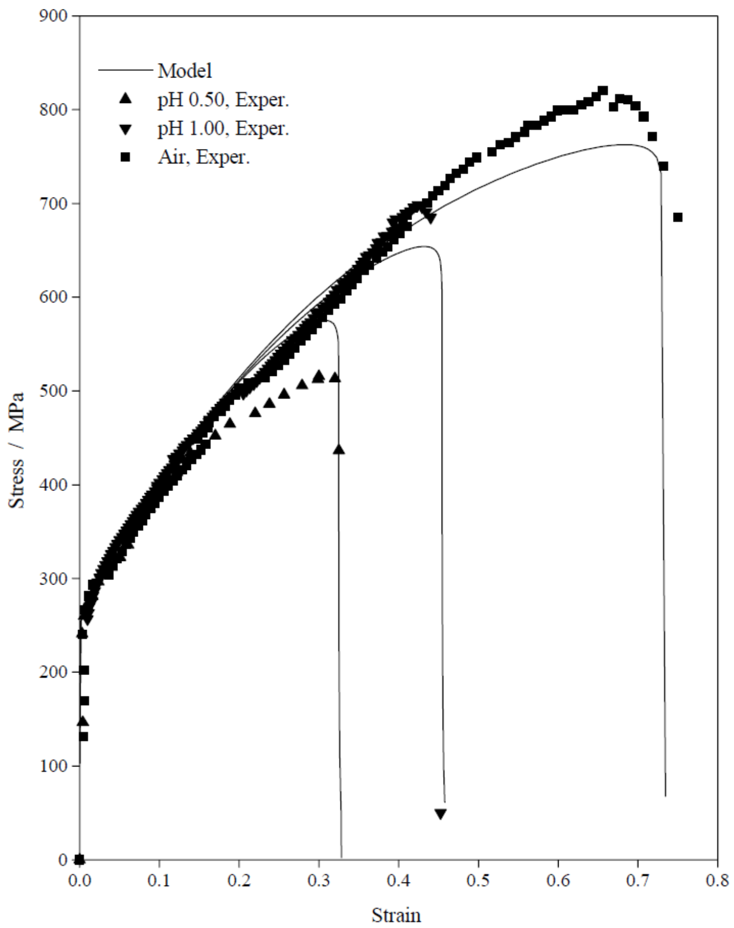
- **Percolation-type models for sensitized materials (IGSCC) (for instance Togho et al., 2009)**
  - Simple model for maximum number of cracks initiated
  - Monte Carlo simulations of crack growth by coalescence, using stress intensity factors to calculate crack growth per time step, and material yield strength to model coalescence of adjacent cracks
  - Mixed crystal plasticity/grain boundary cohesion/percolation type model for IGSCC (Siddiq and Rahimi, 2013)



Togho et al. 2009

SCC Initiation and Propagation Models

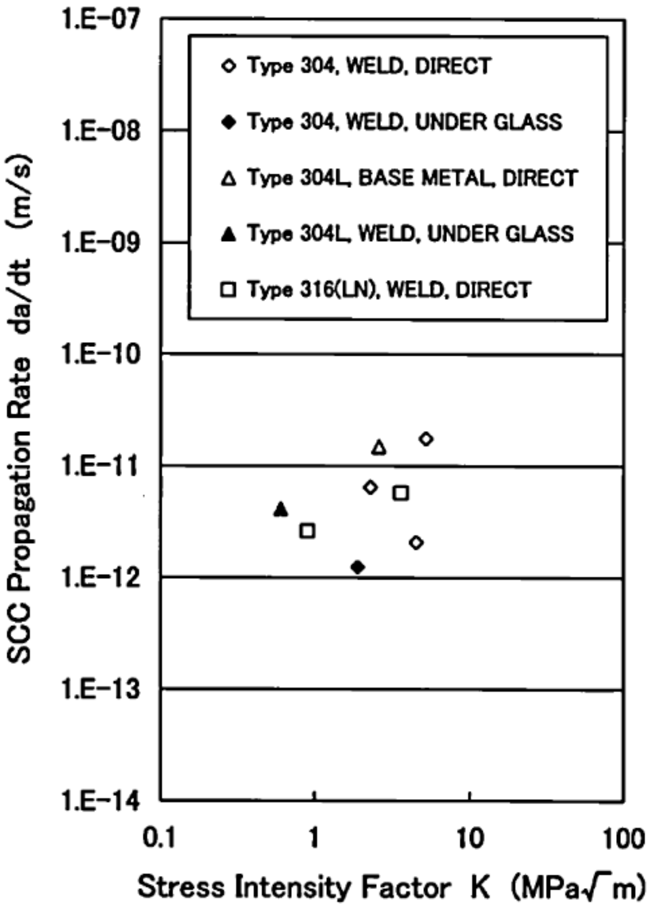
- **Elastoplastic models for crack growth (e.g., XLPR model; and Bastos et al. 2005)**
  - Describe crack growth using damage mechanics models
  - May or may not have an initiation model
  - Bastos et al. 2005 includes an additional variable, tied to the corrosive environment, to account for the effects of corrosion damage



Bastos et al. 2005

SCC Initiation and Propagation Models

- **Empirical models**
  - For example, Shirai et al. 2011; Kosaki 2008;
  - Do not use mechanistic descriptions of processes or parameters.
  - Parameterized by fitting experimental data with simple relationships. Time-to-failure is estimated from measured SCC initiation times, and estimated penetration rates.
  - Environment and sample-specific. Requires experimental data collected under conditions matching those of the systems of interest.



Kosaki, 2008

SCC Initiation and Propagation Models: Implementation

- **Try different models and assess model uncertainty**
  - Mechanical model (elastoplastic)
  - Pit initiation and SCC model
  - Empirical, data-based model (must assemble field data to parameterize or validate the other models, in any case)

Acknowledgments

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