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An Approach to Model Abstract of Stress Corrosion Cracking Damage in the Management of Spent Nuclear Fuel and High-Level Waste

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- Note:

  The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

  This presentation is based on the author's previous analysis.*

* T. Ahn, "Corrosion Damage of Canister (or Container) in Nuclear Waste Management: Perspective and an Approach for Model Abstraction," NRC ADAMS, www.nrc.gov/reading-rm/adams.html - ML13022A324, 2012

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Introduction

- Canisters (or containers) provide confinement of radionuclides from spent nuclear fuel and high-level waste.

- Evaluation of canister performance assumes conditions exist for pitting and crevice corrosion, or stress corrosion cracking (SCC).

- For a SCC induced degraded canister, limited radionuclides may be released through the opening area.

Introduction (continued)

- Inspection and mitigation strategies used to address uncertainties.
- Applying simplified and conservative system performance models.
- Elicit expert views on the approach.

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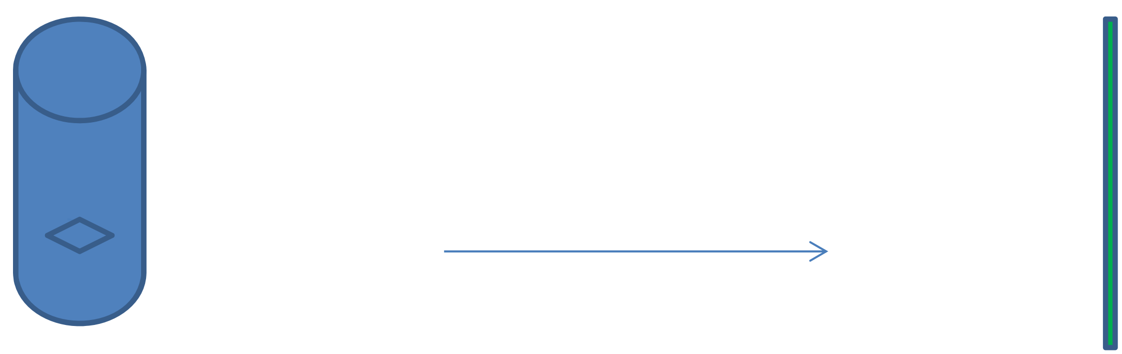
Background: Limited Opening Area

- **SCC opening area could result in limited amount of radionuclide release.**



Background:
Example Material and Environment in the Management of Spent Nuclear Fuel and High-Level Waste

- Stainless Steels, and Nickel-Based Alloys.

- Chloride Environments.

- Not limited to these metals and environments.

- Analysis assumes no inspection and mitigation of canister

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Pit-Induced SCC

Probability	0.001	0.05	0.25	0.75	0.95
K (MPa $m^{1/2}$)	0.43	1.57	2.59	4.57	6.94

Cumulative probability of stress intensification factor, K(MPa $m^{1/2}$) = $\pi^{1/2}$ x stress x (crack size)$^{1/2}$, 1 MPa $m^{1/2}$ = 0.91 ksi $in^{1/2}$

- **Pitting: A Precursory Step for SCC**
- **Data on SCC with Pitting in a Chloride-Bearing Environment with Sufficient Stress and Aqueous Conditions (EPRI, 2005).**
- **Cumulative Probability of Stress Intensification Factor Using Observed Pit Size and an Example Weld Stress (Shirai, et al., 2011).**
- **Possible Stress Intensifications Fall in the Range of Values in Measured Laboratory Tests (EPRI, 2005).**

Single SCC Crack Propagation: Observation

The propagation of a single crack, especially through the canister wall thickness, is an important canister degradation mechanism to consider. The crack propagation behavior of a single crack may be different from that of multiple cracks.

- Stress along the thickness of the canister varies; will be redistributed during crack propagation, with plasticity change.

- Crack branching or tortuous crack path.

- Rapid decrease of residual stress away from the weld (and/or heat affected zone, HAZ) area.

Single SCC Crack Propagation: Observation (continued)

- Rigorous crack growth model and exercise in reactor cases: PRO-LOCA (Shim and Rudland, 2011; Rudland, et al., 2009; Rudland, et al., 2008; Xu, et al., 2006).
- Seismic-induced stress decreases from outside surface along the thickness.
- No significant stress from internal gas pressure; insignificant neutron irradiation.
- Environmental variations (e.g., seasonal temperature).

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Single SCC Crack Propagation: Observation (continued)

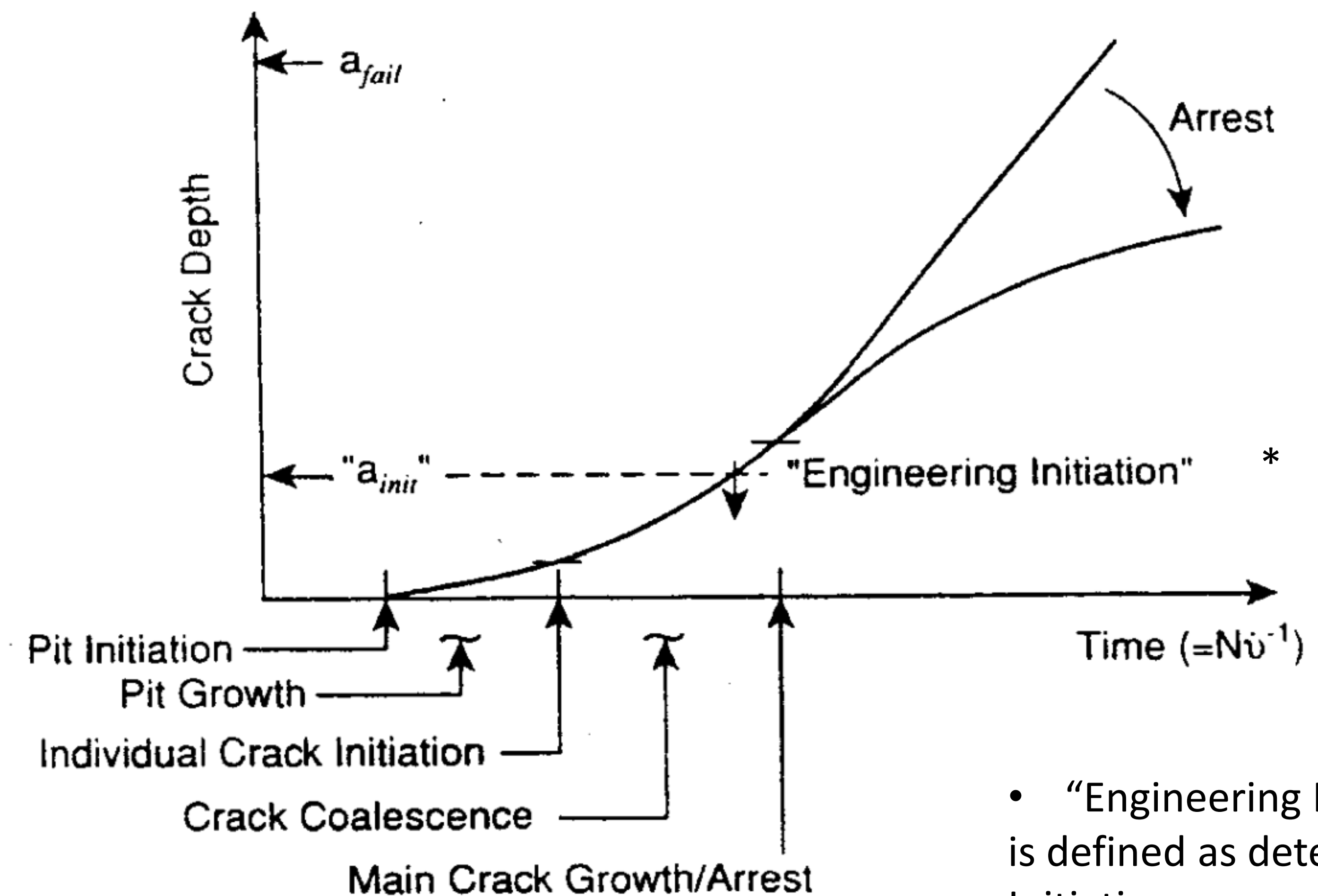
- **Through-wall growth of neighboring cracks has not been observed (SNL, 2007).**

  "Depending on the stress distribution, SCC may initiate and propagate through-wall. If several cracks were to initiate in the same area, coalesce, propagate through-wall while remaining straight (i.e., perpendicular to the surface), and maintain smooth crack faces, a sizable section of material could fall out. The occurrence of all of these events in conjunction is improbable. Only tight and relatively separate through-wall cracks are expected." (note: events such as coalescence of multiple cracks are important for the assessment of reactor structural integrity)

Single SCC Crack Propagation: Crack Arrest

Type 304 stainless steel piping contaminated with chlorides. Crack depth is about 1.2 mm(50 mils) (Stein, et al., 1986). (*permission from ASM International*)

Single SCC Crack Propagation: Crack Behavior (Ford and Andresen, 2004)



- "Engineering Initiation" is defined as detectible Initiation.

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Limited Conditions for SCC

The decreased probability of SCC propagation in a canister is furthered by:

- **Narrow range of environmental and materials conditions for SCC**
- **Limited weld/HAZ area and deformed area (under seismic conditions)**
- **Limited number of pits or flaws**
- **Few through-wall cracks**
- **Inspection and mitigation (e.g., thermal annealing, applying compressive stress)**

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Possible Maximum Opening Area of Multiple Cracks: background

The assessment of single crack propagation or environment/materials conditions for SCC is based on limited data.

- The SCC issue has been under consideration for a disposal environment. For the environment of extended dry storage SCC has been studied and, to date, no SCC has been observed.

- Models for possible maximum opening area of multiple cracks were developed under seismic impact scenarios of disposal (SNL, 2007).

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Possible Maximum Opening Area of Multiple Cracks: background (continued)

- The SNL seismic model conservatively assumes all possible surface cracks to penetrate through the wall thickness.

- The potential applicability of the SNL model for limited radionuclide release is considered.

Possible Maximum Opening Area of Multiple Cracks: SNL Model Assumptions

- The environment for stress corrosion cracking (SCC) is present: stress-based model
- The center of two cracks are separated by a parameter (approximately the thickness of the canister, related to crack geometry) due to stress attenuation.

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Possible Maximum Opening Area of Multiple Cracks: SNL Model Assumptions (continued)

- The distance between two neighboring through-wall cracks would need to be greater than the wall thickness for the stress (and resultant stress intensity) to be sufficient to drive a flaw through-wall. This conclusion is based on stress field interactions between closely spaced parallel cracks. The stress profile of a crack network is shown in the next slide.

- The aspect ratio of a crack (ratio of length to depth) has distribution for various possible crack geometries in a probabilistic system approach, and each value was sampled in the assessment of confinement or limited radionuclide release.

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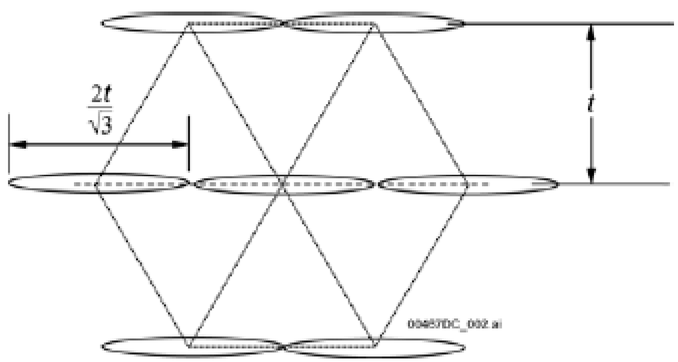
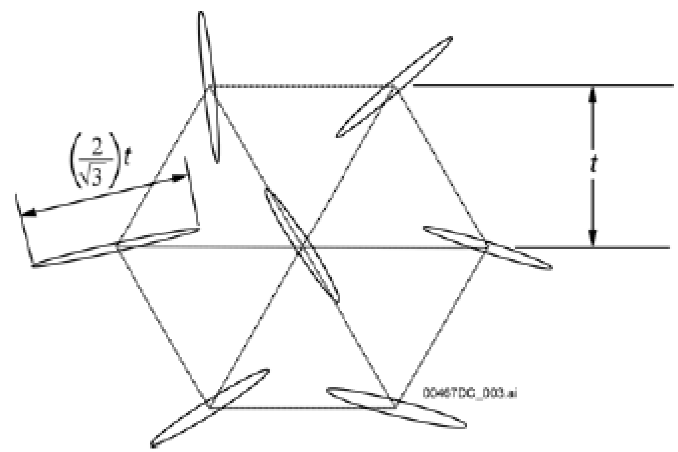
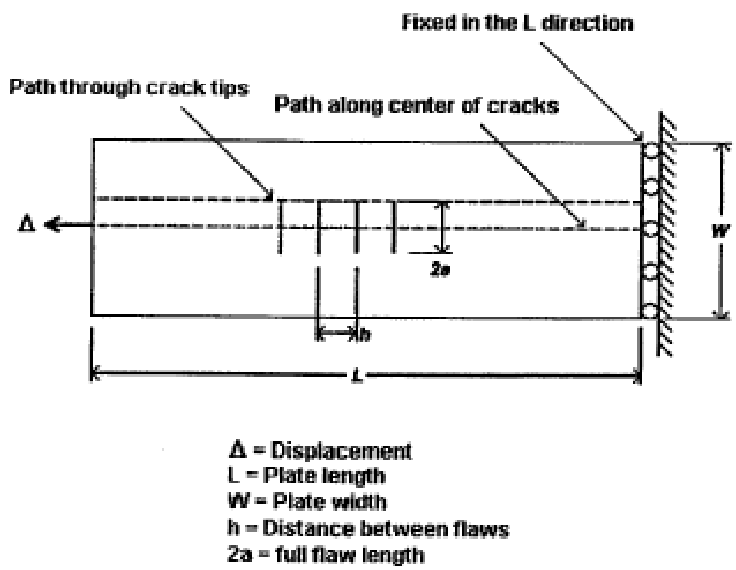
SNL Model: Crack Network from SCC

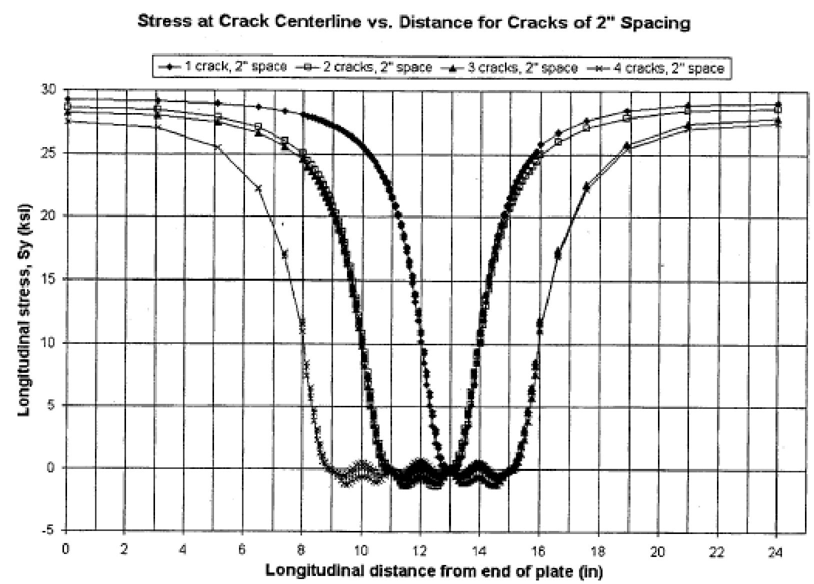




- **Maximum number of cracks**
- **“t” is radial thickness; greater than pit or flaw size**

SNL Model:
Stress Analysis with Crack Network





- Dimensions of the plate and setup for the analysis (left)
- Longitudinal stress distribution along center with 2 inch spacing between cracks (right) (Structural Integrity Associates, 2002), 1 in = 2.54 cm; 1 ksi = 6.9 MPa

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SNL Model: Mathematical Description

- **At a crack length, a(t), the crack width, w(t), will be (SNL, 2007)**

$$w(t) = C \sigma a(t)/E$$

σ: applied stress (MPa)
E: Young's modulus (MPa)
C: geometric constant
t: time

under the conditions of plane stress and infinite size (conservative assumption)

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SNL Model: Mathematical Description (continued)

- **Each crack area is product of crack length and crack width. The number of cracks are proportional to sample area divided by $a(t)^2$. The maximum opening area of multiple cracks are the product of each crack area and the number of cracks (per unit deformed or weld/HAZ area).**

$$\delta = C\, \sigma / E$$

δ: crack areal density (m^2/m^2)

Application of SNL Model

- Results of the numerical analysis of crack spacing were not sensitive to Young's modulus and Poisson's ratio (Structural Integrity Associates, 2002). This implies that the SNL model can be applied to various metals.

- Example light-water reactor (LWR) case: the number and size of surface cracks were reported from welds at the Nine Mile Point Unit 1 main recirculation lines (Xu, et al., 2006).

Application of SNL Model (continued)

- The total number of surface cracks in welds is comparable to the SNL model.
- The dominant area of surface cracks appears to fall in a range of crack sizes, as suggested by the SNL model.
- Only a small fraction of surface cracks were through the wall thickness, with a low probability (Rudland, et al., 2009).
- The aspect ratio of a crack is considered to increase with large surface cracks from 10 to 150 (Xu, et al., 2006).

Application of SNL Model (continued)

- The SNL model appears to be conservative and bounding. The model also appears to be consistent with the above LWR example observation with respect to most probable dominant crack size and potential aspect ratio present.

- This approach provides an estimate for the possible maximum opening area of cracks for various metals. An example is shown in the next slide.

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Application of SNL Model (continued)

- **An exercise was conducted for various metals with example parameter values for various metals.**

	YS (MPa) as an applied stress	E (MPa) x 10^{-3}	YS/E (mean) x 10^{3}
Stainless Steel	170 - 310	193-207	1.2
Carbon Steel	207	207	1.0
Copper	70-310	108-117	1.7
Zircaloy	241	99	2.4

Ratio of Yield Stress (YS) and Young's Modulus for Various Metals (seismic case, Gwo, et al., 2011) YS is used as an applied stress. In the probabilistic confinement assessment, the applied stress value is sampled. 1 MPa = 0.145 ksi

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Application of SNL Model (continued)

- For stainless steel, the mean value of maximum crack opening area per unit weld/HAZ or deformed area is approximately 1.2×10^{-3} (fraction, cm^2/cm^2) for 170-310 MPa (24.6-44.9 ksi) of applied stress, $(193\text{-}207) \times 10^3$ MPa ($[28.0\text{-}30.1] \times 10^3$ ksi) of Young's modulus.
- The weld/HAZ area fraction is about 10^{-2} – 10^{-1} (Ahn, et al., 2012).
- The fraction of the opening area is small.

Summary

- An approach is presented to abstract models for SCC damage of canister in the assessment of confinement and limited radionuclide release in the management of SNF and HLW.
- Localized corrosion, mainly in pitting form, may be a precursory step for SCC. It has limited density and size due to repassivation and cathodic capacity. An example calculation with field data shows that SCC of stainless and carbon steel can be initiated at pits in chloride environments.
- The propagation rate of a single SCC may decrease during propagation. Also, conditions for environments and materials are limited for SCC. Uncertainties may be addressed by inspection and mitigation strategies.

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Summary (continued)

- **Possible maximum opening area of multiple cracks is estimated based on the SNL model for the seismic case in disposal. Example data in LWR welds suggest that the SNL model appears to be conservative and can be used to assess confinement and limited radionuclide release. The SNL model can be used for various metals. For stainless steel, the fraction of possible maximum crack opening area is limited from the model exercise.**