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Flow and Transport through Stress Corrosion Cracks in Dry Storage Canisters:

Opportunities for Research

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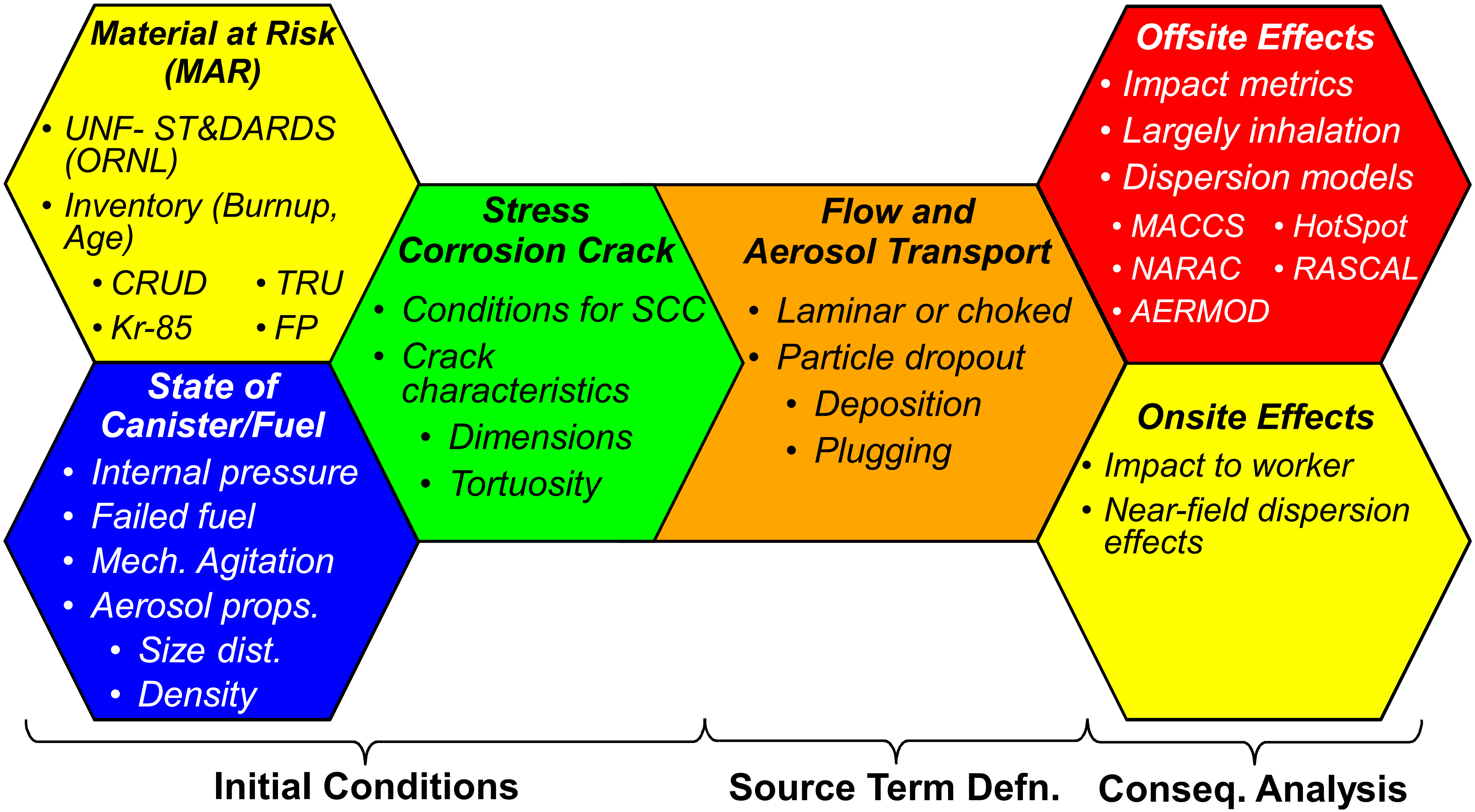
Organization of Analyses



Parametric Study of Flow and Particle Transport through Cracks

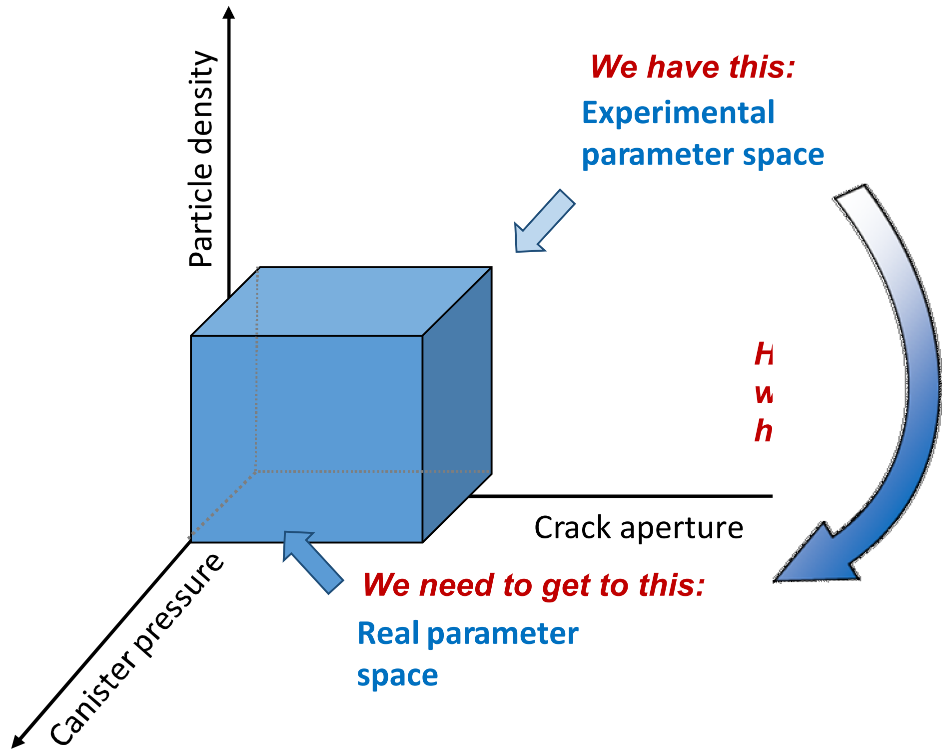
Planned experiments use a parametric approach to assess gas and particle transport through SCC

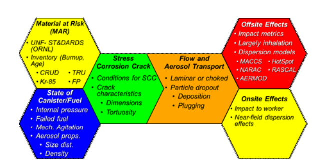
Parametrically vary:

- Geometry of machined "crack" (surface area, dimensions, shape?)
- Aerosol particle size/size distribution
- Aerosol particle densities (particles per unit volume, mg/m^3)
- Canister (upstream) pressure

Performed over a large range of parameter values

Consequence analysis: vary dispersion (plume) and dose models.





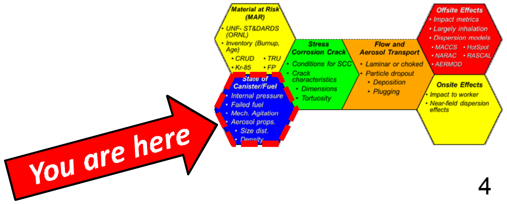
In-Canister Particle Source Term

What is the mechanism of particle generation?

- Rod damage mechanisms and resulting cladding penetration characteristics, and particle size distributions (PSDs) generated
  - Rods damaged in the cask
    - *Corrosion due to air/water ingress*
    - *Vibration/shock during transfer?*
  - Rods damaged prior to dry storage
  - Unoxidized or partially oxidized fuel? (Hanson et al. (2008) say PSD doesn't vary)
  - Cladding "crud"?

What are aerosol particle densities and particle suspension mechanisms?

- Fuel particles settle rapidly. What processes could result in re-suspension of particles? What is the range of applicable aerosol particle densities/PSDs?
  - Initial rod split and internal pressure release
  - Motion during transfer/transport (tipping/lifting, vibration)
  - Convection within the canister



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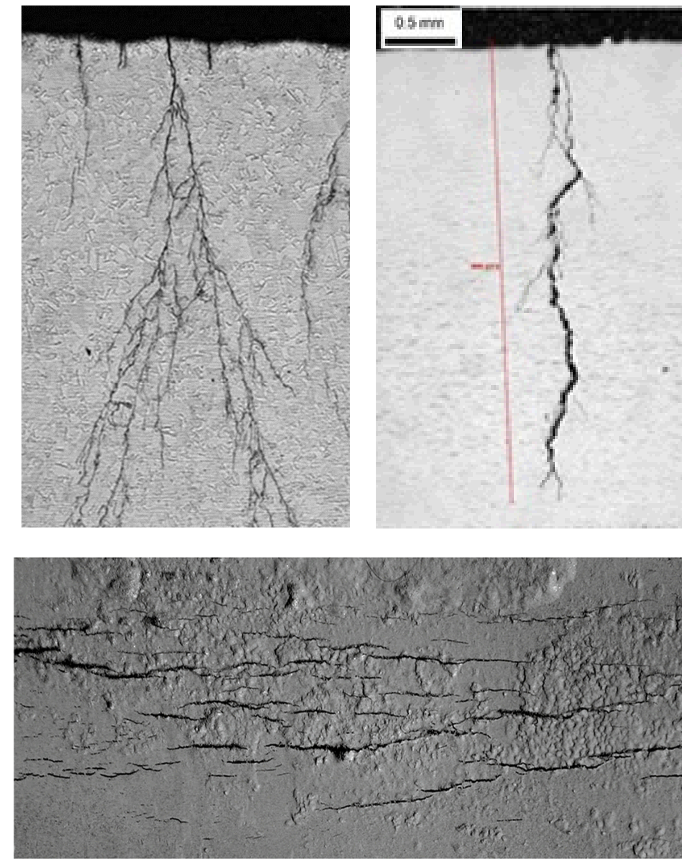
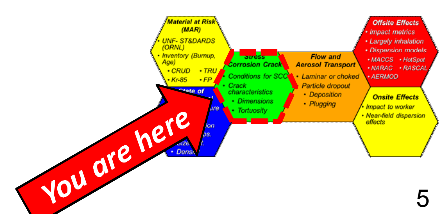
Stress Corrosion Crack Characteristics

SCC crack properties

- Degree of branching (tortuosity)
  - Controlled by stress/stress profile with depth, metallurgical properties, environment(?)
- Crack lengths and crack opening displacements (CODs) (internal and external) at time of penetration. Controls include:
  - Tensile stress profile
  - Crack aspect ratio (half-length/depth ratio)
  - Degree of branching
  - Surface branching—tensile stress distributed over several narrower cracks?

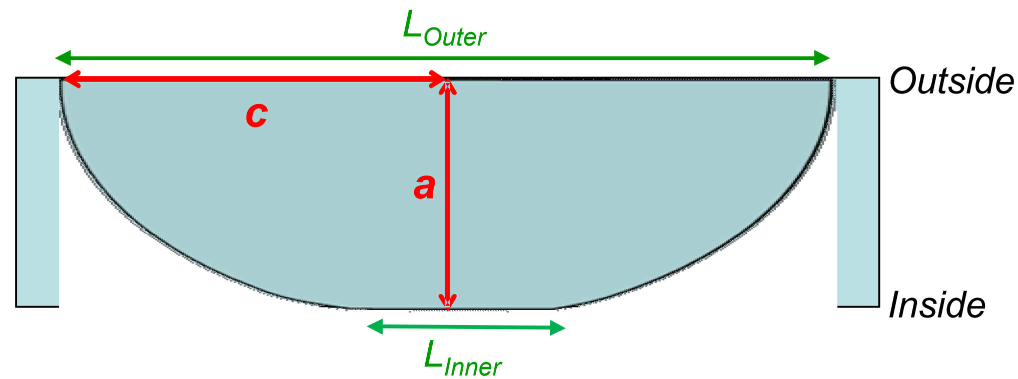


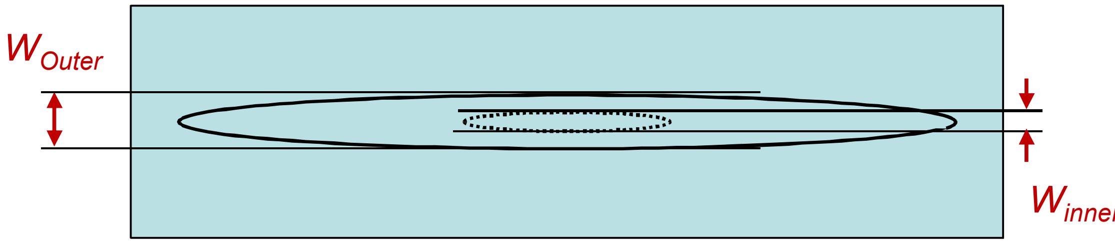


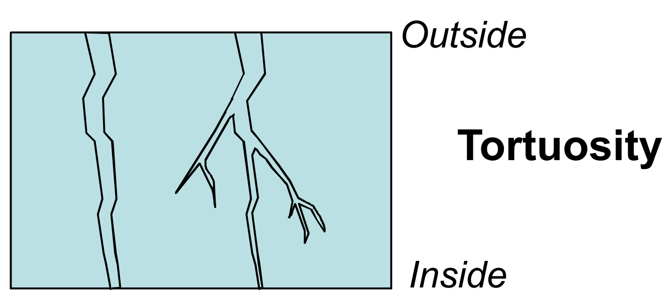
Stress Corrosion Crack Characteristics

Important parameters for flow and particle transport

- External length (L_{outer}) and COD (W_{outer}) at time of penetration
- Internal length (L_{inner}) and COD (W_{inner}) at time of penetration
- Tortuosity of flow pathway
- Controlling factors
  - Tensile stress field
  - Branching (function of stress, texture)
  - Aspect ratio -- half-length/depth (c/a)
  - Surface branching





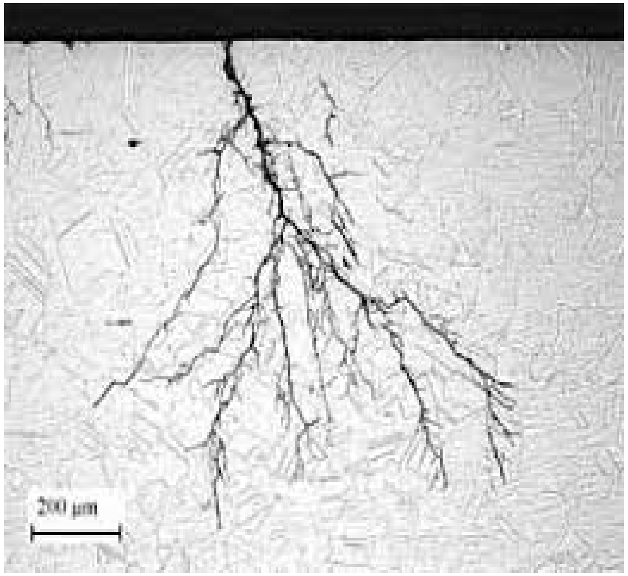


How to characterize a typical SCC crack?

Experimental Approach

Making a representative crack is difficult

- Must duplicate stress conditions
  - Magnitude of tensile stress
  - Stress profile with depth
  - Large sample to avoid edge effects
- Atmospheric versus immersed SCC
  - Possible variations in crack geometry (e.g., branching)
  - Potential effects of cathodic limitation
- Thermal fatigue cracks as analogs?



Crack characterization is difficult

- Cracks held open in part by elastic stresses
- *In situ* methods only, or stabilize crack before characterization?
- Gas flow tests—produce only lumped parameter data (crack permeability)

Creating a representative crack may be time-consuming

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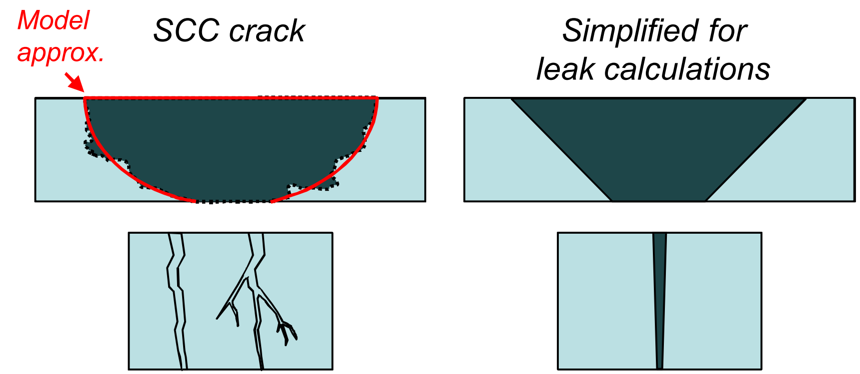
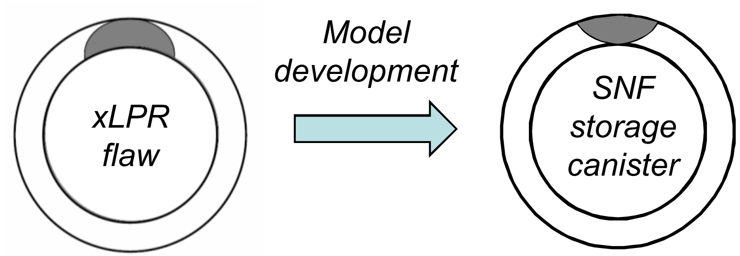
How to characterize a typical SCC crack?
Modeling approaches

xLPR approach—deterministic fracture mechanics model for reactor-related PWSCC and fatigue crack initiation and growth

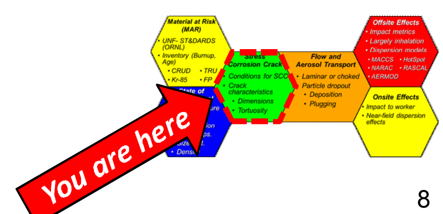
- Utilizes *Universal Weighting Function* approach (ASME Section XI, Appendix A) to calculate K values along crack front
  - *Assumes semielliptical crack shapes (simplified to trapezoids for leak modeling). No branching.*
  - *Estimates crack shape (aspect ratio) at time of penetration, length of inner and outer crack*
  - *For xLPR, used to describe radial and axial inside surface flaws, but Section XI provides solutions for flat plates (external flaw solutions in development). Can be modified for use on SNF storage canisters, e.g., Lam and Sindelar (2015)*
- Calculates CODs at OD, ID, and mid-thickness using mechanical property model and residual stresses
- Well-developed, well-validated approach





Finite element or field effect modeling

- Mechanistic fracture mechanics approaches
- More realistic crack shapes: can include branching, effects of structural heterogeneity
- Requires significant development

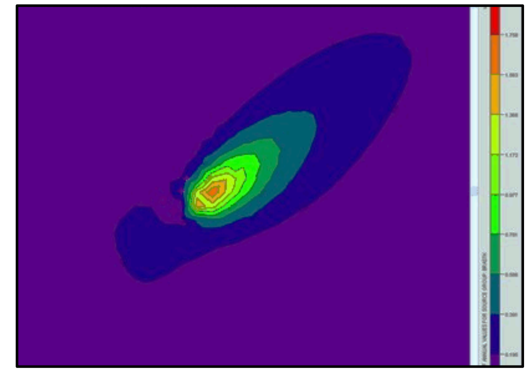


Consequence modeling

What metrics to use?

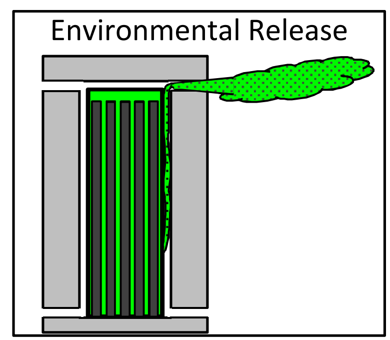
- **Dose to individuals (inhalation only?)**
- **Land contamination?**
- **Costs of mitigation/remediation?**

Contaminant plume



Offsite consequences

- **Effects**
  - Potential dose to the public
  - Land withdrawal or cleanup efforts
- **What factors to consider?**
  - Particle deposition
    - *Initial Contaminant plume*
    - *Re-suspension/re-distribution of particles*
      - Wind
      - Runoff
      - Anthropogenic activities (e.g., farming, vehicular traffic)



Consequence Modeling

Onsite Consequences

- **Effects:**
  - Worker dose
  - Added costs
- **Worker dose: exposure to plume, but additional dose due to…?**
  - Plume mitigation/stabilization/cleanup
  - Storage system mitigation/stabilization/cleanup
  - Canister transfer and transport, repackaging

Consider other potentially important events and processes?

- **Timing of leak formation, discovery, and (potentially) repair**
- **Measures taken to mitigate deposited material (stabilization, remediation)**
- **Measures taken to mitigate worker dose: e.g., restricting access or ES&H (PPE, surveying) requirements**

Conclusions

Opportunities for research

- **In-package source term (particle size and aerosol particle density) for different rod failure scenarios**
- **Determining the realistic range of crack geometries (tortuosity, OD and ID crack lengths and apertures)**
- **Defining metrics and developing consequence model architecture—what to include?**