Aerosol Transmission through Stress Corrosion Crack-Like Geometries

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Objective

- Mimic aerosol transport through a stress corrosion crack (SCC) in a spent nuclear fuel (SNF) canister
  - Pressure-driven flow
    - Prototypic canister pressures
    - Near-prototypic canister volume
- Explore flow rates and aerosol retention of an engineered microchannel
  - Characteristic dimensions similar to those of SCCs
    - Slot orifice (rectangular cross-section)
    - Divergent nozzle – linear transition from inner to outer characteristic crack dimensions
- Measure mass flow and aerosol concentration
  - Upstream and downstream of microchannel
  - Simplified geometry with well-controlled boundary conditions

Source: www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html
Collaborative Modeling and Testing

- Andy Casella
- GOTHIC modeling
  - Aerosol deposition in canister (planned work)
  - 1-D compressible flow model for SCC

- Sam Durbin
- CFD internal flows (Fred Gelbard)
- MELCOR modeling (Jesse Phillips)
  - Aerosol deposition in canister
- Aerosol transmission testing (this presentation)

- Yadu Sasikumar
  - Previous efforts by Stylianos Chatzidakis
  - 1st principles modeling of aerosol transport/depletion in microchannels
Aerodynamic Equivalent Diameter (AED)

• Size of a particle with equivalent diameter of spherical particle with $\rho_o = 1$ g/cm$^3$
  
  – Shape factor ($\chi$) for irregular particles
    • Generally ignored for consequence analyses (Assume $\chi = 1$)
  
  – Conversion factor

$$\sqrt{\frac{\rho}{\rho_o \chi}} \approx \sqrt{\frac{10 \text{ g/cc}}{1 \text{ g/cc}}} = 3.2, \text{ for spent fuel}$$

Irregular particle

d$_e$ = 3 $\mu$m
$\rho$ = 10 g/cc
$\chi$ = 1.4

Aerodynamic equivalent sphere

AED = 8 $\mu$m
$\rho_o$ = 1 g/cc

$V_{TS} = 1.9$ mm/s
Respirable Particles

- Respirable particles conservatively chosen as particles smaller than 10 μm AED
  - Enter and deposit in alveoli
  - Relatively long residence time
- Large particles (> 10 μm) may enter respiratory system
  - More easily expelled
  - Relatively short residence time

American Conference of Governmental Industrial Hygienists (ACGIH), 1997 Threshold Limit Values and Biological Exposure Indices, ACGIH, Cincinnati, OH (1997).
Aerosol Transmission Results

- Transmission of aerosols ↓ as $MMD_o ↑$
  - Transmission ranged from ~0.1 to 0.6 over entire test series
  - Air or helium as carrier gas

- SCC simulated with linearly diverging microchannel
  - Upstream to downstream transition
    - 13 to 25 µm
    - Simulated crack acts as flow restrictor and filter
Initial Aerosol Density

- Respirable particles with an aerodynamic equivalent diameter (AED) < 10 μm
- Respirable release fraction = $8.9 \times 10^{-6}$
- Estimate hypothetical aerosol density available for transport
  - 37 PWRs
  - 520 kg UO₂ per assembly
  - Assume 1% fuel rod failure
  - Assume no deposition
  - Initial pressure 800 kPa (116 psia)
  - Average gas temperature 460 K (187 °C)
  - Assume canister free volume of 6 m³
  - Reference conditions: 101 kPa, 298 K
  - Reference aerosol density: $0.01 \times 37 \text{ PWRs} \times 5.20 \times 10^8 \frac{\text{mg}}{\text{PWR}} \times 8.9 \times 10^{-6} \approx 54 \text{ mg/m}^3 = C_{m, \text{STP, Ref.}}$
Surrogate Selection

• Cerium oxide (CeO₂) chosen as surrogate
  \[ \rho_{\text{CeO}_2} = 7.22 \text{ g/cm}^3 \]
  \[ \rho_{\text{SNF}} \approx 10 \text{ g/cm}^3 \text{ (Spent fuel)} \]

• Particle size distribution
  – Mass median diameter (MMD)
    • MMD = 2.4 \mu m
  – Geometric standard deviation (GSD)
    • GSD = 1.9
  – ~75% particles (by mass) respirable
    • AED < 10 \mu m
Engineered Microchannel

- Microchannel formed with paired blocks
  - High-precision gage blocks
  - Electrical discharge machined to form channel
  - Dimensions
    - Flow length: 8.86 mm (0.349 in.) long
    - Channel width: 12.7 mm (0.500 in.) wide
    - Channel height:
      - Linearly diverging from 13 to 25 µm
- Bolted together to form microchannel
- Replaceable test section
  - Ultimately conduct experiments with representative SCCs

![Isometric view of mounted microchannel on upstream side](image-url)
Test System Photograph

- **Exhaust**
- **Test section**
- **Palas Promo 3000 HP**
- **240-gal storage tank**
- **2 in. ball valve**
- **Mass flow meter**
- **HEPA filter**
- **Downstream aerosol sensor**
- **Microchannel mount**
- **Upstream pressurized aerosol sensor**
Flow Visualization of Microchannel Flow

- Flow visualization of downstream flow by rearrangement of hardware
  - Mounting flange reversed
    - Mounted on upstream nipple
    - Downstream nipple removed
- Upward vectored jet observed at the flow midplane
  - Microchannel mounted on bottom half
  - Possible sensitivity to mounting orientation
  - Full mixing expected with downstream test section installed
### Air Testing

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<th>Date</th>
<th>Test Type</th>
<th>$\Delta P_o$ (kPa)</th>
<th>$C_m$ (mg/m$^3$)</th>
<th>MMD (µm)</th>
<th>GSD (--</th>
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- 17 air tests
  - Mostly blowdowns
  - MMD$_o$ range from 1.4 to 2.4 µm
  - Aerosol mass transmission range from 0.26 to 0.61
  - Average aerosol mass transmission = 0.41
# Helium Testing

- **13 helium tests**
  - Mostly blowdowns
  - MMD<sub>0</sub> range from 1.7 to 3.5 µm
  - Aerosol mass transmission range from ~0.12 to 0.47
  - Average aerosol mass transmission = 0.26

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<th>Date</th>
<th>Test Type</th>
<th>( \Delta P_o ) (kPa)</th>
<th>( C_m ) (mg/m(^3))</th>
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Aerosol Deposits

- Aerosol deposits on microchannel
  - Similar behavior observed for linearly diverging microchannel
    - Streaking
    - “Snowball” accumulation
  - Upstream leading edge
    - More accumulation
  - Streaking due to agglomerate migration
Next Steps in Testing

- Continue to progress toward more prototypic conditions with engineered microchannels
  - Stepped channel to add controlled tortuosity
- Test with EPRI lab-grown cracks
  - Samples and photos from Jon Tatman (EPRI)
    - Sample LT-28 shown on left
  - Independently measure flow versus pressure (no aerosols)
  - Measure aerosol transmission in final test
Independent Modeling

Two independent thermal-hydraulics codes, originally written for analysis of nuclear power plants, have been configured to examine aerosol transport inside of a vertical spent fuel storage canister.

**GOTHIC**

- Generation of Thermal Hydraulic Information in Containment
- Integrated finite volume, general-purpose thermal-hydraulics code
  - Used for design, licensing, safety, and operating analysis of nuclear power plants and components
  - Lumped and multidimensional geometries
  - Tracks evolution of multiple drop/aerosol fields based on transport, phase change, and interactions with other fields and surfaces

**MELCOR**

- Coupled thermal-hydraulic and risk-significant phenomena modeling in a system-level accident code
  - Developed at SNL for US Nuclear Regulatory Commission (NRC)
- Designed to simulate reactor, auxiliary equipment, and other nuclear components
- Uses a “control volume” approach to solve thermal-hydraulics
  - Tracks fuel and fission product release and transport
Aerosol Depletion in SNF Canister

- Normalized depletion nearly independent of initial mass concentration ($C_{m,0}$)
  - 1% fuel failure $\rightarrow \sim 200$ mg/m$^3$
    - $\sim 50$ mg/m$^3$, STP
- Lognormal particle size distribution
  - MMD$_o = 3.46$ µm and GSD$_o = 2.24$
    - Based on measurements from Hanson, et al., 2008
    - Plateauing GOTHIC results from imposition of minimum count density
- Nearly 6 orders of normalized aerosol mass depletion in less than 2 hours
• Explored flow rates and aerosol retention in a diverging microchannel
  – Characterize hypothetical aerosol-laden flow through an SCC
    • Aerosol concentration measured upstream and downstream of microchannel
    • Characteristic dimensions similar to SCCs
  – Large parameter space for aerosol transport under conditions of interest
    • Prototypic maximum canister pressure differentials
    • Air and helium tests

• Preliminary results
  – Aerosol mass transmission ranged from ~12 to 61%
  – Strong dependence on initial particle size distribution
    • As characterized by the mass median diameter

• Preliminary modeling shows significant depletion in less than 2 hours from fuel-to-canister release
  – Differences in codes identified
    • System definitions (particle size distribution, etc.)
    • Treatment of different physical parameters
    • Methods employed by the two codes
Future Work

• Continued testing of diverging microchannel
  – Attempt to isolate effects of carrier gas and particle size distributions

• Prepare for testing of lab-grown cracks
  – Clean testing first for independent flow characterization
  – Final test with aerosol-laden flow to measure particulate transmission

• Modeling will focus on unification of input conditions between codes
  – More meaningful comparisons of outputs

• Identify parameters of highest impact
  – Rank mechanisms of depletion (fallout, diffusion, thermophoresis, etc.)
  – Characterize settled distribution and particle sizes of settled aerosol