U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

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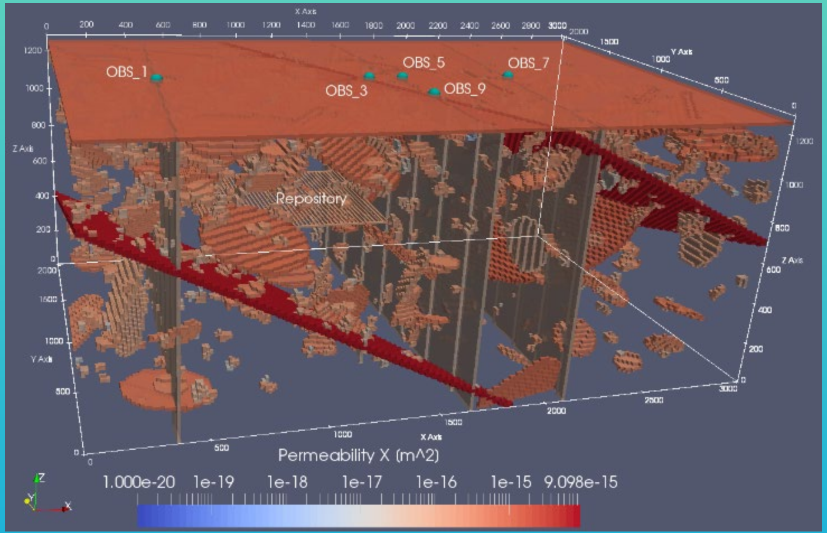

Aerosol Transmission through Stress Corrosion Crack-Like Geometries

SAND2022-1988 PE

U.S. Nuclear Waste Technical Review Board
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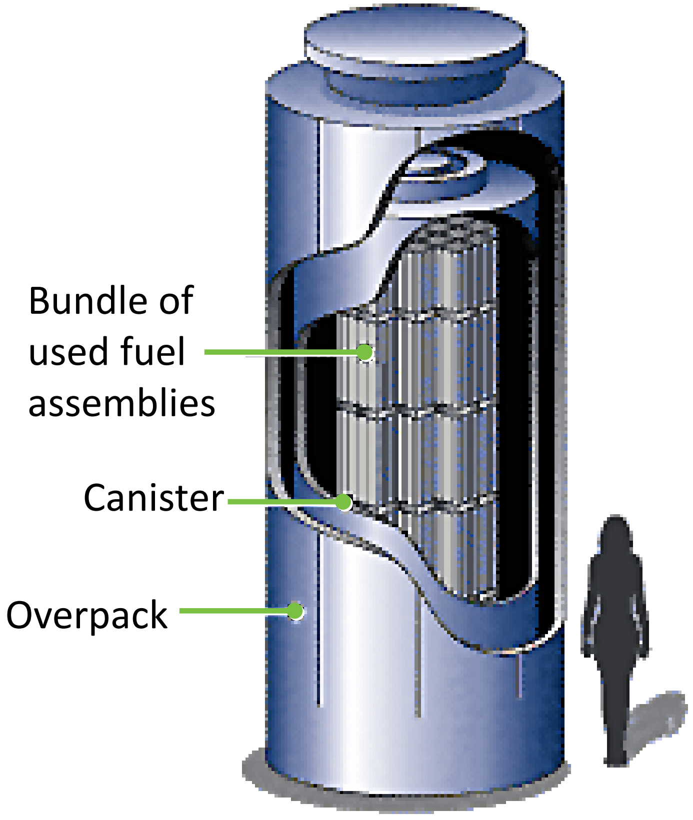
To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

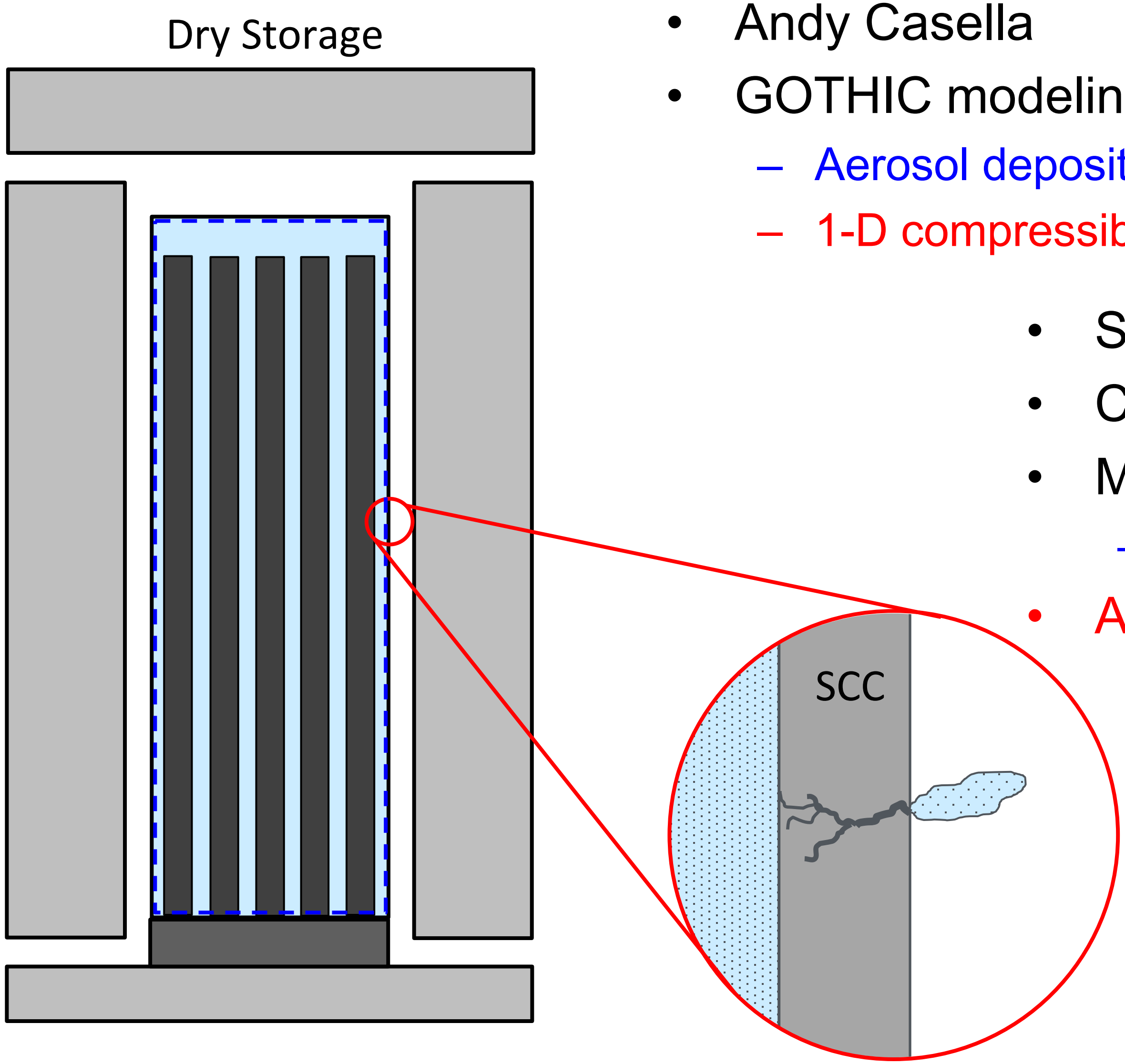
Objective



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

- 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

Collaborative Modeling and Testing



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

Pacific Northwest NATIONAL LABORATORY

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

Sandia National Laboratories

- Yadu Sasikumar
  - Previous efforts by Stylianos Chatzidakis
- 1st principles modeling of aerosol transport/depletion in microchannels

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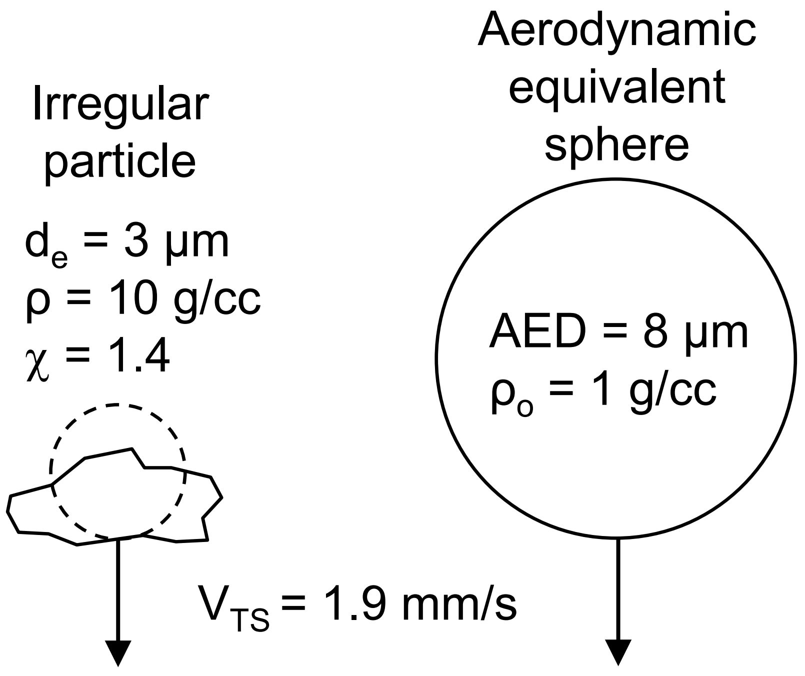
Aerodynamic Equivalent Diameter (AED)



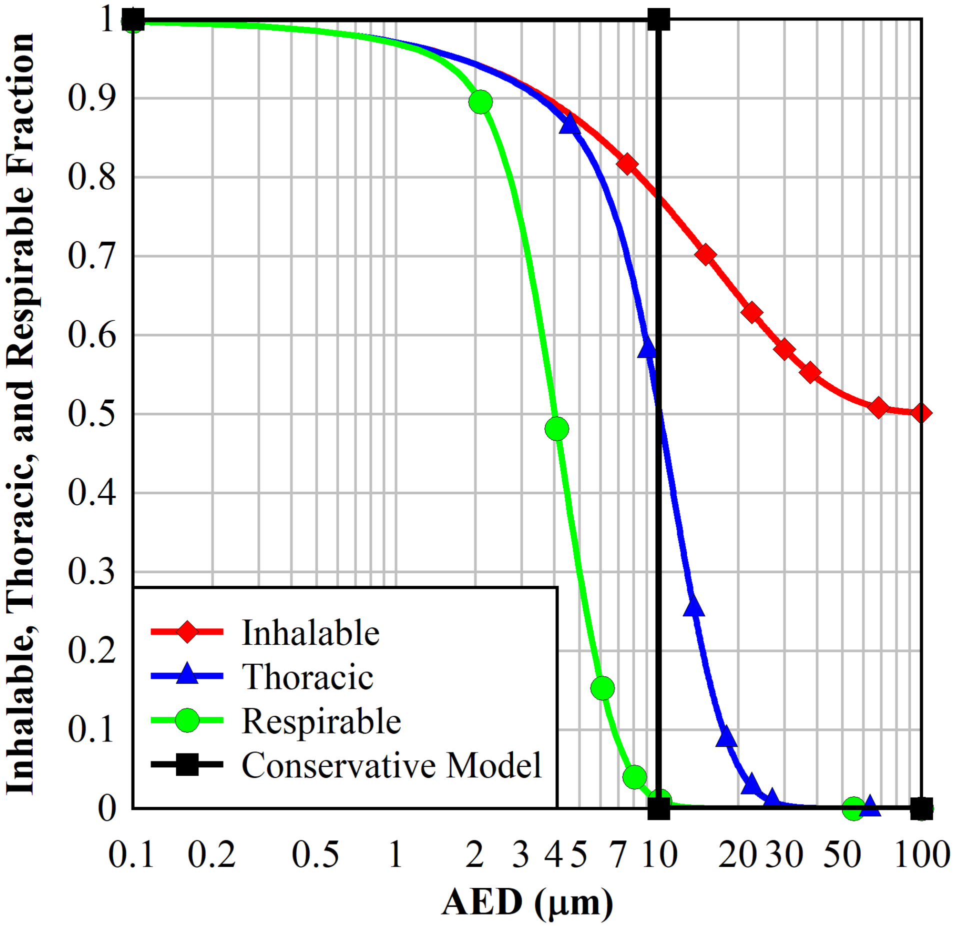
$$AED = d_e \left(\frac{\rho}{\rho_o \chi} \right)^{1/2}$$

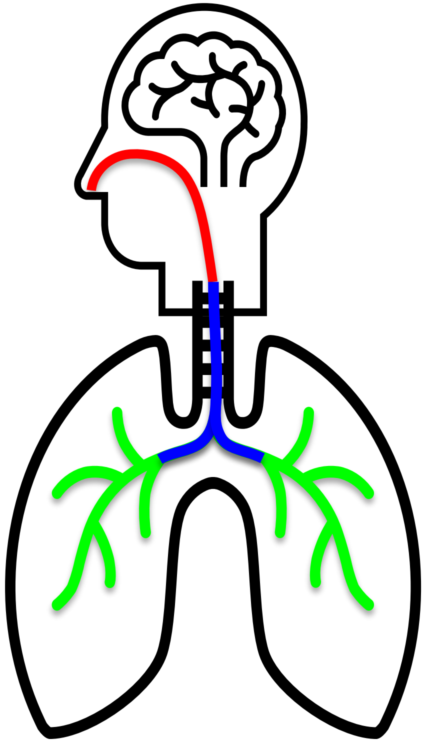
$$AED = d_e \left(\frac{\rho}{\rho_o} \right)^{1/2}, \text{ for spheres}$$

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

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

Respirable Particles

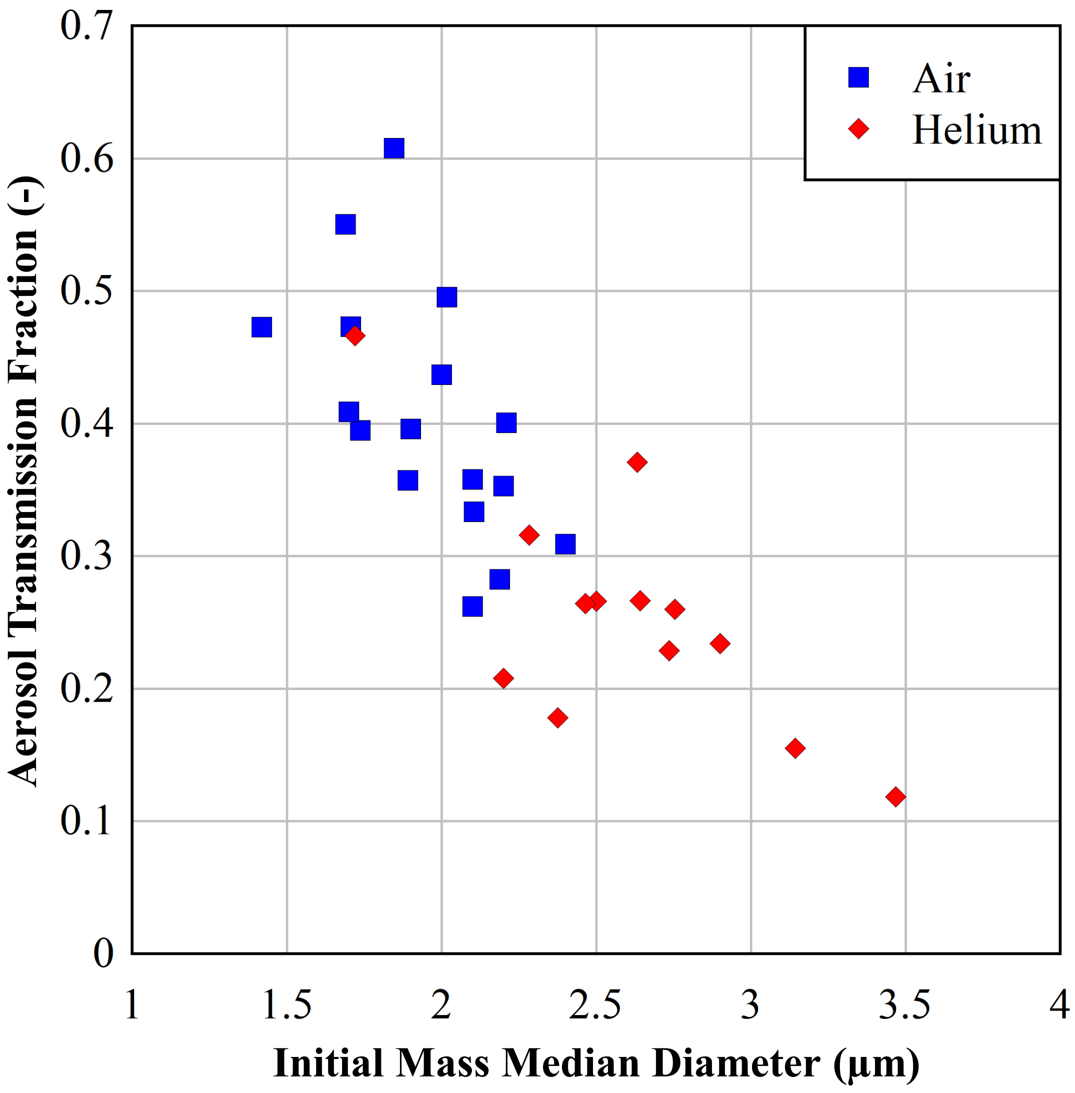




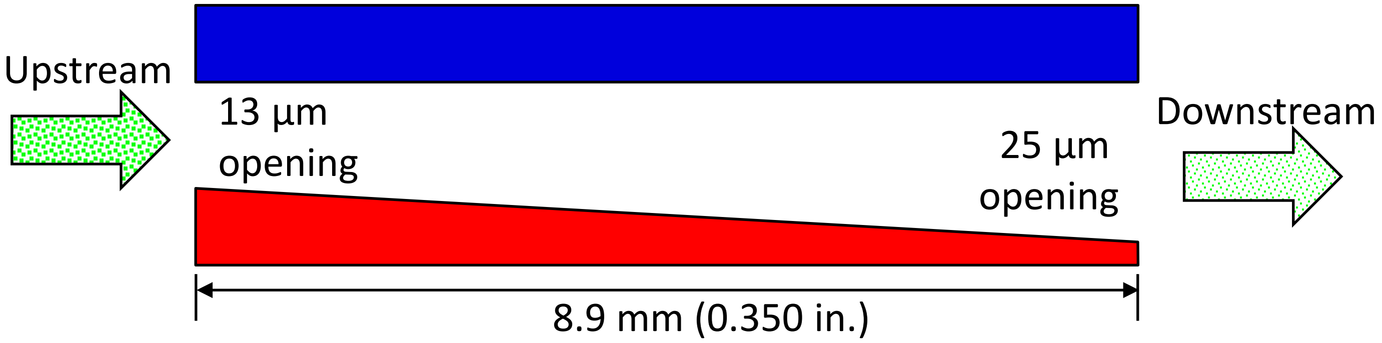
- Respirable particles conservatively chosen as particles smaller than 10 μm AED
  - Enter and deposit in alveoli
  - Relatively long residence time
- Large particles (> 10 μm) may enter respiratory system
  - More easily expelled
  - Relatively short residence time

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

Aerosol Transmission Results



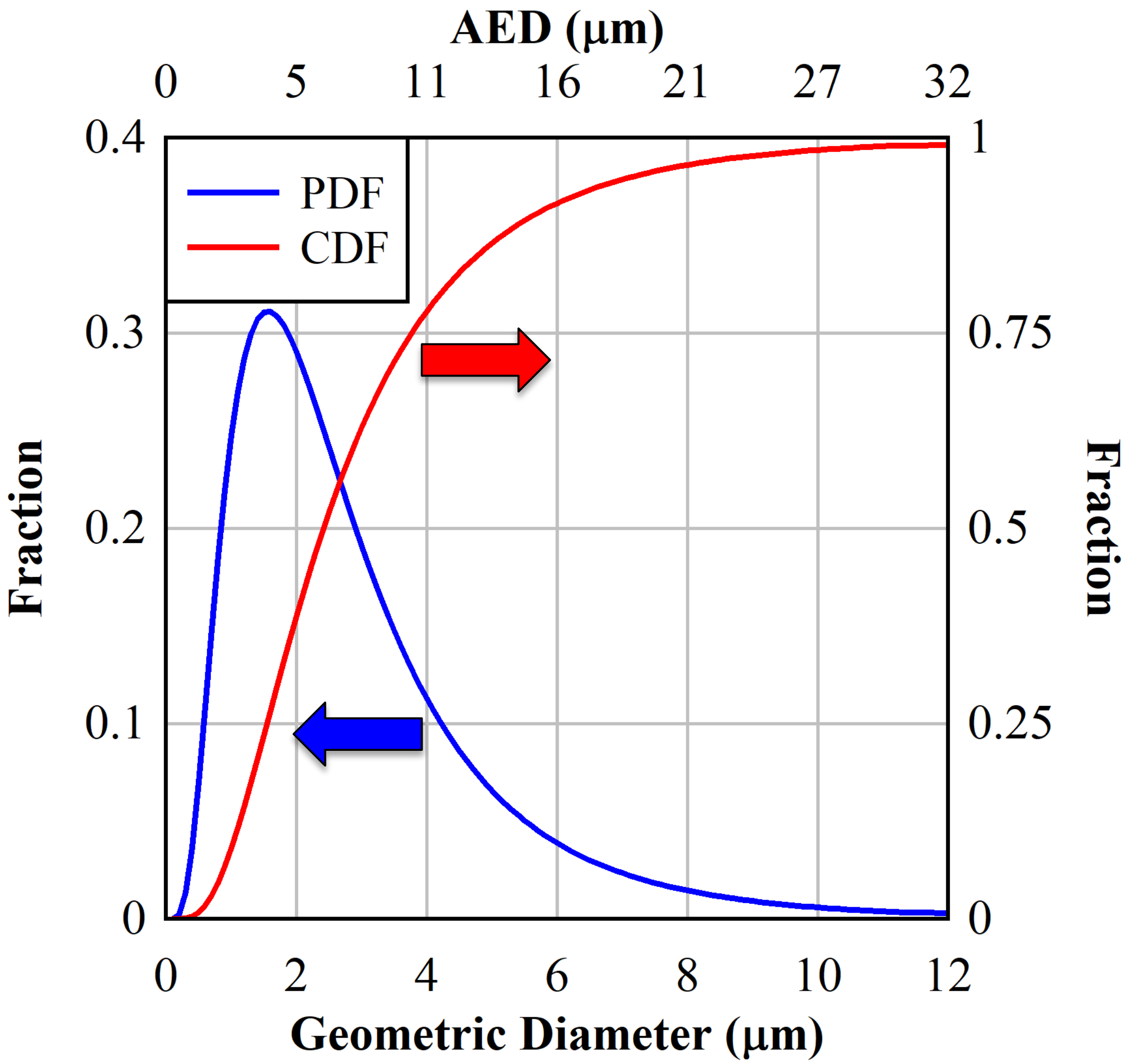
- Transmission of aerosols ↓ as MMD_o ↑
  - Transmission ranged from ~0.1 to 0.6 over entire test series
  - Air or helium as carrier gas
- SCC simulated with linearly diverging microchannel
  - Upstream to downstream transition
    - 13 to 25 µm
  - Simulated crack acts as flow restrictor and filter



Initial Aerosol Density

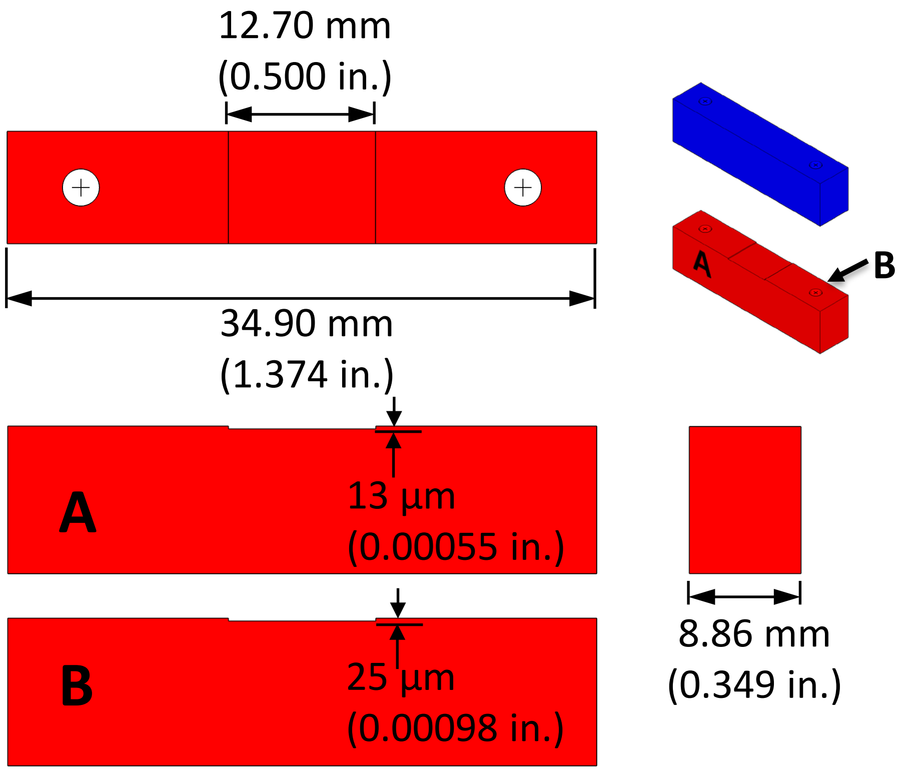
- Respirable particles with an aerodynamic equivalent diameter (AED) < 10 µm
- Respirable release fraction = 8.9×10^{-6}
  - Hanson, B.D., *et al.*, "Fuel-In-Air FY07 Summary Report," Pacific Northwest National Laboratory, PNNL-17275, September 2008
- Estimate hypothetical aerosol density available for transport
  - 37 PWRs
  - 520 kg UO_2 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 m^3
  - Reference conditions: 101 kPa, 298 K
  - Reference aerosol density: $\dfrac{0.01 \times 37 \text{ PWRs} \times 5.20 \times 10^{8}\ \dfrac{\text{mg}}{\text{PWR}} \times 8.9\times10^{-6}}{\left(\dfrac{298\text{ K}}{460\text{ K}}\right) \times \left(\dfrac{800\text{ kPa}}{101\text{ kPa}}\right) \times 6\text{ m}^3} \approx$ 54 $\text{mg/m}^3 = C_{m,\ STP,\ Ref.}$

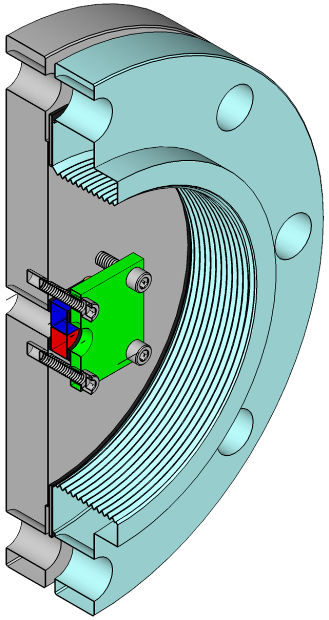
Surrogate Selection



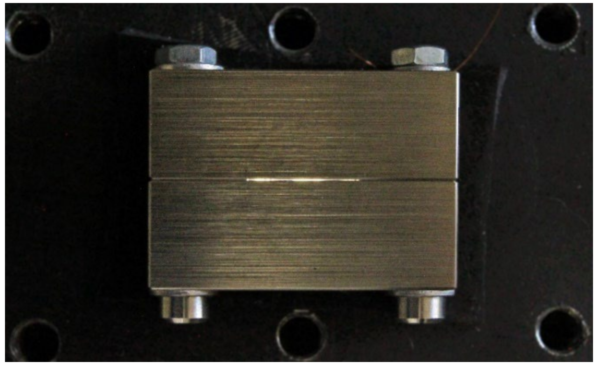
- Cerium oxide (CeO_2) chosen as surrogate
  - ρ_{CeO_2} = 7.22 g/cm^3
  - ρ_{SNF} ≈ 10 g/cm^3 (Spent fuel)
- Particle size distribution
  - Mass median diameter (MMD)
    - MMD = 2.4 µm
  - Geometric standard deviation (GSD)
    - GSD = 1.9
  - ~75% particles (by mass) respirable
    - AED < 10 µm

Engineered Microchannel

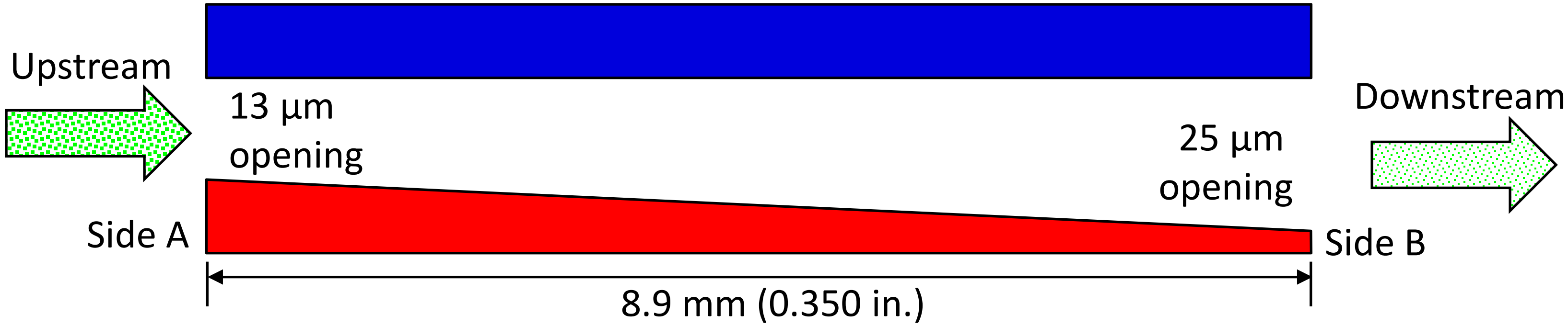




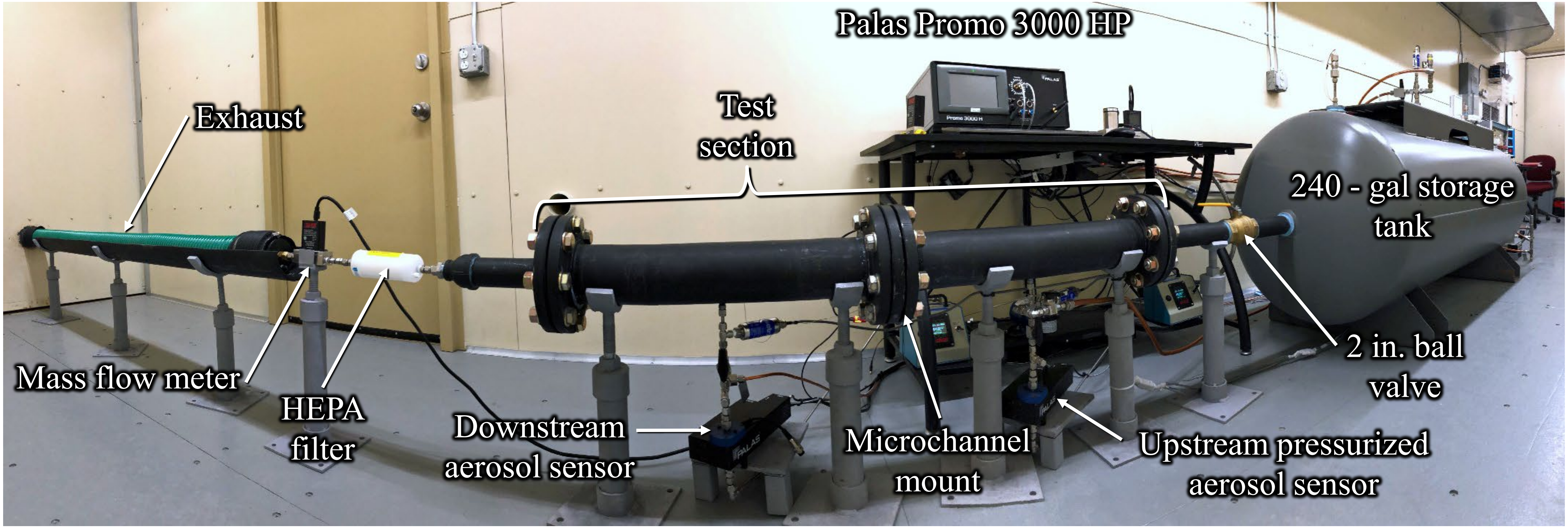
Isometric view of mounted microchannel on upstream side



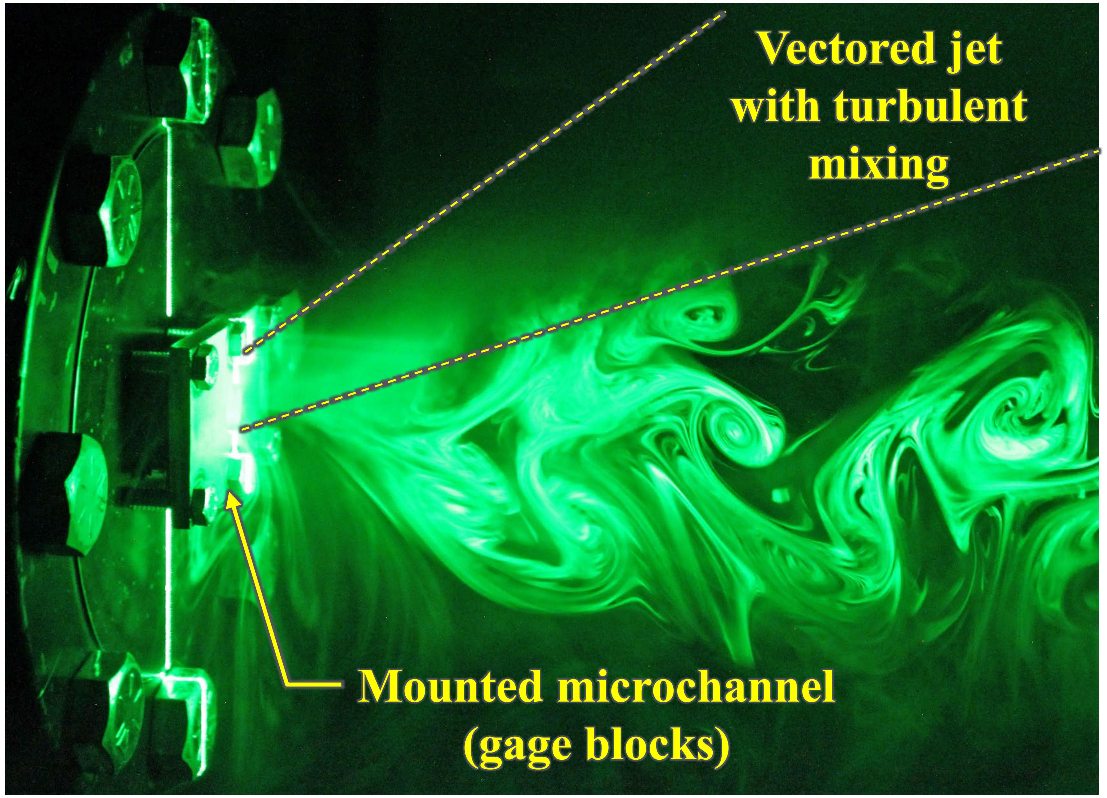
- Microchannel formed with paired blocks
  - High-precision gage blocks
  - Electrical discharge machined to form channel
  - Dimensions
    - Flow length: 8.86 mm (0.349 in.) long
    - Channel width: 12.7 mm (0.500 in.) wide
    - Channel height:
      - Linearly diverging from 13 to 25 µm
- Bolted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



Test System Photograph



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

Date	Test Type	ΔP_o (kPa)	Upstream Initial Conditions			Integrated Transmission
			C_m (mg/m³)	MMD (μm)	GSD (--)	
6/11/2021	Blowdown	119	19	1.4	1.8	0.47
5/6/2021	Blowdown	120	34	1.7	1.8	0.39
6/13/2021	Blowdown	415	25	1.7	2.0	0.55
6/12/2021	Blowdown	418	81	1.8	1.9	0.61
4/29/2021	Blowdown	716	20	1.7	2.1	0.47
6/2/2021	Blowdown	717	34	1.9	2.1	0.40
6/3/2021	Blowdown	723	44	2.0	2.0	0.44
6/8/2021	Blowdown	717	79	1.9	1.9	0.36
5/4/2021	Blowdown	717	81	2.0	2.0	0.50
4/28/2021	Blowdown	717	108	2.1	2.1	0.26
6/1/2021	Blowdown	717	115	2.2	2.0	0.40
6/9/2021	Blowdown	717	123	2.1	1.9	0.36
5/3/2021	Blowdown	717	134	2.2	2.2	0.28
5/26/2021	Blowdown	717	141	2.4	2.1	0.31
6/10/2021	Constant Press.	717	25	1.7	1.9	0.41
6/7/2021	Constant Press.	714	89	2.1	2.0	0.33
6/4/2021	Constant Press.	716	119	2.2	2.1	0.35

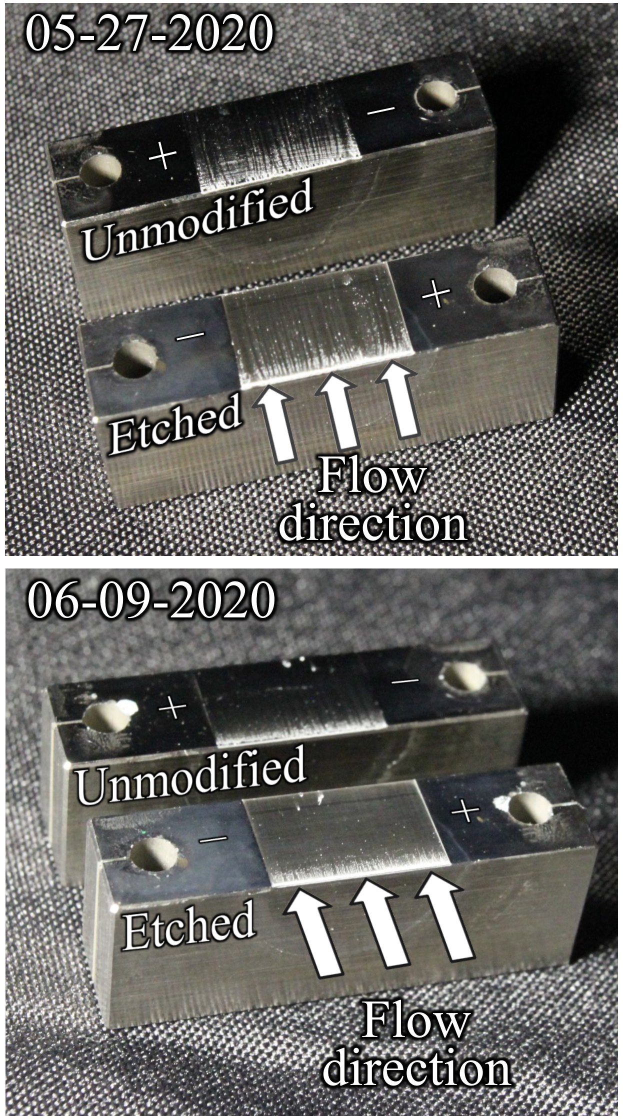
- 17 air tests
  - Mostly blowdowns
  - MMD_o range from 1.4 to 2.4 μm
  - Aerosol mass transmission range from 0.26 to 0.61
  - Average aerosol mass transmission = 0.41

Helium Testing

Date	Test Type	ΔP_o (kPa)	Upstream Initial Conditions			Integrated Transmission
			C_m (mg/m^3)	MMD (µm)	GSD (--)	
6/25/2021	Blowdown	418	36	2.3	1.9	0.32
6/24/2021	Blowdown	417	121	2.8	1.9	0.26
6/30/2021	Constant Press.	417	61	2.6	2.0	0.37
6/29/2021	Constant Press.	418	114	2.5	2.0	0.27
7/13/2021	Blowdown	716	43	1.7	2.0	0.47
6/28/2021	Blowdown	717	75	2.9	1.9	0.23
6/20/2021	Blowdown	739	83	2.5	1.9	0.26
6/17/2021	Blowdown	713	87	2.2	1.8	0.21
6/21/2021	Blowdown	716	139	2.7	1.9	0.23
6/19/2021	Blowdown	719	224	3.1	2.0	0.15
6/29/2021	Blowdown	715	273	3.5	1.9	0.12
6/18/2021	Constant Press.	716	66	2.6	1.9	0.27
6/16/2021	Constant Press.	720	193	2.4	1.9	0.18

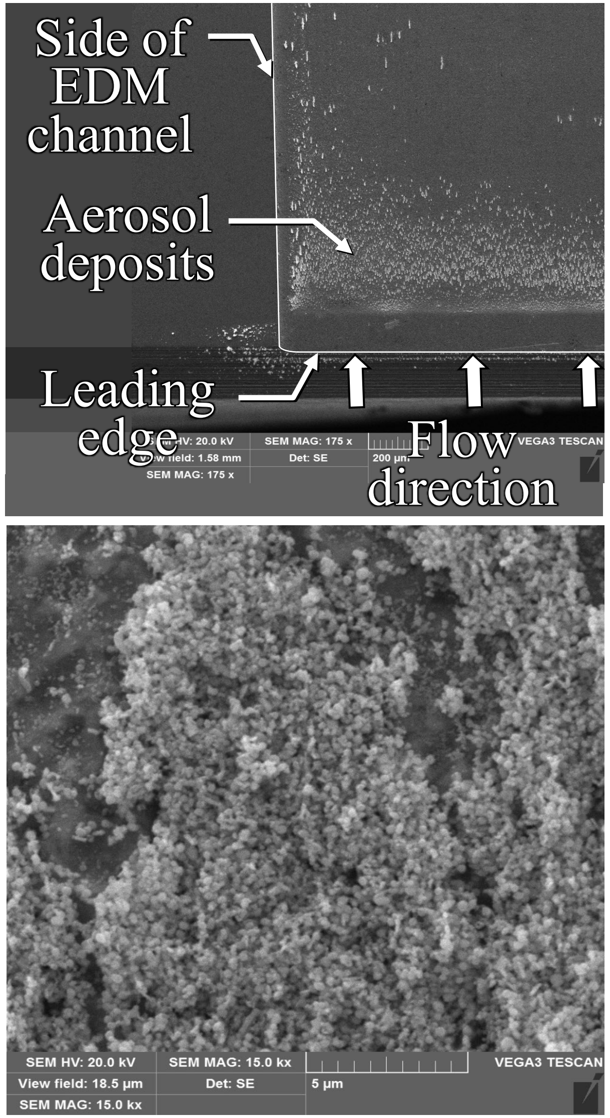
- 13 helium tests
  - Mostly blowdowns
  - MMD_o range from 1.7 to 3.5 µm
  - Aerosol mass transmission range from ~0.12 to 0.47
  - Average aerosol mass transmission = 0.26

Aerosol Deposits



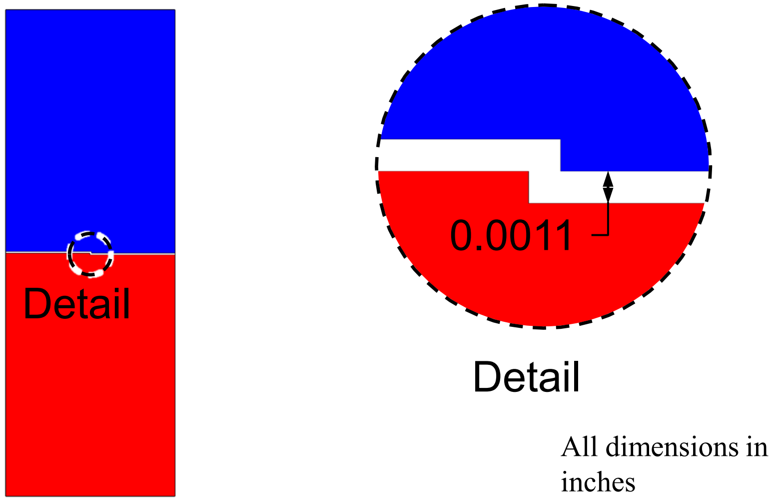
Photographs

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

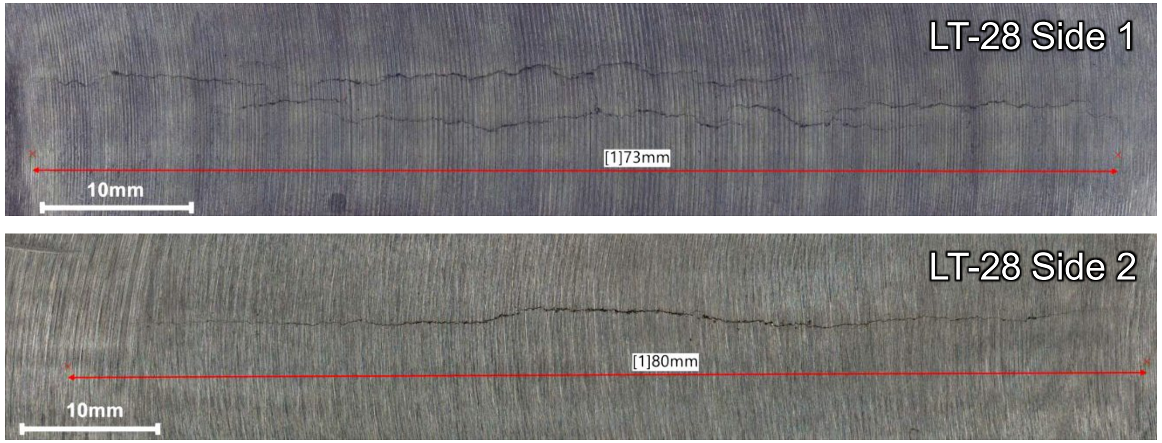


SEM Images

Next Steps in Testing



Stepped channel



Lab-grown cracks

- 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.

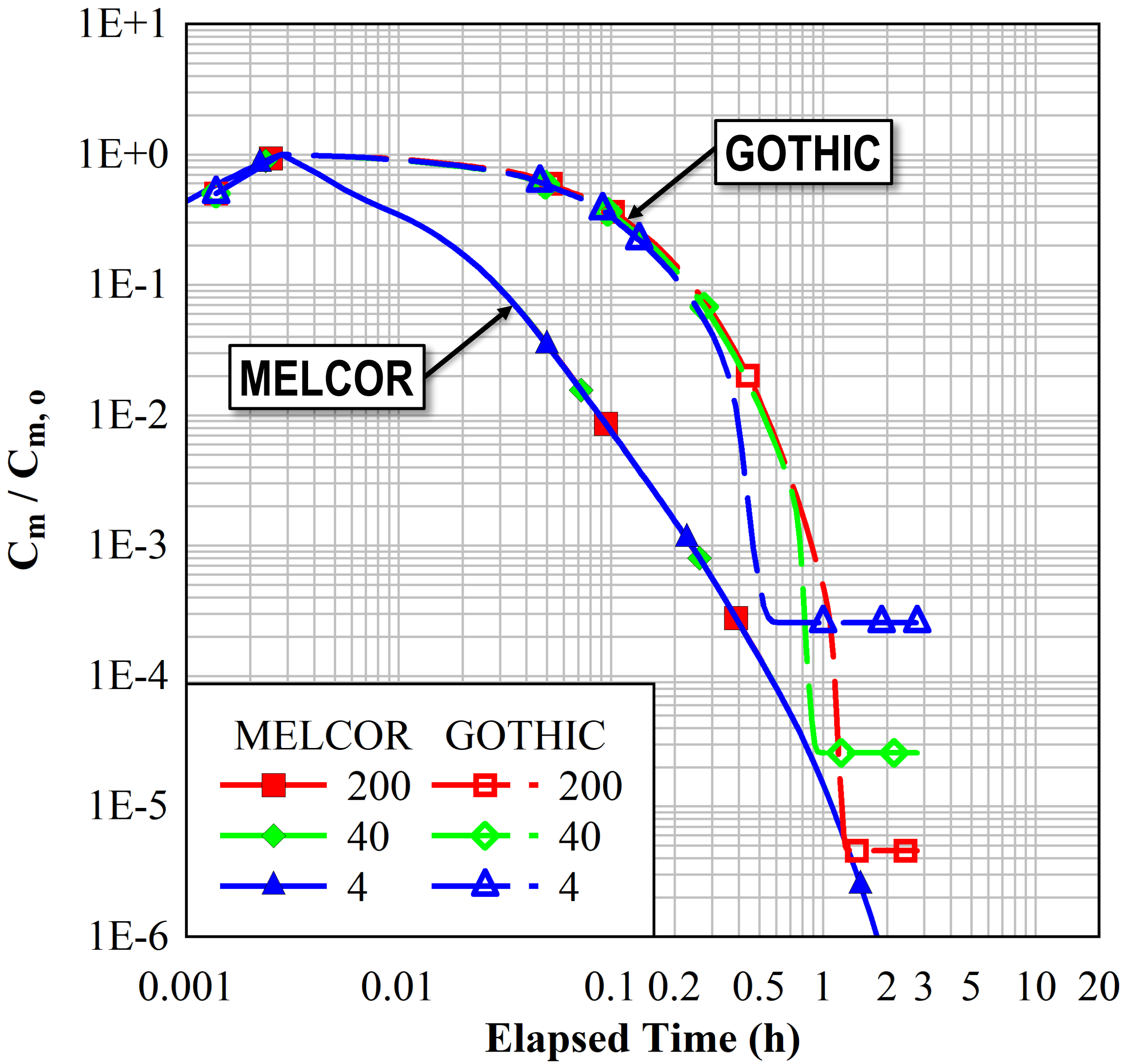
GOTHIC

- 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 ($C_{m,\,o}$)
  - 1% fuel failure → ~200 mg/m^3
    - ~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**

Summary

- 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