INL/MIS-23-74111-Revision-0

Modeling and Measurement of Axial Gas Transport in Nuclear Fuels

August 2023

Changing the World's Energy Future

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Idaho National Laboratory

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Modeling and Measurement of Axial Gas Transport in Nuclear Fuels

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Background

- Axial gas transport plays a crucial role in **determining pressure equilibrium** in nuclear fuel rods
  - Spent fuel storage [1]
  - Loss-of-coolant accident (LOCA) [2]
  - Helium-bonded fast reactor fuel rods
- Permeability currently determined **a posteriori** [3,4]
- Current models assume **instantaneous** pressure equilibrium and laminar flow

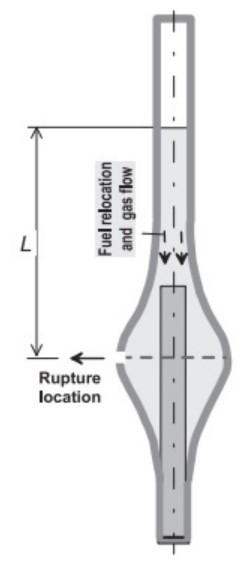

Figure 1: Schematic of gas flow during LOCA

Methodology

- **Verify scalability** of axial gas transport to **enable full microstructural characterization** of specimens for use in model development
- Develop a model for **permeability as a function of microstructural features**

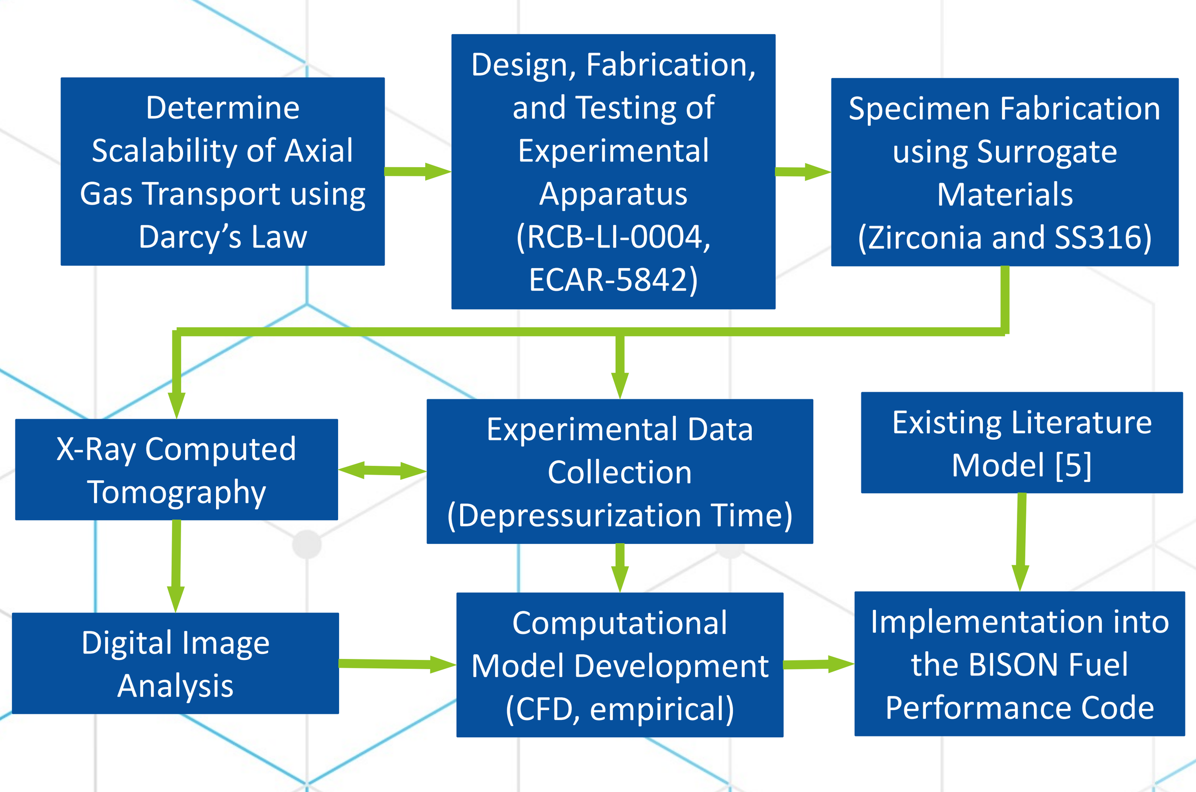

Table 1: List of experimental specimens. Crushed and quenched pellets indicate fracture induced by mechanical and thermal loading, respectively.

Specimen ID	Pellet Status	Number of Pellets	Gap Status
Test tube 1 (TT1)	Crushed	4	Open
Test tube 2 (TT2)	Crushed	8	Open
Control tube 1 (CT1)	Fresh	4	Open
Control tube 2 (CT2)	Quenched	4	Open
Control tube 3 (CT3)	Fresh	6	Closed
Control tube 4 (CT4)	Quenched	4	Closed
Control tube 5 (CT5)	Fresh	8	Closed
Control tube 6 (CT6)	Fresh	4	Closed
Control tube 7 (CT7)	Fresh	4	Closed

Main Research Findings

- Scalability of axial gas transport **confirmed**
- More accurate fracture patterns obtained by **quenching**
- Pressure equilibration is **not instantaneous**
- Gas flow is **turbulent** for short decay times
- Permeability equation developed as a function of **smeared porosity** obtained from image analysis

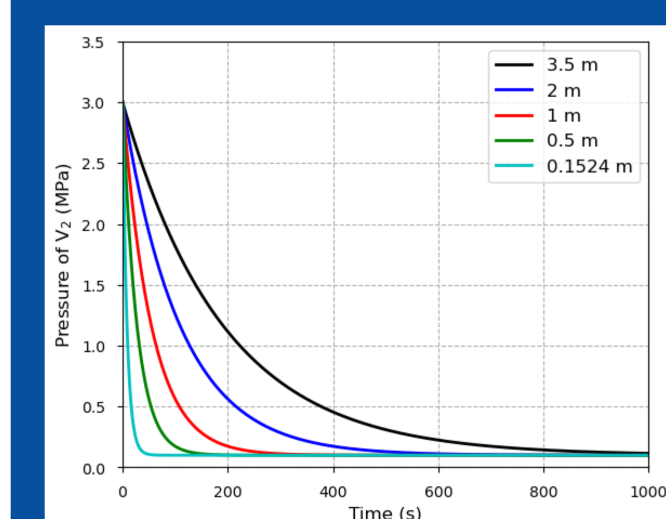

Figure 2: Depressurization as a function of time for varying specimen length

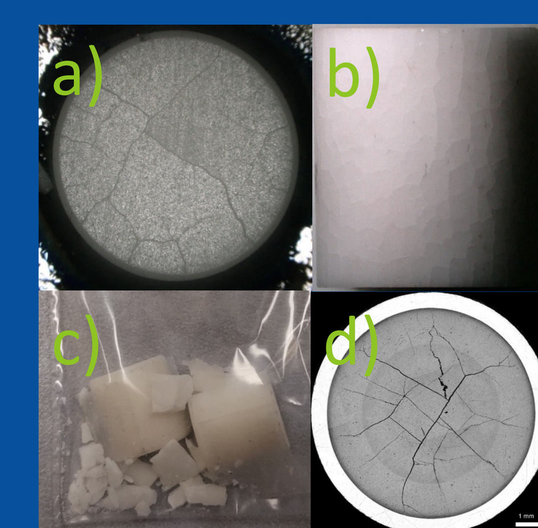

Figure 3: a) Thermal quench (top view) b) thermal quench (side view), c) mechanical crushing, and d) experimental micrograph of irradiated fuel

Laminar Friction Factor (Darcy's Term) — Turbulent Friction Factor (Forchheimer's Term)

$$\frac{\mu \bar{u}}{K_1} + \frac{\rho \bar{u}^2}{K_2}$$

$$K_1 = C_1 \frac{\epsilon_s^3}{(1-\epsilon_s)^2} \qquad K_2 = C_2 \frac{\epsilon_s^3}{(1-\epsilon_s)}$$

ϵ_s = smeared porosity; $\bar{u}$ = velocity; μ = dynamic viscosity; ρ = density; C_1, C_2 = pressure-dependent constants

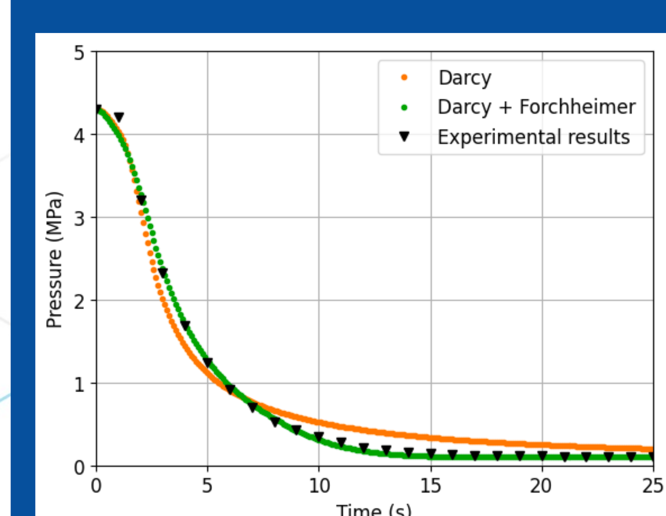

Figure 4: Best-fit curves included and excluding Forchheimer coefficient for experiment TT1 at an initial pressure of 4.3 MPa

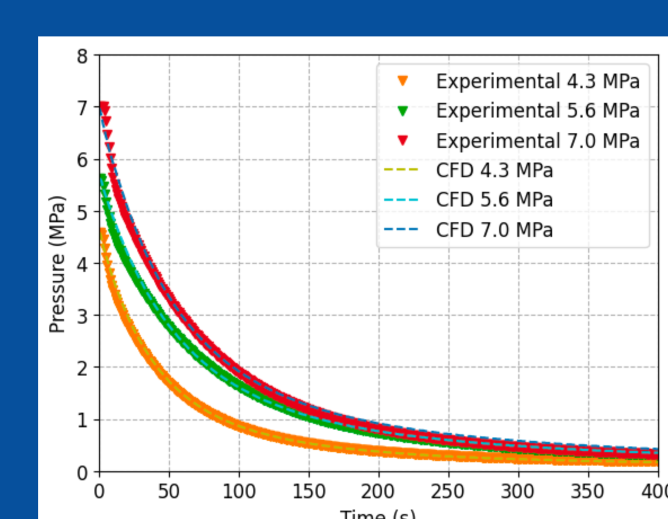

Figure 5: Best-fit curves excluding the Forchheimer coefficient for experiment CT4 at different pressure levels

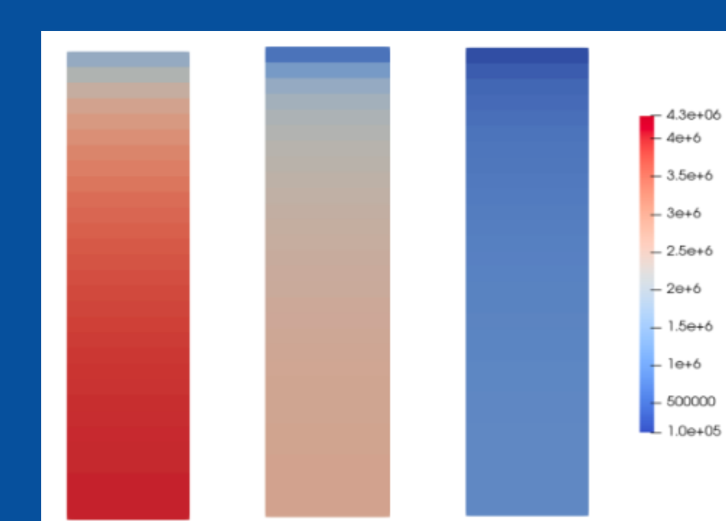

Figure 6: Snapshots of computational fluid dynamicssimulation of CT4 with initial pressure of 4.3 MPa

Publications

[1] C. Genoni, et al., "Modeling and Measurement of Axial Gas Transport in Nuclear Fuels," ANS Annual Meeting, June 2023.
[2] S. Kwon, et al., "Fabrication of Surrogate Oxide Spent Fuel with Various Cracking Patterns and the Design of an Axial Gas Transport Apparatus," to be submitted to the Journal of Nuclear Materials.
[3] C. Genoni, et al., "Investigation of the Impact of Non-Uniform Permeability on Axial Gas Transport within Light Water Reactor Fuel Rods during a Loss-Of-Coolant Accident," to be submitted to Nuclear Engineering and Design.
[4] T. Bergomi, "Fuel Pellets Three-Dimensional Properties Reconstruction Exploiting Image Analysis: A Bridge Between Experiments and Modeling", Masters Thesis, Politecnico Di Milano, expected 2024.

Specimen Fabrication and Experimental Apparatus

- Decay of **inlet pressure measured** as a function of time
  - 4.3, 5.6, and 7 MPa analyzed
- Quenching and mechanical crushing used to **induce** fracture
- Mylar wrapping used to **preserve** pellet position

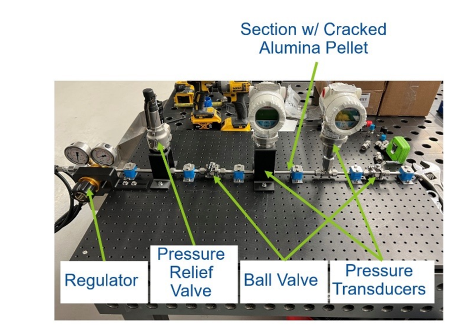

Figure 6: Experimental apparatus

Figure 7: Photo of (a) pellets with mylar wrapping, (b) mechanical compression of individual pellet, and (c) resulting separation-crack formation

Digital Image Analysis

- **Hundreds** of two-dimensional (2D) images obtained per specimen by x-ray computed tomography (CT)
- Image analysis used to estimate features
  - Crack tortuosity
  - Specific surface
  - Porosity distribution
- **3D reconstruction** of the pellets can be performed

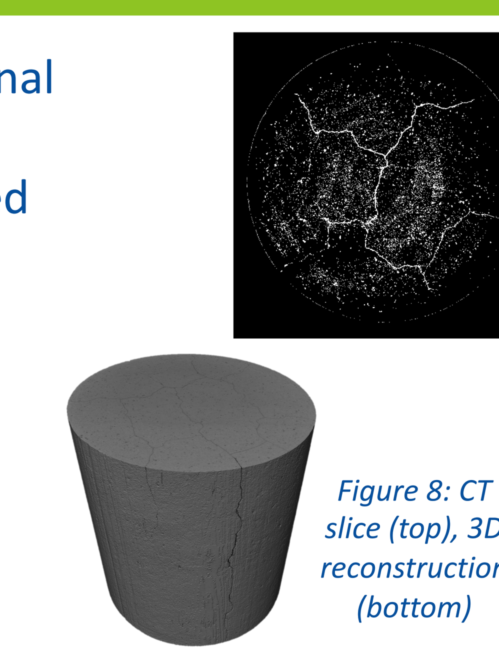

Figure 8: CT slice (top), 3D reconstruction (bottom)

References

[1] V. Rondinella et al., TopFuel 2015. JRC94524.
[2] W. Wiesenack, et al. International Conference on the Physics of Reactors, 2008.
[3] R. Montgomery and R. N. Morris, doi: doi.org/10.1016/j.jnucmat.2019.05.041.
[4] S. J. Dagbjartsson, et al., TREE-NUREG-1158, 1977.
[5] Khvostov, G., et al., doi: doi.org/10.1016/j.nucengdes.2011.03.003.

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