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Axial Gas Communication Modeling with BISON

April 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Idaho National Laboratory

Presentation Overview

- Introduction
- Laboratory Directed Research and Development (LDRD) Project
- Axial Gas Communication Framework in BISON
- Halden Experiments for Gas Communication and Small Plenums
- Conclusions
- Future Work

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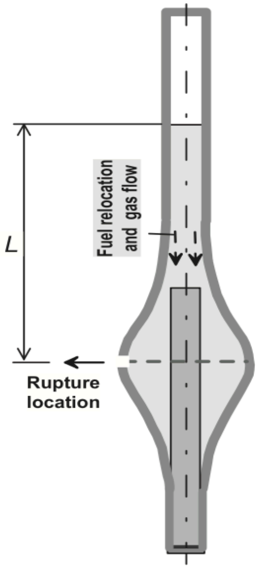
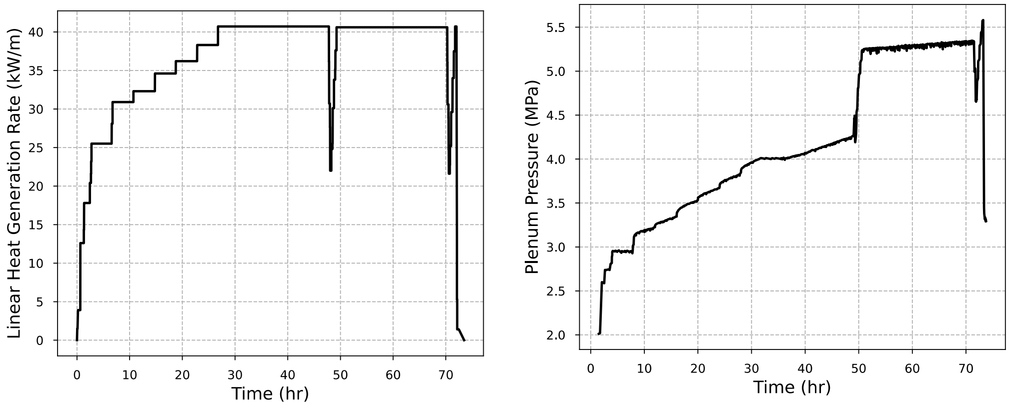
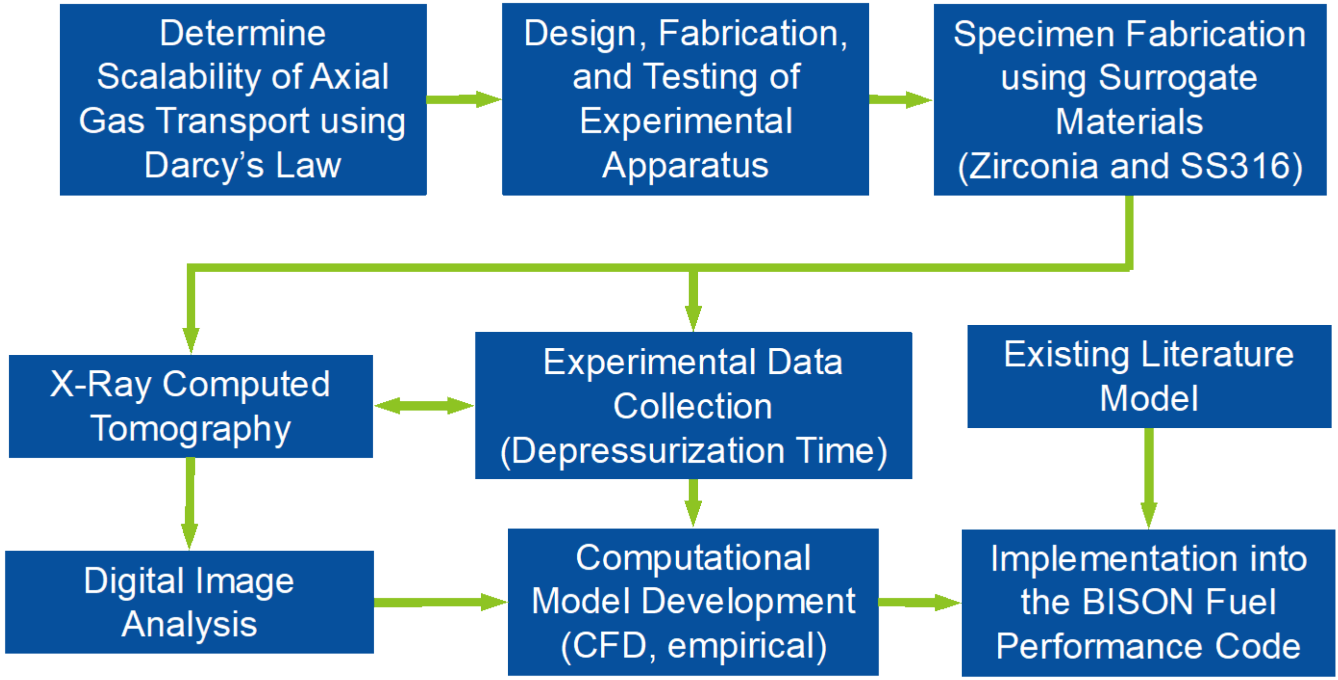
Goals and Purpose

- Enable modeling of axial gas communication to evaluate its impact on:
  - Rod internal pressure evolution during power downs under ramping conditions
  - Depressurization times during LOCA conditions
  - Balloon size and shape
  - Fuel dispersal predictions
  - Small plenum rod behavior
- The model will:
  - Capture flow through an open fuel to clad gap
  - Capture flow through a porous media represented by fragmented fuel
  - Capture flow through intact but cracked fuel pellets when the gap is closed or fuel to clad bonding is present



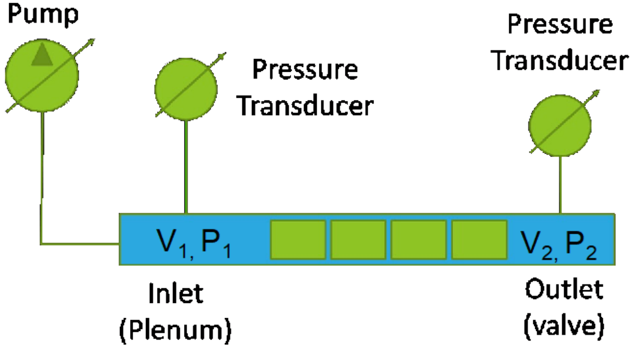


Experimental Power and Pressure from Risø AN3

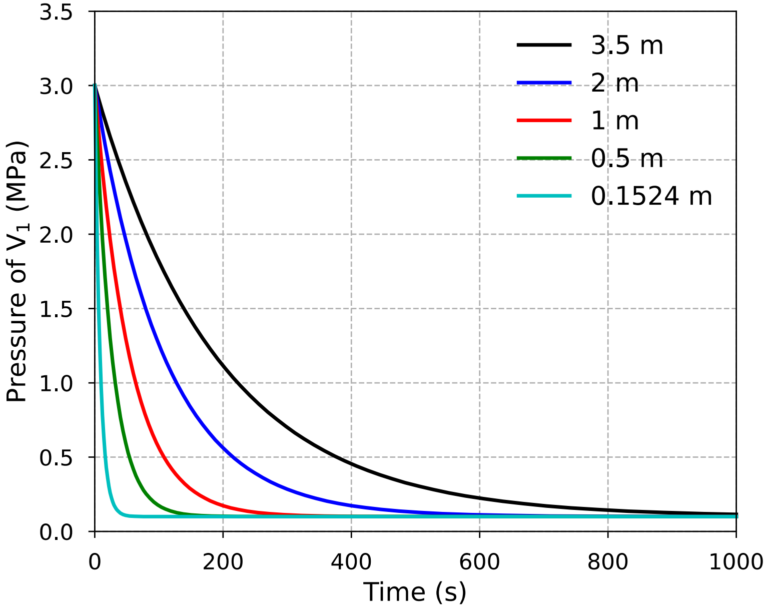


Gas Communication Scalability

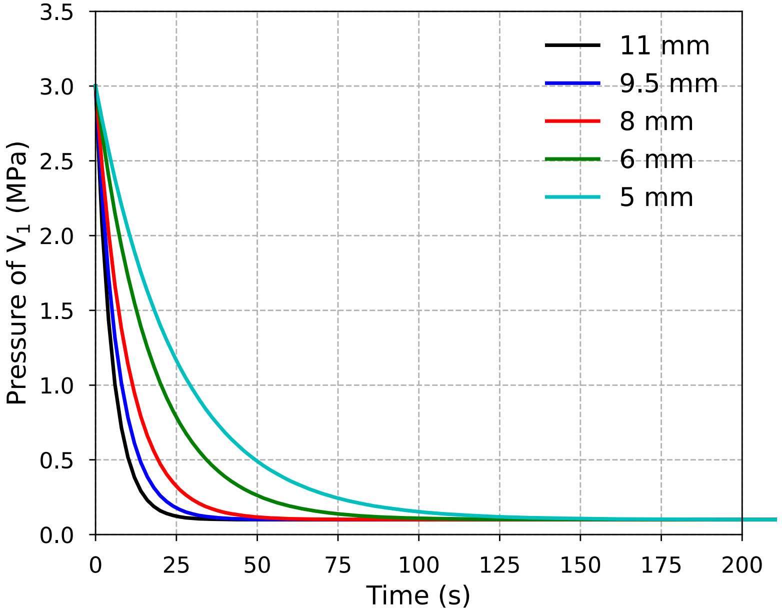
- Consider a simple scenario:
  - V_1 = 12.5 cm^3
  - V_2 = Atmosphere
  - $\mu = 1.79\times10^{-5}$ Pa-s
  - $K = 2\times10^{-14}$ m^2
  - P_i = 3 MPa
  - P_2 = 0.1 MPa
- Case 1: D = 9.5 mm, vary length
- Case 2: L = 0.1524 m, vary diameter



$$P_1 = P_2 + (P_{1i} - P_2) * \exp\left(-\frac{K\pi D^2 (P_{1i} - P_2)}{4\mu V_1 L} t\right)$$



Case 1

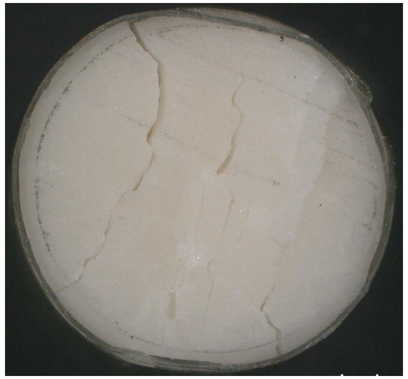


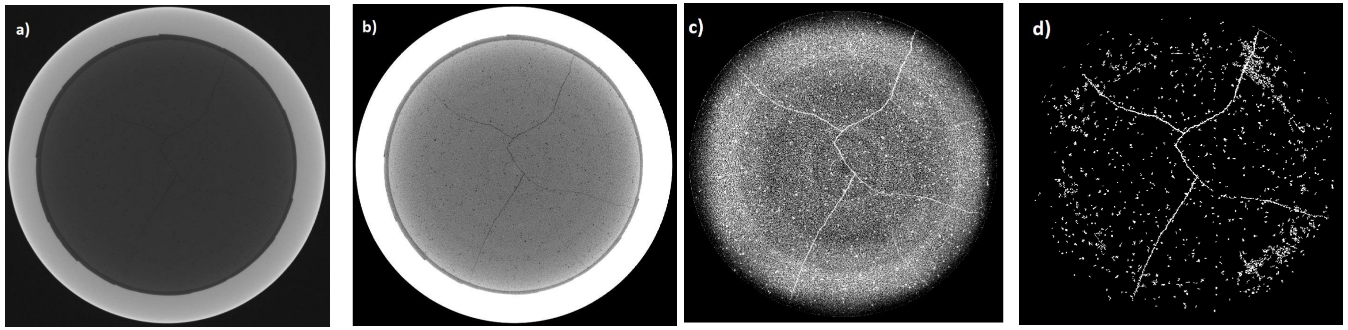
Case 2

Rondinella et al., "Measurement of gas permeability along the axis of a spent fuel rod," *TopFuel* 2015.

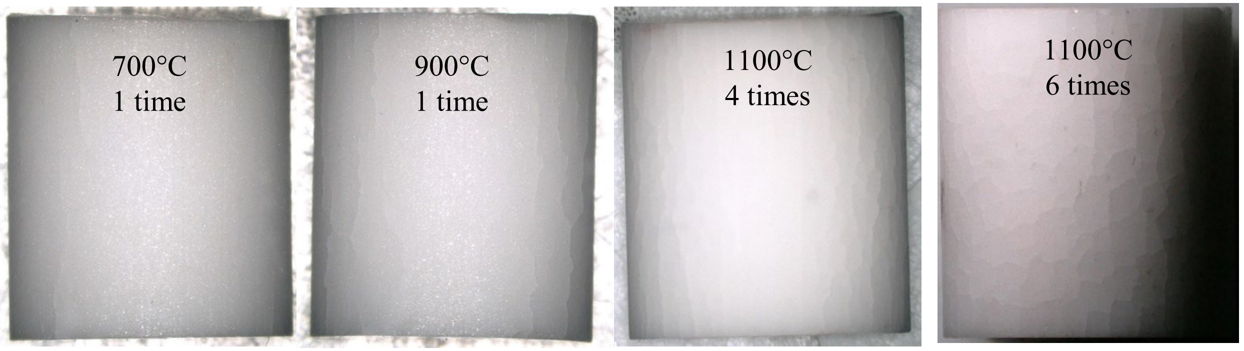
Specimen Fabrication, Characterization, and Experimental Apparatus

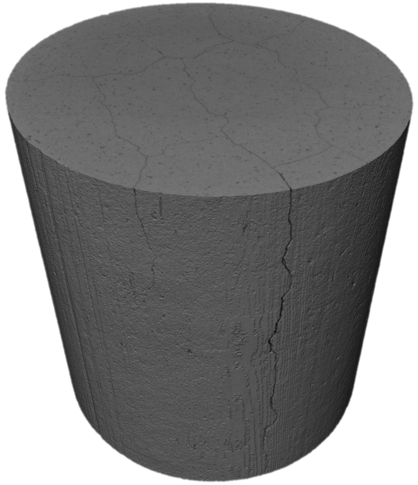
- Two different approaches for fragment formation considered
  - Thermal quenching
  - Mechanical crushing using Instron
- Computed X-ray tomography used for each experimental specimen.
  - Image analysis used to estimate microstructural features
  - 3D reconstruction can be performed

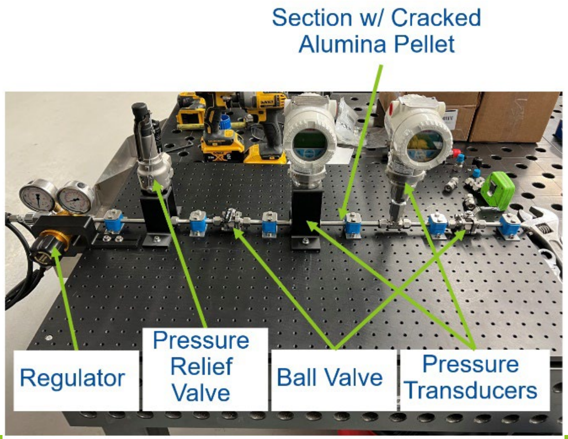




Original X-ray Image | Autocontrast and Image Negation | Cropping Pellet Region | Crack Segmentation



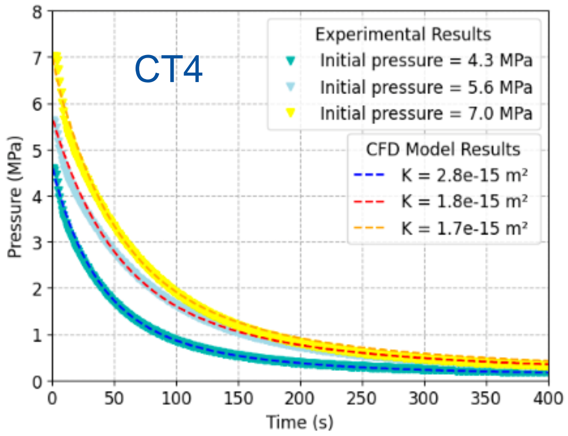


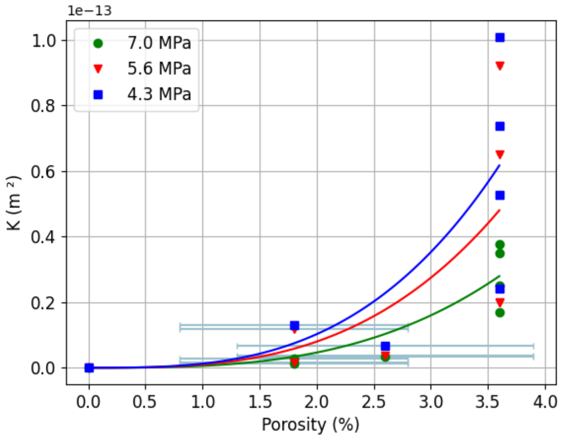


Experimental Measurements and Modeling

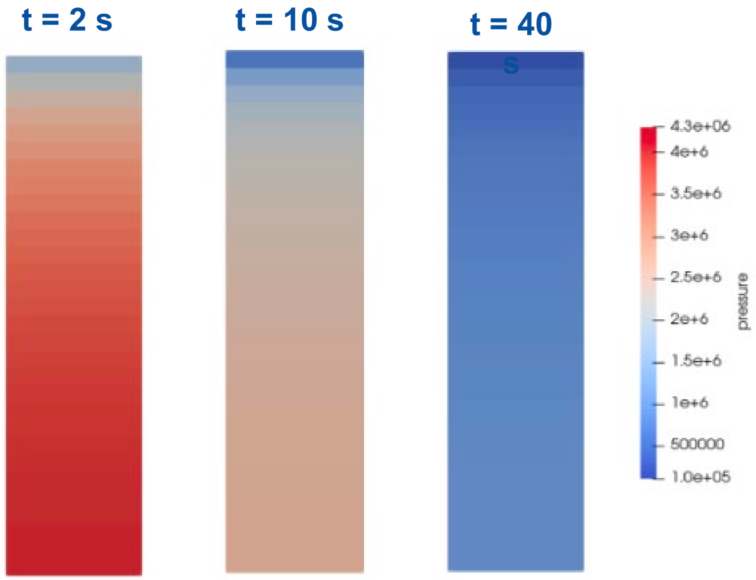
Average permeability values:
JRC-ITU: 2×10^{-13} m^2
ORNL: 4.5×10^{-14} m^2

- Perform multiple runs at three different initial pressures
  - 4.3 MPa, 5.6 MPa, 7 MPa
- Several specimens created using different crack formation techniques, length of pellet stack, and gap closure status
- Utilize weakly compressible Navier Stokes computational fluid dynamics (CFD) capabilities available in MOOSE to predict depressurization curves
- Evaluate closed and open gap configurations and determine whether flow is laminar or turbulent
- Explore impact of pellet positioning on pressure decay rates
- Develop a correlation for permeability as a function of microstructural features





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

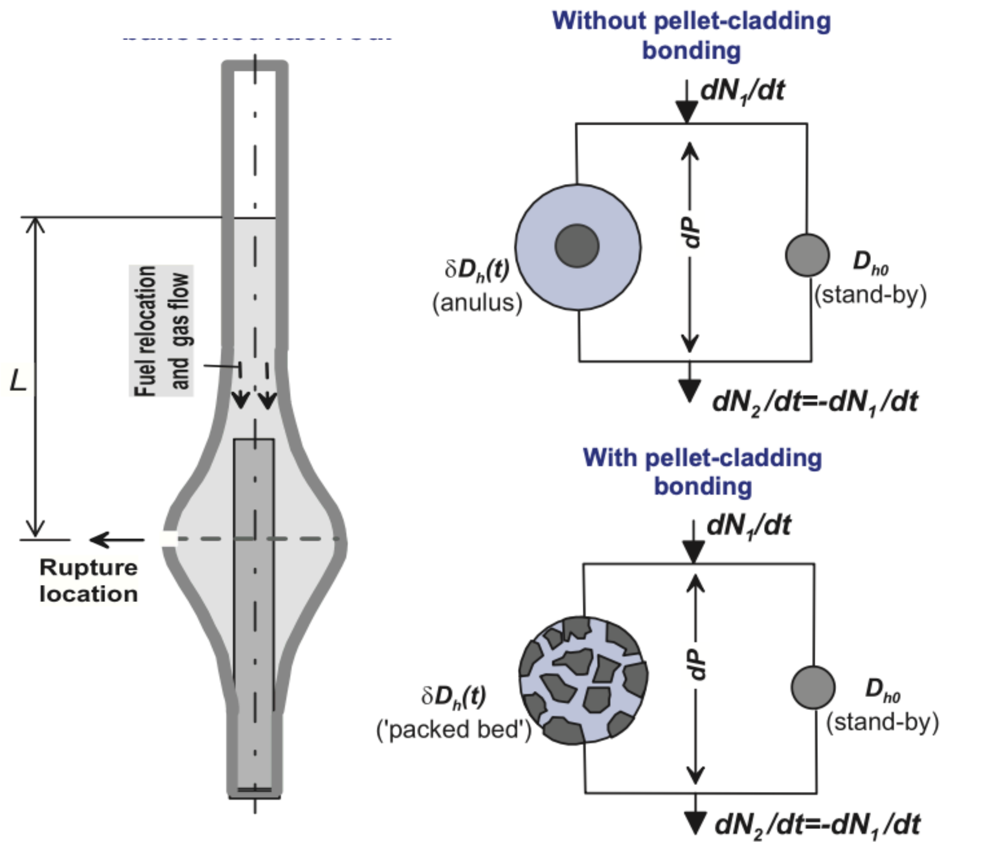


Snapshots of computational fluid dynamics simulation of CT4 with initial pressure of 4.3 MPa

Rondinella et al., "Measurement of gas permeability along the axis of a spent fuel rod," *TopFuel* 2015.
R. Montgomery and R. N. Norris, "Measurement and modeling of the gas permeability of high burnup pressurized water reactor fuel rods, *JNM*, 2019.

Axial Gas Communication in BISON: Framework Implementation

- Points below the rupture are considered to instantaneously deplete until an equilibrium of the outside pressure is met
- For points above the rupture point two paths for gas flow exist:
  - Traveling in the gap between the fuel and cladding
  - Moving through the dispersed voids within the fuel (cracks or porosity)
- Methodology implemented in 1.5D framework in BISON to readily couple to fuel relocation as needed
- To always permit flow through all possible flow paths a change to the method is required to account for total gas volume in each layer
- Fission gas release both during normal operation and transients is inherently included in the algorithm



$$V_g = h_{layer}\,\pi\left(r_{clad}^{2} - r_{fuel}^{2}\right) + F_{leak}$$

$$F_{leak} = h_{layer}\,p\,\pi\,r_{fuel}^{2}$$

$$p = 1 - \phi$$

p = porosity
V_g = gas volume
h_{layer} = layer height
r_{fuel} = fuel radius
r_{clad} = inner clad radius
ϕ = packing fraction

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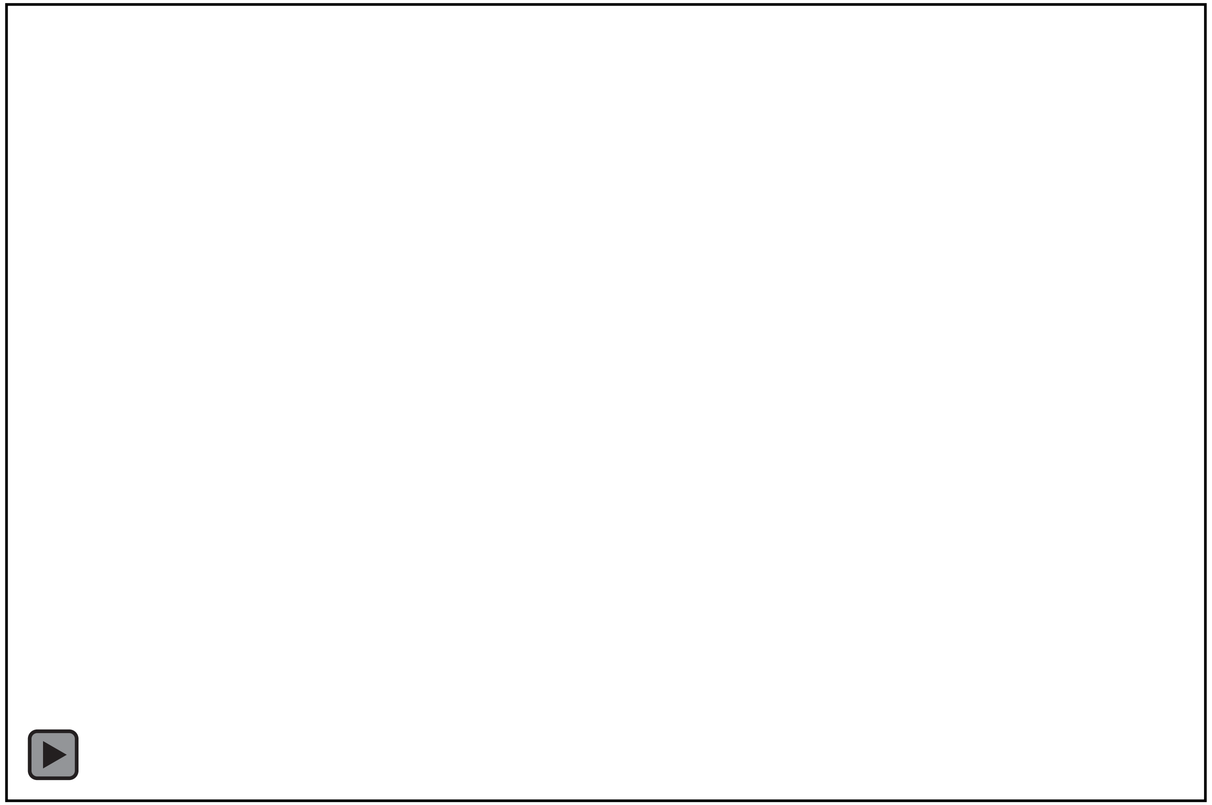
Axial Gas Communication in BISON: Verification

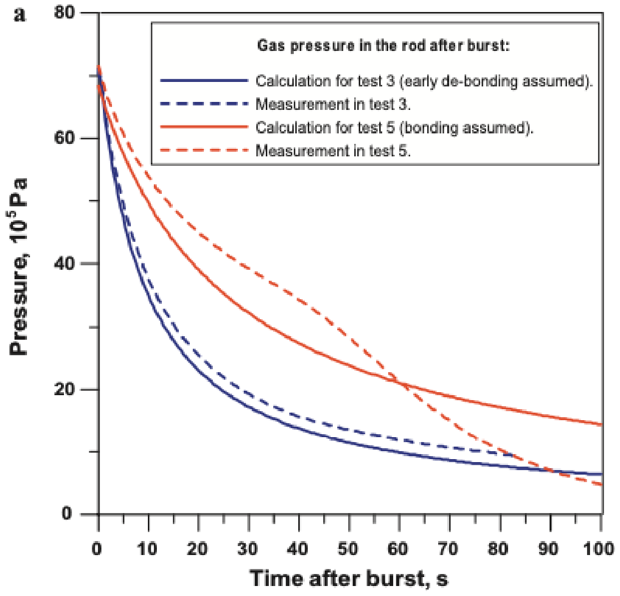
- Simple regression tests are developed to ensure the algorithms are correct
  - i.e., conservation of mass, ideal gas equation, flow limits

- Animation shows gas evacuating for each layer
  - Fuel-cladding gap only in this animation
  - Plenum is top 3 layers
  - Fuel has 30 layers

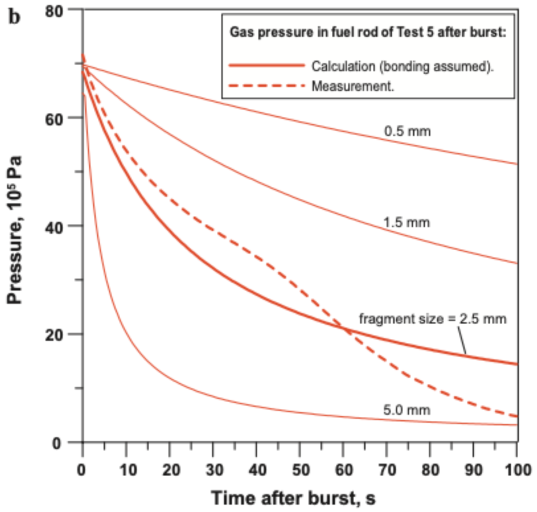


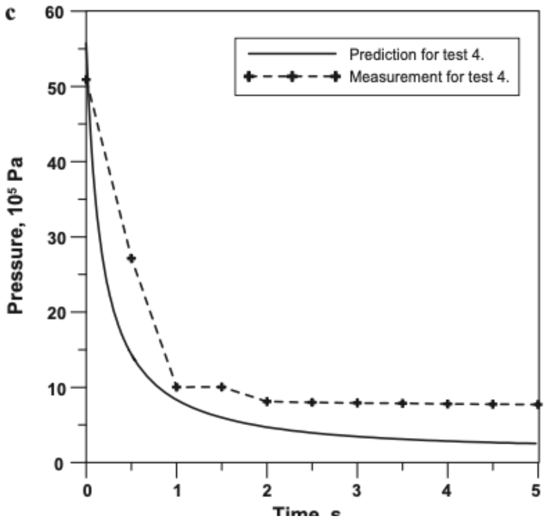
Axial Gas Communication in BISON: Validation

- Validation is planned against the IFA-650 cases which have the evacuating plenum pressure as a function of time
- These cases are already within the BISON repository
- Additional regression tests for verification of the algorithms are needed before validation against the experiments
- Validation to available SCIP experiments.



Results of model calibration by measured gas pressure in the plenum during the post-burst phase of tests 3 and 5 (a), against sensitivity study of the effect of fuel fragment size (b) and prediction for test 4 made with the calibrated parameters (c).





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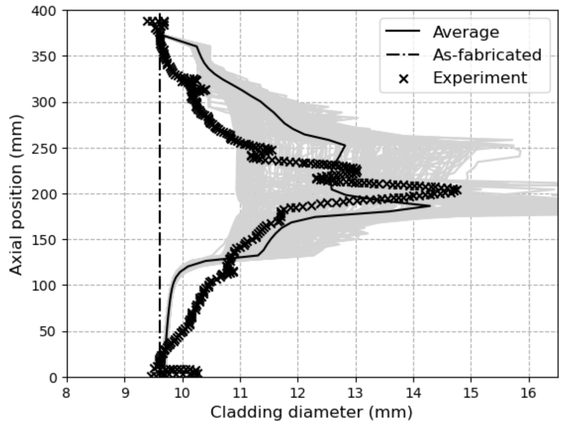
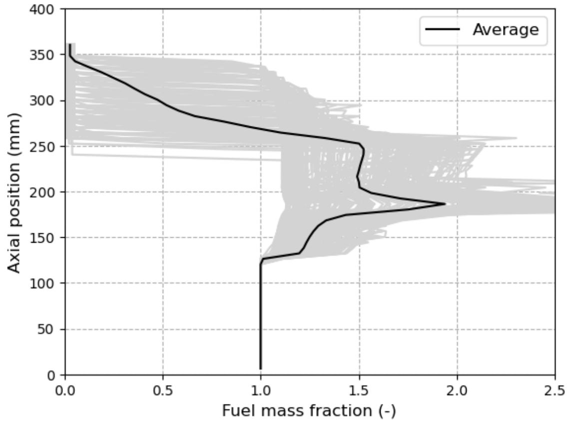
BISON Simulation of Small Plenum Case

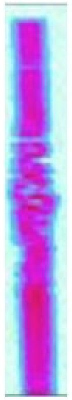
- Simulation of IFA-650.14, a small plenum LOCA experiment conducted at Halden
  - Rod inner free volume 1.9 cm^3
  - No cladding rupture
- It is hypothesized that smaller plenums will yield restricted gas flow and prevent cladding rupture
- Initial simulation of this case neglects gas communication and focuses on cladding deformation and fuel relocation
- Sensitivity study on axial fuel relocation model parameters, mesh density, and thermal hydraulic conditions (radiative heat transfer)

$$h_r = \epsilon\sigma\left(T_c^2 + T_h^2\right)(T_c + T_h) \qquad \epsilon = \epsilon_c\epsilon_h R_h\,(\epsilon_c R_c + \epsilon_h R_h - \epsilon_c\epsilon_h R_c)^{-1}$$

Parameter	Uncertainty Range	Distribution
Gap thickness threshold (m)	$[0.1\times10^{-3}:0.5\times10^{-3}]$	Uniform
Non-relocatable fuel fraction (-)	[0.005:0.05]	Uniform
Pulver characteristic length (μm)	[50:500]	Uniform
Maximum inelastic increment (-)	[0.0001:0.01]	Uniform
Effective emissivity during radiation (-)	[0.4:0.75]	Uniform







Conclusions

- The scalability of gas communication has been determined on a demonstration problem.
- Surrogate materials have been used to create specimens that can be fully characterized to obtain data about microstructural features.
- Characterized specimens used in simulations of fluid flow using the Navier Stokes module in MOOSE.
- Preliminary equations as a function of crack proportion/porosity and initial inlet pressure have been developed on the surrogate materials.
- Verification of proper implementation of literature model with necessary modifications is almost complete.
- Validation of the parallel approaches (CFD and literature model) to modeling gas communication is ongoing.
- BISON simulations of cladding ballooning of a rod with a small plenum predicts no burst as experimentally predicted.

Future Work

- Incorporate equation for permeability as a function of microstructural features into literature-based model.
- Incorporate gas communication model into existing ramp validation cases to explore where increases in release detection are associated with potential trapped gas due to PCMI or microcracking of the fuel on power downs
- Finish validation to existing experiments with measurements of pressure decay post rupture
- Explore impact on coupled tFGR and gas communication on ballooning behavior
- Include gas communication in multi-rod analyses where adjacent rods interact with one another.

Acknowledgments

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- LDRD Team: Fabi Cappia, Seongtae Kwon, Chase Christen, Kastubh Bawane, Chiara Genoni, Tommaso Bergomi

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