Reaction-Induced Changes to Structure and Transmissivity of Foamed Wellbore Cements

NATIONAL ENERGY TECHNOLOGY LABORATORY

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Disclaimer

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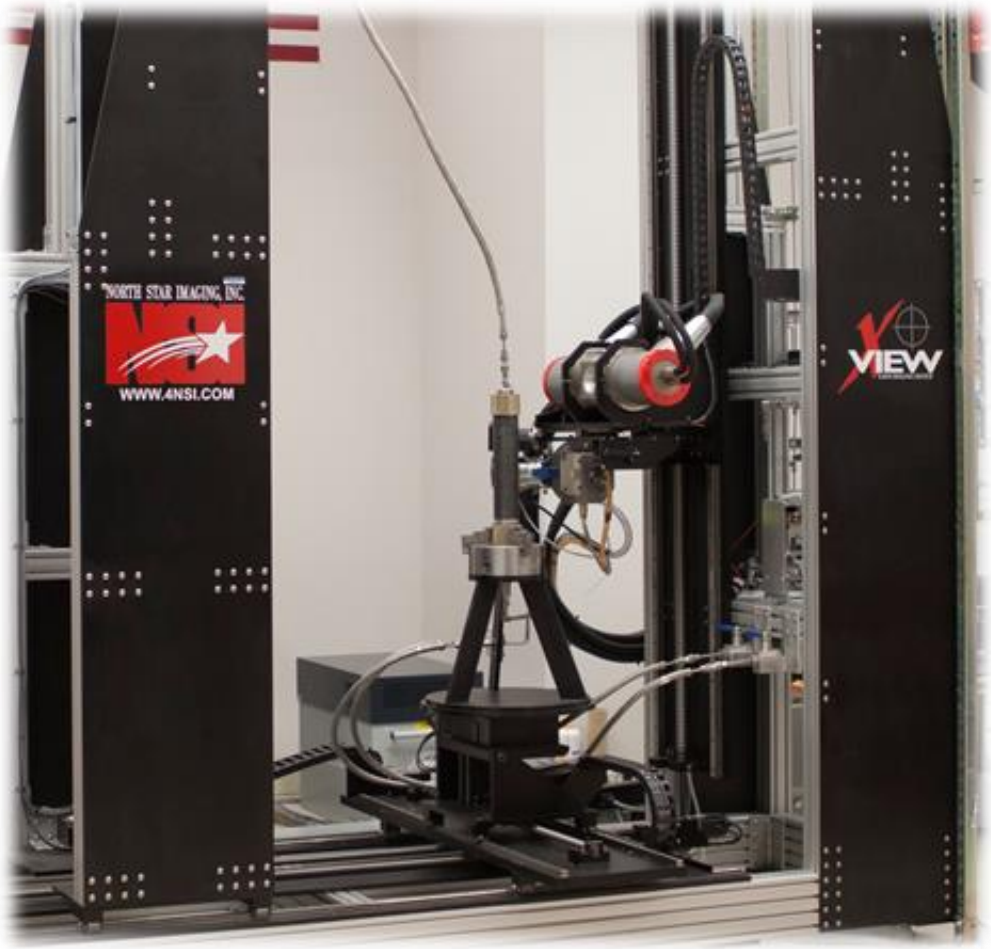
Abstract

Foamed cement is used in deep well construction for its strength, versatility, and ease of density adjustment by changing the gas fraction during slurry injection. When well cement is fractured it may encounter formation and injected fluids. Understanding potential reaction-induced changes in wellbore cement is crucial to managing well integrity in these situations.

To examine the alteration of a fractured foamed cement in a geologic carbon storage system, six Portland class H foamed cement samples were created with different gas fractions, fractured, and exposed to flowing CO_2-acidified water (carbonic acid) over a period of several days. The experiments were conducted at room temperature, under a confining pressure of 8.27 MPa, pore pressure of 5.52 MPa, and were periodically imaged with a Computed Tomography (CT) scanner. The differential pressure across the sample was measured during the experiment to evaluate changes in fracture conductivity.

Image analysis of the progressive changes in the matrix shows that foamed cements are a heterogenous material with varying degrees of susceptibility to reactive liquids. The transformation of cement matrix suggests both matrix dissolution and mineralogic alteration play a part as the reaction front migrates through the sample, with principal reacted zones residing in the immediate vicinity of the fracture. We present a discussion of the morphological changes observed in CT data in the cement matrix, coupled with an analysis of simulated fluid flow paths through the altered fracture geometry and transmissivities as the cement matrix reacts with carbonic acid.

Experimental Setup



Foamed cement: versatile material in well casing

Cement integrity vital for long term well integrity in variety of energy applications: EOR, CCS

Goals

- Visualize medium-term changes to fractures exposed to carbonic acid
- Assess principal flow path development
- Assess changes to fracture transmissivity

Samples

- Portland Class H cement
- Cores fractured using Brazilian technique

Experiment

- Injected with DI water at equilibrium with CO_2
- Flow rate 0.2 ml/min
- Confining pressure 1,200 PSI
- Pore pressure 800 PSI
- Periodically scanned with CT scanner
  - Industrial NorthStar M5000 scanner

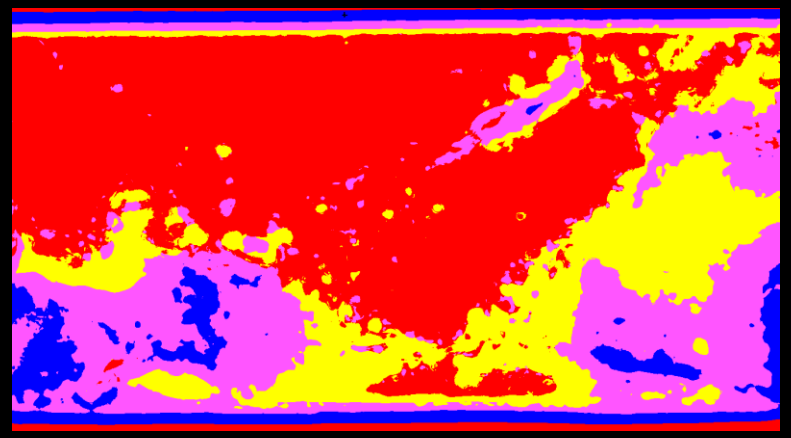
Image Processing

Image segmentation performed with ilastik

- Random forest classifier with user directed pre-filters and training
- User-defined classifiers changed depending on core reaction state

Image processing with Fiji/ImageJ

- Noise reduction, image scaling, cropping

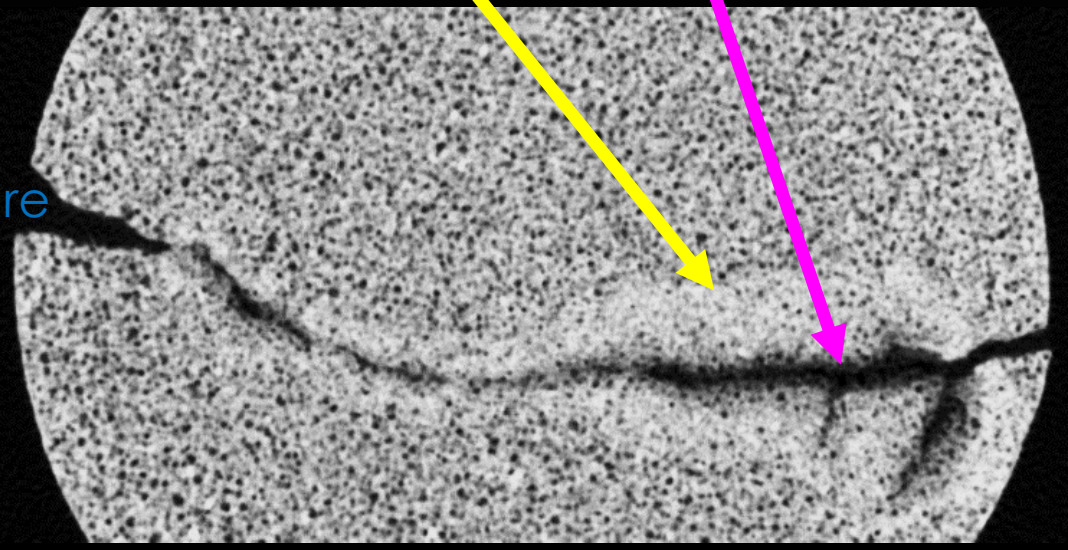


Cement

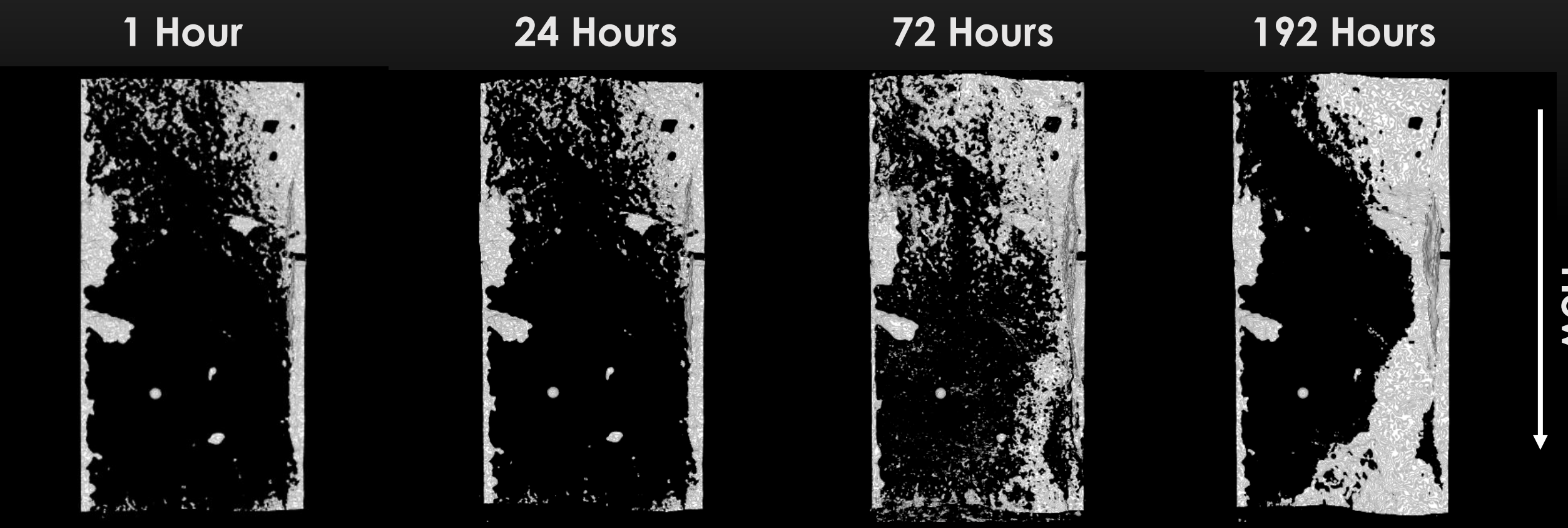
Fracture

Proximal Reaction

Distal Reaction

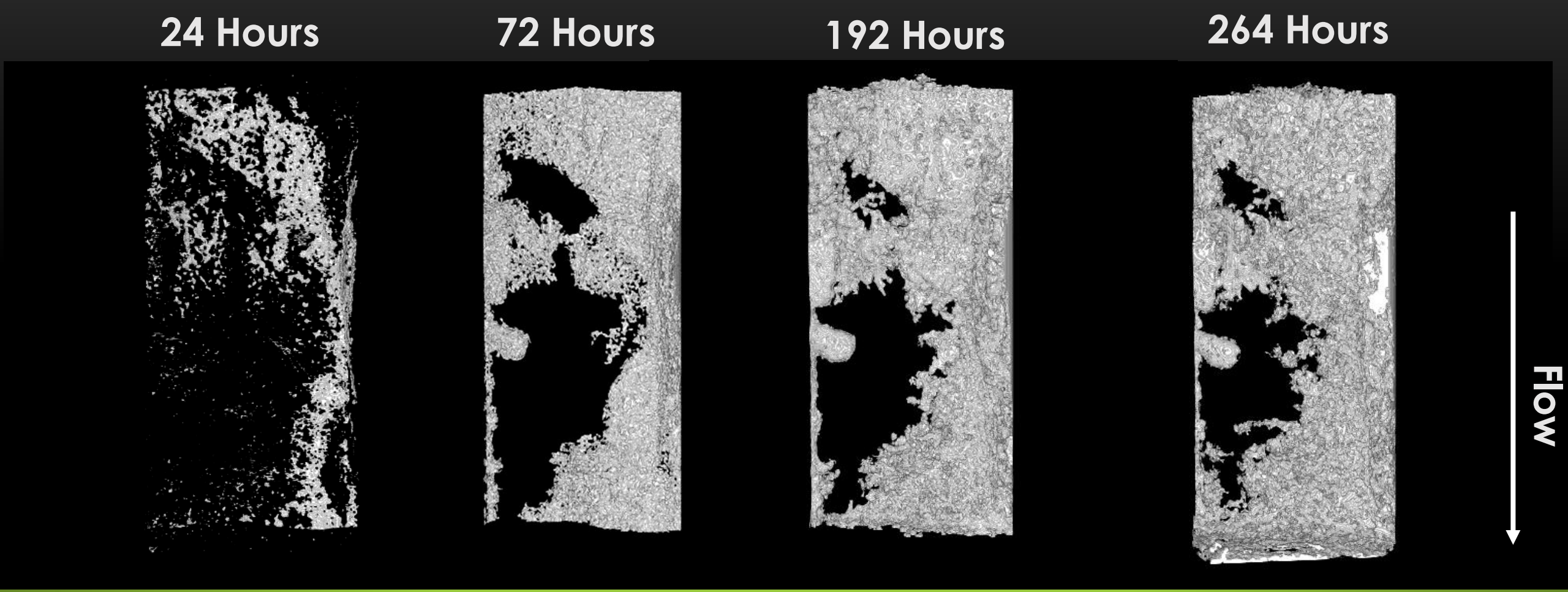


Cement Sample A



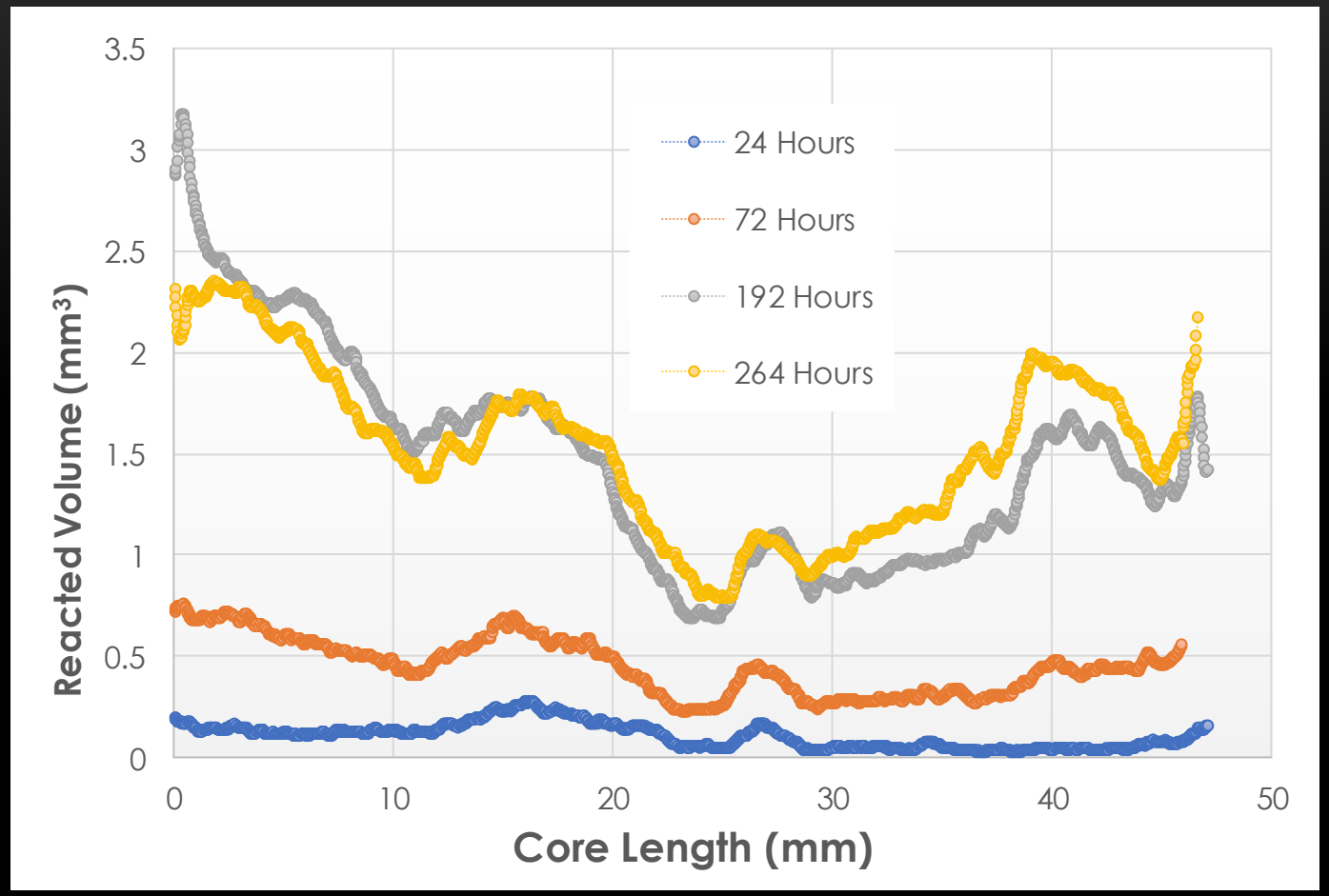
Cement Sample A

Bulk Reaction Zone Development



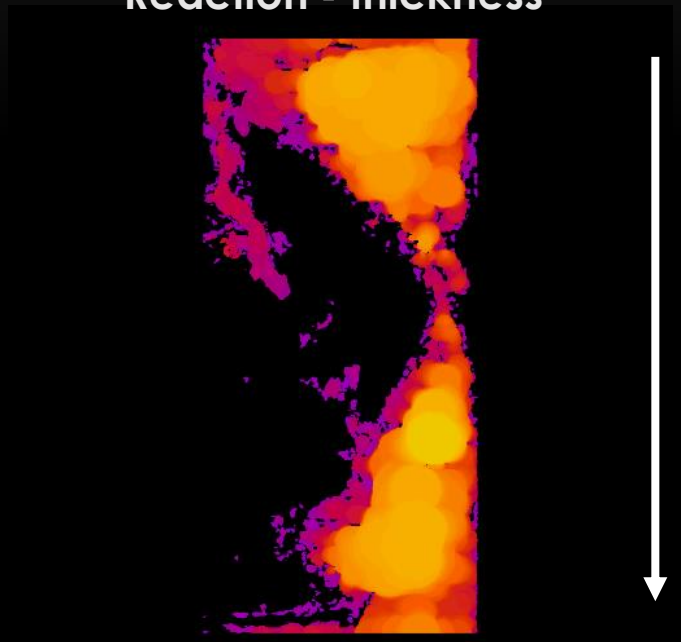
Cement Sample A

Bulk Reaction Zone Development



- End effects – reaction at core ends most pronounced, particularly at inlet

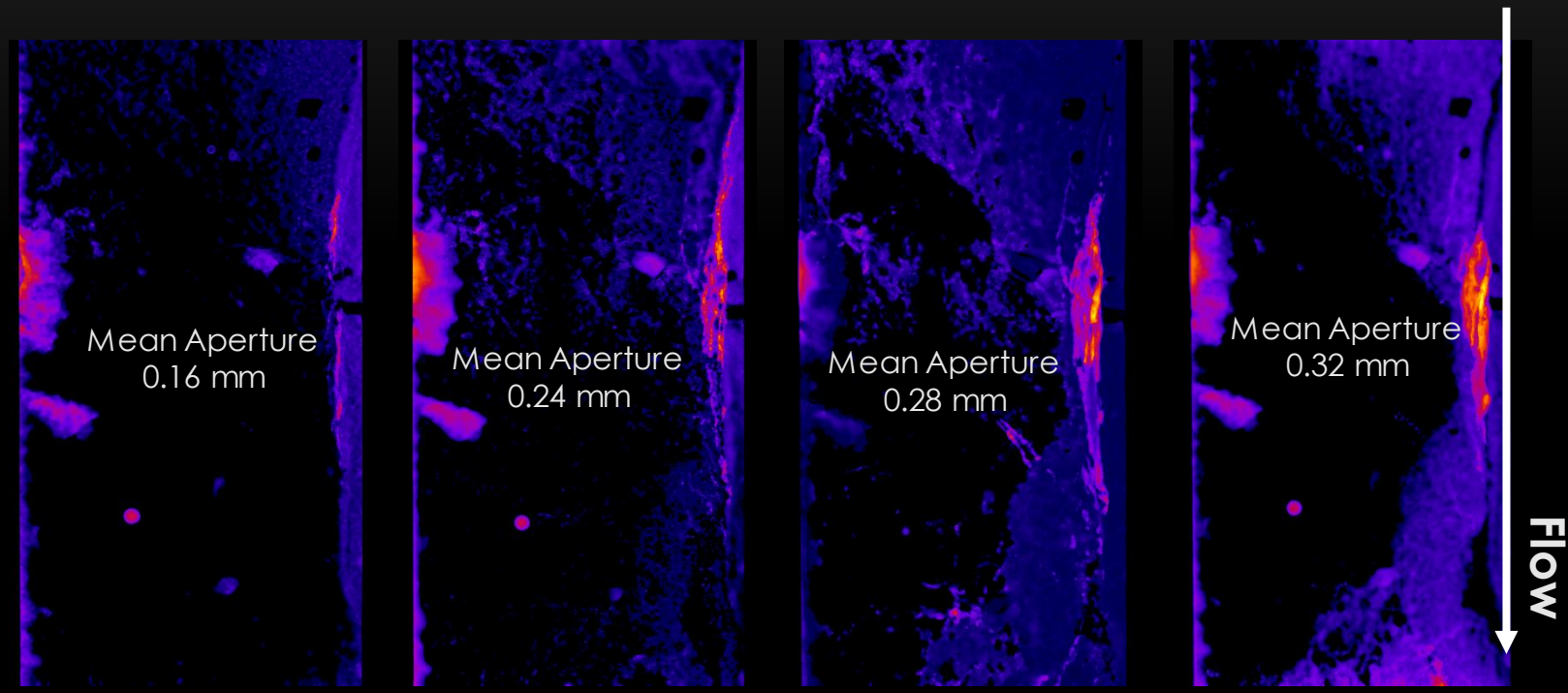
264 Hour
Reaction - thickness



Cement Sample A

- In early stages, large portions of fracture are too tight to segment at the 17 µm scan resolution
- Mean and maximum fracture apertures increase over course of experiment

CarbCem4 - 1hr | CarbCem4 - 24hr | CarbCem4 -72hr | CarbCem4 - 192hr

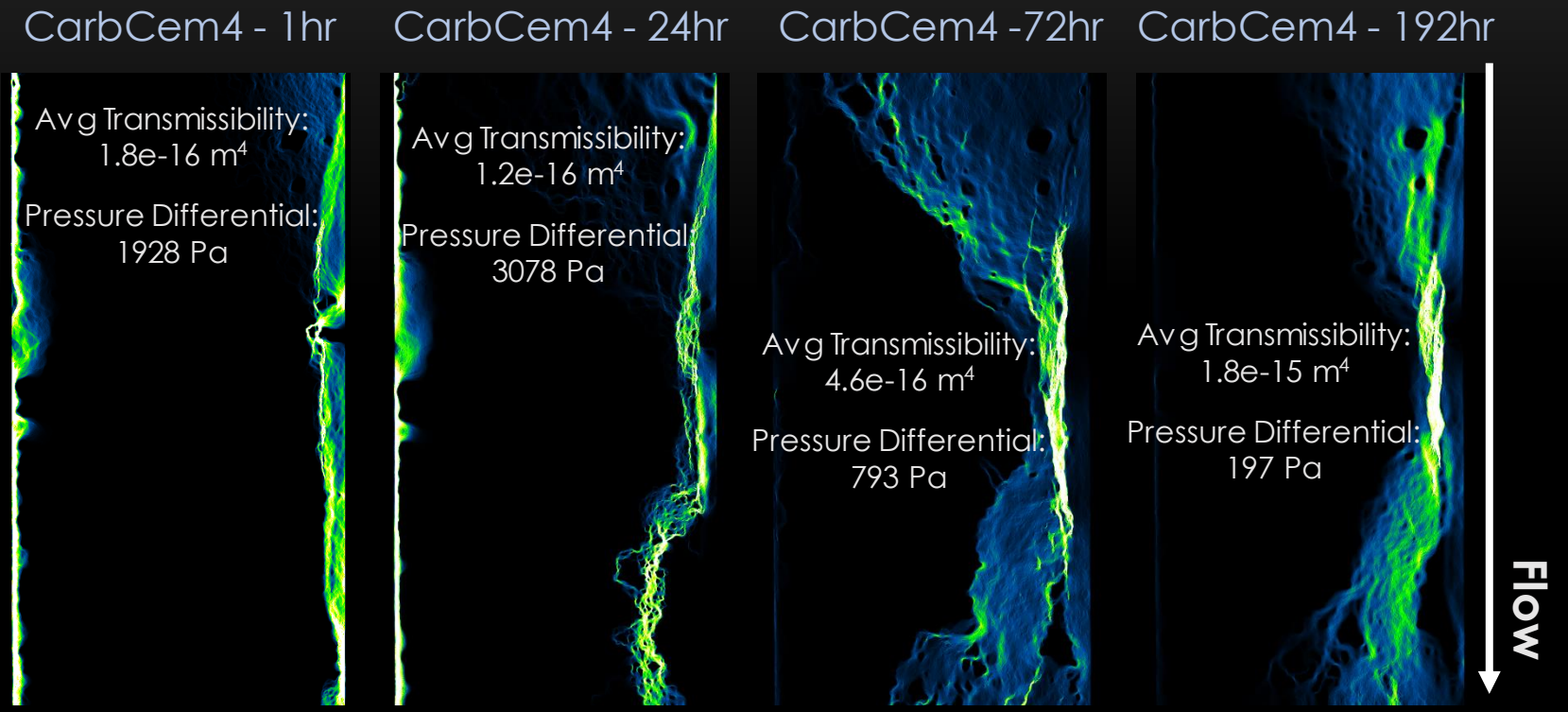


Fracture Aperture Distribution

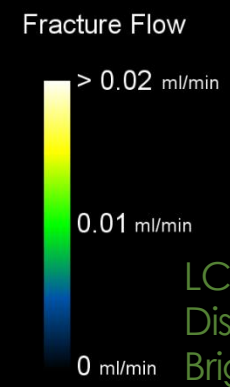
Maximum Aperture: 5.76 mm

Cement Sample A

- Initial flow highly channelized only along fracture edges, where sample was damaged during fracturing



- Two other samples remained in (side channel) state for the duration of the experiment
- After 72 hours, a much higher proportion of the fracture is being utilized by flow, thanks to reactive changes and increased apertures
- Transmissivity increases by an order of magnitude during course of experiment

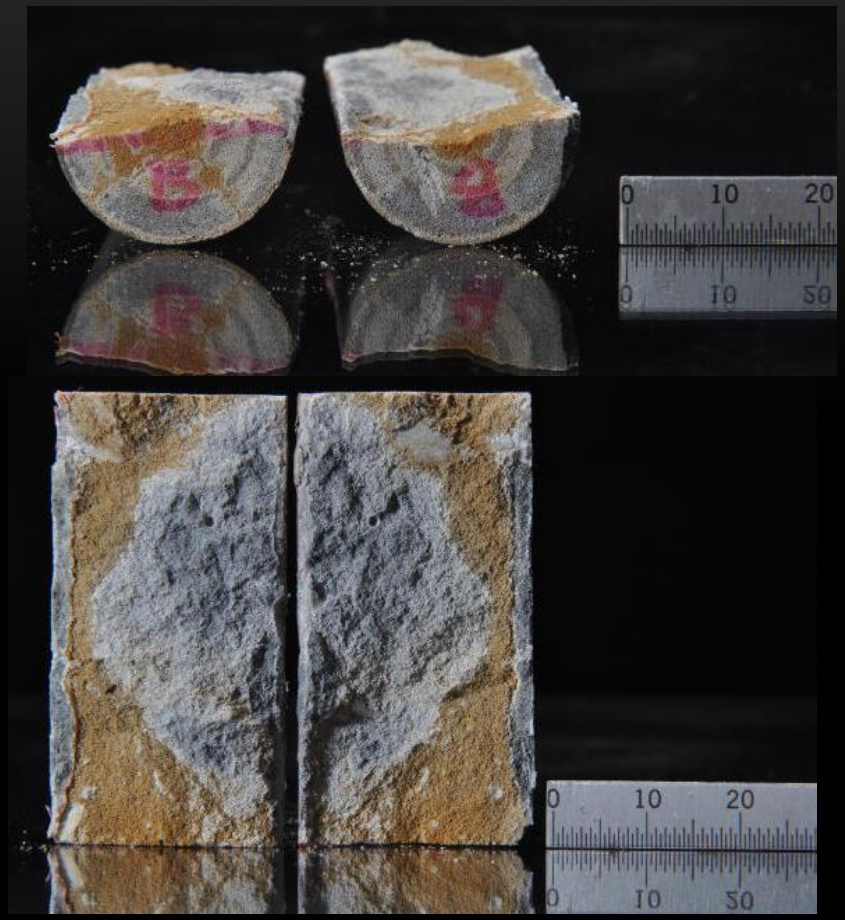


LCL Flow Simulation
Displayed range: 0-0.02 ml/min
Brightest color: 0.02-0.34 ml/min

Cement Sample A

Fracture and Simulated Flow

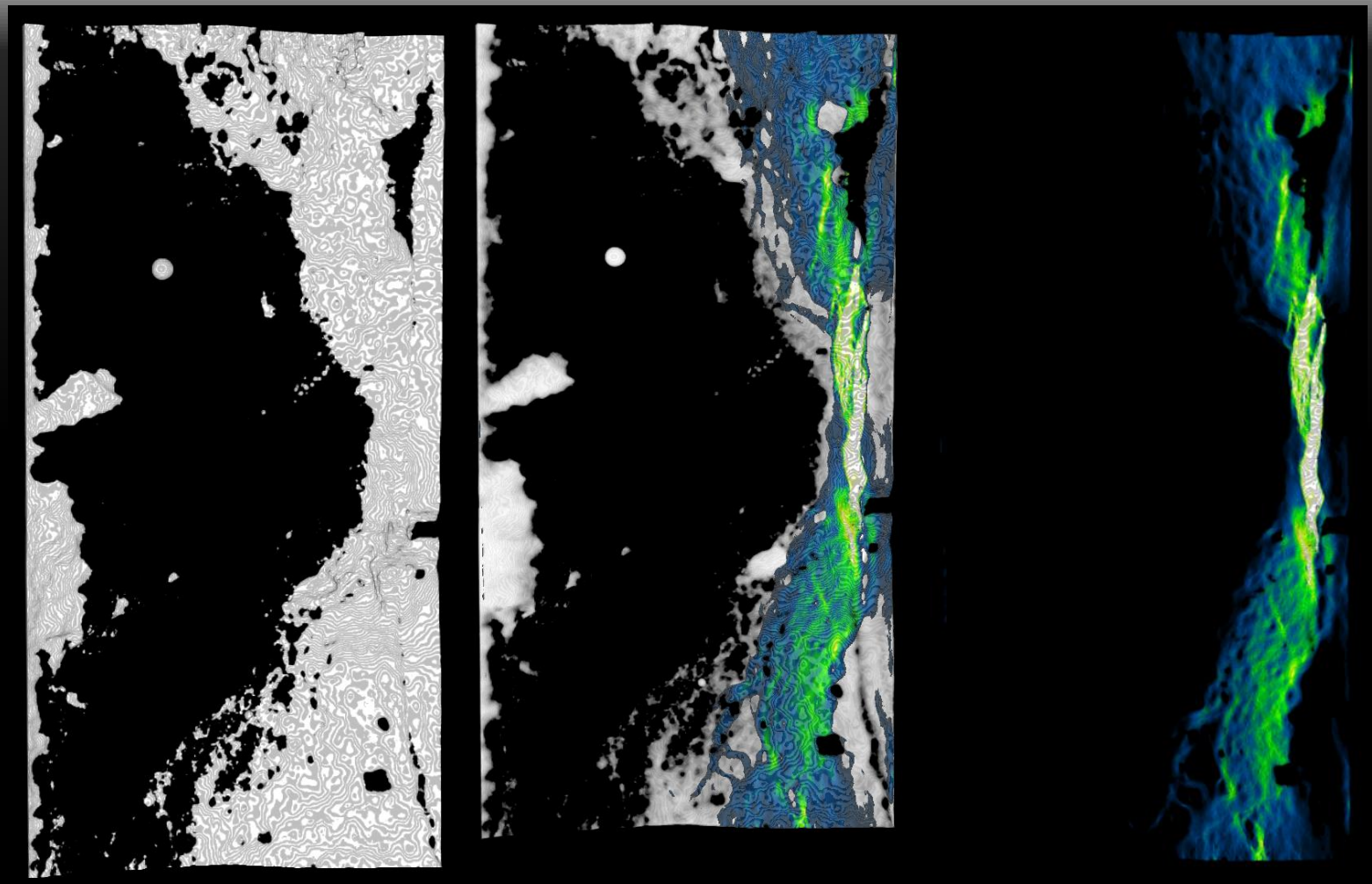
Reacted zone post-experiment



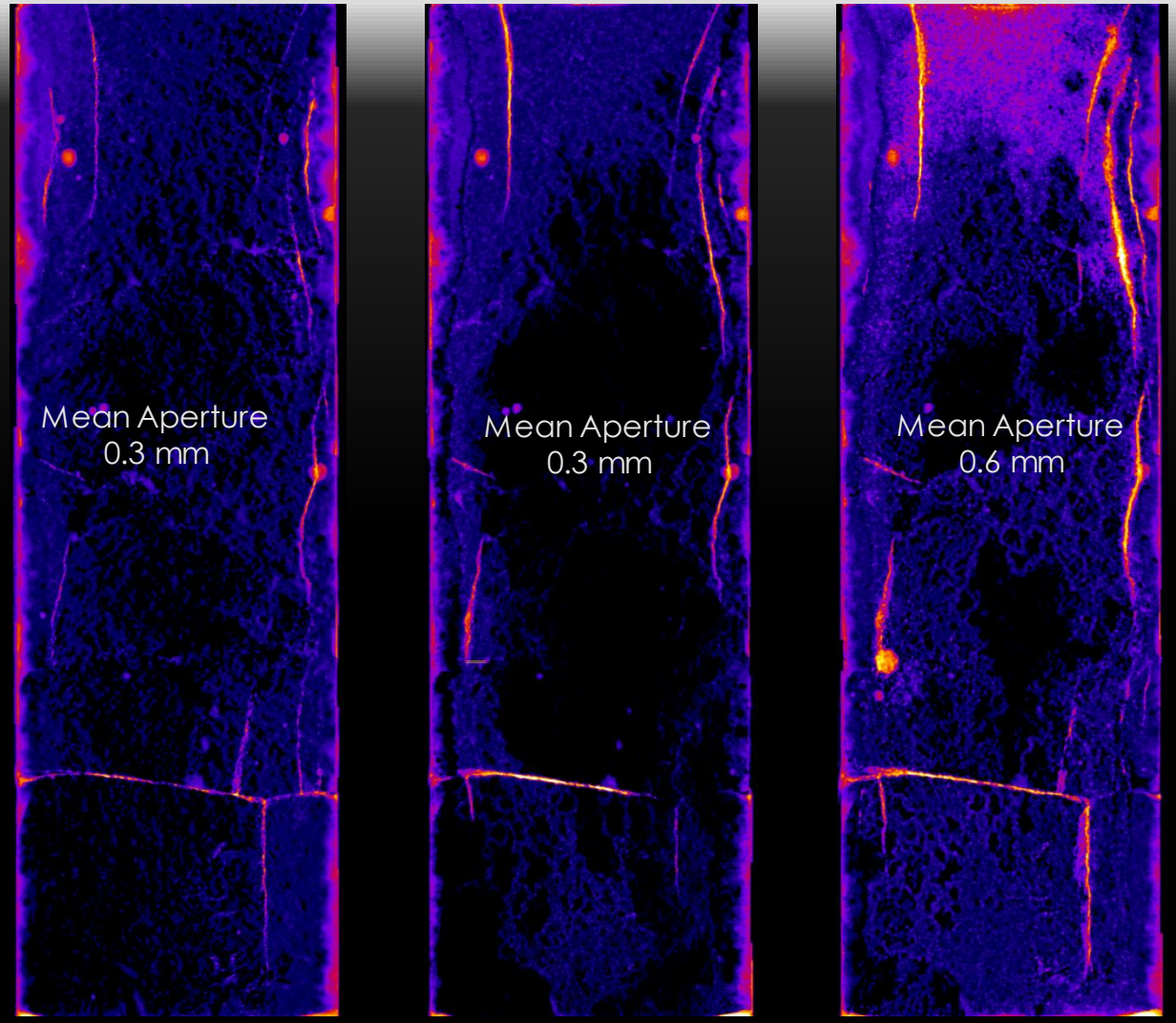
Segmented Fracture

Segmented Fracture with Simulated Flow

Simulated Flow



Cement Sample B



- Fracture aperture shows minor changes in the first 72 hours, primarily along small subfractures
- By the 312 hour scan the fracture shows evidence of widening apertures due to dissolution
- Increase in fracture aperture most notable near inlet

Fracture Aperture Distribution
Maximum Aperture 8.28 mm
Displayed range: 0-5.44 mm

Cement Sample B

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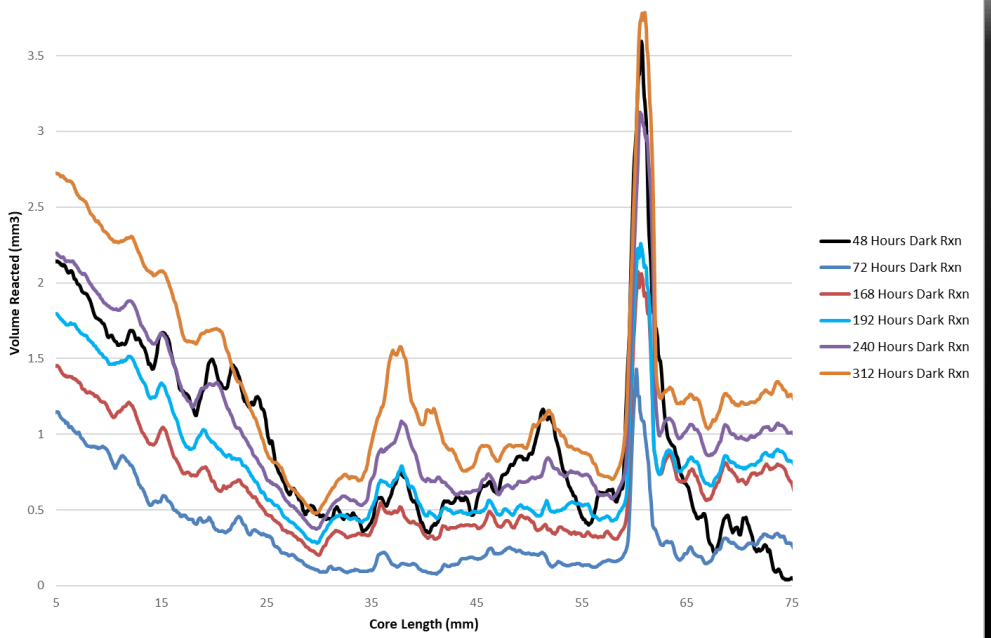
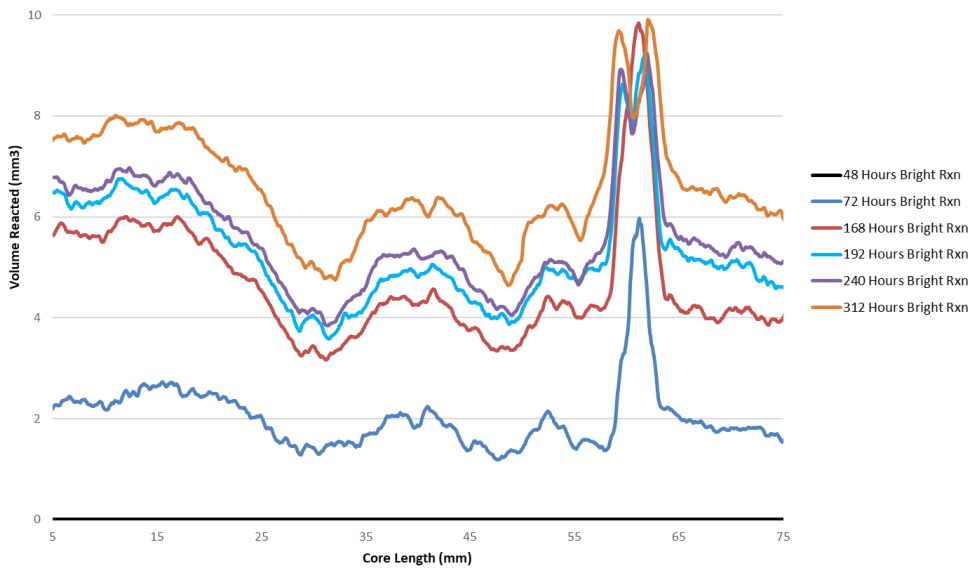
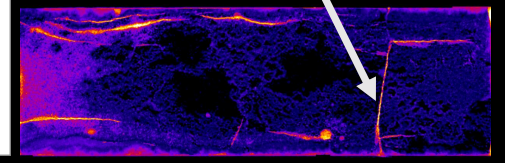
Proximal (dark) reaction zone along length of core



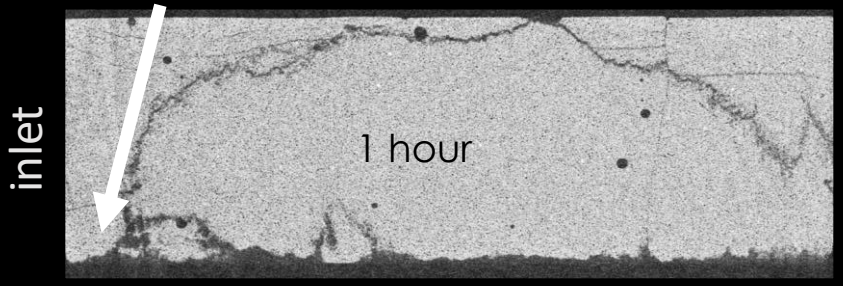
Distal (bright) reaction zone along length of core



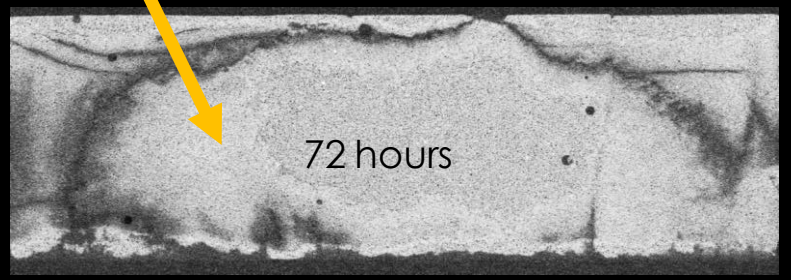
Spike in reaction zone correlates to intersecting small fracture



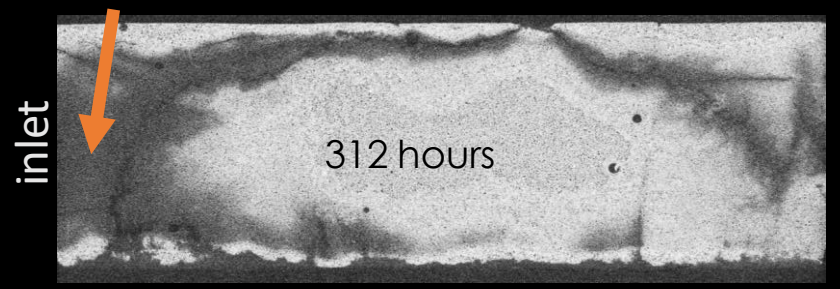
Fracture



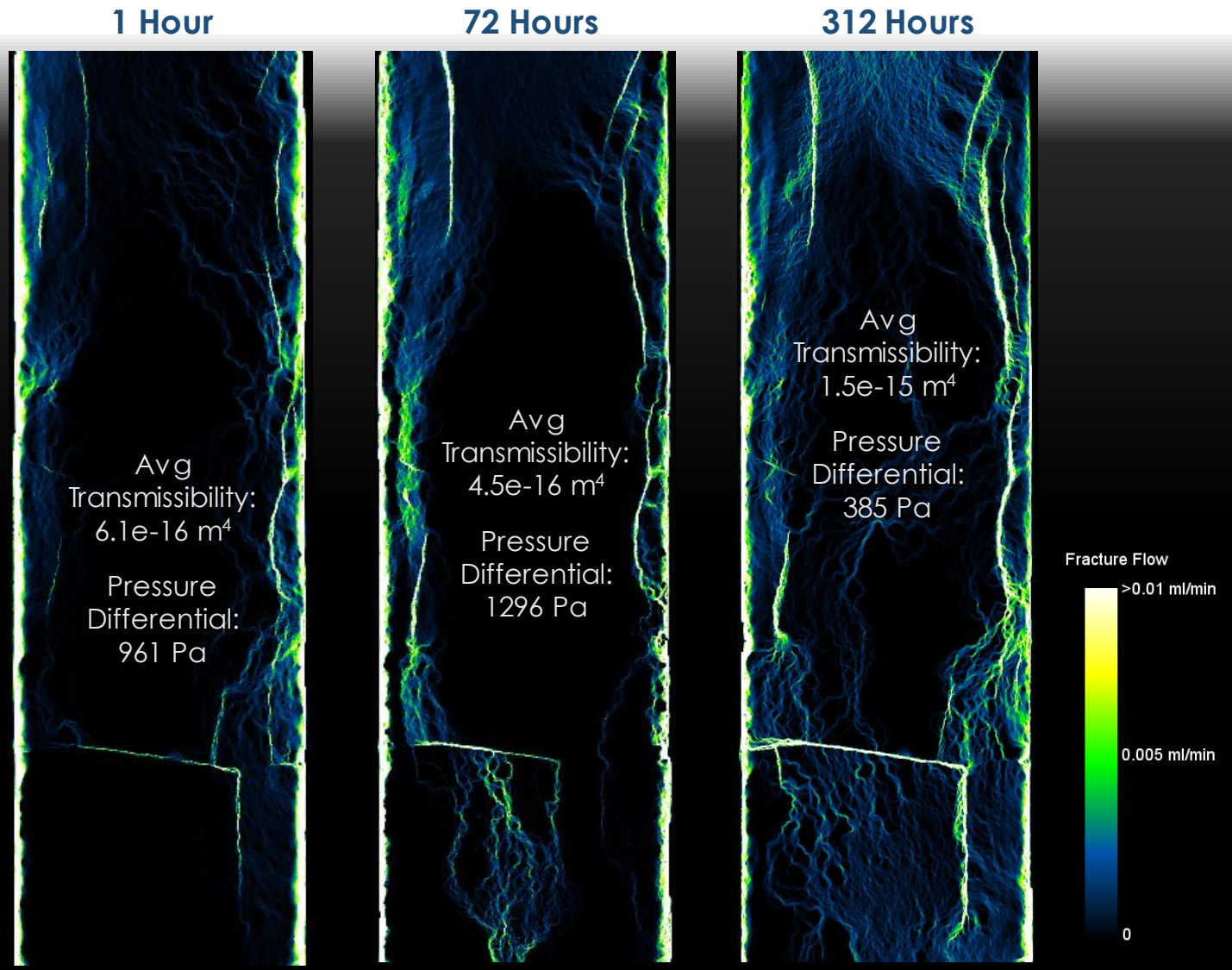
Distal Reaction Zone



Proximal Reaction Zone



Cement Sample B

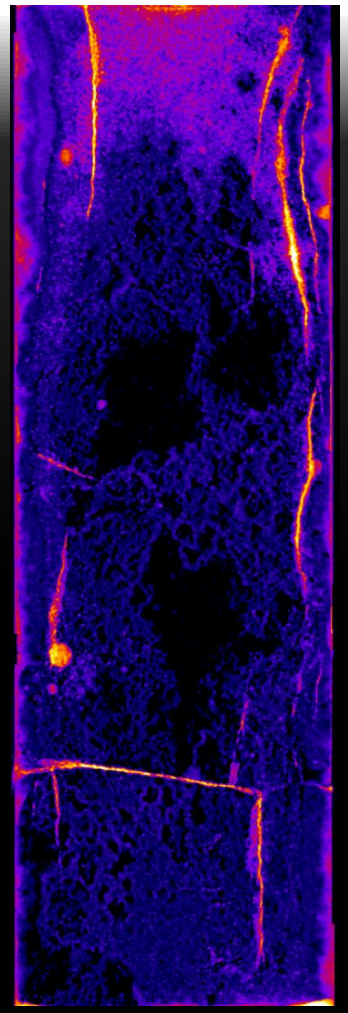


- Participation of smaller sub-fractures aids dissolution and progressive reaction
- Inlet (top) shows significant fracture opening as dissolution progresses at end of experiment

LCL Flow Simulation

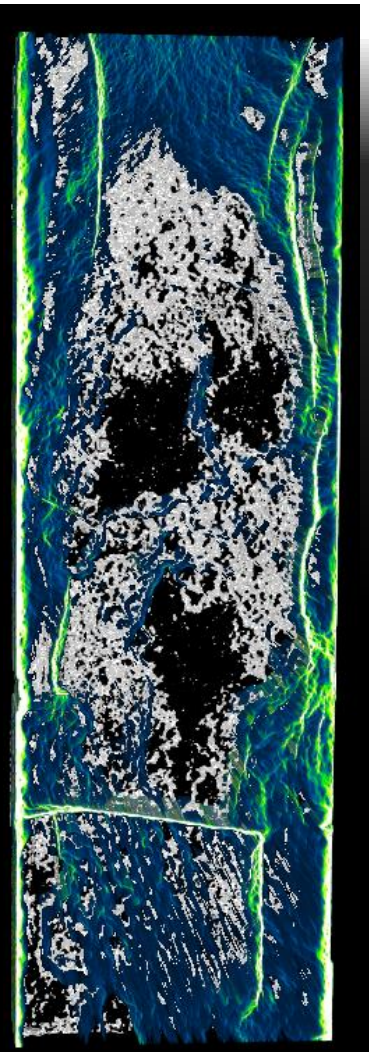
- Displayed range: 0-0.01 ml/min
- Brightest color depicts: 0.01-0.152 ml/min

Cement Sample B – 312 Hours

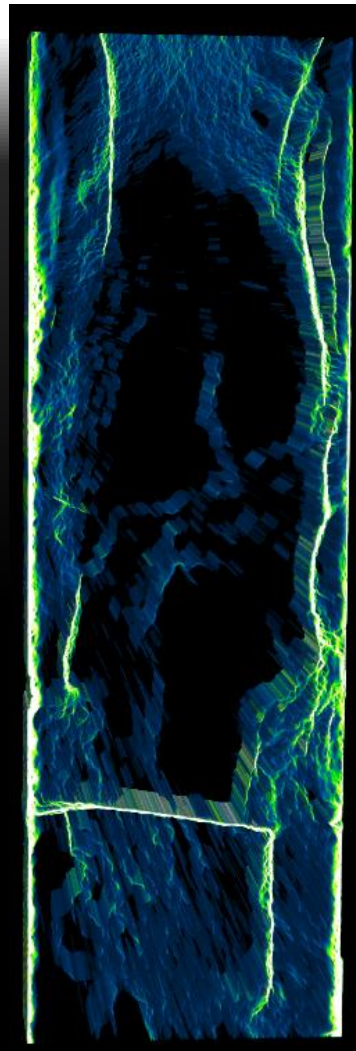


Fracture Aperture

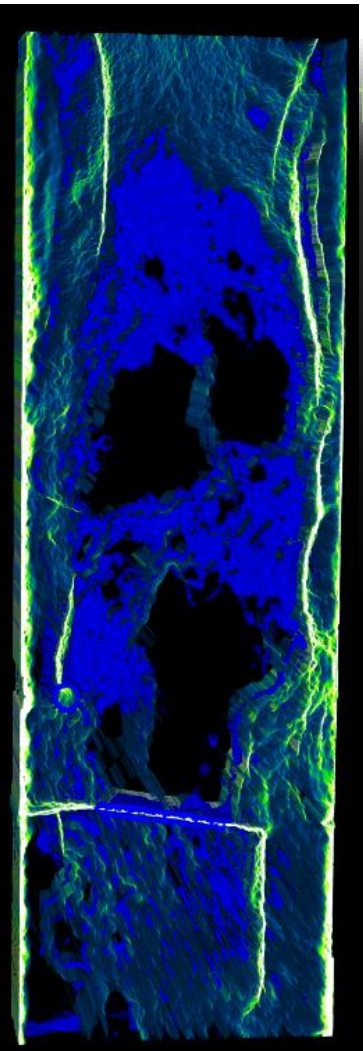
Segmented Fracture



Segmented Fracture With Simulated Flow



Simulated Flow

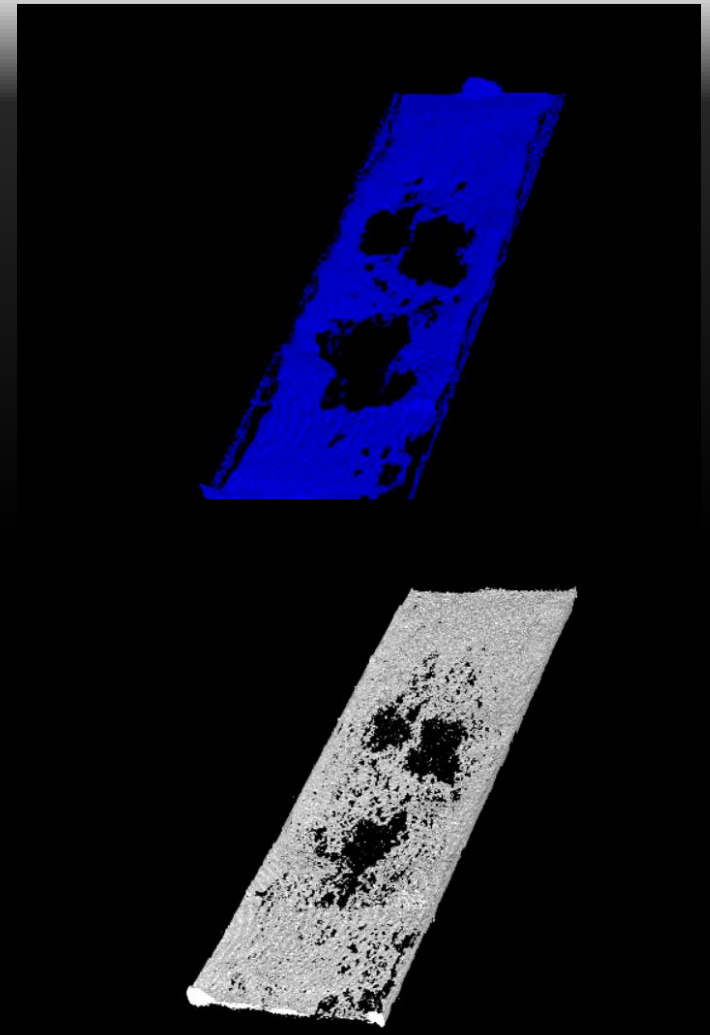


Simulated Flow and Proximal Reaction Rind

- Advective flow: Primary flow paths along higher aperture zones correspond to majority of reaction zones
- Diffusive processes: Low aperture fracture zones also show reaction rind, suggesting diffusion plays a role it tighter portions of the fracture

Conclusions

- Advective versus diffusive changes
  - Advective flow - following primary flow channels
  - Diffusion - along tighter portions
- Proximal to fracture – matrix dissolution
- Distal to fracture – matrix alteration
- Widening of fracture apertures in primary flow channels of the fracture
- Further research:
  - Better quality scans to quantify porosity changes
  - Effulent capture and characterization
  - Mineralogy changes in distal reaction zone



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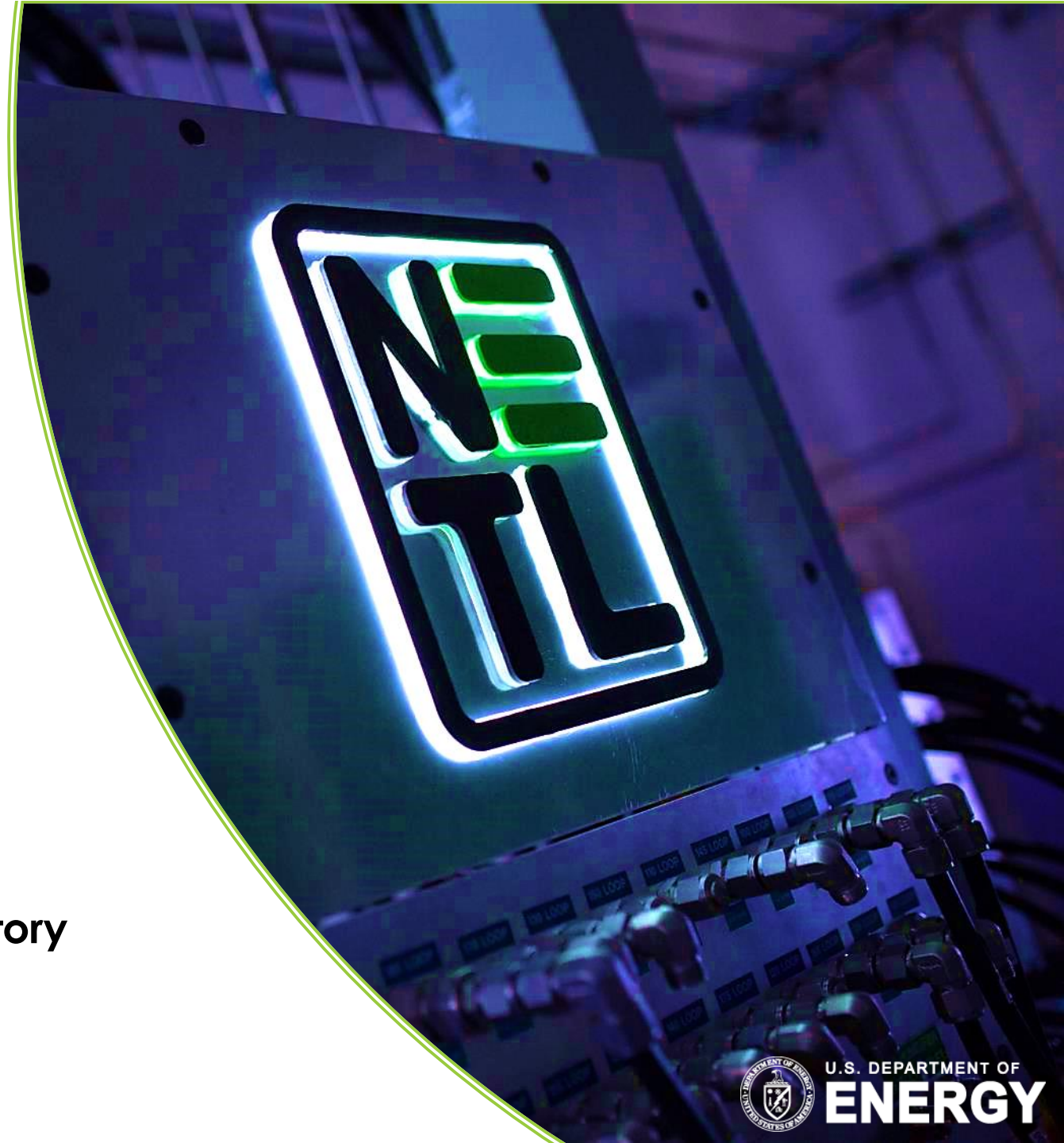

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