MONTANA STATE UNIVERSITY
Energy Research Institute

CENTER FOR BIOFILM ENGINEERING

Methods to Enhance Wellbore Cement Integrity with Microbially-Induced Calcite Precipitation (MICP)

DE-FE0024296

Project Period: October 1, 2014 – September 30, 2019

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 14, 2018

Presentation Outline

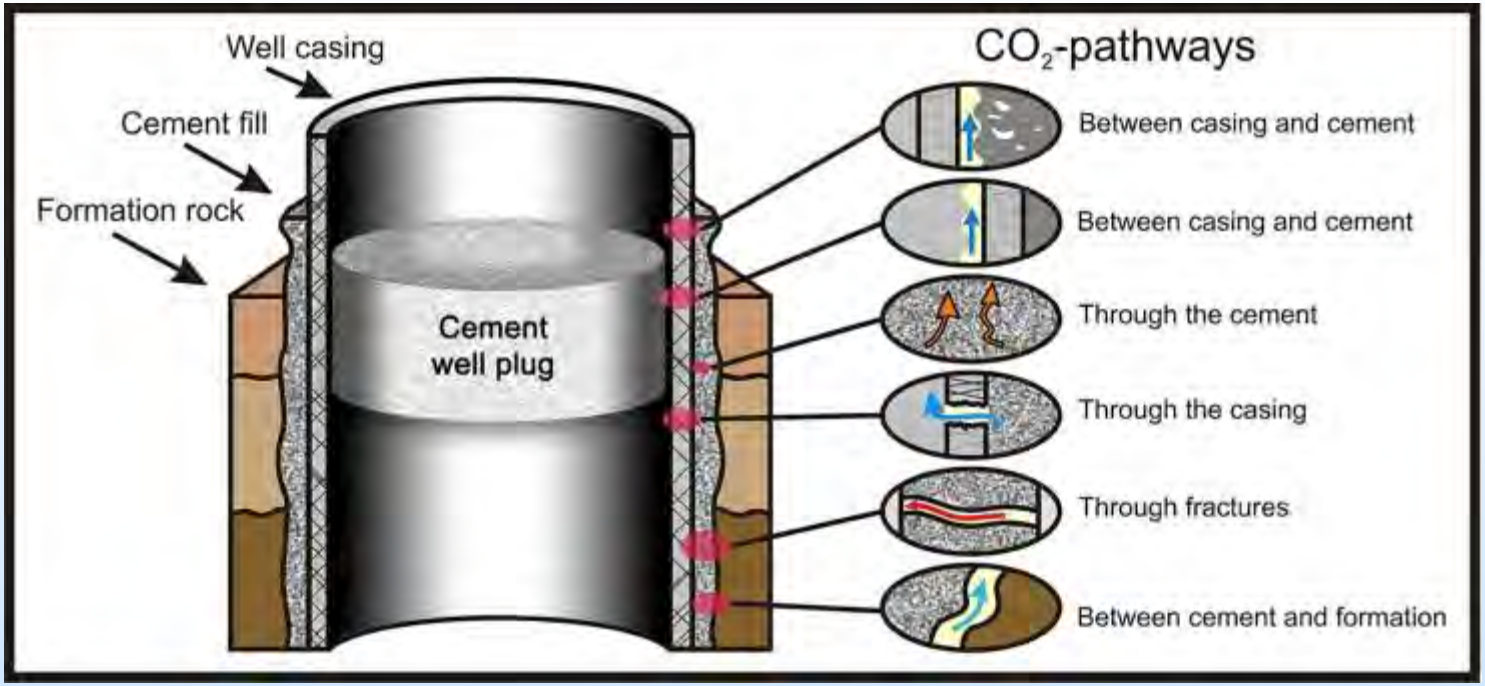
- Technical Status
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Summary

Project Overview: Goals and Objectives

Project goal: develop improved methods for sealing compromised wellbore cement in leaking natural gas and oil wells, thereby reducing the risk of unwanted upward gas migration through laboratory and field testing.

- Objective 1: Laboratory testing of MICP sealing, develop a field test protocol for effective MICP placement and control.
- Objective 2: Prepare for and conduct an initial MICP field test aimed at sealing a poor well cement bond.
- Objective 3: Analyze results from first field test, conduct a second MICP test using improved MICP injection methods.

Mitigating subsurface leakage



Nordbotten and Celia, Geological Storage of CO_2, 2012

Cement is viscous

Microbes are small – thereby creating a niche treatment technology for small aperture fractures that can be delivered via low-viscosity fluids

Grow a seal

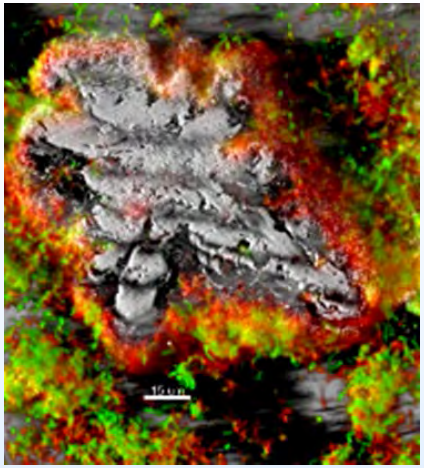
Microbially-Induced $CaCO_3$ Precipitation (MICP)

Ureolysis-driven

$$CO(NH_2)_2 + H_2O \xrightarrow{\text{Urease}} NH_2COOH + NH_3$$

$$NH_2COOH + H_2O \xrightarrow{\text{Spontaneous}} NH_3 + H_2CO_3^*$$

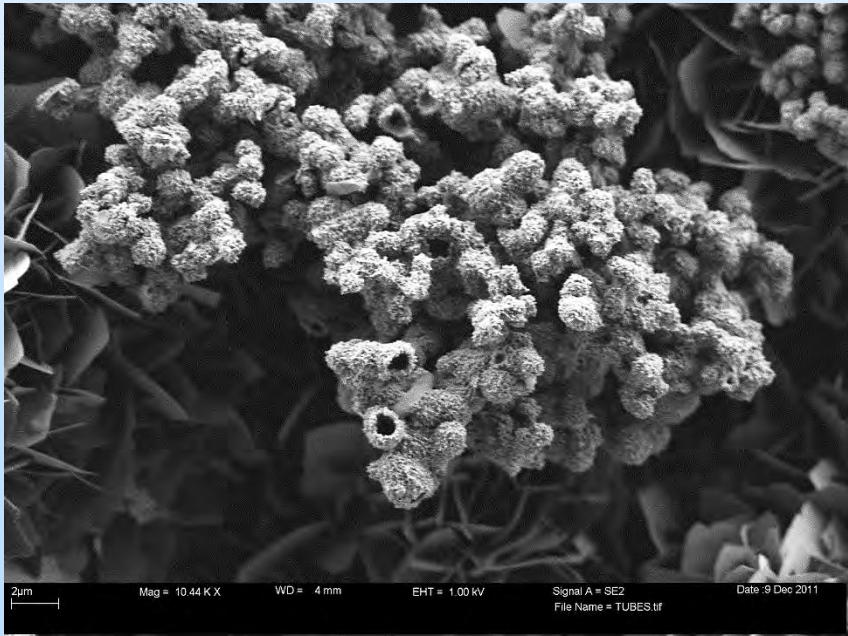
$$2NH_3 + 2H_2O \longleftrightarrow 2NH_4^+ + 2OH^-$$



$$H_2CO_3^* + 2OH^- \xleftrightarrow{pK_{a1}=6.3} HCO_3^- + H_2O + OH^- \xleftrightarrow{pK_{a2}=10.3} CO_3^{2-} + 2H_2O$$

$$(\Omega \text{ or } S) = a(Ca^{2+})a(CO_3^{2-})/K_{sp} \quad \text{or} \quad SI = \log(S)$$

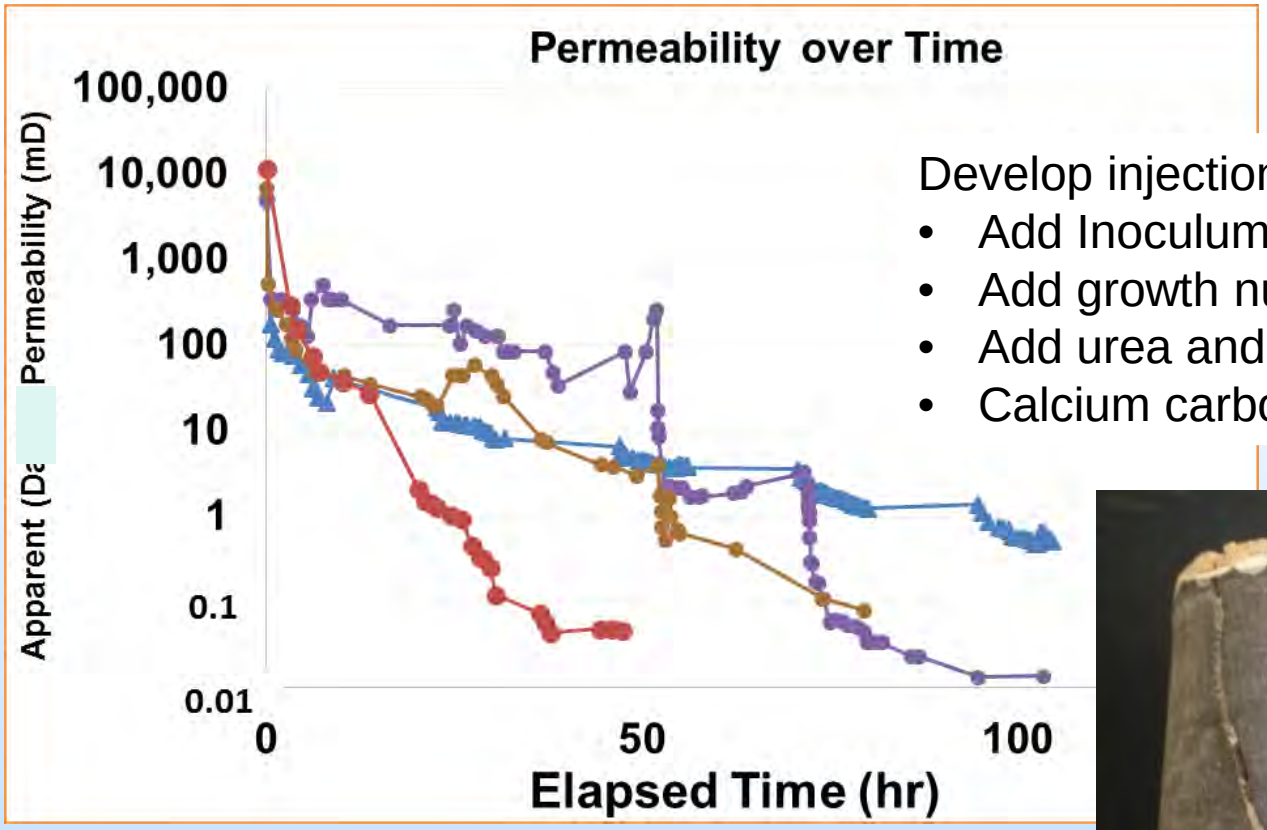
$$Ca^{2+} + CO_3^{2-} \longleftrightarrow CaCO_3\,(s) \qquad K_{sp} = 4.8 \times 10^{-9}$$



Schultz, L, Pitts, B, Mitchell, AC, Cunningham, A, Gerlach, R. Imaging biologically induced mineralization in fully hydrated flow systems. Microscopy Today 2011, 19, (5), 12-15

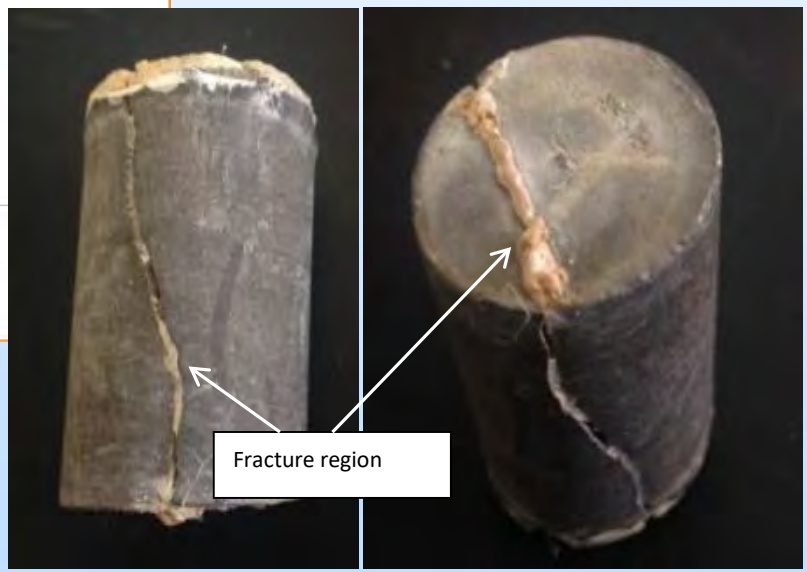
Phillips AJ, Gerlach, R, Lauchnor, E, Mitchell, AC, Cunningham, A, Spangler, L. (2013) Engineered applications of ureolytic biomineralization: a review. Biofouling. 29 (6) 715-733

Objective 1: Lab Scale: Fractured shale cores



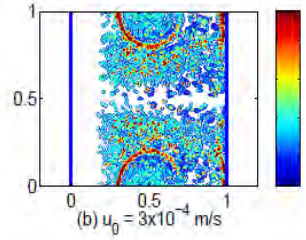
Develop injection strategy

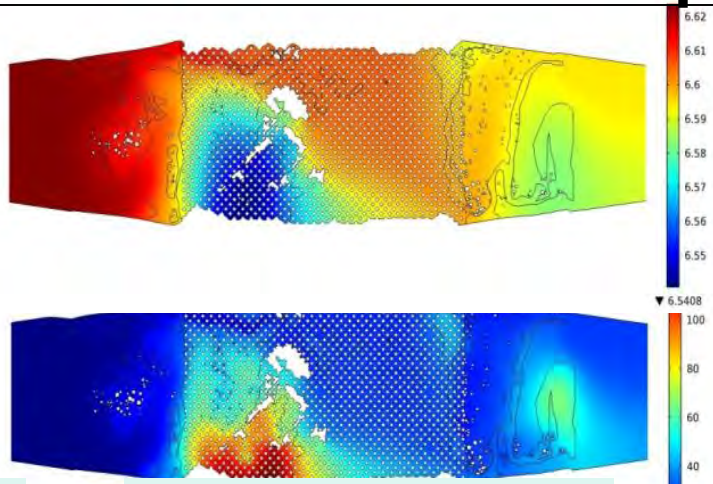
- Add Inoculum *Sporosarcina pasteurii*
- Add growth nutrients
- Add urea and calcium
- Calcium carbonate (calcite) precipitation

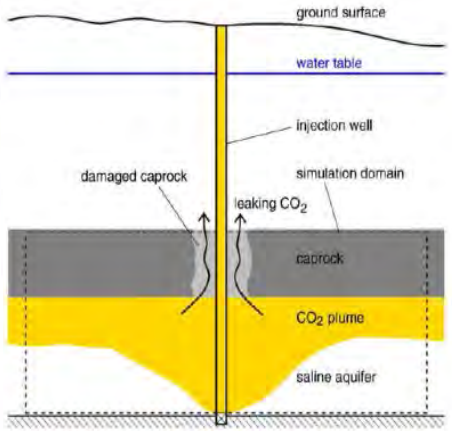


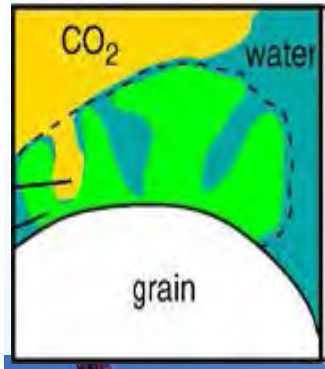
Cunningham, AB, Gerlach, R, Phillips, AJ, Lauchnor, E, Rothman, A, Hiebert, R, Busch, A, Lomans, B, and Spangler, L. (2015) Assessing potential for biomineralization sealing in fractured shale and the Mont Terri Underground Research Facility, Switzerland, Carbon Dioxide Capture for Storage in Deep Geologic Formations Vol. 4, Chapter 48 pg 887 -903

Objective 2: Scale Up





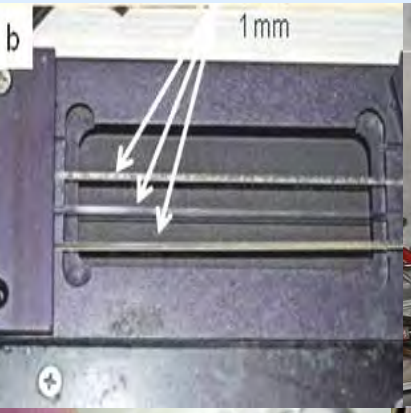


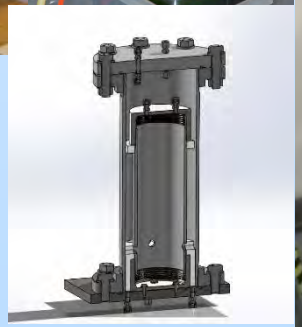


nm to cm

µm to dm

cm to 100s of m



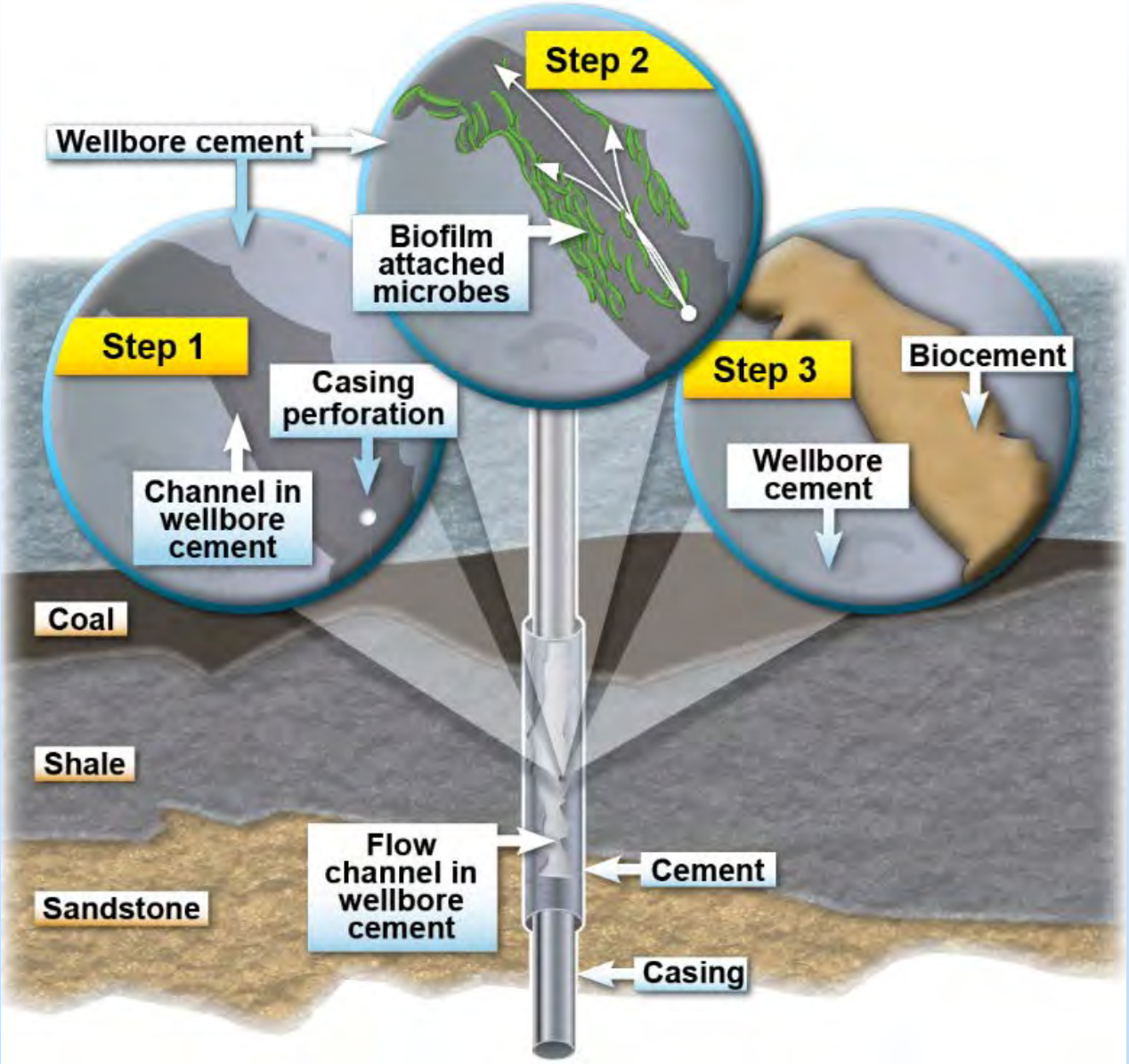


Objective 2: Wellbore sealing

First field test

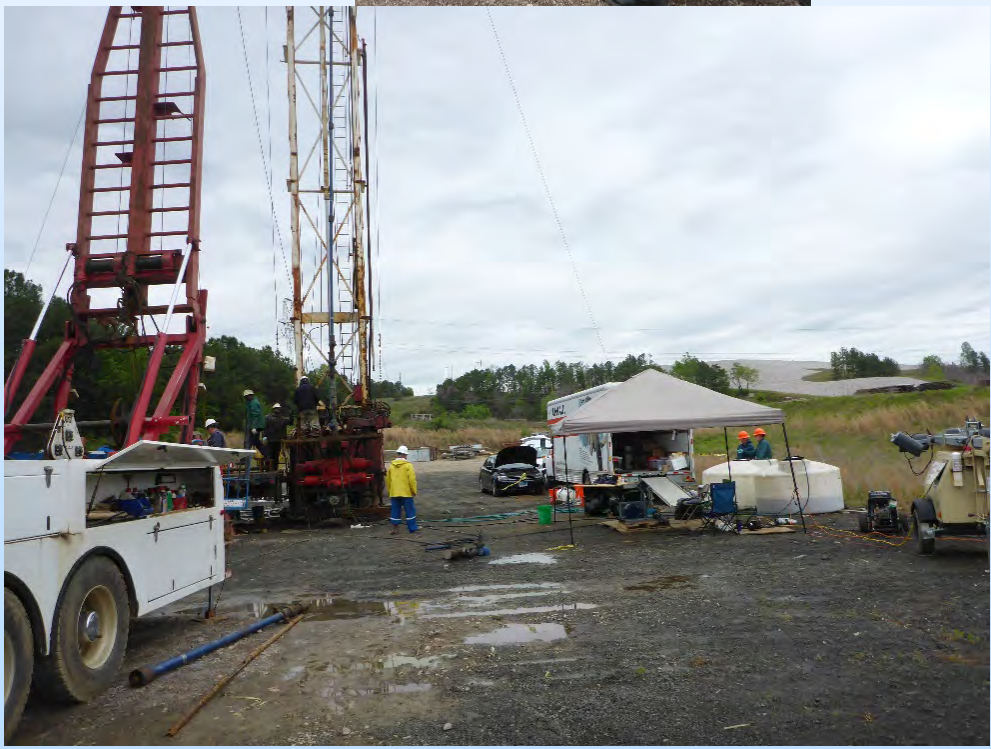
Gorgas well

Side wall coring and injection test



Objective 2: Cement channel sealing

Bailer delivery
Concentrated solutions followed by brine
Inject over 4 days
25 calcium pulses
10 microbial injections



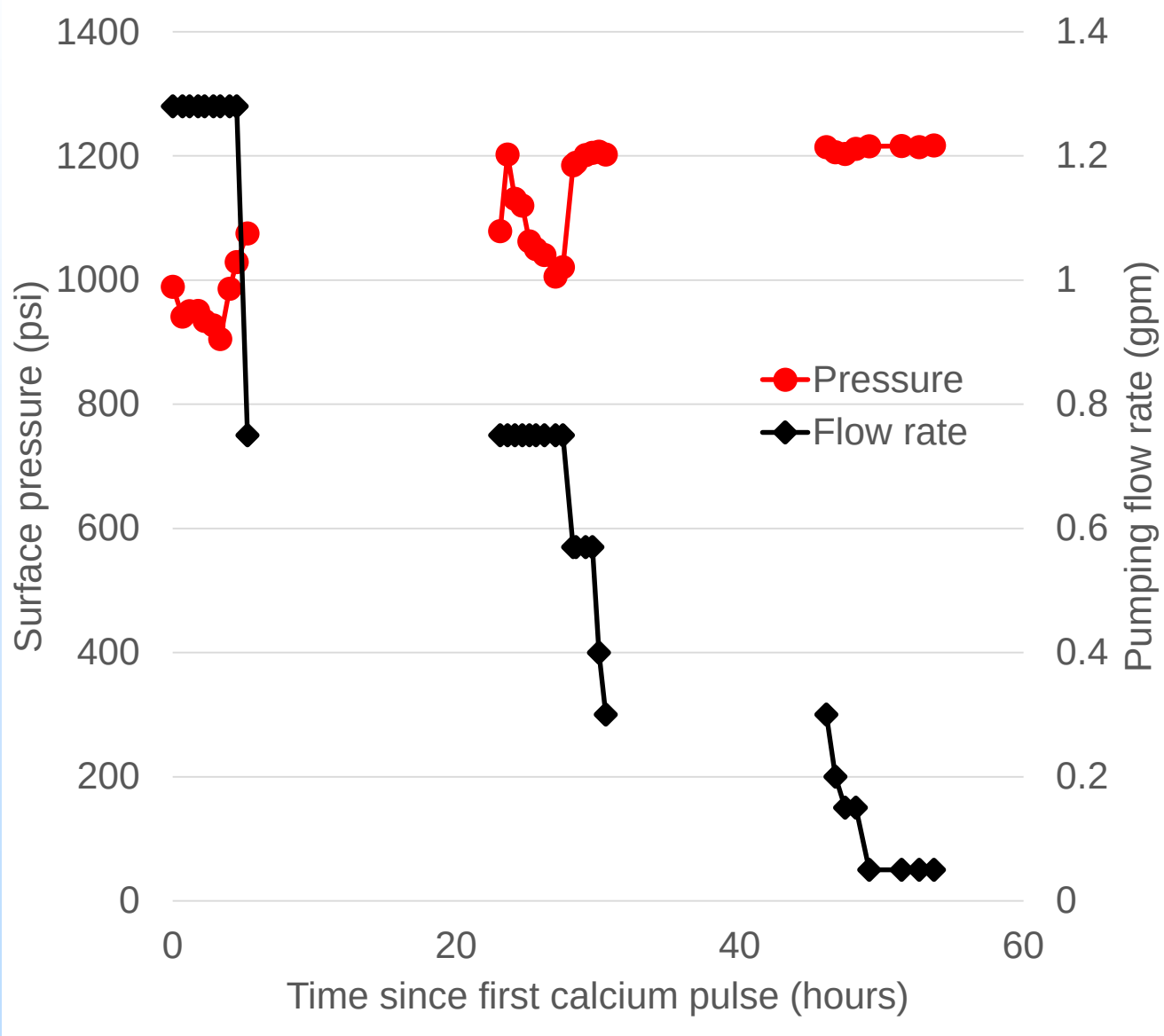
3 measures of success
- Injectivity reduced
- Pressure decay
- USIT Logs

Objective 2: Pressure-flow

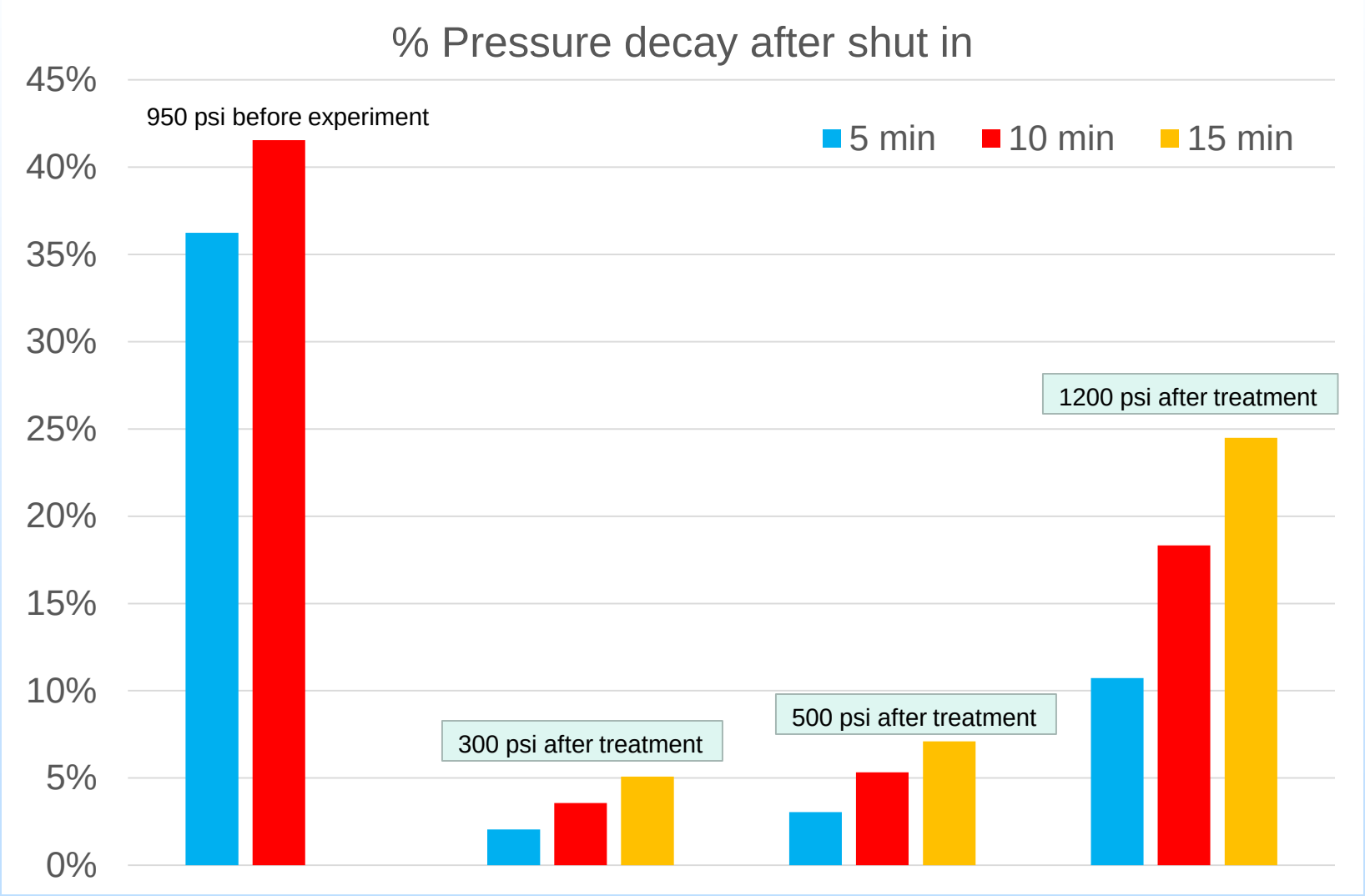
Apparent permeability reduced 1.5 orders of magnitude

Reduced injectivity-pressure increased and flow rate decreased

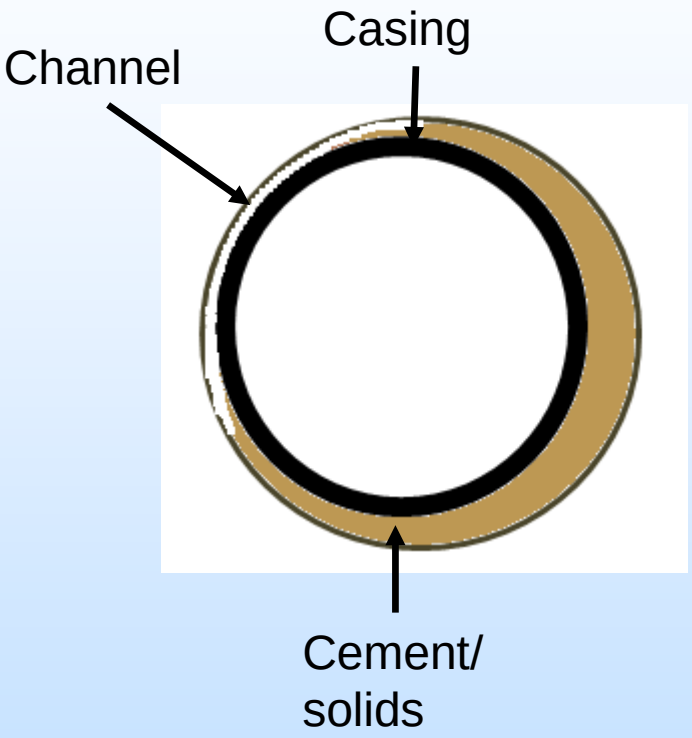
Threshold pressure



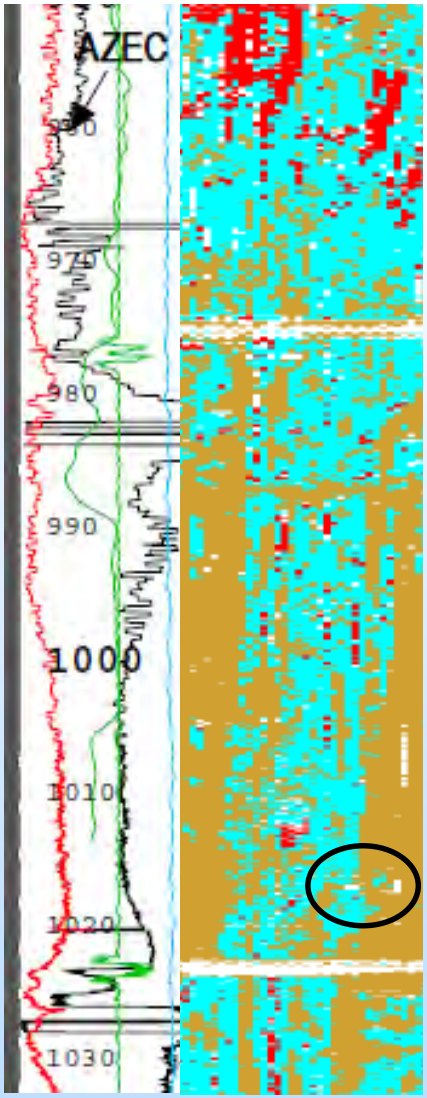
Objective 2: Mechanical Integrity Test



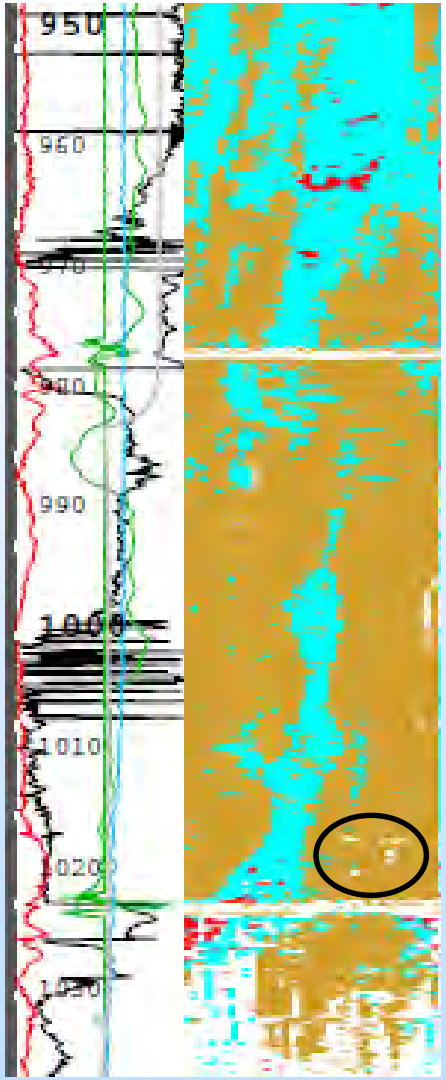
Objective 2: USIT logs



Not centered, channel



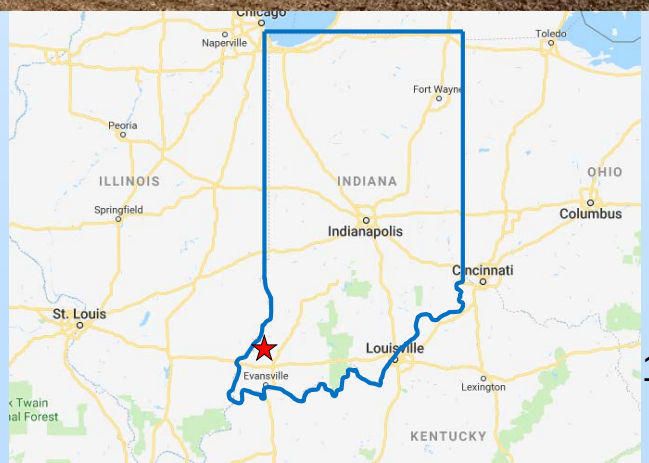
Before



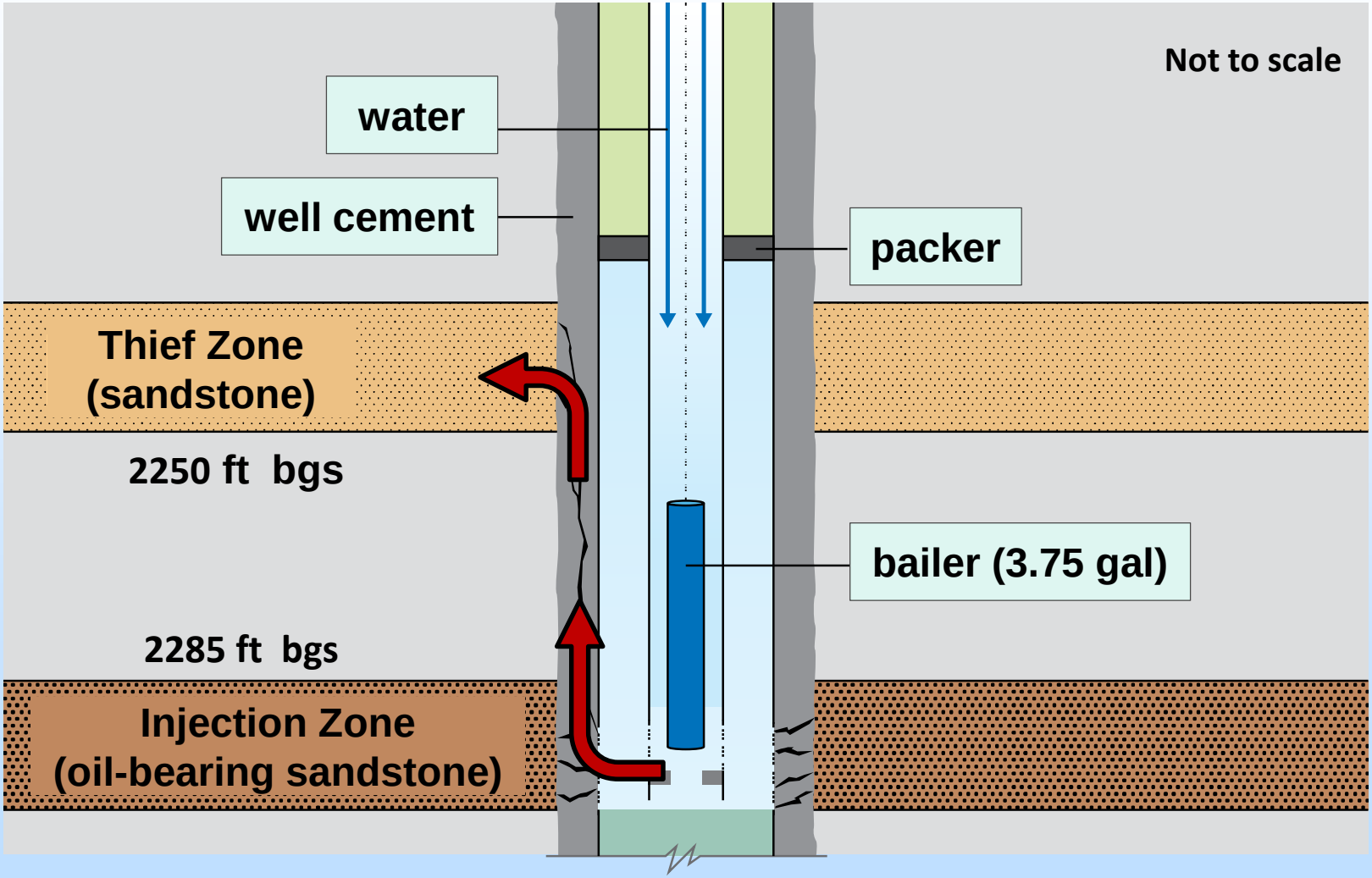
Treated

Objective 3: Rexing #4 Well

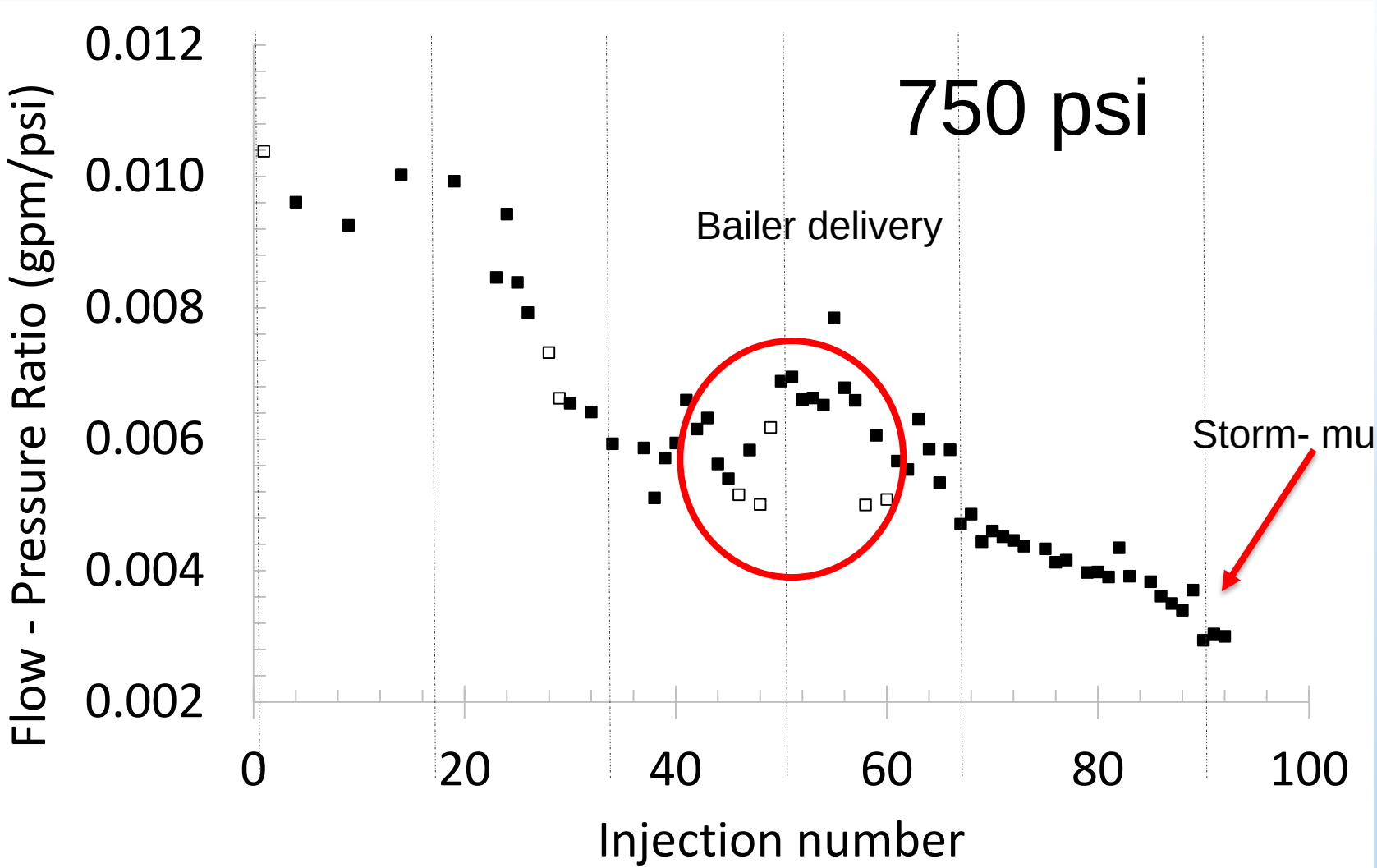
- Injection well used to perform water flooding to increase oil recovery
- Vertical channel formed in the cement
- Water traveling up channel into a thief zone not into targeted oil formation
- Opportunity to treat in an oil field- return to production
- Realistic and typical of established/problem wells



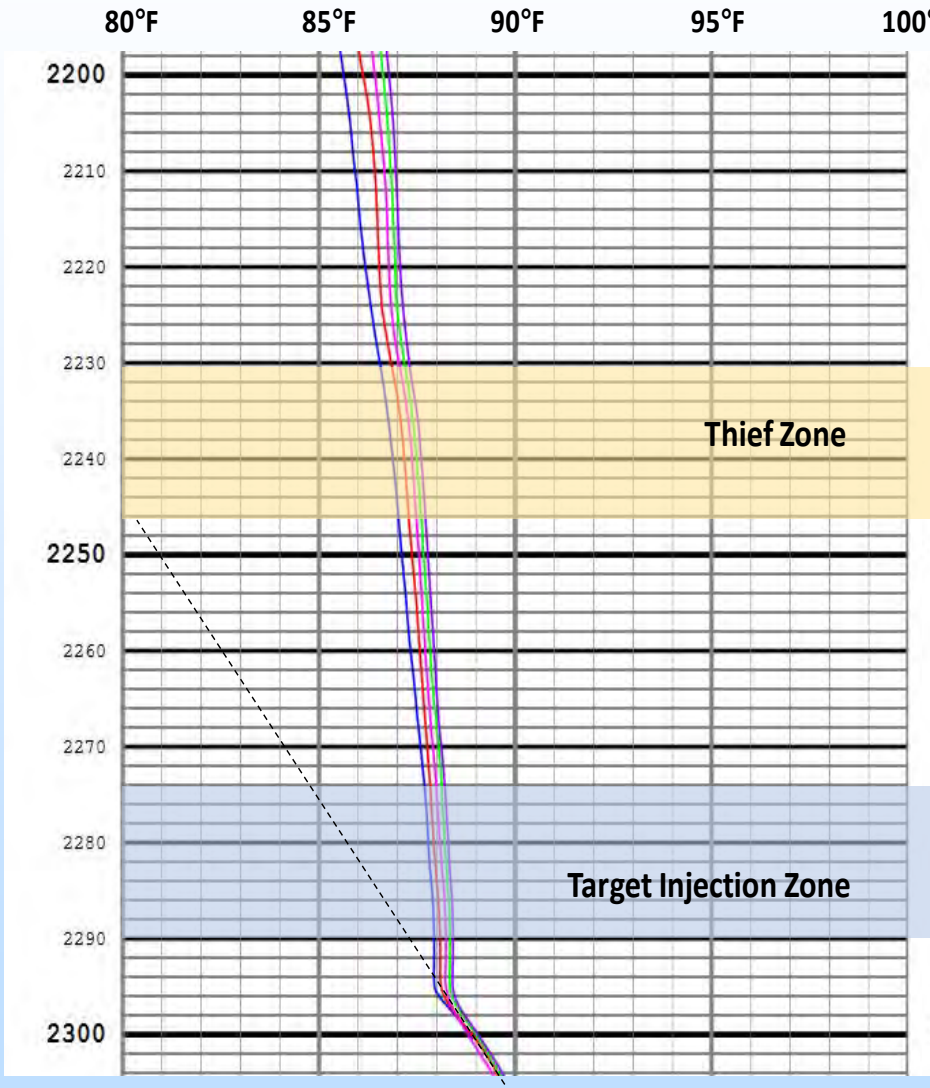
Objective 3: Rexing #4 Well



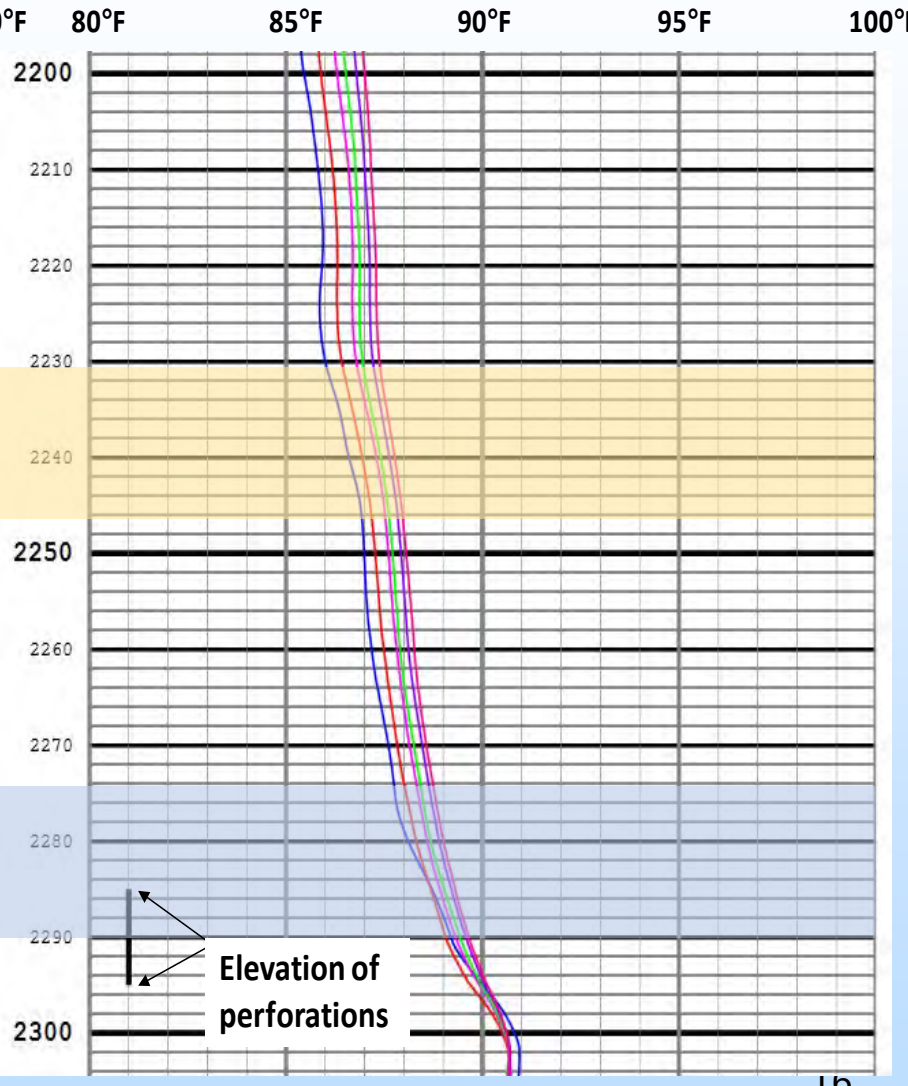
Rexing #4: Flow-pressure



Temperature logs

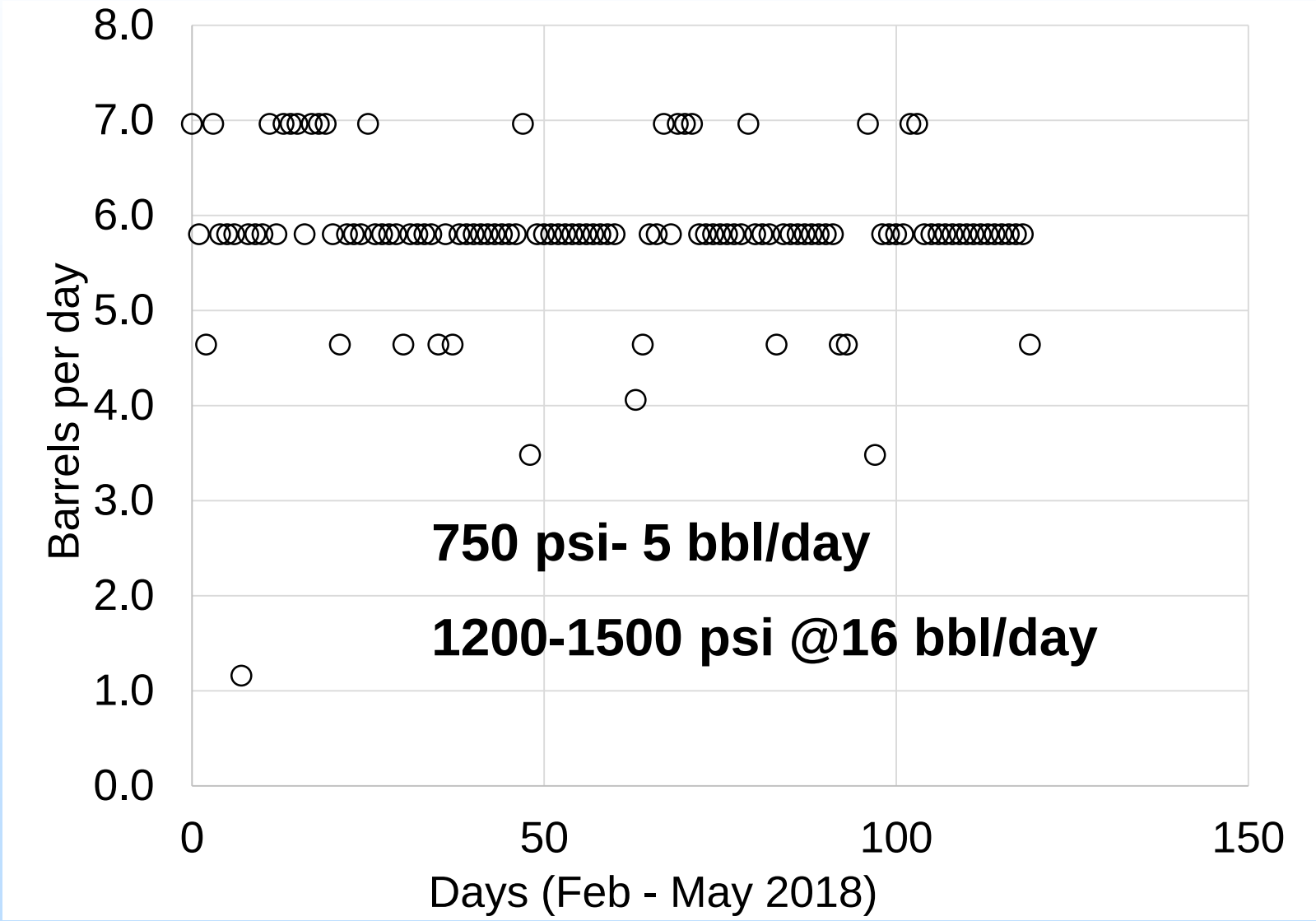


October 2017 – Pre-MICP Treatment

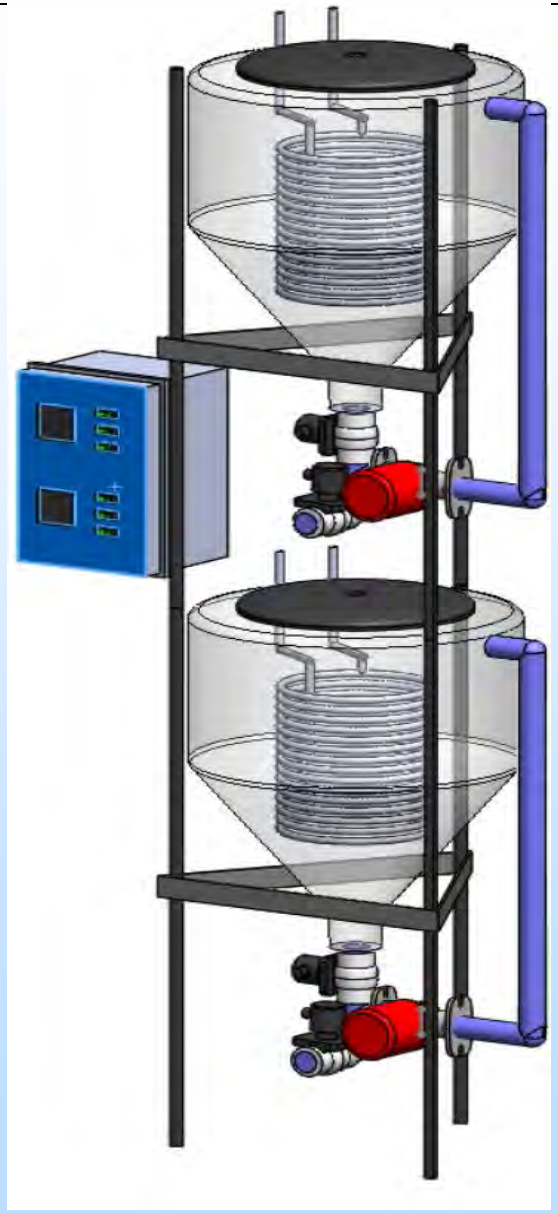


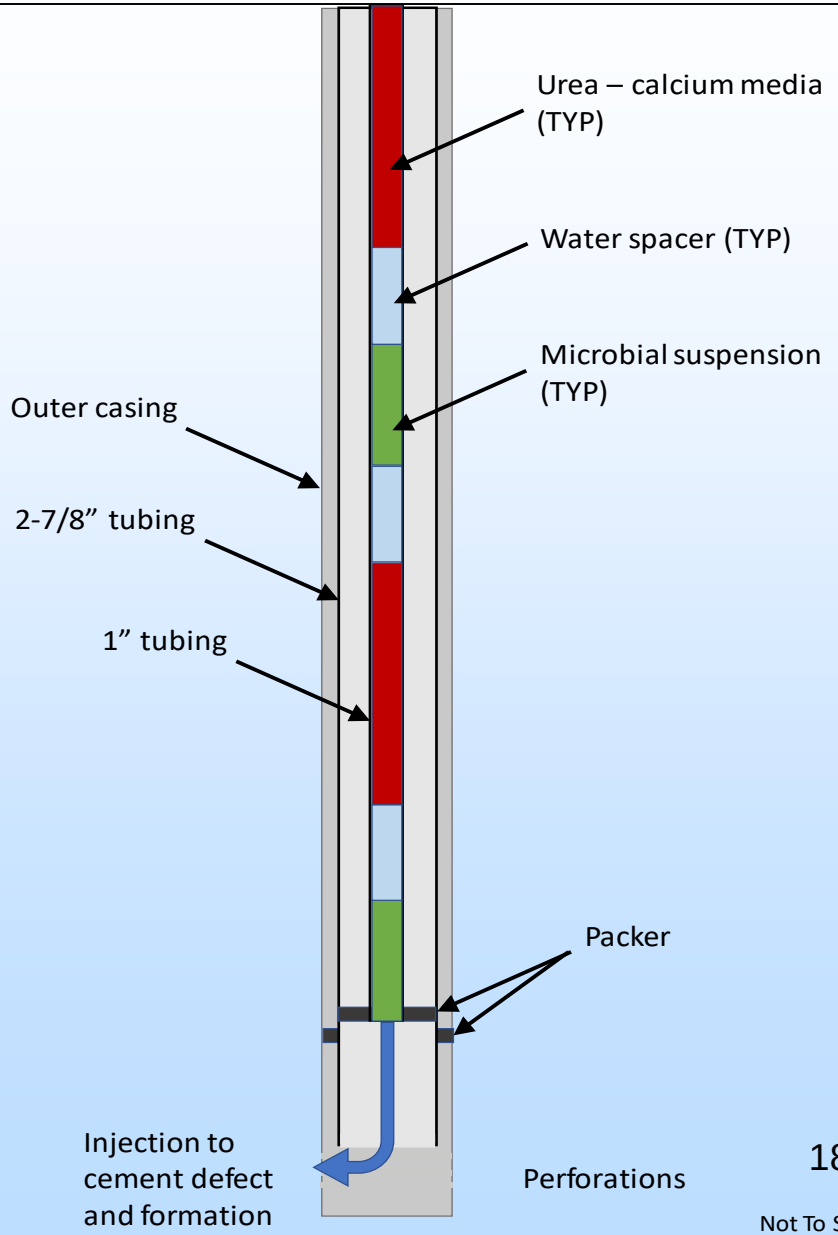
December 2017 – Post-MICP Treatment

Objective 3: Rexing #4 Well



Field Demonstration #3



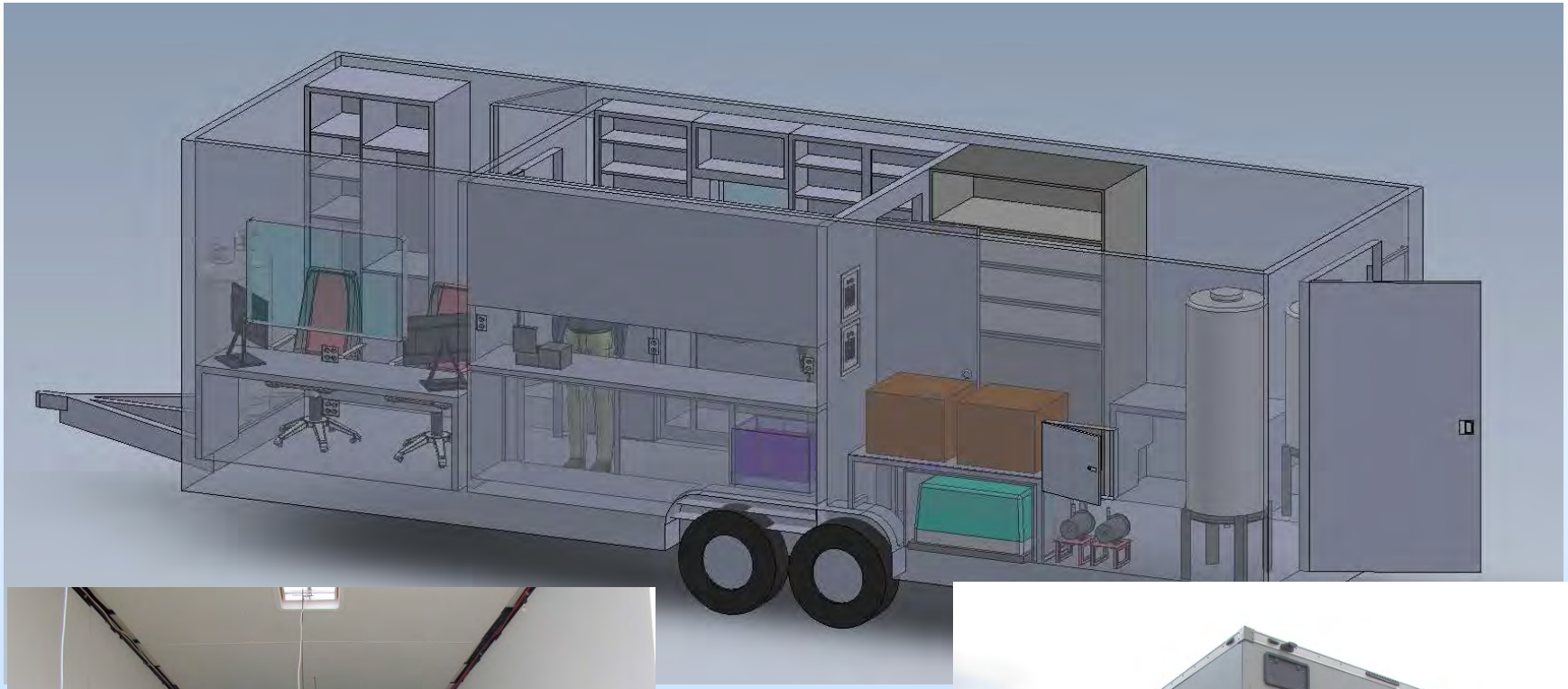


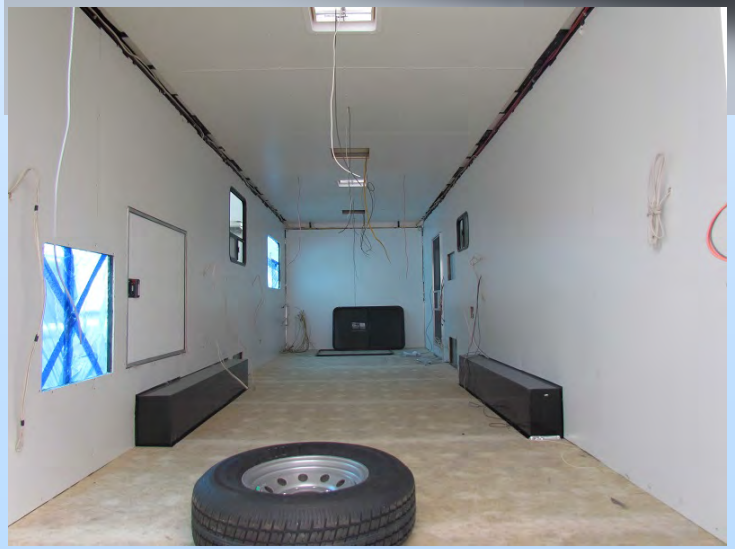
Not To Scale

Accomplishments to Date

- Objective 1: Laboratory testing to develop injection strategies
- Objective 2: Field demonstration with successful results
- Objective 3: Field test- oil bearing
- Scale up- TRL
- Mobile laboratory
- Prepping for final field

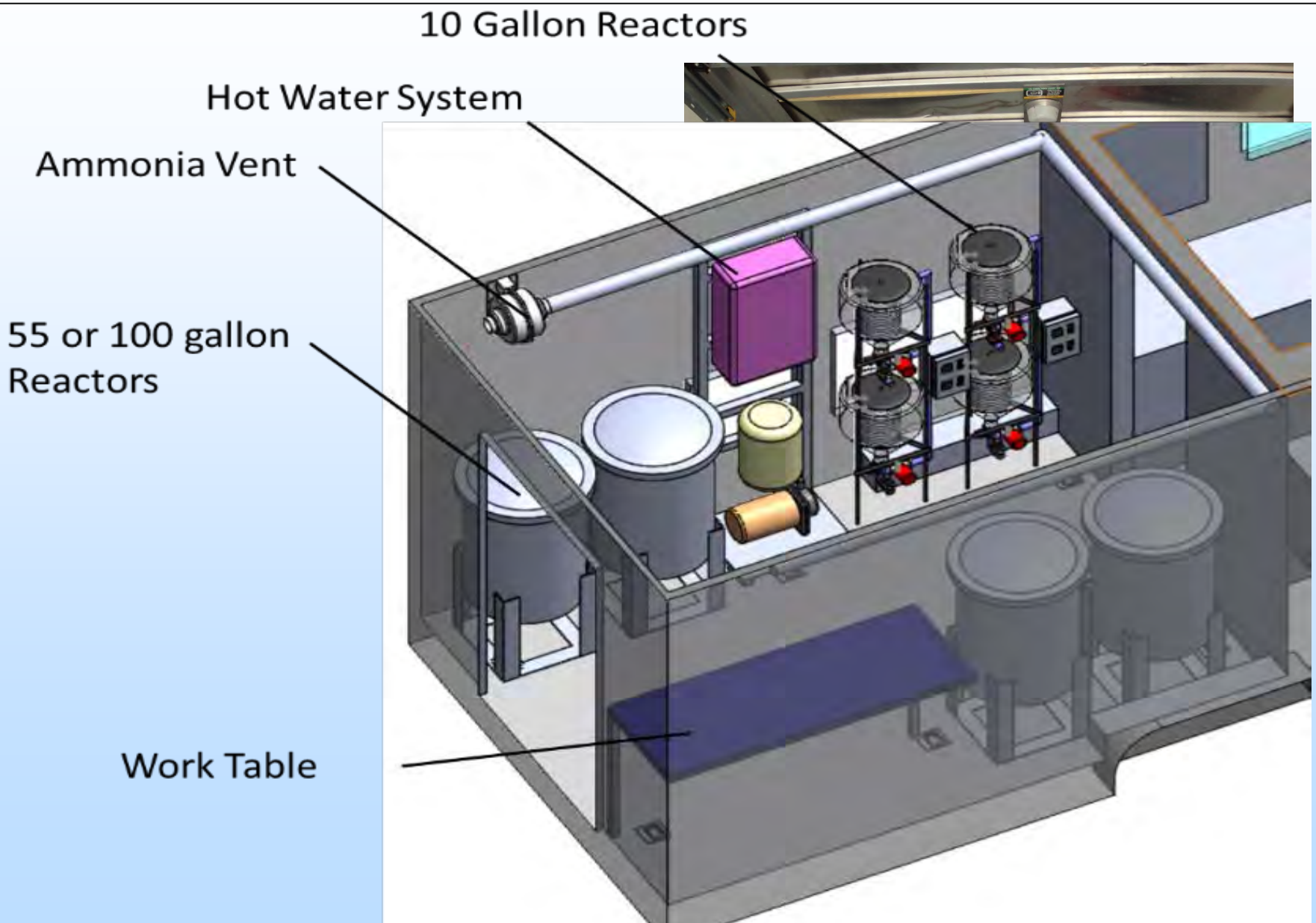
Accomplishment to date: Mobile Mineralization Unit





Accomplishment to date: Mobile Mineralization Unit

Mobile Laboratory



Lessons Learned

- Success at Gorgas- wellbore integrity
  - USIT and mechanical integrity
- Move to oil field well
  - Challenges will face in commercialization
  - Corrosion, cement deterioration greater
  - Successful in returning to service
  - Need to bring up to 1200 psi- still some water traveling in the channel

Synergies (and Synergy Opportunities)

- Additional R&D projects:
  - Wellbore Leakage Mitigation Using Advanced Mineral Precipitation Strategies – Montana State University- (DE-FE0026513)
- Possible synergies with other NETL & FE projects, e.g.
  - Programmable Sealant-Loaded Mesoporous Nanoparticles for Gas/Liquid Leakage Mitigation - C-Crete Technologies, LLC – Rice University, Rouzbah Shasavari (DE-FE0026511)
  - Targeted Mineral Carbonation to Enhance Wellbore Integrity- University of Virginia, Dr. Andres Clarens (DE-FE0026582)
  - Nanoparticle Injection Technology for Remediating Leaks of CO_2 Storage Formation, University of Colorado Boulder, Yunping Xi
  - Bill Carey (LANL) - Wellbore and Seal Integrity
  - Others

Synergy Opportunities

Mesoscale high pressure vessel for scale up work – radial flow, samples up to ~70 cm diameter, ~50 cm height

Designed and built by Joe Eldring & Alaskan Copper, Seattle, WA, USA

Phillips, AJ, Eldring, J, Hiebert, R, Lauchnor, E, Mitchell, AC, Gerlach, R, Cunningham, A, and Spangler, L. High pressure test vessel for the examination of biogeochemical processes. J. Petrol. Sci. Eng. 126, February 2015:55-62, DOI: 10.1016/j.petrol.2014.12.008

Summary

MICP: lab to field

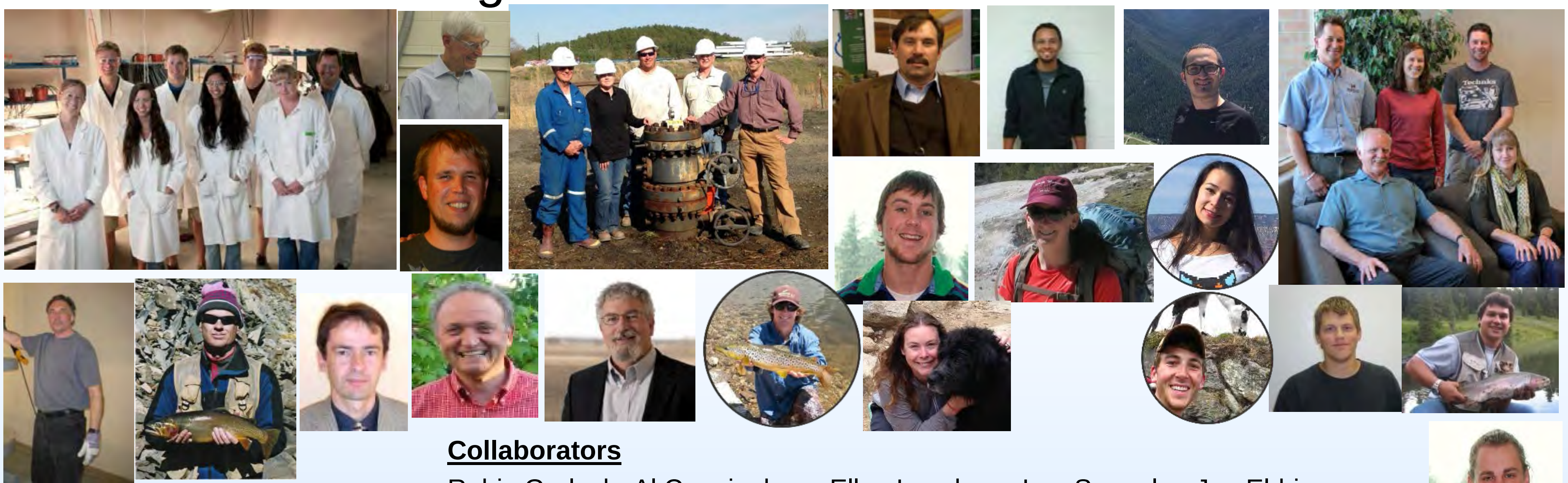
Wellbore integrity

Sealing channels

Scale up

Third field demonstration

Acknowledgements



Collaborators

Robin Gerlach, Al Cunningham, Ellen Lauchnor, Lee Spangler, Joe Eldring, James Connolly, Logan Schultz, Marnie Feder, Laura Dobeck, **Montana State University**

Randy Hiebert, Robert Hyatt, Brian Park, Jay McCloskey, **Montana Emergent Technologies**

Jim Kirksey, Wayne Rowe, **Schlumberger**

Jim Brewer, Bart Lomans, Joe Westrich, **Shell**

Richard Esposito, **Southern Company**

Pete Walsh, **University of Alabama Birmingham**

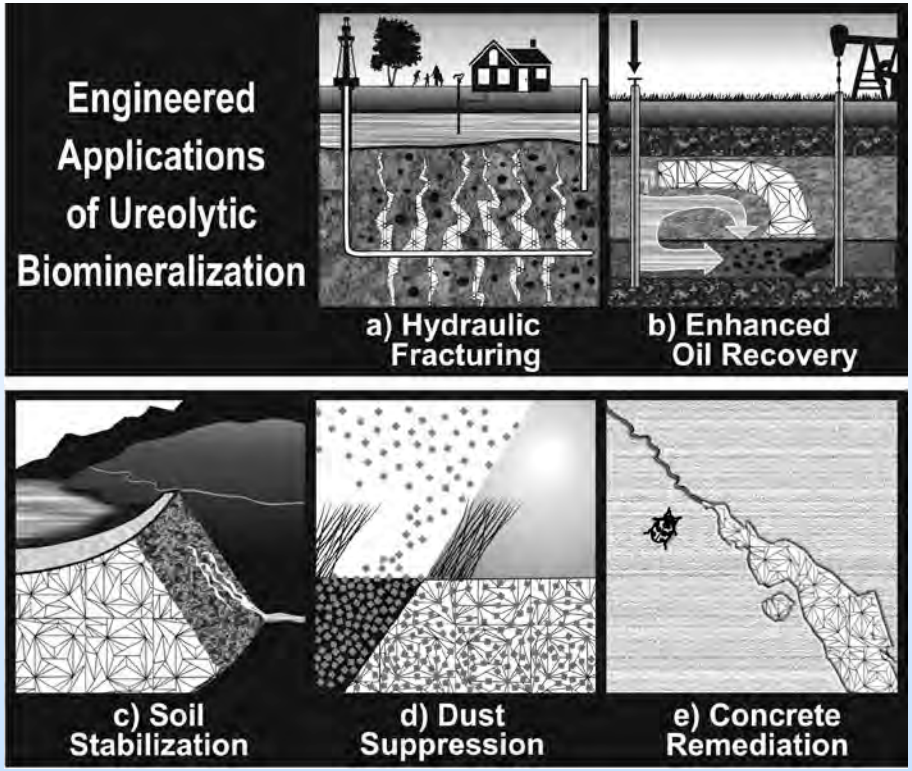
Anozie Ebigbo, Johannes Hommel, Holger Class, and Rainer Helmig, **University of Stuttgart**

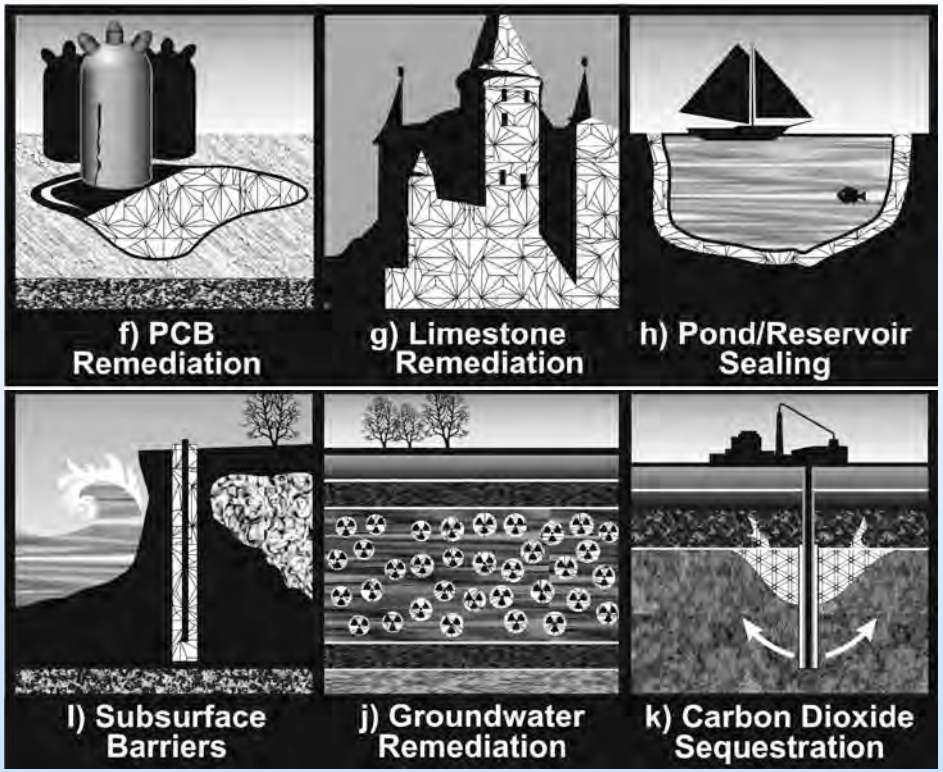
Andrew Mitchell, Sara Edwards **Aberystwyth University**

Burt Todd, Leo Heath, Lee Richards**, Montana Tech**

Supporters: Dayla Topp, Josh Stringam, Adam Rothman, John Barnick, Neerja Zambare, Eric Troyer, Abby Thane, Cody West, Sam Zanetti, Brooke Filanoski, Drew Norton, Vinny Morasko, Zach Frieling, Arda Akyel, Kyle DeVerna, Dicle Beser **CBE, ERI**

Engineered Applications- Biomineralization





Peg Dirckx, 2012

Phillips AJ, Gerlach, R, Lauchnor, E, Mitchell, A, Cunningham, A, Spangler, L. (2013) Engineered applications of ureolytic biomineralization: a review. *Biofouling.* 29 (6) 715-733

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

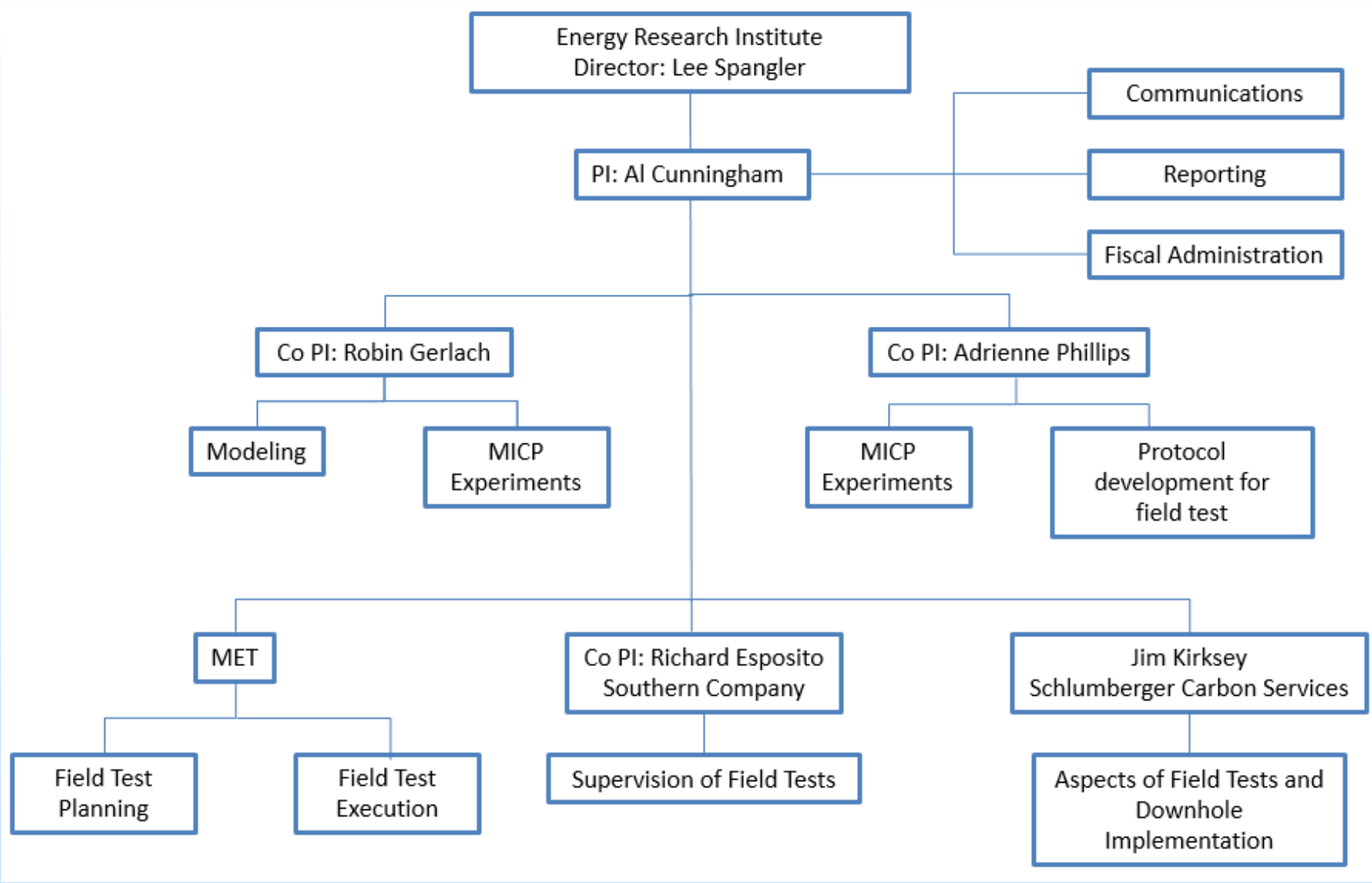
- Environmentally-Prudent Unconventional Resource Development
- FOA objective to minimize environmental impacts and improve the efficiency of UOG development wells.
- Topic Area 2: technology development activities related to:
  - Development of science and technology related to the assurance of the long-term integrity of boreholes and
  - Demonstration of technologies for the effective mitigation of impacts to surface and groundwater resources, ambient air quality/impact, as well as other ecological impacts.
- Project must include a field data collection, validation, and/or demonstration phase

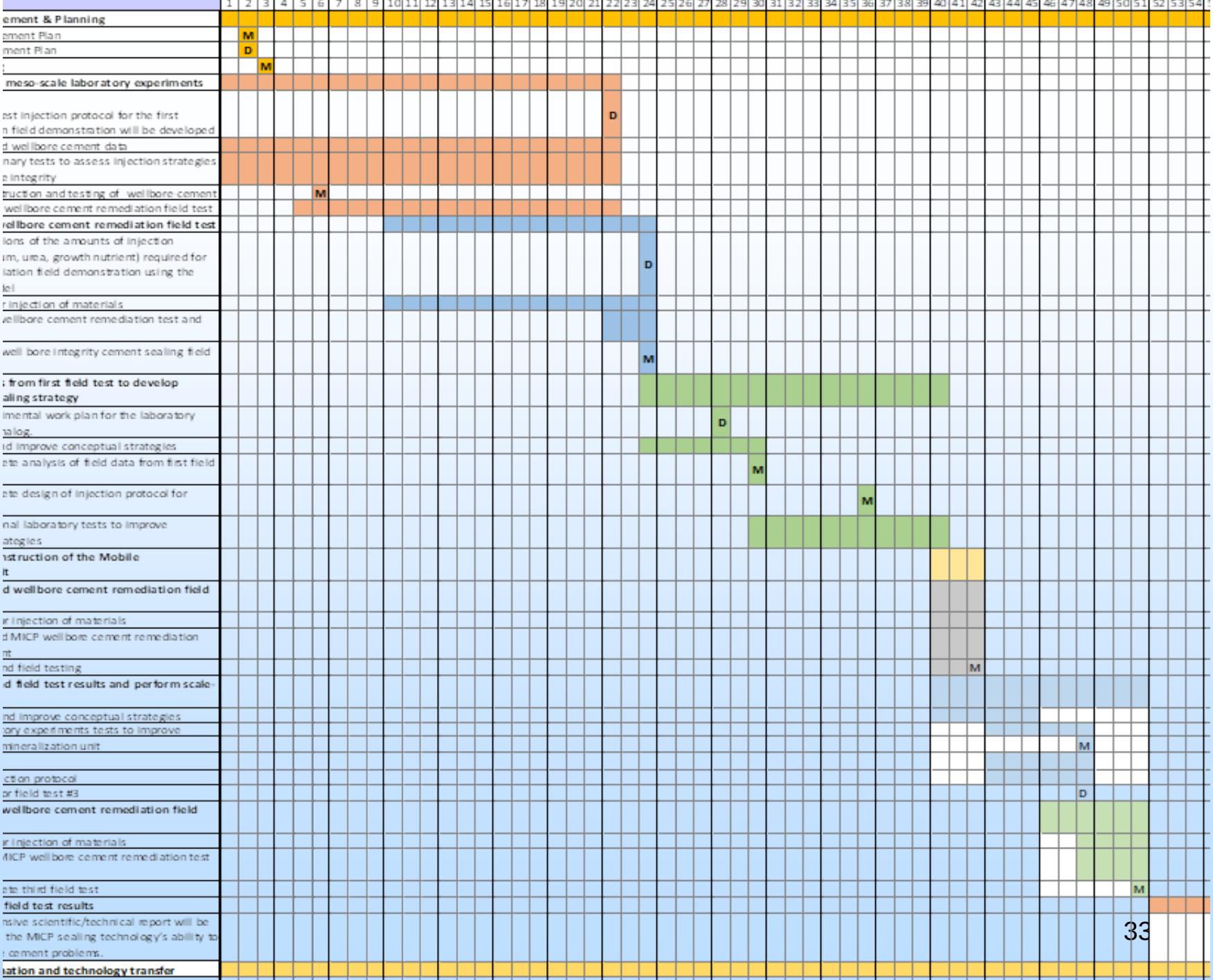
Project Overview:
Goals and Objectives

Project goal: develop improved methods for sealing compromised wellbore cement in leaking natural gas and oil wells, thereby reducing the risk of unwanted upward gas migration through laboratory testing, simulation modeling and field testing.

- Objective 1: Laboratory testing of MICP sealing, develop a field test protocol for effective MICP placement and control.
- Objective 2: Prepare for and conduct an initial MICP field test aimed at sealing a poor well cement bond.
- Objective 3: Analyze results from first field test, conduct a second MICP test using improved MICP injection methods.

Organization Chart

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Bibliography

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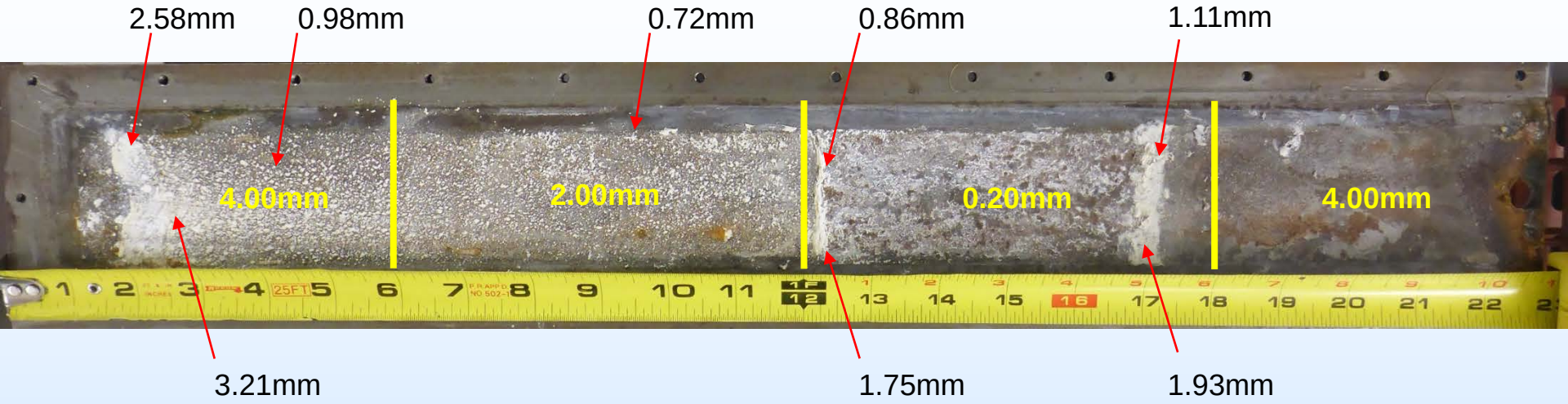
- Kirkland, CM, Zanetti, S, Grunewald, E, Walsh, DO, Codd, SL, Phillips, AJ. (2017) Detecting microbially induced calcite precipitation (MICP) in a model well-bore using downhole low-field NMR Environmental Science and Technology http://pubs.acs.org/doi/abs/10.1021/acs.est.6b04833 DOI: 10.1021/acs.est.6b04833
- Phillips AJ, Cunningham, A, Gerlach, R, Hiebert, R, Hwang, C, Lomans, B, Westrich, J, Mantilla, C, Kirksey, J, Esposito, R, and Spangler, L. (2016) Fracture sealing with microbially-induced calcium carbonate precipitation: A field study. *Environmental Science and Technology*, 50 (7), pp 4111–4117 http://pubs.acs.org/doi/abs/10.1021/acs.est.5b05559 DOI: 10.1021/acs.est.5b05559
- Phillips, AJ, Gerlach, R, Hiebert, R, Kirksey, J, Spangler, L, Esposito, R, and Cunningham, AB Biological influences in the subsurface: A method to seal fractures and reduce permeability with microbially-induced calcite precipitation. American Rock Mechanics Association 49th Annual Meeting Proceedings, June 28-July 1, 2015, San Francisco, CA. https://www.onepetro.org/conference-paper/ARMA-2015-490
- Press release: http://www.montana.edu/news/16313/msu-team-shows-biofilm-and-mineral-producing-bacteria-have-potential-for-plugging-oil-and-gas-leaks
- Anna Martinson was interviewed by the Bozeman Daily Chronicle (at the Undergraduate Research Celebration) about her work. https://www.bozemandailychronicle.com/news/montana_state_university/msu-student-researchers-apply-lessons-to-real-world-problems/article_d48bf9af-38fd-5a5a-98fe-4f9f60c6b362.html

Wellbore Analog and Fracture Fixture Experiment

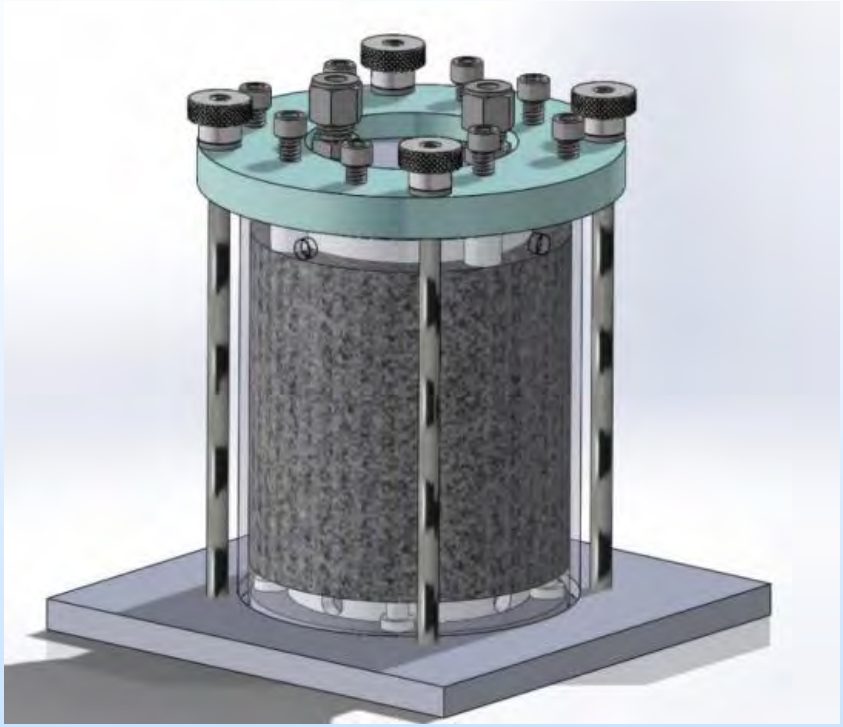
3x concentrated calcium pulses delivered via a perforated pipe inside the clear 6” wellbore.

Measured height of the mineral precipitation

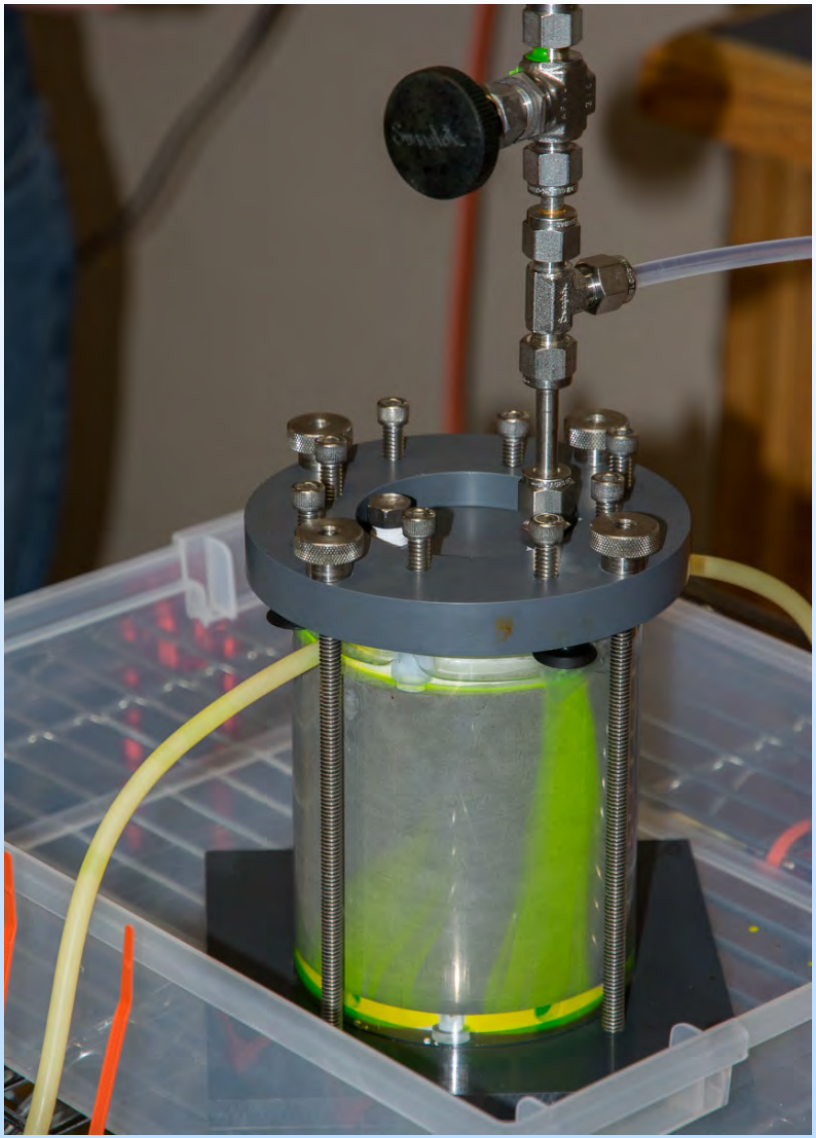


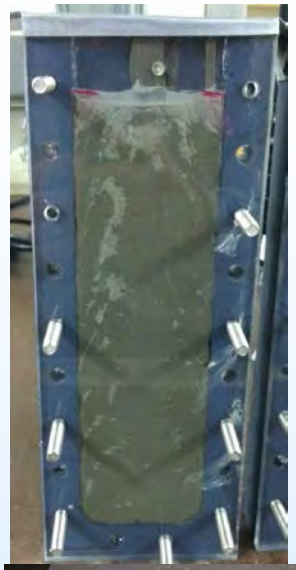
Carbonate seal on cement side of the fracture fixture formed right at the interface of the 0.2mm gap

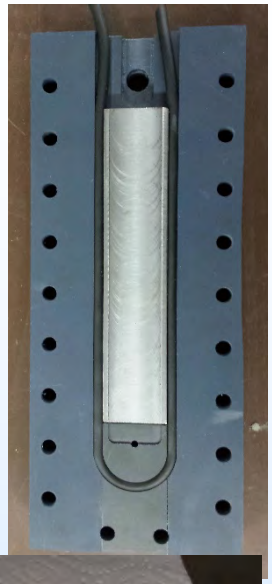
Laboratory- Wellbore Analog- Visualization

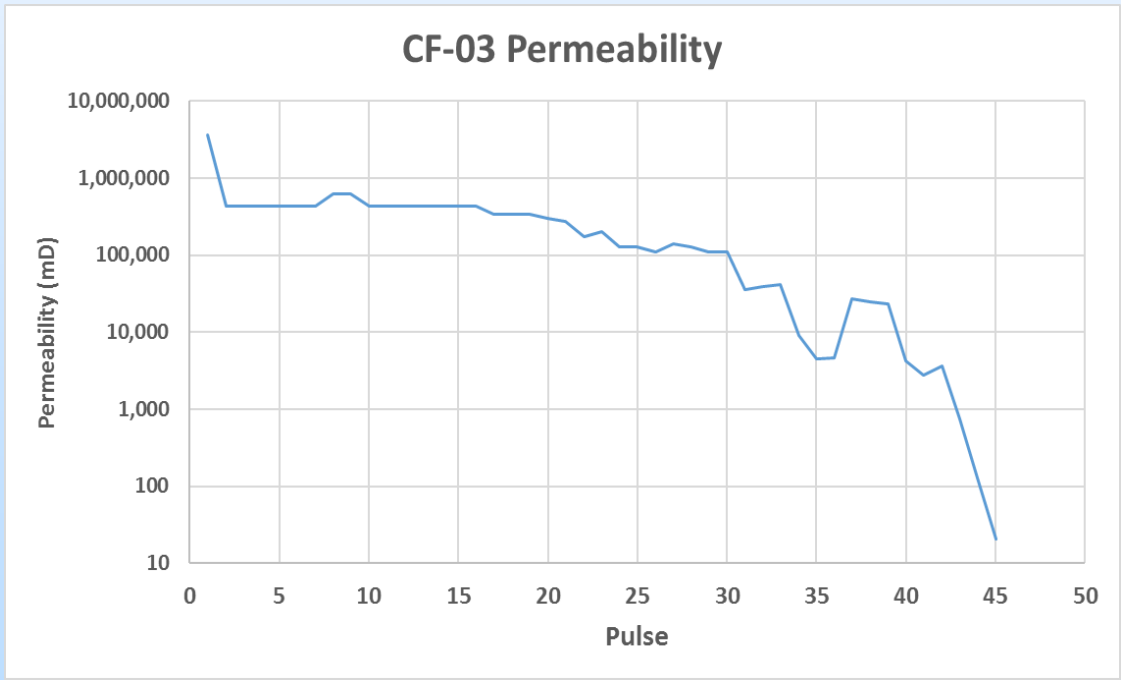


MICP Experiment – 250 µm gap
5 days, 5 orders of magnitude

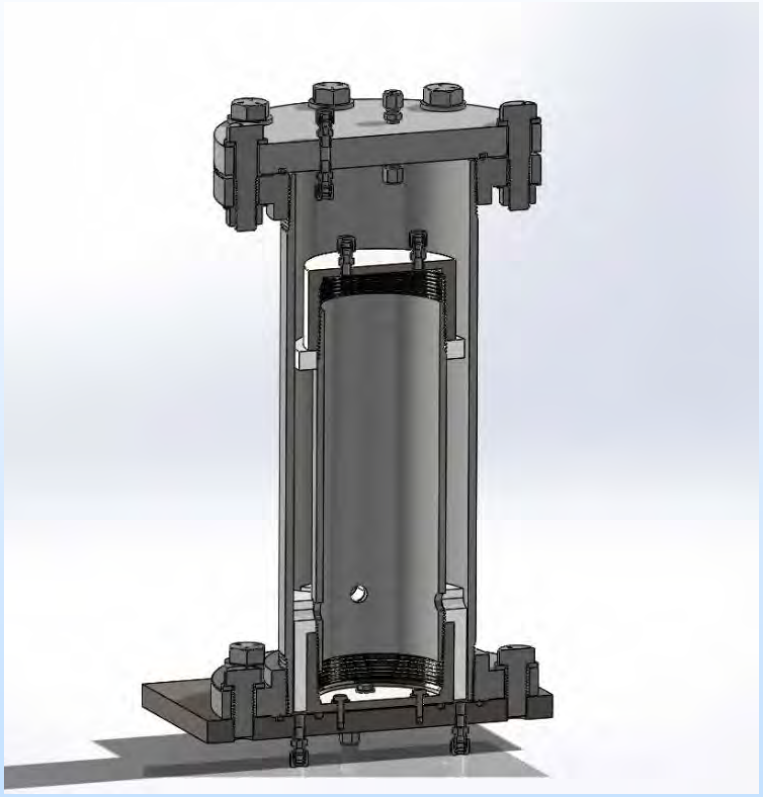






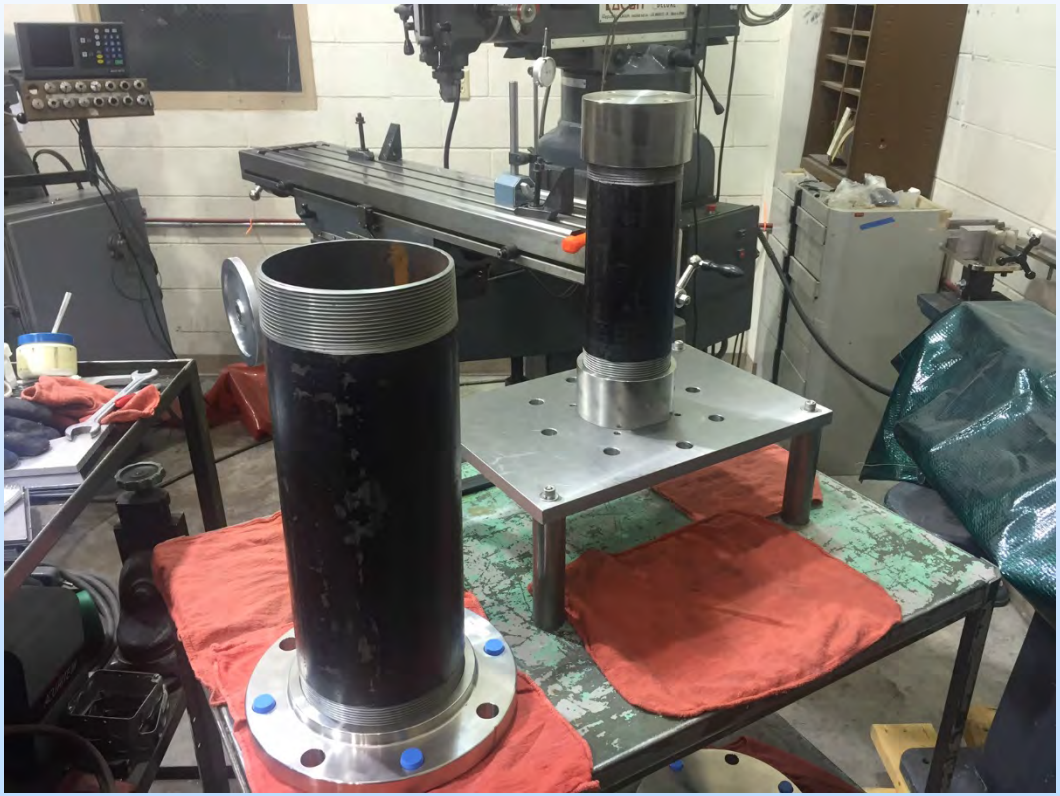

CF-03 Permeability
10,000,000
1,000,000
100,000
10,000
1,000
100
10
Permeability (mD)
0
5
10
15
20
25
30
35
40
45
50
Pulse

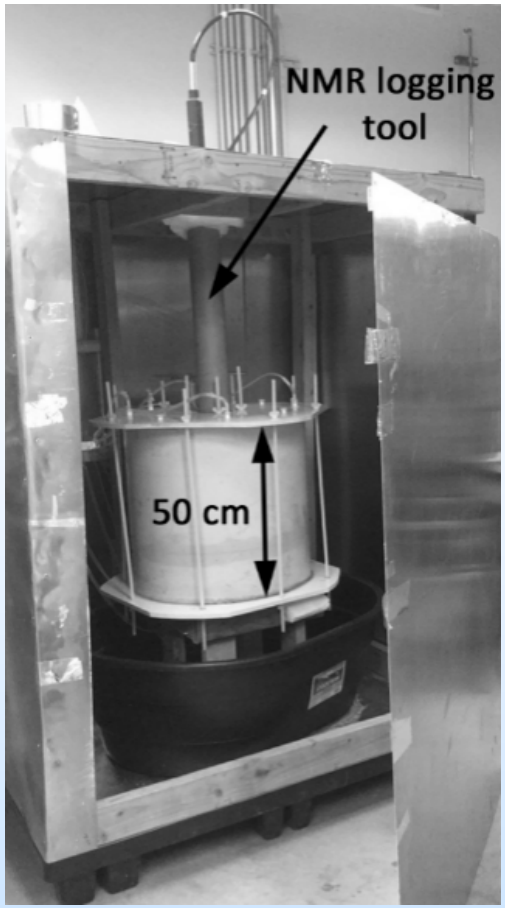
Laboratory -Wellbore Analog- Surface Casing



Resistance to gas flow

Subsurface pressures

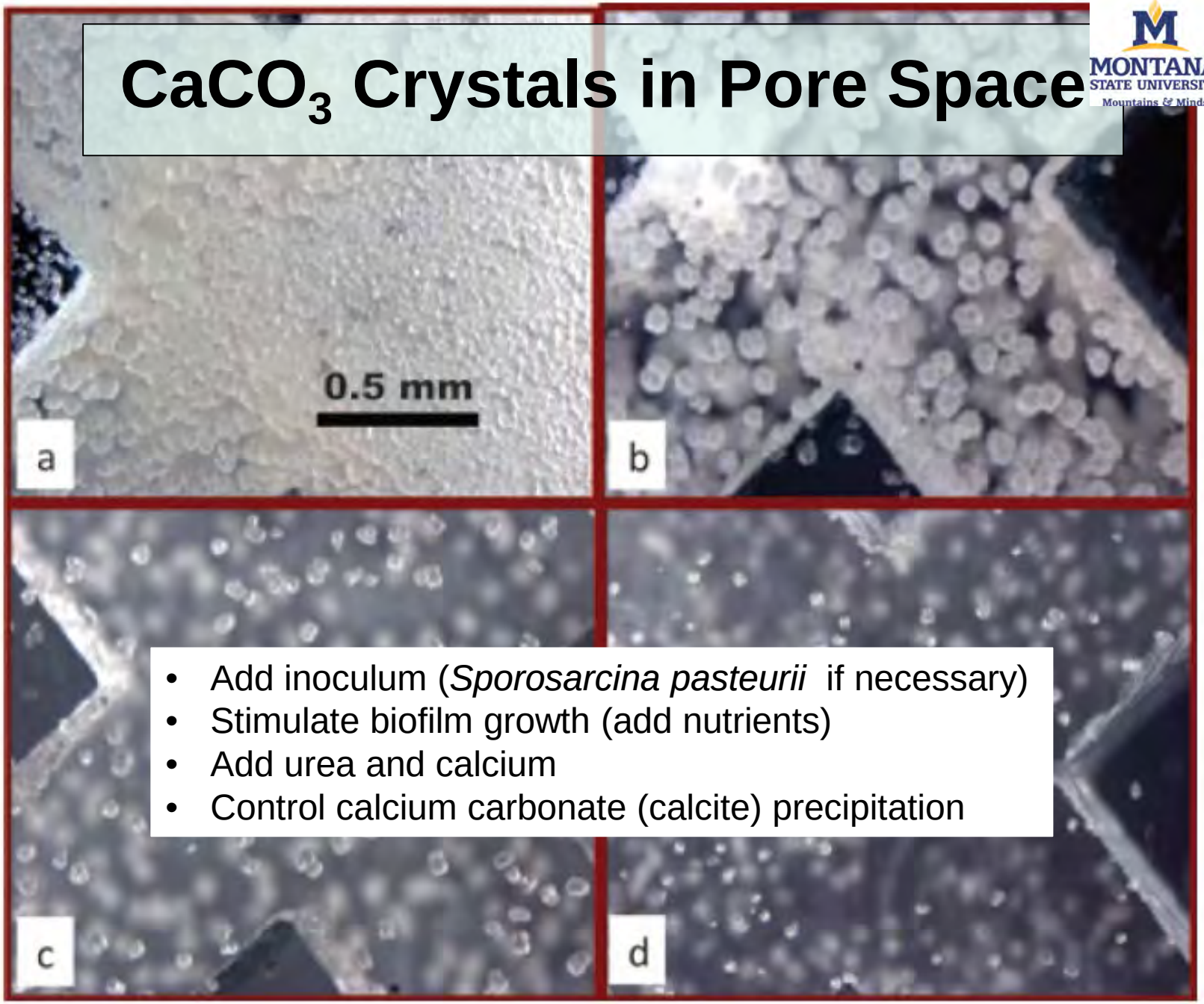




NMR measured water content in the reactor decreased to 76% of its initial value. Destructive sampling confirmed final porosity was approximately 88% of the original value.

Figure 3. The biomineralized sand annulus was destructively sampled to quantify calcite precipitation. The outer pipes of the bioreactor were cut away to expose the biomineralized sand annulus. A saw was used to cut the annulus into quarters, producing the large crack shown here.

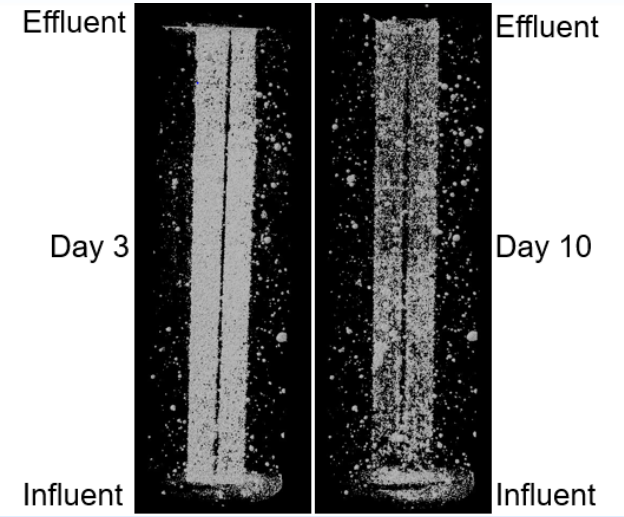
$CaCO_3$ Crystals in Pore Space

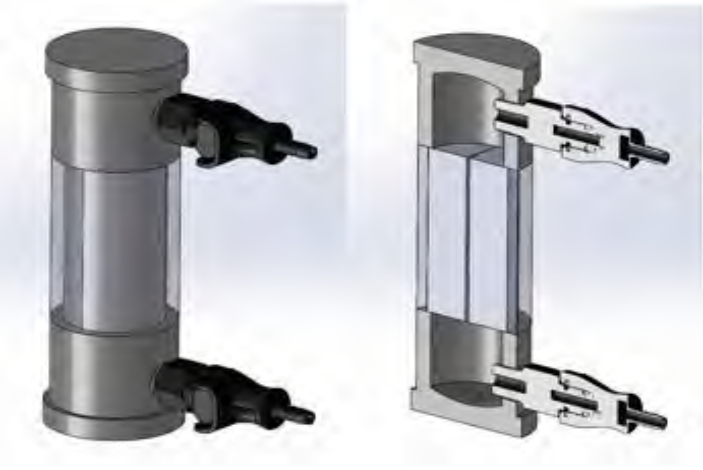


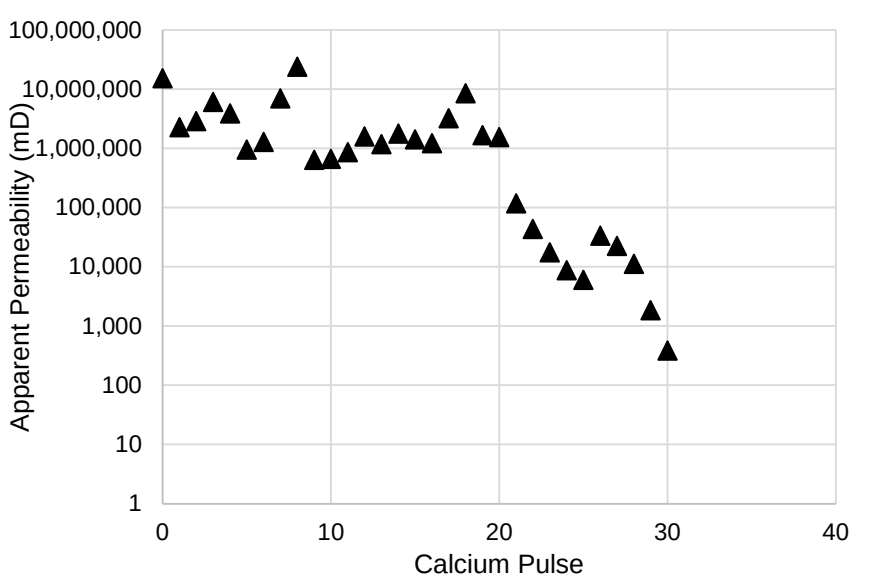
- Add inoculum (*Sporosarcina pasteurii* if necessary)
- Stimulate biofilm growth (add nutrients)
- Add urea and calcium
- Control calcium carbonate (calcite) precipitation

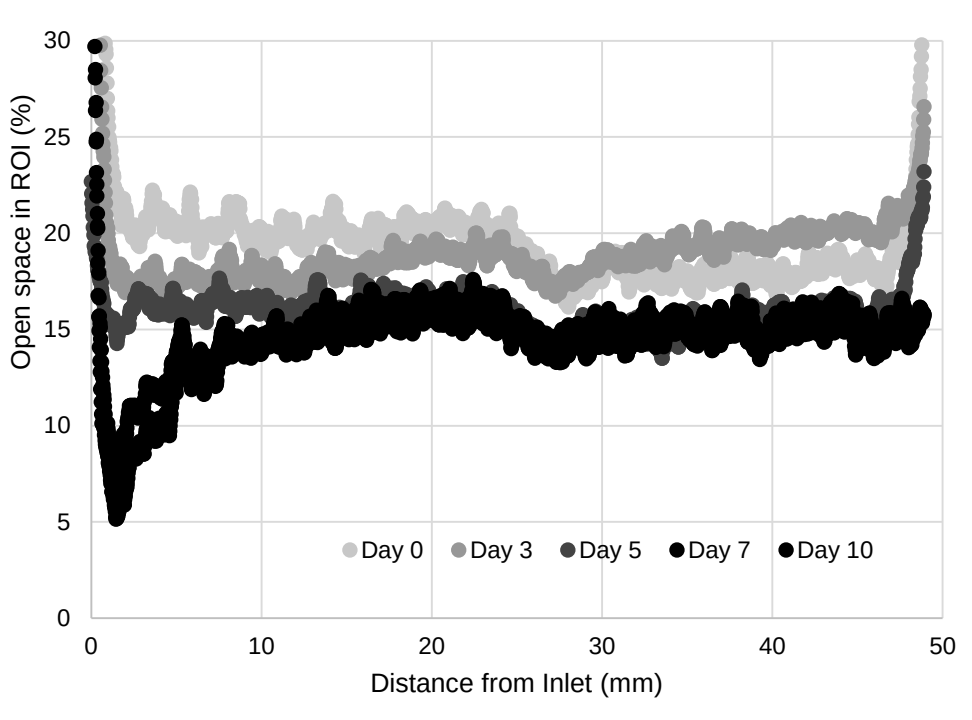
SCHULTZ, L.; ET AL. (2011). *Microscopy Today*. September 2011:10-13.

Objective 1: X-ray CT

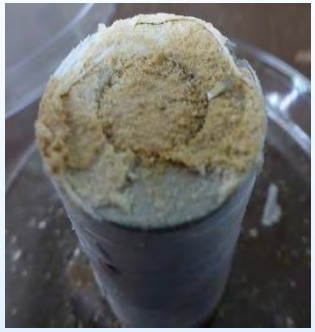


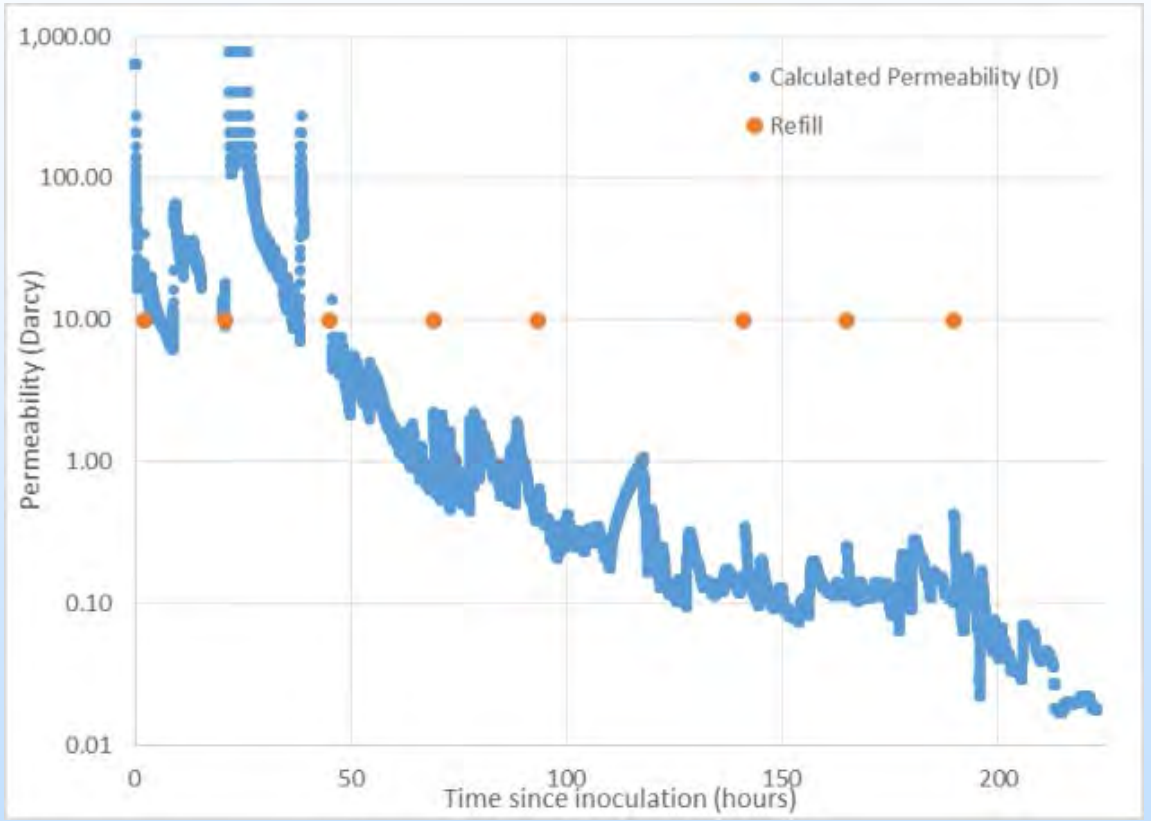






Objective 1: Lab scale: composite cores





Objective 3: Rexing #4 Well