Montana Emergent Technologies

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

DE-FE0024296

Project Period: October 1, 2014 – September 30, 2018

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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 1-3, 2017

Presentation Outline

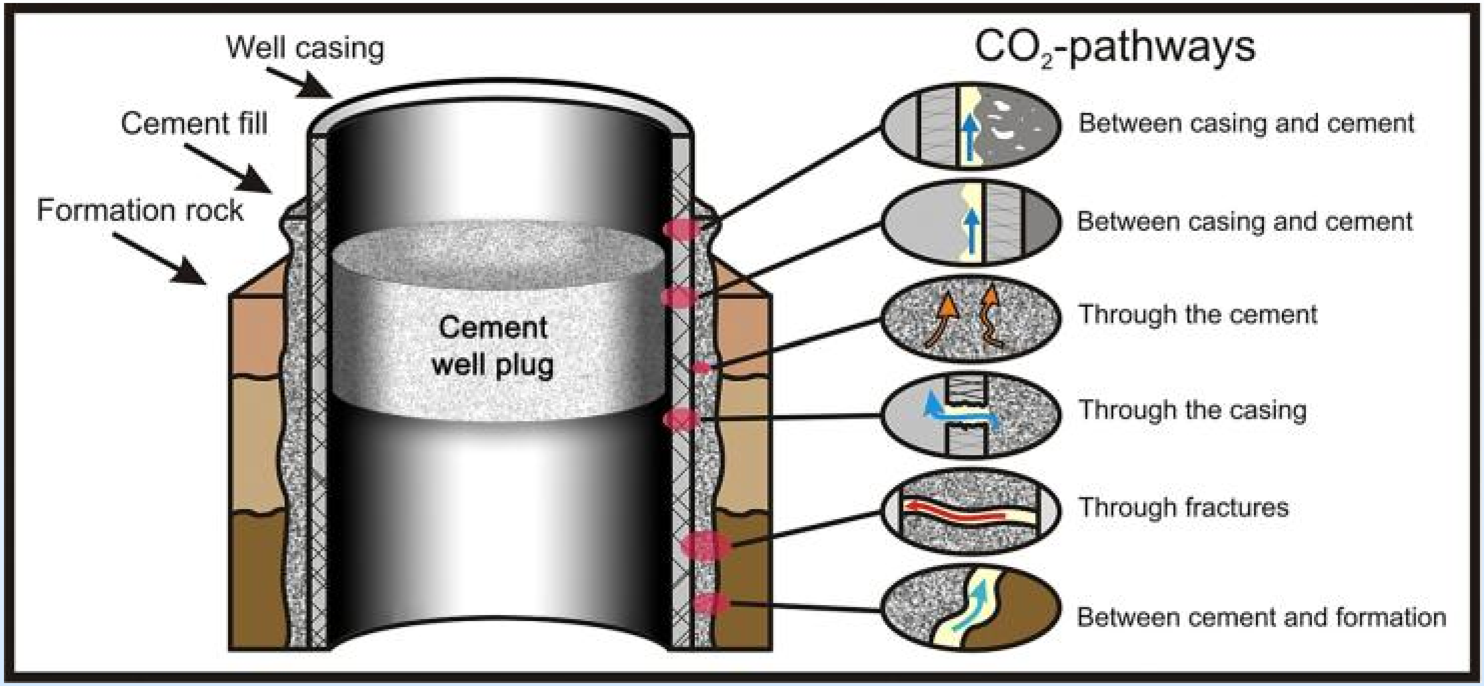
- Technical Status
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Summary

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



After Nordbotten and Celia, Geological Storage of CO_2, 2012

Cement is viscous

Microbes are small –niche treatment technology for small aperture fractures delivered via <u>low-viscosity</u> fluids

Grow a seal

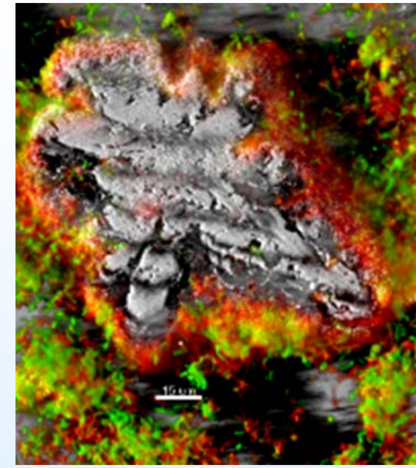
Microbially-Induced $CaCO_3$ Precipitation (MICP)

Ureolysis-driven

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

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

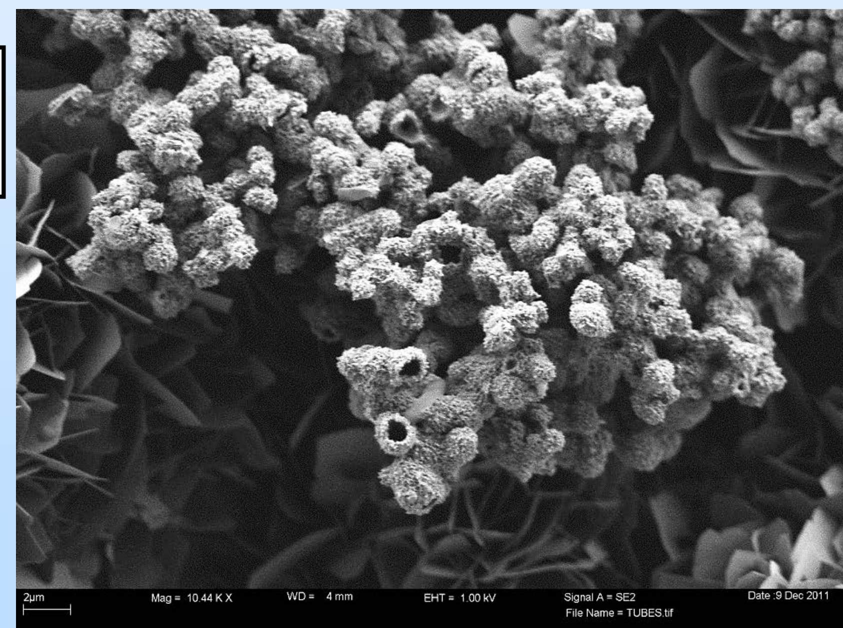
$$2NH_3 + 2H_2O \longleftrightarrow 2NH_4^+ + 2OH^-$$



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

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

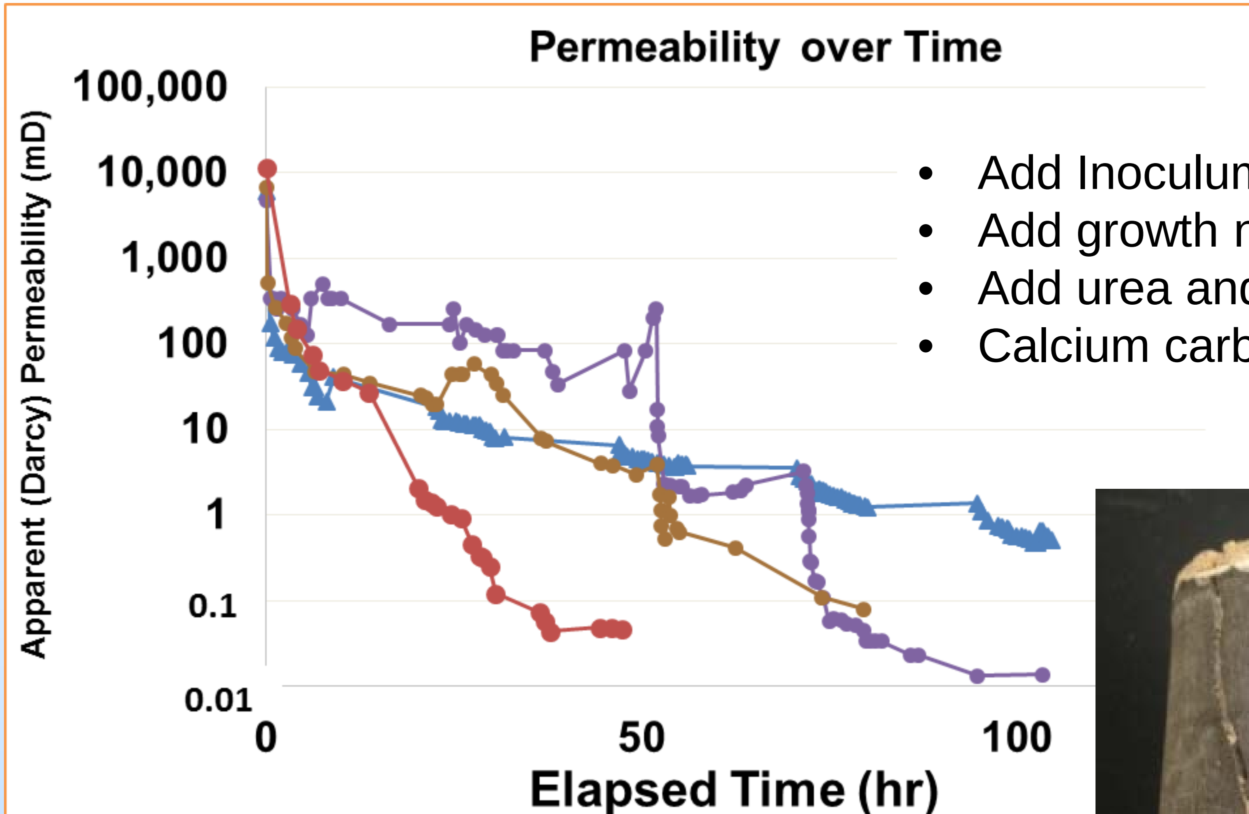
$$Ca^{2+} + CO_3^{2-} \longleftrightarrow CaCO_3\,(s) \qquad K_{sp} = 4.8\text{x}\ 10^{-9}$$



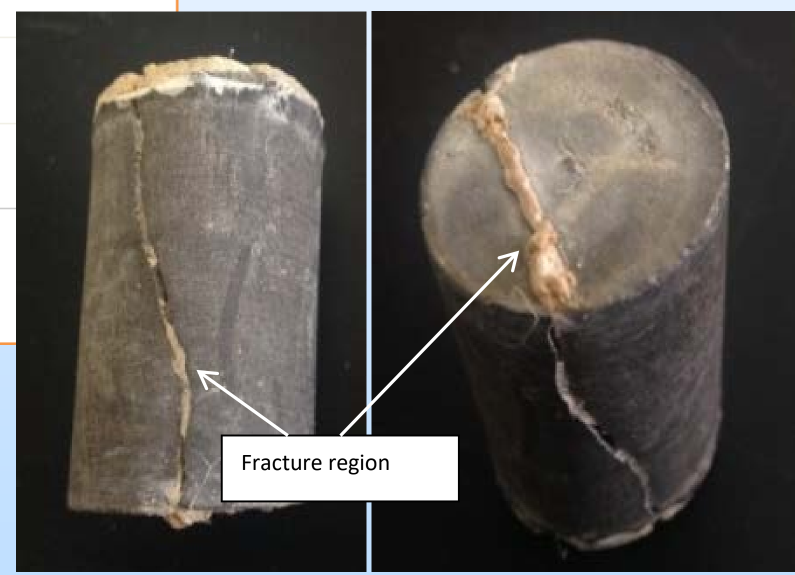
Schultz, L, Pitts, B, Mitchell, AC, Cunningham, A, Gerlach, R. Imaging biologically induced mineralization in fully hydrated flow systems. Microscopy Today 2011, 19, (5), 12-15

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

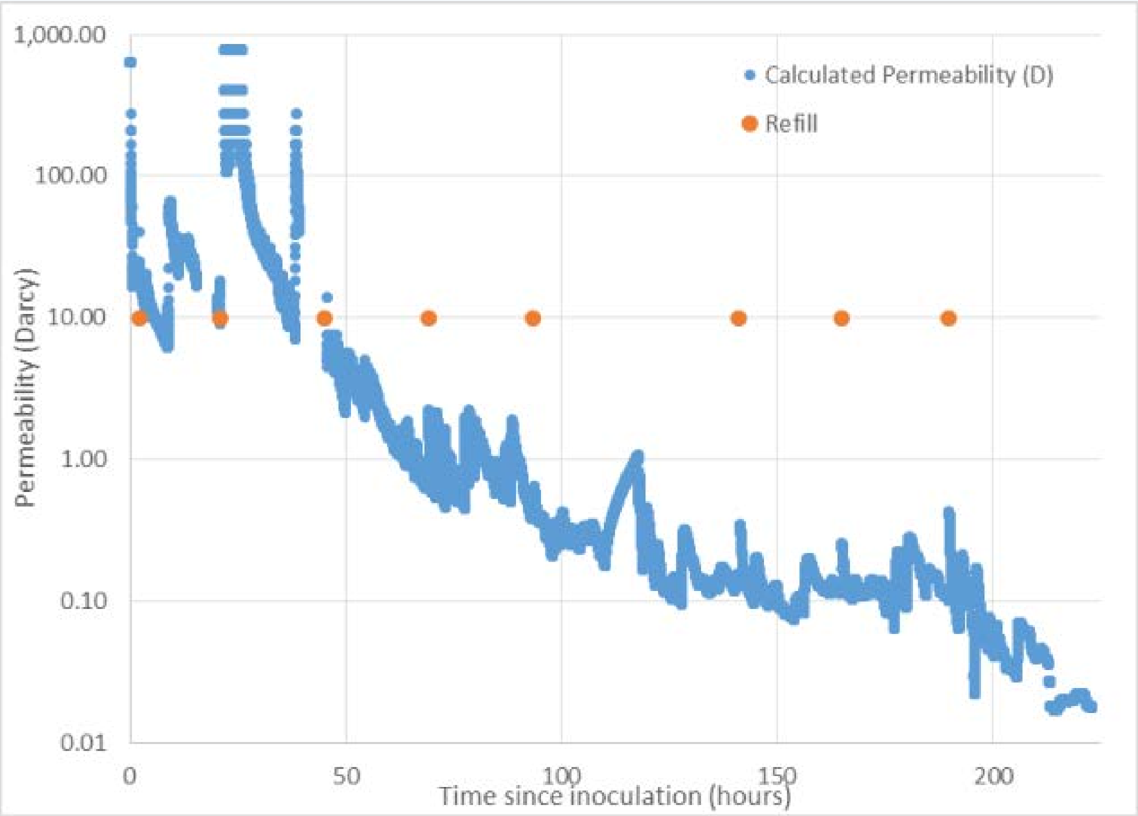


- Add Inoculum *Sporosarcina pasteurii*
- Add growth nutrients
- Add urea and calcium
- Calcium carbonate (calcite) precipitation

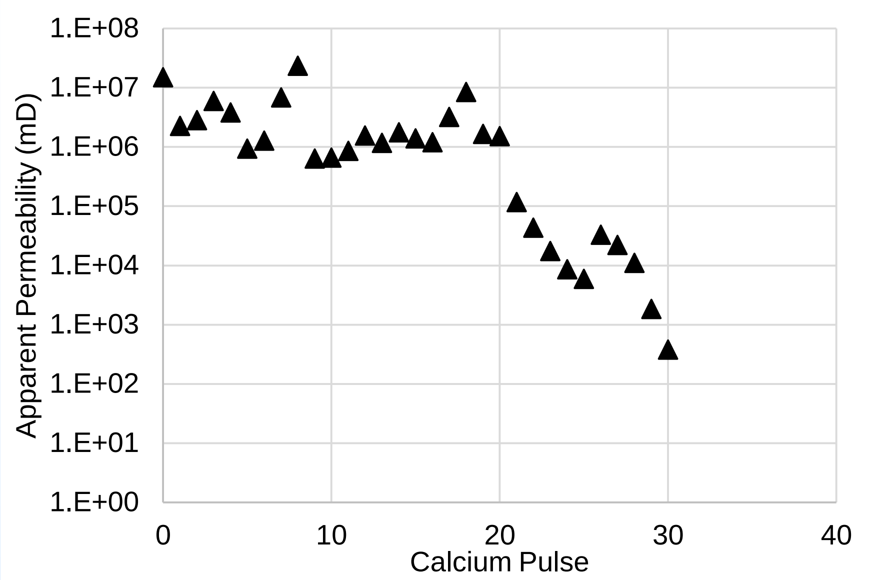


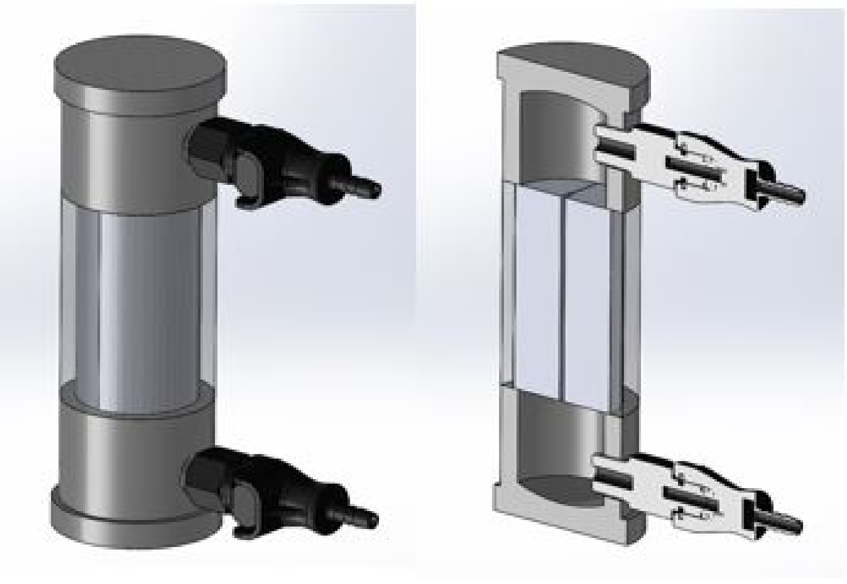
Cunningham, AB, Gerlach, R, Phillips, AJ, Lauchnor, E, Rothman, A, Hiebert, R, Busch, A, Lomans, B, and Spangler, L. (2015) Assessing potential for biomineralization sealing in fractured shale and the Mont Terri Underground Research Facility, Switzerland, Carbon Dioxide Capture for Storage in Deep Geologic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

Objective 1: Lab scale: composite cores

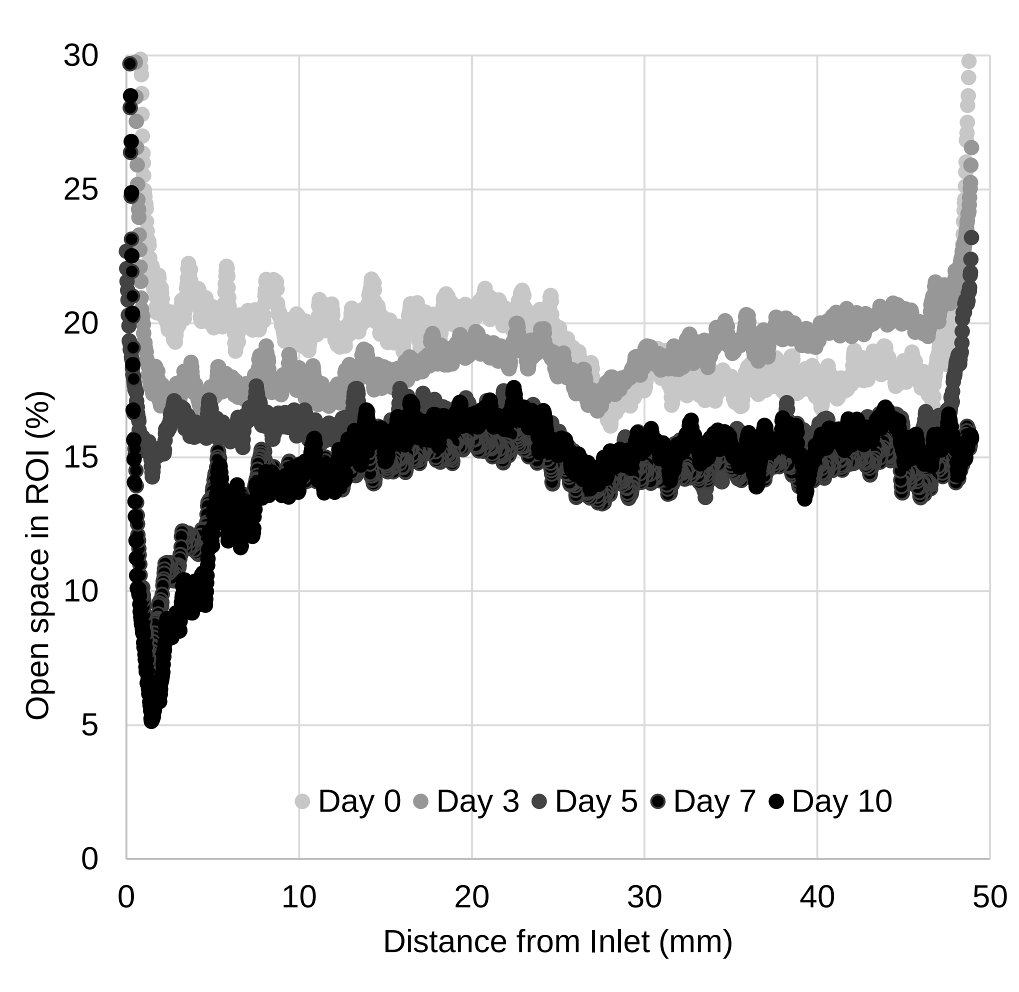


Objective 1: X-ray CT

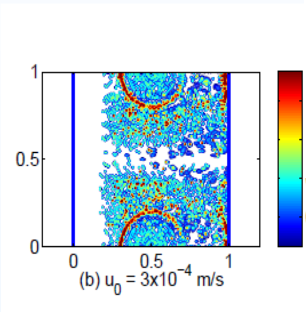


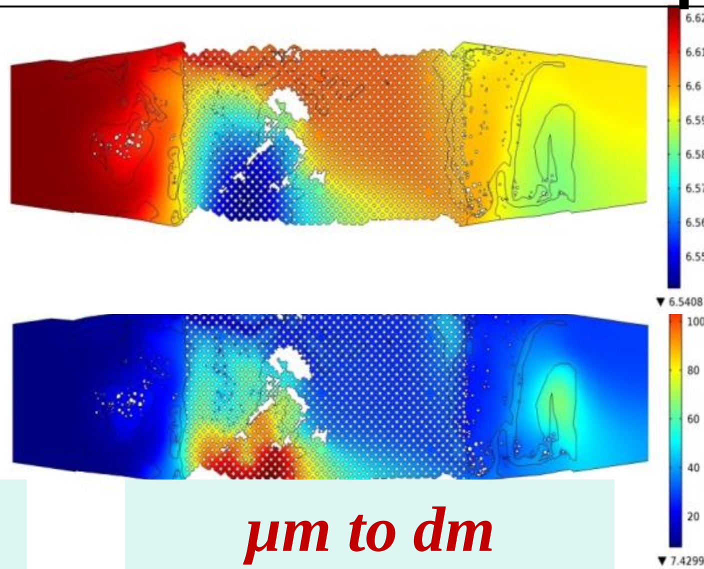


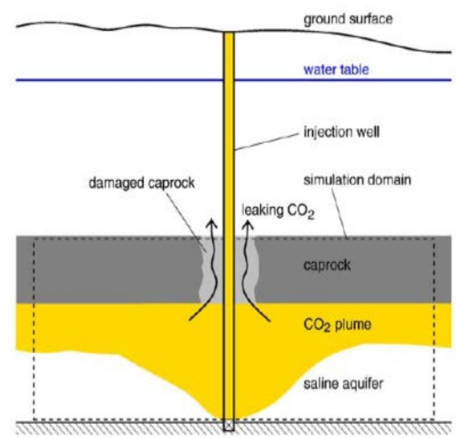
PVC- 15 psi

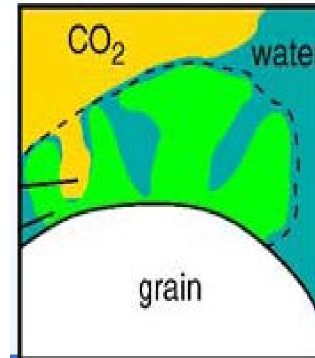


Objective 2: Scale Up





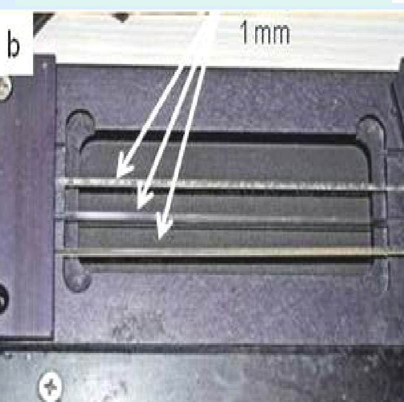


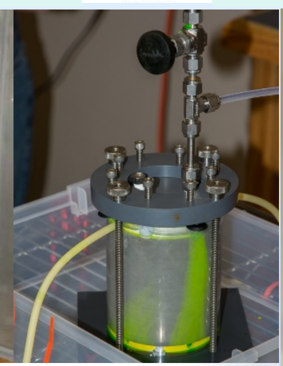


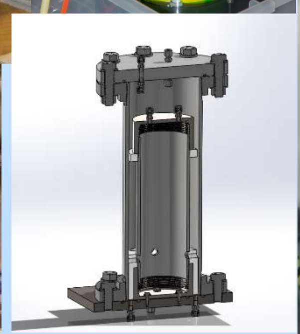
nm to cm

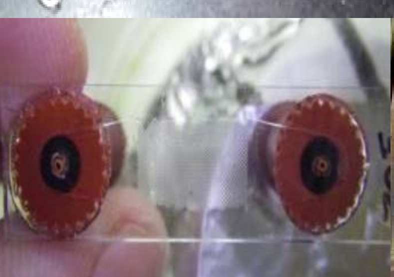
µm to dm

cm to 100s of m





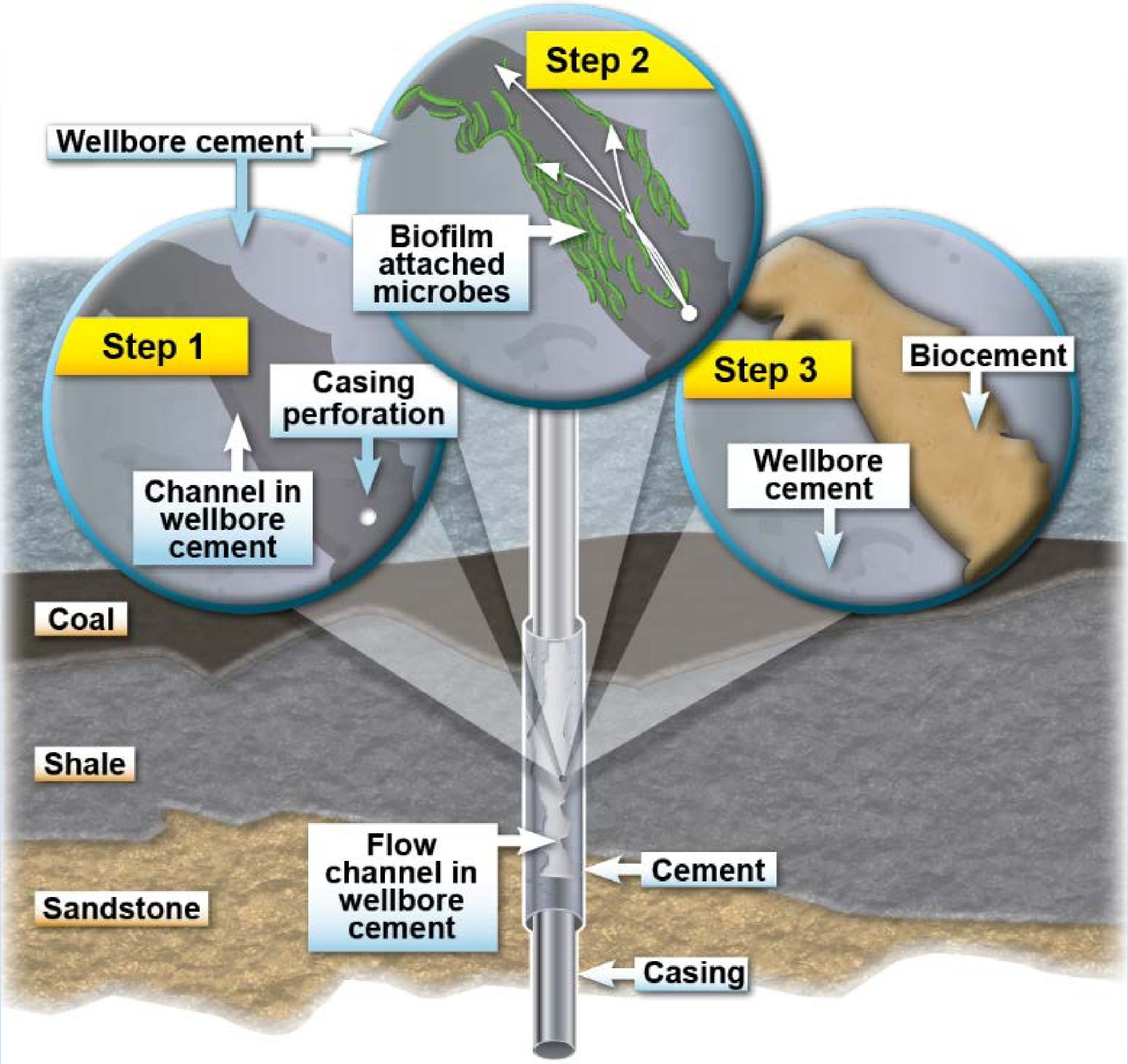




Objective 2: Wellbore sealing

Gorgas well

Side wall coring and injection test



Objective 2: Cement channel sealing

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

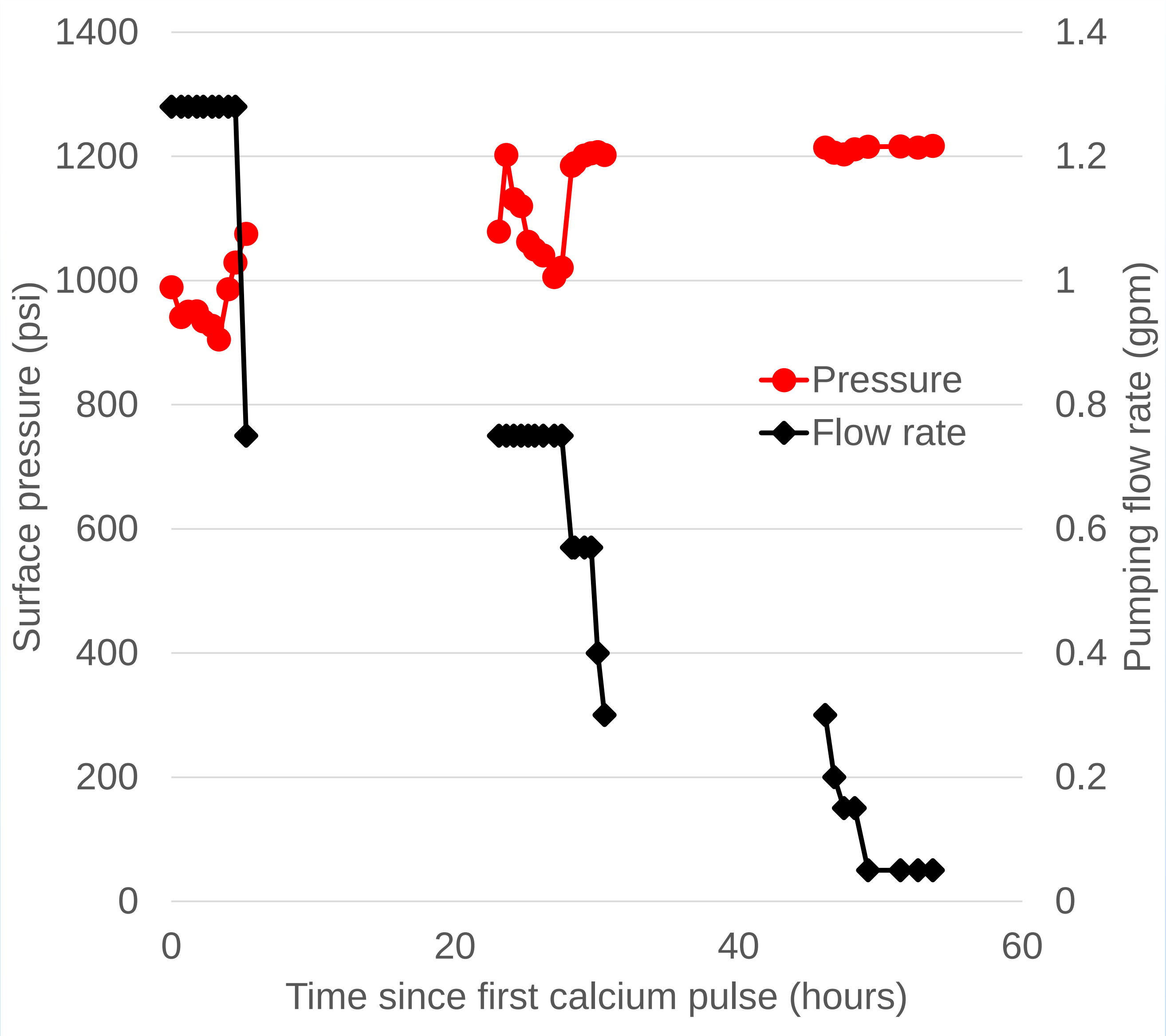
3 measures of success
- Injectivity reduced
- Pressure decay
- USIT Logs

Objective 2: Pressure-flow

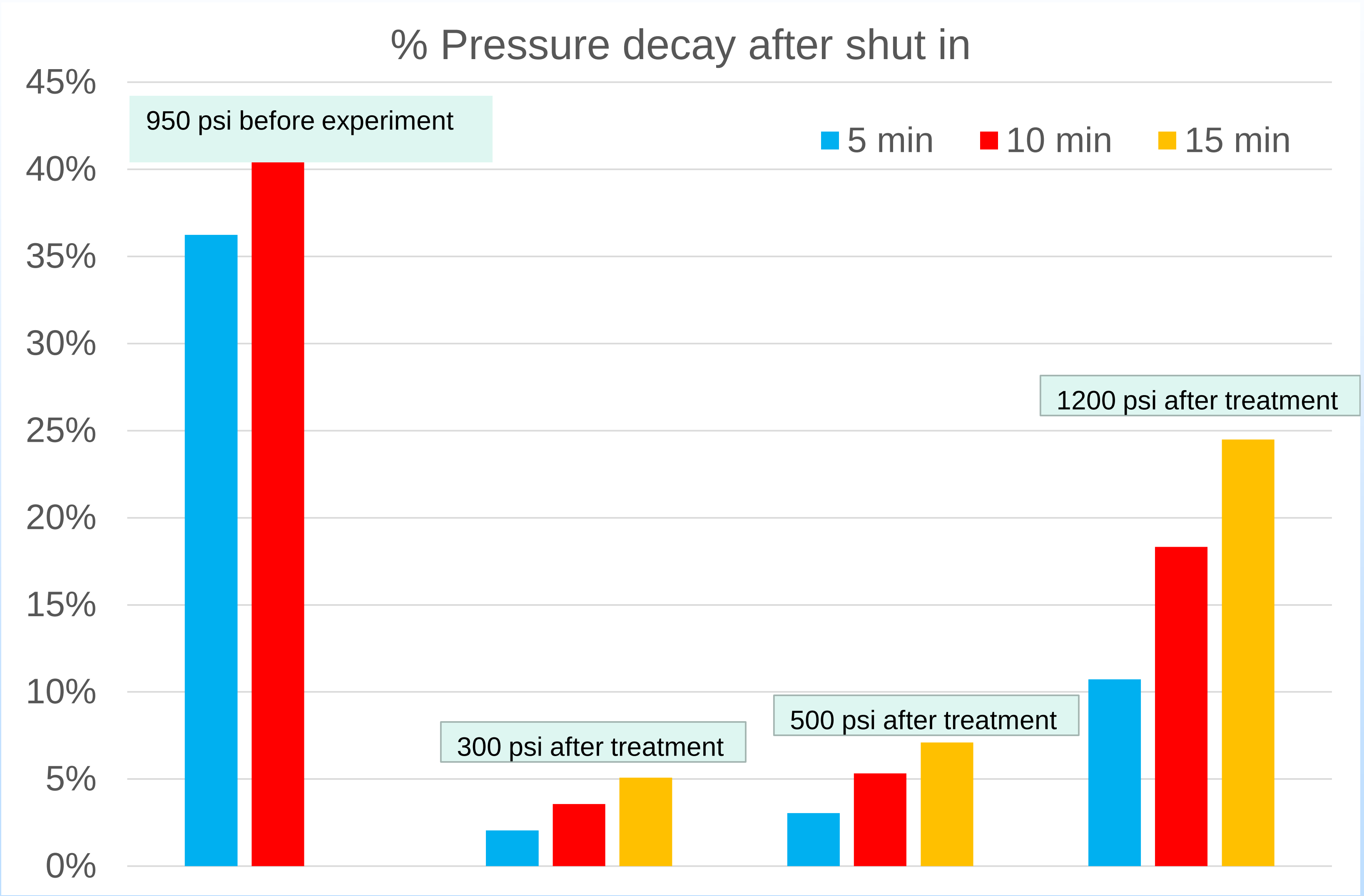
Apparent permeability reduced 1.5 orders of magnitude

Reduced injectivity-pressure increased and flow rate decreased

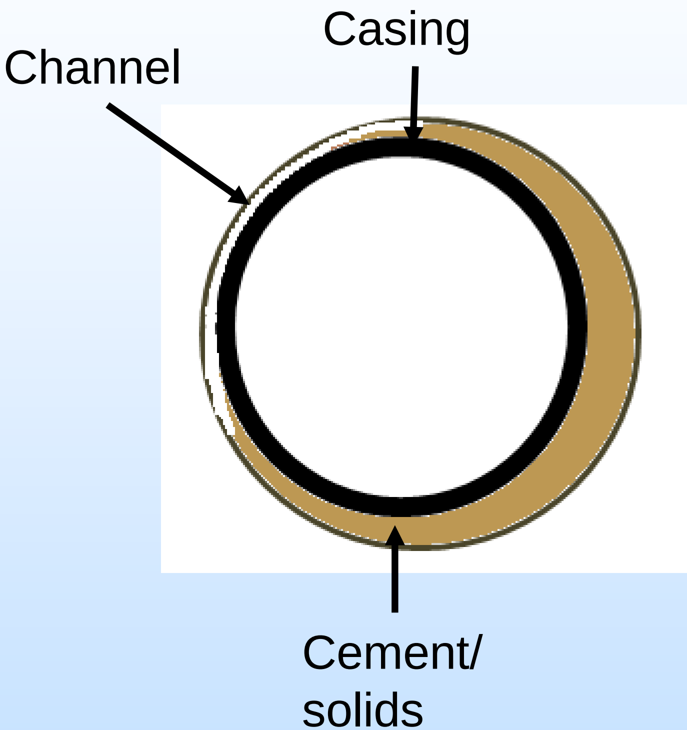
Threshold pressure

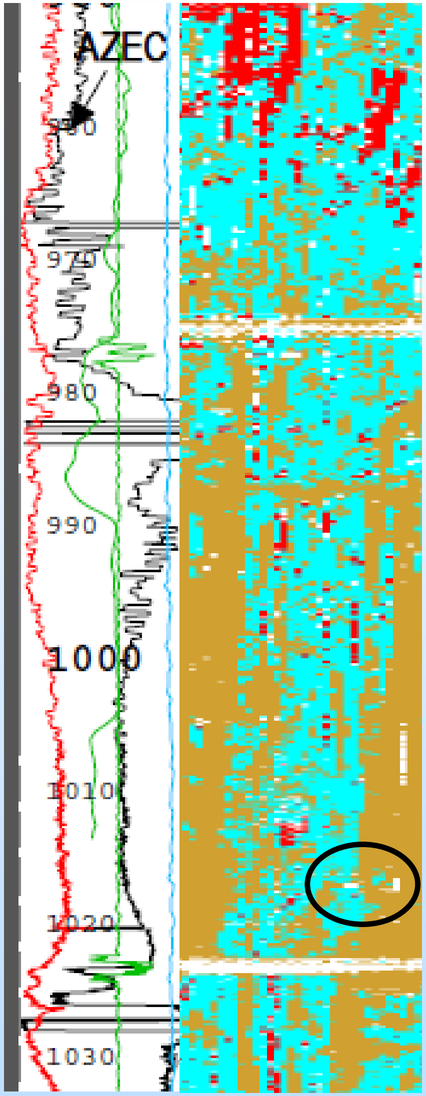


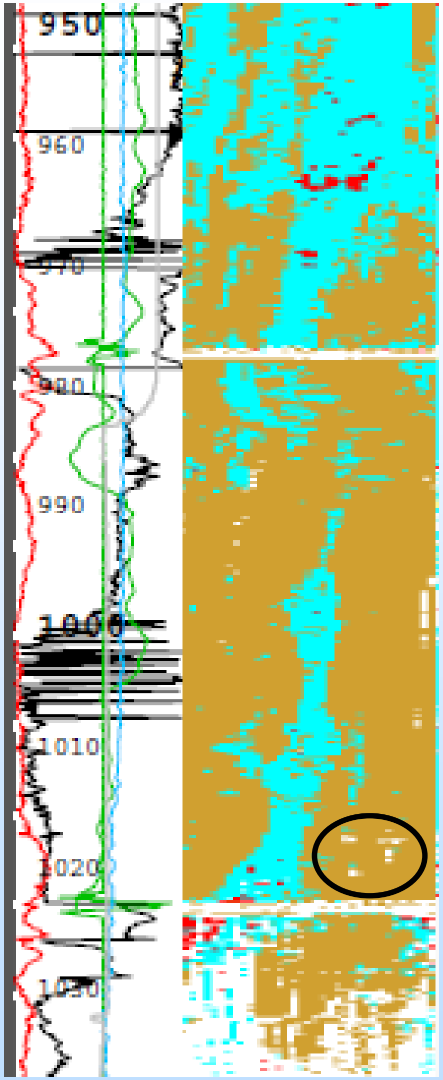
Objective 2: Mechanical Integrity Test



Objective 2: USIT logs







Grow a seal

Objective 3: Rexing #4 Well

- Schlumberger
- Southern Indiana- Gallagher Drilling
- Injection well that was used to perform water flooding to increase oil recovery
- Vertical channel formed in the cement
- Water traveling through the channel into a thief zone above the targeted oil formation
- Opportunity to perform treatment in well part of an oil field- return to production
- Less characterized, realistic and typical of established/problem wells

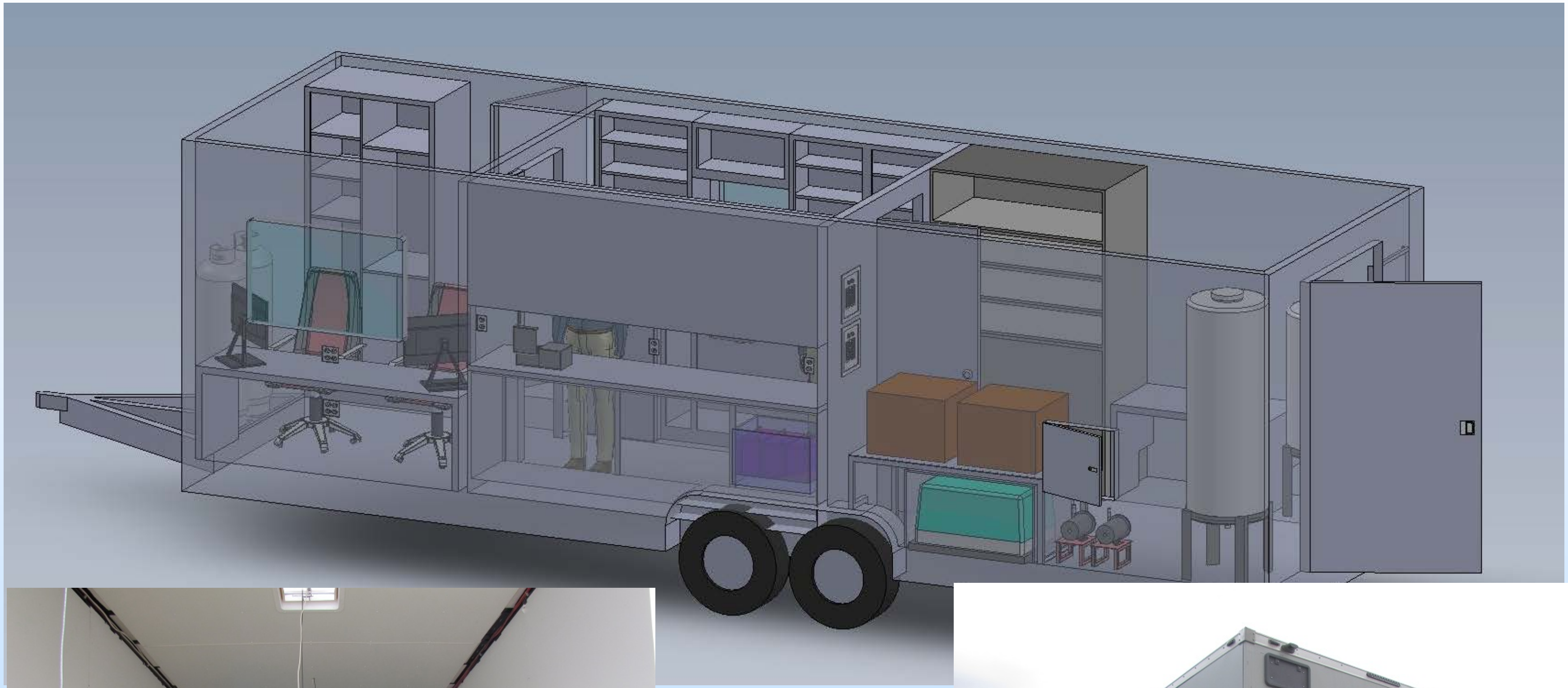
Accomplishments to Date

- Objective 1: Laboratory testing to develop injection strategies
- Objective 2: Field demonstration with successful results
- Objective 3: Plan for field- oil bearing formation

Accomplishment to date: Mobile Mineralization Unit

MONTANA STATE UNIVERSITY Mountains & Minds

CENTER FOR BIOFILM ENGINEERING



Lessons Learned

- Great success at Gorgas because:
  - Lab work and planning
  - New well, cement bond logs, well characterized
  - Cubic's law estimated 200 µm (2-4,000 µm)
- Building a mobile mineralization unit
  - Sourcing materials, set up and tear down time
- Pumping capabilities and reactor pressure limits
- Modify material properties (of wellbore cements) with MICP (data not shown)
- Move to oil field well: typical of challenges will face in commercialization
  - Corrosion, cement deterioration

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

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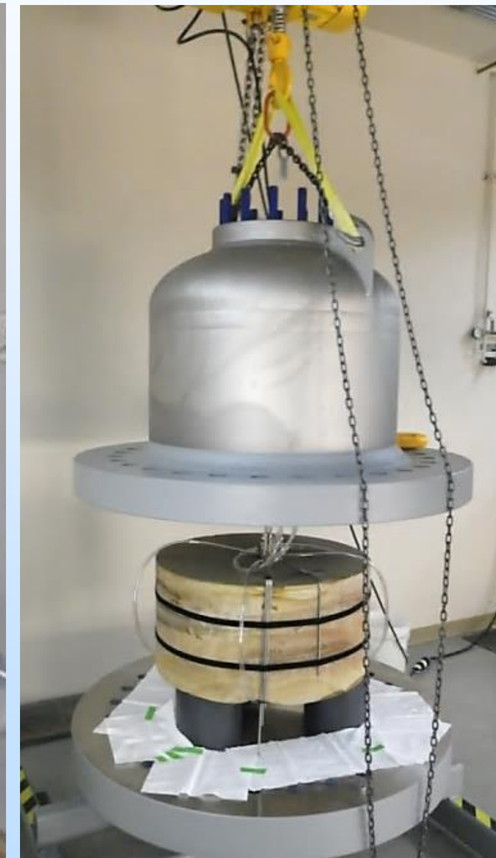
Mesoscale high pressure vessel for scale up work – radial flow, samples up to ~70 cm diameter, ~50 cm height



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

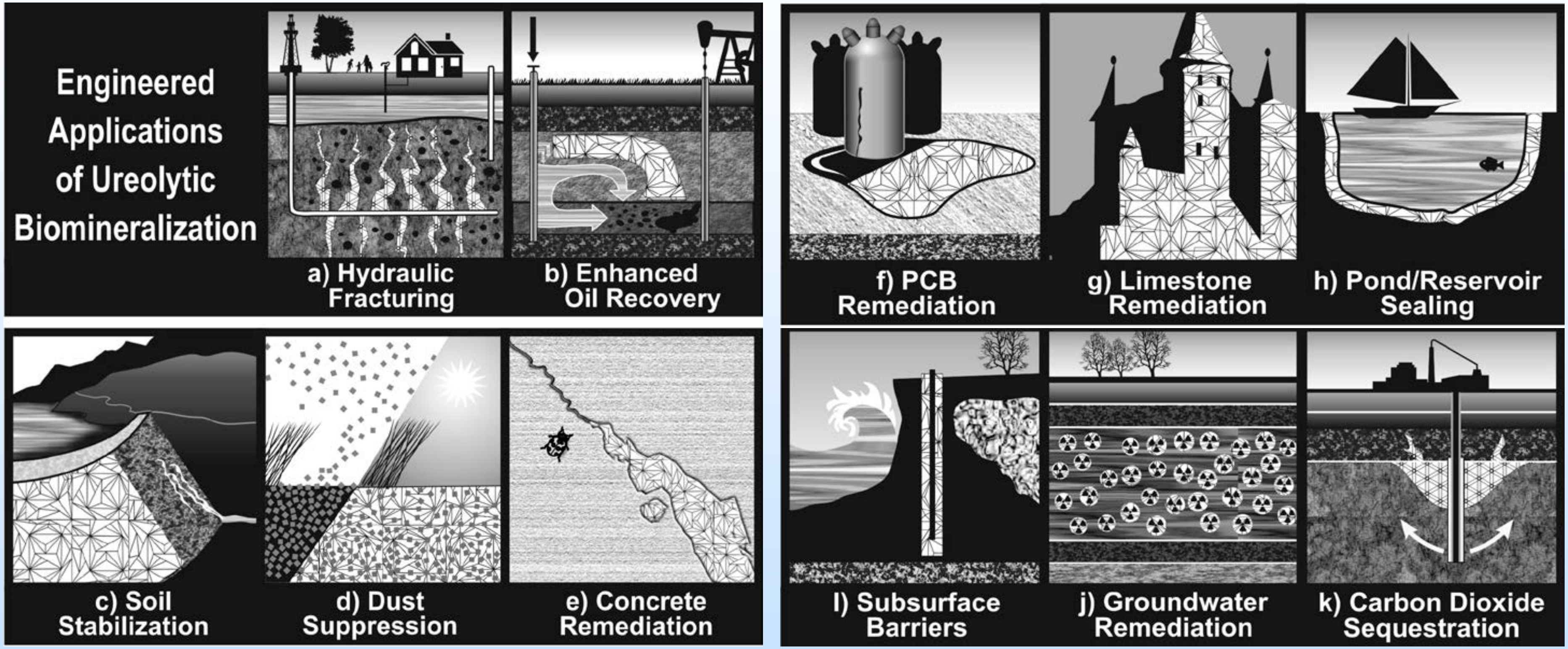
Wellbore integrity

Characterization

Additional lab work and simulation

Second field demonstration

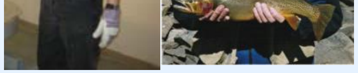
Engineered Applications- Biomineralization

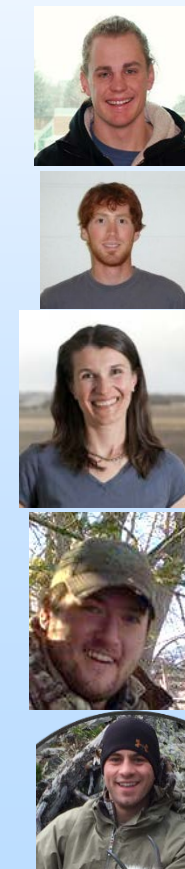


Peg Dirckx, 2012

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

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**

U.S. DEPARTMENT OF ENERGY

NSF

MONTANA

Schlumberger

SOUTHERN COMPANY

University of Stuttgart
Germany

Appendix

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

Benefit to the Program

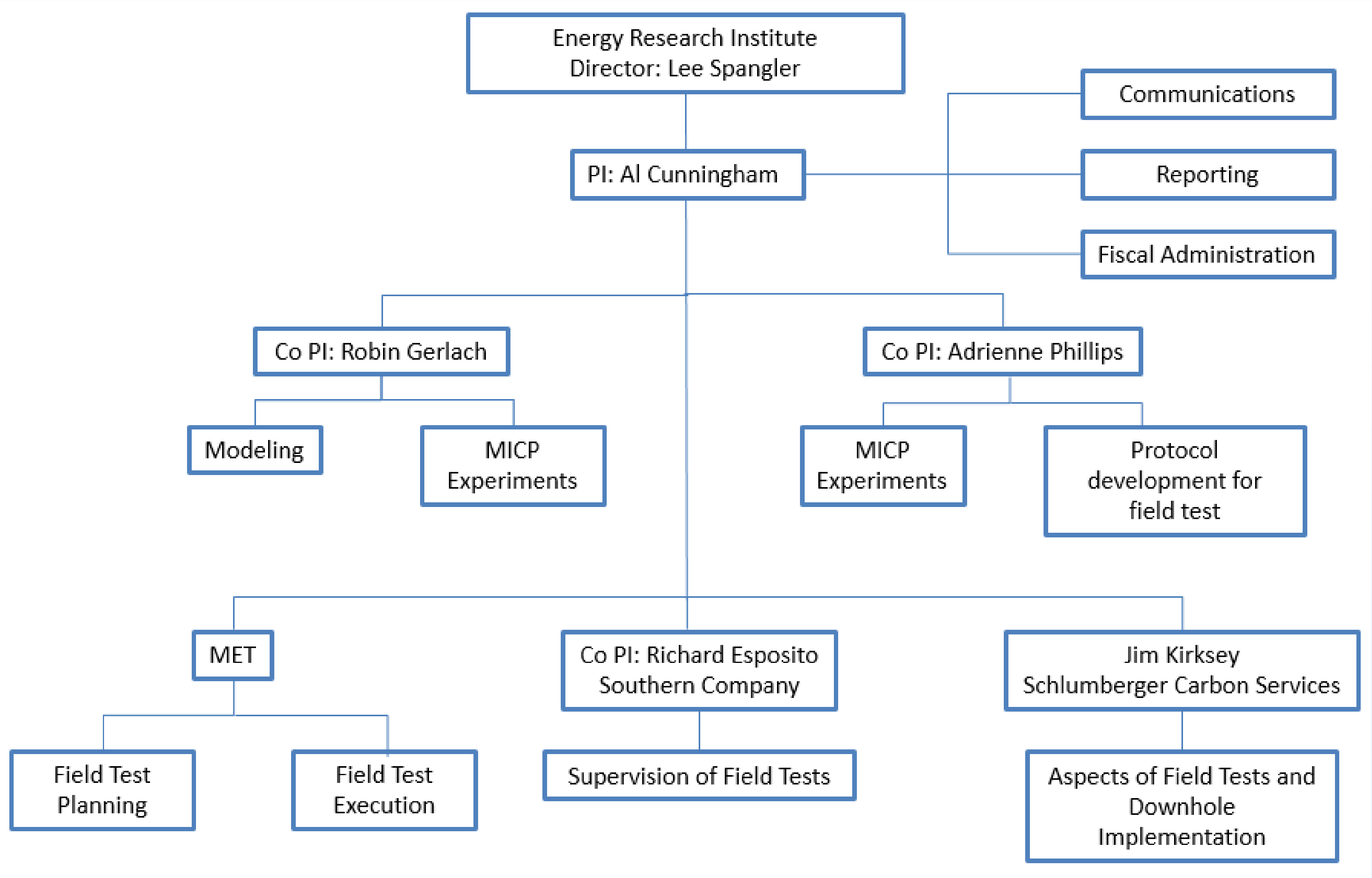
- Environmentally-Prudent Unconventional Resource Development
- FOA objective to minimize environmental impacts and improve the efficiency of UOG development wells.
- Topic Area 2: technology development activities related to:
  - Development of science and technology related to the assurance of the 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

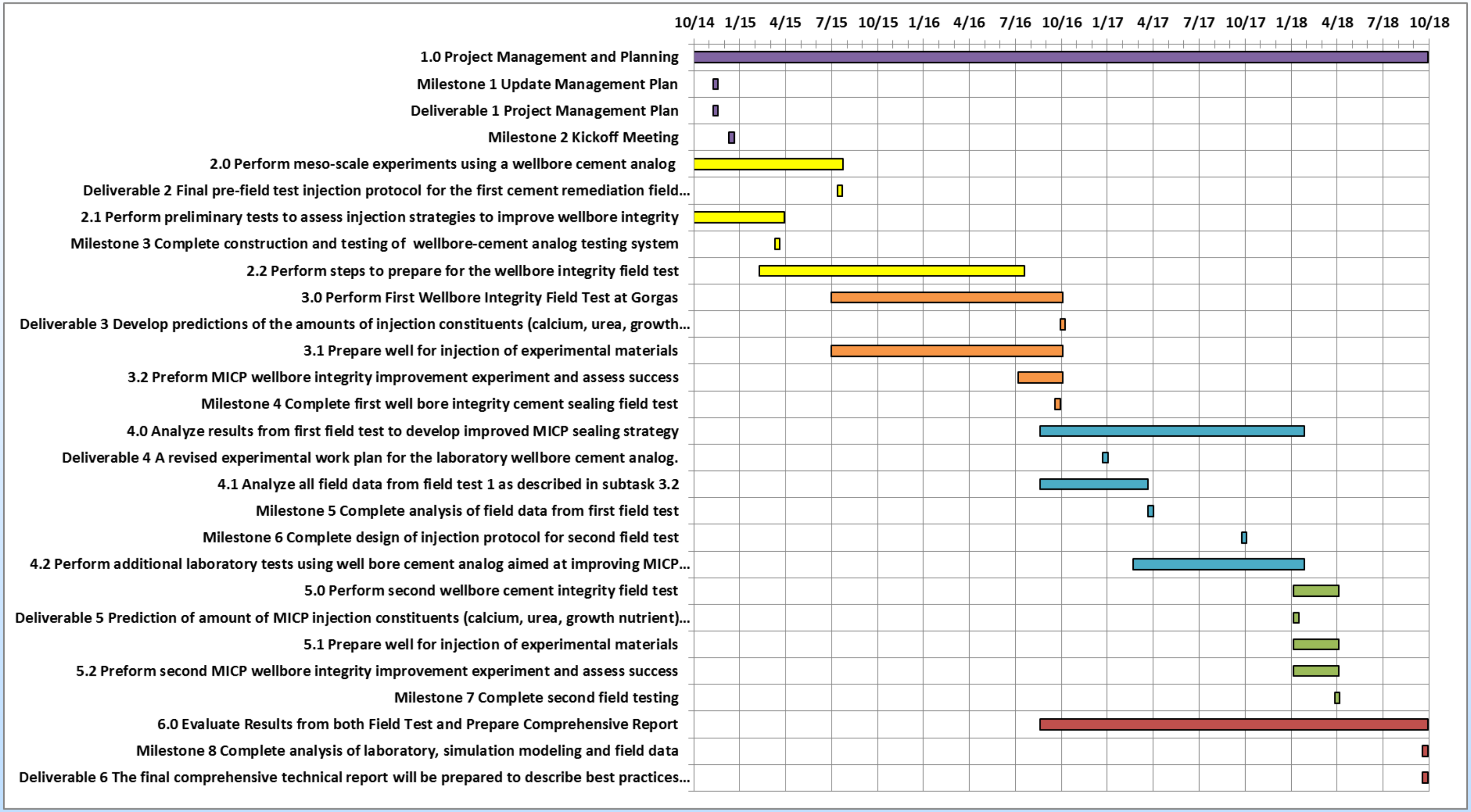
Project goal: develop improved methods for sealing compromised wellbore cement in leaking natural gas and oil wells, thereby reducing the risk of unwanted upward gas migration through laboratory testing, simulation modeling and field testing.

- 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



Gantt Chart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1.0 Project Management and Planning
Milestone 1 Update Management Plan
Deliverable 1 Project Management Plan
Milestone 2 Kickoff Meeting
2.0 Perform meso-scale experiments using a wellbore cement analog
Deliverable 2 Final pre-field test injection protocol for the first cement remediation field...
2.1 Perform preliminary tests to assess injection strategies to improve wellbore integrity
Milestone 3 Complete construction and testing of wellbore-cement analog testing system
2.2 Perform steps to prepare for the wellbore integrity field test
3.0 Perform First Wellbore Integrity Field Test at Gorgas
Deliverable 3 Develop predictions of the amounts of injection constituents (calcium, urea, growth...
3.1 Prepare well for injection of experimental materials
3.2 Preform MICP wellbore integrity improvement experiment and assess success
Milestone 4 Complete first well bore integrity cement sealing field test
4.0 Analyze results from first field test to develop improved MICP sealing strategy
Deliverable 4 A revised experimental work plan for the laboratory wellbore cement analog.
4.1 Analyze all field data from field test 1 as described in subtask 3.2
Milestone 5 Complete analysis of field data from first field test
Milestone 6 Complete design of injection protocol for second field test
4.2 Perform additional laboratory tests using well bore cement analog aimed at improving MICP...
5.0 Perform second wellbore cement integrity field test
Deliverable 5 Prediction of amount of MICP injection constituents (calcium, urea, growth nutrient)...
5.1 Prepare well for injection of experimental materials
5.2 Preform second MICP wellbore integrity improvement experiment and assess success
Milestone 7 Complete second field testing
6.0 Evaluate Results from both Field Test and Prepare Comprehensive Report
Milestone 8 Complete analysis of laboratory, simulation modeling and field data
Deliverable 6 The final comprehensive technical report will be prepared to describe best practices...

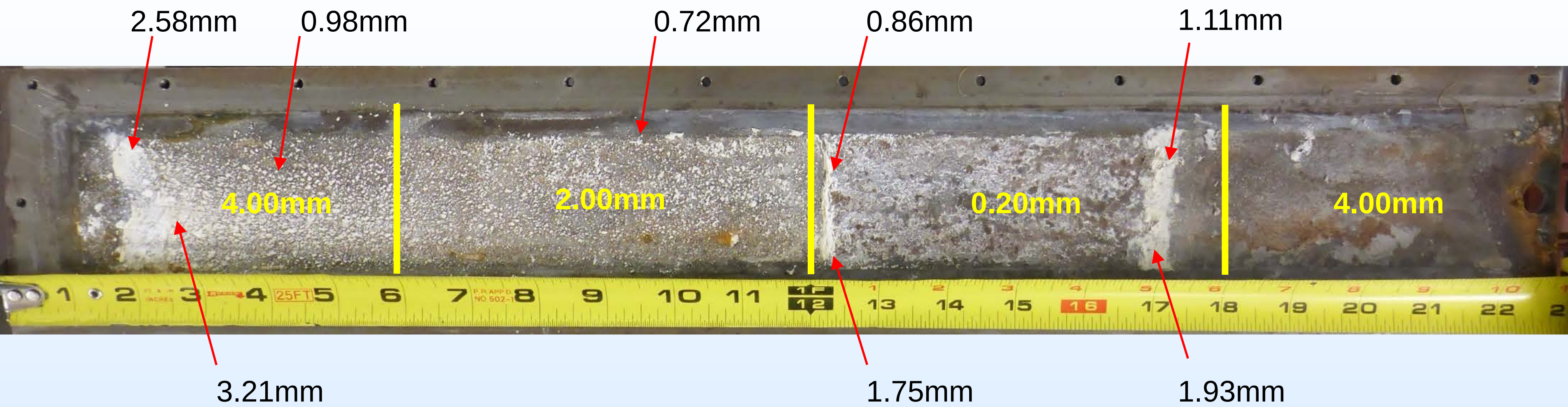
Bibliography

- Phillips, AJ, Troyer, E, Hiebert, R, Kirksey, J, Rowe, W, R, Gerlach, R, Cunningham, A, Esposito, R, Spangler, L. Biomineralization as a tool to remediate wellbore integrity: field application (In preparation)
- 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

Wellbore Analog and Fracture Fixture Experiment

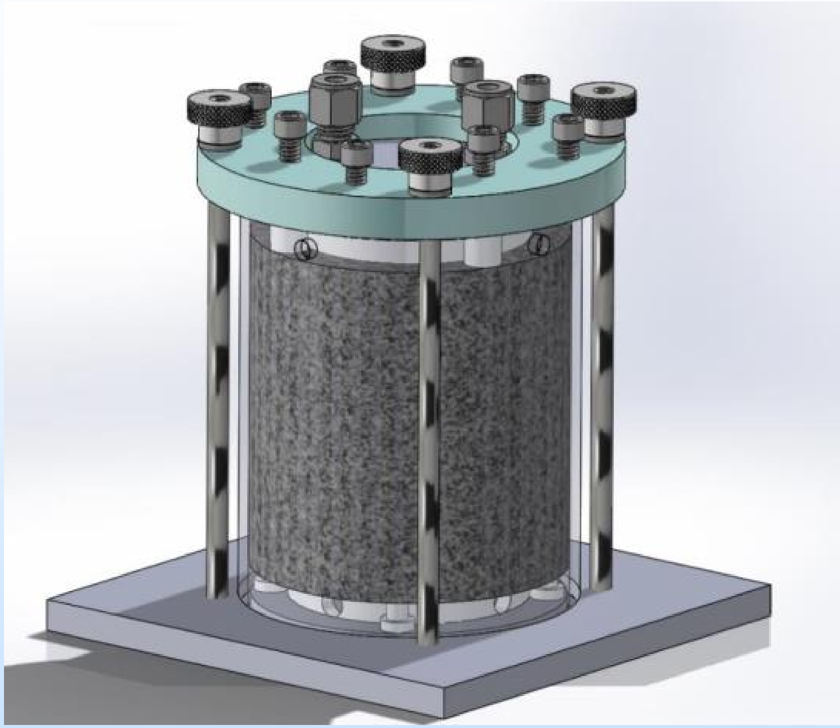
3x concentrated calcium pulses delivered via a perforated pipe inside the clear 6” wellbore.

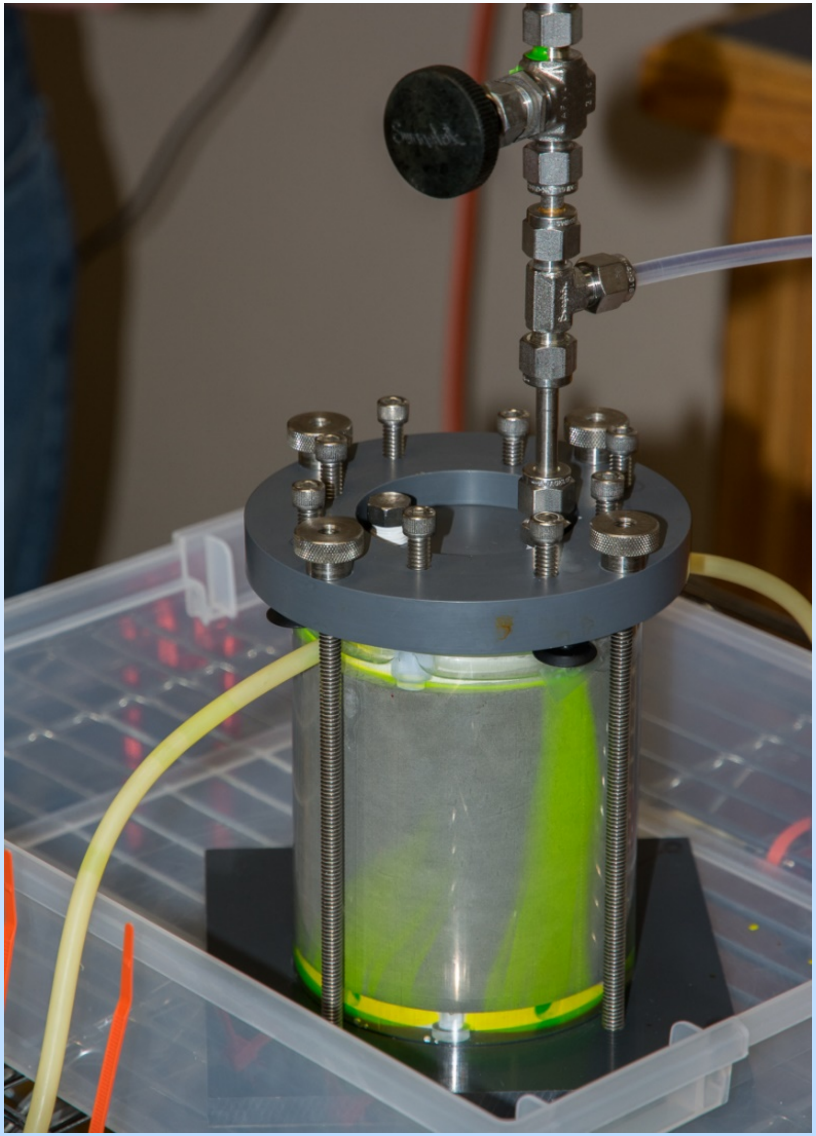
Measured height of the mineral precipitation



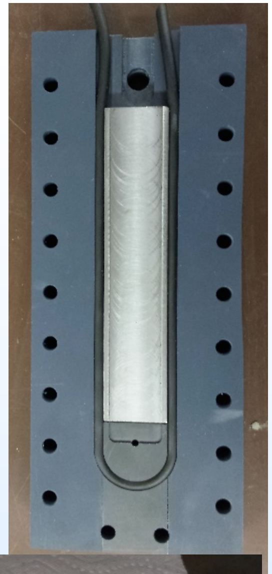
Carbonate seal on cement side of the fracture fixture
formed right at the interface of the 0.2mm gap

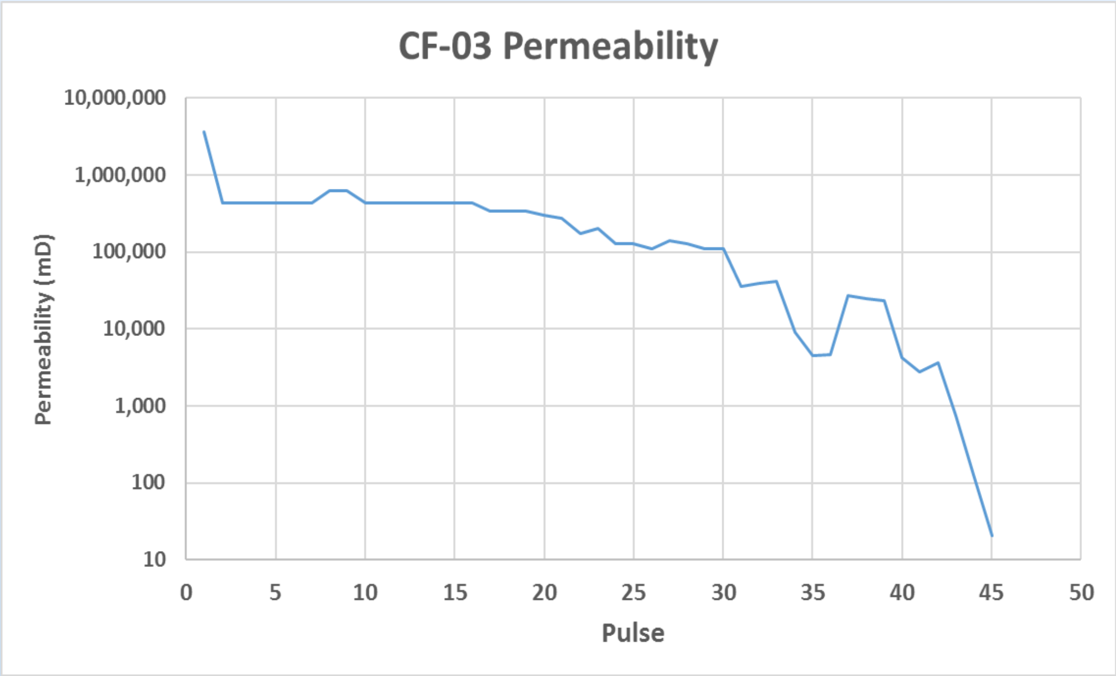
Laboratory- Wellbore Analog- Visualization





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




CF-03 Permeability
Permeability (mD)
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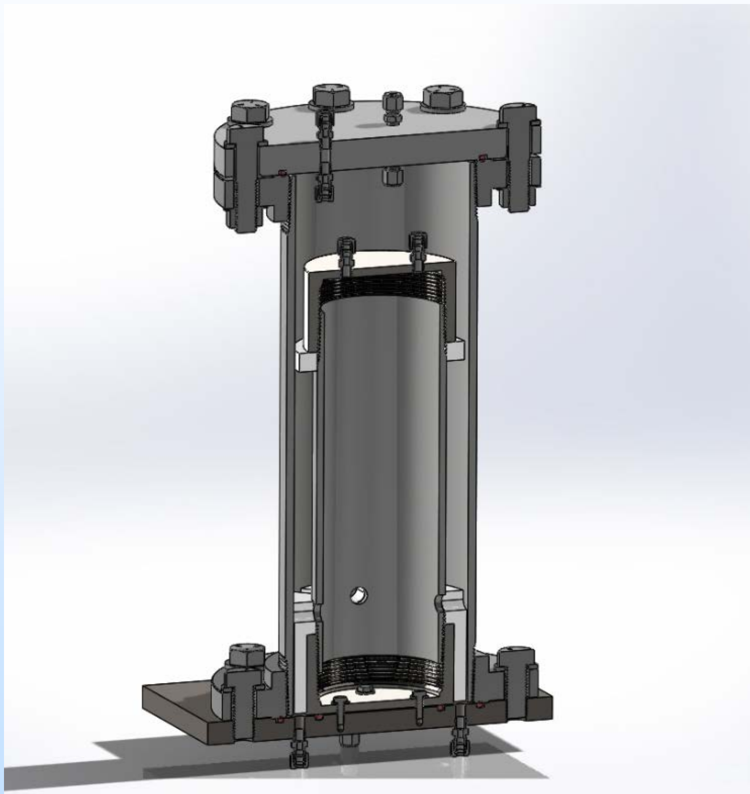
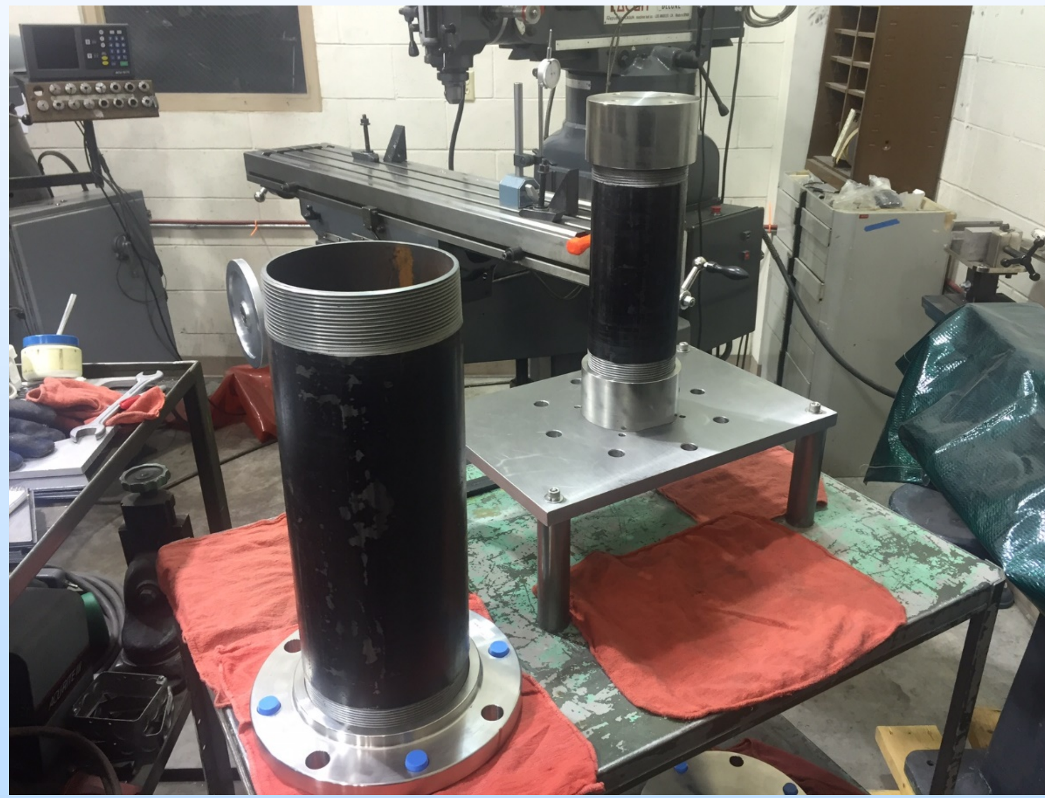
Pulse

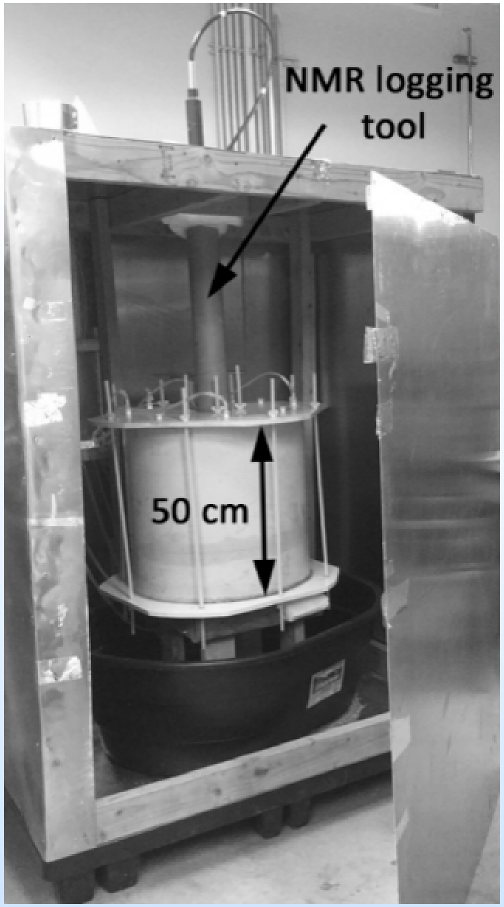
Laboratory -Wellbore Analog- Surface Casing



Resistance to gas flow

Subsurface pressures

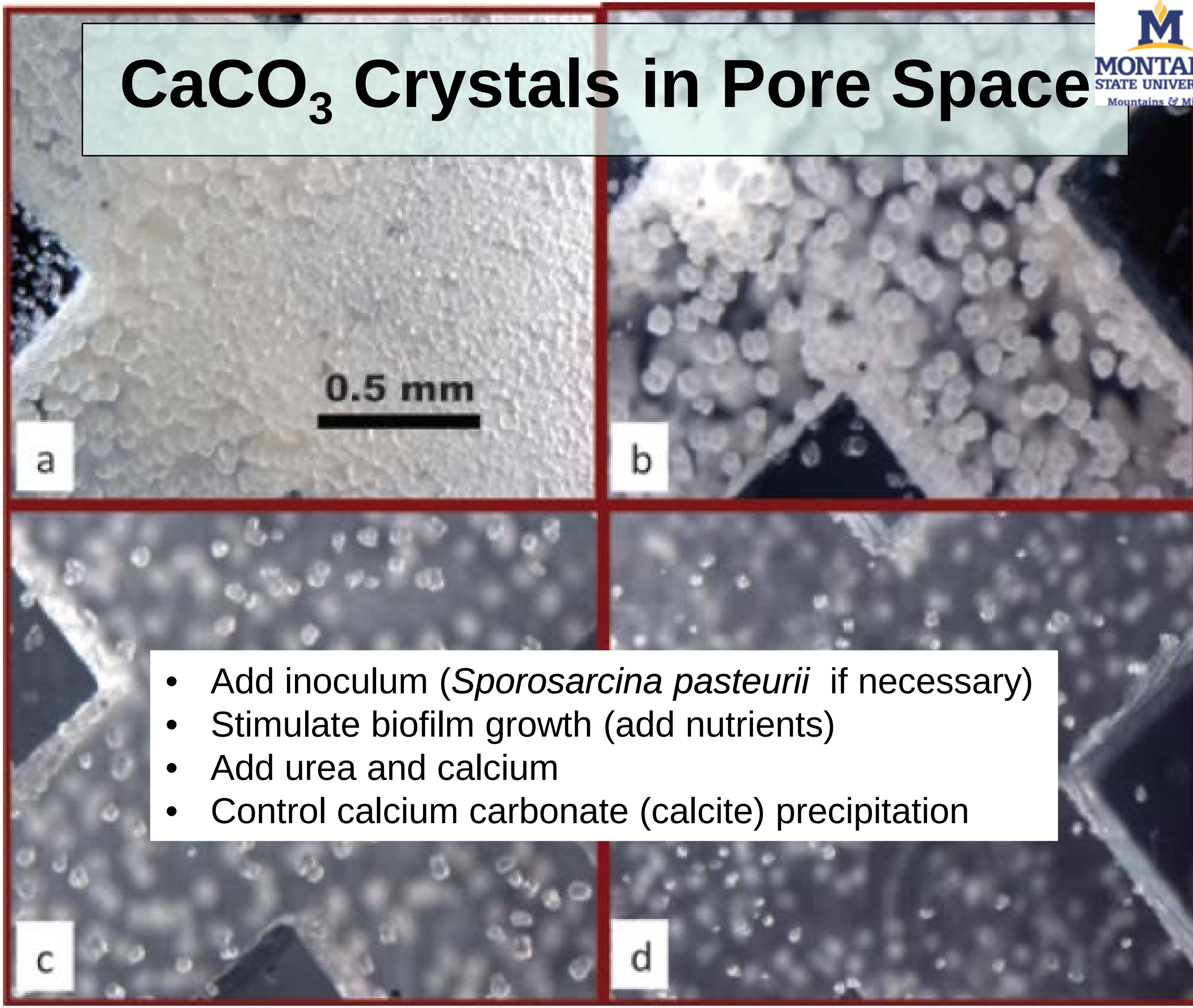




NMR measured water content in the reactor decreased to 76% of its initial value. Destructive sampling confirmed final porosity was approximately 88% of the original value.

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.

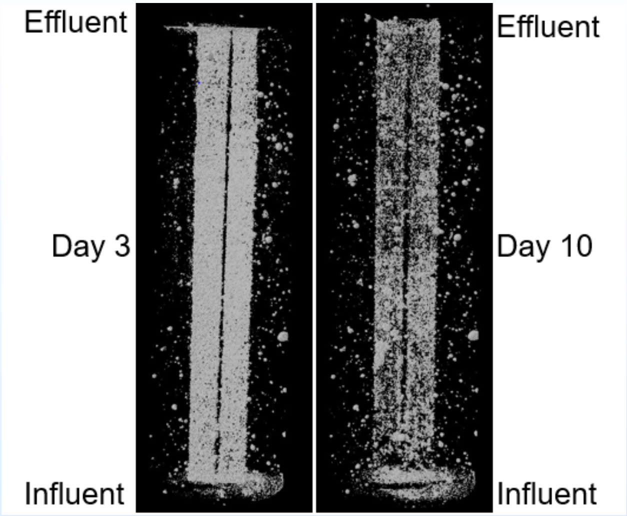
$CaCO_3$ Crystals in Pore Space

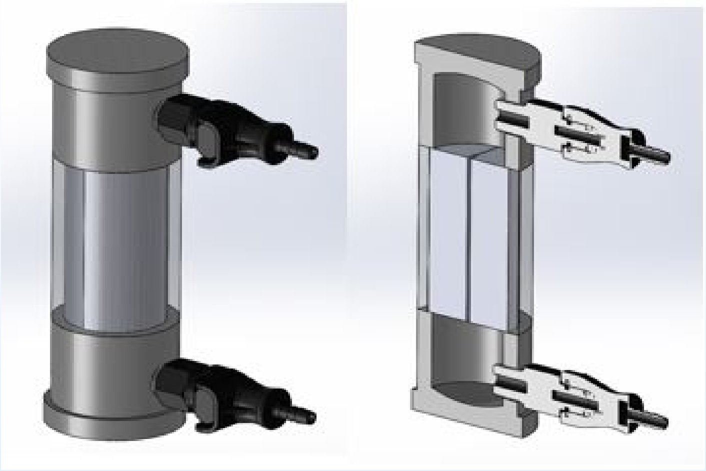


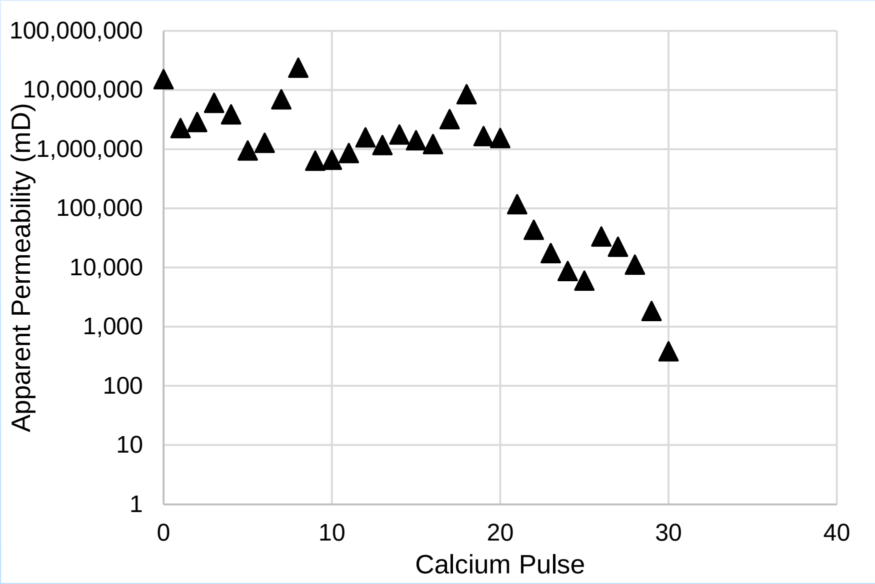
- Add inoculum (*Sporosarcina pasteurii* if necessary)
- Stimulate biofilm growth (add nutrients)
- Add urea and calcium
- Control calcium carbonate (calcite) precipitation

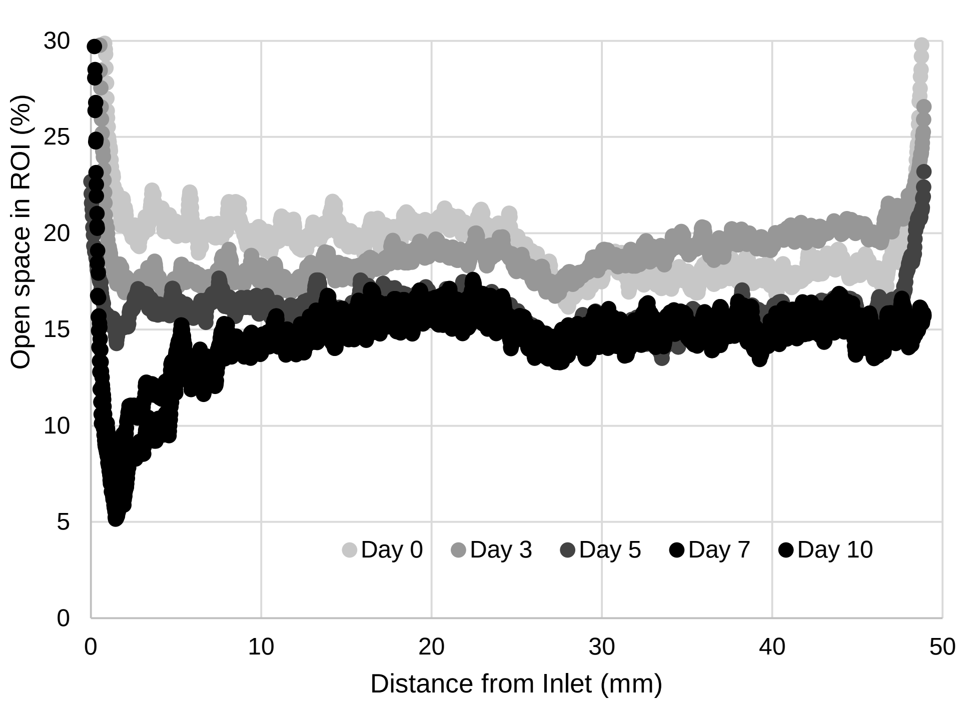
SCHULTZ, L.; ET AL. (2011). *Microscopy Today*. September 2011:10-13.

X-ray CT


Effluent
Day 3
Influent
Effluent
Day 10
Influent




Apparent Permeability (mD)
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0
10
20
30
40
Calcium Pulse


Open space in ROI (%)
30
25
20
15
10
5
0
0
10
20
30
40
50
Distance from Inlet (mm)
Day 0
Day 3
Day 5
Day 7
Day 10