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 29, 2019

Presentation Outline

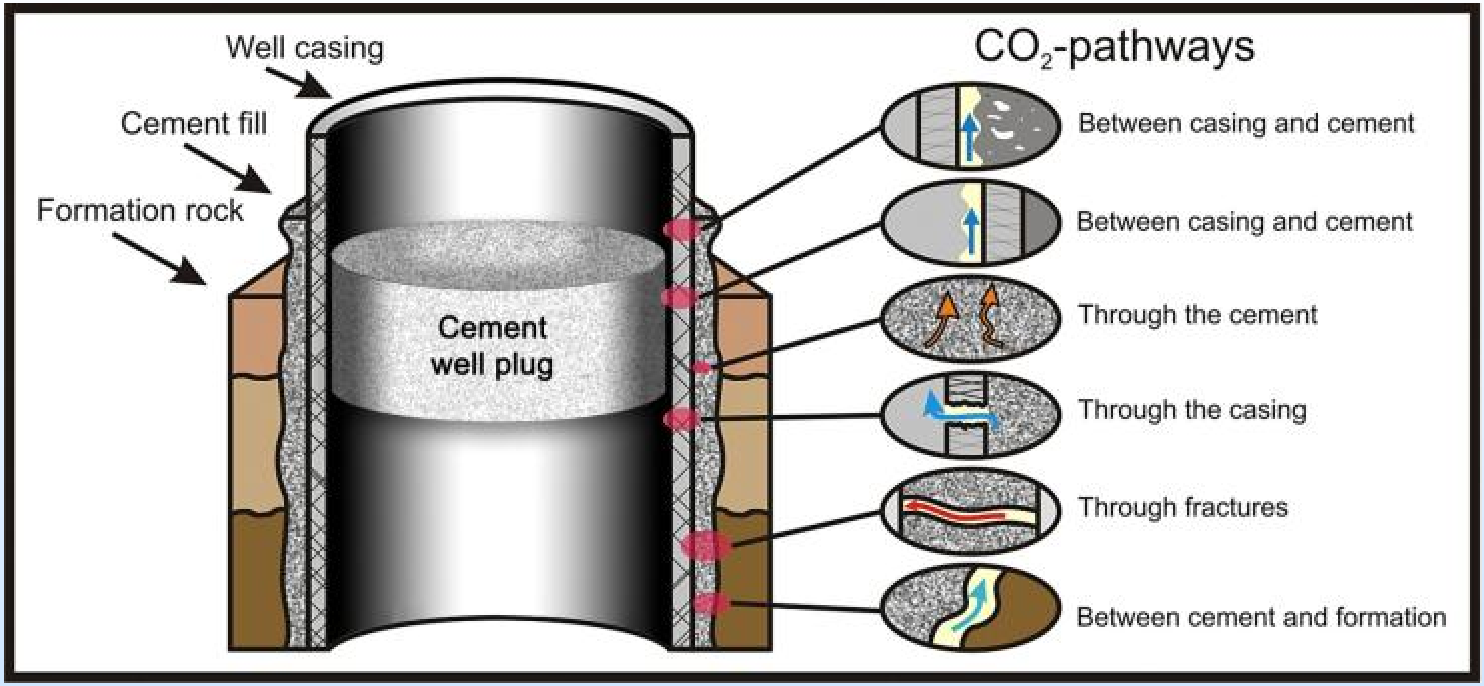
- Technical Status
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Summary

Technical Status: 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. With the following objectives:

- 1: Laboratory testing of MICP sealing, develop a field test protocol for effective MICP placement and control.
- 2: Prepare for and conduct an initial MICP field test aimed at sealing a poor well cement bond (Gorgas)
- 3: Analyze results from first field test, conduct a second (and third) MICP test to improve MICP injection methods (Rexing #1 and 2)

Mitigating subsurface leakage



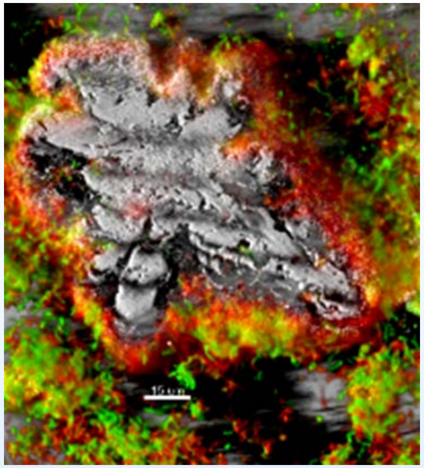
After Nordbotten and Celia, Geological Storage of CO_2, 2012

Cement is viscous

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

Microbially-Induced $CaCO_3$ Precipitation (MICP)

Ureolysis-driven



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

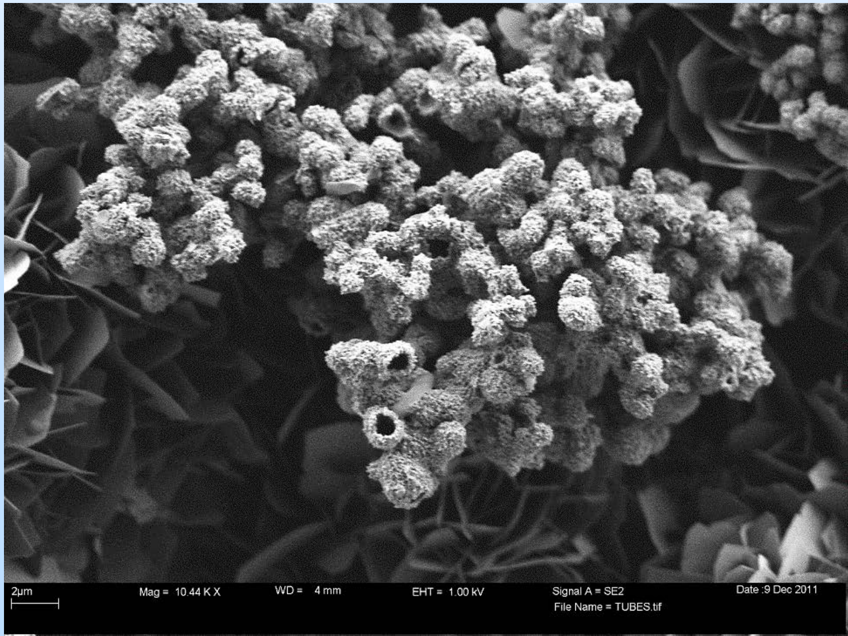
$$NH_2COOH + H_2O \xrightarrow{\text{Spontaneous}} NH_3 + H_2CO_3^{*}$$

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

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

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

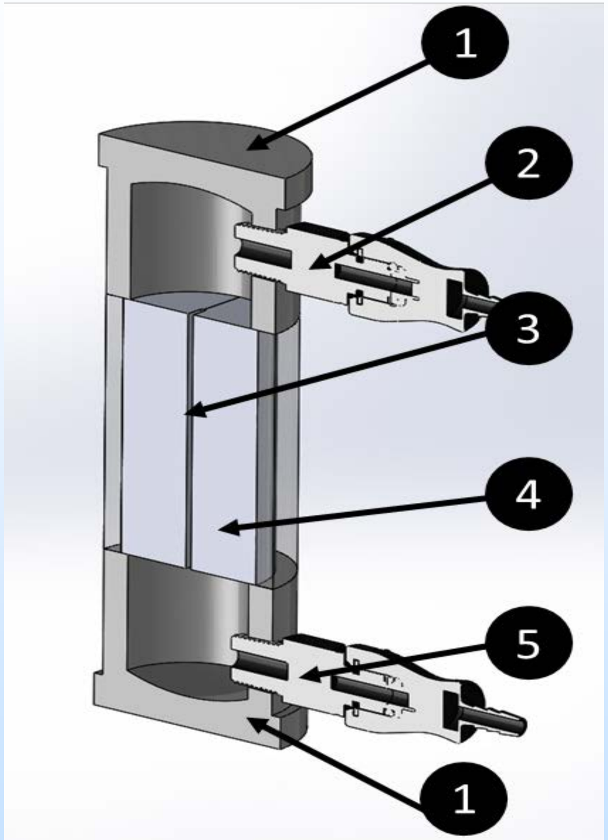
$$Ca^{2+} + CO_3^{2-} \longleftrightarrow CaCO_3\,(s) \qquad K_{sp} = 4.8 \times 10^{-9}$$



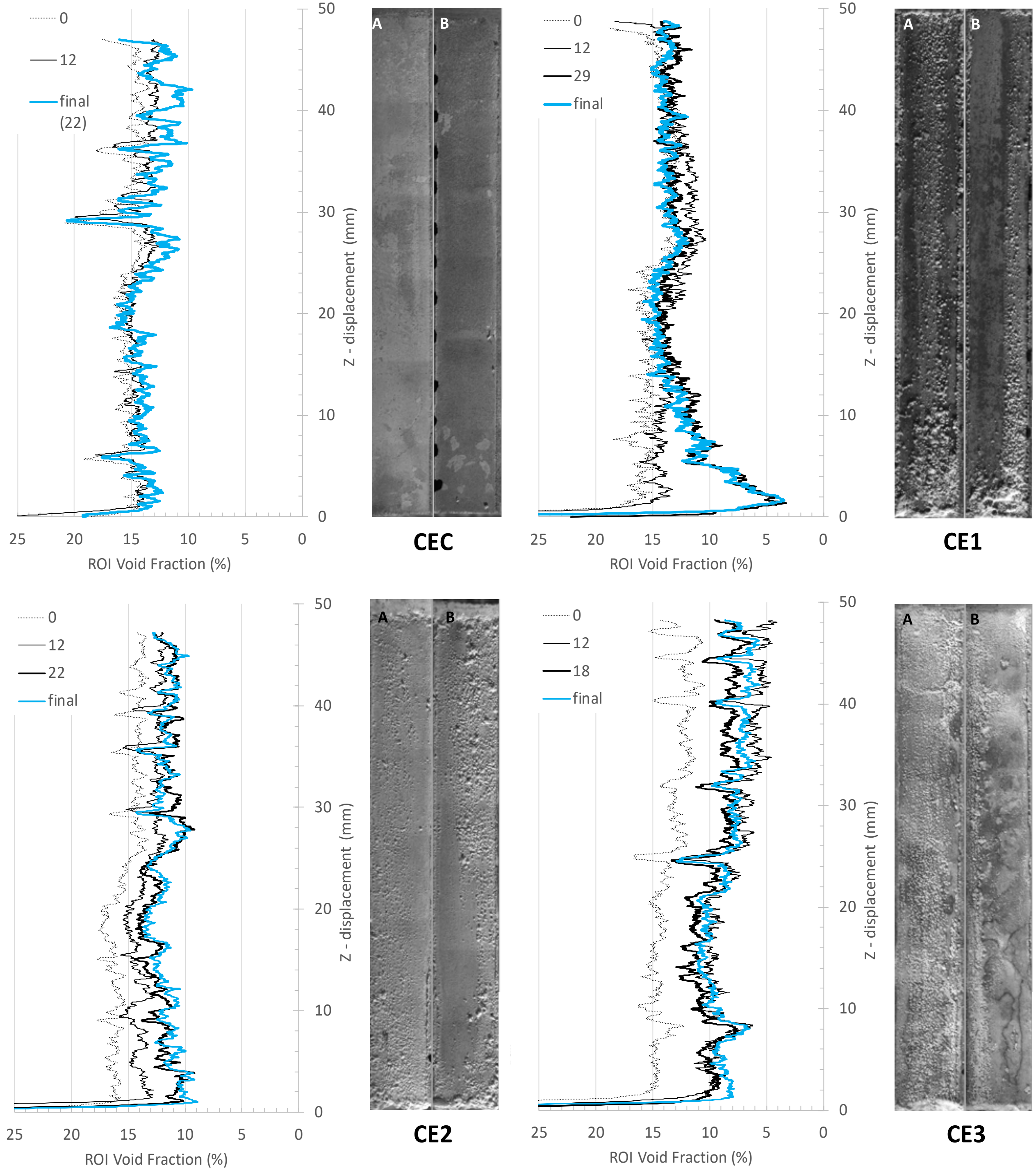
Schultz, L, Pitts, B, Mitchell, AC, Cunningham, A, Gerlach, R. Imaging biologically induced mineralization in fully hydrated flow systems. Microscopy Today 2011, 19, (5), 12-15

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

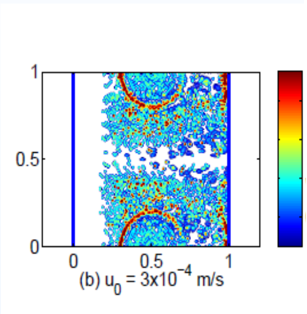
Accomplishments
Objective 1: Fractu

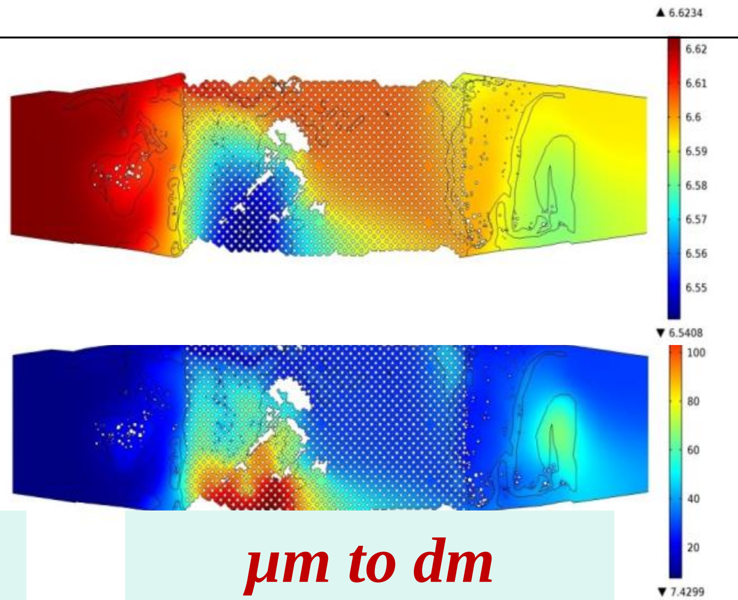


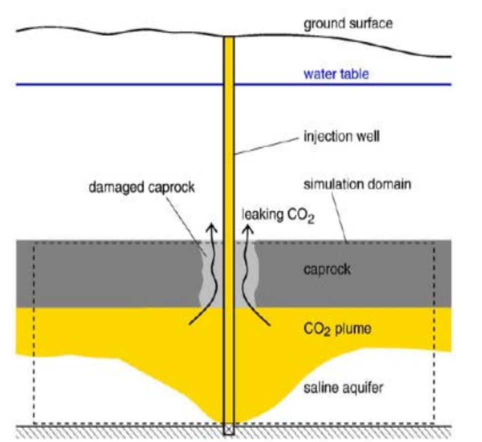
Kirkland, C, Norton, D, Firth, O, Gerlach, R, and Phillips, AJ. (2019) Visualizing MICP with X-ray µ-CT to enhance cement defect sealing, International Journal of Greenhouse Gas Control 86: 93-100

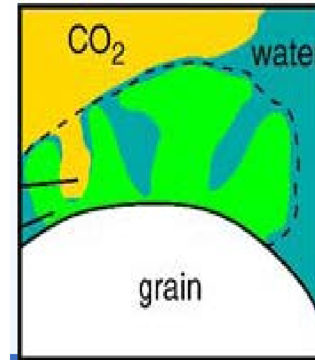


Objective 2: Scale Up





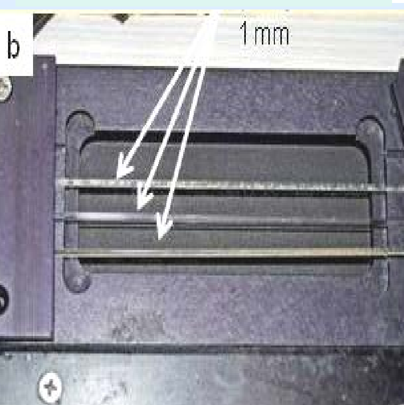


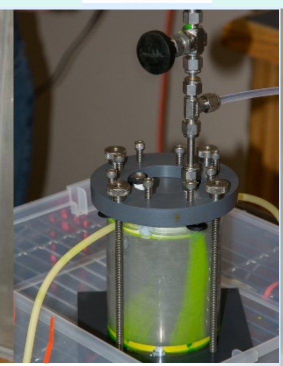


nm to cm

µm to dm

cm to 100s of m



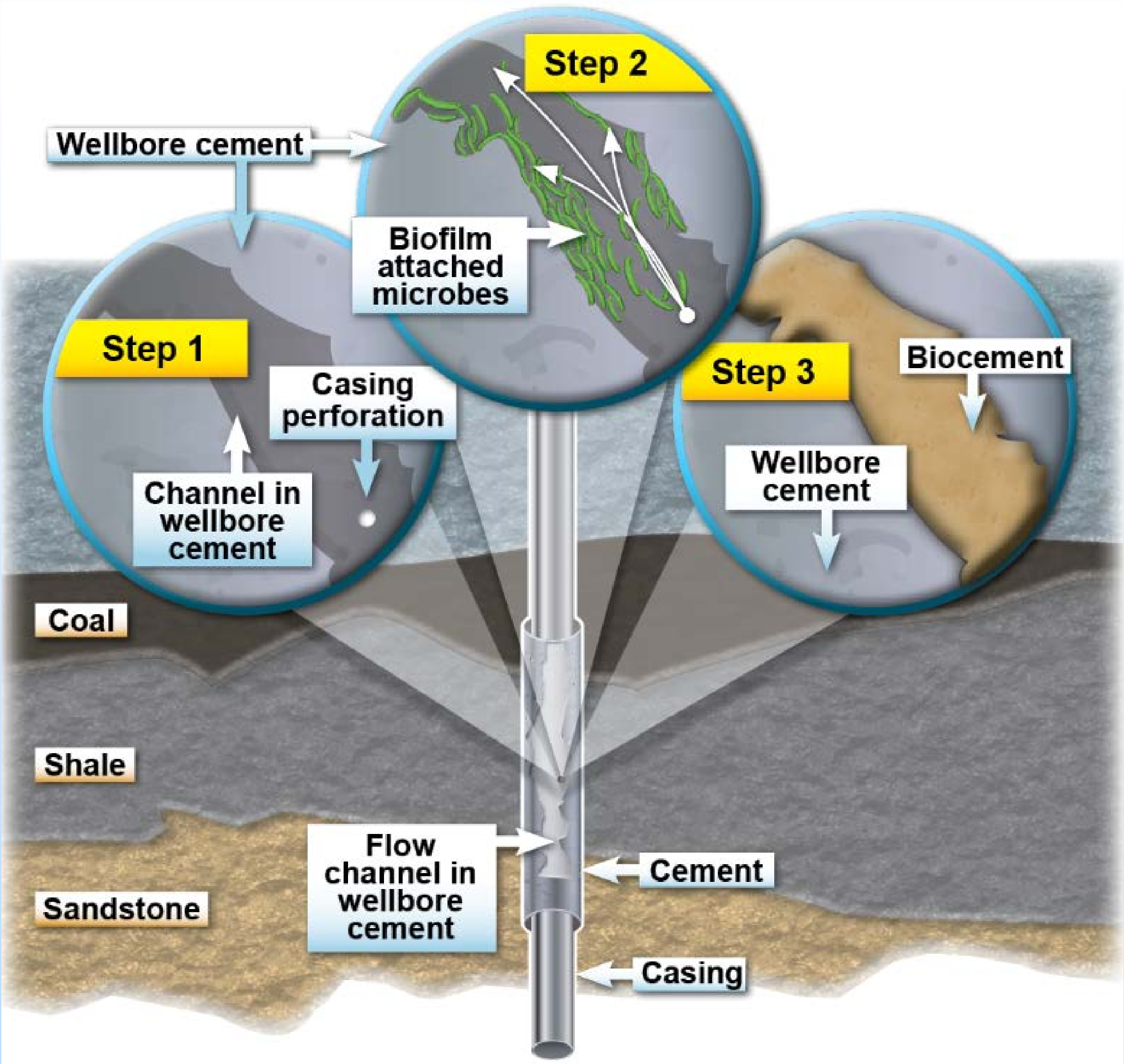


Objective 2: Wellbore sealing

First field test
(April 2016)

Gorgas well

Side wall
coring and
injection test



Objective 2: Cement channel sealing

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

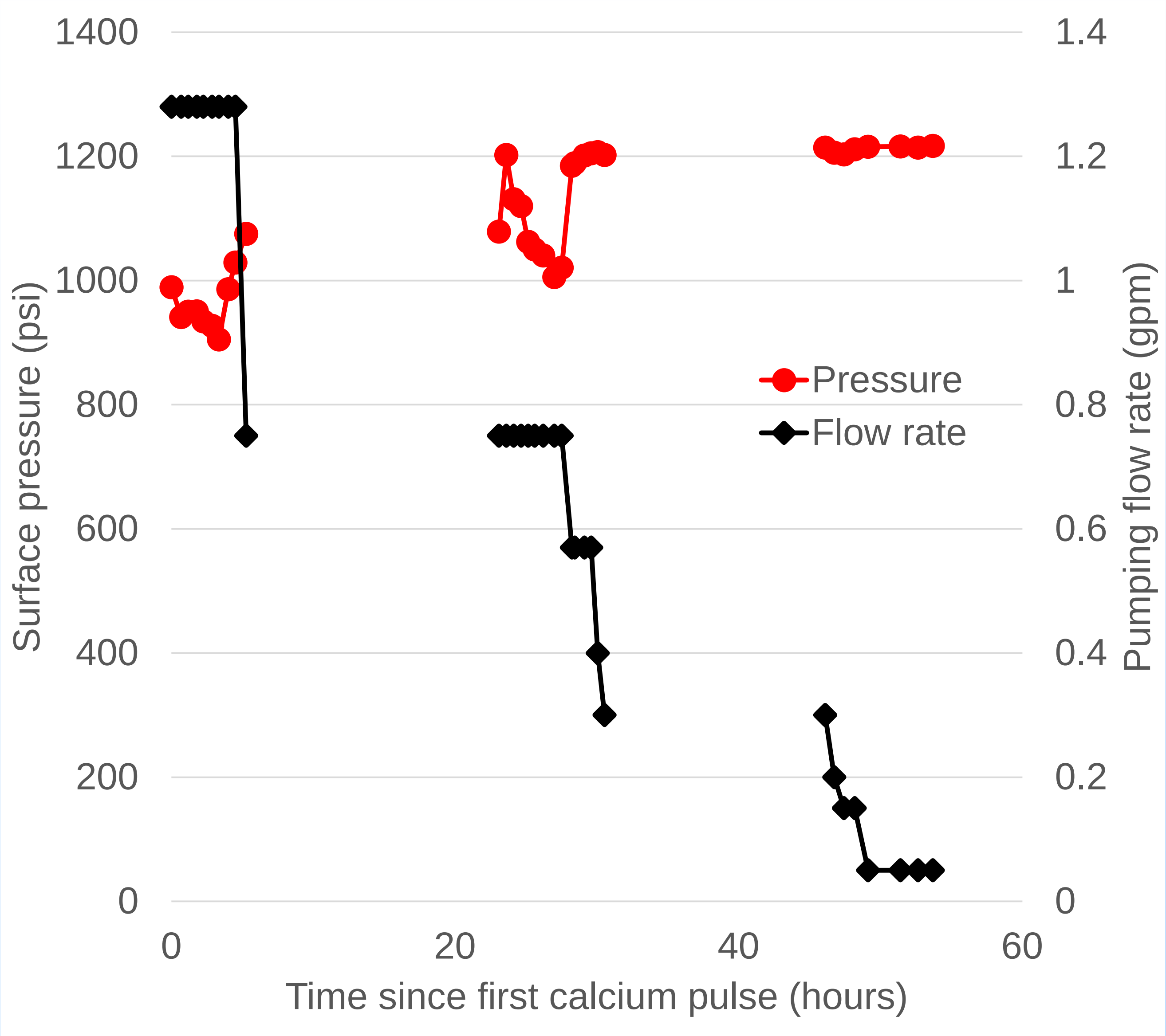
3 measures of success
- Injectivity reduced
- Pressure decay
- USIT Logs

Objective 2: Pressure-flow

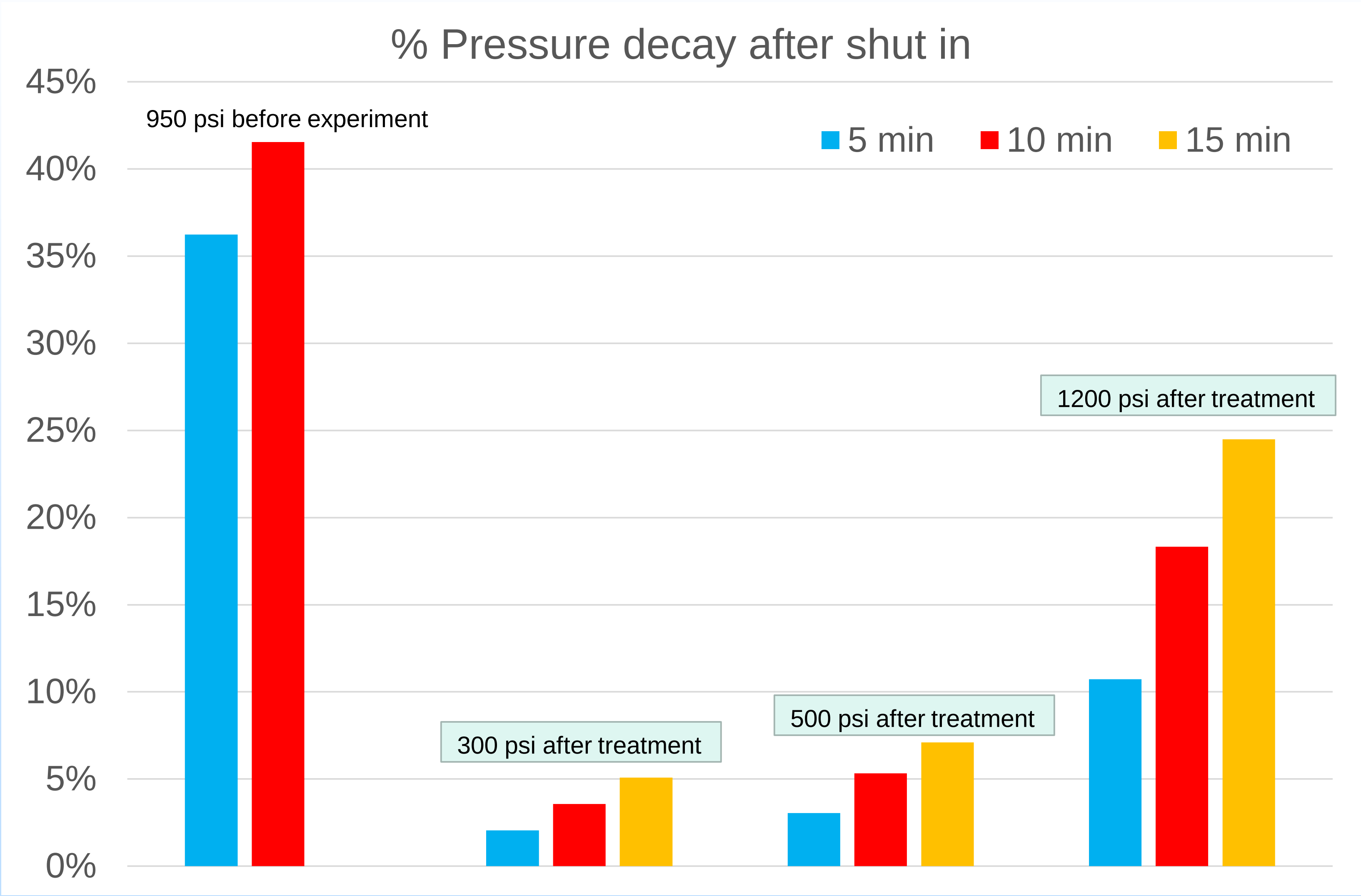
Apparent permeability reduced 1.5 orders of magnitude

Reduced injectivity-pressure increased and flow rate decreased

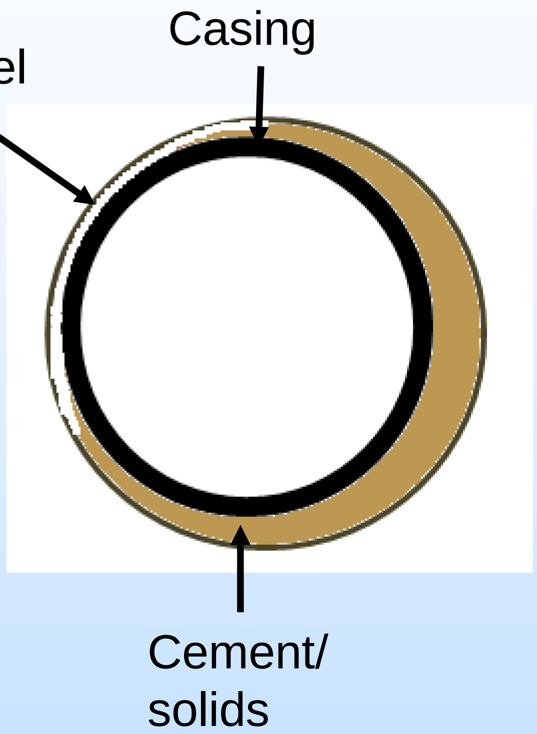
Threshold pressure



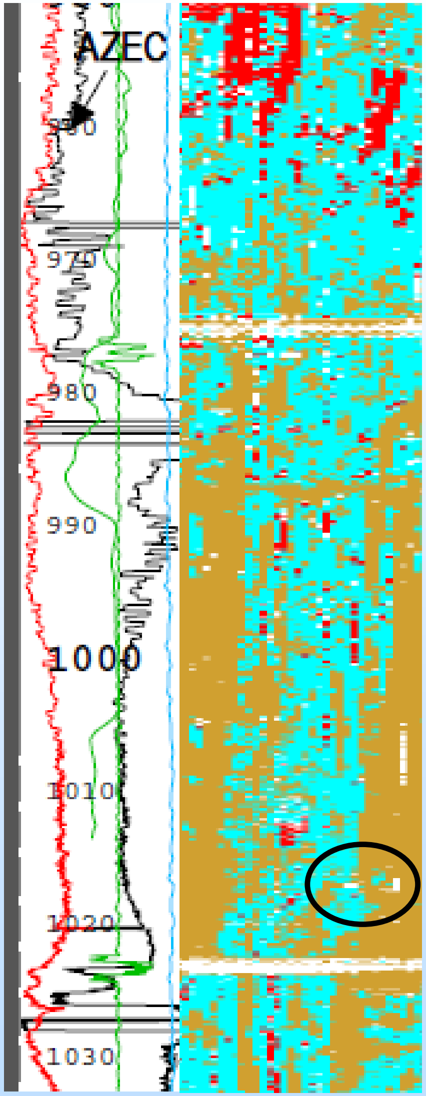
Objective 2: Mechanical Integrity Test

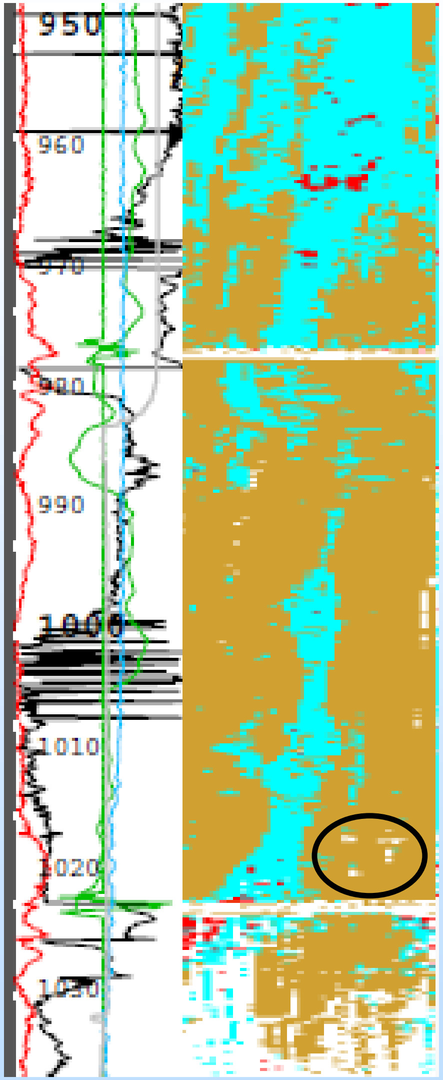


Objective 2: USIT logs on Gorgas Well



Sealed channel

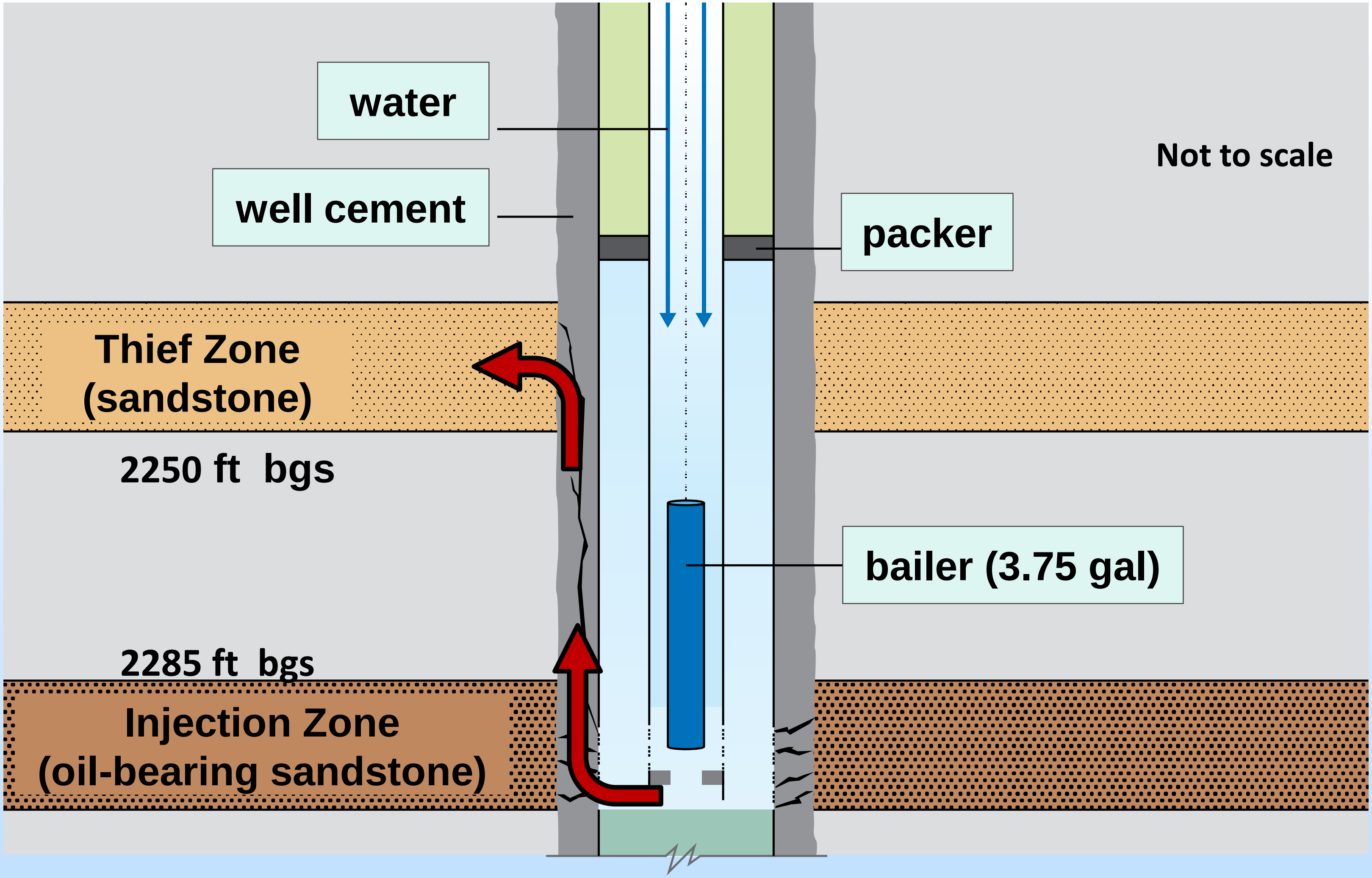




Objective 3: Rexing #4 Well

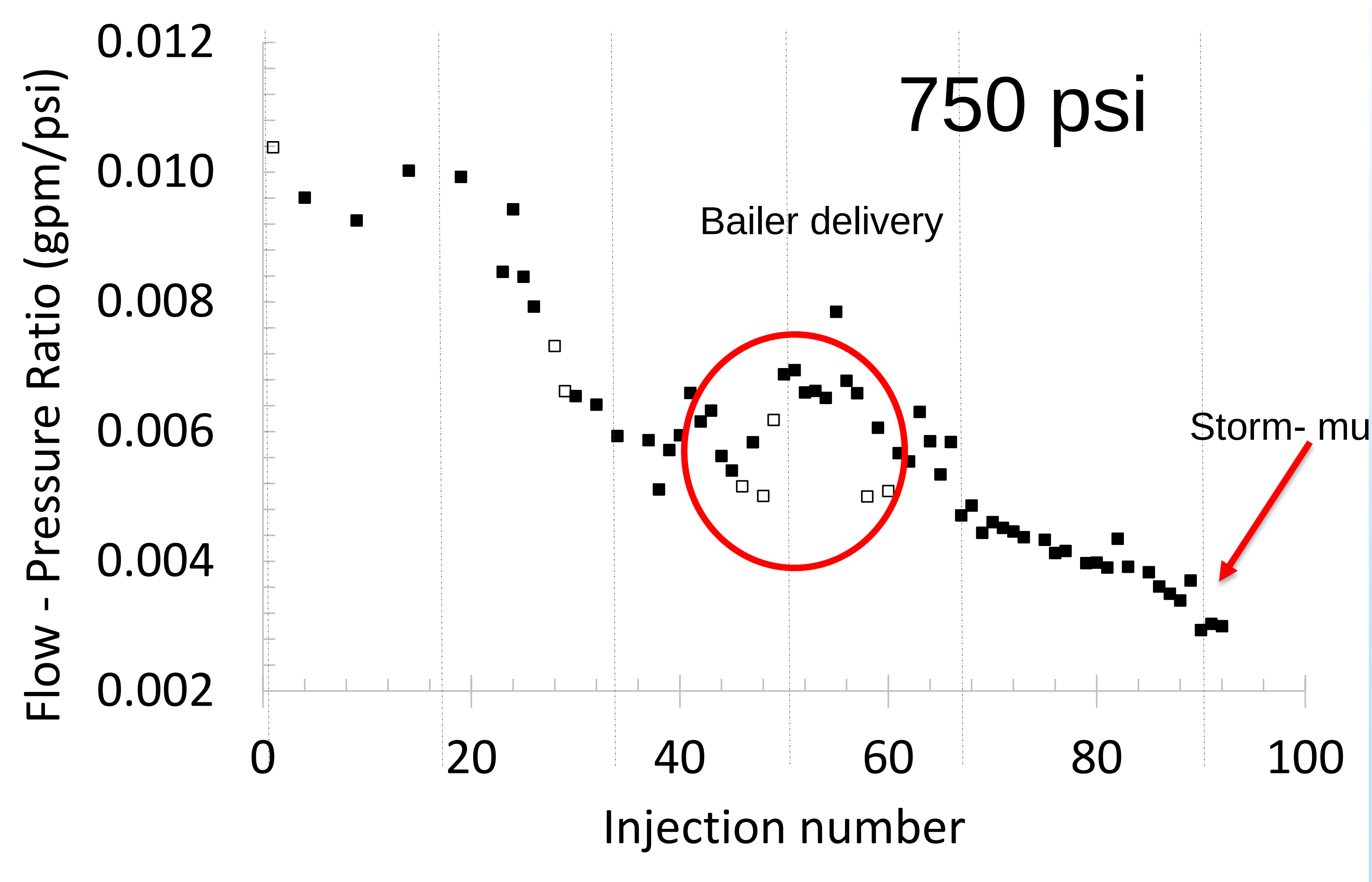
- December 2017 and September 2018
- Water flooding to increase oil recovery
- Vertical channel formed in the cement
- Water traveling through the channel into a thief zone above the targeted oil formation
- Opportunity to treat in an oil field- return to production
- Realistic and typical of established/problem wells

Objective 3: Rexing Well

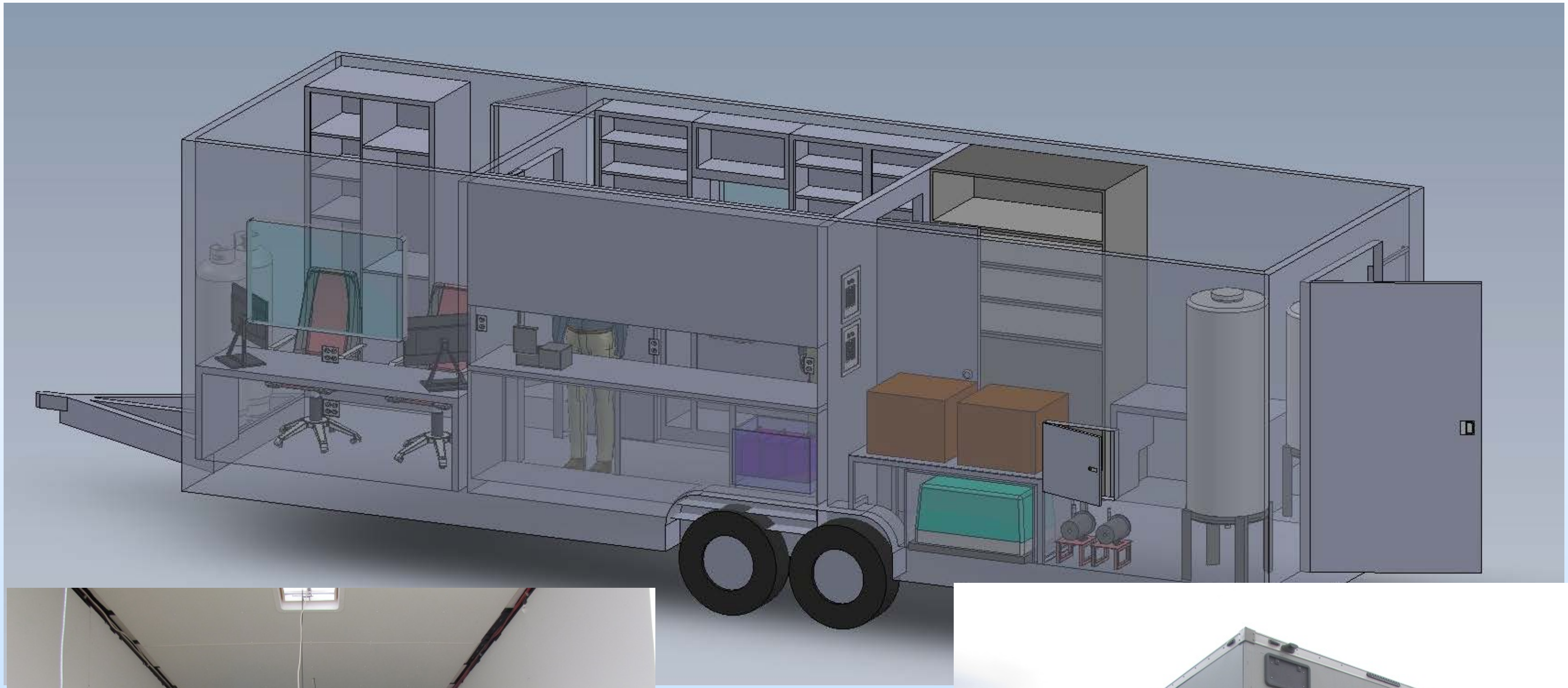


Kirkland, C, Thane, A, Cunningham, A, Gerlach, R, Hiebert, R, Kirksey, J, Spangler, L, Phillips, AJ. Improving waterflood efficiency using microbially-induced calcium carbonate precipitation (MICP): a field demonstration (Submitted July 2019 Journal of Petroleum Science and Engineering, #PETROL17950)

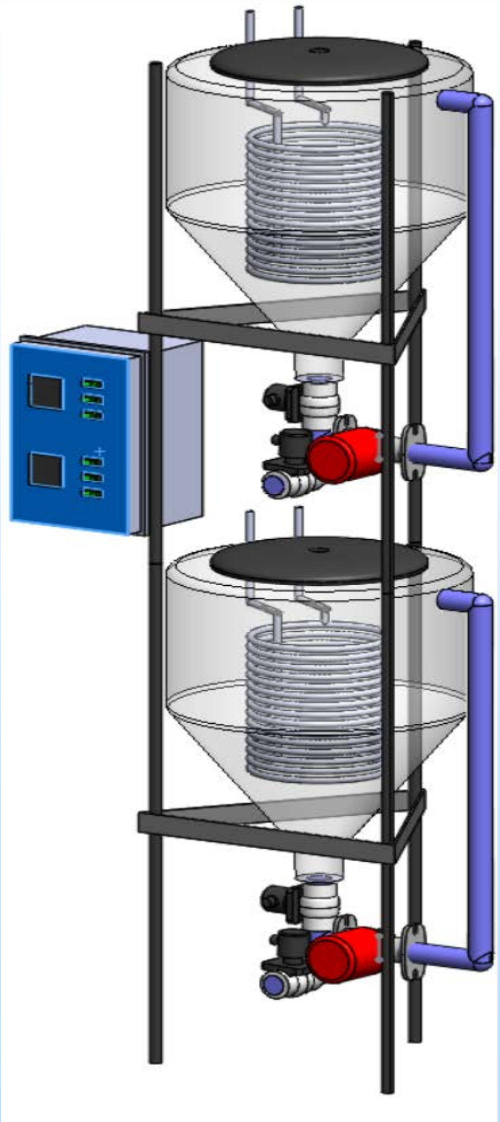
Rexing: Flow-pressure



Mobile Mineralization Unit



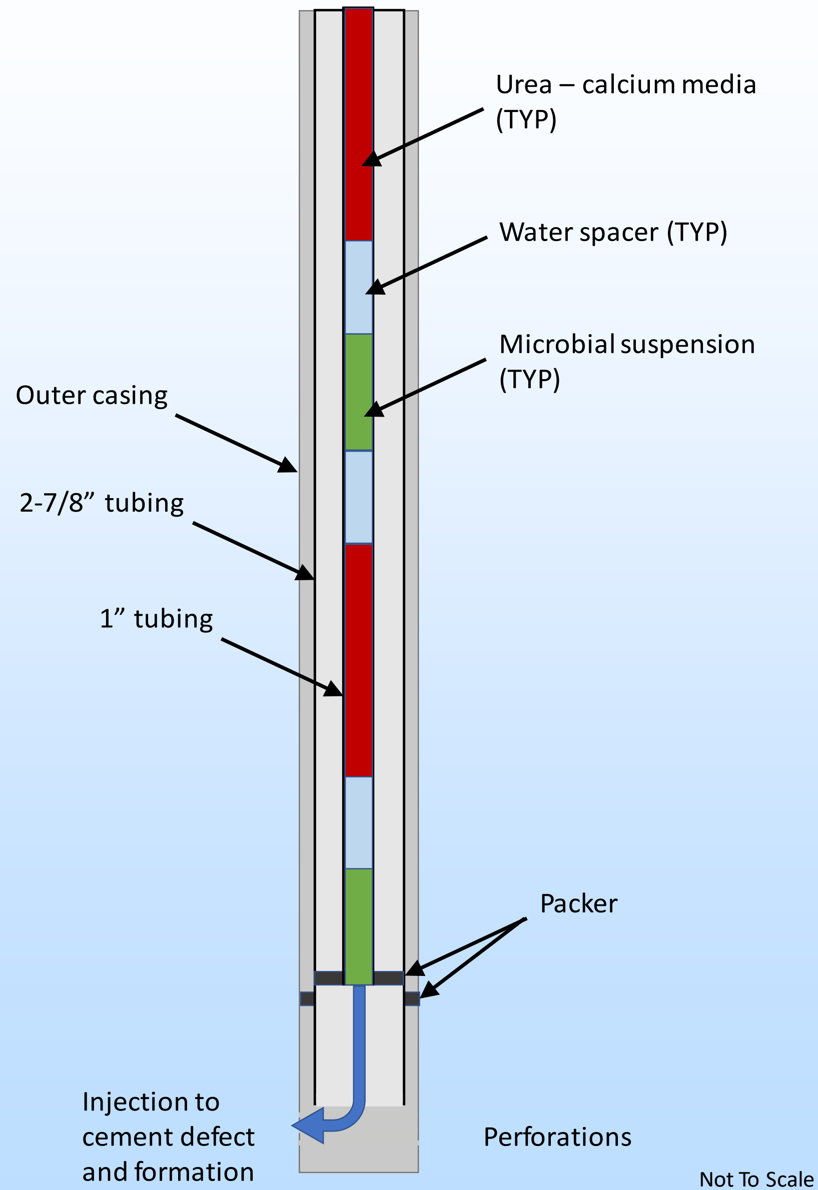
Mobile Laboratory



Mobile Laboratory

48 gal. of microbes grown every 8-12 hours

Continuous Method Injection Strategy



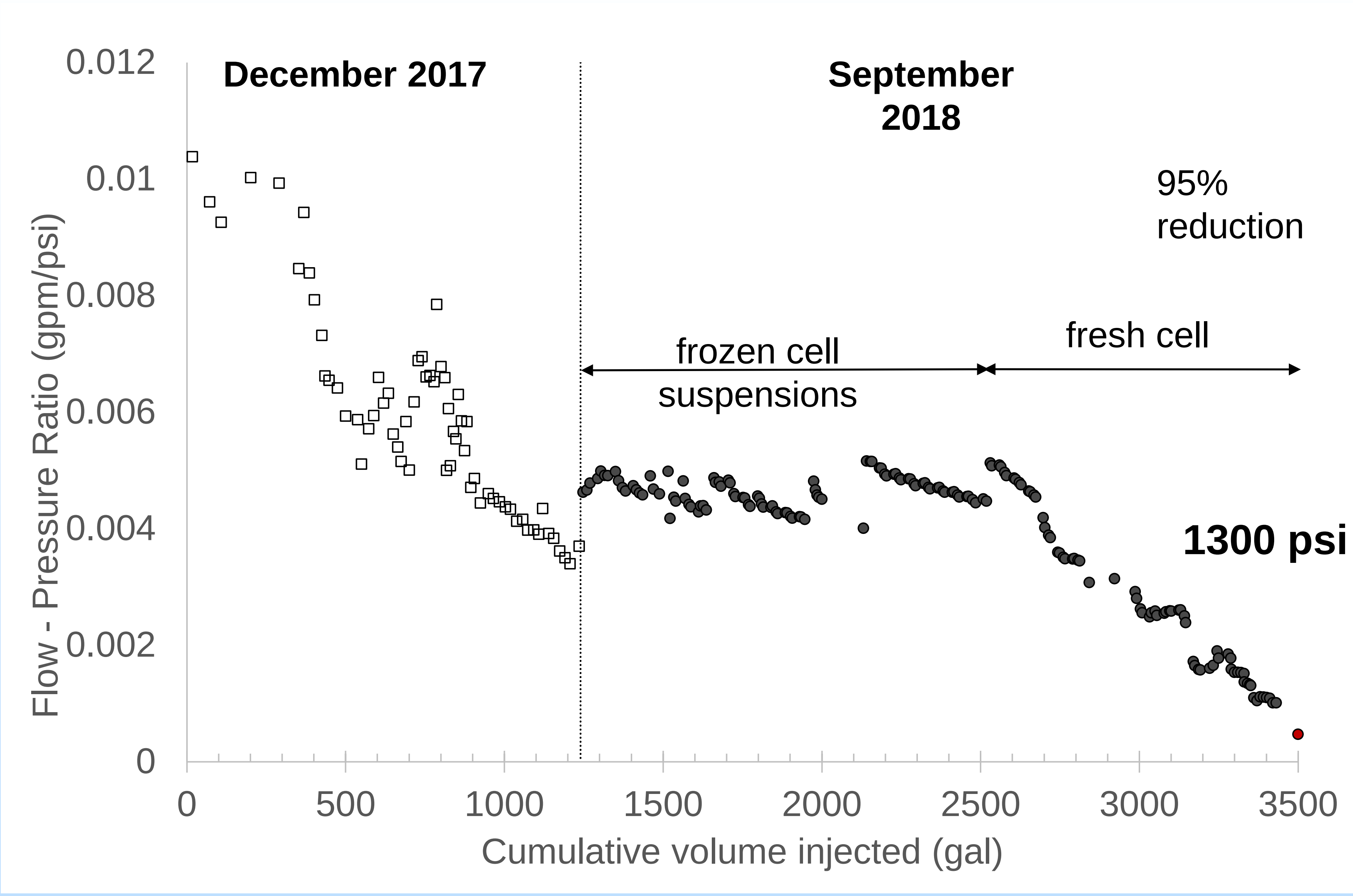
<u>First half- resuspended cells</u>

Inject 270 gallons of resuspended cells, 450 gallons of water spacers and 560 gallons of U+C

<u>Second half- little gain so switch to live cells</u>

Inject 156 gallons of live cells, 360 gallons of water spacers and 394 gallons of U+C

Pressure-flow results



Lessons Learned

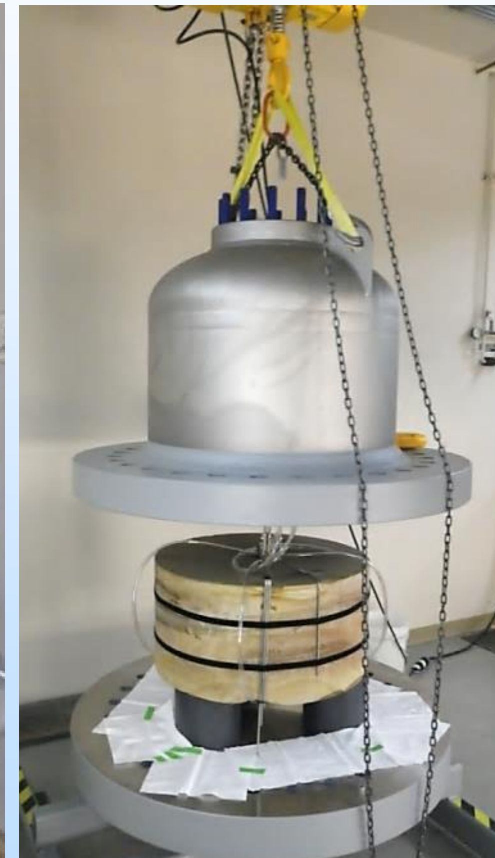
- Success at Gorgas- wellbore integrity
  - Pressure-flow, USIT and mechanical integrity
- Move to Rexing
  - MICP can be applied in situations where corrosion, cement deterioration greater
  - MICP can be applied in situations where there are oil and brine mixtures present
  - Needed to develop new continuous injection strategy for larger volumes
  - Upscaling large volumes of microbes can be accomplished with use of custom bioreactors
  - Reached pressure-flow injection goal

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)
  - 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

Project Summary

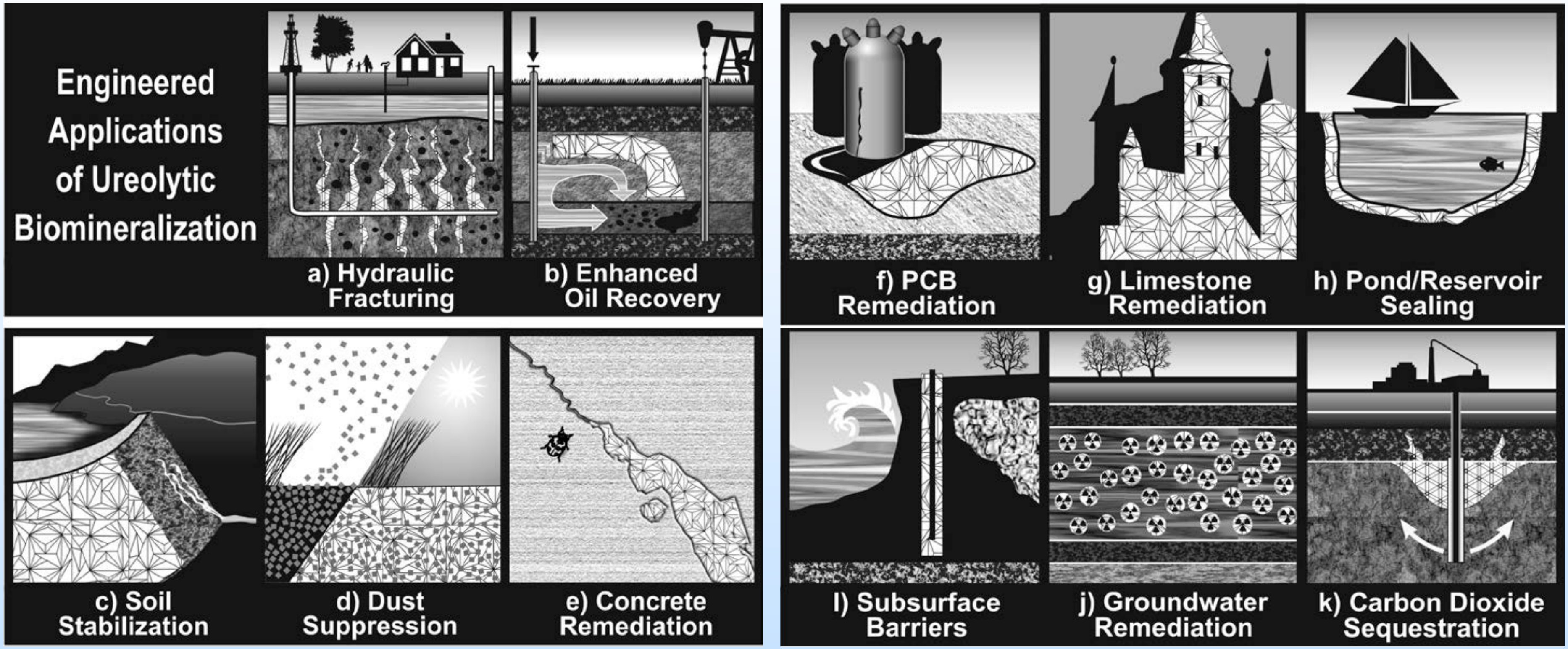
Three project objectives were successfully completed

MICP treatment of wellbore cement was successfully demonstrated

- Laboratory to field
- Two locations
- Gorgas: USIT logs
- Rexing: restored to pre-injection pressure

Advanced commercialization potential

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

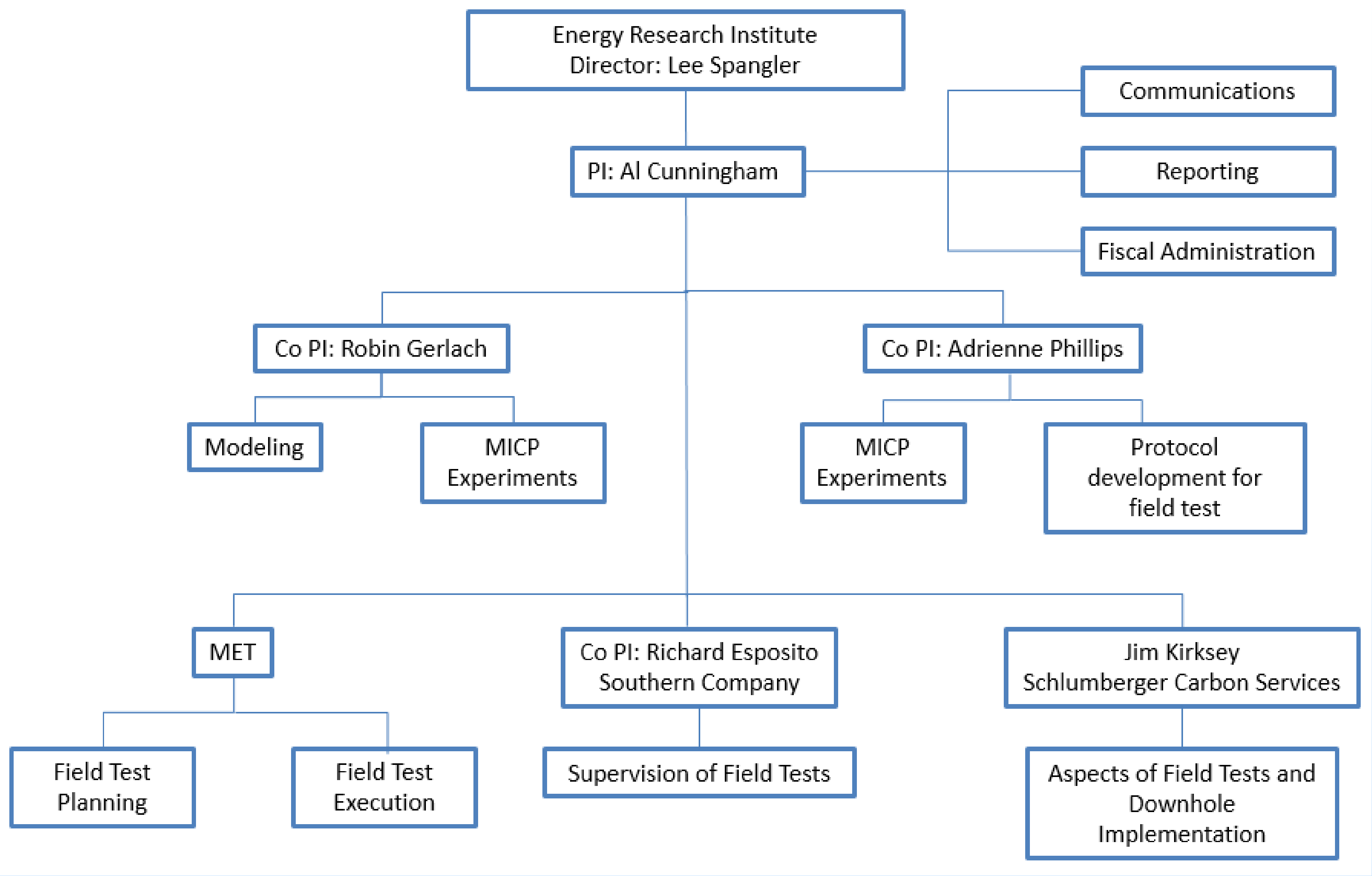
- Environmentally-Prudent Unconventional Resource Development
- FOA objective to minimize environmental impacts and improve the efficiency of UOG development wells.
- Topic Area 2: technology development activities related to:
  - Development of science and technology related to the assurance of the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

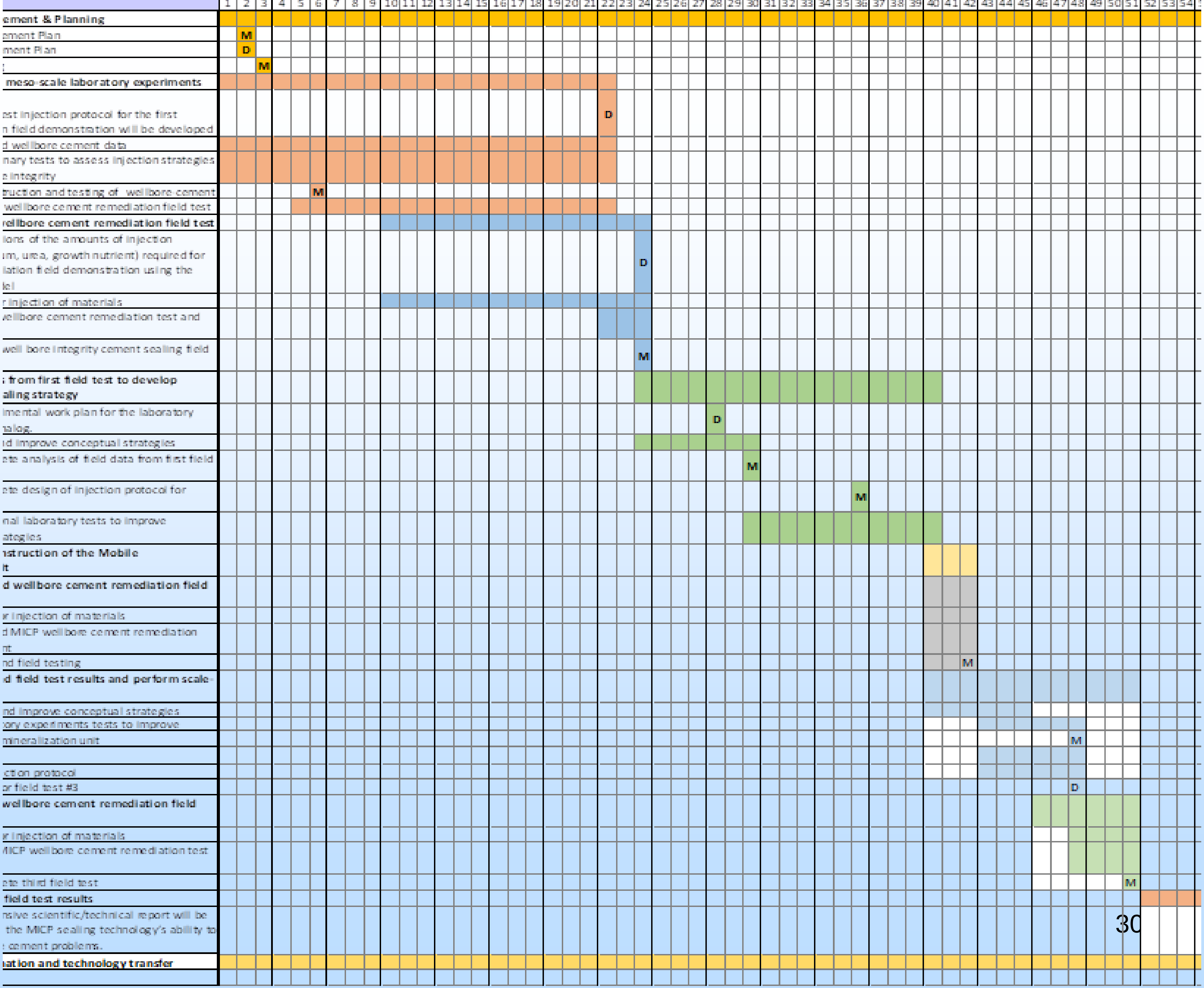
Project Overview: Goals and Objectives

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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ement & Planning
ement Plan
ment Plan
meso-scale laboratory experiments
est injection protocol for the first
n field demonstration will be developed
d wellbore cement data
nary tests to assess injection strategies
e integrity
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wellbore cement remediation field test
wellbore cement remediation field test
ions of the amounts of injection
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cement problems.
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Bibliography

1. Kirkland, C, Thane, A, Cunningham, A, Gerlach, R, Hiebert, R, Kirksey, J, Spangler, L, Phillips, AJ. Improving waterflood efficiency using microbially-induced calcium carbonate precipitation (MICP): a field demonstration (Submitted July 2019 Journal of Petroleum Science and Engineering, #PETROL17950)
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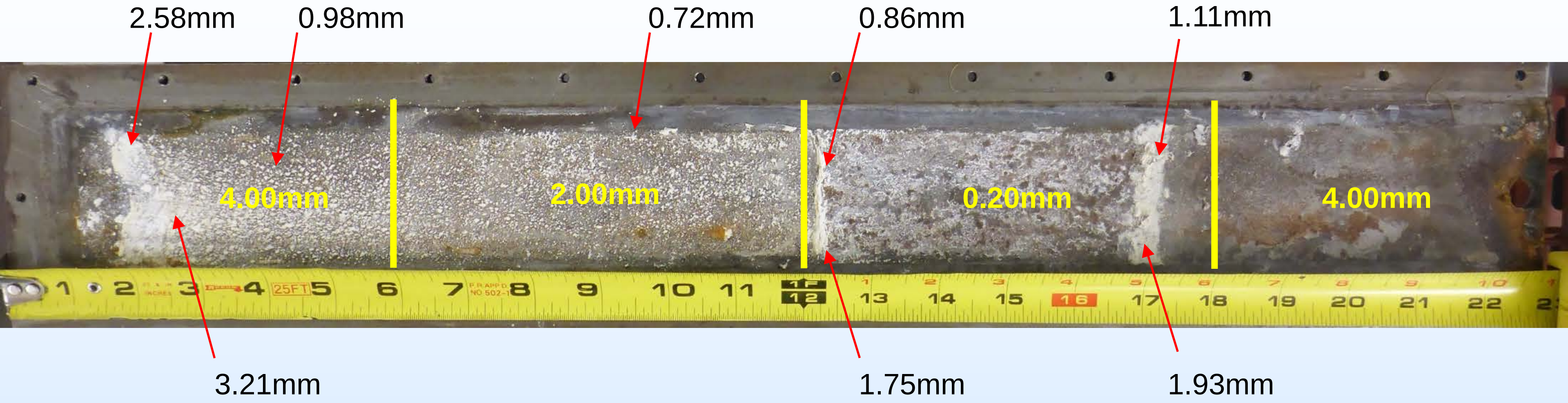
3. Kirkland, C, Norton, D, Firth, O, Gerlach, R, and Phillips, AJ. (2019) Visualizing MICP with X-ray µ-CT to enhance cement defect sealing, International Journal of Greenhouse Gas Control 86: 93-100 https://www.sciencedirect.com/science/article/pii/S1750583618308831
4. Cunningham, A, Class, H, Egbibo, A, Gerlach, R, Phillips, AJ, Hommel, J. (2018) Field-scale modeling of microbially induced calcite precipitation, Computational Geosciences. 23 (2): 399–414 https://doi.org/10.1007/s10596-018-9797-6
5. Phillips, AJ, Troyer, E, Hiebert, R, Kirkland, C, Kirksey, J, Rowe, W, R, Gerlach, R, Cunningham, A, Esposito, R, Spangler, L. (2018) Enhancing wellbore cement integrity with microbially induced calcite precipitation (MICP): a field scale demonstration Journal of Petroleum Science and Engineering, 171: 1141-1148 https://www.sciencedirect.com/science/article/pii/S0920410518306788
6. 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, 51 (3): 1537–1543 http://pubs.acs.org/doi/abs/10.1021/acs.est.6b04833
7. Beser, D, West C, Daily, R, Cunningham, A, Gerlach, R, Fick, D, Spangler, L and Phillips, AJ. (2017) Assessment of ureolysis induced mineral precipitation material properties compared to oil and gas well cements. American Rock Mechanics Association 51st Annual Meeting Proceedings, June 25-28, 2017, San Francisco, CA. (Paper # 588)

Wellbore Analog and Fracture Fixture Experiment

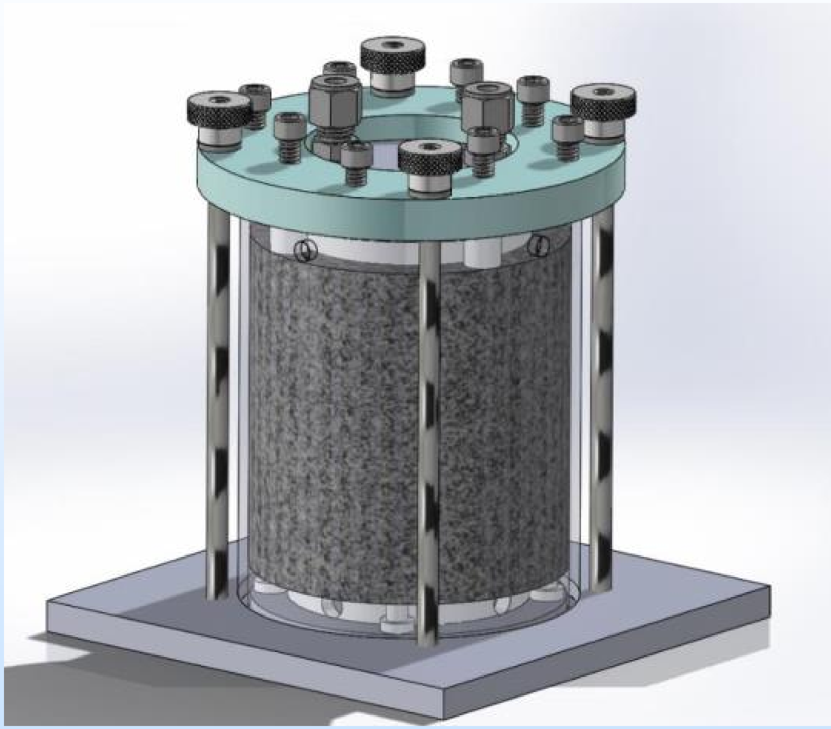
3x concentrated calcium pulses delivered via a perforated pipe inside the clear 6” wellbore.

Measured height of the mineral precipitation

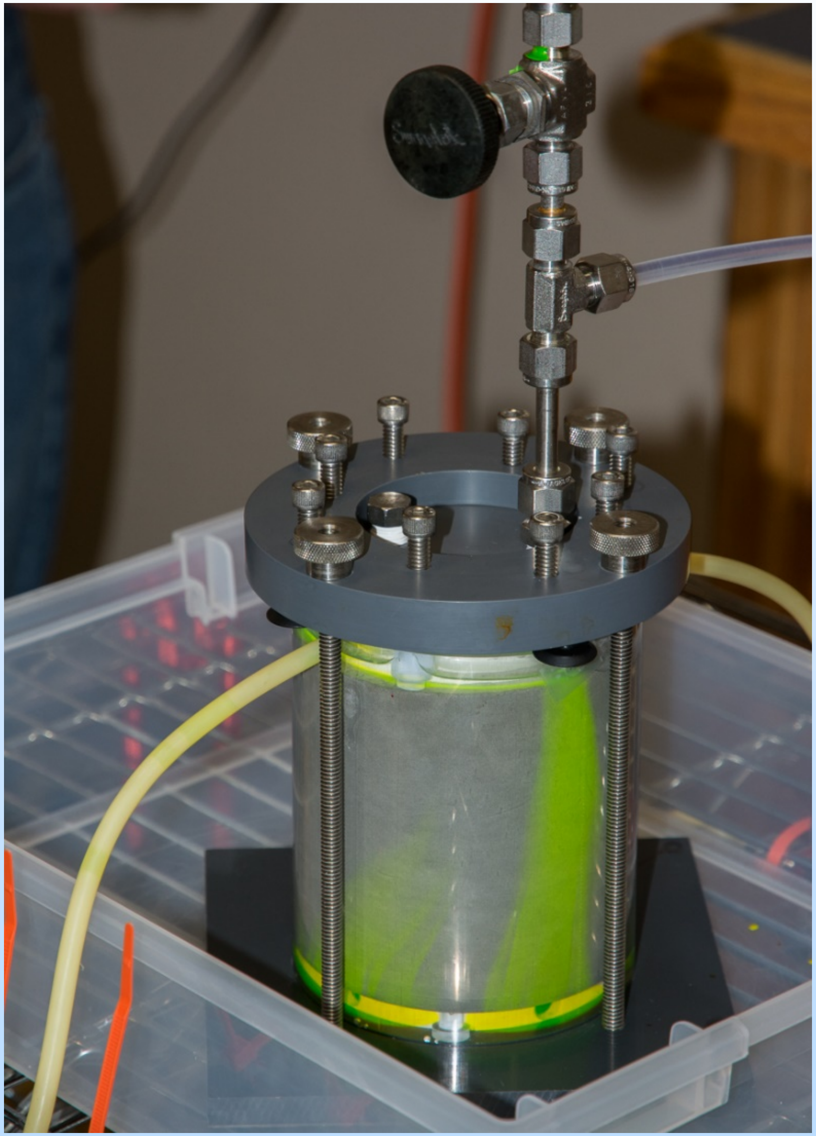


Carbonate seal on cement side of the fracture fixture formed right at the interface of the 0.2mm gap

Laboratory- Wellbore Analog- Visualization



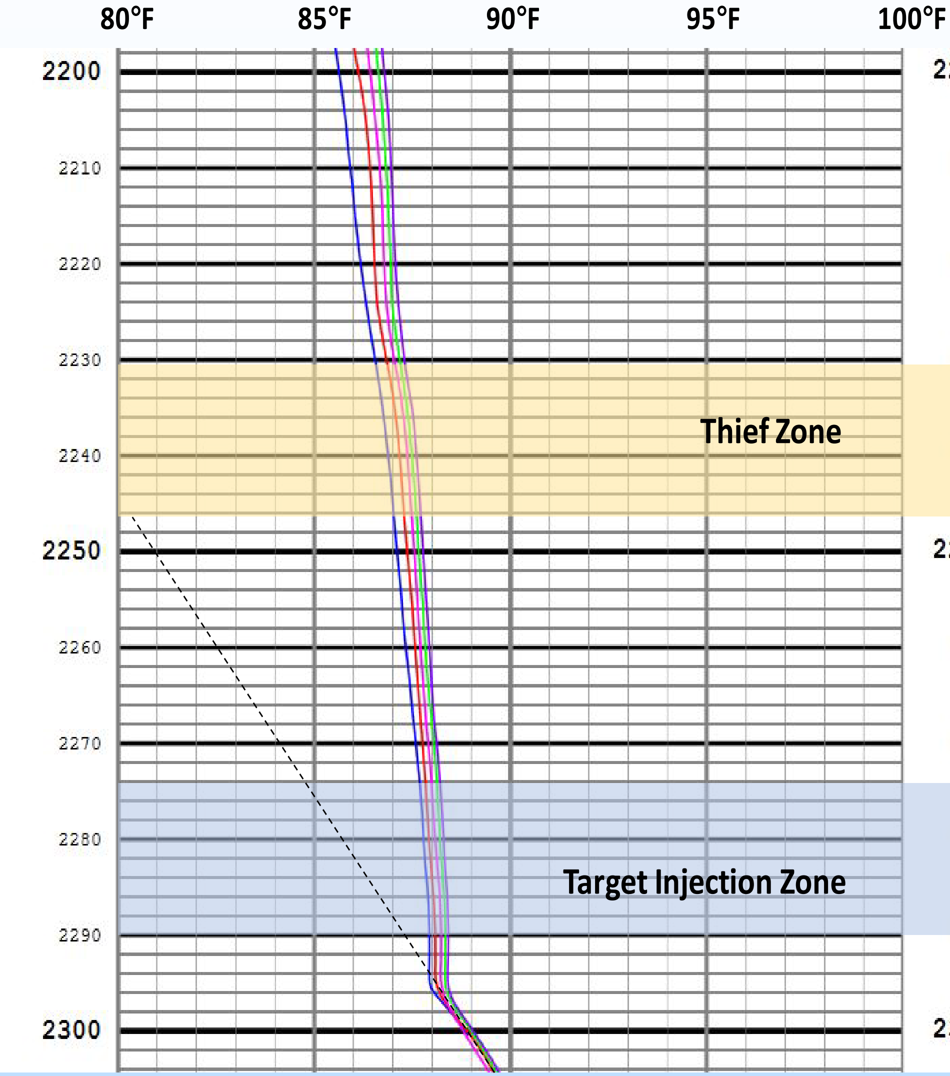
MICP Experiment – 250 µm gap
5 days, 5 orders of magnitude



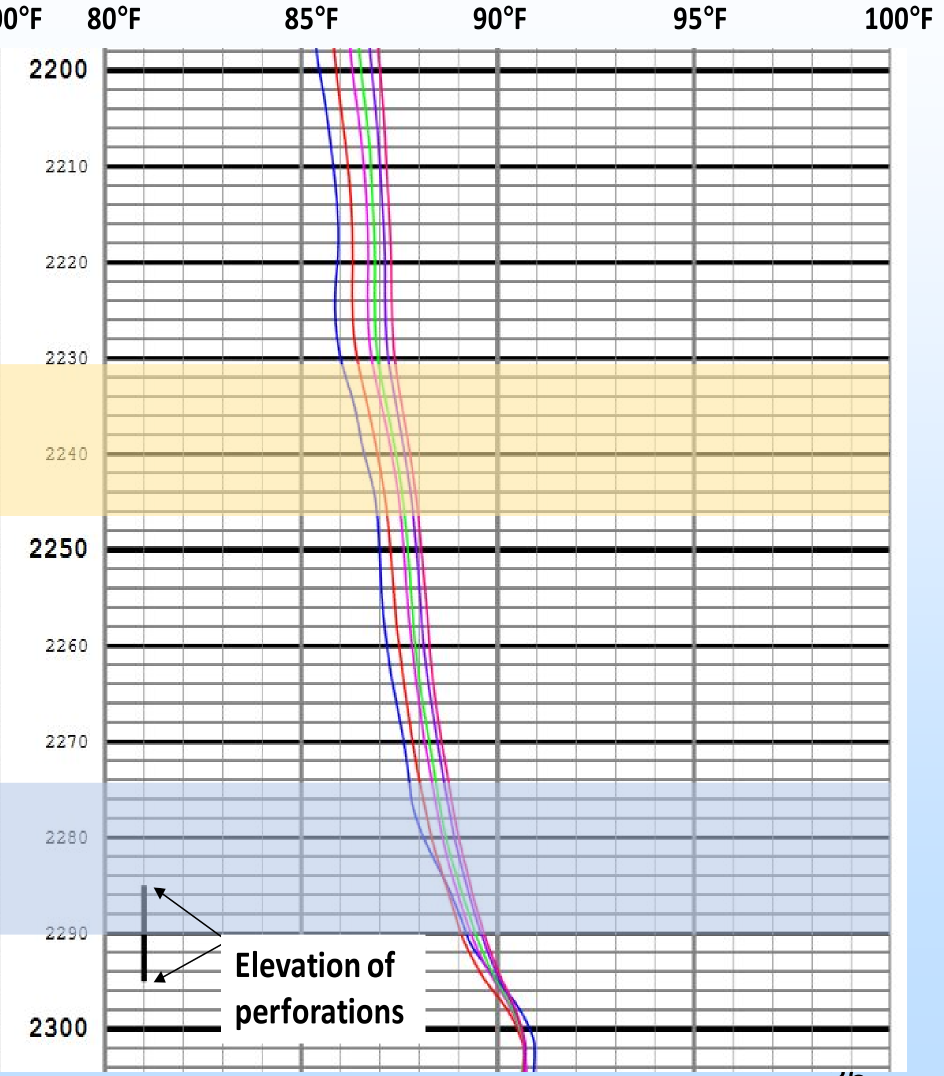
Accomplishments to Date

- Laboratory testing to develop injection strategies
- Three field demonstration with successful results
- Scale up:
  - TRL
  - Mobile laboratory

Temperature logs

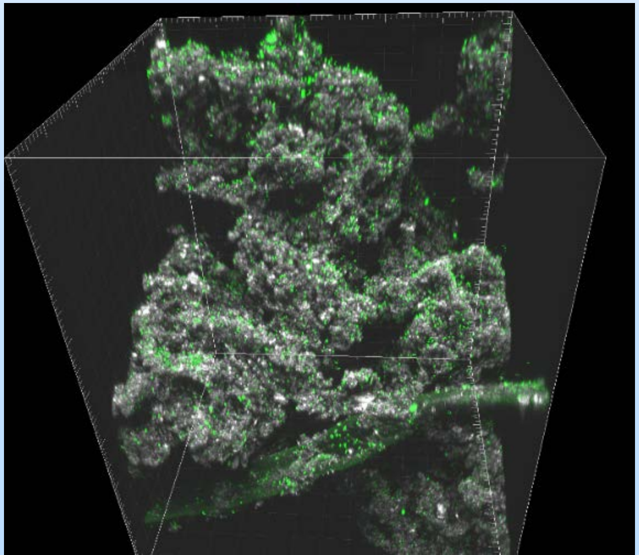


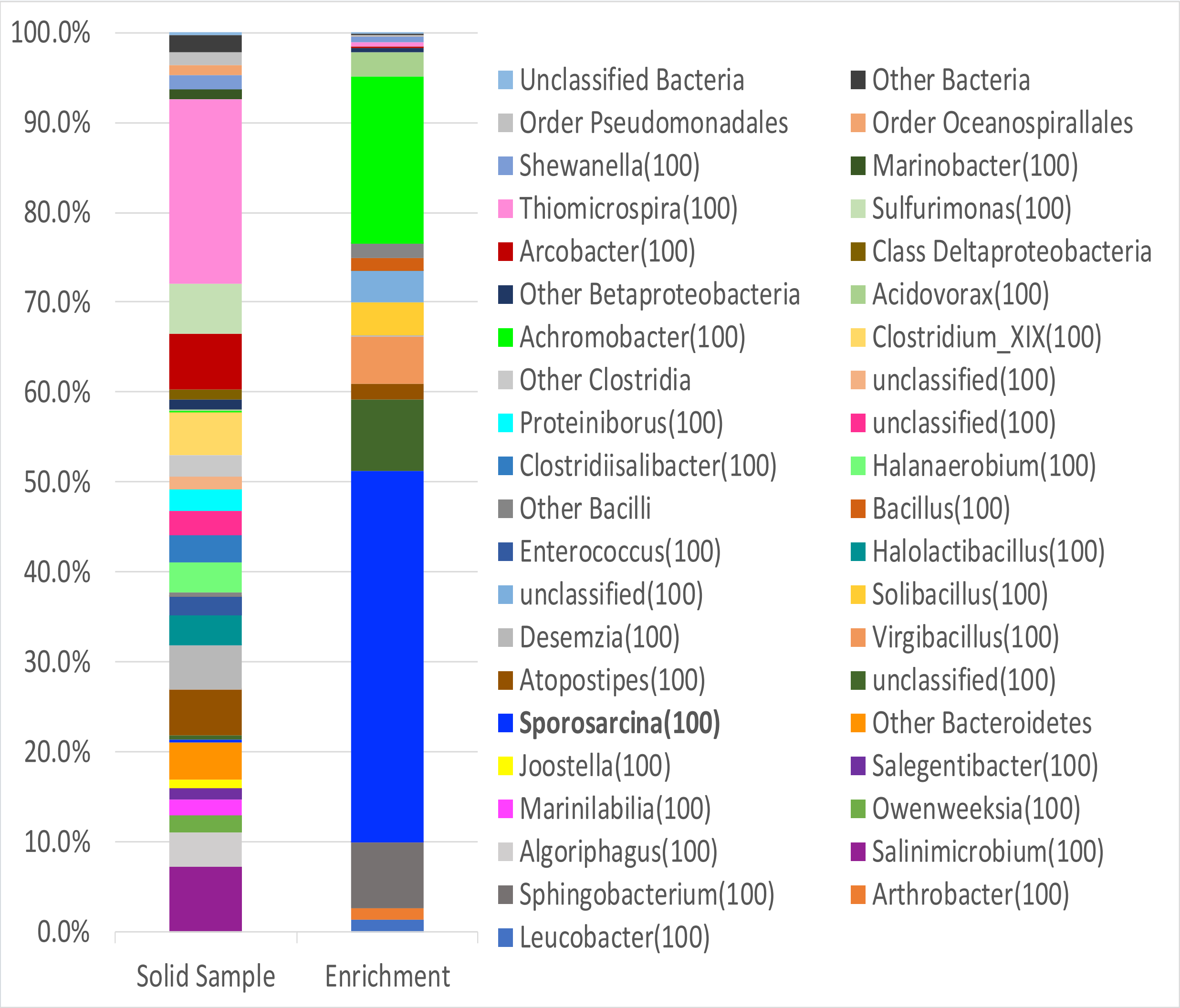
October 2017 – Pre-MICP Treatment



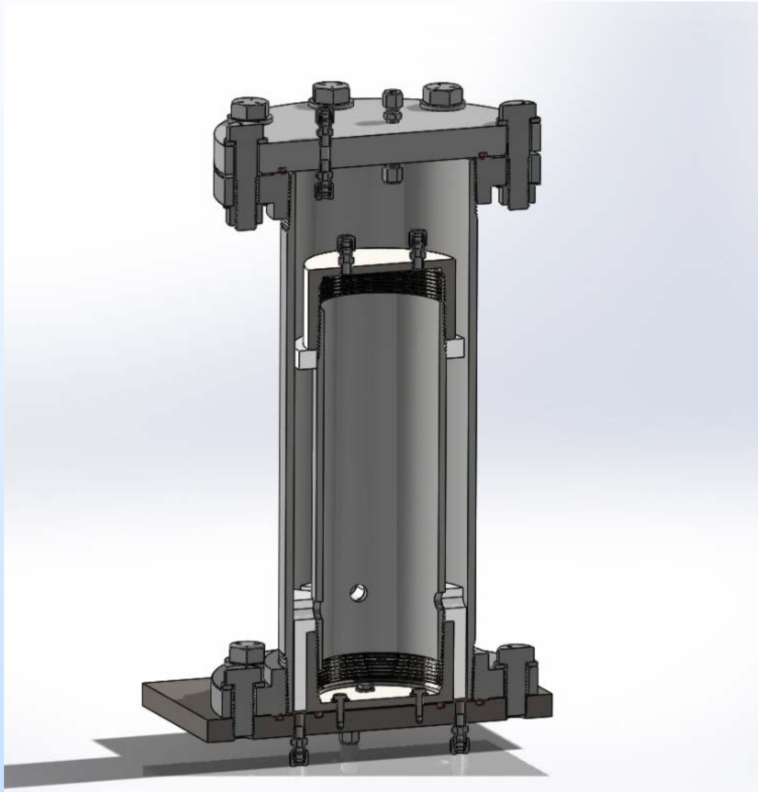
December 2017 – Post-MICP Treatment

Mineral on Pipe and Microbial Community Analysis



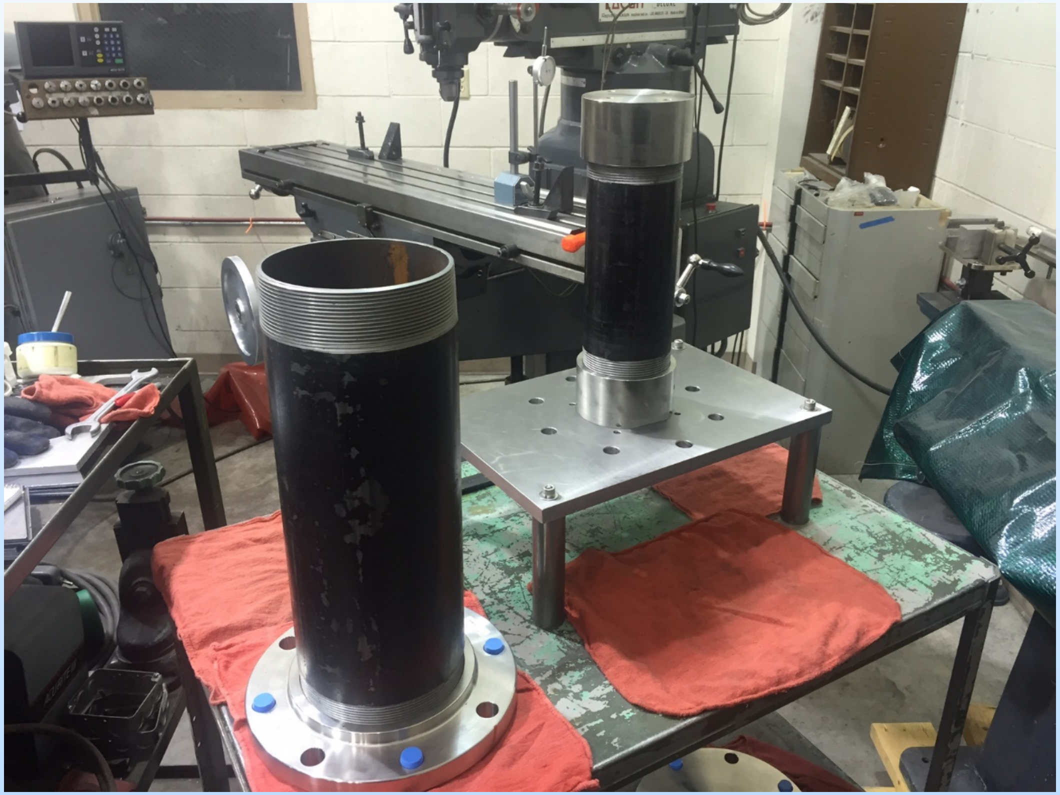


Laboratory -Wellbore Analog- Surface Casing



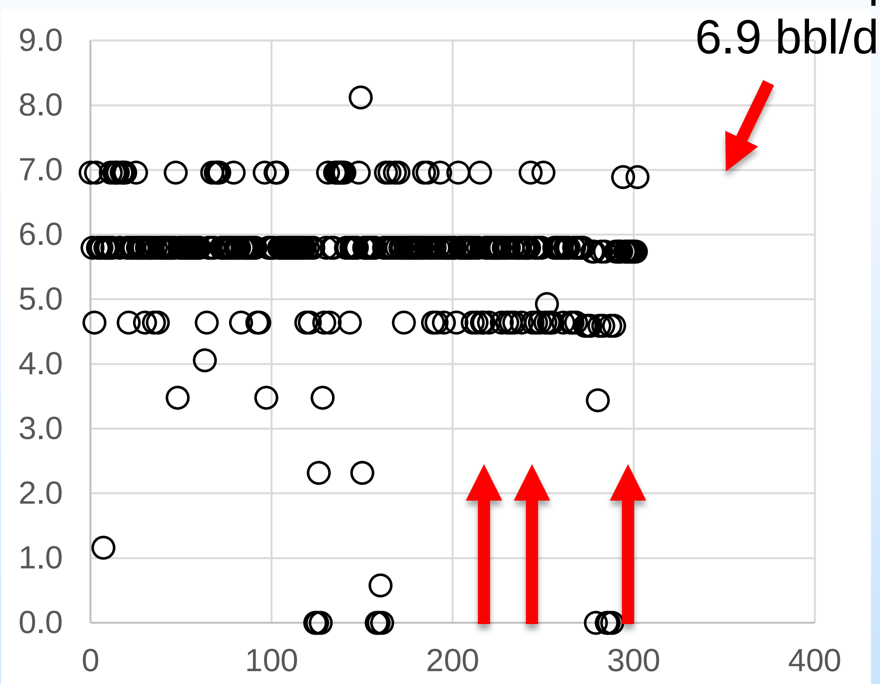
Resistance to gas flow

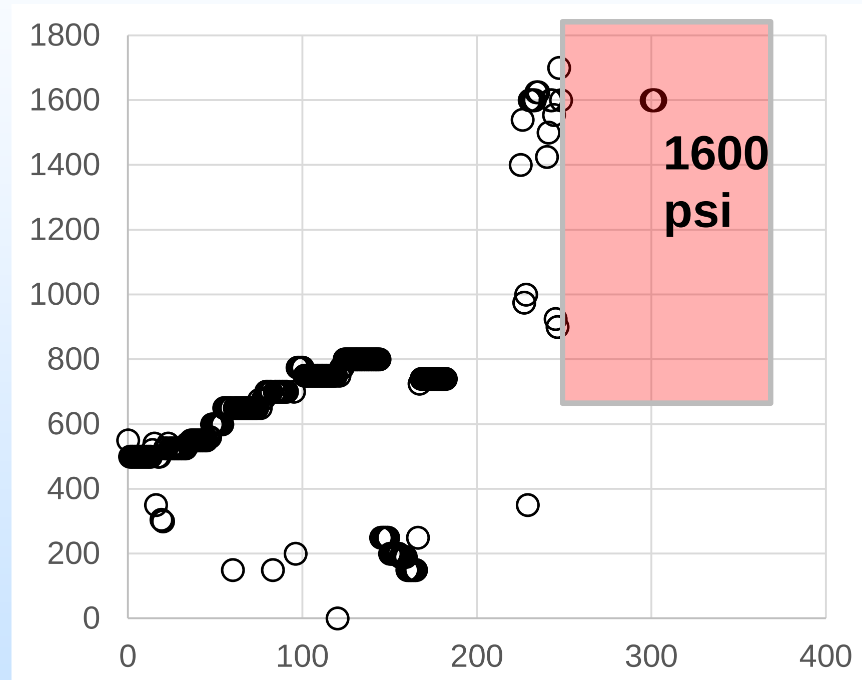
Subsurface pressures



Production data

11/30/18
After re-perf
6.9 bbl/day





Day 225 =field work 9/18
Day 240=return to injection
Day 299= re-perforation- followed by return to injection

Injection pressure at Rexing #4- red box after 9/18 field work

1200-1500 psi @16 bbl/day

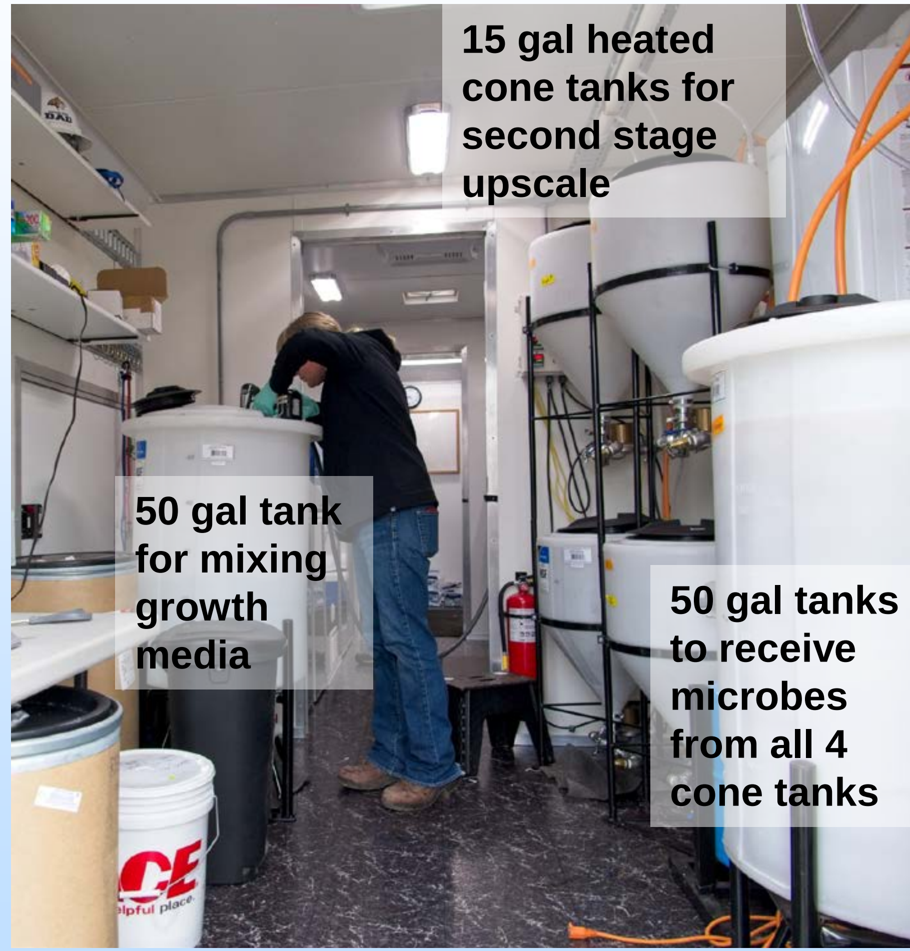
Accomplishment to date: Mobile Mineralization Unit

MONTANA STATE UNIVERSITY Mountains & Minds

CENTER FOR BIOFILM ENGINEERING

Two methods for preparing microbes

Centrifuged microbes grown at MSU

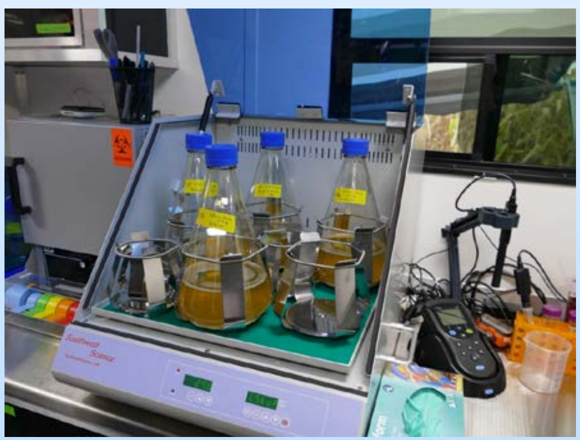


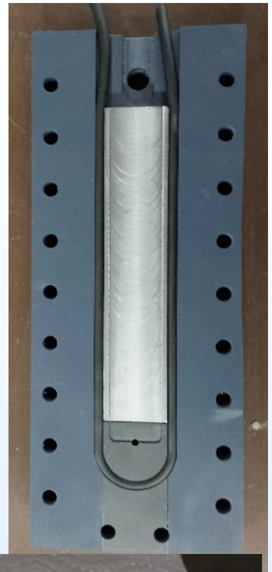
15 gal heated cone tanks for second stage upscale

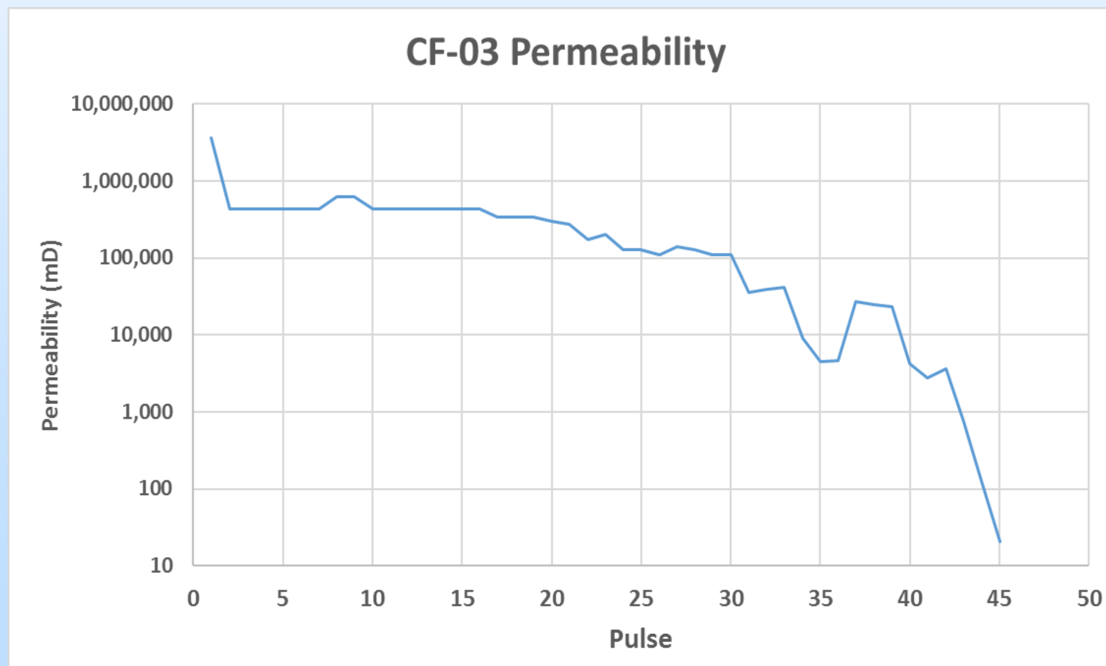
50 gal tank for mixing growth media

50 gal tanks to receive microbes from all 4 cone tanks

Shaker / incubator for first stage upscale to liter volumes



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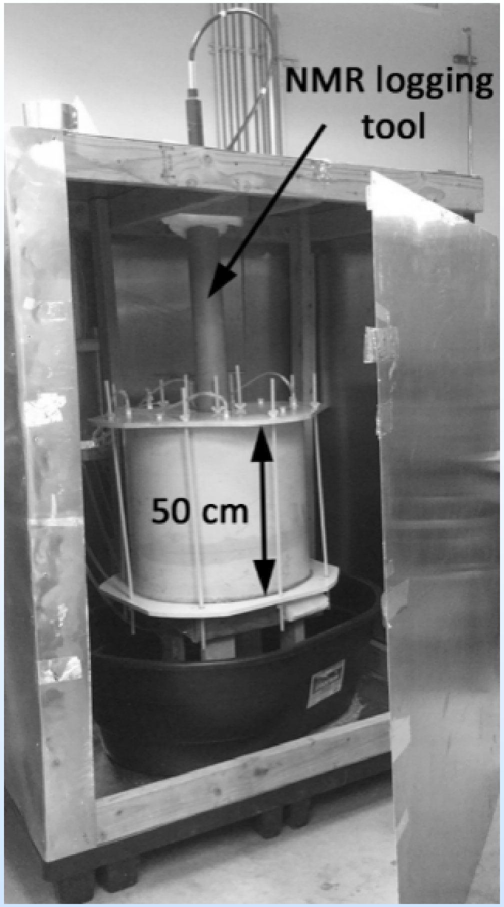
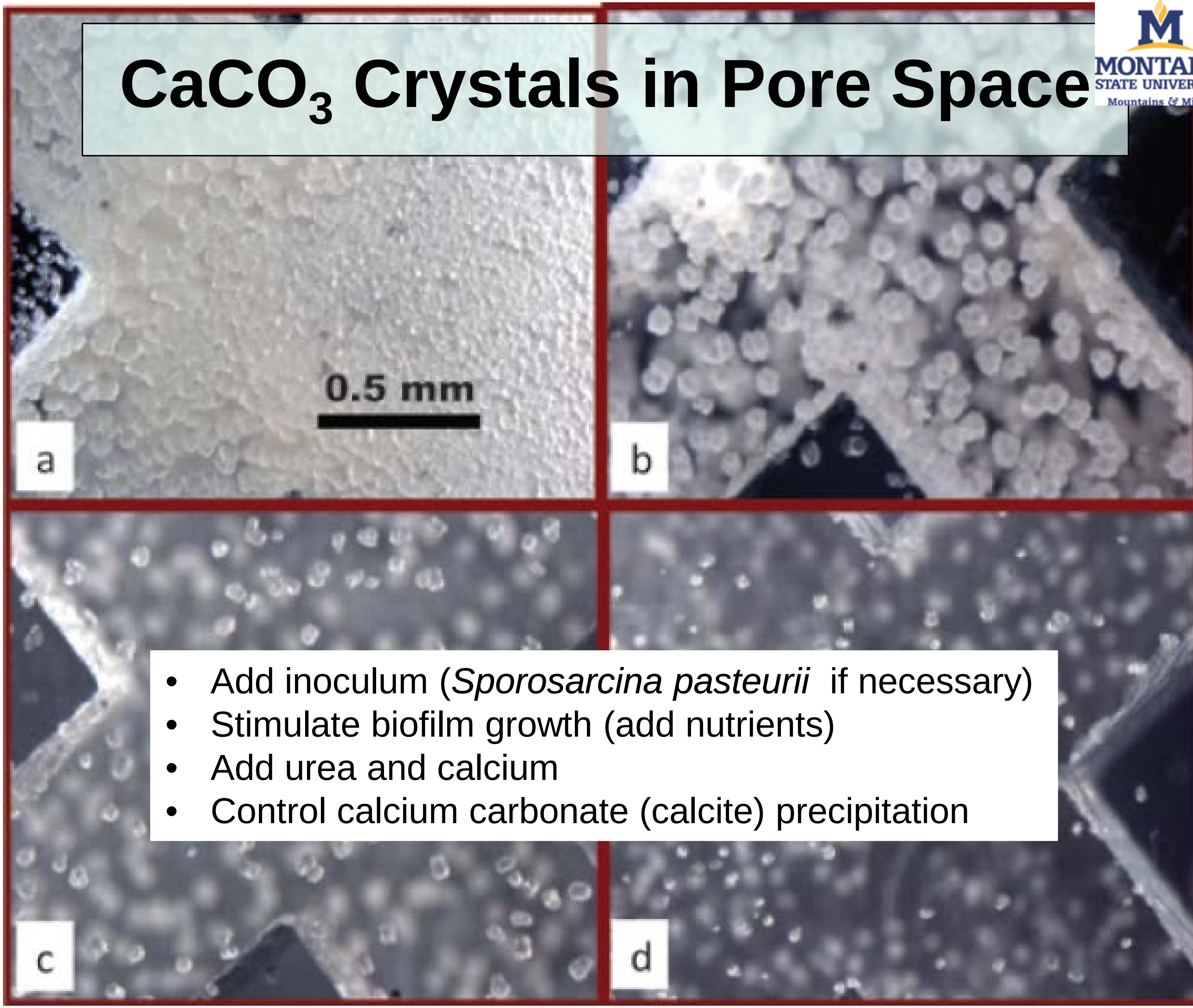
Permeability (mD)
10,000,000
1,000,000
100,000
10,000
1,000
100
10
0
5
10
15
20
25
30
35
40
45
50
Pulse



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.

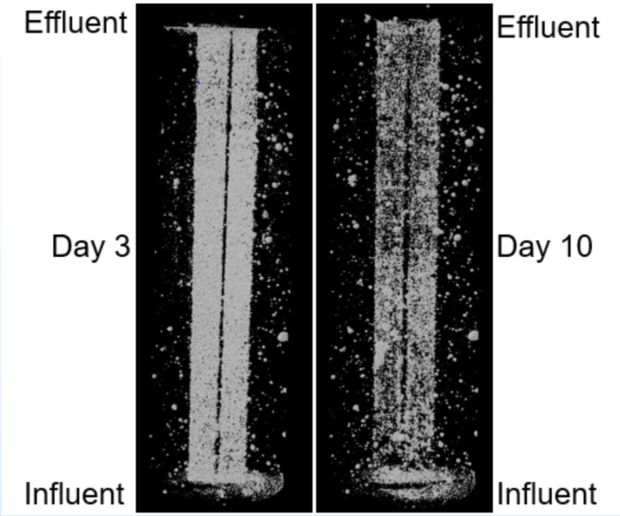
$CaCO_3$ Crystals in Pore Space

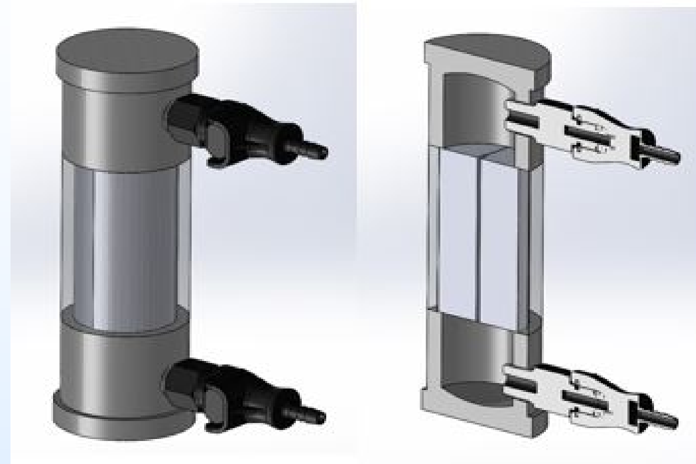


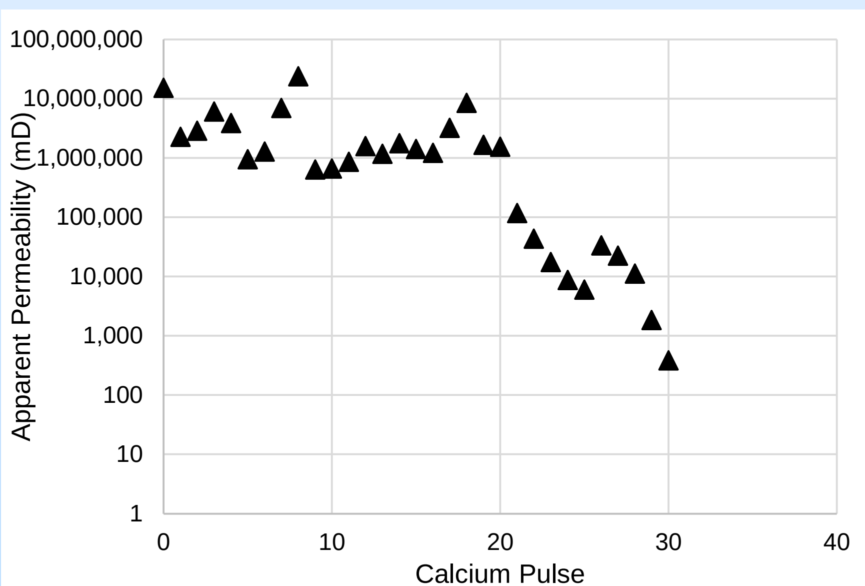
- Add inoculum (*Sporosarcina pasteurii* if necessary)
- Stimulate biofilm growth (add nutrients)
- Add urea and calcium
- Control calcium carbonate (calcite) precipitation

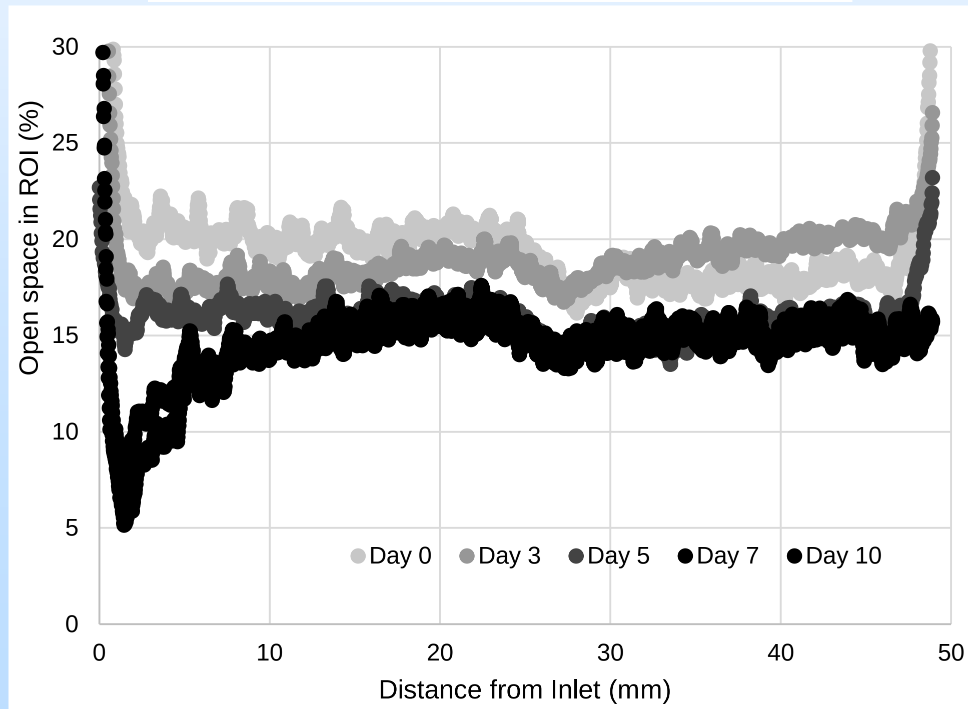
SCHULTZ, L.; ET AL. (2011). *Microscopy Today*. September 2011:10-13.

Objective 1: X-ray CT

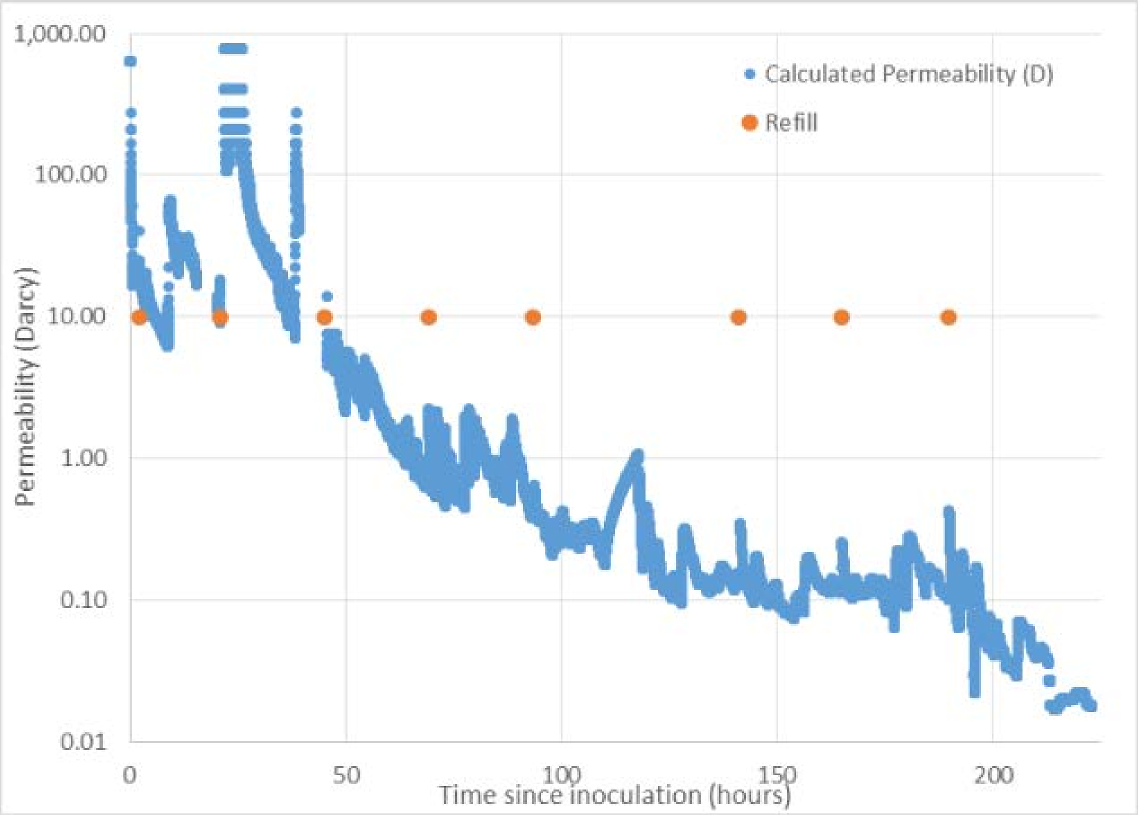








Objective 1: Lab scale: composite cores



Objective 3: Rexing #4 Well

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