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
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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

Cement is viscous

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

After Nordbotten and Celia, Geological Storage of CO₂, 2012
Microbially-Induced CaCO$_3$ Precipitation (MICP)

Ureolysis-driven

$$\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow \text{NH}_2\text{COOH} + \text{NH}_3$$

$$\text{NH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{H}_2\text{CO}_3^*$$

$$2\text{NH}_3 + 2\text{H}_2\text{O} \rightleftharpoons 2\text{NH}_4^+ + 2\text{OH}^-$$

$$\text{H}_2\text{CO}_3^* + 2\text{OH}^- \rightleftharpoons \text{HCO}_3^- + \text{H}_2\text{O} + \text{OH}^- \rightleftharpoons \text{CO}_3^{2-} + 2\text{H}_2\text{O}$$

$$pK_{a1}=6.3$$

$$pK_{a2}=10.3$$

$$(\Omega \text{ or } S)=a(\text{Ca}^{2+})a(\text{CO}_3^{2-})/K_{sp} \quad \text{or} \quad SI= \log (S)$$

$$\text{Ca}^{2+} + \text{CO}_3^{2-} \rightleftharpoons \text{CaCO}_3 \text{ (s)} \quad K_{sp}=4.8 \times 10^{-9}$$


Accomplishments to Date

Objective 1: Fractured Cement Cores

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

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

% Pressure decay after shut in

950 psi before experiment
1200 psi after treatment
300 psi after treatment
500 psi after treatment

5 min  10 min  15 min
Objective 2: USIT logs on Gorgas Well

Channel
Casing
Cement/solids

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

Rexing: Flow-pressure

- Flow - Pressure Ratio (gpm/psi)
- Injection number
- 750 psi
- Bailer delivery
- Storm - muddy field
Mobile Mineralization Unit
Mobile Laboratory
Mobile Laboratory

48 gal. of microbes grown every 8-12 hours
Continuous Method Injection Strategy

First half- resuspended cells

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

Second half- little gain so switch to live cells

Inject 156 gallons of live cells, 360 gallons of water spacers and 394 gallons of U+C
Pressure-flow results

December 2017

Cumulative volume injected (gal)

Pressure-flow results

95% reduction

1300 psi

Cumulative volume injected (gal)

Flow - Pressure Ratio (gpm/psi)

fresh cell

frozen cell suspensions

suspensions

December 2017

September 2018

Pressure-flow results

95% reduction

1300 psi
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

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

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

Energy Research Institute
Director: Lee Spangler

PI: Al Cunningham

Co PI: Robin Gerlach
- Modeling

Co PI: Adrienne Phillips
- Protocol development for field test
- MICP Experiments

Co PI: Richard Esposito
- Southern Company
- Supervision of Field Tests

Jim Kirksey
- Schlumberger Carbon Services
- Aspects of Field Tests and Downhole Implementation
<table>
<thead>
<tr>
<th>Date</th>
<th>Activity Description</th>
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<tbody>
<tr>
<td>M</td>
<td>Injection protocol for the first field demonstration will be developed.</td>
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<tr>
<td>D</td>
<td>Meso-scale laboratory experiments</td>
</tr>
<tr>
<td>M</td>
<td>Injection and testing of wellbore cement integrity</td>
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<tr>
<td>M</td>
<td>Analysis of field data from first field test</td>
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<tr>
<td>M</td>
<td>Injection of materials</td>
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<tr>
<td>D</td>
<td>Wellbore cement remediation field test results and perform scale-up</td>
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<tr>
<td>M</td>
<td>Improvement of conceptual strategies</td>
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<tr>
<td>M</td>
<td>Injection of materials</td>
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<tr>
<td>M</td>
<td>Wellbore cement remediation field test results</td>
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<tr>
<td>M</td>
<td>Design of injection protocol for wellbore cement remediation field test</td>
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**Note:** The dates (M, D) correspond to the months of March and December, respectively.


Wellbore Analog and Fracture Fixture Experiment

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

Thief Zone

Target Injection Zone

Elevation of perforations

80°F 85°F 90°F 95°F 100°F

2200 2210 2220 2230 2240 2250 2260 2270 2280 2290 2300
Mineral on Pipe and Microbial Community Analysis

### Microbial Community Analysis

**Solid Sample**
- Unclassified Bacteria
- Order Pseudomonadales
- Shewanella (100)
- Thiomicrospira (100)
- Arcobacter (100)
- Other Betaproteobacteria
- Achromobacter (100)
- Other Clostridia
- Proteiniborus (100)
- Clostridiisalibacter (100)
- Other Bacilli
- Enterococcus (100)
- unclassified (100)
- Desemzia (100)
- Atopostipes (100)
- **Sporosarcina** (100)
- Joostella (100)
- Marinilabilia (100)
- Algoriphagus (100)
- Sphingobacterium (100)
- Leucobacter (100)

**Enrichment**
- Unclassified Bacteria
- Order Pseudomonadales
- Shewanella (100)
- Thiomicrospira (100)
- Arcobacter (100)
- Other Betaproteobacteria
- Achromobacter (100)
- Other Clostridia
- Proteiniborus (100)
- Clostridiisalibacter (100)
- Other Bacilli
- Enterococcus (100)
- unclassified (100)
- Desemzia (100)
- Atopostipes (100)
- **Sporosarcina** (100)
- Joostella (100)
- Marinilabilia (100)
- Algoriphagus (100)
- Sphingobacterium (100)
- Leucobacter (100)
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
Two methods for preparing microbes

- **Centrifuged microbes grown at MSU**
- **15 gal heated cone tanks for second stage upscale**
- **Shaker / incubator for first stage upscale to liter volumes**
- **50 gal tank for mixing growth media**
- **50 gal tanks to receive microbes from all 4 cone tanks**
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
Objective 1: X-ray CT

- **Day 3**
  - Effluent
  - Influent

- **Day 10**
  - Effluent
  - Influent

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**Graphs**

1. **Apparent Permeability vs. Calcium Pulse**
   - X-axis: Calcium Pulse
   - Y-axis: Apparent Permeability (mD)
   - Legend: Day 0, Day 3, Day 5, Day 7, Day 10

2. **Open space in ROI (%) vs. Distance from Inlet (mm)**
   - X-axis: Distance from Inlet (mm)
   - Y-axis: Open space in ROI (%)
Objective 1: Lab scale: composite cores
Objective 3: Rexing #4 Well