Oil & Natural Gas Technology

DOE Award No.: DE-FE0024296

Quarterly Research Performance

Progress Report (Period Ending 09/30/2017)

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

Project Period (10/1/2014 to 09/30/2018)

Submitted by:
Adrienne Phillips

_____
Signature

Montana State University
DUNS #: 625447982
Energy Research Institute
P.O. Box 172465
Bozeman, MT 59717-2465
Email: adrienne.phillips@biofilm.montana.edu
Phone number: (406) 994-2119

Prepared for:
United States Department of Energy
National Energy Technology Laboratory

November 6, 2017

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

Office of Fossil Energy

ACCOMPLISHMENTS

Goal

The goal of this project is to develop improved methods for sealing compromised wellbore cement in leaking gas wells, thereby reducing the risk of unwanted upward gas migration. To achieve this goal an integrated workplan of laboratory testing, simulation modeling, and field testing is underway. Laboratory testing and simulation modeling (with assistance from the University of Stuttgart) are being conducted at the Center for Biofilm Engineering (CBE) at Montana State University (MSU) and field testing was carried out at the 1498 m (4915 foot) deep Alabama Power Company well located at the Gorgas Power plant in Walker County, Alabama (Gorgas #1 well). This project is designed to develop technologies for sealing compromised wellbore cement using the process known as microbially induced calcite precipitation (MICP). The project has two main objectives:

Objective 1: Prepare for and conduct an initial MICP field test aimed at characterizing a region of compromised well cement in the Gorgas well which is suitable for MICP sealing. The location chosen for MICP sealing is the interval of 310.0 -310.9 m (1017-1020 feet) below ground surface (bgs). The first MICP sealing test was completed in April 2016.

Objective 2: After thorough analysis of the results from the first field test, our team will conduct a second MICP test using improved MICP injection methods. The second field test will target compromised wellbore cement in an injection well used for water flooding to improve oil recovery in Indiana known as the Rexing #4 well.

After each field demonstration, the following (or equivalent) methods are to be employed to assess effectiveness of the MICP seal: pressure falloff testing, sustained natural gas flow rate testing at the well head, and side wall coring. Successful demonstration of improving wellbore integrity and sealing gas leaks from poor cement bond regions will result in a reduction in the pressure falloff, reduction in the sustained gas flow rate at the well head, noticeable differences in the ultrasonic imaging tool (USIT) data in the targeted biomineralization regions, and demonstration of MICP byproducts ($CaCO_3$) in the treated regions on side wall cores. In the case of the new well chosen for the second field demonstration, the return to productivity would be an additional measure of success.

The project milestones are shown below in Table 1. This table was updated to reflect the change in milestone dates per the one year no-cost time extension that went into effect October 1, 2015.

Table 1. Project Milestones

Related Task	Milestone Number	Milestone Title	Planned Completion Date	Revised Completion Date	Verification Method
1.0	1	Update Management Plan	11/30/2014	NA	PMP
1.0	2	Kickoff Meeting	11/06/2014	NA	Presentation
2.1	3	Complete construction and testing of wellbore-cement analog testing system. Expected result is a system which facilitates biomineralization sealing in annular spaces representative of field conditions.	3/31/2015	NA	Quarterly Report
3.2	4	Complete first wellbore cement remediation field test. Expected results include obtaining side wall cores and pressure testing to evaluate the extent of biomineralization sealing.	9/30/2015	9/30/2016	Quarterly Report
4.1	5	Complete analysis of field data from first field test. Expected result is a data set which will enhance the design of the second field test.	3/31/2016	3/31/2017	Quarterly Report
4.1	6	Complete design of injection protocol for second field test.	9/30/2016	9/30/2017	Quarterly Report
5.2	7	Complete second field test. Expected results include obtaining side wall cores and pressure testing to evaluate the extent of biomineralization sealing.	3/31/2017	3/31/2018	Quarterly Report
6.0	8	Complete analysis of laboratory, simulation modeling and field data. The expected result will be a comprehensive evaluation of MICP sealing technology for well cement repair.	9/30/2017	9/30/2018	Quarterly Report

Accomplishments under the goals

Project Planning. During this reporting period, teleconference calls were conducted and included Jim Kirksey of Loudon Technical Services for Schlumberger (SLB), Robin Gerlach, Lee Spangler, Al Cunningham, and Adie Phillips (MSU), and Randy Hiebert of Montana Emergent Technologies (MET). The subjects of these calls have been: construction and development of the mobile operations center, work to characterize the Rexing #4 well and planning of the second field test. A request for an extension to the milestone report that was due September 30, 2017, was made on October 2, 2017. This request was made because field work

was planned for the Rexing #4 well characterization work for the week of September 11, 2017. Unfortunately, Hurricane Irma threatened the weather conditions even as far north as Southern Indiana where the well is located. Given that the well is located in a low-lying area and potential flooding was projected, the field work was delayed. The field work was rescheduled and completed the week of October 9, 2017. Work now focuses on the preparation for the field demonstration, tentatively scheduled to begin the week of November 27, 2017.

April 2016 MICP field test results. As previously reported, the MICP cement channel sealing treatment demonstration was performed in April 2016 over the course of five days where biomineralization fluids and microbial growth media components were delivered downhole using a delivery bailer method. The experiment was successful and three major results were obtained through the demonstration: (1) injectivity was significantly reduced after MICP treatment; (2) a comparison of USIT logs taken before and after MICP treatment of the target interval indicated a significant increase in the solids content after sealing; and (3) pressure fall-off tests after MICP treatment met a definition of mechanical integrity for shut in wells. The positive results have been discussed among MSU, MET, and SLB and the team is in agreement that additional development of the technology (including the addition of a mobile operations center) will advance the technology readiness level of the sealing method.

Cement Channel Laboratory Experiment

As previously reported, estimates on the gap size in the Rexing #4 well is not completely known but the well appears to 'take significant fluids' (i.e. there may be a large gap). Hence, an experiment was conducted where we successfully reduced permeability in a 2 mm (0.079 inches) wide gap between a cement and a steel coupon. After 45 calcium pulses over nine days, the apparent permeability was reduced by more than five orders of magnitude from about 3,800 Darcys for the open channel to 0.021 Darcys. It was observed after the reactor was destructively sampled, that a significant amount of calcium carbonate formed in the lower half of the gap. Calcium carbonate adhered to both the cement and the steel, with more calcite adhering to the cement. This was an important experiment for building confidence toward the planned field demonstration effort. This successful demonstration of MICP in a large gap provides evidence that even if the gap size in the Rexing #4 well is large, with enough time on-site the gap could be sealed.

Rexing #4 Characterization

The Rexing #4 well lies in southern Indiana. This well is an injection well that was used to perform water flooding to increase oil recovery. Based on the injection and well characterization data, it is believed that a channel formed in the cement in the proximity of the well, resulting in the injected water traveling through the channel into a thief zone above the targeted oil formation. We are intending to seal the channel in the cement, therefore directing water flow back into the oil-bearing formation and ultimately increasing oil production again. The advantage of using this well for the second demonstration is that there is oil present in the formation, which makes this sealing experiment more applicable in a real-world oil field technology.

During the week of October 9, 2017, Jim Kirksey mobilized to the site to perform characterization of the well and channel. Briefly, a tubing string with packer was set and 100

bbls of water were injected from the surface into the channel overnight. A temperature log was run the next morning to observe where the fluids were transporting behind the casing. The well was logged with five passes at thirty-minute intervals. The results of the logging suggested that the fluid had travelled from the perforations between 2284 and -2294 feet bgs back up alongside the casing into the sand body at around 2230 feet bgs (Figure 1).

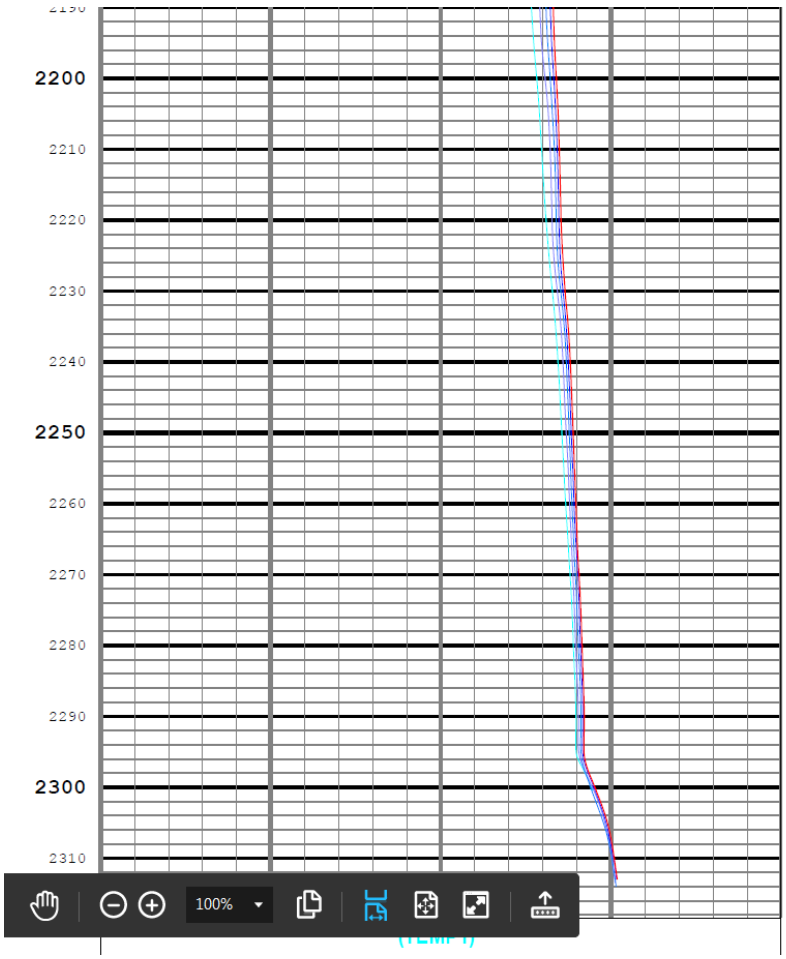

Figure 1. Temperature log for the Rexing #4 well. As the lines of the temperature log passes come together it indicates that the flow is observed to be in a channel behind the casing.

After the temperature log was run, injection tests were performed to determine the pressure flow relationship and estimate the aperture and volume of the gap. Two flow rates were used to inject fluids and monitor pressure: (1) 2.1 gpm at 404 psia stabilizing at 1.78 gpm at 433 psia and (2) 1.66 gpm at 600 psia. A total of 450 gallons was injected during the pressure flow test. Finally, the pressure fall-off was recorded overnight to get a baseline pressure fall-off analysis. Using the pressure and flow monitored values and Cubic's law, it is estimated that the fracture aperture is around 400 µm or smaller in aperture in the approximately 50-foot-long channel.

Planning Second Field Test

Flask Growth Study with Rexing Well Water

A bacterial growth study was performed to evaluate whether the water sampled from the Rexing well field is inhibitory to *S. pasteurii* growth and urea hydrolysis. The experiment was conducted

in triplicate using 3 g/L yeast extract medium. The medium in three flasks was made with deionized (DI) water as a control, while the medium in three other flasks was made with water sampled from a well in the same well field as the well to be used in the Rexing field demonstration; media were not sterilized for this test. The overnight culture used for the inoculum was grown in BHI (brain heart infusion) + urea medium.

During the centrifugation step during the concentration of the pre-grown cells for inoculation, precipitation was observed in the Falcon tube containing cells and the medium prepared in well water. The flasks were inoculated with cells and placed on the shaker table at room temperature. Population assay samples were collected at 0 and 24 hours. Samples for pH and urea analysis with the Jung assay were collected at 0, 2, 4, 8, 24, and 48 hours.

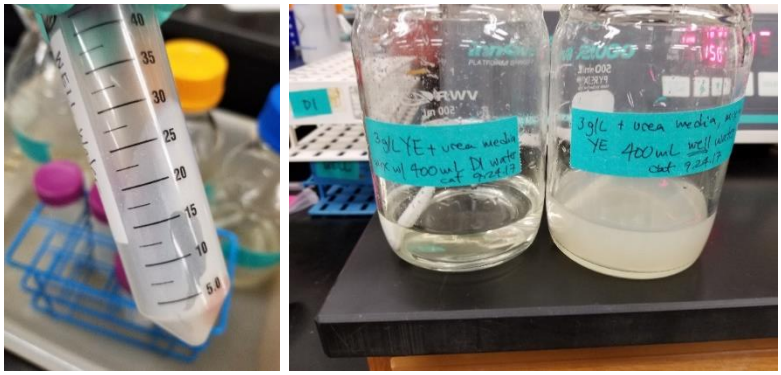

Figure 2. Mineral formed during centrifugation of cells suspended in media mixed with well water (left). The unfiltered well water media also showed signs of mineral formation within seven hours of mixing and without inoculation (right).

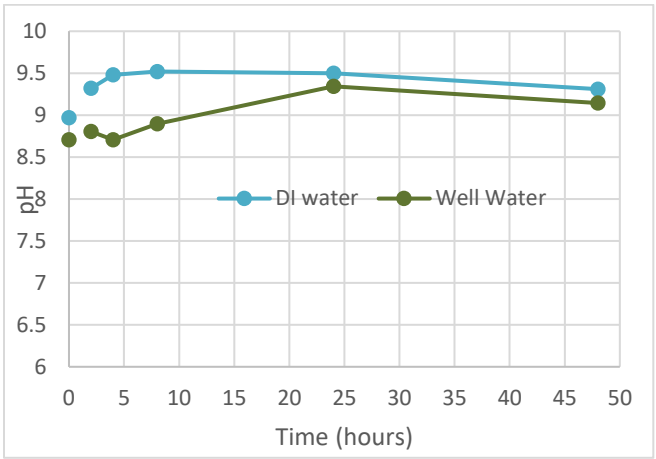

Figure 3. pH increase lagged in the well water media flasks but was similar to the DI water media flasks by 24 hours.

Plate counts indicate that at t=0, DI water media flasks had an average cell count of 3.3E7 cfu/mL while the well water media flasks started with a cell count of approximately 2.8E7 cfu/mL. By 24 hours, cell populations in the DI water media flasks increased to an average of 1.4E8 cfu/mL. The well water media flasks on the other hand decreased slightly in population to 2.2E7 cfu/mL. There was significant precipitation observed in the well water media flasks, and it

is likely that many bacteria were removed from suspension inside the mineral precipitate. Calcium measurements on the well water sample indicate that there is approximately 1-1.5 g/L Ca^{2+} in the water. The conductivity was 60.9 mS/cm at 6.4 °C. The well water smells of sulfides and the pH was approximately 7.7. While the cell growth and ureolysis do not seem significantly inhibited by well water, we plan at the beginning of the field experiment to inject fresh water into the well and channel. This injection will likely rinse away calcium containing fluids and minimize instantaneous precipitation close to the well which could cause plugging in areas not targeted.

We are performing an experiment to test the growth conditions of *S. pasteurii* at a larger scale to prepare for the field experiment. We are planning an experiment utilizing a 6" diameter wellbore analog attached to a reactor that has an engineered gap between cement and steel interfaces; fluids exit the gap and enter a sand filled reactor. This will mimic conditions in the field where injected fluids will travel up a channel behind the casing into a sandstone formation.

Mobile Mineralization Operations Center Development

MET, MSU, and Jim Kirksey of Loudon Technical Services have finalized the layout of the mobile operations center. The final design maintains the major desired functions: (1) operations control and communications; (2) laboratory activities; (3) storage; and (4) pumping (to bailer or downhole). The mobile laboratory was delivered in August to Montana Emergent Technologies who are the subcontractors tasked with completing the construction and addition of shelves, desk space and water system (Figure 4).

Figure 4. Images of the build-out of the mobile operations center. Left: drying rack for laboratory glassware, middle: ion exchange water treatment system, right: storage cabinet attached to wall.

Opportunities for training and professional development

During this quarter, Dr. Adrienne Phillips attended and presented at the 2017 Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting in Pittsburgh August 1-3, 2017. In July 2017, Drew Norton, a Master's student who worked on the project successfully defended his thesis. On September 20, 2017, Rouzbeh Shahsavari, Assistant Professor in the Department of Civil and Environmental Engineering and inventor of C-Crete visited Montana State University to tour laboratories and discuss synergistic research opportunities. A new post-doctoral scholar,

Dr. Catherine Kirkland began working on the project and has been training in the laboratory to prepare for work in the field.

Disseminating results to communities of interest
N/A

Planned activities during the next reporting period
We plan to complete the work on the construction of the mobile operations center. We are continuing discussions and laboratory work to prepare for the second field demonstration.

Products

Presentations
Norton, D. Visualizing and Quantifying Biomineralization in Wellbore Analog Reactors. Masters Defense, July 14, 2017, Montana State University

Beser, D., West C., Daily, R., Cunningham, A., Gerlach, R., Fick, D., Spangler, L., Phillips, AJ. Assessment of ureolysis induced mineral precipitation material properties compared to oil and gas well cements. Montana Biofilms Meeting July 18, 2017, Bozeman, Montana.

Phillips, AJ., Cunningham, A., Gerlach, R., Spangler, L. "Methods to Enhance Wellbore Cement Integrity with Microbially-Induced Calcite Precipitation (MICP)". 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, Pittsburg, PA.

Papers
Troyer, E., West, C., Berninghaus, A., Joyce, J., Gerlach, R., Phillips, A. and Foreman, C. Biomineralized Art: Using Microbes and Minds to Make Mountains. in American Rock Mechanics Association 51st Annual Meeting. 2017. San Francisco, CA. (Paper # 460)

Besser, D., West, C., Daily, R., Cunningham, A., Gerlach, R., Fick, D., Spangler, L. and Phillips, A. Assessment of ureolysis induced mineral precipitation material properties compared to oil and gas well cements. American Rock Mechanics Association 51st Annual Meeting. 2017. San Francisco, CA. (Paper # 588)

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Other organizations involved as partners

Schlumberger (SLB). SLB is providing matching support for this project. During this reporting period, Jim Kirksey and others from SLB participated in the decision to request a change in wells for the second field demonstration.

Southern Company (SC). SC is providing matching support for this project. Dr. Richard Esposito of SC, identified and secured the 1493 m (4915 foot) deep well (Gorgas #1 well, Walker County, Alabama) which was used for the first MICP field test.

Montana Emergent Technologies (MET). MET attended meetings where discussion surrounded the current laboratory efforts, the mobile operations center, and the field planning. MET participated at a very high level in performing the April 2016 Gorgas field test and will contribute equally to the 2017 field test.

University of Alabama at Birmingham (UAB). Dr. Peter Walsh is in charge of the UAB Core Testing Laboratory. He will continue conducting core testing activities throughout the duration of this project.

University of Stuttgart. Dr. Rainer Helmig, Director of the Institute for Modelling Hydraulic and Environmental Systems (IWS), and Dr. Johannes Hommel, postdoctoral researcher, are project collaborators at the University of Stuttgart. They along with other colleagues have developed a reactive transport simulation model, referred to herein as the Stuttgart MICP model, that has been integrated with previous laboratory and field research. This model was successfully used to design the Gorgas field test in April 2016 and will be used to model the injection strategy that will be used at Rexing #4.

IMPACT

As reported previously, the results of the April 2016 Gorgas MICP sealing test were positively received by Mr. Jim Kirksey and Mr. Wayne Rowe of Schlumberger. In addition, the success of the experiment has been disseminated through news articles to increase the audience aware of the technology.

Dollar amount of award budget spent in foreign country(ies)

Al Cunningham traveled to Stuttgart, Germany from July 9-14, 2017, for collaboration and review of the University of Stuttgart's modeling work. Airfare and hotel were reimbursed by Stuttgart. Total funds spent in foreign countries was $141.94.

CHANGES/PROBLEMS

As of this reporting period there are no problems to report. As noted above, the project milestone deadlines were revised due to the budget period 1 no cost time extension.

SPECIAL REPORTING REQUIREMENTS

At this time there are no special reporting requirements.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

13131 Dairy Ashford Road, Suite 225
Sugar Land, TX 77478

1450 Queen Avenue SW
Albany, OR 97321-2198

Arctic Energy Office
420 L Street, Suite 305
Anchorage, AK 99501

Visit the NETL website at:
www.netl.doe.gov

Customer Service Line:
1-800-553-7681

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY