Oil & Natural Gas Technology

DOE Award No.: DE-FE0024296

Quarterly Research Performance Progress Report

(Period Ending 6/30/2018)

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

Project Period (October 1, 2014- September 30, 2019)

Submitted by:
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National Energy Technology Laboratory

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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 work plan of laboratory testing, simulation modeling, and field testing is underway. Laboratory testing and simulation modeling (with assistance from the University of Stuttgart) are conducted at the Center for Biofilm Engineering (CBE) at Montana State University (MSU). Field testing was carried out at the 1,498 m (4,915 foot) deep Alabama Power Company well (Gorgas #1 well) and the Rexing #4 well in Indiana owned by Gallagher Drilling. 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 a 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 the effectiveness of the MICP seal: pressure falloff testing, sustained natural gas flow rate testing at the wellhead, and sidewall 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 wellhead, noticeable differences in the ultrasonic imaging tool (USIT) or temperature logging data in the targeted biomineralization regions, and demonstration of MICP byproducts ($CaCO_3$) in the treated regions on side wall cores or downhole tubing. 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. It has also been updated to reflect the extension of the project to 2019 and the additional scope (added tasks) to the project that were approved in April 2018.

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	Project Management Plan
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
7.0	8	Complete design and modifications to the mobile unit	9/30/2018		Quarterly Report
8.0	9	Complete third field test	12/31/2018		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	9/30/2019	Quarterly Report

Accomplishments under the goals

Project Planning. During this reporting period, meetings were conducted with Robin Gerlach, Lee Spangler, Al Cunningham, Catherine Kirkland, and Adie Phillips (MSU), as well as Randy Hiebert of Montana Emergent Technologies (MET) and Jim Kirksey of Loudon Technical Services (LTS). The subjects of these meetings were a characterization of the Rexing #4 well field test and discussions of methods to increase volumes of biocementation solutions to develop a continuous injection (rather than bailer delivery) method. DOE approved the request for an extension with additional scope (Tasks) to the project in April. This request was made to develop the technology further and potentially advance the technology readiness level. The new tasks include evaluation of the second field test results, determining methods to scale-up, and preparing a field test injection plan (Task 7). This will be accomplished by performing laboratory experiments tests to improve implementation strategies and modifying the mobile mineralization unit. We then plan to perform a third wellbore cement remediation field test and assess its success (Task 8). We plan to evaluate the third field test results resulting in a final comprehensive scientific/technical report to assess the MICP sealing technology's ability to remediate wellbore cement problems (Task 9) which will be part of the data dissemination and technology transfer task (Task 10).

April 2016 MICP field test results. As previously reported, the MICP cement channel sealing treatment demonstration was performed in April 2016 where biomineralization fluids 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 were discussed among MSU, MET, LTS, and Schlumberger and the team is in agreement that additional development and demonstration of the technology will advance the technology readiness level of the sealing method.

Thief Zone Laboratory Experiment. To prepare for the second field demonstration, a lab-scale reactor was constructed consisting of (a) two sand columns to model the target injection formation (a low permeability sandstone) and the thief zone (a higher permeability sandstone); (b) a fracture fixture to model the well cement defect; and (c) a pumping reservoir to model the wellbore injection methods applied in the field to represent the Rexing #4 field conditions. Injection of biomineralization fluids resulted in the injection pressure exceeding system limits and a two order of magnitude reduction in the ratio of flow to pressure. This experiment helped researchers prepare for the field experiment by mimicking the injection strategies.

Rexing #4 Field Experiment. As reported in the previous quarter, a second field experiment was conducted in December of 2017 at the Rexing #4 well, located near Cynthiana, IN. This well was historically used to sweep residual oil to production wells until injection pressure was lost presumably due to a fracture in the wellbore cement. Well logging data suggested that rather than entering the target formation, injectate was traveling up the casing-borehole annulus through defects in the well cement to a sandstone thief zone approximately 30-50 feet above the target formation. MICP treatment was used to remediate flow into the thief zone. After a total of 25 inoculum injections and 49 calcium solution injections, the flow to a pressure ratio of the system decreased by approximately 70%. In addition, the temperature logging results indicated that less of the injected cold water was traveling up the channel after MICP sealing. The reducing of injected water traveling up the channel suggests that MICP treatment did seal or partially seal the leakage pathway. When the injection tubing was pulled from the well, a buildup of biomineral was observed which was scraped and sent to MSU for analysis including microbial community analysis and microscopy (results shared last quarter).

Samples of the carbonate mineral were also added to the microbial growth-promoting solution. Four of the isolated microbes were identified in close homology to *Pseudomonas koreensis* (99%), *Shewanella algae and Shewanella chilikensis* (99%), *Sporosarcina pasteurii* (98%) and *Sphingobacterium* (97%). Studies performed this quarter showed that two isolates are ureolytic (Figure 1). Attempts to reculture the *Sphingobacterium* were unsuccessful.

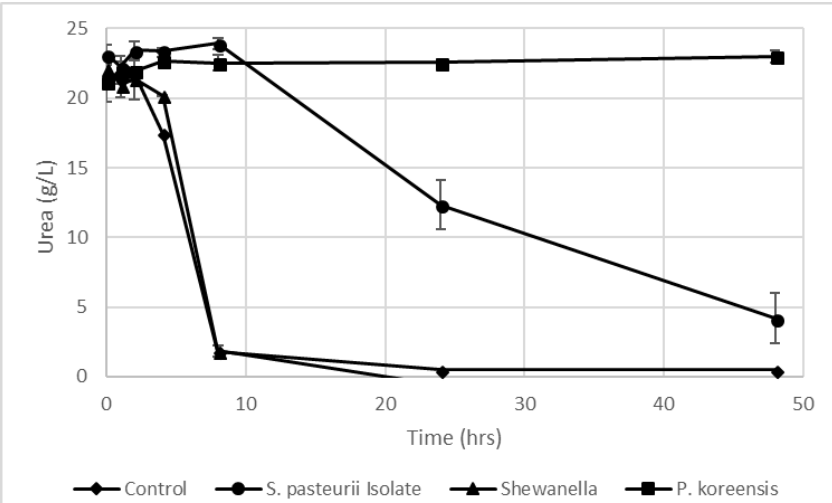


Figure 1. The *S. pasteurii* identified isolate and the *Shewanella* isolate reduced the urea concentration in the media to less than 5 g/L from 20 g/L in 24 hours. The *Psuedomonas* isolate did not hydrolyze any of the urea over the course of time-tested.

Additionally, DNA extraction and sequencing was performed on the community that grew up in the liquid growth solution and from the carbonate mineral itself (Figure 2).

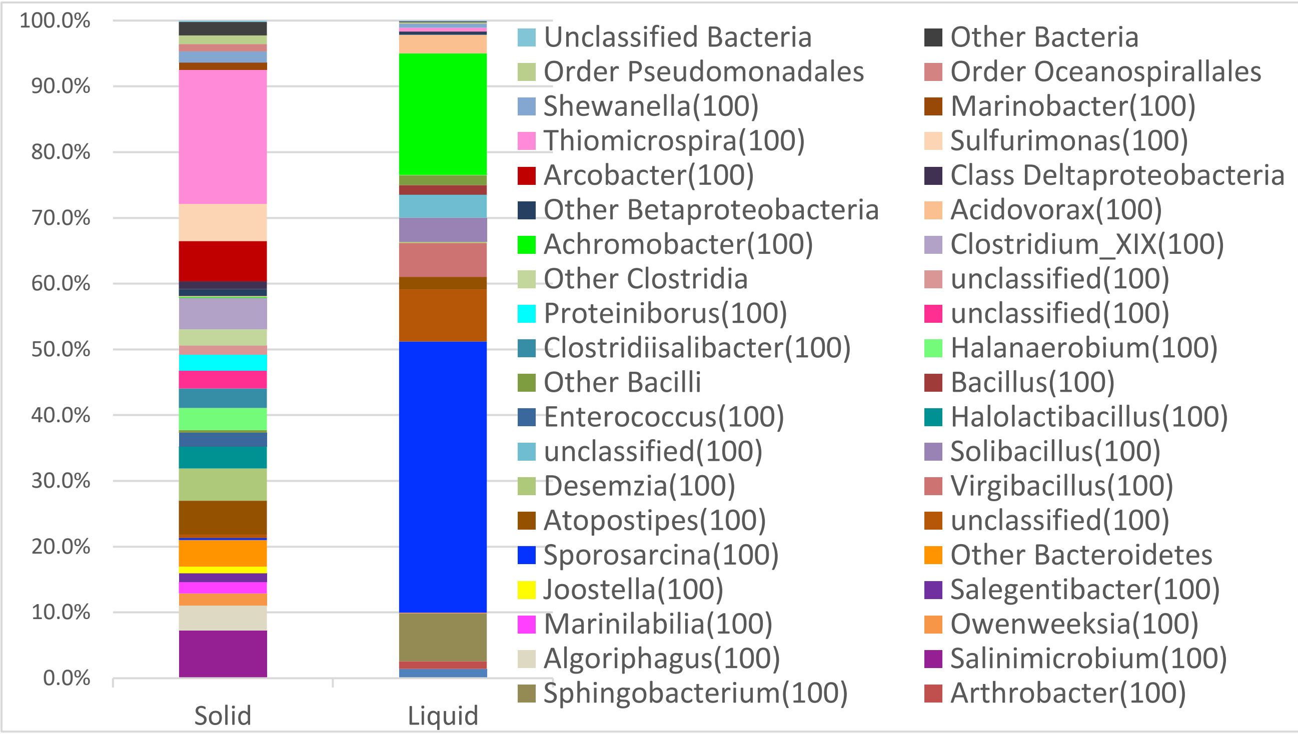


Figure 2. The microbial community extracted from the carbonate mineral itself resulted in a rich diversity with a small percentage (0.3%) of the population identified as *Sporosarcina*, the injected microorganism. In contrast, in the liquid sample that was enriched in the laboratory, *Sporsarcina* was dominant, making up 41% of the population.

The well was returned to injection on February 1, 2018. The results of oil production from the closest recovery well Rexing #3 were collected since the return to injection (Figure 3). The pressure at the injection well (Rexing #4) has varied between 500-750 psi between February 1-May 31.

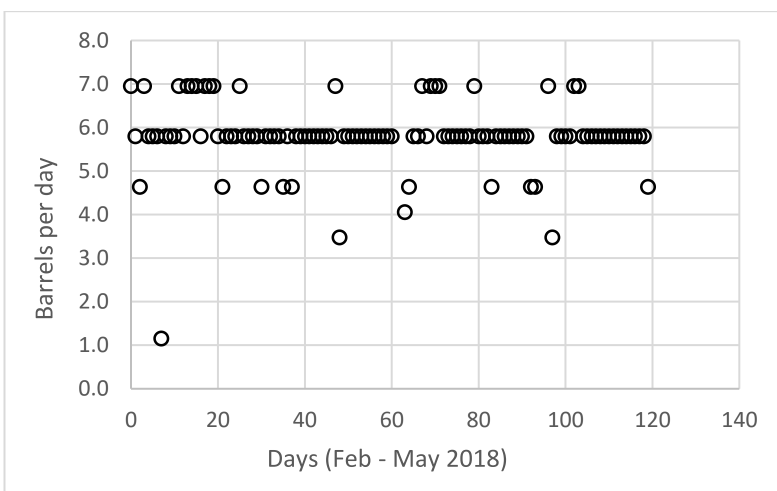


Figure 3. Injection of water has restarted in the Rexing #4 well, and produced fluids (oil and water) are being extracted from the Rexing #3 well. The average production of oil was 5.8 bbls/day from February 1 (day 0)-May 31 (day 119).

Mobile Mineralization Operations Center Development. As described previously, MET completed the construction and addition of shelves, desk space, and water system before the Mobile Mineralization Operations Center's (trailer) use in the Rexing #4 field experiment. During the experiment and continuing in this quarter, further modifications to the trailer were discussed. Potential modifications include built-in counter and storage space, a hopper-type system for handling dry chemicals, larger liquid storage tanks with integrated mixing and aeration systems, and an improved ventilation system. During this quarter, we continued to revise the ideas and MET prepared a new conceptual drawing showing potential modifications to the interior of the trailer (Figure 4). MSU and MET continue to discuss the modifications. Purchases of the tanks, control equipment, hot water system, and venting system are underway.

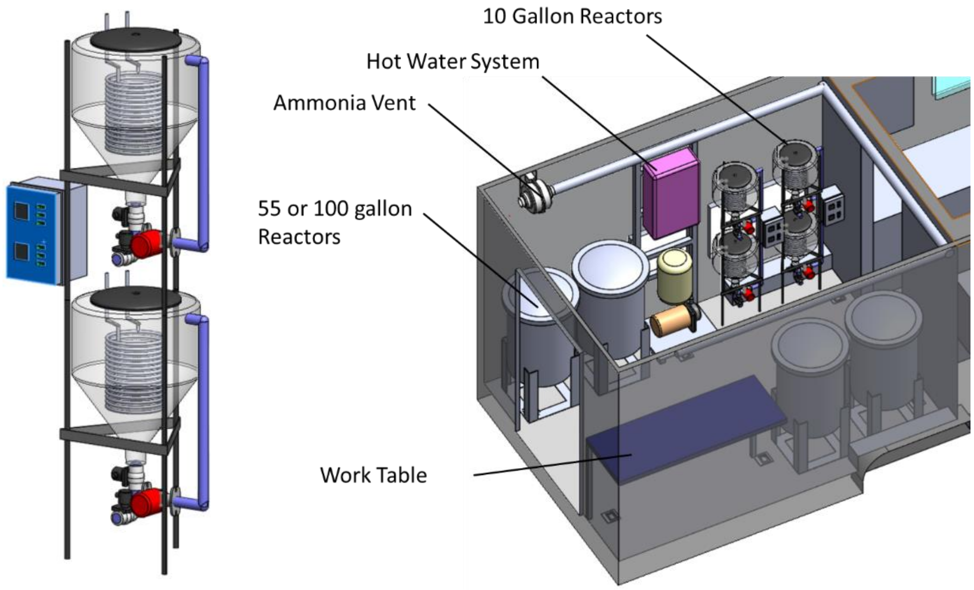
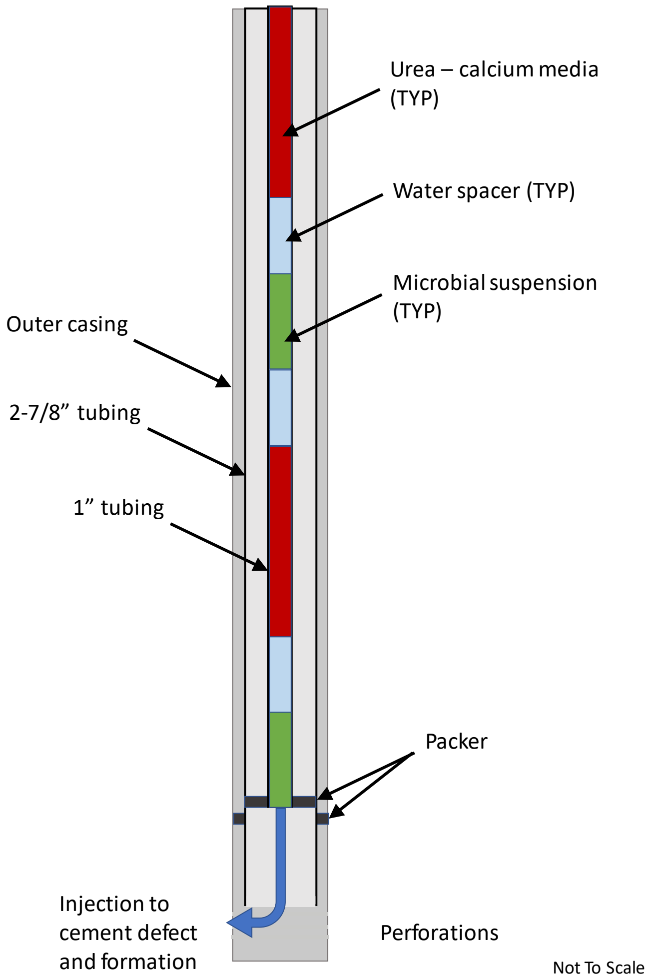


Figure 4. Left, the design of growth tanks with heating coils and valved mixing systems. Right, a conceptual model of the back of the trailer to cultivate large inoculum batches and mix calcium medium for injection.

Rexing #4 Scale-Up Field Experiment. A continuous injection strategy is proposed for the second MICP field demonstration at the Rexing #4 well near Cynthiana, IN. Rather than using a fixed-volume slickline dump bailer to deliver fluids downhole in a pulse fashion, the MICP-promoting fluids will be pumped directly down the tubing string. A conceptual delivery model would be to inject a volume of microbes (approximately twelve gallons (45L)), followed by urea-calcium media (approximately 24 gallons (91L)), followed by 12 gallons (45L) of microbes, and so on. Water spacers of approximately 10 gallons could separate the two fluid types (Figure 1). This method will allow for delivery of larger volumes of the MICP-promoting fluids in a shorter time.



There are several challenges with this method, however. First, the pace of pumping will require hundreds of gallons of microbes to be available for injection daily at sufficient cell concentration to promote mineralization. Second, proper hydraulic conditions must be maintained to minimize fluid mixing and mineral precipitation within the injection tubing. Finally, most MICP studies conducted to date in our lab have used a pulse flow strategy to promote homogeneous mineral precipitation. Continuous injection of cells and reactants may result in a different pattern of mineral precipitation within the thief zone formation and cement defect than was previously observed in the lab. Each of these challenges will be addressed by ongoing laboratory work and by developing a final plan to go to the field.

Figure 5. Schematic of Rexing #4 well with spotted fluids for continuous injection of MICP-promoting fluids.

Opportunities for training and professional development

Ryanne Daily, a graduate student on the project, Catherine Kirkland, an assistant research professor on the project, Adrienne (Adie) Phillips (PI) and Robin Gerlach (Co-PI) attended the Subsurface Biotechnology Workshop from June 5-7, 2018. The host for the workshop and sponsor for the travel of the MSU team was the Interdisciplinary Centre for Environmental Microbiology at Aberystwyth University in Wales, UK. Several presentations were given and are listed in the "Products" section below.

Catherine Kirkland, Robin Gerlach, Adie Phillips, and Al Cunningham traveled to New Orleans, Louisiana to attend the 10th International Conference on Porous Media (Interpore) May 14-17, 2018. Several presentations were given and are listed in the "Products" section below. Al, Robin, and Adie also chaired sessions at this conference with US and international collaborators.

Disseminating results to communities of interest

Two manuscripts are in preparation:

1. Kirkland, C, Thane, A, Cunningham, A, Gerlach, R, Hiebert, R, Kirksey, J, Spangler, L, Phillips, AJ. Permeability modification using Microbially-Induced Calcite Precipitation (MICP) to enhance wellbore integrity: a field demonstration *(In preparation).*

2. Kirkland, C, Norton, D#, Firth, O#, Gerlach, R, and Phillips, AJ. Applying X-ray µ-CT to enhance MICP for cement fracture leakage mitigation. (*In preparation*).

One manuscript has been submitted, revised and is awaiting a final decision from the editor:

1. 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 revision for* the Journal of Petroleum Science and Engineering*).*

<u>Presentation(s)</u>

Catherine Kirkland**,** Abby Thane, Robin Gerlach, Randy Hiebert, Robert Hyatt, Jim Kirksey, Al Cunningham, Lee Spangler, Adrienne Phillips, "MICP in the Field: Enhancement of wellbore cement integrity and permeability modification. MS 4.05: Biochemical mineral precipitation for subsurface applications. 10th International Conference on Porous Media (Interpore) May 14-17, 2018.

Adrienne Phillips, Robin Gerlach, Al Cunningham, Lee Spangler, Ellen Lauchnor, Randy Hiebert, Catherine Kirkland, Abby Thane, Lee Spangler, "Mineral precipitation in engineering applications" Subsurface Biotechnology Workshop, Interdisciplinary Centre for Environmental Microbiology at Aberystwyth University in Wales, UK, June 5-7, 2018.

Robin Gerlach, Adrienne Phillips, Al Cunningham, Catherine Kirkland, Randy Hiebert, Lee Spangler, "Biocementation as an Advanced Well Remediation Technology – Technology Development from the Microscale to the Field-Scale" Subsurface Biotechnology Workshop, Interdisciplinary Centre for Environmental Microbiology at Aberystwyth University in Wales, UK, June 5-7, 2018.

Catherine Kirkland, Randy Hiebert, Robert Hyatt, Jim Kirksey, Robin Gerlach, Al Cunningham, Lee Spangler, Adrienne Phillips, "MICP in the Field: Enhancement of Wellbore Cement Integrity and Permeability Modification" Subsurface Biotechnology Workshop, Interdisciplinary Centre for Environmental Microbiology at Aberystwyth University in Wales, UK, June 5-7, 2018.

Ryanne Daily, Linn Thrane, Robin Gerlach, Sarah Codd, Adrienne Phillips, "Biomineralization at High Pressures" Subsurface Biotechnology Workshop, Interdisciplinary Centre for Environmental Microbiology at Aberystwyth University in Wales, UK, June 5-7, 2018.

<u>Interpore Session Chairs</u>

Al Cunningham, GS 3: Experimental achievements (organizer); MS 4.05: Biochemical mineral precipitation for subsurface applications (co-organizer); MS 4.09: Biofilm processes in porous media (co-organizer).

Robin Gerlach, MS 4.03: Applications of biochemical modification of porous media (co-organizer); MS 4.05: Biochemical mineral precipitation for subsurface applications (co-organizer); MS 4.09: Biofilm processes in porous media (co-organizer).

Adrienne Phillips, MS 4.05: Biochemical mineral precipitation for subsurface applications (co-organizer); MS 4.09: Biofilm processes in porous media (organizer).

Poster presentations:
Robin Gerlach, Adrienne Phillips, Al Cunningham, Randy Hiebert "Overview of experimental systems and approaches supporting in situ mineral precipitation research," 10th International Conference on Porous Media (Interpore) May 14-17, 2018, New Orleans, Louisiana.

Drew Norton, Catherine Kirkland, Joe Eldring, Al Cunningham, Robin Gerlach, Lee Spangler, and Adrienne Phillips "Visualizing and quantifying biomineralization in a wellbore analog reactor." 10th International Conference on Porous Media (Interpore) May 14-17, 2018, New Orleans, Louisiana.

Anna Martinson, Dicle Beser, Damon Fick, and Adrienne Phillips. "Effect of MICP and EICP Additives on the Mechanical Strength of Concrete", MSU Student Research Celebration, April 18, 2018 Bozeman, Montana.

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

Planned activities during the next reporting period
We continue to work on methods to cultivate increased volume of inoculum and plan additional build-out of the mobile operations center. We are preparing publications related to this work and plan to submit this quarter.

Products
No activity to report.

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 assisted in evaluating the results from 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 mineralization operations center, and the additional scope planning. MET participated at a very high level at the Rexing #4 field test, is contributing to the analysis of the field test results, planning the trailer build out, and planning the additional fieldwork.

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 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 was integrated with previous laboratory and field research. This model was successfully used to design the Gorgas field test in April 2016 and was also used to model the injection strategy that was 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.

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

- N/A

CHANGES/PROBLEMS

As of this reporting period, there are no problems to report.

SPECIAL REPORTING REQUIREMENTS

At this time there are no special reporting requirements.

BUDGETARY INFORMATION

Table 2. Cost Plan Status

Baseline Reporting Quarter	YEAR 1 Start:	10/1/2014	End:	9/30/2015	YEAR 1 Start:	10/1/2015	End:	9/30/2016	YEAR 2 Start:	10/1/2016	End:	9/30/2017	YEAR 3 Start: 10/1/2017		END:9/30/2018		Total
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	
Baseline Cost Plan (from SF424A)																	
Federal Share	163,575	163,575	163,575	163,575					110,921	110,921	110,921	110,921	100,000	211,266	155,633	155,632	1,720,515
																	-
Non-Federal Share	31,739	31,739	31,739	31,739					34,271	34,271	34,271	34,271	41,633	41,633	41,633	41,632	430,571
																	-
Total Planned Shares	195,314	195,314	195,314	195,314	-	-	-	-	145,192	145,192	145,192	145,192	141,633	252,899	197,266	197,264	2,151,086
																	-
Cumulative Shares	195,314	390,628	585,942	781,256					926,448	1,071,640	1,216,832	1,362,024	1,503,657	1,756,556	1,953,822	2,151,086	2,151,086
Actual Incurred Costs																	
Federal Share	6,268	19,082	30,237	53,029	83,125	165,886	200,454	48,527	127,979	94,391	61,164	101,608	90,994	309,435	76,500		1,468,679
																	-
Non-Federal Share			53,559	51,624	-	12,527	16,622	11,029	41,339	22,843	52,808	37,264	20,900	49,720	7,880		378,115
																	-
Total Incurred Costs	6,268	19,082	83,796	104,652	83,125	178,413	217,076	59,556	169,318	117,234	113,973	138,872	111,894	359,155	84,380		1,846,794
																	-
Cumulative Incurred Costs	6,268	25,350	109,146	213,798	296,923	475,336	692,412	751,968	921,286	1,038,520	1,152,493	1,291,365	1,403,259	1,762,414	1,846,794		1,846,794
Variance																	
Federal Share	157,307	144,493	133,338	110,546	(83,125)	(165,886)	(200,454)	(48,527)	(17,058)	16,530	49,757	9,313	9,006	(98,169)	79,133		251,836
														-	-		-
Non-Federal Share	31,739	31,739	(21,820)	(19,885)	-	(12,527)	(16,622)	(11,029)	(7,068)	11,428	(18,537)	(2,993)	20,733	(8,087)	33,753		52,456
														-	-		-
Total Variance	189,046	176,232	111,518	90,662	(83,125)	(178,413)	(217,076)	(59,556)	(24,126)	27,958	31,219	6,320	29,739	(106,256)	112,886		304,292
Cumulative Variance	189,046	365,278	476,796	567,458	484,333	305,920	88,844	29,288	5,162	33,120	64,339	70,659	100,398	(5,858)	107,028		304,292
	12/31/2014	3/31/2015	6/30/2015	9/30/2015	12/31/2015	3/31/2016	6/30/2016	9/30/2016	12/31/2016	3/31/2017	6/30/2017	9/30/2017	12/31/2017	3/31/2018	6/30/2018		

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