Oil & Natural Gas Technology

DOE Award No.: DE-FE0024296

Quarterly Research Performance Progress Report

(Period ending: 3/31/18)

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

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

Submitted by:
Adrienne Phillips

Adrienne Phillips

Digitally signed by Adrienne Phillips
DN: cn=Adrienne Phillips, o=Montana State University, ou=Energy Research Institute, email=adrienne.phillips@biofilm.montana.edu, c=US
Date: 2018.05.02 13:21:02 -06'00'

Montana State University
DUN's Number: 625447982
Energy Research Institute
P.O. Box 172465
Bozeman, MT 59717-2465
adrienne.phillips@biofilm.montana.edu
(406) 994-2119

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

May 2, 2018

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 being 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 at 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. This table does not yet include the extension of the project to 2019 or the additional scope (added tasks) to the project that were granted in April 2018. The table will be modified in the next quarterly report.

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, 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). The subjects of these meetings have been: 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. A request for an extension with additional scope (Tasks) to the project was made this quarter and was approved in April which will be discussed in the next quarterly report. This request was made to develop the technology further and potentially advance the technology readiness level.

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 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

As described in the previous quarterly report, a lab-scale reactor 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 where media solutions were diluted and pumped into the system to model the wellbore injection methods applied in the field to represent the Rexing #4 field conditions. Ten pulses of *Sporosarcina pasteurii* inoculum and 19 pulses of calcium medium created conditions that resulted in the injection pressure exceeding system limits, where the ratio of flow to pressure was observed to decrease two orders of magnitude over the four days of the experiment. It appeared that much of the mineral formation occurred in the higher permeability sand, the model for the thief zone sandstone formation at the Rexing #4 well. The laboratory efforts mimicked the design of the Rexing #4 well field injection strategy where it was planned to use pulsed injection with a bailer delivery method.

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 cement associated with the wellbore. 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 had decreased from 10.4×10^{-3} gpm/psi to 3×10^{-3} gpm/psi, a reduction of approximately 70%. In addition, the temperature logging results indicated that less of the injected cold water was traveling up the channel after MICP sealing. This suggests that MICP treatment indeed sealed or partially sealed the leakage pathway.

When the tubing was pulled from the well it was observed that a buildup of biomineral formed which was scraped and sent to MSU for analysis. The observation of this build-up suggests that calcite precipitation can be promoted under these field conditions including in the presence of oil. The analysis performed at MSU included microscopy, culturing, and identification of isolated microbes. Confocal microscope stacks of images were combined using the Imaris software to produce the combined 3D reflection and fluorescent confocal image of the Rexing pup joint mineral material (Figure 1). The green flecks are presumed to be bacteria on the solid mineral phase material, as they were stained with Sybr-green, a nucleic acid stain.

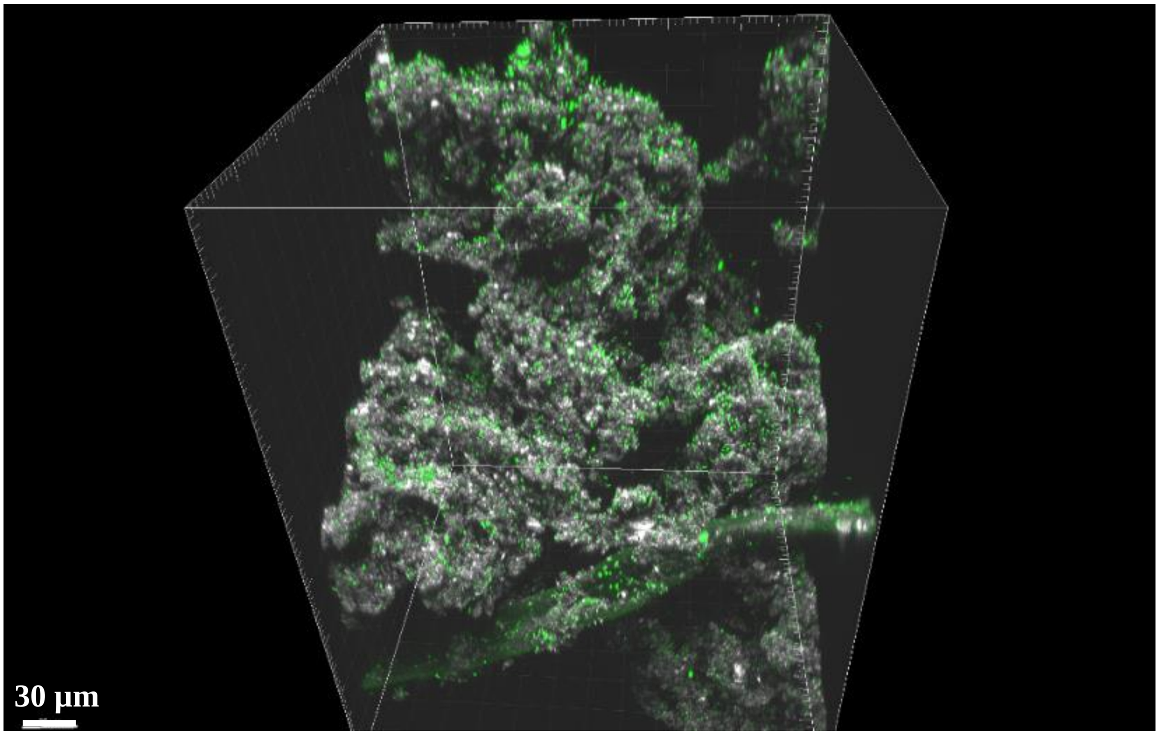

Figure 1. Volume rendered image from the confocal microscope shows nucleic acids/bacteria in green (FITC) in association with mineral precipitation. Scale bar is 30 µm. Image by Sobia Anjum, image analysis by Betsey Pitts.

Samples of the carbonate mineral were also added to the microbial growth-promoting solution. Cultures were allowed to grow until the solution was cloudy, an indication of microbial growth. The cloudy cultures were then plated and unique colony morphologies were streaked to isolation. DNA was extracted from the isolated colony types and sequenced. Sample number 1 and 4 failed to amplify but the other isolates were sequenced and were identified with close homology to the following organisms:

- Sample 2: Pseudomonas koreensis 99%
- Sample 3: Shewanella algae and Shewanella chilikensis 99%
- Sample 5: Sporosarcina pasteurii 98%
- Sample 6: Sphingobacterium 97%

Work is ongoing to determine whether the isolates are ureolytic and adapted to grow in oil/water mixtures. Additionally, DNA extraction and sequencing was performed on the community that grew up in the growth solution and from the carbonate mineral itself. Results of the sequencing and community analysis are currently being analyzed.

The well was returned to injection on February 1, 2018. Preliminary results of oil production from the closest recovery well Rexing #3 are shown in Figure 2. The pressure at the injection well (Rexing #4) has varied between 500-650 psi between February 1-March 31. Additional time is required to determine if significant improvements will be made. Also, additional information is required to determine how this compares to the pre-channel production data and how much oil compared to water was produced. This data has been requested.

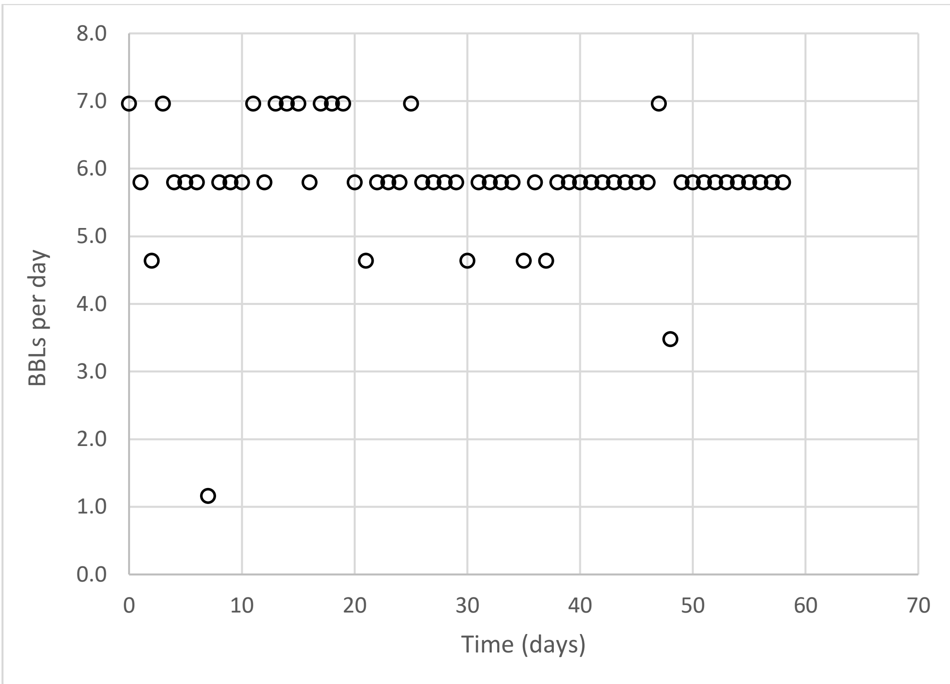

Figure 2. Injection of water has restarted in the Rexing #4 well and produced fluids (oil and water) are being extracted from the Rexing #3 well. The average production of oil was 5.7 bbls/day from February 1(day 0)-March 31 (day 58).

Mobile Mineralization Operations Center Development

As described previously, MET completed the construction and addition of shelves, desk space, and water system prior to the Mobile Mineralization Operations Center's (trailer) use in the Rexing #4 field experiment. The trailer was mobilized to Indiana in November 2017 and was successfully used for the field experiment performed at the Rexing #4 well. The Rexing #4 experiment was the first time MSU's new DOE-funded mobile laboratory was used for a field demonstration of MICP. The trailer assisted in the efficiency of injections by making cultivation more efficient with the ability to heat the cultures to the optimal temperature for microbial growth. During the experiment and continuing in this quarter, further modifications to the space were discussed. Potential modifications include built-in counter and storage space, a hopper-type system for handling of dry chemicals, larger liquid storage tanks with integrated mixing and aeration systems, and an improved ventilation system. MET has prepared a conceptual drawing showing potential modifications to the interior of the trailer (Figure 3). MSU and MET continue to discuss the modifications and Figure 3 displays a preliminary idea.

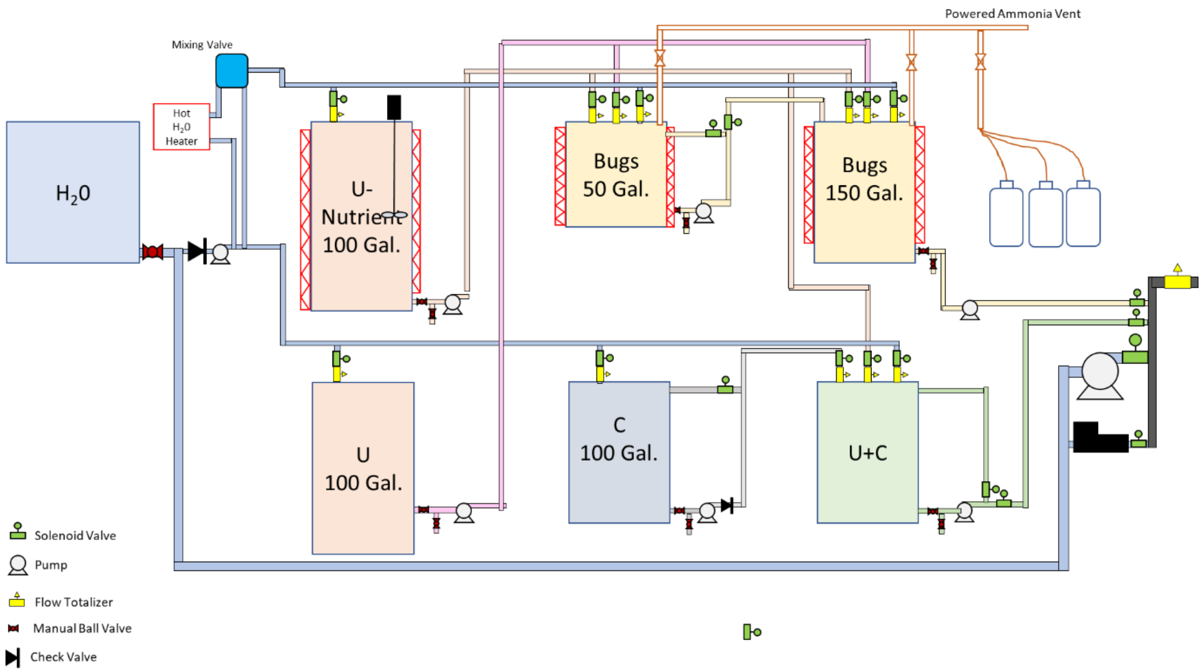

Figure 3. A conceptual model to cultivate large inoculum batches and mix calcium medium for injection in the operations room of the trailer.

Opportunities for training and professional development
No activity to report.

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

Presentation(s)
Phillips A., Morasko, V., Daily, R., Frieling, Z., Kirkland, C., Gerlach, R., Cunningham, A., and Spangler, L. 2018, Urease: a journey from laboratory to field, Montana State University, Center for Biofilm Engineering Weekly Seminar Series, Bozeman, MT, February 15, 2018.

Gerlach, R. 2018, Controlling Stone-Producing Microbes – The Good Ones and the Evil Ones, Montana State University 125th Anniversary, Faculty Symposium. Montana State University-Bozeman. February 17, 2018.

Planned activities during the next reporting period
We plan to specifically define the scope and milestones for the additional planned laboratory and fieldwork. We also plan to start determining how best 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 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 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. In addition, the success of the experiment has been disseminated through news articles to increase the audience awareness of the technology. A news article was published by Montana State University dated January 18, 2018, about the mobile laboratory and the recent field test: “MSU field tests push well-sealing technology closer to commercial application” http://www.montana.edu/news/17399.

Dollar amount of award budget spent in foreign country(ies)
Total dollars spent in foreign countries was $2,048.73 this quarter.

- Al Cunningham traveled to Stuttgart, Germany February 5 through 11, 2018, for collaborations with Johannes Hommel at the University of Stuttgart. The travel costs were shared with other funding sources and $898.73 was charged to this project.
- InterPore 10th Annual Meeting registration fees were paid in US dollars for Catherine Kirkland and Adrienne Phillips for a total of $1,150.
- InterPore 10th Annual Meeting registration fee was paid in Euros for Al Cunningham in the amount $683.86.

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			1,392,179
																	-
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			370,235
																	-
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			1,762,414
																	-
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			1,762,414
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)			328,336
														-			-
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)			60,336
														-			-
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)			388,672
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)			388,672
	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			

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, Suite 225
Sugarland, TX 77478

1450 Queen Avenue SW
Albany, OR 97321-2198

2175 University Ave. South
Suite 201
Fairbanks, AK 99709

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