Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report

(Period ending: 12/31/2016)

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

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

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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 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 located near the underground coal seam at an as of yet undetermined location.

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, ultrasonic imaging tool (USIT) logging to assess the cement bond log, 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 USIT data in the targeted biomineralization regions, and demonstration of MICP byproducts ($CaCO_3$) in the treated regions on side wall cores.

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	3/31/2015	NA	Quarterly Report

		sealing in annular spaces representative of field conditions.			
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 have been conducted including 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: analysis of the first field test results, development of the mobile operations center, and planning of the second field test. A milestone report for completed milestone #5 was submitted April 3, 2017. This milestone reported: *"The results from the MICP field test performed in April 2016 have been analyzed and the following conclusions made: (1) injectivity was highly reduced; (2) a substantial deposition of precipitated solids along the cement wellbore flow channel was observed; and (3) the sealing in the cement channel created conditions that allowed for the well to meet a definition of mechanical integrity for shut in wells. These results have led the research team to develop injection strategies for the second field demonstration which is being planned."*

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.

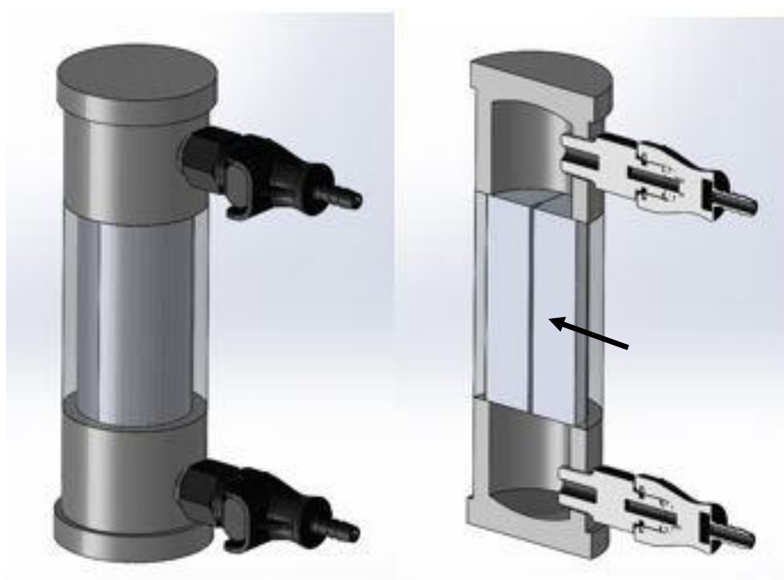
After Schlumberger analysts reviewed the cement bond logs collected prior to MICP treatment and after, it was noted the significant improvement to the cement quality was observed in the MICP treated region. Also, in November 2016, Jim Kirksey mobilized to the site to perform side wall coring and an injection test. Cores retrieved during sidewall coring from 1004 ft below ground surface was observed to have auto-fluorescent mineral on the formation side of the steel disk. Calcium carbonate that is the product of MICP can be auto-fluorescent suggesting that MICP material may be observed attached in a channel behind the casing. 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

Reactor System and Experimental Design

A new reactor system has been designed at Montana State University to measure and visualize the formation of microbially induced calcium carbonate precipitation (MICP) within a channel engineered in a cement core (Figure 1). The PVC reactor and core system was designed to be X-Ray Computed Tomography (X-Ray CT) compatible to monitor the distribution of mineral and subsequent reduction in porosity along the flow path of the channel as MICP forms.

Figure 1: Rendering of the new reactor used for examining the spatial and temporal formation of MICP in channel or fracture porous medium defects. The channel (arrow) was designed with dimensions 50 x 6.35 x 0.5 mm (length, width and aperture respectively).



An experiment was performed to analyze spatially and temporally the permeability and porosity reduction due to MICP in the channel in the cement. MICP promoting solutions were pulsed into the channel with batch periods of no flow in between injections. The injections were performed over ten days. Once per day, the channel porosity was observed by scanning the core with a Bruker Skyscan 1172 X-Ray CT instrument. The apparent permeability of the channel was calculated using Cubic's law for flow through a fracture from the pressure and flow rate measurements that were collected throughout the experiment.

Permeability Reduction

It was observed that the permeability decreased more than four orders of magnitude over the course of the experiment as MICP promoting fluids (calcium pulses) were injected into the channel (Figure 2). As the experiment progressed, the permeability decreased only approximately one order of magnitude until calcium pulse #21 which occurred on day seven. At that point, the permeability decreased more significantly (3.6 orders of magnitude) until the pressure limitations of the system were reached and the experiment was terminated.

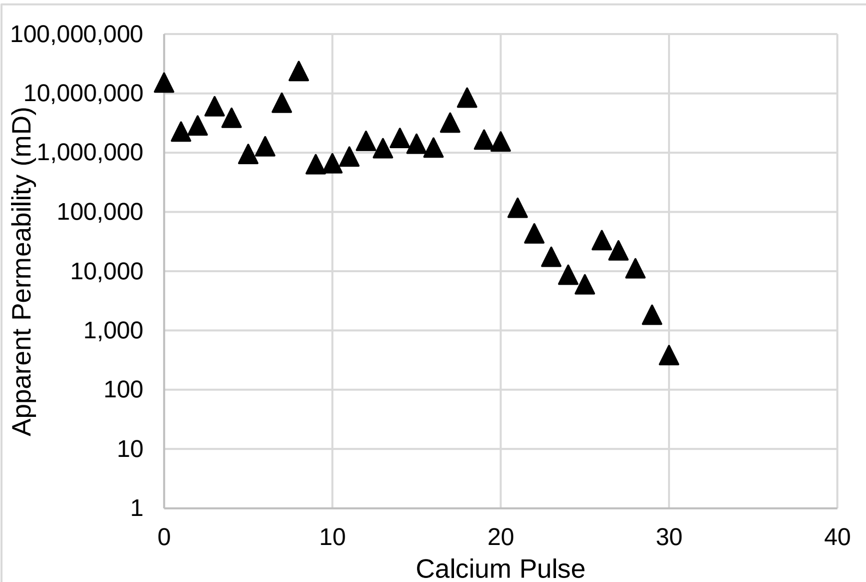


Figure 2: Apparent permeability of the channel decreased over the course of the experiment. It was observed that after calcium pulse #21, the permeability decreased more significantly until termination of the experiment.

Previous experiments have shown similar trends of a period of little to no permeability reduction prior to a relatively rapid decrease in permeability, ultimately leading to an inability to inject additional fluids. One hypothesis to explain this behavior was there may be a critical permeability (k_{crit}) which may be correlated to a critical porosity where MICP treatment can more easily impact the permeability reduction.

Porosity Reduction

From the X-Ray CT scans, a 2D series (stacks) of projection images were produced from the measured signal attenuated through the reactor and cement core. The data was reconstructed in NRecon and analyzed by means of CTAn (Bruker software). First, the data was pre-processed to remove noise, then a rectangular region of interest 9mm x 2mm was drawn around the channel region and a new data set was saved. The images from this data set were then binarized to distinguish solid (cement and MICP) vs open (fluids in the channel) based upon the individual attenuation of each voxel. The binarization threshold was determined from scans of the reactor prior to MICP treated (Day 0) to match the calculated pore space of the core. This threshold then applied to the data sets produced from scans on all subsequent days of the experiment. Finally, the images (2D) were stacked together to form a 3D reconstruction of the reactor (Figure 3). The reconstructions of the channel can be created for each day and compared side by side. This allows visualization of the MICP formation within the reactor over the course of the multiple day experiments.

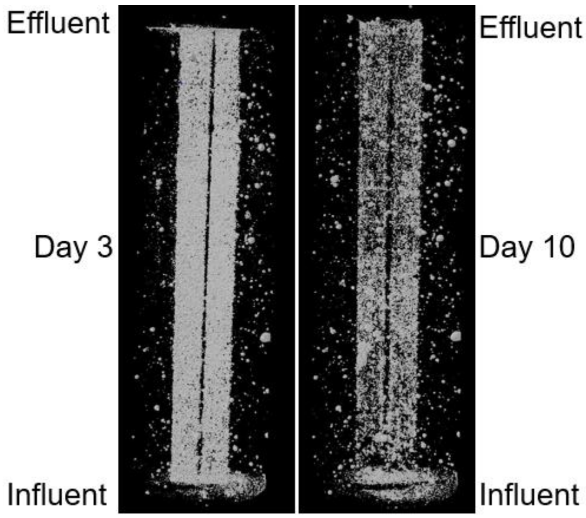


Figure 3: Preliminary 3D reconstructions of the channel from the cement core reactor system.

It was observed that the total 3D porosity (calculated as a % of open pore space within the region of interest) decreased 23% over the course of the experiment. For better understanding of where this porosity reduction occurred, spatially resolved analysis was performed by plotting the 2D slice porosity distance from the inlet of the channel defect. From this analysis, the observation was made that the most significant porosity reduction occurred in the first 10 mm (inlet region) resulting in a non-uniform distribution of MICP along the flow path of the channel (Figure 4).

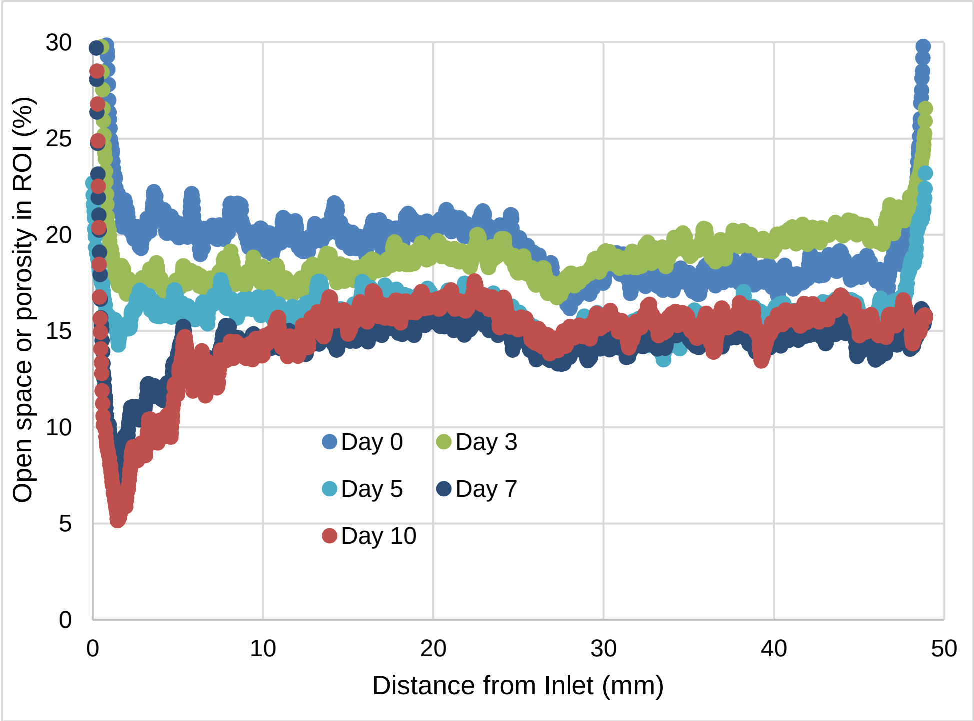


Figure 4: Porosity vs. distance from the channel inlet (0mm = inlet). The general trend in porosity was an overall decrease over the course of the experiment (day 0, blue higher overall porosity vs day 10, orange lower overall porosity). More porosity reduction was observed in the inlet region(first 10 mm).

This new reactor has shown capability to further MICP research, providing a better understanding of the seal formation in engineered cement channel or fractures. The use of X-Ray CT allows not only for the visualization of MICP formation but also to provide quantitative data of seal formation in time and space. X-Ray CT scanning has provided a non-destructive method for imaging the physical changes due to MICP in cores and estimating porosity along the length of the flow path in the channel. Further experiments using this reactor system can improve the understanding of how MICP can be used to modify channel or fracture porosity and the resulting permeability.

Mobile Mineralization Operations Center Development

MET, MSU, and Jim Kirksey of Loudon Technical Services 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).

<u>Layout and specific equipment needed</u>

The final specification for the Mobile Mineralization Operations Center was completed, released for competitive bid and is currently under construction (Figure 5). The front of the trailer houses the operations and control center, the middle is the laboratory, and the back is the fluid handling section housed in a 28 ft long, 8.5 ft wide, 8 ft tall cargo trailer.

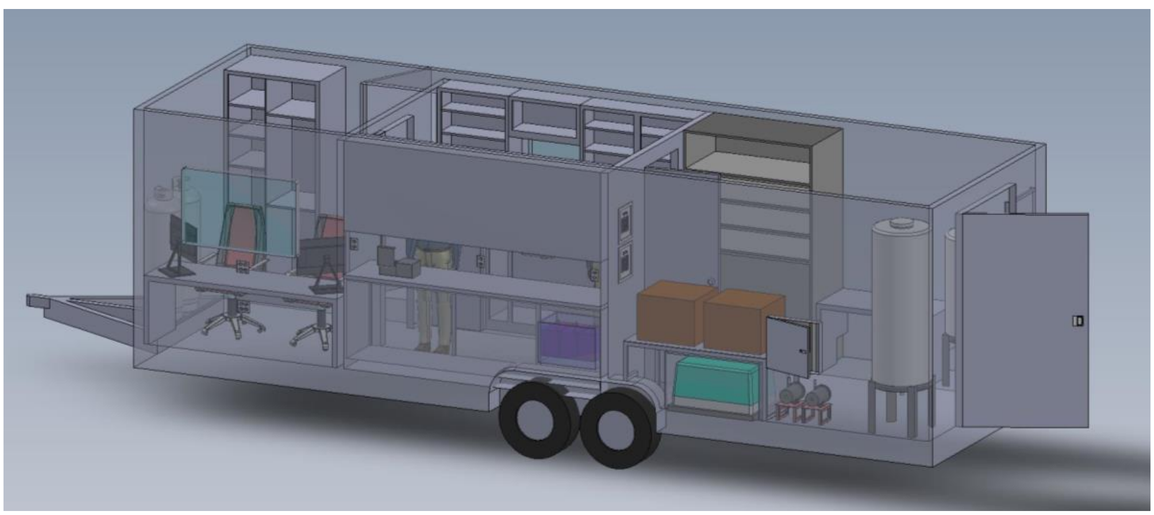


Figure 5. Schematic of design ideas for the development of a mobile operations center.

The competitive bid process terminated the third week in January 2017. The purchase order from MSU to Becker Custom Trailer was executed on February 16, 2017. The trailer manufacturer has estimated delivery of mid May 2017. MSU and MET will then add additional equipment, install pumps and tanks, and plan to have the trailer completed prior to the end of the next quarter.

Opportunities for training and professional development

No opportunities for professional development occurred in this quarter.

Disseminating results to communities of interest

A press release was launched on the homepage for the Center for Biofilm Engineering which describes the results of the April 2016 MICP field demonstration at Gorgas. http://www.biofilm.montana.edu/news/2016/06/msu-team-reaches-milestone-toward-commercialization-fracture-sealing-process.html. This press release was picked up by the Montana State University News service and the Bozeman Daily Chronicle for further dissemination. (http://www.montana.edu/news/16313/msu-team-shows-biofilm-and-mineral-producing-bacteria-have-potential-for-plugging-oil-and-gas-leaks), and (http://www.bozemandailychronicle.com/news/montana_state_university/msu-research-shows-bacteria-could-plug-oil-and-gas-leaks/article_7d9bef62-08c9-5649-8e96-b24cf77592e9.html).

On March 3, 2017, Drew Norton a graduate student working on the project was selected as the Judges award winner for MSU's College of Engineering Three Minute Thesis competition. The Three Minute Thesis competition is a "super-condensed, science-based Pecha Kucha" style presentation where students explain the importance of their research to a general non-specialist audience. A news brief highlighting the event and an additional brief highlighting Drew's accomplishment presenting on how "bacteria can seal leaky wells" were published:
http://www.montana.edu/news/16750/three-minute-thesis-event-set-for-march-3-at-msu
http://www.biofilm.montana.edu/news/article.html?id=16768

Planned activities during the next reporting period

The major activity planned for next reporting period is to complete the manuscript started in the previous quarter highlighting the April 2016 field test. Work will continue on the construction of the mobile operations center. Additionally, we will continue discussions about the second field demonstration.

Products

No products were produced during this quarter.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Other organizations involved as partners

Schlumberger (SLB). SLB is providing matching support for this project. SLB field workers, led by Jim Kirksey, performed well logging and coring. During this reporting period, Jim Kirksey and others from SLB also participated in the November 2016 field work.

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) to be used for MICP field tests.

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.

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.

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)

Dr. Al Cunningham traveled to Stuttgart, Germany March 2017 for planning meetings regarding the reactive transport modeling with Rainir Helmig, Holger Class, and Johannes Hommel of the Institute for Modeling Hydraulic and Environmental Systems, University of Stuttgart. A total of $1,337.37 was spent for this trip/meeting.

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.

BUDGETARY INFORMATION

Table 2. Cost Plan Status

Baseline Reporting Quarter	YEAR 1 Start:	10/1/2014	End:	9/30/2015	YEAR 2 Start:	10/1/2015	End:	9/30/2016	YEAR 3 Start:	10/1/2016	End:	9/30/2017	Total
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
Baseline Cost Plan													
(from SF424A)													
Federal Share	163,575	163,575	163,575	163,575					110,921	110,921	110,921	110,921	1,097,984
													-
Non-Federal Share	31,739	31,739	31,739	31,739					34,271	34,271	34,271	34,271	264,040
													-
Total Planned Shares	195,314	195,314	195,314	195,314	-	-	-	-	145,192	145,192	145,192	145,192	1,362,024
													-
Cumulative Shares	195,314	390,628	585,942	781,256					926,448	1,071,640	1,216,832	1,362,024	1,362,024
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			828,977
													-
Non-Federal Share			53,559	51,624	-	12,527	16,622	11,029	41,339	22,843			209,542
													-
Total Incurred Costs	6,268	19,082	83,796	104,652	83,125	178,413	217,076	59,556	169,318	117,234			1,038,520
													-
Cumulative Incurred Costs	6,268	25,350	109,146	213,798	296,923	475,336	692,412	751,968	921,286	1,038,520			1,038,520
Variance													
Federal Share	157,307	144,493	133,338	110,546	(83,125)	(165,886)	(200,454)	(48,527)	(17,058)	16,530			47,165
													-
Non-Federal Share	31,739	31,739	(21,820)	(19,885)	-	(12,527)	(16,622)	(11,029)	(7,068)	11,428			(14,044)
													-
Total Variance	189,046	176,232	111,518	90,662	(83,125)	(178,413)	(217,076)	(59,556)	(24,126)	27,958			33,120
Cumulative Variance	189,046	365,278	476,796	567,458	484,333	305,920	88,844	29,288	5,162	33,120			33,120
	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	

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