Oil & Natural Gas Technology

DOE Award No.: DE-FE0024296

Quarterly Research Performance Progress Report

(Period Ending 9/30/2018)

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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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 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	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 and discuss the timing and details of the field work. 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 was accomplished by performing laboratory experiment tests to improve implementation strategies and modifying the mobile mineralization unit. We then performed a third wellbore cement remediation field test and currently are assessing 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 ultrasonic imaging tool (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 reduction 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 to include microbial community analysis and microscopy.

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 and made. Modifications included built-in counter and storage space, larger liquid storage tanks with integrated mixing and aeration systems, and an improved ventilation system. We used the MET prepared conceptual drawings to build out the interior of the trailer (Figure 1). MSU and MET purchased the tanks, control equipment, hot water system, and venting system which were installed right before the field experiment. Thus, milestone "Complete design and modifications to the mobile unit" was met.

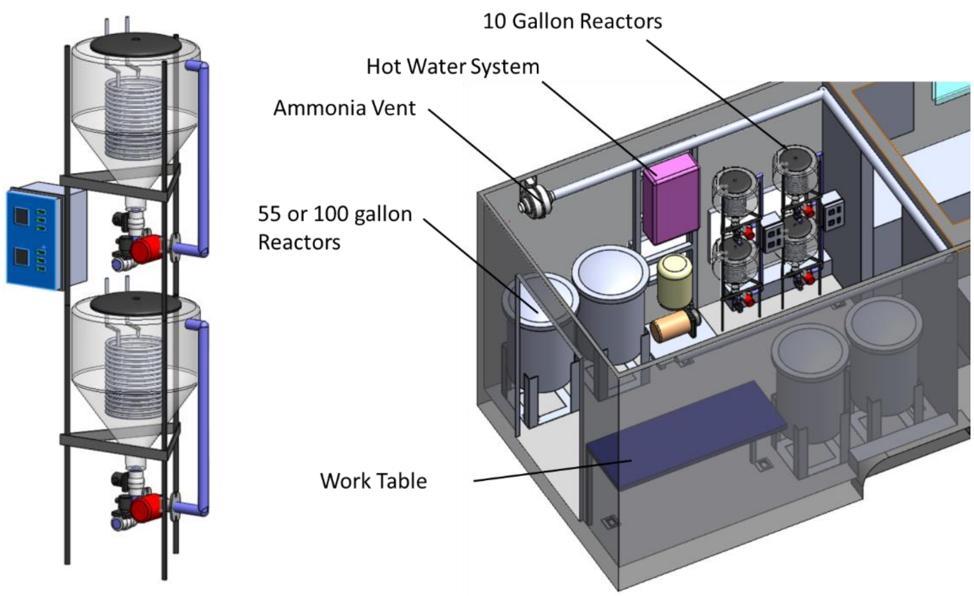


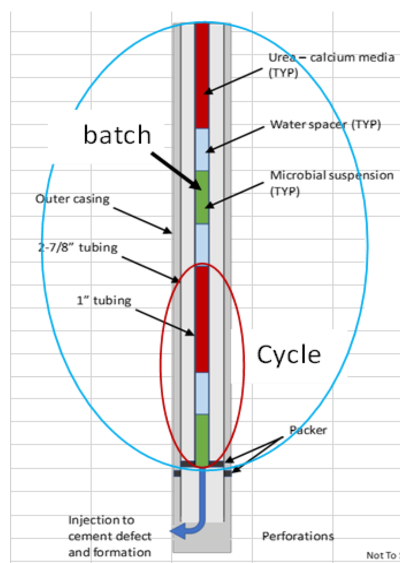
Figure 1. Left, the design of growth tanks with heating coils and valved mixing systems. Right, a conceptual model of the back of the trailer to cultivate large inoculum batches and mix calcium medium for injection.

Rexing #4 Scale-Up Field Experiment. Field work was conducted in September 2018 at the Rexing #4 injection well (Figure 2) where the MSU/MET/LTS team attempted to complete the repair of a suspected channel in the wellbore cement. The channel was hypothesized to allow injected fluids to be diverted from the desired oil-bearing formation into a thief zone of higher permeability sandstone approximately 30 feet above the target formation. Previous biomineralization treatment on the well in December 2017 had served to reduce the channel or thief zone permeability (based on results from the injection pressure and flow relationship (ending pressure 700 psi at 4 gpm) and the temperature logging profiles) and restore the well to service. Well owner, Mike Gallagher, indicated that the water level in a monitoring well had increased after the December 2017 treatment. Mike Gallagher also stated that the oil-bearing formation was "very tight" and "only accepts approximately 1 gpm with injection pressures around 1,400 psi", indicating that the December treatment might have only partially sealed the channel or reduced permeability in the thief zone. Thus, the goal of this experiment was to achieve this desired injection pressure and flow (1400 psi, ~1 gpm) relationship and completely seal the channel.

Figure 2. Field work was conducted at the Rexing #4 well head in September of 2018. A workover rig, the mobile laboratory, and a frac tank filled with 100bbl of fresh water were on site during the field work.

Since the volume of the channel leading to the thief zone was unknown and the thief zone appeared to be very porous, the team was prepared to inject increased volumes of biomineralization promoting solutions compared to the December test volumes injected. In the December 2017 field work, 95 gallons of microbes and 195 gallons of urea and calcium solution were injected. To accomplish the new project objectives of more complete sealing, larger volumes of solutions would be necessary. Thus, instead of bailer-based delivery as performed in December 2017, the biomineralization solutions were staged and injected down a one-inch concentric tubing string placed inside the 2 7/8'' tubing string with both strings isolated by a packer (Figure 3). To grow more cells and keep up with the increased volumes needed, the mobile laboratory was modified to include a scaled-up bioreactor growing system equipped with water heating, recirculation, aeration, and ventilation (Figure 4).

Figure 3. Biomineralization solutions were injected as follows: microbes (green), brine spacer (blue), urea/calcium (red), followed by another brine spacer. The cycle was repeated until the desired injection pressure-flow relationship was achieved.



Two methods of cell preparation were evaluated during the field test. First, cells that had been cultured and centrifuged in the laboratory at MSU were frozen and shipped to the well-site to be re-suspended on site (Figure 5). The cells were resuspended in a 55-gallon tank with 10 g/L ammonium chloride salt solution prior to injection downhole. The second method of cell preparation was to grow cells in the new bioreactor systems. Briefly, as pictured in Figure 6, 1L cultures were started from frozen stocks and were allowed to grow in a 30 °C incubator for 7-15 hours. These cultures were used to inoculate the 15-gallon bioreactors that were equipped with aeration, ventilation, recirculation, and heating. Additional growth occurred over 7-15 hours in the 15-gallon bioreactors before the cell suspensions were transferred to 55-gallon or 100-gallon storage tanks prior to downhole injection.

Figure 4. Bioreactor systems were designed to grow increased cell culture volumes. The bioreactors were equipped with re-circulation, aeration, heating, and ventilation.

Figure 5. Frozen cultures were stored in the freezer after shipment from MSU before resuspension in brine prior to injection.

Only moderate pressure increases were observed during the resuspended cells injection, so on the second day of the experiment freshly cultured cells grown in the new bioreactor system were used. An increase in pressure was observed over the course of the afternoon and during the third day of injection until the targeted pressure of close to 1400 psi at an injection flowrate of 1.5 gpm was achieved, and the experiment was determined to be successful. Figure 7 shows the flow-pressure ratio recorded during injection in both field demonstrations in the Rexing #4 well as a function of the volume of fluids injected. A lower value means that it is more difficult to inject fluids into the formation and suggests that flow paths are restricted. The flow-pressure ratio decreased slightly the first day of the September 2018 field project (between 1,240 and 2,530 cumulative gal injected). After the switch to fresh cells occurred (at 2530 cumulative gal injected), a steady decrease in the flow-pressure ratio was observed until the target injection pressure and flowrate were achieved. Over three days, a total of 269 gallons of frozen cell suspension, 156 gallons of fresh cell cultures, 955 gallons of urea+calcium media, 658 gallons of brine, and 156 gallons of fresh water were injected.

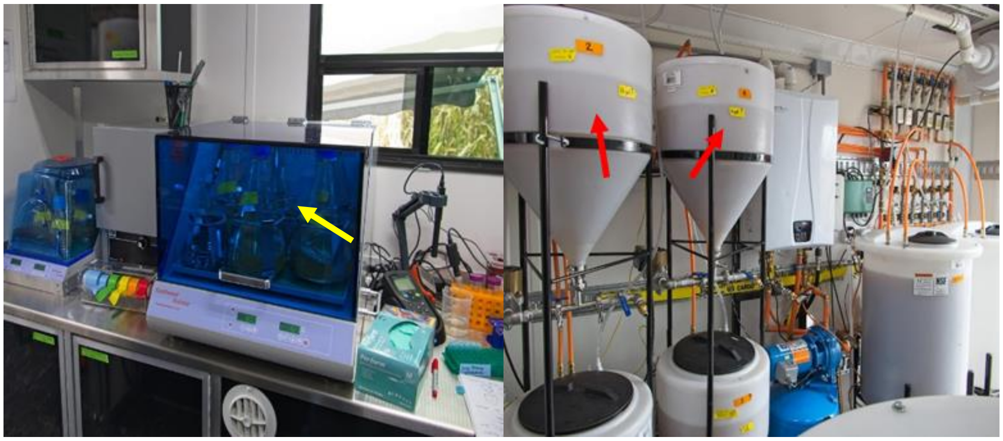


Figure 6. Left, 1L cultures were grown in a shaking incubator (yellow arrow), then transferred to 15-gallon bioreactors (red arrows), and finally transferred to 55- or 100-gallon bioreactors or storage tanks (purple arrow).

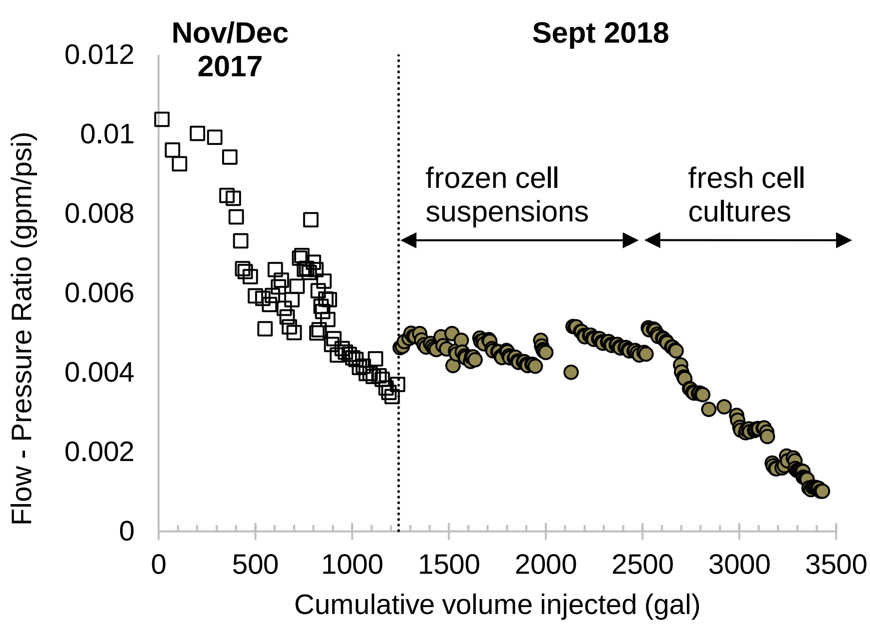


Figure 7. Moderate pressure increases but little change in the flow – pressure ratios were observed during frozen cell suspension injections. The flow-pressure ratio decreased significantly during the injection of the freshly cultured cells followed by urea-calcium solutions.

After the desired pressure flow relationship was achieved, the injection tubing was pulled from the well and (likely) biomineral was observed on the tubing, which was located below the packer (Figure 8). A sample was collected and shipped back to MSU for additional analysis. This result is similar to the observed mineral formed on the tubing during the December experiment. During the September 2018 test a float valve was placed in the 2 7/8'' tubing to prevent any backflow so the presence of biomineralization on the outside of the tubing below the packer might indicate that a hole in the casing exists near the thief zone. The temperature logs ran in December did not suggest this but the presence of the biomineralization raises the question. If a hole in the casing was present it is now likely sealed along with the channel behind the casing. Monitoring the production well and oil recovery is ongoing.

Figure 8. Mineral was observed to be attached to the tubing string that was located in the region of injection (red arrow).

Opportunities for training and professional development
N/A

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. O., Firth, O., Gerlach, R, and Phillips, AJ. Visualizing MICP with X-ray µ-CT to enhance cement defect sealing. *Energy and Fuels* (*submitted*).

One manuscript has been published:

1. Phillips, A. J., Troyer, E., Hiebert, R., Kirkland, C. M., Gerlach, R., Cunningham, A., Spangler, L., Kirksey, J., Rowe, W., Esposito, R. (2018). Enhancing wellbore cement integrity with microbially induced calcite precipitation (MICP): a field scale demonstration. Journal of Petroleum Science and Engineering, 171, 1141-1148. doi:10.1016/j.petrol.2018.08.012

Planned activities during the next reporting period
We plan to monitor the production of oil over the coming months to evaluate the success of the mineral seal. We are preparing publications related to this work.

<u>Products</u>
No activity to report.

<u>PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS</u>

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 and 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	46,023	1,514,702
																	-
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	80,074	458,189
																	-
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	126,097	1,972,891
																	-
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	1,972,891	1,972,891
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	109,609	205,813
														-	-	-	-
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	(38,442)	(27,618)
														-	-	-	-
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	71,167	178,195
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	178,195	178,195
	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	9/30/2018	

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