Quarterly Report

Enhancing Montana's Energy Resources: Research in Support of the State of Montana Energy Policy Goals

Montana Board of Regents
The Office of the Commissioner of Higher Education
Agreement Number: 51040-MUSRI2015-05

Lee Spangler
Project Director
spangler@montana.edu
(406) 994-4399

Principle Investigators/Authors:

Adrienne Phillips
Robin Gerlach
Ellen Lauchnor
Stacey Fairweather
Matthew Fields
Brent Peyton
Martha Apple
Xiaobing Zhou

Submission Date: December 6, 2016

Montana State University
Energy Research Institute
P.O. Box 172465
Bozeman, MT 59717-2465

Project Period: August 24, 2015 – June 30, 2017
Reporting Period End Date: October 31, 2016
Report Term/Frequency: Quarterly

Enhancing Montana's Energy Resources

During the reporting period, the outreach team continued to focus on tracking news and regulatory actions related to the Colstrip Power Plant. This includes the outcome of the September 8-9, 2016 Montana Energy Telecommunications and Interim Committee meeting that discussed seven legislative proposals associated with impacts from the pending closure of Colstrip Units 1 and 2; the settlement terms for addressing groundwater pollution related to Colstrip fly ash disposal; updates to the EPA's final rule on coal ash disposal; the Governor's meeting with DOE officials to discuss carbon capture options for the plant; and proposed tax credit incentives for CCUS and CCS. A summary of each is provided below.

Legislative Proposals LC COL1- LC COL7

The Energy Telecommunications and Interim Committee (ETIC) met September 8-9, 2016, to discuss and vote on the seven legislative proposals that were drafted in response to the pending closures of Colstrip Units 1 and 2. Below is a summary that was prepared following the ETIC's September meeting that outlines the drafts that moved forward, and the amendments that the committee made during the meeting. The drafts that were passed have been entered into the 2017 LAWS systems and can be tracked throughout the upcoming legislative session(s) via this link: http://laws.leg.mt.gov/legprd/law0203w$.startup?P_SESS=20171.

The committee received close to 1,200 pages of public comment on its legislative proposals related to Colstrip. In July 2016 the owners of the four-unit Colstrip Generating Station, a coal-fired generating facility with a combined peak output of 2,094 megawatts, and environmental groups reached a settlement agreeing that Colstrip's oldest units, Units 1 and 2, will shut down by 2022, at the latest. The settlement also requires changes in operations at Units 3 and 4. Shortly after the announcement, the committee requested a series of legislative proposals in response.

The committee developed seven draft proposals for public comment aimed at assisting the state of Montana in planning for the pending closure of the facilities. Of the seven drafts, the committee amended three of the proposals and ultimately forwarded on a total of five bills for consideration in 2017. Two drafts, one that would have increased the electrical energy transaction tax and one that would have allowed large customers to self-direct universal system benefits money to assist with energy costs, were not approved. The drafts that moved forward, include:

- LC COL1 Appropriate money to the Department of Justice and the Governor's Office to assist in securing the future of communities affected by the closure of coal-fired generating units in Montana. This draft was amended to also include an appropriation to establish a stakeholder's group in the Governor's Office to identify future energy generation initiatives that utilize transmission systems currently used by coal-fired generation.
- LC COL2 – Establish the Coal-Fired Generating Unit Decommissioning and Remediation Act and provide requirements for submission, review, modification, and approval of a decommissioning and remediation plan for a coal-fired generating units and affected properties. This draft was amended to include a series of amendments requested by the Department of Environmental Quality to assist in the implementation of the act.
- LC COL3 – Establish the Treasure State Restore and Rebuild Act. This draft was significantly amended. Instead of using money in the coal trust permanent fund, the draft

doubles the Wholesale Energy Transaction tax paid by entities that export power from Montana generation. The increased revenue is placed in a fund for counties impacted by the closure of coal-fired generating units. Counties or local government entities would be able to use the money for loans or to bond against to address revenue impacts when coal-fired generating units close.

- LC COL5 – Establish the Montana Energy Accountability Act and requires an electrical company, wholesale exempt generator, or a public utility that retires a coal-fired generating unit to pay a coal-county impact fee for 10 years following closure of the unit or units. The money is provided to entities (local governments, schools, etc.) impacted by the closure of the unit.
- LC COL6 – Establish a benefits and retirement security task force in the Governor's Office.

Groundwater Contamination Lawsuit Update

A settlement was reached on the groundwater contamination lawsuit that was filed against the Colstrip Generating Station this quarter. The Administrative Order of Consent (AOC document) describes the terms of the July 19, 2016, settlement between Colstrip owners and several environmental groups regarding groundwater pollution from coal combustion residuals (CCR) generated by Units 1-4 and is relevant to *Objectives 2 & 3*. The key settlement terms described in the AOC require the following:

- Units 3 and 4 are required to convert to dry disposal for the plant's coal ash waste. Disposal of the coal ash in slurry form into the existing holding ponds must be phased out.
- By 2018, a portion of Units 3 and 4 waste ash (aka "bottom ash") from the existing ponds must be dewatered and disposed of.
- By July 1, 2022, all waste from the Units 3 and 4 scrubbers must be disposed of as dry waste.

EPA Final Rule on Coal Ash Disposal

On October 4, 2016 additional measures to the EPA's final rule on the *Disposal of Coal Combustion Residuals from Electric Utilities* went into effect. The rule provides a comprehensive set of requirements for the safe disposal of Coal Combustion Residuals (CCR) such as fly ash, bottom ash, and boiler slag and is very relevant to *Objective 2*. More specifically, the rule establishes technical requirements for the design, maintenance, and closure of CCR landfills and surface impoundments. The rule also defines CCR as a 'non-hazardous' waste under subtitle D of the Resource Conservation and Recovery Act (RCRA), the primary law that regulates solid waste in the U.S. Presentation slides developed by the EPA to describe the final rule in more detail are linked here: https://www.epa.gov/sites/production/files/2015-03/documents/ccr_webinar_slides_508.pdf

*Capturing Carbon at Colstrip Unit 3 (*relevant to *Objective 4*).

Governor Steve Bullock hosted a meeting with DOE officials on August 31, 2016, to discuss DOE's preliminary analysis on ways to reduce carbon emissions from Colstrip Units 3 and 4, such as carbon capture and enhanced oil recovery (EOR) options. Angelos Kokkinos, the director of DOE's Office of Advanced Fossil Technology Systems, estimated that it would cost approximately $1.2-$1.4 billion to retrofit Units 3 and 4 to reduce emissions between 30%-40%.

According to his analysis, carbon capture for regional EOR production could generate $3.0-$4.4 billion in revenue over the next 25 years. However, this number is based on projected CO_2 demands with oil selling at $106 per barrel. The revenue estimates also do not account for the increased operating costs. Other ways to reduce carbon emissions from Units 3 and 4 that were discussed included beneficial use options such as converting CO_2 to methane and producing fertilizer. Carbon emissions could also be reduced by improving plant efficiencies, using natural gas, biomass, or geothermal sources instead of coal for power generation (*Source: http://www.greatfallstribune.com/story/news/local/2016/08/31/capturing-carbon-colstrip-discussed/89676942/*).

Proposed Bill to Extend & Expand 45Q Tax Credit for CCS/CCUS
On October 27, 2016, Department of Energy (DOE) officials met with Capitol Hill energy advisors and other energy experts for a panel discussion at the U.S. Energy Association on the environmental and economic benefits of upgrading the 45Q tax credit through the Carbon Capture, Utilization and Storage Act (S. 3179). The proposed changes to the tax bill include the following:

- The bill increases the current tax credit offered to large carbon emitters in an effort to encourage industry to sequester CO_2 emissions. It also lowers the threshold for facilities to qualify for the tax credit. The bill removes the 75 million ton cap on tax credits, of which more than half have already been claimed (currently, about 40-45M tons have been claimed and it is estimated that the 75M ton cap will be reached over the next three years).
- CO_2 can be stored in a geologic formation or saline aquifer, or piped into an oilfield for use in the CO_2 enhanced oil recovery (EOR) process. For CO_2 stored in geologic formations, the tax credit will increase from $20/ ton to $50/ ton of CO_2.
- For CO_2 used in the EOR process, the tax credit will increase from $10/ ton to $35/ ton of CO_2. The Act also credits different forms of CO_2 utilization beyond EOR, including in the production of biomass, biofuels, and plastic.

Objective 1

Develop methods for creating mineral seals for leaky wells at greater depths (> 5000 feet bgs) and higher ambient temperatures (>35 °C) than current ERI biomineralization technology.

Quarter activities and accomplishments
Research continued to extend the temperature range for in situ mineral precipitation including experiments performed by Montana Emergent Technologies in wellbore analog reactors at 60 and 70 °C. Ureolysis kinetics as well as inactivation kinetics were determined for bacterial and plant-based ureases. Thermal ureolysis kinetics were determined at increasing temperatures and increasing concentrations of urea and in the presence of calcium. Montana State University and Montana Emergent Technologies personnel have had discussions with several oil and gas companies and an oil field service provider to evaluate possible applications of mineralization-based subsurface technologies. Work continues in collaboration with Montana Emergent Technologies to design a mobile laboratory which will be used to implement these mineral precipitation technologies in the field. On September 27, 2016, representatives from the Montana Legislature, the Board of Regents, and administrators from Montana Universities toured the

laboratory where much of the research is conducted. They met several of the students supported by the funding and were updated on the progress made to date.

Hirings
No additional hires were made this quarter. Postdoctoral researcher Dr. Marnie Feder; M.S. students Arda Akyel, Vinny Morasko, and Kyle DeVerna; and undergraduate student Zach Frieling continue to work on the development of advanced mineral precipitation strategies. They are also studying the differences in material properties between abiotic, enzymatic, and bacterially precipitated calcium carbonates.

Equipment Purchased
No equipment has been purchased to date.

Proposal *(leverage the overall MUS research enterprise)*
As reported in the previous quarter, a Budget Amendment Request was submitted for DOE Project DE-FE0024296 "Methods to enhance wellbore cement integrity with microbially-induced calcite precipitation (MICP)". This budget amendment request was approved by DOE to add an additional $140,000 to the project for design and construction of a mobile laboratory.

Milestones

A. August 2015-June 2017: Perform laboratory bench experiments to extend the temperature range for mineral precipitation, and thief zone plugging for enhanced oil recovery (EOR)
    a. Enzymatic urea hydrolysis kinetics from plant based sources of enzyme appear to be the fastest between 60 and 70 °C; and inactivation of the jack bean urease was observed as a function of time and temperature. At 80 °C the urease was observed to be inactivated after 45 minutes. After six hours exposure to 70 °C, JBM urease demonstrated a > 97% decrease in activity. A series inactivation type mathematical model has been derived to predict the kinetics of deactivation of the JBM urease. A manuscript, titled "Plant-based ureolysis kinetics and urease inactivation at elevated temperatures for use in engineered mineralization applications" is in preparation presenting the results from the experimental and modeling results.

    Work continues to evaluate the urease enzyme from Sporosarcina pasteurii. Ureolytic activity can be observed up to approximately 80 °C but growth of S. pasteurii ceases at approximately 40 °C. Methods are being developed to extract the enzyme from the bacterial cells and to compare the activity of the bacterial urease from S. pasteurii to the enzyme derived from plant based sources.

    A flow through reactor experiment was conducted at 60 °C where the microbe was injected into a 1mm gap between cement and steel to mimic the near wellbore environment. Fluids that promote MICP were then injected and the result was a significant reduction in permeability over the course of 40 injections (Figure 1).

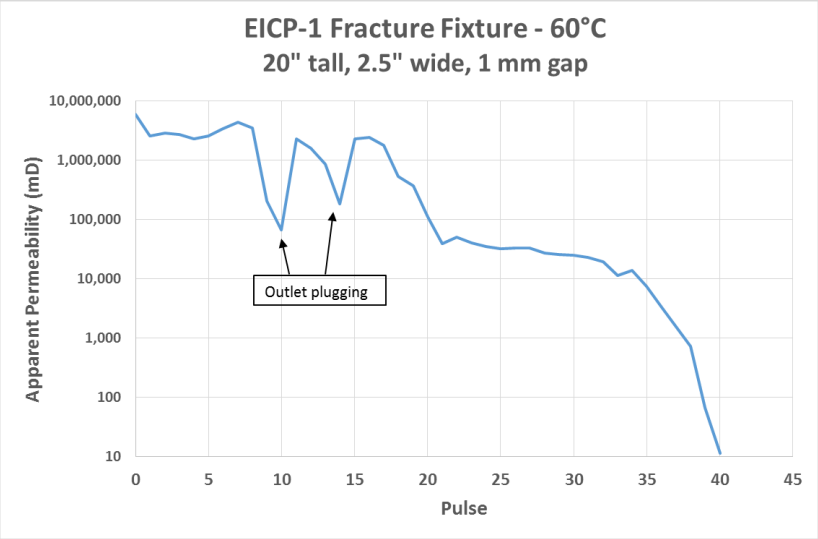

Figure 1. The permeability was reduced by over 5 orders of magnitude by promoting MICP in a 1mm gap. The experiment was performed at 60 °C pointing to the promise of using the enzymatic mineralize seal in deeper subsurface applications.

b. The kinetics of thermal urea hydrolysis (thermally induced calcite precipitation or TICP) were determined for temperatures between 30 and 130 °C. Increasing ureolysis rates were observed with increasing temperatures. Preliminary data suggested that in the presence of calcium the ureolysis rate from thermal induction is slower than without calcium. Additional investigations are underway to determine rates of ureolysis in the presence of calcium and other salts which may be representative of subsurface brines.

B. August 2015-June 2017: Leverage federal funds and partner with a Montana company to initiate and plan a mineral precipitation well sealing field test. Identify interested stake holders, share relevant results and field plan.
   a. Montana Emergent Technologies (Butte, Montana) and MSU are continuing to pursue the development of biomineralization-based technologies. Conversations with several oil and gas companies have occurred. In October, Montana Emergent Technologies held a meeting with Schlumberger. Candidate wells and field deployment strategies were discussed. Montana Emergent Technologies is a collaborator on the design and construction of the mobile laboratory which was funded by DOE through a budget amendment request. The mobile laboratory will be used for upcoming field projects and advances the technology readiness level and commercialization potential of mineral-based sealing technologies.

Dissemination of Results
Presentations

Phillips, AJ, Gerlach, R, Cunningham, AB, Spangler, L. "Wellbore Leakage Mitigation Using Advanced Mineral Precipitation Strategies" Department of Energy, Mastering the Subsurface through Technology Innovation & Collaboration: Carbon Storage & Oil & Natural Gas Technologies Review Meeting, August 17, 2016, Pittsburgh, PA.

Phillips, AJ, Gerlach, R, Cunningham, AB, Troyer, E, Norton, D, Hiebert, R, Kirksey, J, Rowe, W, Esposito, R, and Spangler, L. "Biomineralization: A Strategy to Modify Permeability in the Subsurface". Geologic Society of America Annual Meeting, September 25-28, 2016, Denver, Colorado.

Norton, D, Gerlach, R, Eldring, J, Thane, A, Hiebert, R, Cunningham, A, Spangler, L, Phillips, AJ "Visualizing and Quantifying Biomineralization in a Wellbore Analog Reactor". Geologic Society of America Annual Meeting, September 25-28, 2016, Denver, Colorado. Poster.

News Story
Swearingen, Marshall. "MSU team shows biofilm and mineral-producing bacteria have potential for plugging oil and gas leaks." *MSU News* 17 Aug. 2016.
http://www.montana.edu/news/16313/msu-team-shows-biofilm-and-mineral-producing-bacteria-have-potential-for-plugging-oil-and-gas-leaks

The results of this work and the role that the MREDI funding has played into the success of experiments was recently highlighted by the above mentioned MSU news story. The story was picked up by the Bozeman Daily Chronicle, JWN, NPJ Biofilms and Microbiomes, The Winnower, and several other online news services.

Objective 2

Test use of microbially induced calcite precipitation (MICP) to remediate fly ash storage to comply with a new federal regulation (40 CFR Parts 257 and 261 Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals (CCR) From Electric Utilities).

Quarter activities and accomplishments

During this reporting period, Southern Company sent new baghouse waste material of interest to possibly determine alternate disposal methods. This material was investigated in the laboratory to determine the potential of MICP to consolidate and bind the particles together. An abstract titled "Remediation of Coal Combustion Residuals Using Microbially-Induced Calcite Precipitation" was submitted for consideration of presentation and conference proceeding at the World of Coal Ash conference to be held May 2017 in Kentucky. On September 27, 2016, representatives from the Montana Legislature, the Board of Regents, and administrators from Montana Universities toured the laboratory where much of the research is conducted. They met students supported by the funding and were updated on the progress made to date.

Hirings

An undergraduate researcher Steven Jones, a senior in Civil Engineering, was hired in September. Abby Thane continued to research MICP (microbially induced calcite precipitation or biomineralization) in coal combustion residuals (CCRs) material.

Equipment Purchased
No equipment was purchased this reporting period.

Proposal *(leverage the overall MUS research enterprise)*
The following proposal was contracted this quarter: Laboratory testing of the effects of biomineralization on coal combustion residuals. PI: A. Phillips. Collaborators: A. Cunningham (MSU), Ben Gallagher (Southern Company). Total: $40,000. 08/16-12/16.

Milestones

A. August 2015-June 2017: Collect samples of bottom ash, fly ash and pond water at the Colstrip plant ponds. Perform laboratory studies to assess the feasibility of MICP CCR pond remediation.
    a. As previously reported samples of the Colstrip coal-fired power plant coal combustion residuals (paste) were collected in October 2015 and June 2016. Biomineralization experiments performed with the paste showed that noticeable binding of the materials was observed when we mixed increasing concentrations of paste with biomineralizing microbes and solutions. The promise of these findings is the potential to enhance binding to minimize fugitive dust emissions from paste materials. This could allow for less water to be used to store the materials. The advantage to using less water is reduced risk of leaching of contaminants from the paste into the water which could impact groundwater sources. Biomineralization of paste particles also points to the potential for safely storing these materials dry where little or no water could be used.

    Also described in the previous quarter, a method to enhance the ureolysis rate was determined. It was observed in previous experiments using fly ash that the pH is driven significantly higher than the optimal conditions for microbially induced calcite precipitation (MICP). We found that adding a phosphate buffer solution to the triplicate batch study flasks along with the microbes and mineralizing solutions resulted in complete ureolysis in high concentrations of ash materials.

    These results show promise for biomineralization to bind together CCR materials at higher concentrations to reduce the amount of water needed to store these materials. Additional work to understand how to control the pH in samples with higher concentrations of fly ash and the new ash material sent to the laboratory from Southern Company is underway.

    b. Experiments continue with the baghouse waste material supplied by Southern Company. The primary research question we address is: Can baghouse waste cohesiveness be improved with biomineralization?

    An initial screening study was performed to assess the capacity of MICP to bind together the baghouse waste materials. It was observed that urea hydrolysis occurred over 48 hours in samples with up to 50% baghouse waste and ureolytic microbes or jack bean meal (another source of the urease enzyme).

B. August 2016-June 2017: Assess and plan field demonstration of MICP in CCR ponds (as appropriate). Work with MT company (Montana Emergent Technologies, MET) to implement the MICP technology in the field.

    a. Conversations with MET continued on ideas for field deployment.

    b. A conference call was held in September with Ben Gallagher of Southern Company to discuss design of meso-scale experiments addressing the consolidation of baghouse waste materials.

Objective 3

Assess the potential to use bacterially driven mineral formation for removal of heavy metals, such as cadmium, arsenic and selenate from water produced by coal mining operations, coalbed methane, and enhanced oil recovery.

Quarter activities and accomplishments

Research continued on strontium and barium co-precipitation in laboratory porous media flow cells. A new method of analysis, laser ablation of solid precipitates, allow for spatial determination of relative concentrations of metal elements in minerals. This method is being utilized in flow cell studies of MICP and strontium co-precipitation. Batch studies of mine influenced water (MIW) from the Carpenter-Snow Creek Mining District National Priority List site have been completed. Ongoing work on MIW remediation at the mine site is focusing on enrichment of native bacteria for MICP and flow studies to determine feasibility of a flow-through treatment process. Enrichment of selenium reducing bacteria from groundwater at the Colstrip Power Plant is ongoing. Bacterial community analysis of DNA collected from the Colstrip groundwater has identified organisms potentially capable of selenium reduction.

Hirings

Ph.D. student Hannah Koepnick was hired to perform studies of selenium biomineralization via selenate reduction in groundwater from the Colstrip Power Plant. PhD student Neerja Zambare continued work on biomineralization studies in flow-cell reactors and MS student Emily Stoick continued research on mineralization of heavy metals in mine influenced water samples.

Equipment Purchased

No equipment was purchased this quarter.

Milestones

A. May 2016: Laboratory studies in synthetic mining wastewater with key heavy metal contaminants using model bacterial strains. Contact site(s) of interest to obtain water samples. Discuss potential and strategies for implementation of the technology with local Montana companies (e.g. Montana Emergent Technologies and Enviromin).

    a. Experiments with metal contaminants strontium and barium are ongoing in flow cell reactors. A 2-D porous media flow cell system with spatial sampling ports, shown in Figure 2, has been utilized to evaluate spatial and temporal dynamics of strontium removal from artificial groundwater. As demonstrated in Figure 3, analysis of precipitates indicates spatial gradients of strontium co-precipitation.

While greater total removal of strontium is observed nearer to the flow cell effluent due to more overall precipitation, the ratio of Sr:Ca in the precipitate decreases with distance from the inlet. Sr:Ca ratio in CaCO3 precipitate formed by MICP has been shown to correlate with the rate of precipitate formation. Additional experiments with the spatial flow cell and strontium co-precipitation are ongoing.

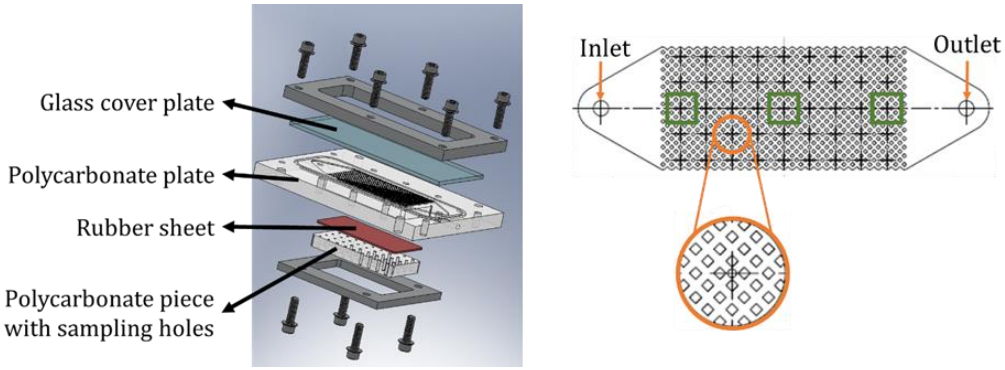

Figure 2. Schematic of spatial flow cell reactor.

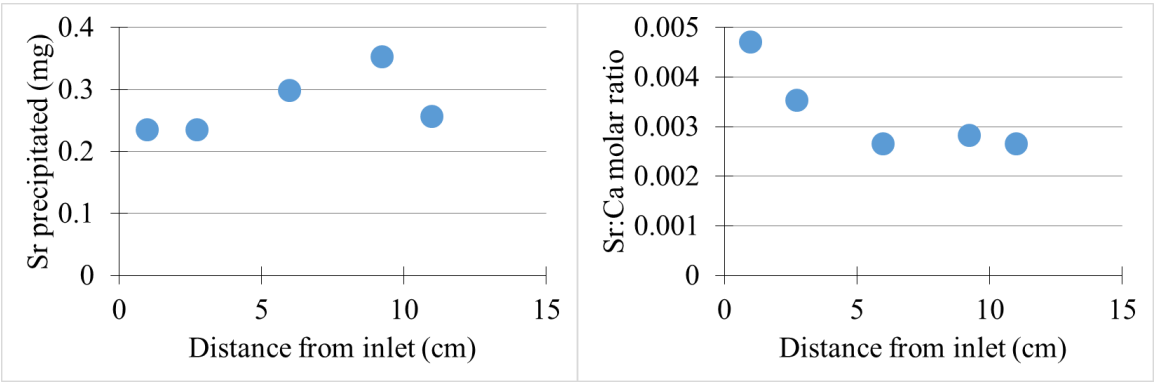

Figure 3. Left: Mass of strontium precipitated in spatial flow cell along flow path. Right: Ratio of strontium to calcium in precipitate from spatial flow cell. Data from single experiment conducted over three days.

b. We collaborated with a local Bozeman company, New Wave Research, recently acquired by Electro Scientific Industries, to analyze solid phase mineral composition using laser ablation of the minerals and analysis via ICP-MS. A sample analysis of the Sr:Ca ration in minerals formed within the spatial flow cell reactor during the first continuous flow experiment is shown in Figure 4. The technology has immense potential for spatial analysis of mineral composition.

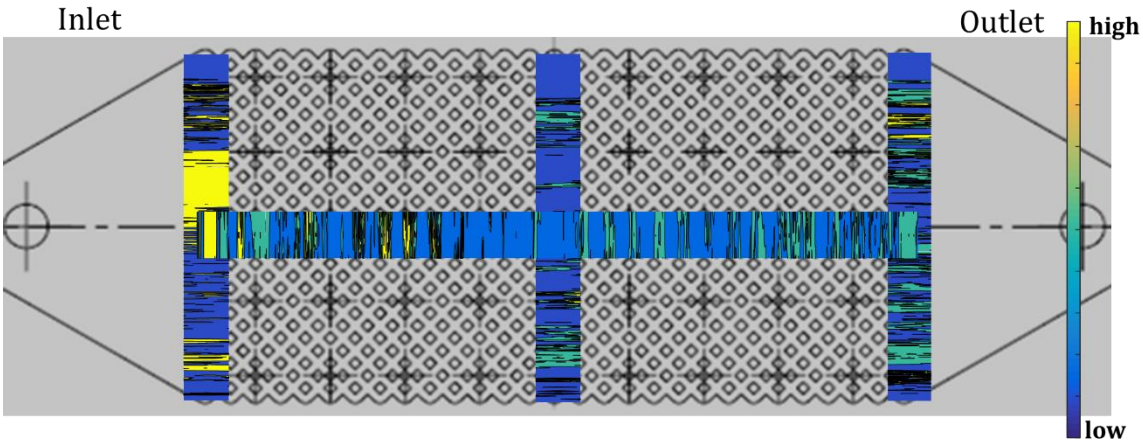

Figure 4. Strontium:calcium ratio of mineral precipitate in spatial flow cell reactor, as determined by laser ablation and inductively coupled plasma mass spectrometry (ICP-MS). Yellow indicates higher relative strontium concentration.

B. January 2017: Biomineralization studies in batch and flow reactors using real or synthetic waste water.

a. Surface water and sediment samples were collected from three adits at the Carpenter-Snow Creek site releasing MIW: Compromise, Moulton, and Evening Star. MIW samples from each of the three adits were evaluated for the feasibility of microbially induced calcium carbonate precipitation (MICP) and the potential for heavy metal co-precipitation. Batch experiments were conducted for all three mine adit water samples in bottles shown in Figure 5. Triplicates of each treatment were used. Filtered and unfiltered MIW treatments were used to determine if there were any native bacteria contributing to or inhibiting urea consumption and metal precipitation.

Figure 5. Photo of Batch Experiment Bottles

b. In the MIW from the Evening Star and Compromise adits, ureolysis successfully occurred (Figure 6). Only Moulton MIW that had been filtered experienced

ureolysis, indicating a potential competing microbial process in the unfiltered samples.

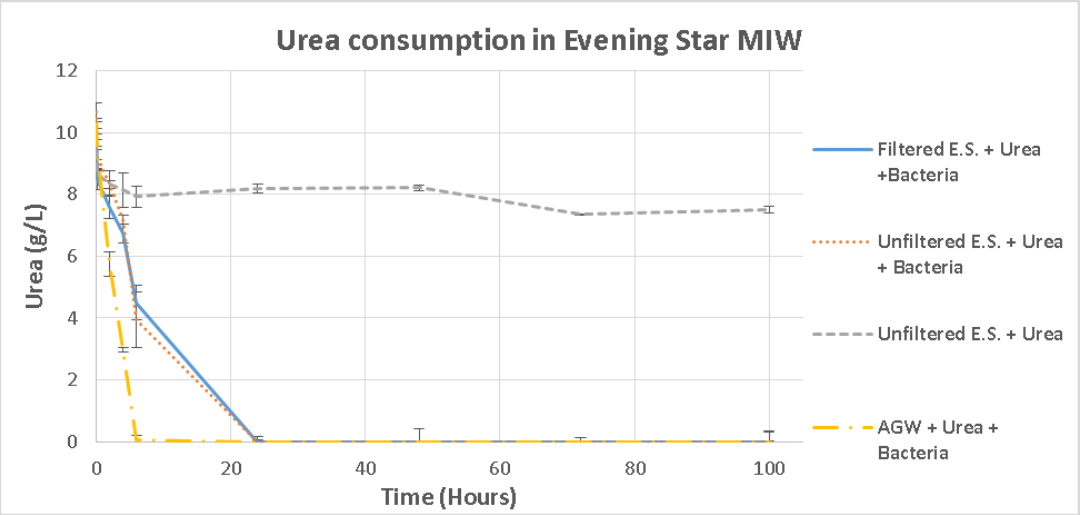

Figure 6. Average Urea Concentration Change of Each Condition Tested in Evening Star MIW. Sample bottles for each condition were tested in triplicate and error bars indicate standard deviation of these bottles among duplicate experiments.

c. Analysis of MIW before and after treatment indicated that heavy metal removal occurred to varying extents in the batch tests (Table 1). Removal varied both between different metals and between the different adits, which also varied in composition and concentrations of dissolved metals.

Table 1. Average Percent of Metals Removed from Solution

	Compromise	**Evening Star**	**Moulton** *(Filtered Only)*
Average Percent Removed from Solution (%)			
Manganese	92.3	99.0	99.7
Nickel	59.7	39.4	100.0
Zinc	95.3	59.7	98.8
Barium	39.3	73.3	95.7
Cadmium	BQL	----	BQL
Copper	----	BQL	----
Cobalt	----	BQL	----

Enrichments of selenium reducing bacteria from Colstrip groundwater have thus far shown removal of nitrate and selenate reduction is currently being evaluated.

C. June 2017: Completion of laboratory investigations on technology scale-up and final assessment of potential for bioremediation of coal- and enhanced oil recovery-generated industrial wastewater.

a. Two posters on heavy metals co-precipitation and remediation of mine influenced water were presented at the annual 2016 conference of the National Association of Abandoned Mine Land Programs, held in Bozeman, September 25-28. A progress report on the MIW feasibility studies was issued to the EPA and Tetra Tech collaborators and a dialogue was initiated on potential flow cell designs for field implementation of MICP for remediation of mine water from adits at the Carpenter Snow Creek District. Upcoming experiments will be designed according to discussions with our collaborators.

Objective 4

Assess geologic carbon sequestration potential via EOR in oil and gas fields and storage in saline formations near Colstrip, MT, utilizing fine-resolution geospatial methodologies to estimate storage potential, source to sink infrastructure, and enhanced oil production from fields that meet screening criteria.

Quarter activities and accomplishments

The primary focus this past quarter was ongoing cyberinfrastructure development. A GIS portal was developed to house, organize, and share the results of the EOR assessments. Building upon existing ESRI ArcGIS software and server infrastructure, Portal for ArcGIS was installed and configured to provide a central repository for web application development and user access. Development also began on an interactive atlas to display project results.

The interactive, web-based atlas (Figure 7) was built using the ArcGIS API for JavaScript. Using the ESRI software framework, results from the EOR assessments and pipeline analysis were posted to a Microsoft SQL Server database using ArcGIS for Server. The data repository was configured to make mapping services and data layers available to online users to view, query, and interact with the data via an application like the interactive atlas.

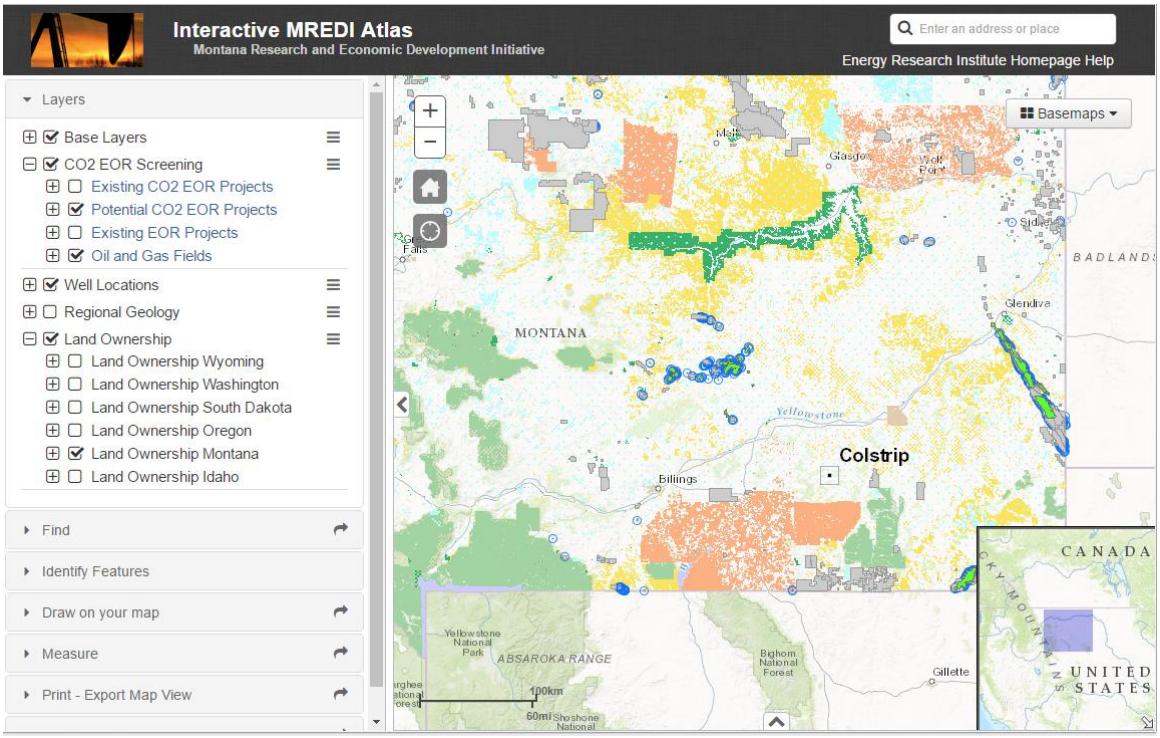

Figure 7. Screen shot of the interactive atlas.

The JavaScript application was developed using an open source framework that acts as a template. This framework is known as the "Configurable Map Viewer" or CMV. This framework is designed to use JavaScript 3.x versions of the API and supports 2D rendering and mapping. The framework uses widgets as tools within the map (measurement tools, geospatial bookmarks, drawing tools, queries, and more) to create a desired outcome when an even takes place in the application (such as clicking on a feature to return a pop-up with attribute info for that data point). The CMV also allows for any number of aesthetic and operational customization opportunities with the editing of configuration files within the file package. The GIS team was able to develop a custom widget for integration into this framework that allowed for the display of tabular data associated with a spatial layer.

The team also participated in the MREDI state legislature tour at MSU in September, preparing graphics and a fact sheet to present progress to date. Graphics were created to display the general workflow of the geospatial analysis and explain how the modeling tools utilize the input data to calculate the least cost path and ultimately define a route from Colstrip out to the selected fields that could be used for a pipeline. Figure 8 shows a graphical example of the data layers used for analysis, such as landownership, slope, and soil depth, and the pixel by pixel sampling used in the networking model.

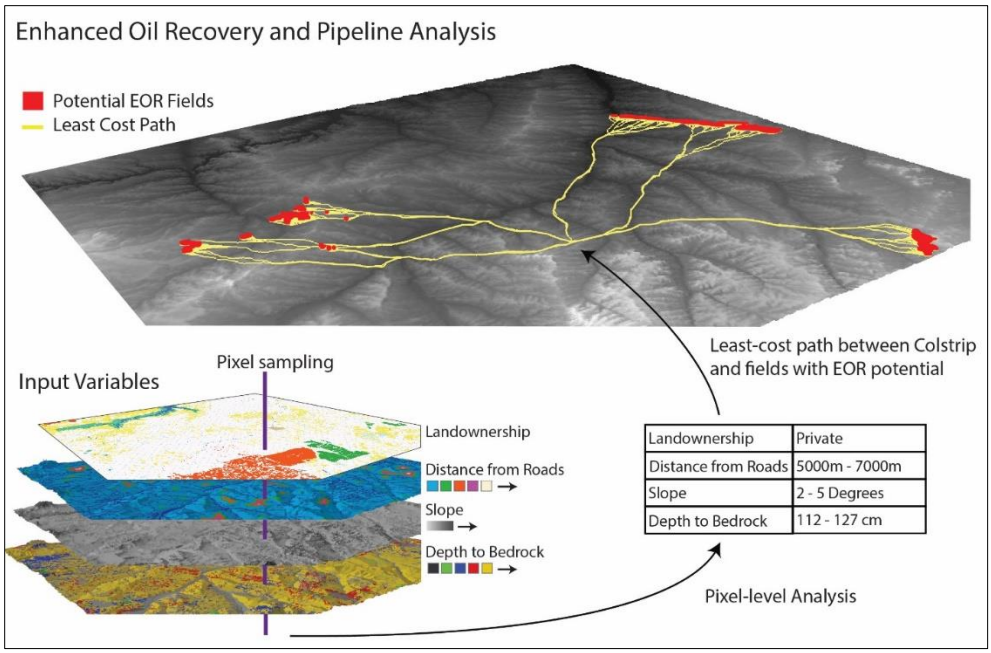

Figure 8. Image demonstrating the data inputs and calculation method for the least cost analysis for potential pipeline routing.

Hirings

There were no new hires this quarter.

Equipment Purchased

No equipment has been purchased to date.

Milestones

A. July 2015 – July 2016: Assessment of carbon storage and EOR potential
   a. Oil and gas data for all producing horizons in the study area underwent three levels of screening based on reservoir characteristics including oil gravity, depth, thickness, fracture pressure, temperature, and historical production. Seven regional field-reservoir combinations were found to have complete data and meet all screening criteria. Network analysis has been conducted on the high-potential target fields, and routes to each were determined using a Least Cost Analysis method.

B. December 2016: Completion of the interactive mapping application
   a. Programming continues for the JavaScript-based interactive map as well as the new GIS Portal and associated resources.

C. June 30, 2017: Final Report and data package
   a. No activity to report this period.

Objective 5

Develop methods to integrate phototrophic microbe based air capture of CO_2 and evaluate potential byproducts.

Quarter activities and accomplishments

This quarter, we have continued with and expanded our research on the potential use of phototrophic microbes as fertilizers for economically important plants of Montana. We have scaled up our cultures of *Anabaen*a *cylindrical*, a filamentous nitrogen-fixing genus in the Cyanobacteria and have continued to culture *Chlorella* sp. and *Nanochloropsis gaditana* from the Coal Bed Methane Ponds of southeastern Montana.

A. cylindrica was grown in flasks, carboys, and raceway ponds for the accumulation of large quantities of biomass. The biomass was used for the inoculation of potato soil at MT Tech. The intention was to optimize the growth of potatoes using *A. cylindrica* as nitrogen fixing soil fertilizer. When scaling up reactor volumes, it was found that *A. cylindrica* grew best under moderate light conditions, between 50-200 PAR, 10:14 L:D in BG-11 (without nitrogen) medium. The nitrogen fixing cyanobacteria grew well in carboys but struggled to survive in the outdoor raceways due to a number of factors including variable temperature, photobleaching, and limited carbon dioxide transport, as the raceway paddles did not deliver as much carbon dioxide as bubbling ambient air through the carboy reactors. The raceway pond Anabaena cultures crashed out and were overtaken by a red algae. The biomass provided to Montana Tech was grown in three 20L carboys under optimal growth, at conditions outlined above.

Potato plants were given highly-concentrated solutions of *Chlorella* sp. and allowed to grow for approximately three months, after which they were harvested and assessed for weight and number of potatoes produced. An additional cohort of potato plants were given *A. cylindrica* and remain under cultivation until their harvest at approximately three months. Seedlings of flax plants (*Linum usitassimum*) are growing in the greenhouse and will receive a solution of *Anabaena* to test its effectiveness as a fertilizer. *A. cylindrica* is potentially a very important fertilizer because it is autotrophic (does not require organic carbon), and especially because it fixes nitrogen and thus can use atmospheric nitrogen for its nitrogen requirements.

Olakunle Ogunsakin, graduate student, is developing prototypes of a flocculating system for the concentration of microalgae as a means of reducing potential costs in transporting microalgae and/or cyanobacteria to plants that will be fertilized with it.

Olakunle Ogunsakin is the first author of a presentation on this work that will be presented at the American Geophysical Union's Fall Meeting in December 2016 in San Francisco, California. Other authors include Apple, Zhou, and collaborating MREDI researchers from MSU.

Coal Bed Methane Ponds

Analyses continue for the growth of algal consortia in non-sterile CBM production water and the changes in microbial community dynamics. Experiments have been initiated to grow mixed algal cultures (strain PW95, strain WC-1, and strain X) together in defined medium and test for outdoor growth (natural light and temperature fluctuations) along with biomass and lipid

accumulation. Each respective culture was grown individually in the laboratory and then combined into a single inoculum. In September 2016, we inoculated two 200L raceway ponds (Figure 9 and Figure 10) with a consortium of three alkaliphilic alga taxa Alga X, WC-1, and PW-95. The cultures were allowed to grow for two weeks outdoors before the weather turned colder and cloudier. A paddle wheel insured mixing and a modified livestock trough heater maintained a water temperature >15°C. Samples for chlorophyll, ion chromatograph, high-throughput sequencing, and GC-MS analysis of fatty acid methylesters (FAME) were also collected daily and frozen at -80 °C for future processing.

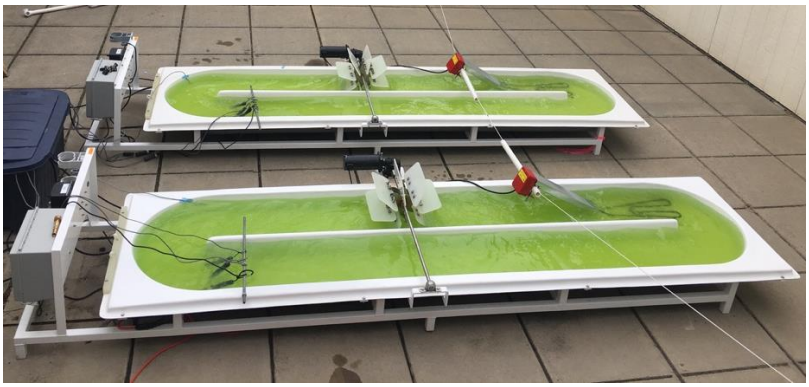

Figure 9. Cultivation of alga consortia that contains strains PW95, WC-1, and Alga X.

Figure 10. Raceway ponds after nine days of outdoor cultivation.

Hirings

MSU
The efforts of a Ph.D. student have been shifted to conduct experiments with mixed algal cultures and the cultivation outdoors.

MT Tech

Mr. Olakunle (Kunle) Ogunsakin continues to work towards his master's degree in Environmental Engineering through the MREDI project.

Equipment Purchased

MSU
No major equipment purchases were made this quarter.

MT Tech
Eight liter glass carboys and stoppers were purchased in order to scale up culturing facilities. In addition, a new laptop computer was purchased for the project.

Milestones

A. December 2016: Growth characteristics under outdoor conditions (temperature and sunlight) in meso-scale ponds will be determined

   a. MT Tech: These are being scaled up from the 1-2 liter scale to the 19 liter carboy scale. Suitable conditions for outdoor growth are in the process of being assessed at MSU.

      MSU: The first attempt for outdoor growth was completed in September 2016. We are awaiting warmer weather in the spring to attempt further growth outdoors with natural sunlight.

B. July 2016: Obtain and test algal byproducts for macronutrient and micronutrient composition. Recruit a graduate student to work on this project.

   a. MT Tech: Olakunle Ogunsakin was recruited in December 2015 for continuing work on this project and he has worked to culture microalgae and cyanobacteria to test its macronutrient and micronutrient composition.

      MSU: Elemental composition has been tested for indoor laboratory algal cultures. We will next test PW95 grown outdoors in spring 2017.

C. July 2017: Tests will be targeted towards those plants that showed responses to the algal fertilizer.

   a. MT Tech: Wheat has shown the greatest response to algal fertilizer to date, so further tests of the effectiveness of microalgae and cyanobacteria will be conducted on wheat between now and July 2017.

      MSU: Tests will be targeted towards those plants that showed responses to the algal fertilizer.

Objective 6

Develop methods to stimulate repeated methane production in coal bed methane (CBM) projects.

Quarter activities and accomplishments

During the fifth quarter, MT Tech refined the development of the algorithm used to determine water area from satellite images. Using Google Earth satellite images on ten coal-bed water ponds, area coverage and water volume were estimated, ground truthing was completed, recording was done, and water area was extracted. Also, the hyperspectral system was used for image collection which, in turn, were used for identifying the hyper-spectral signature of different species of micro-algae, measuring micro-algae cell concentration, and correlation analysis between hyperspectral signature and cell concentration.

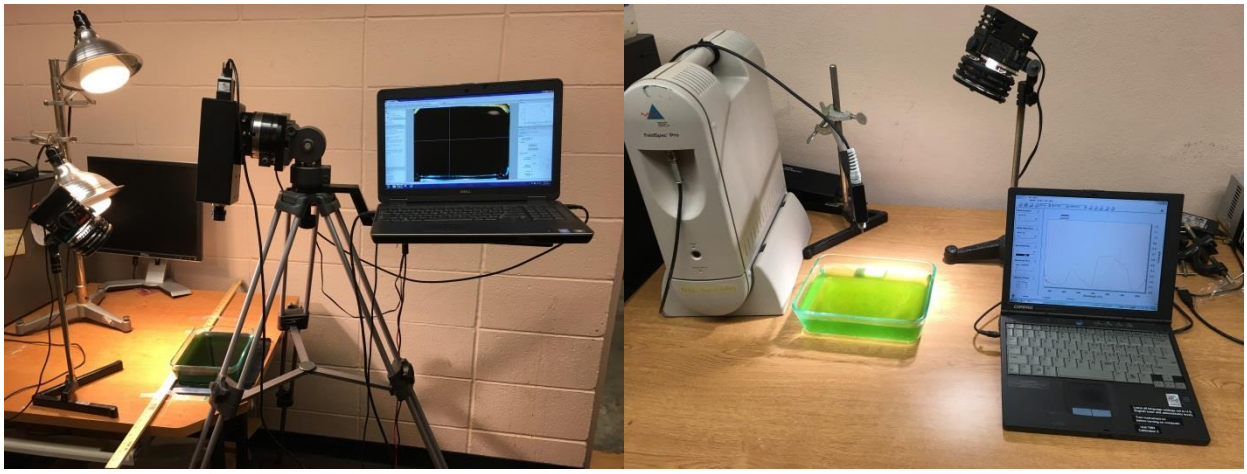

Figure 11. Hyperspectral systems used to spectral signature measurement for microalgae. Left-panel: measurement on filamentous cyanobacteria (*Anabaena*) and right panel: spectral measurement on green algae (*Chlorella* sp.).

Major accomplishments this quarter include:

- The graduate student used the hyperspectral imaging system for algae image collection and spectral data extraction.
- MT Tech collected cell concentration and spectral signature data for two species of micro-algae: unicellular green algae (Chlorella sp.) and filamentous cyanobacteria (*Anabaena*) from the coal bed methane ponds cultured in aerated beakers, flasks, and aquaria with Bold's Basic Growth Medium and natural and/or supplemental lighting, both were provided by Martha Apple's group.
- An algorithm was applied to determine water area of the ten Coal-bed Methane ponds within the Montana Powder River Basin from satellite images. Water volume and area were also extracted from the original documents provided from Summit Gas Summit Gas Resources, Inc. for comparison.
- MT Tech measured Raman scattering of the two species of the micro-algae. Analysis of these Raman scattering data will be performed in the following months.
- MT Tech performed a preliminary regression analysis between the cell concentration and hyperspectral reflectance data and found that the spectral reflectance at certain absorption bands is very well correlated with cell concentration of Chlorella. Further analysis will be performed in the following months. Similar analysis will also be performed for anabaena.

Hirings
No new hires were made this quarter.

Equipment Purchased
No major equipment purchases were made this quarter.

Milestones

A. August 2015 – October 2016: Estimate areal coverage of CBM ponds using Hyperion or Landsat data
   a. For this objective, the algorithm developed was used to extract water area from the Google image of very high-resolution (0.20-0.30 m) covering the ten CBM ponds within PRB. MT Tech analyzed the original documents on the ten ponds and extracted the water volume of each pond. Table 2 summarizes the surface area and water volume of each pond and the totals of all ponds. Overall, the ten CBM water retention ponds within the Montana PRB has about 746.92 acre-feet coal-bed water over 52.09 acre surface area. These ponds have great potential for micro-algae growth to generate biofuel or/and bio-fertilizers.

Table 2. The water area and volume of each CBM pond and the totals

Pond Name	**Volume AC-ft**	**Surface (AC)**
Big Nose Kate	194.38	13.40
Wild Bill Hickock pit #2	97.00	3.88
Sundance Kid	59.90	3.56
Porter4-15	89.93	8.00
Doc Holiday pit #10 (Doc Holiday 1)	36.44	2.79
Rancholme 4-34(Doc Holiday 2)	29.20	2.90
John Wayne	100.07	6.23
Calamity Jane #15	42.38	3.08
Jesse James	38.26	4.21
Bronco Billy	58.92	4.04
Total:	**746.48**	**52.09**

B. July 2015 – December 2016: Evaluate time-course for methane production during consecutive stimulations
   a. Experiments are on-going for re-stimulation of coal-dependent methanogenesis. Algal extract is being tested and compared to yeast extract and cyanobacteria extract. Preliminary results suggest that coal-dependent methanogenesis can be sequentially stimulated; however, the coal-dependent nature of the methane production appears to subside. Algal and cyanobacterial extract appears to perform better in terms of subsequent stimulations for coal-dependent methanogenesis, as indicated by the calculated extent of carbon from coal versus added nutrient. Community dynamics for the initial stimulation are being determined, and both the bacterial and archaeal populations are different for both the type and amount of nutrient amendment. Results suggest that the bacterial populations are more impacted by the presence of

coal as well as the nutrient level. Archaeal populations were not as impacted and did not correlate to the type or level of nutrient. Analyses are on-going.

C. July 2016 – June 2017: Monitor mesoscale growth of algae using spectral methods

a. This task is the focus of the second year for this project. MT Tech used the hyperspectral imaging system and spectroradiometer for hyperspectral data collection on two species of microalgae (Chlorella sp. and *anabaena*). Cell concentration and hyperspectral signature were also measured. A preliminary regression analysis between cell concentrations of Chlorella with hyper-spectral reflectance data at some absorption bands in the red spectral region showed that there is a strong correlation between them. This relationship provided a useful tool to estimate cell concentration within a water pond from spectral data that can be easily acquired from space-based measurement.

Expenditures to Date

Quarterly Report 10/31/2016

	All Budgets	Spent to Date
Salaries & Benefits	717,237	282,466
Subcontract Payments		
Montana Tech	222,667	103,827
Montana Emergent Technologies	75,000	39,125
Operations	160,096	48,196
Equipment	25,000	
Total Costs	**1,200,000**	**473,614**