Quarterly Report

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

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Report Term/Frequency: Quarterly

Enhancing Montana's Energy Resources

During the reporting period, the outreach team developed a website and database to track interactions that project researchers have with project stakeholders. The website has a form that the investigators can use to record all interactions with industry, local community and agency stakeholders. Stakeholders are defined as any persons or organizations with an interest in the research or who may be affected by the research outcomes. This information will be used to develop a stakeholder network. The purpose of the stakeholder database is to: (1) obtain stakeholder feedback on the usefulness of the research to the industry (and the state) and generate new ideas for research relevant to the state; (2) expand and improve industry relations and identify future funding opportunities; and (3) create distribution lists for future communications, event planning, networking, collaboration, etc.

The outreach team also coordinated a one-day visit to MSU by Gordon Criswell on April 8, 2016. Gordon is employed by Talen Energy and is the Director of Environmental, Safety and Compliance at the Colstrip Power Plant. Throughout the day he met with all of the research leads at MSU. He was given lab tours and demonstrations to learn more about the MREDI funded projects. The visit was very productive and there were meaningful interactions allowing MSU investigators to learn more about Colstrip needs. Some of the challenges faced at Colstrip include the following:

- Bringing Colstrip into compliance with the new EPA regulations on coal combustion residuals or CCRs. This will require Colstrip to convert to dry disposal of the coal ash.
- Colstrip will also need to put in liners for the ponds. To do this, they need to determine a way for removal of 700 million gallons of water that is currently in the ponds to install the new liners.
- Colstrip is continuing to look into carbon capture and storage options to reduce their CO_2 emissions.
- There is selenium groundwater contamination that needs to be cleaned up. This is combined with other groundwater contamination issues Colstrip is working on.

A result of the meeting with Gordon was that he invited the MSU MREDI team to present at one of the 'owners' meetings which occur every two months. MSU is planning to present an overview of the MREDI projects and progress at the September 2016 'owners' meeting. Gordon Criswell has offered to help MSU coordinate the meeting.

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 was continued to extend the temperature range for in situ mineral precipitation. Ureolysis kinetics as well as inactivation kinetics for a number of bacterial and plant-based ureases were determined. Thermal ureolysis kinetics were determined at three separate temperatures. The mechanical properties of sand stabilized using microbially induced and enzymatically induced calcium carbonate mineral precipitates were assessed. Montana State

University (MSU) and Montana Emergent Technologies (MET) personnel had discussions with several oil and gas companies to evaluate possible applications as well as field deployment strategies in support of the development of biomineralization-based technologies.

Hirings

No additional personnel was hired this quarter. Postdoctoral researcher Dr. Marnie Feder, M.S. student Arda Akyel, and undergraduate student Cody West are working on the development of advanced mineral precipitation strategies and are 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)*

A proposal was submitted to the U.S. Department of Energy's (DOE) Small Business Technology Transfer (STTR) program (DE-FOA-0001490). The proposal is entitled Developing Biomineralization Technology for Ensuring Wellbore Integrity and Enhancing Oil Recovery. Dr. Robin Gerlach would be the principle investigator, and Randy Hiebert (MET), Adie Phillips (MSU), and Al Cunningham (MSU) would be collaborators. If awarded, the total budget would be $1,000,000 and span over two years (08/16-07/18).

Milestones

A. September 2015-September 2016: Perform laboratory bench experiments to extend the temperature range for mineral precipitation, and thief zone plugging for enhanced oil recovery (EOR)
    a. The team has continued to assess the temperature range and upper temperature limits of jack bean meal urease (JBM). Cottonseed and soy bean meal were identified as additional possible sources of urease and have been purchased. Enzymatic urea hydrolysis kinetics 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 where urea hydrolysis occurred for the first 30 minutes but then reaction did not proceed. After six hours of exposure to 70 °C, JBM urease demonstrated a > 97% decrease in activity. Additional experiments are ongoing to evaluate the rate of inactivation as a function of temperature.

       Similar results have been observed for the *Sporosarcina pasteurii* urease. Ureolytic activity can be observed up to approximately 80 °C but growth of *S. pasteurii* ceases at approximately 40 °C.

    b. The kinetics of thermal urea hydrolysis (thermally induced calcite precipitation or TICP) have been determined for temperatures between 30 and 120 °C. Increasing ureolysis rates were observed at higher temperatures. Additional experiments are being performed to determine the type of mineral and amount of mineral that can form during TICP.

c. Experiments were performed to reassess the compressive strength between the enzymatic (enzyme induced calcite precipitation or EICP) and microbiological (microbially induced calcite precipitation or MICP) types of cement. Experiments were normalized to the overall mass of urea hydrolyzed. The compressive strength testing revealed the enzymatic cement (EICP) had a greater yield stress as compared to the microbial cement (MICP). The EICP samples actually had compressive strengths similar to a 28-day cured well cement that was provided by an industrial stakeholder, Schlumberger. Scanning electron microscopy (SEM) observation revealed a different structure between the EICP and MICP which may contribute to the material properties (Figure 1). One possible explanation of the difference is that the MICP is preferentially induced by microbes attached to the sand grain while EICP might be preferentially induced by suspended (or dissolved) enzyme present in the fluid between the sand grains. The Young's modulus of the material, which is a measure of the stiffness of the material, has not yet been determined.

   Thermal gravimetric analysis of the precipitates will be conducted next quarter to assess the relative content of organics versus calcium carbonate in the precipitates.

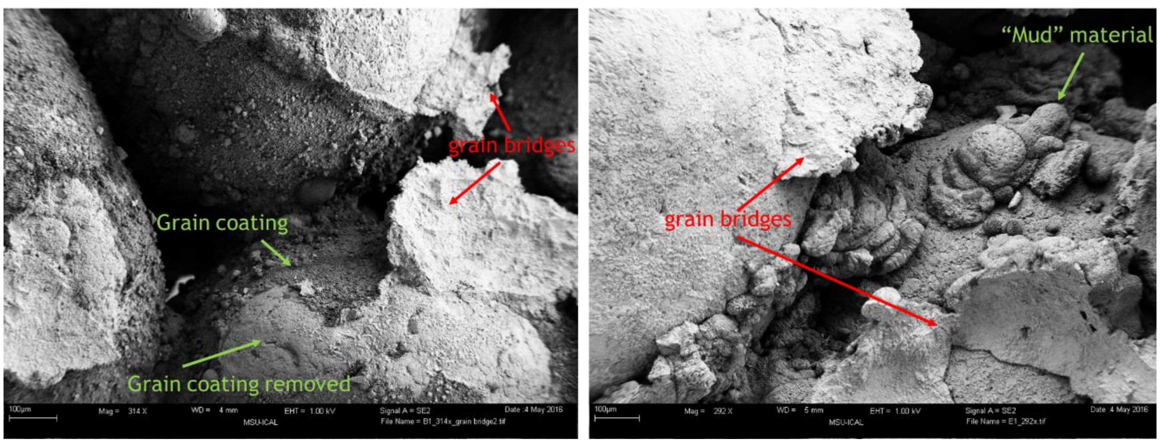

Figure 1. MICP (left) was observed to more completely coat the sand grain with overall smaller calcite crystals but still with significant sand grain bridging. EICP (right) was observed to have more mud-type features where the calcite crystals were larger in between the crystals but less coating of the sand grain was observed.

B. September 2015-September 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 and possible applications have been discussed. Wells as well as field deployment strategies have been discussed.

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, two meetings were conducted with industrial stakeholders related to coal combustion residuals research. The first meeting was conducted April 8, 2016 with Gordon Criswell, Talen Energy, which focused on updating him on the experiments performed on the Colstrip paste samples collected last October. A second meeting with industry (Ben Gallagher, Southern Company) was held April 17, 2016. This meeting included an update on the work done to date with the samples collected from two coal-fired power plants in Georgia. The meeting also led to a discussion of the scope of work to be performed during the upcoming funding period. Finally, a manuscript is in development to be submitted to a peer reviewed journal and/or the World of Coal Ash conference proceedings.

Hirings

No additional researchers were hired this reporting period. Eric Troyer and Abby Thane continued to research MICP (microbially induced calcite precipitation or biomineralization) in CCR material.

Equipment Purchased

No equipment was purchased this reporting period.

Proposal *(leverage the overall MUS research enterprise)*

Dr. Adie Phillips with collaborator Dr. Al Cunningham submitted a proposal to Southern Company entitled Laboratory Testing of The Effects of Biomineralization on Coal Combustion Residuals. If awarded, the total budget would be $40,000 for seven months (05/16-12/16).

Milestones

A. September 2015- September 2016: 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. Samples of the Colstrip coal-fired power plant coal combustion residuals (paste) were collected during a previous reporting period (October 2015). During this reporting period, a meeting was held with Gordon Criswell of Talen Energy (Colstrip) to share the data from biomineralization experiments performed to date with the collected paste. These experiments involved mixing increasing concentrations of paste with biomineralizing microbes and solutions to promote binding of the particles together. Noticeable binding of the material was observed. Increasing concentration (by mass %) of the paste mixed with biomineralizing solutions was noted to decrease the ureolysis rate. Though the rate was reduced, ureolysis and enhanced material binding was observed to still occur even in 50% paste, 50% mineralizing solution mixtures (**Figure 2**). 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.

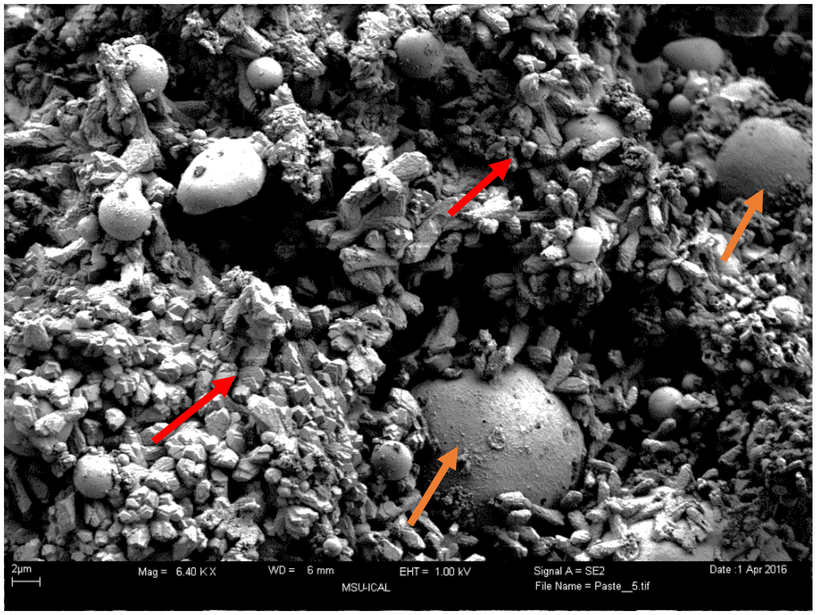

Figure 2. Calcite type minerals (red arrows) were observed to be coating and bridging between ash materials (orange arrows) after biomineralization treatment.

b. A plan was made during the meeting with Southern Company's Ben Gallagher, Senior Engineer of Research and Technology Management, for the additional experiments to be performed during the 2016 funding period (proposal details discussed above). The scope of work was modified to include an additional research question (#3) of direct interest to Southern Company at this time. The three research questions of industrial interest are:

(1) How does biomineralization impact the leachability of hazardous contaminants from CCRs?
(2) What is the magnitude of permeability reduction that can be achieved with biomineralization in CCR materials?
(3) Can baghouse waste cohesiveness be improved with biomineralization?

Experiments continued to be performed to evaluate biomineralization in fly ash and scrubber residuals (gypsum and wastewater) in flask batch studies. In the flask studies, increasing concentrations of fly ash and/or gypsum were mixed with biomineralization promoting solutions. To measure the impacts of biomineralization, the ureolysis rate was monitored, and at the end of the experiment, the samples were observed with microscopy to assess binding of the materials. When 50% fly ash alone was mixed with biomineralizing solutions, the ureolysis rate was significantly decreased compared to lower concentrations of fly ash or the gypsum samples. Significant binding of the material (both ash and gypsum) was noted (**Figure 3**). Experiments to assess the impact of fly ash on the ureolysis rate are planned for the next quarter.

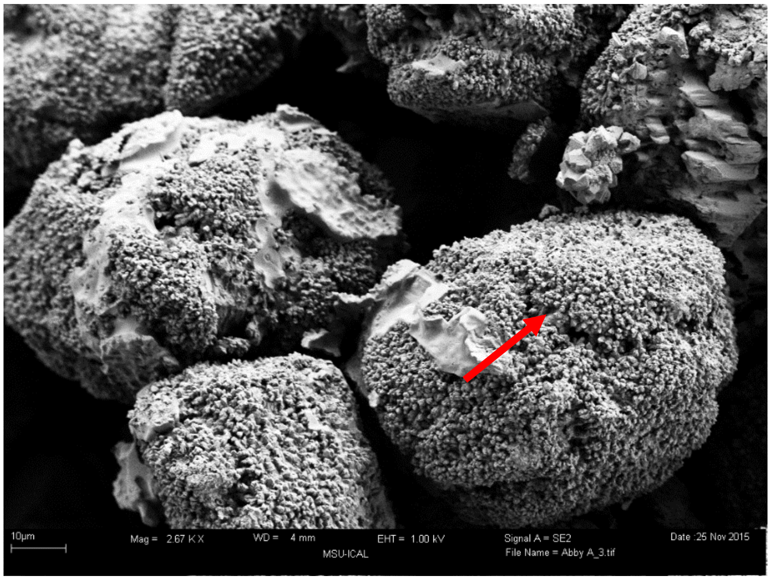

Figure 3. Scrubber waste material mixed with biomineralization solutions - significant calcite type mineral was observed on the surface and between (red arrow) the gypsum particles suggesting binding.

When the fly ash and gypsum materials were mixed it was observed that the increasing concentration of fly ash also had an impact on the ureolysis rate but a less significant impact than with fly ash alone (Figure 4).

Fly ash and gypsum were mixed in varying masses and then added to flasks with an equal mass ratio of biomineralizing solution (total of 100 g fly ash/gypsum + 100 g biomineralization solution). For example, the 25:75 fly ash: gypsum sample was prepared by mixing 25 g of fly ash with 75 g of gypsum in a flask and then adding 100 g of biomineralization solution. The 25:75 fly ash: gypsum mixture did not significantly impact the overall urea degraded (in 24 hours the concentration decreased from 20 to 2 g/L. As the concentration of fly ash increased (75:25 fly ash: gypsum), less overall urea was degraded in 24 hours (20 to 4 g/L). In all of the samples, binding of the materials was observed and evidence of calcite type minerals were observed by microscopy.

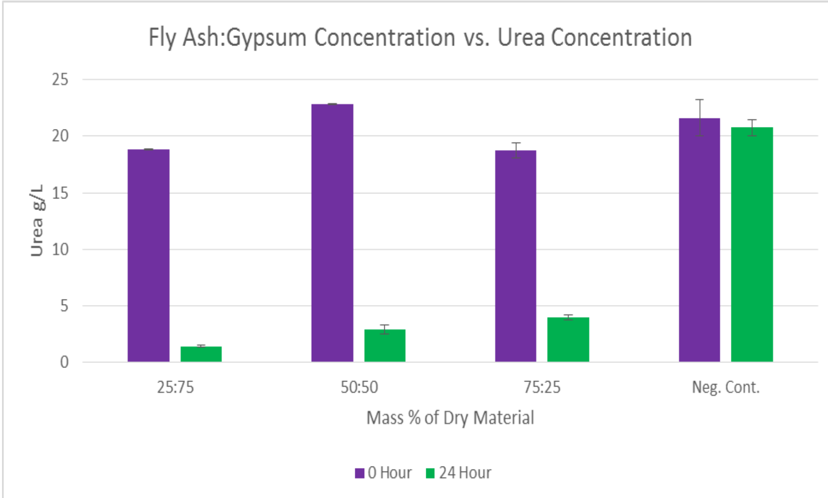

Figure 4. Fly Ash: Gypsum Concentration vs. Urea Concentration

These results show promise for biomineralization to bind together fly ash and gypsum materials at higher concentrations to reduce the amount of water needed to store these materials. Additional work to understand the reason for reduced ureolysis rate in higher concentrations of fly ash in these batch studies is underway. Leachability studies were planned in this quarter and are scheduled to begin in the next quarter.

B. September 2016-September 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.

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

Batch studies were conducted to determine if microbially induced carbonate precipitation (MICP) can facilitate removal of selenium, strontium and barium from artificial groundwater and selenium in pond wastewater from the Colstrip coal-fired power plant. Studies with strontium and barium were initiated to represent potential contamination of groundwater from produced water ponds. Porous media, flow cell reactor systems were constructed, and flow-through experiments of MICP and co-precipitation of strontium and barium are scheduled for next quarter.

Site visits were taken to the Carpenter-Snow Creek Mining district and the Colstrip power plant. Water samples were taken from several adits at the mining district, a now abandoned silver mine and National Priorities List site due to heavy metals contamination. Batch studies to determine the potential for biomineralization based remediation of the contaminated mine water are scheduled for next quarter. At the Colstrip plant, microbial sampling devices were placed down two monitoring wells to survey native microorganisms suitable for selenium bioremediation. Mine tailings were also obtained from the Golden Sunlight Mine and initial tests were conducted to assess the potential for MICP to stabilize and prevent leaching of metals from the tailings.

Hirings

No new personnel were hired this quarter. Ph.D. student Neerja Zambare and undergraduate students Kevin Burt and Lydia Aman continued working on batch studies and constructing flow cell systems for biomineralization and remediation tests.

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. A collaboration to investigate mine tailing remediation using biologically driven mineralization was initiated with Dr. Paul Conrad, professor of mining engineering at Montana Tech. Dr. Conrad provided mine tailing samples from the Golden Sunlight Mine in western Montana. Initial studies to determine extent of metals leaching from tailings and potential for ureolysis driven mineralization and stabilization of the tailings have begun.

    b. Microbial samplers have been placed in two monitoring wells containing selenium contamination at the Colstrip power plant. Samplers will be retrieved in one month and the attached microorganisms analyzed for potential to perform selenium bioremediation.

    c. Collaboration with EPA site manager at Carpenter-Snow Creek mining district, a National Priorities List site near Neihart, MT, was initiated. A sampling trip to the mining district was taken and several abandoned mine adits were sampled for water and sediment. Water is reported to contain high concentrations of zinc and calcium, along with lead, nickel, cadmium and other metals. Several of these metals have been shown to co-precipitate with calcium carbonate and, thus, show promise for removal via MICP.

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

    a. Batch studies were conducted with the mine tailings and leachate obtained from Golden Sunlight. The leachate was analyzed and contained molybdenum, strontium, cobalt and antimony. Initial experiments in batch reactors containing tailings and utilizing model ureolytic bacterium, *Sporosarcina pasteurii*, have visually shown successful MICP on tailings. Results are currently being analyzed.

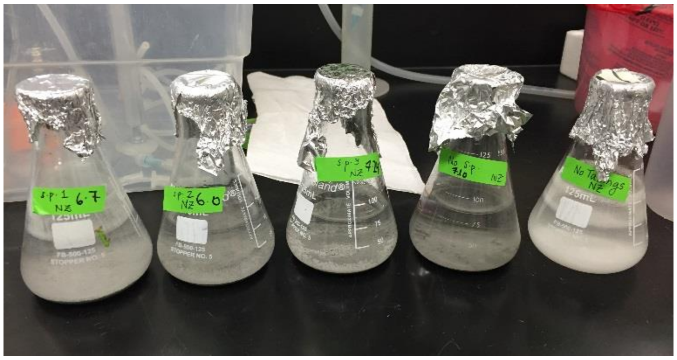

Figure 5. Batch reactors containing mine tailings.

b. Two flow cell reactor systems have been constructed to visualize biologically driven mineralization and co-precipitation in a flow system. The reactors consist of a polycarbonate base with etched porous media channels and a clear glass coverslip to allow time dependent imaging of precipitate formation. The reactor systems will be operated with two inlets to represent mixing of injected fluids with native contaminated groundwater.

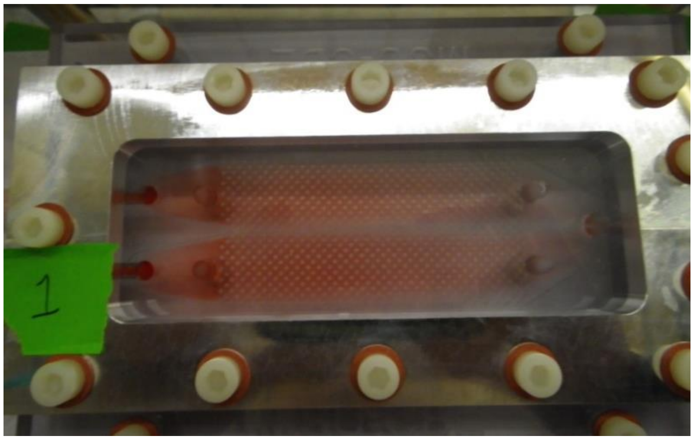

Figure 6. Dye tracer test in flow cell reactor with artificial porous medium. Flow is from left to right.

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. Discussions with Talen Energy engineers regarding potential remediation strategies for selenium contaminated groundwater at Colstrip.

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

This quarter, oil and gas data for all producing horizons in the study area underwent three levels of screening. Criteria for screening EOR suitability was designed around the physical reservoir and rock characteristics used in Van't Veld and Phillips (2010), where the "Analog Method" was used to determine EOR suitability for individual field-reservoir combinations (FRCs). The Analog method scales historical production and injection flows at an existing, mature EOR project (the analog) to predict production and flows of new, proposed EOR projects. However, for this initial screening we focused solely on whether a reservoir passes the preliminary miscibility requirement. Minimum miscibility pressure (MMP) is defined as a reservoir's capability to be pressured to a level at which injected CO_2 mixes with oil. The physical reservoir and rock characteristics required to calculate MMP include depth, API (American Petroleum Institute) gravity, temperature, and fracture pressure (the pressure in the wellbore at which a formation will crack). A reservoir is considered miscible if the calculated MMP is less than the measured fracture pressure.

To accomplish the screening, an ArcGIS shapefile containing the names of 471 FRCs was generated. First, the physical characteristics and production history of the reservoirs were compiled from several data sources including the Montana Geological Society (MGS), Montana Board of Oil and Gas Conservation (MBOGC), IHS Enerdeq Browser, and the National Petroleum Council database (NPC). The compiled data was then added to the attribute table of the shapefile with ArcMap 10.3. Following the compilation of available data, screening and elimination of unsuitable FRCs was initiated by first eliminating all FRCs only producing gas with 370 remaining. From here, the second and third screening criteria were applied, removing all FRCs with a depth less than 2500 feet and historical production less than 5MMbo of oil; 9 remained. Due to the sparse return of suitable fields, screening criteria was modified to include historical production greater than 2MMbo, and small reservoirs were included if another reservoir (producing formation) in the same field met the 2MMbo criterion; 38 FRCs remained after the modified screening. Fracture pressure is recorded in only a small number of drill stem tests compiled from IHS; thus, only 15 FRCs had the necessary data to calculate MMP (the third screening level), and of those 15 only seven were miscible (Figure 7).

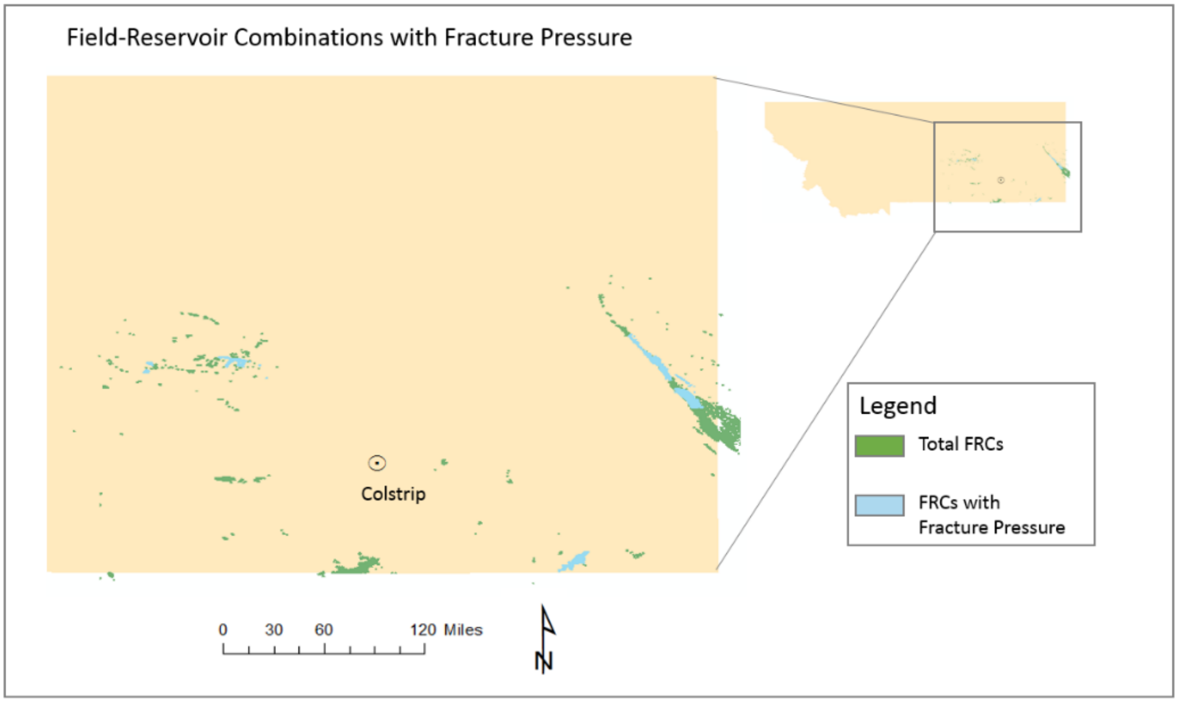

Figure 7. Map of regional FRCs (green) and FRCs that met criteria for depth, production, and miscibility (blue).

Results show that of the seven FRCs calculated to be miscible, all are existing EOR units. However, only one has undergone tertiary CO_2-EOR. With a more accurate and complete data set, more FRCs could be considered miscible. Requirements for a more complete and accurate data set include measured fracture pressures for all field-reservoir combinations, measured formation volumetric factors (FVF) in order to assess economic potential using the analog method, and missing reservoir characteristics such as API gravity, depth, temperature, etc. The team will explore additional data sources next quarter to attempt to fill in data gaps and expand the assessment.

Progress also began on the interactive mapping application. A programming testing environment was created to start developing code and implementing the JavaScript application.

Lastly, Stacey Fairweather participated in a meeting with Gordon Criswell of Talen Energy, to present the current project status and discuss steps for ongoing characterization at Colstrip.

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.

B. December 2016: Completion of the interactive mapping application

   a. Screening results were added to the project geodatabase, which will ultimately house the complete dataset and be tuned for use with the interactive mapping application software. Setup and programming began for the JavaScript-based interactive map.

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

MSU

The MSU team has conducted preliminary bacterial community analysis of algal isolate coal bed methane production water (CBM-W) growth in non-sterile CBM-W. The population dynamics were tracked for one day, seven days, and 14 days of water alone and water inoculated with the algal isolate. Both water and algal aggregates have distinct bacterial communities that shift upon inoculation with the algal culture. Subsequently, the bacterial community shifts further from Day 1 to Day 7 with a more stable community between Week 1 and Week 2. The CBM water is predominated by *Flavobacterium*, *Lutibacter*, *Sediminibacterium*, *Methylophilales*, *Methylosoma*, and *Luteolibacter*. In Day 1 post-inoculation, the water continues to be predominated by *Flavobacterium*, *Lutibacter*, and *Methylosoma*. After one week of algal growth, the CBM-W becomes predominated by *Sediminibacterium*. The algal clumps appear to become predominated by *Flexibacter*, *Flavobacterium*, and *Lewinella*. Further experiments are planned to track community dynamics during outdoor growth as well as on-going data analyses.

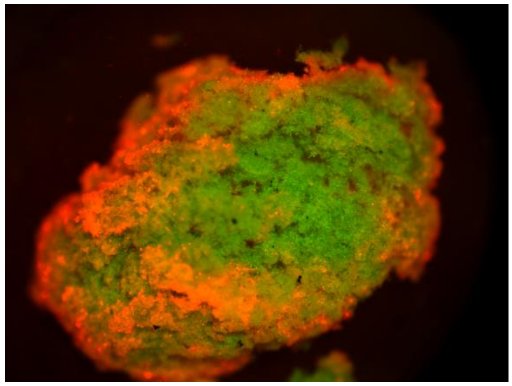

Figure 8. Algal aggregate imaged with Stereomicroscope.

MT Tech

Culturing

Cultures of CBM-W algae were obtained from colleagues at MSU and derivative cultures of the algae were established with 20 ml Bold's Basal Medium/ liter DH_2O in 50 ml Falcon tubes, 2000 ml flasks and beakers, and in a 10 gallon (37.84 L) aquarium. Flasks and beakers are aerated with an aquarium pump and tubing for the smaller vessels, and the aquarium is aerated with a Millipore pump, tubing, and a hollow plastic pipe with holes that is placed around the periphery of the inside of the aquarium. Cultures are grown on laboratory benches with daylight from a bank of south-facing windows, ambient temperatures, and fluorescent room lighting.

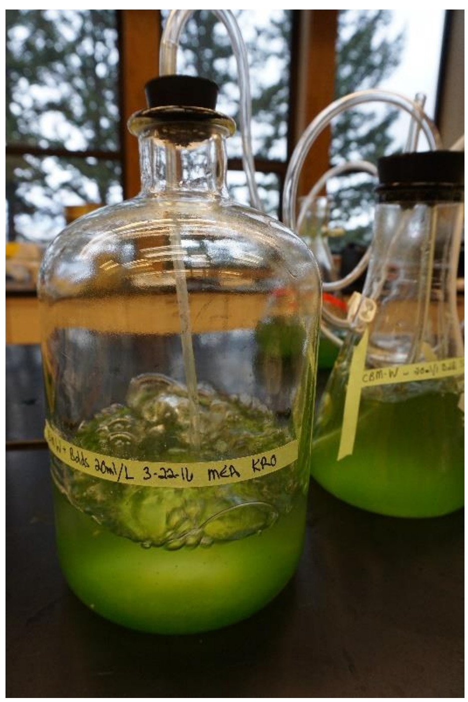

Figure 9. Aerated culture vessels

Nutrient Testing

Nutrient testing was conducted on CBM-W algal samples that were sent to the Agricultural and Environmental Services Laboratory at the University of Georgia – Athens.

Figure 10. Algae in graduated cylinders used to collect samples for nutrient analysis.

Plants

Grains of hard red spring wheat from the Northern Seed Company, LLC, were planted in soil and provided with water, water + CBM-W algae, or water + conventional fertilizer in the Montana Tech greenhouse. Wheat seedlings are now being monitored for growth and chlorophyll content.

Figure 11. One of the trays of wheat seedlings from the wheat + water, wheat + algae, and wheat + conventional fertilizer experiment.

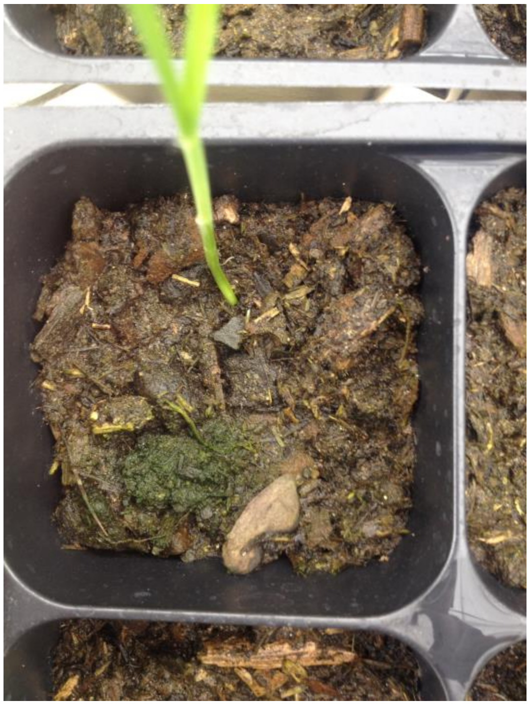

Figure 12. Wheat seedling with a biofilm of the algae growing on the soil.

Russett Burbank seed potatoes are kindly being supplied by Nina Zidack of Montana State University's Potato Lab with the goal of testing them for growth with CBM-W algae as fertilizer.

Hirings

MSU
Logan Hodgskiss resigned from MSU to start his Ph.D. studies in Europe. Efforts have begun to replace the vacant position.

MT Tech
Mr. Olakunle (Kunle) Ogunsakin was hired as a graduate student in December 2015.

Equipment Purchased

MSU
No major equipment purchase were made this quarter.

MT Tech
Flasks, Falcon tubes, flexible tubing for aeration, and an aquarium pump have been purchased for culturing the algae. Seeds were purchased from the Northern Seed Company, LLC for testing with CBM-W algae as fertilizer.

Proposal *(leverage the overall MUS research enterprise)*

MT Tech
Dr. Apple is among the collaborators on a proposal lead by Dr. Brent Peyton (MSU) entitled **Formulating, Processing, and Testing Living Biofertilizers for Restoration of Energy and Mining Landscapes** that was submitted to the National Science Foundation Experimental Program to Stimulate Competitive Research (NSF-EPSCoR). This proposal is related to the MREDI project. (Lead: B Peyton-MSU, co-lead: R Pal-MT Tech).

Milestones

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

   a. MT Tech: Continued collaborative discussions take place among the researchers in Objective 5 on summer 2016 field research and other relevant topics.

      MSU: Cultivation equipment continues to be setup for outdoor use once temperatures warm and outdoor light increases.

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: CBM-W algal samples have been analyzed for macronutrient and micronutrient composition. Olakunle Ogunsakin has been recruited and hired as a graduate student for this project.

      MSU: Recruiting began for the postdoc/technician position. Methods are being developed for the growth of algal biofilms to aid in biomass collection and elemental composition.

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

   a. MT Tech: Preliminary experiments with plants and algal fertilizer are taking place at Montana Tech.

      MSU: No activity to report this period.

Objective 6

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

Quarter activities and accomplishments
During this reporting period, we mainly have carried out satellite image data collection, processing, and instrument acquisition, and started algorithm development for this objective. The main activities during this period of time include completion of instrument purchase, satellite data acquisition covering the research sites, image processing, continue literature review and started the initiation of algorithm development. (1) The graduate student has started image processing including image classification for this project. (2) Instrument purchase: the purchase of a hyperspectral imaging system was completed. (3) We collected Google high-resolution

satellite images covering the ten Coal-bed Methane ponds within the Montana Powder River Basin; (4) The high-resolution satellites were successfully georeferenced in UTM coordinate system for areal extraction; (5) We continued literature review of efficient algorithm for water body extraction so that the area of ponds can be automatically derived. We started some preliminary algorithms and wrote MATLAB programs and testing.

Hirings
No hires were made during this quarter.

Equipment Purchased
The purchase request including three quotes for a hyperspectroradiometer was submitted to the business department. The equipment is expected to be ordered next quarter.

Milestones

A. July 2015 – July 2016: Estimate areal coverage of CBM ponds using Hyperion or Landsat data
    a. Google very high-resolution (0.20-0.30 m) satellite data acquisition covering the ten CBM ponds within the Montana Powder River Basin (PRB) was completed.
    b. The extremely high-resolution images were collected individually for each pond. We started image processing including georeference and classification.
    c. Literature review on the algorithm development continued.
    d. A preliminary procedure was established for the automatic areal extraction of CBM ponds.

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.
    b. Algal extract is being tested and compared to yeast extract and cyanobacteria extract.
    c. Preliminary results suggest that coal-dependent methanogenesis can be sequentially stimulated; however, the coal-dependent nature of the methane production appears to subside.
    d. Algal and cyanobacterial extract appears to perform better in terms of subsequent stimulations for coal-dependent methanogenesis.

C. July 2016 – July 2017: Monitor mesoscale growth of algae using spectral methods
    a. The acquisition of the hyperspectral imaging system was completed for algae spectral measurement.
    b. Several meetings were held with Martha Apple's group regarding algae growing and monitoring in Montana Tech. Dr. Apples's group has successfully grown algae on a benchmark scale.

c. When the density of algae is high enough, most likely this summer, the spectral data and biomass will be measured.

d. Literature review continued for algae monitoring from remote the sensing point of view.

Expenditures to Date

Quarterly Report		04/30/2016
	All Budgets	Spent to Date
Salaries & Benefits	717,237	92,916
Subcontract Payments		
Montana Tech	222,667	4,604
Montana Emergent Technologies	75,000	25,250
Operations	160,096	26,815
Equipment	25,000	
Total Costs	**1,200,000**	**149,585**

References

Van't Veld, Klaas, and Owen R. Phillips. "The Economics of Enhanced Oil Recovery: Estimating Incremental Oil Supply and CO_2 Demand in the Powder River Basin." The Energy Journal (2010): 31-55.