A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach
  Task 2 - Developing Nutrient Solutions for Sites #1 and #2
  Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions
  Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification
  Task 5 - Determining In Situ Permeability Evolution
  Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems

Project Structure
Project Schedule
Project Budget
Project Management Plan and Risk Management
Background

Geographic Distribution

Methods of production

A

(1) Nutrient Injection Skid: Nutrients added to water and injected into well using gravity

(2) Well closed off and nutrients allowed to soak for several years

(3) Water and methane (in place gas + newly generated gas) produced from well

(4) Produced water used to inject nutrient into wells in other parts of the field

Projected US Gas Production

MECBM Scheduling

[Science, Oct 18, 2012]

[Nuccio, 2000]
Objectives

Develop Nutrient Solutions
   Extend work on Illinois Basin
   Initiate work on San Juan Basin

Optimize Methods of Delivery
   Explore hydraulic fracturing for improved sweep
   Define longevity of fracture treatment
   Permeability evolution - nutrient delivery & CH₄ productivity

Evaluate Potential Improvement

Synthesize Response
   Microbiology - improved productivity
   Geomechanics - delivery and longevity

Design Field Experiment
   Define/refine key questions
   Identify key location
   Identify unique tools/methods
A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach

Task 2 - Developing Nutrient Solutions for Sites #1 and #2 (SIU)
- Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
- Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
- Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions
- Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
- Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
- Subtask 3.3 - Evaluating properties of coal after bioconversion

Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification
- Subtask 4.1 - Understanding hydraulic fracture characteristics
- Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
- Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures

Task 5 - Determining In Situ Permeability Evolution
- Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
- Subtask 5.2 - Quantifying gas recovery after microbial growth
- Subtask 5.3 - Developing models for permeability evolution in the reservoir

Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
- Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
- Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
- Subtask 6.3 - Complete preliminary economic analysis

Project Structure
Project Schedule (use Gantt chart)
Project Budget
Project Management Plan and Risk Management
Rationale for Task 2

1. The nutrient solution we have developed for IL coal so far is tap water based without considering composition of the formation water.

2. For this project, we will test nutrient recipes based on the exact composition of the formation water at the two sites.

3. Composition and structure of the microbial community at the SJ basin is unknown.
Task 2: Accomplishments

1. Formation water collection

Two trips: IL basin: 10/14/2015
   SJ basin: 10/23-27/2015

Procedure:
1) Water samples were added to containers containing: Na₂S (1 mM) and resazurin (2 mg/l).
2) During transportation, containers were kept on ice.
3) Upon arrival in the lab, part of water was filtered to collect microbial cells, part was centrifuged to obtain concentrated cells. One half gallon was sent for chemical analyses. All the others were stored in a freezer (-20°C) directly.

Results:
1) 200 frozen stocks (-80°C) of microbial community for each site.
2) 10 gallon of water frozen (-20°C) for each site.
3) Active cultures from each site are growing in our lab.
2. **Chemical analysis**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>IL basin</th>
<th>SJ basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>25-32</td>
<td>41-44</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>7.65</td>
<td>8.19</td>
</tr>
<tr>
<td>Free ammonia</td>
<td>mg/l</td>
<td>0.012</td>
<td>0.23</td>
</tr>
<tr>
<td>Total ammonia</td>
<td>mg/l</td>
<td>9.05</td>
<td>1.78</td>
</tr>
<tr>
<td>Total Nitrogen-N</td>
<td>mg/l</td>
<td>&lt;5.0</td>
<td>2.4</td>
</tr>
<tr>
<td>COD</td>
<td>mg/l</td>
<td>650</td>
<td>2497</td>
</tr>
<tr>
<td>H$_2$S</td>
<td>mg/l</td>
<td>431</td>
<td>33</td>
</tr>
<tr>
<td>Fluoride</td>
<td>mg/l</td>
<td>1.8</td>
<td>4</td>
</tr>
<tr>
<td>Nitrite</td>
<td>mg/l</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg/l</td>
<td>&lt;0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Phosphate</td>
<td>mg/l</td>
<td>&lt;0.75</td>
<td>&lt;0.75</td>
</tr>
<tr>
<td>Total phosphate-P</td>
<td>mg/l</td>
<td>&lt;5.0</td>
<td>0.171</td>
</tr>
<tr>
<td>Sulfate</td>
<td>mg/l</td>
<td>&lt;0.75</td>
<td>&lt;0.75</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/l</td>
<td>21665</td>
<td>161</td>
</tr>
<tr>
<td>Iron</td>
<td>mg/l</td>
<td>0.3</td>
<td>1.11</td>
</tr>
<tr>
<td>Total dissolved organic carbon</td>
<td>mg/l</td>
<td>0.44</td>
<td>1.15</td>
</tr>
<tr>
<td>Alkalinity as CaCO3</td>
<td>mg/l</td>
<td>400</td>
<td>1280</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>ug/l</td>
<td>Pending</td>
<td>Pending</td>
</tr>
</tbody>
</table>

3. **Microbial analysis**

1. **DNA was extracted from water samples from SJ basin.**
2. **Samples of DNA with good concentration and quality were sent for sequencing.**
Task 2: Accomplishments - cont.

4. Active cultures in the lab

**Fig.** Cultures developed from frozen stocks from two sites. For IL basin, the microcosms contained: IL coal + one nutrient solution + cells and incubated at 28°C. For SJ basin, the microcosms contained: SJ coal + SJ formation water + cells and incubated at 43°C. YE: yeast extract, TP: trypticase peptone. A: total gas volume; B: methane content.
A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach
Task 2 - Developing Nutrient Solutions for Sites #1 and #2
  Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
  Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
  Subtask 2.3 - Developing nutrient recipes for site #2
Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (SIU)
  Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
  Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
  Subtask 3.3 - Evaluating properties of coal after bioconversion
Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification
  Subtask 4.1 - Understanding hydraulic fracture characteristics
  Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
  Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures
Task 5 - Determining In Situ Permeability Evolution (Shimin)
  Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
  Subtask 5.2 - Quantifying gas recovery after microbial growth
  Subtask 5.3 - Developing models for permeability evolution in the reservoir
Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
  Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
  Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
  Subtask 6.3 - Complete preliminary economic analysis

Project Structure
Project Schedule (use Gantt chart)
Project Budget
Project Management Plan and Risk Management
Rationale for Task 3

1. For fractured coal, we need to understand how often nutrients should be provided under in situ conditions and how methane yield can be affected by different fracturing.

2. Comparing methane yield between setups where nutrients are fed intermittently vs. continuously.

3. Understand changes made to coals at the two sites due to biogasification.
Future work

Task 2

Subtask 2.2 - Analyzing DNA sequencing data and understanding microbial composition of formation waters from site #2
Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (Satya, Yanna)
Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
Subtask 3.3 - Evaluating properties of coal after bioconversion
Background

Project Objective

Technical Approach

Task 2 - Developing Nutrient Solutions for Sites #1 and #2 (Yanna)
  Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
  Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
  Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (Satya)
  Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
  Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
  Subtask 3.3 - Evaluating properties of coal after bioconversion

Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification (PSU)
  Subtask 4.1 - Understanding hydraulic fracture characteristics
  Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
  Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures

Task 5 - Determining In Situ Permeability Evolution (Shimin)
  Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
  Subtask 5.2 - Quantifying gas recovery after microbial growth
  Subtask 5.3 - Developing models for permeability evolution in the reservoir

Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
  Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
  Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
  Subtask 6.3 - Complete preliminary economic analysis

Project Structure

Project Schedule (use Gantt chart)

Project Budget

Project Management Plan and Risk Management
**Rationale for Task 4**

1. One method to effectively sweep the entire reservoir is to use hydraulic fracturing.

If we do this, we need to understand:

1. What will be the dimensions of the hydraulic fractures?
2. What will be the permeability - with proppants?
3. How will this permeability change with time?
4. How will permeability change away from the fracture?
Hydraulic Fracturing

Sample Geometry

Sample Platens/Seals

\( \sigma_a \)

\( P_{IJ} \)

\( \sigma_c \)

\( D = 1'' \)

\( L = 2'' \)

Confining Pressure

Fluid Pressure

Pressure (MPa)

Time (mins)
Results for Shales

Stress-dependent failure modes

Case 1: If $\sigma_d \ll \sigma_c$

Case 2: If $\sigma_c \ll \sigma_d$

Breakdown pressures

- CO2 Longitudinal Fracture
- N2 Longitudinal Fracture
- H2O Longitudinal Fracture
- Linear (CO2 Longitudinal Fracture)
- Linear (N2 Longitudinal Fracture)

\[ p_b = 1.3375\sigma_c + 4.375 \quad R^2 = 0.8983 \]
\[ p_b = 1.0296\sigma_c + 6.0185 \quad R^2 = 0.8425 \]
Proppant Embedment - Measurements

Split sample

Embedment and swelling

Apparatus

Observation
Proppant Embedment - Analysis

White light interferometry

Irrecoverable embedment

Permeability model
A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach

Task 2 - Developing Nutrient Solutions for Sites #1 and #2
  Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
  Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
  Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions
  Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
  Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
  Subtask 3.3 - Evaluating properties of coal after bioconversion

Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification
  Subtask 4.1 - Understanding hydraulic fracture characteristics
  Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
  Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures

Task 5 - Determining In Situ Permeability Evolution (PSU)
  Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
  Subtask 5.2 - Quantifying gas recovery after microbial growth
  Subtask 5.3 - Developing models for permeability evolution in the reservoir

Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
  Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
  Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
  Subtask 6.3 - Complete preliminary economic analysis

Project Structure
Project Schedule (use Gantt chart)
Project Budget
Project Management Plan and Risk Management
Rationale for Task 5

1. Delivery of nutrients is dependent on changes in permeability with time

We need to understand:

1. What is the initial permeability of coal?
2. How does this permeability change with nutrient delivery?
   1. Duration
   2. Concentration
   3. Gas production
3. How does gas recovery change with nutrient delivery - in situ?
Multi-Porosity Multi-Permeability and Multi-Scale Medium

Desorption from coal grain
Diffusion through micro-pores
Flow in cleats
Coal seam

<3
-2
-1
0
>1
Log (m)

Overlapping Continua

Storage
- Dissolved in water
- Free-gas
- Sorbed gas

Transport
- Multi porosity/permeability
- Matrix interchange
- Fickian diffusion
- Advection

Deformation
- Aggregate response
- Strain partitioning
- Fluid pressures
- Compliances
Key Mechanistic Features [2] - Permeability

Permeability Model:

Fracture permeability

$$k = \frac{b^3}{12s}$$

Initial aperture

$$b_0 = \frac{3\sqrt{12ks}}{b}$$

Dynamic permeability of the cracked system:

$$\frac{k}{k_0} = \left(1 + \frac{\Delta b}{b_0}\right)^3 \sim \left(\frac{\phi}{\phi_0}\right)^3$$
Experimental Investigation

- Triaxial loading
- Temperature control
- Deformation monitoring
- High accurate pressure monitoring

Schematic of experimental setup

Experimental setup

Coal Core samples
Ensemble Response

Permeability relationship:

\[
\frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3
\]

Fracture stiffness:

\[
\overline{K_n} = \frac{E_a}{b} \frac{s-a}{s} + K_n \frac{a}{s}
\]

Permeability evolution:

\[
\frac{k}{k_0} = \left(1 + \frac{(\alpha_f - \alpha_s)}{1 + K_n s/E_s} \frac{s(P-P_0)}{b_0 E_s} - 3 \epsilon_L P_L \frac{(P-P_0)}{P_0 + P_L} \right)^3 \quad [\text{parallel}]
\]

\[
\frac{k}{k_0} = \left(1 + \frac{(\alpha_f - \alpha_s)}{1 + K_n s/E_s} \frac{s(P-P_0)}{b_0 E_s} \right)^3 \left(1 - 3 \epsilon_L P_L \frac{(P-P_0)}{P_0 + P_L} \phi_0 \frac{(P+P_L)(P_0+P_L)}{\phi_0} \right)^3 \quad [\text{series}]
\]

[Wang et al., JGR, 2011]
Permeability Evolution During Sweep Experiments - Dry

Experimental Sequence
- Helium
- Methane
- CO₂ sweep of Methane
- CO₂
- Helium sweep of CO₂

Observations

Pore Pressure Effects
- Non-sorbing (He) – effective stress
- Swelling (CH₄, CO₂) - Swelling effect
- Irrespective of displacement constraint

Effective Stress Effects
- K decreases with eff. stress increase

Gas Saturation
- Different affinities (not shown)
- K change He<CH₄<CO₂

CO₂ Sweep Effects
- Slight perm increase over displaced CH₄
Permeability Evolution During Sweep Experiments - Wet

**Experimental Sequence**
- Helium
- Methane
- CO₂ sweep of Methane
- CO₂
- Helium sweep of CO₂

**Observations**

**Increased Water Saturation**
- Perm changes in same order: He<CH₄<CO₂
- Relative perm changes are of the same magnitude as dry
- But absolute perm is reduced x10 when wet
- Reduced sorption capacity (not shown)

![Confining Stress 10 MPa](graph)
Mechanistic model

\[ \frac{k}{k_0} = \alpha \exp(-\beta \sigma') \]

\[ \frac{k}{k_0} = \left(1 + C \left(\frac{p}{p + p_L}\right)\right)^3 \]

\[ \frac{k}{k_0} = \gamma \exp(-\delta S_w) \]

Effective stress \quad Swelling \quad Saturation

\[ \left(\frac{k}{k_0}\right) = f(\sigma', p_{CO_2}, p_{CH_4}, p_{He}, S_w) = \left(1 + C \left(\frac{p}{p + p_L}\right)\right)^3 + \exp(-\beta \sigma') \times \exp(-\delta S_w) \]
A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach
Task 2 - Developing Nutrient Solutions for Sites #1 and #2 (Yanna)
  Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
  Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
  Subtask 2.3 - Developing nutrient recipes for site #2
Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (Satya)
  Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
  Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
  Subtask 3.3 - Evaluating properties of coal after bioconversion
Task 4 - Characterizing Hydraulic Fracturing for Improved Bio-Gasification (Derek)
  Subtask 4.1 - Understanding hydraulic fracture characteristics
  Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
  Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures
Task 5 - Determining In Situ Permeability Evolution (Shimin)
  Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
  Subtask 5.2 - Quantifying gas recovery after microbial growth
  Subtask 5.3 - Developing models for permeability evolution in the reservoir
Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
  Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
  Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
  Subtask 6.3 - Complete preliminary economic analysis

Project Structure
Project Schedule (use Gantt chart)
Project Budget
Project Management Plan and Risk Management
Rationale for Task 6

1. How do the gas production magnitudes from lab-batch reactors scale to field-scale?

We need to understand:

1. What are the key microbial factors influencing gas-yield?
   1. Nutrient composition/type?
   2. Rate of supply?
   3. Duration of supply?

2. How are these factors aided by engineering?
   1. Hydraulic Fracturing versus no-HF?
   2. Dimensioning of fracture and complexity?
   3. Longevity of fractures?
   4. Evolution of permeability?

3. What are key measurements needed in a field project? Field-scale influences and scalability
   1. Nutrient delivery - key parameters?
   2. Gas recovery - key parameters?
   3. Roles of fracturing and field permeability evolution in these?
   4. Experimental design to probe these influences.
Project Structure and Management Plan

Background
Project Objective
Technical Approach

**Task 2** - Developing Nutrient Solutions for Sites #1 and #2 (SIU - Liang/Harpalani)
- Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
- Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
- Subtask 2.3 - Developing nutrient recipes for site #2

**Task 3** - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (SIU - Harpalani/Liang)
- Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
- Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
- Subtask 3.3 - Evaluating properties of coal after bioconversion

**Task 4** - Characterizing Hydraulic Fracturing for Improved Bio-Gasification (PSU - Elsworth/Liu)
- Subtask 4.1 - Understanding hydraulic fracture characteristics
- Subtask 4.2 - Quantifying loss of permeability by proppant embedment and fracture diagenesis
- Subtask 4.3 - Developing models for field-scale permeability evolution of hydraulic fractures

**Task 5** - Determining In Situ Permeability Evolution (PSU - Liu/Elsworth)
- Subtask 5.1 - Quantifying permeability evolution with nutrient delivery and microbial growth
- Subtask 5.2 - Quantifying gas recovery after microbial growth
- Subtask 5.3 - Developing models for permeability evolution in the reservoir

**Task 6** - Define the Viability of Bio-Gasification (MECBM) Systems (All)
- Subtask 6.1 - Define upscaled bio-gasification productivity for field implementation
- Subtask 6.2 - Define timescales and bio-stimulation yields of prototypical field experiments
- Subtask 6.3 - Complete preliminary economic analysis
# Project Schedule

## Schedule of Tasks and Milestones

<table>
<thead>
<tr>
<th>Task 1: Project Management and Planning (PSU &amp; SIUC)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 2: Developing Nutrient Solutions for Sites #1 and # 2 (SIUC)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Characterizing chemical composition of formation waters for sites #1 and #2</td>
<td></td>
</tr>
<tr>
<td>2.2 Characterizing microbial composition of formation waters from site #2</td>
<td></td>
</tr>
<tr>
<td>2.3 Developing nutrient recipes for site #2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 3: Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (SIUC)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Evaluating methane yield from the core holder operated under fed-batch</td>
<td></td>
</tr>
<tr>
<td>3.2 Evaluating methane yield from core holders operated under continuous mode</td>
<td></td>
</tr>
<tr>
<td>3.3 Evaluating properties of coal after bioconversion</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 4: Characterizing Hydraulic Fracturing for Improved Bio-Gasification (PSU)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Understanding hydraulic fracture characteristics</td>
<td></td>
</tr>
<tr>
<td>4.2 Quantifying loss of permeability by proppant embedment and fracture diagenesis</td>
<td></td>
</tr>
<tr>
<td>4.3 Developing models for field-scale permeability evolution of hydraulic fractures</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 5: Determining In Situ Permeability Evolution (PSU)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Quantifying permeability evolution with nutrient delivery and microbial growth</td>
<td></td>
</tr>
<tr>
<td>5.2 Quantifying gas recovery after microbial growth</td>
<td></td>
</tr>
<tr>
<td>5.3 Developing models for permeability evolution in the reservoir</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 6: Define the Viability of Bio-Gasification (MECBM) Systems (PSU &amp; SIUC)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Define upscaled bio-gasification productivity for field implementation</td>
<td></td>
</tr>
<tr>
<td>6.2 Define timescales and bio-stimulation yields of prototypical field experiments</td>
<td></td>
</tr>
<tr>
<td>6.3 Complete preliminary economic analysis</td>
<td></td>
</tr>
</tbody>
</table>

## Deliverables - Quarterly and Final Reports

<table>
<thead>
<tr>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Briefings/Technical Presentations

<table>
<thead>
<tr>
<th>Group meetings</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

x: Completed