SITE CODE: NETL - National Energy Technology Laboratory, Pittsburgh, PA, and Morgantown, WV

A. STI PRODUCT IDENTIFIERS:
*1. Report/Product Number(s): DOE/NT/15549
*2. DOE Contract Number(s): DE-FC26-05NT15549
3. Other Identifying Number(s):

B. ORIGINATING RESEARCH ORGANIZATION:

C. STI PRODUCT TITLE: Produced Water Management and Beneficial Use

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E. STI PRODUCT PUBLICATION/ISSUE DATE: 5/31/2007

F. STI PRODUCT TYPE: Technical Report

Technical Report Type: 4th Semi-annual progress report

G. STI PRODUCT OR TECHNICAL REPORTING PERIOD:


H. SPONSORING ORGANIZATION: USDOE - Office of Fossil Energy (FE)
I. SUBJECT CATEGORIES: 03 NATURAL GAS; 01 COAL, LIGNITE, AND PEAT

Keywords: Coal Bed Methane Produced Water Treatment

This document contains the fourth semi-annual report on the two year Produced Water Management and Beneficial Use project that is overseen by the Colorado Energy Research Institute (CERI) at Colorado School of Mines, Golden, Colorado. This project is investigating means to manage and treat co-produced Coal Bed Methane water for beneficial use in the Powder River Basin. The fundamental logic of this project is the recognition that no single treatment can be applied to all co-produced water from Coal Bed Methane (CBM) operations. This project is focused on the Powder River Basin of Wyoming, but the management and treatment procedures can be exported to other CBM areas in the US. There are several challenges to disposal of CBM water. First, water production has an inverse trend over well life compared to traditional gas wells; second, the need to maintain low reservoir pressures renders disposal by re-injection problematic; third, the unique water chemistry makes surface disposal complicated. The produced water is potentially potable water and thus, represents a potential economic benefit to farmers and ranchers. Therefore, a variety of options will be developed and evaluated to provide CBM operators with the most cost-effective and environmentally sound practices for disposal of co-produced water. The project consists of 10 tasks divided among several research Institutions including Argonne National Laboratory, Gas Technology Institute, Montana Technical University, PVES Inc., Stanford University, Pennsylvania State University, and the University of Wyoming. The project is being managed by the Colorado Energy Research Institute.

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*Organization: Colorado Energy Research Institute
Overview

This document contains the fourth semiannual report on the two year Produced Water Management and Beneficial Use project that is overseen by the Colorado Energy Research Institute (CERI) at Colorado School of Mines, Golden, Colorado. The fundamental logic of this project is the recognition that no single treatment can be applied to all co-produced water from Coal Bed Methane (CBM) operations. This project is focused on the Powder River Basin of Wyoming, but the management and treatment procedures can be exported to other CBM areas in the US. There are several challenges to the disposal of CBM water. The production of CBM water follows an inverse pattern compared to traditional wells (high to low). CBM wells need to maintain low reservoir pressures to promote gas production making the normal practice of re-injection counterproductive. The unique water chemistry of the produced water can damage soil making surface disposal difficult. Finally, the produced water is potable, making this a valuable resource in the western US rather than an undesirable by-product, the usual case in traditional petroleum operations. Therefore, a variety of options will be developed and evaluated to provide CBM operators with the most cost-effective and environmentally sound practices for co-produced water.

The project has a total of ten tasks (1-10) with subcontractors from the Argonne National Laboratory, the Gas Technology Institute, University of Wyoming, Stanford University, Montana Tech, Pennsylvania State University and a private firm, PVES Inc. The report is divided in sections for each task. Task 9 was a one-year task and has been completed. Please note that task 2a is the responsibility of Argonne National Laboratory and is funded separately through Argonne. Task 10 is also the responsibility of Argonne National Laboratory and is funded separately through Argonne. In both case (tasks 2a and 10), separate progress reports are filed directly with DOE by those PI’s.

DOE Contract DE-FC26-05NT15549
Recipient - Colorado Energy Research Institute
Task 0 Management of Projects
PI – Dag Nummedal

Results
Funding was established for this project starting April 29, 2005. All subcontracts were in place by June 2005. CERI (Colorado Energy Research Institute) has held four meetings with all the subcontractors attending to establish financial and reporting procedures identify areas of potential collaboration between projects and facilitate collaboration between projects. A fourth project meeting was held on March 1, 2007 with all PI’s presenting updates on their tasks and much inter-group discussion taking place. The following day, a workshop was held with attendance by industry representatives where a summary of our research was presented in an effort to foster technology transfer and a dialog with industry to better understand their problems. On April 24, 2007, Dag Nummedal and Lee Landkamer traveled to Tulsa Oklahoma to present a summary of research results to NETL personnel and the project manager, Jesse Garcia. The
presentation was well received and valuable discussion took place. The organizational structure of this project is diagrammed below. Copies of all the presentation files from presentations by subcontractors are sent to our DOE project officer, Jesse Garcia in Tulsa.

CERI is actively working to identify specific areas of research not presently included to add to this project in future funding cycles as well as supplementing the technical capabilities of some subcontractors by providing geochemical modeling expertise. CERI has also been participating in resolving land access issues for the Beaver Creek Field Site, which should be formalized in the near future.

The remainder of this document is organized to facilitate the reader’s grasp of this complex project. The original task numbers were arbitrarily assigned, not organized to group related task together. Therefore this report is divided into five sections consistent with the task area rather than task number. The five areas of research are:

<table>
<thead>
<tr>
<th>Research Area (and overview pg number)</th>
<th>Tasks (and pg number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Fluid Reduction (6-7)</td>
<td>1 (8-23), 4 (24-33)</td>
</tr>
<tr>
<td>2 – Surface Disposal (34-39)</td>
<td>3 (40-51), 6 (44-52), 7 (61-68)</td>
</tr>
<tr>
<td>3 – Beneficial Agricultural Use (69)</td>
<td>5 (70-73)</td>
</tr>
<tr>
<td>4 – Re-Injection</td>
<td>completed</td>
</tr>
<tr>
<td>5 – Water Treatment &amp; Mobile Testing Unit (82-83)</td>
<td>2 (76-81), 8 (82-84)</td>
</tr>
</tbody>
</table>
The figure below summarizes the project organization in terms of work categories and flow.
FLUID REDUCTION – TASKS 1 AND 4

Conclusions

Using underground membranes to produce methane from coal beds without de-watering would be impracticable in the absence of a free gas phase due to the very large amount of membrane surface area required. However, if a free gas phase is present, the required membrane area drops dramatically and the concept becomes more viable.

Test on intact coal cores from the Powder River Basin indicate that coal swelling and subsequent decreases in permeability are not a problem when CO₂ is injected, contrary to previous results by other researchers on different types of coals.

Injection of produced CBM water into sands overlying coal beds should be feasible due to low pore pressures in these sands. However, sands that are within 200 feet of a coal bed should not be used for re-injection because these sands tend to be in hydraulic communication with the coal beds. Re-injection into sands near coal beds could potentially result in re-saturation of the coal beds.

Schedule Status
Anticipated Completion Date for all Tasks – 10-31-07

Significant Accomplishments

Task 1:
A mathematical model that describes the mass transfer rates of methane and CO₂ between a liquid phase and a gas phase across the gas permeable membrane selected for this project has been developed and verified.

Long-term imbibition experiments designed to characterize pore-size distributions of intact coal coupons are within weeks of being finished. The most critical parameter, the amount of microporosity present, was found to be 17.7% and 19.5 % of the total porosity for the Canyon and Smith coals, respectively.

The first multi-gas injection experiments with intact cores have been finished and a gas isotherm experiment was performed with an intact core and methane.

Task 4:
We have calculated pore pressures in 250 wells that monitor water levels in coalbeds and adjacent sands within the PRB, all 250 wells have pore pressures below hydrostatic pressure, implying that injection of CBM water should be feasible.

Fluid flow simulations were run to determine the rates at which CBM water can be injected into shallow (~300 ft) and deep (~1000 ft) aquifers. We find that for the shallow sand model we can inject water at a rate of ~160 bbl/day, whereas for the deeper sand, whose pore pressures are lower than the shallow sand, the rate is ~435 bbl/day.
Additional fluid flow simulations indicate that natural hydraulic communication between coals and overlying sands is not the cause of excessive water production observed in some CBM wells, suggesting that vertical hydraulic fractures and normal faults may play a role in the water production.

**Actual or anticipated problems or delays**
None during this project period

**Product Produced or Technology Transfer Activities**
None

**Publications to Date:**


Ross, H. E. and Zoback, M. D., 2006, Sub-hydrostatic pore pressure in the Powder River
Basin, WY and MT, and implications for re-injection of CBM produced waters: AAPG-Rocky Mountain Section, Billings, MT, June 11-13.

DOE Contract DE-FC26-05NT15549
Recipient - University of Wyoming

Task 1 Membrane-Enhanced CBM to minimize produced water
Date of Report – 1/31/07  Period Covered – 4/29/06 through 10/28/06
Anticipated Completion Date – 5-25-07

Brief Summary Statement of Project Goals

The objective of Task 1 is to evaluate the feasibility of minimizing CBM water production using a combination of gas injection and gas permeable membranes to recover methane without de-watering the coalbed. The conceptual approach uses four CO₂ injection wells and a central recovery well. The injected CO₂ will preferentially bind to the coal, desorbing the methane. The released methane would be extracted from the center recovery well by locating the semi-permeable membranes down-hole, which will allow the production of methane but not water. In addition to eliminating produced waters, this approach may also provide a means of CO₂ sequestration (global warming mitigation). The project subtasks are designed to evaluate the feasibility of the approach with respect to the gas recovery properties of porous membranes and the gas transport properties of coal in saturated environments.

Executive Summary

Sub-Task 1: Studies are being conducted to determine the feasibility of using gas permeable membranes to simultaneously inject carbon dioxide gas for carbon sequestration while stripping methane gas from coal seam groundwater for energy production. We initially investigated a vacuum degassing approach then switched to a carbon dioxide sweep gas because too much water entered the membranes during methane recovery. In this current configuration, pure carbon dioxide is fed to hollow fiber membrane lumens with the membranes submerged in water saturated with methane gas. Gas partitioning occurs as gas flows along the length of the membranes with carbon dioxide leaving the membranes and methane gas entering the membranes. A mathematical model has been developed to describe the process and verified through laboratory experiments. Parametric studies are being conducted to optimize the amount and rates of carbon dioxide transfer and methane recovery.

Sub-Task 2: Imbibition experiments are still proceeding on intact coal samples for the purpose of understanding the pore size distributions of Canyon and Smith coals. Based upon the data collected at this point, and averaging the triplicate samples, the total porosity of the Canyon coal samples can be broken down as 17.7 % microporosity, 19.2 % mesoporosity and 63.1 % macroporosity. A similar breakdown of the Smith coal
samples results in 19.5 % microporosity, 19.2 % mesoporosity, and 61.3 % macroporosity.

**Sub-Task 3:** A Trautwein Soil Permeameter is being used to evaluate the two-phase mass transport of gases through an intact saturated coal core. In addition to characterizing the flow of gases through the core, the same apparatus is being used to measure the sorption/desorption of methane, CO₂ and nitrogen to/from saturated intact coal cores. The results to date indicate that while confining pressure does affect the flow of gases through intact cores, the adsorption of CO₂ does not appear to cause swelling in the coals and a subsequent reduction of flow rates.

**Specific Subtasks**

**Subtask 1**

**Task 1: Membrane-Enhanced CBM to minimize produced water**

Evaluate the mass transfer characteristics of gas permeable membranes.
- Compare the membrane gas transfer rates of an inert gas and water vapor at typical formation pressures.
- Formulate a conceptual coal seam model to evaluate the feasibility of using gas permeable membranes to recovery methane.

Studies are being conducted to determine the feasibility of using gas permeable membranes to simultaneously inject carbon dioxide gas for carbon sequestration while stripping methane gas from coal seam groundwater for energy production. We initially investigated a vacuum degassing approach then switched to a carbon dioxide sweep gas because too much water entered the membranes during methane recovery. In this current configuration, pure carbon dioxide is fed to hollow fiber membrane lumens with the membranes submerged in water saturated with methane gas. Gas partitioning occurs as gas flows along the length of the membranes with carbon dioxide leaving the membranes and methane gas entering the membranes. A mathematical model has been developed to describe the process and verified through laboratory experiments. Parametric studies are being conducted to optimize the amount and rates of carbon dioxide transfer and methane recovery.

Tests were conducted in a pressure vessel to determine the liquid-phase mass transfer coefficient, Kₐ, a parameter that describes how quickly methane is transported to the membrane surface across a stagnant water layer. Initial tests were conducted using oxygen because oxygen concentration measurements are easily performed using dissolved gas probes. Results are presented in Figure 1 using common dimensionless groupings. Through a linear regression (Equation 1) of the plot shown in Figure 1, coefficients necessary for determining the Kₐ values for CO₂ and CH₄ were determined. Using Equation 2, Kₐ values were calculated based on the coefficients a and b from Equation 1 and the diffusivities of the gas of interest.
Equation 1  \[ \log\left(\frac{Sh_{O_2}}{Sc}\right) = b \log(Re_{water}) + \log(a) \]

Equation 2  \[ K_{L,i} = a Re_{water}^b Sc_i^{1/3} \frac{D_i}{2R_o} \]

In these equations, Sc is the Schmidt number, Sh is the Reynolds number, Kl is the liquid-phase mass transfer coefficient (m/s), Di is the diffusivity of species, i, into water (m^2/s), Ro is the outside fiber radius (m) and a and b are fitting coefficients.

Pressure vessel tests were also performed to evaluate gas partitioning across the membranes from a liquid phase. In these tests, methane saturated water was passed by membrane fibers in which CO2 sweep-gas was introduced on the lumen side of the tubular membranes. Trans-membrane pressure was maintained at zero, while upstream and downstream lumen pressure was atmospheric. The measured gas composition at the outlet of the lumen side of the membranes as a function of shell-side lateral water flow rate and lumen CO2 flow rate is shown in Figure 2 and 3, respectively. Higher percentages of methane gas are recovered in the lumen exhaust stream as the water flow rate increases because boundary layer transport limitations diminish as water velocities are increased. Higher concentrations of methane gas are recovered as sweep-gas flow rates decrease because more time is provided for methane to enter the membrane and for carbon dioxide to leave the membranes before the gas exits the membrane system.
Figure 2: Measured gas composition dependence on water flow rate when the sweep-gas flow rate is 1 standard ml per minute.

Figure 3: Measured gas composition dependence on lumen CO\textsubscript{2} flow rate when the water flow rate is 1.0 E\textsuperscript{-6} m\textsuperscript{3}/s.

Comparisons of model predictions and experimentally obtained fiber outlet flow rates are shown in Figures 4 and 5.
Figure 4: Parity plot of membrane outlet flow rate of CH₄ for the various water and sweep gas flow rates from Figures 3 and 4. The solid line indicates a one to one correspondence between the model and measured results.

Figure 5: Parity plot of membrane outlet flow rate of CO₂ for the various water and sweep gas flow rates from Figures 3 and 4. The solid line indicates a one to one correspondence between the model and measured results.

There was good agreement between measured and predicted exiting carbon dioxide concentrations and flow rates. Reasonable agreement between measured and predicted exiting methane concentrations and flow rates was also found, although the measured values tended to be greater than predicted values at the higher flow rates. Why the model under-predicts in this scenario is unclear but considering the complexity of the model, the agreement appears reasonable for verification purposes.

The model was used to evaluate the feasibility of using gas permeable membranes to recovery methane. In these calculations, a coal seam with pore pressure of 150 psi,
(limits of the ideal gas law assumptions used in our model), was considered. The coal seam considered was 120 ft thick with a lateral groundwater flow rate of 100 cm/day. Conventional CBM gas wells on average produce 550,000 ft³/day of methane after 1-6 months of dewatering. If membrane systems that avoid dewatering operations were to be used and if the water in the coal bed is saturated with methane, model results indicate the total active membrane surface area required is 290,000 m². Under this approach, 14.5 mcf of the CO₂ sweep gas would be sequestered per day and 16.8% of the dissolved methane would be recovered. The predicted composition of the recovered gas stream is 95% CH₄, 4.4% CO₂, 0.6% H₂O(g). Assuming a single pass system where only one layer of membranes is used, 4.8 linear miles of fiber spanning the thickness of the coal seam would be required, assuming center-to-center spacing of two membrane diameters. This distance could be considerably shortened if multiple layers of membranes are used.

The active membrane surface area required to recover 550,000 ft³/day methane (equivalent to average conventional CBM well production) are shown in Figure 6 and 7 for various groundwater velocities and pore pressures. As groundwater velocities increase, the required membrane area decreases to achieve equivalent gas recovery. Similarly, as deeper coals seams are used, required membrane area also decreases because higher gas concentrations are present at deeper depths if the water is saturated with methane.

![Figure 6: Required membrane area to achieve 550,000 ft³/day methane production (>97% CH₄) for various groundwater velocities assuming no free gas phase is present.](image)
Conclusions from the work done to date are that a large amount of membrane area would be required for adequate gas recovery and the approach is not feasible in its current form. Feasibility may improve if methods to generate groundwater velocities greater than those that occur naturally were used or if a methane gas phase were present in the coal bed. This scenario is conservative because a free gas phase may also exist in the coal seam that would substantially decrease the amount of membrane area required. How much free gas exists in typical coal seams is not well understood at this time but this free gas could also be recovered with a membrane system without the transport limitations of the dissolved form. Estimates of this component of recovery will be included in future modeling work for the proposed system.

Nomenclature

- $Sc$: Schmidt number
- $Sh$: Sherwood number
- $Re$: Reynolds number
- $K_L$: Liquid-phase mass transfer coefficient (m/s)
- $D_i$: diffusivity of species, i, into water (m$^2$/s)
- $R_o$: outside fiber radius (m)
- $a, b$: coefficients
**Plans for the Next Report Period**

Ongoing work involves continued modeling and the dissemination of our results. Findings from this study will be incorporated into a student thesis and also a manuscript suitable for submission to a peer reviewed publication.

**Conferences to Date**


**Subtask 2**

Coal characterization study

- Quantify the relative pore structure of intact coal cores.
- Characterize the water-gas-coal interactions.

Imbibition experiments are still proceeding on intact coal samples for the purpose of understanding the pore size distributions of Canyon and Smith coals. (The Canyon and Smith coal seams are located in the Upper Wyodak Formation and were collected along the Wyoming-Montana border in the Powder River Basin.) Water adsorption isotherms are being carried out on the coal samples, during which a water balance is maintained on samples placed in controlled-humidity environments. Aqueous glycerol solutions are used to maintain a constant relative humidity (relative vapor pressure), which is established by controlling the weight percent of glycerol in each solution. The mass of water adsorbed at each relative humidity can be directly related to the capillary pressure through the general Kelvin equation, as shown below:

\[ RT \ln \left( \frac{p}{p^0} \right) = -P_c \cdot u \]

where, \( R = \) universal gas constant (0.0821 L-atm/mol-K), \( T = \) temperature (K), \( \left( \frac{p}{p^0} \right) = \) relative vapor pressure, \( P_c = \) capillary pressure (MPa) and \( u = \) molar volume of \( H_2O \) (18.05 cm\(^3\)/mol)

The capillary pressure, in turn, can be expressed as a pore size radius.

Data collected at a relative humidity of 60%, which relates to a pore size of 2.1 nm, may provide the most telling data. A pore size of 2.1 nm is the cut-off between microporosity and mesoporosity, and defines the transition from surface adsorption upon the coal matrix and capillary condensation within the fracture spaces. In effect, this provides the
microporosity of the coal. It should also be noted that the highest relative humidity utilized is 98%, corresponding to a pore size of 53 nm, which defines the cut-off from mesoporosity to macroporosity. The macroporosity is therefore determined as the remaining total porosity not saturated at a relative humidity of 98%.

Trials composed of initially saturated samples and initially dry samples for both the Canyon and Smith coals are currently underway. The adsorption isotherms, in terms of capillary pressure versus the percentage of total porosity, are shown in Figure 1. The pore size distribution, expressing pore sizes against the percentage of total porosity, is shown in Figure 2.

Figure 1: Adsorption isotherms of Canyon and Smith coals, representing the average of triplicate samples.
At this time, all samples are being exposed to a relative humidity of 80%. Upon reaching equilibrium within these samples, expected to occur within two weeks, it will be possible to “match” the two trials (initially dry and initially saturated) together for a complete pore size distribution. Based upon the data collected at this point, and averaging the triplicate samples, the total porosity of the Canyon coal samples can be broken down as 17.7 % microporosity, 19.2 % mesoporosity and 63.1 % macroporosity. A similar breakdown of the Smith coal samples results in 19.5 % microporosity, 19.2 % mesoporosity, and 61.3 % macroporosity. The percentage of total porosity saturated at each pore size is shown below in Table 1.

Table 1: Pore size distribution of Canyon and Smith coals, representing the average of triplicate samples.

<table>
<thead>
<tr>
<th>Pore Size (nm)</th>
<th>Porosity</th>
<th>Percentage of Total Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Canyon Coal</td>
</tr>
<tr>
<td>&lt;0.6</td>
<td>Micro-</td>
<td>2.8%</td>
</tr>
<tr>
<td>&lt;1.2</td>
<td></td>
<td>9.4%</td>
</tr>
<tr>
<td>&lt;2.1</td>
<td></td>
<td>17.7%</td>
</tr>
<tr>
<td>&lt;3.0</td>
<td>Meso-</td>
<td>21.0%</td>
</tr>
<tr>
<td>&lt;9.5</td>
<td></td>
<td>32.7%</td>
</tr>
<tr>
<td>&lt;19</td>
<td></td>
<td>35.0%</td>
</tr>
<tr>
<td>&lt;40</td>
<td></td>
<td>36.5%</td>
</tr>
<tr>
<td>&lt;53</td>
<td></td>
<td>36.9%</td>
</tr>
<tr>
<td>&gt;53</td>
<td>Macro-</td>
<td>63.1%</td>
</tr>
</tbody>
</table>
Plans for the Next Report Period

1. The data from the initially saturated samples and initially dry samples will be combined for a complete pore size distribution.
2. The coal characterization study will be completed and the results from the study will be published.

Subtask 3
Dual-phase mass transfer study
- Compare the competitive adsorption/desorption of methane, carbon dioxide and nitrogen across intact coal cores.
- Develop counter-diffusion breakthrough curves for methane, carbon dioxide and nitrogen.
- Determine the relative effect of changes in gas type and content on coal properties including coal strength, shrinkage/swelling, and permeability.

Based upon the successful trials carried out with the originally developed experimental apparatus, and confident that encountered problems have been resolved, two additional experimental apparatuses have been constructed. A schematic of the experimental system is shown in Figure 3. A schematic of the third apparatus, in use during an experimental trial, is shown in Figure 4.

Figure 3: Schematic of experimental apparatus for determining gas flow properties of saturated, intact coal samples.
The experimental procedure has been described in detail in the previous project report. In short, a saturated coal core is mounted in a Trautwein Soil Permeameter, and confining pressure is applied by way of a compressed air cylinder. The permeameter is placed on an Acculab VA-12KG digital balance, which is connected to a computer in order to automatically log the data. Compressed gas cylinders supply the injection gas, which can be methane, carbon dioxide, or nitrogen. The injected gas flows through an Alicat Scientific mass flowmeter with a range of 0 to 100 standard cubic centimeters per minute (sccm). (Multiplying by the density of the gas, with appropriate conversion factors, gives the flow data in grams per minute.) The flow data is logged to the same computer. After flowing through the flowmeter, the injection gas passes through a column of water and fine gravel for the purpose of hydrating the gas before reaching the core. The purpose of hydrating the gas is to minimize the effects of drying within the core. After passing through the core, the effluent gas can either be captured in a Tedlar bag for analysis or vented to a vapor collection hood. All logged data is imported into Microsoft Excel\textsuperscript{TM} spreadsheet for analysis.

Because of its inert nature and low affinity for sorption to coal, nitrogen was used for preliminary experiments. This topic has been covered in the previous project report. The collected data showed that drying was occurring within the core at high flow rates, resulting in a corresponding increase in mass flowrates. Therefore, in order to minimize and account for drying effects it was important to inject gas at a low injection rate and maintain a water balance on water being extruded from the coal core. A summary of the
mass flow data for nitrogen, collected at two confining pressures and an injection pressure of 20 psi, is shown in Table 2.

Table 2: Mass flow data for preliminary experiments involving the injection of nitrogen through Canyon coal cores.

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>50</th>
<th>75</th>
<th>psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flowrate</td>
<td>0.09 - 0.11</td>
<td>0.03 - 0.05</td>
<td>g/min</td>
</tr>
<tr>
<td>Mass Flux</td>
<td>28 - 35</td>
<td>9-16</td>
<td>kg/day-m²</td>
</tr>
<tr>
<td>Permeability</td>
<td>2.5 - 3.5</td>
<td>1.1 - 1.8</td>
<td>md</td>
</tr>
</tbody>
</table>

During the second round of experiments, methane, carbon dioxide and nitrogen (in this order) were injected through one core in succession in order to compare mass flowrates of the three gases. The collected mass flow data is show in Figure 5. As can be seen in the figure, the mass flowrate through the core remained fairly constant between the three injected gases. By accounting for water loss from the core, the adsorption of gas within the coal was also successfully quantified, as shown in Figure 6.

![Figure 5: Mass flowrates of methane, carbon dioxide, and nitrogen through a saturated core of Canyon coal.](image-url)
The data suggests that there is a substantial difference in the rate of adsorption between the three gases. However, it is hypothesized that methane is leaving the core during the carbon dioxide and nitrogen injections, which would result in a lower increase in mass during this time period. Therefore, it will be necessary to analyze the composition of the effluent gas in order to more fully understand any exchange taking place within the coal. An operating gas chromatograph (GC) has recently been assembled within the UW Civil & Architectural Engineering Department, and we are currently undergoing training in its use. The GC will provide high-quality compositional data of the effluent gases. It is expected that analysis of effluent gases will begin within the next two weeks. A summary of the mass flow data for the multi-gas experiments, collected under a confining pressure of 80 psi, is shown below in Table 3. It should be noted that all the values are roughly one-tenth of those collected during previous experiments, showing the inherent heterogeneity between different cores.

### Table 3: Mass flow data for multi-gas experiments through Canyon coal cores.

<table>
<thead>
<tr>
<th>Confining Pressure:</th>
<th>80 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flowrate:</td>
<td>0.012 - 0.015 g/min</td>
</tr>
<tr>
<td>Mass Flux:</td>
<td>3-5 kg/day-m²</td>
</tr>
<tr>
<td>Permeability:</td>
<td>0.10 - 0.23 md</td>
</tr>
</tbody>
</table>

Experimental trials have also been initiated for developing methane adsorption isotherms for the intact coal samples. During the first adsorption trial, methane gas was injected at 10 psi until the increase in mass, that is the adsorbed gas, reached a relatively constant value. The injection pressure was then increased to 20 psi and the core was again
allowed to reach equilibrium. This process was continued in 10-psi increments up to a final pressure of 70 psi (10 psi below the confining pressure of 80 psi). The results of this first adsorption isotherm are shown in Figure 7. Figure 8 shows a detail of the kinetics of gas adsorption.

The results of the preliminary adsorption experiments show that the experimental apparatus can be used to successfully evaluate the mass of adsorbed methane within a saturated coal core. Additionally, the confining and injection pressures at which the experiment is conducted are believed to be comparable to the subsurface pressures encountered in shallow coal seams targeted for coal bed natural gas production. In the next month, adsorption isotherms will be completed for carbon dioxide and nitrogen, so that comparisons can be made to methane adsorption capacities. It is hypothesized that the coal samples will show a greater affinity for adsorption of carbon dioxide than for methane, while showing a lesser affinity for adsorbing nitrogen. Therefore, the mass of adsorbed gas is expected to be greatest for carbon dioxide (on a mass of gas per mass of coal basis), and least for nitrogen.

Figure 7: Preliminary methane adsorption isotherm with 10-psi incremental steps for Canyon coal.
Publications to Date


Plans for the Next Report Period

1. Utilize the three experimental apparatuses in order to verify repeatability of data.
2. The competitive adsorption and desorption of the various gases will be evaluated and breakthrough curves will be developed.
3. The relative effect of gas type and content on the structural and mass transfer properties of coal will be determined.
Executive Summary

Task 4 will evaluate wellbore completion practices to determine if there are ways to produce less CBM water and still achieve adequate depressurization for gas production. In addition, we will evaluate whether it is feasible to re-inject CBM water into sand aquifers by analyzing water monitoring wells in the PRB to determine pore pressures and hydraulic communication between sands and underlying coalbeds. The analysis of ~600 wells indicates that current drilling and water enhancement techniques are causing hydraulic fracturing of the coal. In many cases the hydraulic fractures appear to propagate into adjacent strata, resulting in inefficient depressurization of coals and excess CBM water production. Alternative wellbore completion techniques will be recommended to maximize gas production and minimize produced water.

Executive Summary

Coalbed methane (CBM) production in the Powder River Basin (PRB), Wyoming, is associated with the production of large volumes of CBM water. CBM water from the PRB has high saline and sodium contents, making it unsuitable for direct agriculture application without mitigation and environmentally damaging. One option for the disposal of CBM water is injection into aquifers, but for injection to be feasible the porosity and permeability of the sands needs to be high, the pore pressure needs to be low, and the aquifer cannot be in hydraulic communication with the coalbeds.

In order to determine if pore pressures in the aquifers are low enough to allow for significant CBM water injection and to determine whether the coals and sands are in hydraulic communication with each other we have calculated pore pressures in 250 wells that monitor water levels in coalbeds and adjacent sands within the PRB. All 250 wells have pore pressures below hydrostatic pressure, implying that injection of CBM water should be feasible. However, by analyzing pore pressure changes with time for both the coals and their overlying sands, we find that sands less than 200 ft from coal appear to be in communication with the coalbed. Therefore, injection of CBM water should be carried out in sands further than 200 ft from adjacent coalbeds.

In addition, we ran fluid flow simulations to determine the rates at which CBM water can be injected into shallow (~300 ft) and deep (~1000 ft) aquifers, with the stipulation that
the injection pressure should not exceed hydrostatic pressure for 4000 days (~11 yrs). We find that for the shallow sand model we can inject water at a rate of ~160 bbl/day, whereas for the deeper sand, whose pore pressures are lower than the shallow sand, the rate is ~435 bbl/day. Both these rates are higher than the average water production rate from CBM wells in the PRB, which is ~100 bbl/day.

Finally, it appears that natural hydraulic communication between coals and overlying sands is not the cause of excessive water production observed in some CBM wells, suggesting that vertical hydraulic fractures and normal faults may play a role in the water production.

Results

Subtask 1: Calculate coalbed and sand pore pressures to determine if there are areas in the basin where pore pressure is sub-hydrostatic and are therefore potential sites for injection of produced water

We calculated present day (2005) pore pressures for sands and coals in both the Montana and Wyoming parts of the PRB and found that they are sub-hydrostatic (Figure 1). Figure 1 shows that the pore pressure magnitudes for both coals and sands in Montana and Wyoming plot below the hydrostatic pore pressure line, indicating that pore pressures are sub-hydrostatic. Pore pressures for the coalbeds in Wyoming are much lower than for overlying sands because of CBM production, which has reduced pore pressures in the coalbeds through water extraction.
Figure 1: a) Present day pore pressure in a) Wyoming and b) Montana. $S_v$ corresponds to the overburden pressure and the black line is the overburden pressure gradient. Grey line corresponds to the hydrostatic pore pressure gradient (~0.44 psi/ft). Black squares correspond to coal and red crosses to sand.

Subtask 2: Determine if coalbeds and overlying sands are in hydraulic communication with each other

At the time of the last report we had looked at hydraulic communication between coalbeds and sands in the Wyoming part of the basin. Using paired wells, we found that in general sands that were less than ~200 ft from underlying/overlying coalbeds had the greatest change in pore pressure with time (Figure 2).

Figure 2: Separation between sand and coal pairs (in feet) versus change in pore pressure ($P_p$) with time for monitored sands in Wyoming.
To determine if the large changes in pore pressure for the underlying/overlying sands was because of hydraulic communication with the underlying/overlying coalbeds, we looked at pore pressure changes with time for both the coalbed and paired sand. We plotted the pore pressure changes with time for all paired wells, looking to see if the sands had similar pore pressure depletion histories as their paired coalbeds. We found that pore pressure changes with time for almost all of the sands less than 200 ft from underlying coals had similar pore pressure trends as the underlying coalbed, implying that the sands are in hydraulic communication with the underlying coalbeds.

CBM production in Montana is on a much smaller scale than in the Wyoming part of the PRB. Because of the limited CBM activities in the Montana part of the basin we have observed much smaller ground water drawdown than in the Wyoming part of the basin. Hence, when analyzing pore pressure changes with time for 11 paired wells in Montana, only 5 of the 11 coals had significant decreases in pore pressure with time (between 50 and 90 psi) (Figure 3). From our limited dataset it appears that at present overlying sand aquifers are not being drained through CBM production. The greatest pore pressure decrease observed in overlying sands is ~5 psi, compared with over 100 psi in the Wyoming part of the basin. Even if we analyze pore pressure changes with time for overlying sands not part of well pairs, the greatest decrease in pore pressure is only 2 psi.

Figure 3: Separation between sand and coal pairs (in feet) versus change in pore pressure with time for sand and coal pairs in Montana.

**Subtask 3: Analyze new water enhancement tests to map stress across the basin**

At the time of the last report we had begun to analyze approximately 40 water enhancement tests from UCROSS. However, the water enhancement tests appear to be corrupted, as we derive magnitudes for the least principal stress well above the overburden pressure, which cannot happen. The least principal stress must either be less than the overburden or equal to the overburden stress. We will work on understanding the results from our UCROSS analysis.

However, we have continued to investigate the cause of stress variations throughout the PRB and this has lead us to define three different stress states in the PRB: areas that have active normal faults, areas that are slightly more compressive (either normal or strike-slip...
stress regimes) and finally, areas with reverse faulting regimes. We find that normal, compressive and reverse stress regimes exist very close to each other within the lower half of the study area, but to the north we see only compressive and reverse regimes. It appears that the magnitudes of the horizontal stresses are changing within coalbeds in the PRB, and that in general the horizontal stresses are decreasing toward the south and west.

When we compare $S_3/S_v$ with water production for wells from Colmenares and Zoback’s (2007) study as well as the current study, we find a correlation in the Big George coal between active normal faulting areas and wells with vertical hydraulic fractures that produce very large volumes of water (> 25,000 bbl/month) (Figure 4).

Figure 4 implies that active normal faults in communication with vertical hydraulic fractures may play a role in CBM wells with very large water production, where the faults may act as permeable conduits for fluid migration from overlying aquifers to the producing coalbed.

![Figure 4: The ratio of $S_3:S_v$ plotted against water production for the Big George coal. $S_3:S_v < 0.58$ means that the well is in an active normal faulting regime.](image)

**Subtask 4: Modeling CBM water injection into sand aquifers**

Subtask 4 is a new task we recently completed research for.

We have constructed two 3D stochastic reservoir models of conceptualized sand units in the PRB and have run fluid flow simulations to determine the rate at which CBM water can be injected into the aquifers.

We modeled water injection into both shallow and deep sands because our pore pressure analysis showed that deeper sands and coals have lower initial pore pressures than the shallower sands and coals and this suggests that we should be able to inject a larger volume of CBM water into the deeper sands.

Our simulations show that for the shallower sand, water can be injected at a rate of ~160 bbl/day for ~4000 days before the BHP reaches hydrostatic (Figure 5). In contrast, for the deeper sand, water can be injected at a rate of ~435 bbl/day for ~4000 days (Figure 5). At present the average water production rate per CBM well in the PRB is ~100 bbl/day (WOGCC, 2007) and the average lifetime of a CBM well is ~7 to 15 years (2555
to 5500 days) (Ayers, 2002; De Bruin et al., 2004). Therefore, if operators were to inject CBM water into shallow sands they would be able to dispose of the water production from one and a half CBM wells using one disposal well. If injection took place in deeper sands, operators would be able to dispose of the water production from four CBM wells using one disposal well.

In Figure 5 we have marked the water injection rate achievable in our two different sand models and have also plotted the average water production in bbl/day for CBM wells analyzed by Colmenares and Zoback (2007) and Ross and Zoback (this project). Colmenares and Zoback (2007) looked at over 500 water-enhancement tests that are used by CBM operators in the PRB to connect the natural coal fracture network to their CBM wells. Through their analysis, Colmenares and Zoback (2007) discovered that water-enhancement actually hydraulically fractures the coal and in some areas the fractures grow horizontally and in other areas they propagate vertically. Approximately 30% of wells with vertical hydraulic fractures produce excessive volumes of water and little to no gas. Colmenares and Zoback (2007) define excessive water production as ~230 bbl/day and higher. From Figure 5 we see that for CBM wells with excessive water production, deeper sand aquifers will need to be used as water disposal sites for these wells. The shallower sands do not have the capacity to store water from excessive water producing wells over the lifetime of the CBM well.

![Figure 5: Water production rate per well for CBM wells analyzed by Colmenares and Zoback (2007) and Ross and Zoback (this project) compared with the injection rates obtained from fluid flow simulations for our shallow (orange) and deep (green) sand models. Average CBM water production for the PRB is from the WOGCC (2007).](image)

Subtask 5: Modeling natural hydraulic communication between coalbeds and overlying aquifers
Subtask 5 is also a new task we recently completed research for.

We have run fluid flow simulations attempting to re-produce the large volumes of water produced by CBM wells with vertical hydraulic fractures and the pore pressure changes observed for monitored sands in the PRB in order to determine if natural hydraulic
communication between a coalbed and overlying sand body can explain the observed pore pressure changes and excessive CBM water production. We built a 3D stochastic reservoir model that includes a 65 ft (20 m) thick coalbed, overlain by a 13 ft (4 m) thick confining unit (minimum thickness of the confining unit between the coalbeds and sands across the PRB; Applied Hydrology Associates and Greystone Environmental Consultants, 2002), which is in turn overlain by a 39 ft (12 m) thick sand unit.

Our base case simulation includes CBM production for ~18 years from the coalbed only, where the grid cells corresponding to the confining unit and sand have been removed from the simulations (made NULL). We then ran 5 additional cases (Table 1), where both the confining unit and sand are now included in the simulations and where we vary the horizontal and vertical permeabilities of the confining unit (Table 1).

Table 1: Confining unit permeability and porosity values for five different cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Horizontal permeability of confining unit (mD)</th>
<th>Vertical permeability of confining unit (mD)</th>
<th>Porosity of confining unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>0.009</td>
<td>0.009</td>
<td>0.1</td>
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<tr>
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<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 6 shows average water production per well in bbl/day for production from the coalbed only and the additional five cases with different confining unit permeabilities. We observe that if the confining unit has vertical permeabilities less than ~0.002 mD, there is no significant downward migration of water from the units above the coal (no significant increase in the water production rate). The coal and sand are effectively isolated from one another and there is no hydraulic communication. In contrast, for confining unit permeabilities in the vertical direction greater than ~0.002 mD, the water production rate per well is greater than in the base case, implying that water has been produced from the overlying units and the overlying units are in hydraulic communication with the coalbed.
Water Production Rate Per Well (bbl/day)

Average Water Production Per Well
80 82 84 86 88 90 92 94 96 98 100
Coalbed only
Case 5
Case 4
Case 3
Case 2
Case 1

Figure 6: Average water production per well for each case outlined in Table 1. \( k \) stands for permeability and the values correspond to the shale permeability in both the horizontal (x and y) and vertical (z) directions for each simulation case. \( k \) is in units of mD.

When we look at pore pressure changes with time in the overlying sand for each simulation case, we see that even when we model a very “leaky” confining unit (case 2) we only produce a pore pressure change in the sand of \(~20\) psi over an 18 year time period. In contrast, some of the monitored sands less than \(~200\) ft from underlying coal have pore pressure changes on the order of \(~100\) psi.

The results from our hydraulic communication modeling suggest that the large water production from wells with vertical fractures and the large pore pressure changes observed in some monitored sands could be due to the propagation of vertical hydraulic fractures into overlying units, since the natural hydraulic communication that we have modeled does not account for the large water production or large changes in pore pressure.

In addition, as shown above, normal faults may also play a role in water migration from overlying aquifers. Normal faults seem to explain the very large water production (\(>~25,000\) bbl/month) reported in the Big George coal. It is possible that active normal faults that are in communication with vertical hydraulic fractures give rise to the production of very large volumes of water.

One option for the disposal of CBM water in the PRB is injection into aquifers. The modeling reported in this subtask suggests that vertical hydraulic fractures could penetrate aquifers overlying coalbeds and therefore, the presence of vertical fractures should be investigated when determining potential sites for CBM water disposal. However, we have found that sands further than \(~200\) ft from producing coalbeds show no change in pore pressure with time and must not be in hydraulic communication with the coalbeds. Therefore, we believe that vertical hydraulic fractures have not propagated further than 200 ft into overlying strata. In fact, Holditch et al. (1988) and Abass et al. (1990) have shown that hydraulic fractures in coal have half lengths of only 30 to 250 ft. This supports our conclusions that aquifers further than 200 ft from producing coalbeds are potential sites for CBM water injection.
Publications to Date


References


Ayers, W., 2002, Coalbed gas systems, resources, and production and a review of contrasting cases from the San Juan and Powder River basins: AAPG Bulletin, 86, 1853-1890.


Publications to Date


Conferences to Date


**Awards to Date**

**W.G.A. John Runge best student paper award given to Hannah Ross**  
A.A.P.G. Rocky Mountain Section Meeting, Billings, Montana, June 11-13, 2006

**Plans for the Next Report Period**

1) Obtain more data on fluid pressure changes due to coalbed methane production.  
2) Extend our fluid flow simulations.
SURFACE DISPOSAL – TASKS 3, 6 and 7

Conclusions

Task 3: Subtask 1: We have used Sr isotopes to trace the infiltration of product water and show a connection between changes in water quality and strontium concentration at an on-channel CBM disposal site at Beaver Creek, Wyoming. We suggest that on-channel discharge shows promise for future disposal because salts in the soil are minimal in existing channels due to annual flushing. However, the amount and duration of CBM discharge may exceed the water mounding caused by annual flooding, in which case stream bank salts may be mobilized. Additionally, the change in vegetation species and biomass that occurs due to the creation of a perennial stream may be of concern to landowners if the local vegetation, adapted to semi-arid conditions, is out-competed by undesirable riparian vegetation or by a floral community that is not stable when the source of water is removed. Our conclusion that existing ephemeral channels have fewer soluble salts than the associated floodplain implies that ponds excavated off existing channels (off-channel) may also experience the mobilization of local salts.

Subtask 2: New data collected during this reporting period corroborates earlier work showing that water samples from coal aquifers have Sr isotopic compositions that are distinct from Sr isotopic compositions of water withdrawn from sandstone aquifers. Water samples from coal seams that are in hydraulic connection with other aquifers can be identified using Sr isotope ratio measurements. There are geographic variations in Sr isotope ratio of co-produced water, and in some cases Sr isotope ratios appear to correlate with amount of ash in the coal seam or with rate of water production.

Subtask 3: O and H stable isotopic data on CBM-produced water samples from a variety of locations and coal zones in the Powder River basin was obtained. However, O and H isotopic ratios do not appear to vary as a function of geography or coal zone and therefore this line of research will not be pursued further.

Task 6: CBM-water–production rates in Montana continue to be less than predicted, suggesting that the volume included in overall water management planning can be revised.

Reduced rates of infiltration at CBM ponds can be expected. The vertical hydraulic conductivity at one infiltration pond site was calculated to have decreased by one order of magnitude from approximately 0.1 to 0.01 feet/day. At other sites long-term low vertical hydraulic conductivity values are apparent.

Salts have been mobilized beneath the Coal Creek pond by infiltrating water. Saturated paste extract data indicate the salts migrated no further than 10 to 15 feet vertically and water-quality data indicate horizontal migration of between 200 to 300 feet beyond the pond perimeter.

Laboratory trials indicate that leonardite can be used to decrease SAR in discharged water. The decrease in SAR is accompanied by an initial increase in TDS concentration which then decreases.
Data from a three year period at the Coal Creek site show that about 65% of the total water discharged to ponds actually helps recharge shallow aquifers.

The increase in total dissolved solids noted beneath ponds is temporary. The salt load decreases with time due both to flushing of salts along the flow path and dilution as infiltrated water mixes with native ground water.

**Task 7:** Time series data indicated a clear trend of increasing peak channel conveyance loss in the summer months for the lower stream reach at the Beaver Creek study area, which runs in a well-confined channel. This is a key finding because it indicates significantly increased transpiration losses over time; the significant contribution of transpiration to the water budget also results in a high seasonal variability in conveyance loss. In contrast, at the upper stream reach, which runs in a broad, shallow channel, we find that the temporal evolution of conveyance losses is more complicated. In general, the same increase in transpiration over time is evident, but the signal is superimposed on significant variations in channel width with increased discharge.

Using weir and precipitation gauge data, we have performed an analysis of rainfall-runoff response in the Beaver Creek study area. The results indicate that the watershed behaves predictably to storm events. Forward models of the rainfall-runoff response are consistent with observations only if (a) there is little dependence on antecedent moisture, and (b) the soils have a high infiltration capacity. This is consistent with our field observations, and suggests that similar analyses of gauged watersheds prior to development may be a useful tool for estimating or predicting conveyance losses.

**Schedule Status**
Anticipated Completion Date for all Tasks – 10-31-07

**Significant Accomplishments**

**Task 3:**
Submission, revision and acceptance of manuscript summarizing subtask 1 activities. The paper (Brinck and Frost, 2007) is in press in *Ground Water*.

Continued extension of the Sr isotopic database for CBM-produced water beyond the Beaver Creek and Coal Creek monitoring sites with additional analyses. Analysis of all Sr isotopic data for the Powder River Basin, and classification by coal zone of aquifer from which samples were withdrawn has been accomplished.

Task 6:

Continued compilation of monitoring database for on-channel and off-channel infiltration-pond sites in the PRB.

The quantity of water produced from CBM wells in Montana is less than originally anticipated. As of December, 2006, the reported CBM-water–production rates in Montana indicate an average normalized discharge rate per well of 7.8 gpm after 5 months as compared to 13 gpm projected in the Montana EIS. After 90 months, the average discharge rate per well in Montana was 2.6 gpm compared to 1.7 gpm in the analyses used in the MT EIS. For those wells with a full period of record (92 months) the average cumulative water production per well is 48.6 acre-feet, compared to the projected cumulative production from the MT EIS of 71.7 acre-feet.

Beneath the Coal Creek infiltration pond, salts have been mobilized by infiltrating water. Cores were collected through the pond floor both prior to it being filled with CBM water and again after it had dried out when CBM discharges ended. Saturated Paste Extract data from the cores indicate the salts migrated no further than 10 to 15 feet vertically. Ground-water quality data from monitoring wells indicate the salts may have moved horizontally about 200 to 300 feet beyond the pond perimeter.

Leonardite appears to be a promising sodium adsorption medium that can be used to reduce SAR of managed water. Sodium concentration in the CBM water was 614 mg/L. After exposure to leonardite, Na concentrations were reduced to between 280 and 180 mg/L. In combination with calcium and magnesium leached from the leonardite, SAR values in the treated water were reduced from 54.3 (CBM water) to less than 6.

Analysis of ASTER data indicate dominance of epsomite in soils at the Coal Creek site which is consistent with water-quality changes measured beneath the pond. ASTR data may provide a useful tool to assess possible pond sites, but needs further evaluation.

Task 7:

New agreements with the landowner and the CBM operating company at the Beaver Creek site have been negotiated and access is anticipated to be approved starting in May or early June.

Collection of soil cores from beneath the Coal Creek infiltration pond and analysis of same using saturation paste extract techniques.

Actual or anticipated problems or delays
None.
Product Produced or Technology Transfer Activities

Publications to Date:

Catherine Campbell, April 2006, presentation on Subtask 2 for the University of Wyoming Graduate Student Symposium, Student Union, University of Wyoming, Laramie.


A paper for oral presentation and extended abstract were presented at the Billings Land Reclamation Symposium in June, 2006 and a field tour of water management sites was lead by J. Wheaton.

A white paper was written for the Montana Department of Environmental Quality on the subject of injecting CBM-produced water. This paper drew upon the work of Dr. David Lopez, PI for Task 9 and John Wheaton, PI for Task 6 of this project.

A talk was given on CBM and water management at the Montana Governor’s Restoration Forum in June, 2006 by J. Wheaton.

Public education is considered important in Montana and talks on CBM, including water management, were given by J. Wheaton to the Association for the Advancement of Indigenous Resources and the Citizens For Resource Development in May, June and October, 2006.


Wheaton, John R, Bobst, Andrew L, and Brinck, Elizabeth L, 2007, Considerations for Evaluating Coalbed Methane Infiltration Pond Sites Based on Site Studies in the Powder


Wheaton, John, Gunderson, Jay, March 29, 2007, Coalbed Methane and Water Management in Montana: 8th Annual Coal Bed Methane Conference, Strategic Research Institute, Denver, CO.

Government conference
Wheaton, J., April 24, 2007, Coalbed methane water issues, Yellowstone River Compact Commission, Sheridan, WY.

Public education


**Website**
[http://mbmggwic.mtech.edu/](http://mbmggwic.mtech.edu/)

**Networks or Collaborations fostered**
This group of researchers continues to develop closer professional collaborations. PRB coal samples have been shipped to other members of this project on request.
Water quality samples collected as part of the field effort for Task 6 are split and shared with Dr. Carol Frost (Task 3).

**Technologies/Techniques**

Preliminary laboratory investigation of leonardite as a sodium adsorption medium has provided encouraging results. Additional tests are planned.

**Inventions/Patent Applications**

None during this project period

**Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment**

All field data collected under Task 6 are incorporated in the Montana Ground Water Information Center (GWIC) which is publicly available and used by industry, government agencies and researchers. (http://mbmggwic.mtech.edu/)
Summary Statement of Project Goals
Task 3 will develop an understanding of the fate of CBM (coal bed natural gas)-produced water following discharge, as well as locations where coal seams are isolated from adjacent aquifers and where, therefore, water production will be limited to the coal. These goals require fingerprinting of the produced water so that it may be traced through the hydrogeologic environment. The strontium isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr}$ will be used to distinguish waters from different parts of the basin as well as water from coal and sandstone aquifers.

Executive Summary
The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of CBM water is markedly different than that of the surface and near surface waters in the Powder River Basin. In situations where $^{87}\text{Sr}/^{86}\text{Sr}$ is measurably different in surface and groundwater the volume of contributed water can be calculated using simple mixing calculations. At the Beaver Creek site, CBM water was found to have a more radiogenic signature than the local alluvial aquifer water. This measurable difference allows the strontium isotope ratio and concentration to be used as tracers of CBM water following its discharge to the surface. Monitoring wells down-gradient from a CBM produced water impoundment had an intermediate strontium isotope ratio between that of the CBM water and the local groundwater. We calculate that approximately 70% of water in these wells originated from CBM discharge. The dissolution and mobilization of salts from soil is an important contributor to groundwater quality degradation. In the Powder River Basin the soils are calcium carbonate buffered systems. The chemical similarity of strontium to calcium allows it to substitute into calcium minerals and enabled us to use strontium isotopes to identify calcium salts mobilized from the soil.

We have used this tool to trace the infiltration of product water and show a connection between changes in water quality and strontium concentration at an on-channel CBM disposal site. We suggest that on-channel discharge shows promise for future disposal in that there are fewer salts in existing channels due to annual flushing. However, the amount and duration of CBM discharge may exceed the water mounding caused by annual flooding, in which case stream bank salts may be mobilized. Additionally, the change in vegetation species and biomass that occurs due to the creation of a perennial stream may be of concern to landowners if the local vegetation, adapted to semi-arid conditions, is out-competed by undesirable riparian vegetation or by a floral community that is not stable when the source of water is removed. The conclusions drawn here that existing ephemeral channels have fewer soluble salts than the associated floodplain imply that ponds excavated off existing channels (off-channel) may also experience the
mobilization of local salts. Results of this portion of the project are now in press in *Ground Water* (Brinck and Frost, 2007).

Additional samples from CBM wells in the southern Powder River basin have been obtained for isotopic analyses. The purpose is to determine the source of the water being withdrawn from the coal seams, specifically if the water is derived entirely from the coal or a portion is derived from the adjacent sandstone intervals. In addition, for each well sampled we have classified the producing coal to determine whether different coal zones have different Sr isotopic and/or hydraulic characteristics. Finally, the isotopic analyses have been correlated with gamma ray log stratigraphy and the fracture patterns as determined by Task 4 efforts. The expectation is that the strontium isotopic signature in the produced water will be radiogenic for coal beds that have horizontal fractures, but non-radiogenic for coal beds that have vertical fractures that extend into adjacent sandstones due to the increased amounts of sandstone formation water that will be produced. This portion of the project is summarized in the M.S. thesis by Catherine Campbell (2007) and manuscripts in preparation.

**Publications to Date**


Catherine Campbell, April 2006, presentation on Subtask 2 for the University of Wyoming Graduate Student Symposium, Student Union, University of Wyoming, Laramie.


**Plans for the Next Report Period**
1. Take results from Subtask 2 presented in Campbell’s M.S. thesis and write and submit a manuscript on Sr isotopes as tracers of water co-produced with coal bed natural gas in the Powder River Basin, Wyoming.

2. Analyze water quality data from University of Wyoming M.S. theses by Campbell (2007) and Pearson (2002) and other published sources and write a review paper on the variations in produced water quality as a function of geographic location and coal zone.

**References cited:**


**Publications to Date**


Catherine Campbell, April 2006, presentation on Subtask 2 for the University of Wyoming Graduate Student Symposium, Student Union, University of Wyoming, Laramie.


References cited:


Summary Statement of Project Goals
Task 6 will verify and improve assessment methods for identifying infiltration pond sites in the Powder River Basin, evaluate concepts for sequestering sodium and controlling salt migration from infiltration ponds, and test remote-sensing techniques for identifying good and poor infiltration pond sites. The results of this task will help industry and regulators select and evaluate proposed infiltration pond sites, yield faster and more efficient well-field designs with fewer delays, and a reduction in the likelihood of expensive reclamation at inappropriate sites.

Executive Summary

An analysis of CBM-water–production rates in Montana indicates that water production was over-predicted in the Montana EIS. A comparison of the values used in the Montana EIS and the evaluation of 92 months of data from Montana CBM wells significantly decreases the quantity of water that must be included in overall water management planning. As of December, 2006, the reported CBM-water–production rates in Montana indicate an average normalized discharge rate per well of 7.8 gpm after 5 months as compared to 13 gpm projected in the Montana EIS. After 90 months, the average normalized discharge rate per well in Montana is 2.6 gpm compared to 1.7 gpm in the analysis used in the MT EIS. For those wells with a full period of record (92 months) the average cumulative water production per well is 48.6 acre-feet compared to the projected cumulative production from the MT EIS of 71.7 acre-feet.

Ground and surface water quality and water level networks were maintained during this period of the project. Data collected (ground water and meteorological) have been entered in to GWIC, an Internet based, publicly available database (http://mbmggwic.mtech.edu/).

Ground-water levels beneath and adjacent to ponds rise in response to infiltration and decrease as the pond bottoms seal or as the pond is allowed to dry when it no longer receives CBM water. Total dissolved solids (TDS) loads in the underlying and adjacent shallow aquifers increase, then decrease as available salts are flushed from the system. Both water levels and water quality have returned to near baseline conditions in monitoring wells around the perimeter of the pond. Directly beneath the pond TDS concentrations have remained high as the ground-water mound slowly dissipates. It is anticipated that the mobilized salts will eventually be sequestered by the decreased permeability of the pond floors.
Sodium in the CBM-production water appears to cause dispersion of the clays in the pond floor and walls, thus infiltration decreases over a period of time. Even a very small percentage clay can result in reduced infiltration rates. The vertical hydraulic conductivity at the Coal Creek infiltration pond was calculated to have decreased from an initial value of 0.1 feet/day to approximately 0.01 feet/day over a period of 7 months.

Cores were collected through the Coal Creek pond floor both prior to it being filled with CBM water and again after it had dried out when CBM discharges ended. Data from these cores provide insight to the fate of the mobilized salts. Saturated paste extract (SPE) data from the cores indicate the salts migrated no further than 10 to 15 feet vertically. Ground-water quality data from monitoring wells indicate the salts have moved horizontally a fairly short distance beyond the pond perimeter.

In laboratory tests, leonardite has been shown to be a promising sodium adsorption medium which can be used to reduce sodium adsorption ratio (SAR) of managed water. Sodium concentration in the CBM water used for these tests was 614 mg/L. After exposure to leonardite, Na concentrations were reduced to between 280 and 180 mg/L. Due to calcium and magnesium leached from the leonardite, SAR values in the treated water were reduced from 54.3 (CBM water) to less than 6.

Multispectral satellite data were evaluated to determine if specific mineral species in the soils could be identified and associated with salt loading in the ground water beneath the Coal Creek pond. Analysis of ASTER data indicate dominance of epsomite in soils at the Coal Creek site which is consistent with water-quality changes measured beneath the pond. ASTER data may provide a useful tool to assess possible pond sites, but needs further evaluation.

Water quality samples collected as part of the field effort for this task are split and shared with Dr. Carol Frost (Task 3). Coal samples have been collected and sent to other investigators as requested.

**Results**

**Subtask 1**
Collect CBM-production water quantity and quality data, and water quality in ground-water and surface water systems downgradient of infiltration ponds in Montana and Wyoming. Using these site studies, evaluate methods that can efficiently be used to assess potential pond sites.

Ground-water monitoring has continued at 4 infiltration pond sites, 3 in Montana and 1 in Wyoming. Two sites in Montana were constructed by another researcher as part of a project that is not related to the CERI efforts. These ponds were very small and little useful results have been obtained from them. The monitoring wells at these sites will be decommissioned.
A monitoring well near Decker, Montana, active since 1977, is being monitored as it responds to infiltration from a nearby CBM pond (Figure 1). One new water-quality sample was collected during the current reporting period. During 2000, the ground-water level began rising in response to infiltrating CBM-produced water. Concurrently, the TDS concentration increased. CBM discharge to the pond stopped in 2003 and the ground-water level began recovering toward baseline levels and the TDS concentration also appeared to be on a decreasing trend. A sample in November, 2006 indicates that the TDS concentration is slowly decreasing.

![Figure 1: Ground-water levels and water quality respond to infiltration from a CBM pond. The infiltration recharges the local aquifer, in this case at a depth of 88 feet below ground surface.](image)

The Coal Creek infiltration pond near Ucross, Wyoming is the primary research site for Task 6. Monitoring at this site has provided changes in ground-water levels and water quality, a water budget estimate for CBM-produced water released to an off-channel pond, and changes in infiltration rates with time. The CBM water being discharged to the infiltration pond had a SAR of 23.6 and a TDS of 995 mg/L.

Ground-water levels directly beneath the pond rose in response to infiltrating water, and then dropped as CBM water was no longer discharged to the pond (Figure 2). Both TDS and SAR also increased in response to the dissolution of naturally occurring salts along the flow path beneath the pond. The lack of continued infiltration precludes complete flushing of the available salts along the flow path and eventual decreased TDS concentrations. Even though the ground-water level has dropped to near baseline conditions, there is still a ground-water mound beneath the pond site. Within the mound there is no mixing of infiltrated water and native ground water and no dilution is occurring.
About 200 feet north of the pond, water levels in monitoring well 2B rose and fell in response to water levels in the infiltration pond (Figure 3). Ground-water levels at this location are nearly back to baseline conditions. Both TDS and SAR showed increases in samples collected from this well. Water quality at this well apparently shows dilution as the mound of infiltrated water mixes with the receiving aquifer. As water levels approach baseline conditions and the original flow directions return, water quality also approaches baseline.

Figure 2. Beneath the Coal Creek CBM infiltration pond the ground-water levels (7B) decreased as CBM discharges to the pond stopped and the pond became dry. Available salts were flushed from along the flow path, and now are being carried away from the pond.
Figure 3. Adjacent to the Coal Creek CBM infiltration pond the ground-water levels (2B) rose and now have dropped as the pond dried up. Available salts are flushed from along the flow path and then diluted as they mix with the undisturbed ground water flowing around the mound under the pond. This well is located 200 feet from the edge of the water surface in the pond.

At a distance of 300 feet from the pond, ground-water levels responded to changes in pressure as the infiltrating water formed a ground-water mound beneath the pond (Figure 4). No changes in water quality have been measured at this well. Therefore, the distance from the pond where water-quality changes have been measured exceeds 200 ft (well 2B) but is less than 300 ft (well 12B).
Figure 4. Between the Coal Creek CBM infiltration pond and Coal Creek, the ground-water levels (12B) responded to changes in ground-water pressure. No change occurred in water quality at this well. This well is located 300 feet from the edge of the water surface in the pond.
Using CBM-water production records from the Wyoming Oil and Gas Commission website, and measurements of pond water levels and ground-water levels in wells completed within the pond, the outflows of water from the Coal Creek pond were estimated (Figure 5). CBM water was discharged from July, 2003 through October, 2004. Evaporation was calculated from the pond surface area (adjusted for stage) and regional free-water evaporation rates. There is no surface discharge from this pond, therefore infiltration was calculated as the difference between inputs (CBM discharge and precipitation), change in storage in the pond, and evaporative loss from the pond. The period of largest infiltration began after the material below the pond floor became saturated in April, 2004. Infiltration then decreased in November, 2004, apparently in response to dispersed clays plugging the flow paths.

![Figure 5. Infiltration rates were highest the material beneath the pond became saturated and decreased with time.](image)

Using the water outflow calculations (Figure 5) and the pond-water levels and ground-water levels, the vertical hydraulic conductivity at the Coal Creek pond was estimated. The results, shown on Figure 6, indicate that the maximum vertical hydraulic conductivity was 0.1 ft/day and then it decreased to about 0.01 ft/day. Roughly an order of magnitude decrease which likely is a due to the affect of sodium dispersion of clays. Significant reduction in infiltration rates with time can likely be considered the norm for ponds filled with high-SAR water.
Figure 6. Vertical hydraulic conductivity was highest when the pond was being filled. Slightly longer than one year after initial inflow to the pond, the vertical hydraulic conductivity decreased significantly.

Before the pond was filled with water, solid phase material was collected to identify salt-rich zones beneath the pond, and ions within those zones that might be mobilized by infiltrating water. These data were used to predict changes in ground-water quality. After discharges to the pond ceased and the pond became dry, a second set of solid phase samples were collected to track the fate of the salts that were mobilized by the infiltration water (Figure 7). Data from the cores collected during the winter of 2006-2007 are compared to earlier samples in Figures 8 through 13. Saturated paste extract (SPE) data from the cores indicate the salts migrated no further than 10 to 15 feet vertically, as shown by electrical conductance (EC) data (Figure 8).

Sodium adsorption ratio decreased directly beneath the pond floor but increased in the sand and clay zone at a depth of 15 to 25 ft below the pond primarily due to mobilization of sodium (Figures 9 and 10). Calcium does not appear to have been mobilized (Figure 11), but magnesium was removed from the shallow zone and moved to the zone at about 20 ft below the pond floor (Figure 12). Sulfate was also removed from the shallow zone (Figure 13).
Figure 7. Core samples were collected from beneath the pond for saturated paste extract analysis.

Figure 8. Based on electrical conductance (EC) data, infiltrating CBM water from the pond flushed salts from the silt and clay zone at 0 to 10 ft below the pond floor. The salts are now concentrated within the sand and clay zone at 15 to 25 feet below the pond floor.
Figure 9. In response to the infiltrating CBM water, SAR values directly beneath the pond decreased and at a depth of 15 to 25 ft the SAR values increased.

Figure 10. The change in SAR values shown in Figure 8 is a result of sodium being removed from the shallow material beneath the pond floor.
Figure 11. It appears that calcium is not involved in the chemical reactions occurring as the infiltrating CBM water moves through the system beneath the pond.

Figure 12. Magnesium was flushed from the material directly beneath the pond floor, and became more concentrated at a depth of about 20 feet.
Figure 13. Infiltrating CBM water removed sulfate from the upper 10 feet of the profile.

**Subtask 2**
Run laboratory column leach tests of leonardite as a sodium sequestration medium.

A laboratory experiment was conducted to determine if leonardite could potentially be used to sequester sodium from CBM-production water. Water, collected from CBM wells, was exposed to uniform sized, granular leonardite in flow-through columns. Water was pumped into the columns from the bottom to allow complete saturation. The water was left in contact with the leonardite for 48 hours, then displaced by the next pore volume of water. During the seventh replication, piping (channeling) became apparent in the column, and thereafter only a limited portion of the leonardite was exposed to each successive batch of water.

A total of 15,822 mL of water was run through the column containing 1,131 grams of leonardite. This ratio extrapolates to an equivalent of 3,350 gallons of water being treated by 1 ton of leonardite. A significant improvement in the SAR of the treated water was evident even with the limited exposure (Figure 14). Sodium was absorbed by the leonardite, and the SAR was further reduced by release of Ca and Mg (Table 1). Total dissolved solids (indicated here by specific conductance) increased, pH decreased and interestingly, Al increased.

If complete mixing of the water with the leonardite could be maintained, it is possible that greater decreases in SAR could be achieved. The encouraging results have prompted us to repeat the experiment, but by using small batch mixes to avoid problems with piping and to maximize contact.
Figure 14. CBM-produced water, when exposed to leonardite, shows a significant decrease in SAR as the sodium is absorbed.
Table 1. Laboratory data from CBM-produced water treated by exposure to 1,131 grams of leonardite.

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**Subtask 3**

Evaluate the potential for using multi-spectral images to identify candidate sites for infiltration ponds.

An ASTER image of the Coal Creek study area was taken in Aug 7, 2001. Data from three bands of the image were acquired and processed (georectified, resized and calibrated). The three bands were: Band 1 - 0.5560 micrometers; Band 2 - 0.6610 micrometers; and Band 3N - 0.8070 micrometers. The bands were analyzed using Spectral Image Mapper. The results were then compared to USGS spectral signatures for calcite, epsomite, gypsum, kaolinite, montmorillonite and halite (a control species). Each pixel in the image was assigned the mineral value for the best match. The values were then plotted on a map of the Coal Creek study area (Figure 15).
Figure 15. Analysis of ASTER data from wavelengths less than 1 um show good correlation with epsomite, and lesser amounts of montmorillonite, kaolinite and minor gypsum and calcite. The tan colored areas indicate no correlation.

This analysis suggests that epsomite is by far the most predominant mineral species in the soils. Epsomite is a mineral of interest as it is highly soluble and provides a source for Mg and SO4, which are major contributors to the increased TDS noted in infiltrated water. Large areas of the study site did not indicate a predominant mineral species, which may be a matter of the bands chosen for analysis or the mineral species (spectral signatures) used. The mineral species were selected based on published analyses in the Powder River Basin. Based on these results, additional bands will be purchased and analyzed.

Publications to Date

One report, written as part of the predecessor project to this one, was released. A paper for oral presentation and extended abstract were presented at the Billings Land Reclamation Symposium in June, 2006 and a field tour of water management sites was lead by J. Wheaton. A white paper was written for the Montana Department of Environmental Quality on the subject of injecting CBM-produced water. This paper
drew upon the work of Dr. David Lopez, PI for Task 9 and John Wheaton, PI for Task 6 of this project.

A talk was given on CBM and water management at the Montana Governor’s Restoration Forum in June, 2006 by J. Wheaton.

Public education is considered important in Montana and invited talks on CBM, including water management, were given to the Association for the Advancement of Indigenous Resources and the Citizens For Resource Development in May, June and October, 2006.


**Presentations:**

**Industry conference**
Wheaton, John, Gunderson, Jay, March 29, 2007, Coalbed Methane and Water Management in Montana: 8th Annual Coal Bed Methane Conference, Strategic Research Institute, Denver, CO.

**Government conference**
Wheaton, J. April 24, 2007, Coalbed methane water issues, Yellowstone River Compact Commission, Sheridan, WY.
Public education

**Plans for the Next Report Period**

1. Re-establish data collection at the Beaver Creek site, an on-channel infiltration pond site.

2. Continue data collection at both field sites.

3. At the end of this field season, monitoring facilities at Beaver Creek (wells, flumes, weirs and met stations) will be removed and the sites reclaimed. The Coal Creek pond is scheduled for complete reclamation and our monitoring facilities will be left in place to document ground-water responses after reclamation of an infiltration pond. Additional funding is being sought to support this effort.

4. Present findings at the American Society for Mine Reclamation in Gillette, WY in June, 2007, and lead a field trip during that symposium to look at CBM-water management operations in the Powder River Basin.

5. Model flow and calculate a mass balance for Coal Creek site.

6. Repeat the leonardite tests using a batch mixing approach. The new material is on hand.

7. Purchase additional ASTER data and further evaluate mineral identification at the Coal Creek site.

8. Using the results of the site studies, evaluate methods used to assess potential infiltration pond sites. A decision matrix has been developed and the steps will be considered for potential benefits and expediency of decisions.

9. Finish reports and publish results.
Summary Statement of Project Goals
Task 7 will evaluate/quantify the factors controlling the exchange of CBM discharge to shallow groundwater, calibrate numerical models of groundwater flow (and chemical transport), and develop models which will be transferable to other regions. The study will focus on an existing study area in the upper reaches of Beaver Creek to evaluate the fate and transport of co-produced waters. Tools developed in this study can be used to predict infiltration in undeveloped watersheds, streamlining the permitting process, and aiding in the efficient location of future discharge sites or infiltration ponds.

Executive Summary
Activities on Task 7, “Controls on the fate of CBM Co-produced waters and impacts to shallow aquifer groundwater quality”, have focused on three fronts: (1) planning for a final field campaign in summer, 2007 to download water level and streamflow data, and conduct a suite of infiltration tests, (2) continued analysis of time series data over the three year study period for which complete data are available, in order to quantify systematic temporal trends in infiltration and transpiration losses, and (3) evaluation of watershed response to rainfall events as a potential proxy for a priori prediction or estimation of infiltration losses. As part of these efforts, we have worked with colleagues at CSM and MT Tech over the past several months to re-negotiate access to the site with the land owner and new producer. In late fall of 2006, we shut the site down for the winter season, and we plan to restart all dataloggers in June, 2007 for the summer-fall season.

Based on the three year record, we have isolated the components of conveyance loss due to infiltration and evapo-transpiration by taking advantage of observed systematic seasonal variations. With direct measurements of pan evaporation, we can further separate the evaporation and transpiration components. Our previous analysis of the time series data indicated a clear trend of increasing peak channel conveyance loss in the summer months for the lower stream reach, which runs in a well-confined channel (Section IV). This is a key finding because it indicates significantly increased transpiration losses over time; the significant contribution of transpiration to the water budget also results in a high seasonal variability in conveyance loss. In contrast, at the upper stream reach, which runs in a broad, shallow channel, we find that the temporal evolution of conveyance losses is more complicated. In general, the same increase in transpiration over time is evident, but the signal is superimposed on significant variations in channel width with increased discharge.

Using weir and precipitation gauge data, we have performed an analysis of rainfall-runoff response in the study area. The results indicate that the watershed behaves predictably to
storm events. Forward models of the rainfall-runoff response are consistent with observations only if (a) there is little dependence on antecedent moisture, and (b) the soils have a high infiltration capacity. This is consistent with our field observations, and suggests that similar analyses of gauged watersheds prior to development may be a useful tool for estimating or predicting conveyance losses.

Results

**Subtasks 1 & 2:** (1) Evaluate and quantify controls on fate of discharged waters. Provide both time-averaged and time series of water budgets. (2) Use water budget analyses to evaluate long-term infiltration rates.

As discussed in the previous report, our analysis of the time series data document that conveyance losses in stream channels have increased and its seasonality has increased as vegetation cover and transpiration have increased (Figures 2-4). This suggests that the changes in vegetation in response to the increased water from produced water discharge will slowly change the local water budget and cause a decline in the volume of surface discharge that reaches the river during summer months (Figures 3-4). During winter months, the vegetation has a minimal effect, and the volume of water reaching the river should depend primarily on infiltration. Our subsequent, more detailed analysis of the
stream channel water budgets confirms this finding, but also identifies new complexities that must be considered in predictive models. We suggest that these additional complexities in the conveyance loss time-series are related to channel morphology, and resulting changes in stream area as a function of discharge.

Specifically, we find that in Block II (the upper stream reach), which runs in a broad, shallow channel, the temporal evolution of conveyance losses is different than in the well-confined lower channel of Block IV (Figure 2). In general, the same monotonic increase in transpiration with time is evident in both reaches, but the signal is superimposed on significant variations in channel width in Block II associated with increased discharge. As a result, in this channel reach, conveyance losses are largest during spring runoff, when transpiration and infiltration act as sinks over a large channel area. At these times, we posit that transpiration is moderately increased, and channel width is extremely large due to runoff and snow melt. In summer, conveyance losses are moderate, due to offsetting factors of increased transpiration (which tends to increase conveyance loss), and decreased channel area.

![Figure 2. Time series of conveyance losses in stream channel for well-confined channel reach in Block IV (left) and broad, shallow channel reach in Block II (right). Conveyance losses during the cold months reflect only infiltration (solid line). Increased peak losses during the summer are not explained by evaporation, and are interpreted to reflect increasing transpiration losses. This trend is shown by the dashed line. Note that highest conveyance losses in the broad channel of Block II occur in spring and fall.](image)

Based on the time-series data, we have successfully separated the conveyance losses into an infiltration component of 1.5-2 in/d, which remains constant throughout the study period, and transpiration losses that increase from 2.2 in/d in Block IV and 0.5 in/d in Block II in year 1, to 4.3 in/d and 3.3 in/d in year 2, respectively, to 6.8 in/d in year 3 (Block IV only). As noted above, this increase is coincident with significant increase in peak vegetation cover over time (Figures 3-4). Evaporation losses are negligible in comparison, ranging from 0.04 inches/day in the winter, to 0.25 inches/day in July-August.

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Subtask 3: Evaluate and develop proxies for infiltration that can be applied to undeveloped watersheds, to estimate or predict fate of CBM discharge, including infiltration tests and rainfall runoff analyses.

Infiltration Tests:
A series of short-term (~1.5-2 hr) and long-term (~8-12 hr) infiltration tests are planned as part of our field campaign this summer. These data will be compared to results from simple rainfall runoff models, to infiltration rates inferred from water budgets, and to modeling results from Rosetta and saturated-unsaturated flow models (Payne and Saffer, 2004, 2005), to evaluate the utility of such tests as a proxy for infiltration. We plan to conduct the tests both in-channel and adjacent to channel, and in both dry reaches (South...
of the Upper Pond, upstream of development, and unaffected by CBM development) and actively flowing reaches (Blocks II and IV).

**Rainfall Runoff Models:**
By determining the effective precipitation (the portion of the precipitation in the watershed that becomes stream discharge), the spatially averaged infiltration properties of the watershed can be estimated. Normally, this approach is applied as a forward model to predict runoff from storms of particular intensity and/or duration; here we use it to evaluate the utility of rainfall-runoff systematics as a proxy for infiltration behavior.

In general, the fate of precipitation ($W$) falling in a watershed can be described by:

$$W_{\text{eff}} = W - (ET + \Delta S_c + \Delta D + \Delta \theta),$$

where $ET$ is evapotranspiration, $\Delta S_c$ is the change in storage in a vegetation canopy), $\Delta D$ is the change in depression storage, and $\Delta \theta$ is change in soil water content associated with infiltration. All except $\Delta \theta$ are all inconsequential for our small watershed; $ET$ is typically small during rainfall events because relative humidity is high during rainfall events, and $D$ and $S_c$ are negligible at the Beaver Creek site. Therefore, we expect that $W_{\text{eff}}$, or the ratio $W_{\text{eff}}/W$, will depend primarily on the spatially averaged infiltration properties of the soil in the watershed. For areas characterized by soils with high infiltration capacity, we would expect $W_{\text{eff}}/W$ to be small, and vice-versa.

Total event streamflow can be determined by integration of the hydrograph over time after separation of baseflow. For our purposes, baseflow is constant and approximately equal to the CBM input, and so is easily separated from the hydrograph. The effective precipitation ($W_{\text{eff}}$) is determined for each event by:

$$W_{\text{eff}} = \frac{Q_{\text{int}}}{A_D},$$

where $A_D$ is the drainage basin area. The drainage basin area is different for each weir, and is calculated from USGS digital elevation data.

We find that $W_{\text{eff}}$ increases with $W$, but the ratio $W_{\text{eff}}/W$ is generally very small, ranging from 0.002 to 0.2 (Figure 6). In general, this is consistent with high infiltration rates, which limit runoff. This is also consistent with infiltration rates calculated from our water budget data, which indicate rates of $\sim$1.5-2 in/day. To more precisely evaluate the implications of the rainfall-runoff data as a predictor of infiltration properties, we modeled runoff using the SCS method (U.S. Soil Conservation Service, 1964). In this method, $W_{\text{eff}}$ is related to $W$ through a set of empirical parameters that describe general soil infiltration behavior and antecedent moisture conditions due to previous precipitation. Our results show that in order to fit the data, there must be little dependence on antecedent moisture, and SCS soil types with moderate to high infiltration capacity (0.15-0.30 in/hr) are necessary (Figure 6).

These model results are consistent with the observation of high infiltration capacity in the Beaver Creek watershed (c.f. Figure 2), and with data indicating that runoff does not increase with antecedent rainfall (Figure 7). Broadly, our systematic and consistent results suggest that the use of rainfall-runoff models holds promise as a tool for predicting watershed response to CBM discharge. However, considerably more detailed work is needed in order to use such data sets as a quantitative predictor of infiltration.
Figure 5. Example of precipitation and runoff records from summer-fall, 2003 used for rainfall-runoff analyses. Top: precipitation at Beaver Creek site measured with tipping bucket rain gauge, resolution of 0.01 in. Bottom: weir records for the same time period showing creek discharge associated with precipitation events.
Figure 6: Plots of $W_{ef}$ vs. $W$. Weir numbers increase from upstream to downstream (see Figure 1). Left: $W_{ef}$ determined as described in text, $W$ measured directly by tipping bucket rain gauge at Weir #2, for all precipitation events from July, 2003 through Oct., 2005. Right: Data plotted with modeled $W_{ef}$ based on SCS method. Upper curve corresponds to a curve number (CN) of 8, lower curve is for CN = 6. CN is an empirical indicator of infiltration rate, a lower CN indicates a higher infiltration rate.

Figure 7: $W_{ef}$ vs. antecedent rainfall, indicating little dependence of $W_{ef}$ (and therefore little dependence of infiltration losses).

Publications to Date:

Plans for the Next Report Period

1. Conduct field measurements of infiltration capacity for comparison with values from water budget analyses.
2. Continue watershed monitoring, provide database. Continue to determine time series of water budgets and conveyance losses as data permit.
BENEFICIAL USE – AGRICULTURAL APPLICATION – Task 5

Conclusions
None for this period

Schedule Status
Anticipated Completion Date for all Tasks – 10-31-07

Significant Accomplishments
The research plots were prepared for the second irrigation season. Application of amendments was completed in the area adjacent to the plots.

Soil water, temperature and electrical conductivity data continues to be collected from two of the research plots.

A study is underway to evaluate the use of amendments to reclaim sodic soil sites impacted by CBM produced water. Baseline data was collected and the site was treated with gypsum. Samples were collected one year after reclamation was completed. The results of this work are under review and will be included in the final report.

Results from a greenhouse study were tabulated.

Actual or anticipated problems or delays
None

Product Produced or Technology Transfer Activities
The status and results to date were presented in a web conference with the State of Montana, the State of Wyoming, USBLM – Wyoming and Montana, University of Wyoming, Montana Bureau of Mines and Geology, and others.

Publications to Date:
None for this reporting period. Several publications will be written at the end of the 2007 growing season.

Website
None during this project period

Networks or Collaborations fostered
None during this project period

Technologies/Techniques
None during this project period

Inventions/Patent Applications
None during this project period
Brief Summary Statement of Project Goals

Task 5 will determine how CBM-produced waters affect the physical and chemical nature of Powder River Basin soils and will study the interaction between water quality (conductivity, TDS, SAR, and alkalinity) and soil quality. This study is a continuation of an effort initiated in 2001 under the Western Resources Project. Field sites have been established and baseline soil chemistry and hydraulic property evaluations completed. Soil moisture probes and a lysimeter (Gee Drain Gauge) have been placed below the root zone at one site. Two center-pivot irrigation systems were installed at the site for the purpose of demonstrating the beneficial use of CBM produced water for irrigation. The proposed efforts will establish gypsum and sulfur application rates required to maintain soil quality, determine allowable water application rates, and develop models of the soil chemistry impacted with CBM produced water. The first year of operation was truncated due to the delayed construction of the pivots. However, an attempt will be made to extend the project another year with the funding currently available.

Executive Summary

The irrigation research site was characterized and instrumented prior to initiating irrigation. Eight (8) plots were established in two fields to be irrigated with large pivot systems. Each plot contained 7 subplots each representing a different treatment. A lysimeter was placed at one site to collect water exiting the root zone. Two sites were instrumented to a depth of 6 feet with soil probes to measure continuous soil water content, solution salt content, and soil temperature.

Baseline conditions were established for soil characteristics for chemical and physical parameters. The research plots were sampled after the conclusion of the first irrigation season. Samples were analyzed and preliminary conclusions were made.

An irrigation model was completed using baseline conditions to simulate projected soil conditions over a 10-year period. As data are generated from the research plot, the model will be more closely calibrated to Wyoming and Montana climatic conditions.

The plots have been prepared for an additional irrigation season. Approximately 30 inches of CBM water will be applied to the irrigation sites during 2007.
Soil fertility evaluations will continue to determine the impact of soil amendments and CBM produced water on the production of alfalfa. The work will continue at the field sites located north of Sheridan, Wyoming. The basic problem at the field site was associated with localized acid formation resulting from the use of sulfur as a soil amendment. The acid’s influence on the solubility of iron and manganese along with the localized water saturation and its affect on solubility are thought responsible for iron and manganese toxicity. Continuation of this work will provide 3 years of data for the final report.

**Results**

The research plots at the WJ irrigation test site were prepared for the second irrigation season. Application of amendments was completed in the area adjacent to the plots. Soil water, temperature and electrical conductivity data continues to be collected from two of the research plots.

A study is underway to evaluate the use of amendments to reclaim sodic soil sites impacted by CBM produced water. Baseline data was collected and the site was treated with gypsum. Samples were collected one year after reclamation was completed. The results of this work are under review and will be included in the final report.

The following results are from the greenhouse study and are presented as averages from four (4) replicates. Statistical evaluation of the data is on going and will be presented in the final report.

The amendment treatments used in the greenhouse study are shown in Table 1. A combination of gypsum (CaSO₄), ag-lime (CaCO₃) and phosphorous were used. Two quantities of ag-lime were used, one low and one high. The ag-lime was used to increase the pH while the gypsum was applied to maintain the physical condition of the soil, preventing the acidification and dispersion of soil particles. Phosphorous was added as a fertilizer to enhance plant growth.
Table 1. Amendment treatments used in the greenhouse study.

<table>
<thead>
<tr>
<th>Treatment Number Used</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control – No treatment</td>
</tr>
<tr>
<td>2</td>
<td>Gypsum Only</td>
</tr>
<tr>
<td>3</td>
<td>Ag Lime – Level 1</td>
</tr>
<tr>
<td>4</td>
<td>Gypsum and Ag Lime – Level 1</td>
</tr>
<tr>
<td>5</td>
<td>P$_2$O$_5$</td>
</tr>
<tr>
<td>6</td>
<td>Gypsum + P$_2$O$_5$</td>
</tr>
<tr>
<td>7</td>
<td>Ag Lime – Level 1 + P$_2$O$_5$</td>
</tr>
<tr>
<td>8</td>
<td>Gypsum + Ag Lime – Level 1 + P$_2$O$_5$</td>
</tr>
<tr>
<td>9</td>
<td>Ag Lime – Level 2</td>
</tr>
<tr>
<td>10</td>
<td>Gypsum + Ag Lime – Level 2</td>
</tr>
<tr>
<td>11</td>
<td>Ag Lime – Level 2 + P$_2$O$_5$</td>
</tr>
<tr>
<td>12</td>
<td>Ag Lime – Level 2 + Gypsum + P$_2$O$_5$</td>
</tr>
</tbody>
</table>

The results associated with the amendment applications are presented in Table 2. The data suggest that the North Pivot soils do best when amended with the highest level of ag-lime and phosphorous. However, a statistical evaluation will be needed to sort out the apparent large variability in the data set. The South Pivot soil appears to be much more productive compared to the North Pivot soil as plant production is about 2 times larger. This is likely due to the pH difference between the soils. The data show a likely difference between the treated and untreated (control) soils.

However, there appears to be very little difference between treatments. The data will be evaluated using an appropriate statistical design for presentation in the final report. In addition, the data collected previously and the data that will be collected at the conclusion of the 2007 growing season will be statistically evaluated and presented in the final report.
Table 2. Average plant production by treatment for the north and south pivot soil materials.

<table>
<thead>
<tr>
<th>North Pivot Soil Materials – Study Averages</th>
<th>South Pivot Soil Materials – Study Averages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td># of Pots</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
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<tr>
<td>4</td>
<td>4</td>
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<td>5</td>
<td>4</td>
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<tr>
<td>6</td>
<td>4</td>
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<tr>
<td>7</td>
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<td>8</td>
<td>4</td>
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<tr>
<td>9</td>
<td>4</td>
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<td>10</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>
WATER TREATMENT – Task 2 Summary

Conclusions

Schedule Status
Anticipated Completion Date for all Tasks – 5-25-07

Significant Accomplishments

A second large aliquot of CBM water from the Powder River Basin was collected from the field and used to assess the long term performance of non-selective electrodialysis membranes. This aliquot was also used to assess the performance of clean in place protocols.

No discontinuity in the decreasing conductivity was observed in any of the runs with the non-selective membranes, suggesting that no back-diffusion occurs at the 70 g/l level on the concentrate side of the ED membranes.

Energy consumption data from the experiments indicate the feasibility of achieving high product water recovery efficiencies (>90%) at low electricity inputs (less than 0.18 kWh/lb salt removed (NaCl equivalent)). This translates to an energy cost less than 0.4 cents per barrel (assuming electricity cost is 6 cents per kWh) if partial demineralization only requires a reduction of 1,000 mg/l of TDS in a produced water stream to allow beneficial use of the water.

Actual or anticipated problems or delays
None during this project period

Product Produced or Technology Transfer Activities
Publications to Date:


**Website**
None during this project period

**Networks or Collaborations fostered**
This group of researchers continues to develop closer professional collaborations with the overall group.

**Technologies/Techniques**
None during this project period

**Inventions/Patent Applications**
None during this project period

**Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment**
None during this project period
Summary Statement of Project Goals
The overall objective of this effort is the development of electrodialysis (ED) processing for reliable, low-cost treatment of produced waters for the purpose of brine volume reduction with the simultaneous generation of demineralized water that is suitable for beneficial use. The rationale for the work is to avoid the costly membrane fouling that has hindered the field operation of other demineralization processes (such as reverse osmosis). The goals of this task are to:

- Achieve product water recovery efficiency greater than 90%.
- Achieve a brine volume reduction greater than 10:1.
- Maximize membrane life.
- Generate a product water of a quality suitable for agricultural beneficial use.
  - Sodium Adsorption Ratio < 3-5
  - Total Dissolved Solids < 1,000-2,000 mg/l
  - Address chemicals of concern (e.g. Benzene < 5 ppb)

Specific Subtasks

Subtask 1. Produced Water Characterization. (Completed)

Subtask 2. Fabrication of ED Laboratory Prototype. (Completed)

Subtask 3. Large PW Sample Collection. Obtained large water aliquot to use in the testing the laboratory prototype. (Completed)

Subtask 4. Prototype operation. Experiments have been focused on completing the comparison of the performance characteristics of two cationic membranes and on determining the capability of ED to concentrate salts and reduce volumes of brines requiring disposal. The initial experiments have focused on a comparison of two cationic membranes in the performance of the ED unit. (In Progress)
Technical problems of the management of CBM produced water include: 1) the lack of Class II injection well capacities (especially in basins of the Rocky Mountains); 2) high carbonates that foul conventional membrane separation processes (such as reverse osmosis); and, 3) generation of produced waters at remote and dispersed fields in CBM basins. Since much of this water is generated in arid areas, serious consideration is being given to the conditioning of CBM produced water for beneficial uses such as irrigation, watering of livestock and recharge of aquifers. Treatment needs often include demineralization to total dissolved solids (TDS) levels below 2,000 mg/l and the adjustment of the sodium absorption ratio (SAR) to levels (below 6) that are not damaging to clayey soils. Based on the analysis of more than ten produced water samples taken from four regions in the Powder River Basin (PRB) of Wyoming, it would appear that CBM produced water does not typically exhibit the problems of significant concentrations of oils and greases and high levels of soluble organic compounds (e.g. volatile acids). This absence of organic constituent concentrations portends an easier challenge in the treatment of produced water for beneficial use (e.g. irrigation, habitat maintenance, groundwater recharge, etc.). The overall objective of Task 2 was to evaluate the feasibility (technical and economic) of using an electrodialysis based process train to convert CBM produced water to a water stream suitable for beneficial use.

Electrodialysis (ED) is an electrically-driven membrane process for removing ions from process streams. The anticipated benefits of this process include enhanced CBM produced water quality, extended life of injection wells by 10-fold, reduce treatment cost to 10-15 cents per barrel and use of 90% of the water for beneficial use. If treatment system effluent is to be made available for beneficial use (such as irrigation, livestock operations, groundwater recharge, etc.), the water stream must comply with certain water quality criteria; some of these guidelines are defined by State regulations. Since coalbed methane (CBM) generates a water stream that is usually very low in organic content, beneficial use criteria that are applicable to CBM produced water mainly focus on three parameters: total dissolved solids, sodium absorption ratio and pH. For example, in many areas of Wyoming and Montana, a parameter called “sodium absorption ratio” or “SAR” is required to be reduced from above 40 to less than 6 for purposes of protecting clayey soils during irrigation. For most beneficial uses, recommended averages for total dissolved solids (TDS) fall in the range of 1,000-2,000 mg/l and the recommended pH range is usually 6-8.

The effort to develop ED for the conditioning of produced water for beneficial use has employed laboratory scale ED prototype equipment obtained from Ameridia Division of Eurodia, an international commercial vendor of demineralization processes. The project is aimed at improving the performance and reliability of membrane processes in converting CBM produced water to beneficial-use product water. The project team is focused on minimizing both the capital costs and power use for processing. Experimental results with actual CBM produced water using selective and non-selective electrodialysis membranes, long term membrane performance, membrane fouling and power requirements have been addressed.
**Results**

Technical results will highlight degree of desalination of the desalted water as it relates to SAR, pH and TDS values suitable for beneficial use target (livestock drinking and water irrigation in the Power River Basin) as well as an estimate of the upper salt concentration in the rejected stream. Recent tests on the laboratory ED prototype on actual produced waters have indicated the technical feasibility of achieving product water recovery efficiencies of 95% with the concomitant generation of a concentrated brine stream that is only 5% of the flow of the influent produced water feed. This small-flow brine stream can be disposed of through injection in a Class II well. Alternatively, the stream can be processed with thermal drying to produce a high-purity (98%) sodium bicarbonate product that can be utilized in power plants, agriculture, manufacturing, etc. Concepts for zero-discharge produced water management using this ED system design will also be discussed.

At the beginning of this performance period, Tasks 1 and 2 had been completed. During this period, Task 3 was fully completed and the laboratory electrodialysis (ED) testing aspects of Task 4 (which emphasized evaluations of membrane integrity and the development of clean-in-place procedures) were concluded. The laboratory ED prototype is shown in Figure 1.

The laboratory scale ED unit, containing 10 cell pairs and operated in batch configuration at a constant current with an average voltage drop per cell of less than 1.5 volts, was used to conduct six types of investigations: 1) Pre-treatment with a sub-micron filter to control suspended solids; 2) Comparison of the selective cationic membrane with the non-selective cationic membrane; 3) Evaluation of electrodialysis membrane back diffusion effect of a dilute produced water treatment end point on one side of the membrane and a concentrated salt solution (> 300 g/l) on the other for purposes of testing the integrity of the process; 4) Post-demineralization treatment to adjust the sodium adsorption ratio (SAR) to levels suited to beneficial use; 5) Integrity testing for the ED membranes; and, 6) Development of clean-in-place protocols for the ED process suitable for CBM produced water treatment. The first year of the project emphasized the first three types of investigations and the second year has emphasized the latter three. The current period of...
performance has worked on the completion of the last two types of investigations regarding ED testing in the laboratory.

Since the last semi-annual report, a second, large aliquot of produced water has been collected from a CBM field in Wyoming. Specifically, in the course of the entire laboratory testing effort, two large aliquots of water (collected in 55 gallon drums) were obtained from a CBM produced water gathering site near Sheridan, WY. The aliquot called “Large Aliquot 1” was collected in 2006, and the aliquot called “Large Aliquot 2” was collected in January of 2007. Composition of these large aliquots were similar to the composition of most of the samples taken from seven locations in the Powder River Basin. Compositional data of these aliquots are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Large Aliquot 1</th>
<th>Large Aliquot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>-</td>
<td>8.4</td>
<td>8.8</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/l</td>
<td>670</td>
<td>680</td>
</tr>
<tr>
<td>Calcium</td>
<td>mg/l</td>
<td>6.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>mg/l</td>
<td>2.3</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/l</td>
<td>7</td>
<td>40</td>
</tr>
<tr>
<td>Conductivity</td>
<td>µS/cm</td>
<td>1783</td>
<td>2620</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/l as CaCO₃</td>
<td>1300</td>
<td>1600</td>
</tr>
</tbody>
</table>

Using produced water from the two large aliquots, a number of electrodialysis runs were conducted to examine the long term integrity of ED membranes and to examine the potential for back-diffusion while maintaining a 70 g/l level of sodium bicarbonate in the concentrate and while using non-selective cationic membranes (CMX) obtained from Ameridia. Efficient reductions (>90%) of conductivity in the batch solution of CBM produced water was achieved within 50 minutes; a typical plot of conductivity and pH with time for an ED treatment run is shown in Figure 2. Conductivity reductions coincided with the removal of sodium and bicarbonate from solution. Sodium concentrations were reduced from approximately 680 mg/l to 100 mg/l and alkalinity decreased from 1,600 mg/l to
about 300 mg/l. Though alkalinity was significantly reduced, pH values decreased from 8.5 to the 6.5−7.0 range (a neutral pH condition for beneficial use waters). No discontinuity in the decreasing conductivity was observed in any of the runs with the non-selective membranes, suggesting that no back-diffusion occurs at the 70 g/l level on the concentrate side of the ED membranes. In continuous processing of a CBM produced water stream containing 2,000 to 3,000 mg/l of total dissolved solids (TDS), the recovery of over 90 percent of the product water containing 1,000 mg/l of TDS would result in a concentrate stream containing far less than 30 g/l.

Energy consumption data from the experiments indicate the feasibility of achieving high product water recovery efficiencies (>90%) at low electricity inputs (less than 0.18 kWh/lb salt removed (NaCl equivalent)); this is consistent with earlier ED runs conducted with 300 g/l NaCl in the concentrate. This translates to an energy cost less than 0.4 cents per barrel (assuming electricity cost is 6 cents per kWh) if partial demineralization only requires a reduction of 1,000 mg/l of TDS in a produced water stream to allow beneficial use of the water. If demineralization required ten times this level of TDS reduction, energy costs would likely extrapolate to less than 4 cents per barrel of CBM produced water. Thus, electrodialysis electricity requirements seem reasonable for the beneficial use treatment of CBM produced waters of moderate concentrations (< 12,000 mg/l TDS).

Publications to Date


Conferences

Plans for the Next Report Period

1. Complete analysis of the data obtained from all experiments.
2. Complete an economic analysis using vendor information on scale-up requirements and equipment costs.
3. Final reporting.
Summary Statement of Project Goals
The goal of Task 8 is to establish procedures for comparative evaluation of treatment technologies that are offered for reducing sodium content of coalbed-methane-production water. The goal is to be accomplished by construction and deployment of a mobile laboratory.

Executive Summary
Task 8 was funded during the second year of this project.

Originally intended to be a trailer-mounted unit, the design has been altered and is now planned as a pickup camper with a small storage trailer. This will allow greater flexibility in applications. One company preparing to test a high-pressure reverse osmosis systems has voiced an interest in using the unit. The field version of the electrodialysis unit being designed by Argonne and GTI (Task 2 of this overall project) is intended to be tested using this unit. However, funding has not yet been received for field test of the ED unit.

Originally planned as a water treatment evaluation unit, other water-management applications are now apparent. The unit can be deployed to provide water-budget monitoring for irrigation applications (Task 5) and for injection of CBM water if future funding of work initiated under Task 9 is received. A company that has developed a downhole separator and pump has submitted a letter committing their system to being tested for an injection test if funding becomes available.

Results

Subtask 1
Design and construct the mobile testing facility.

The field laboratory has been designed to maximize open space that can allow an enclosed lab/office and still provide ample secure storage for equipment. As designed the unit can be easily removed from the pickup truck and set on supports allowing it to be left at a field location for an extended time. A supplier for the basic unit has been identified in Montana. A small electric hoist has been included to allow lifting heavier items in and out of the unit. A small propane heater will allow for winter use. Counter tops will be used for water handling, desk space and computer workspace. Ports on the sides will allow access for electrical lines (sensors) and water lines for clean sampling conditions.
A generator will provide electrical power in remote settings. An external pig-tail will ensure the generator is kept at a safe and clean distance from the lab. Internal power will include both 12-volt DC and 120-volt AC.

A small utility trailer will be used for on-site storage as needed and will allow transportation of items that should not be transported in the laboratory space such as a gasoline generator.

Several suppliers have submitted information on sensors and data loggers. The final design will likely include equipment from more than one company, as each has an area of expertise. The equipment will be commercial grade to withstand the rigors of field use. Sensors will include full-pipe flow meters, pressure transducers, specific conductance, temperature and ion-specific electrodes. The unit will be stocked with a variety of plumbing supplies to allow connection of the sensors to the water flow streams.

**Subtask 2**
Deploy the facility to a test site.

This subtask will occur after the completion of subtask 1. Several sites have been volunteered by landowners that are not CBM-production wells but that do have the same water quality. If appropriate, these sites will be considered as they will not put a producing company in dependence on a technology that is under primary field testing. Also, private sites avoid permitting, access and other issues associated with CBM production fields.

In addition to standard water treatment research such as the ED unit being developed by Argonne and GTI (Task 2), we are looking at other water treatment approaches such as irrigation. This unit can be deployed and provide significant assistance to Dr. Terry Brown in his irrigation work under Task 5.

This unit is being designed for long-term applications to CBM research. Future deployments are expected to include providing a clean work space and field laboratory for collecting methanogenic microbes for methane generation research. Funding for microbial research is being pursued by Argonne lab in hope of furthering methane reserves.

Once equipped, the unit will also be available to monitor injection tests. Dr. David Lopez identified several key injection intervals (Task 9). Due to the nature and shape of these channels sandstone units, research in to the water-pressure response during injection will be critical to fully develop these zones.

**Subtask 3**
Test treatment systems.
CERI team members from Argonne National Laboratory have a treatment design that we hope will be the first system tested by this new facility. This design, using electrodialysis processing is innovative and if proven in a field test could make a significant improvement in water treatment options.

Publications to Date
None.

Plans for the Next Report Period
1. Purchase the individual parts for the facility (basic shell, trailer, sensors, dataloggers and laptop computer).
2. Test all aspects to verify performance.
4. Select a test site and a treatment method for testing.
5. Deploy to the treatment site.
6. Evaluate data on treatment method.