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This document contains the first 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 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 Research 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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Overview

This document contains the first 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. Please note that task 2 is the responsibility of Argonne National Laboratory in collaboration with the Gas Research Institute. As such, that task 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 2 and 10), separate progress reports are filed directly with DOE by those PI’s. Abbreviated progress reports from those tasks are included in this report.

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 three meetings with all the subcontractors attending to establish financial and reporting procedures identify areas of potential collaboration between projects and facilitate collaboration between projects. 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 File Site.

Expenditures of year 1 funds are slightly behind the original projected track due to the modified start date of April 29, 2005 rather than the planned February 2005 project start. This delay caused some of the subcontractors to abbreviate their 2005 spring field season. These projects are Tasks 3, 5 and 6.

The remained of this document is organized to facilitate the reader’s grasp of this complex project. The figure below summarizes the project organization in terms of work categories and flow. 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</th>
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<td>1 – Fluid Reduction</td>
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</tr>
<tr>
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Task 8 is not slated to start until the year 2 period (May 2006-2007). Task 10 involves overview of the regulatory environment to ensure any methodology or technique developed can be implemented.
FLUID REDUCTION – TASKS 1 AND 4
Conclusions
Coal bed stress regime can control the orientation of fractures (vertical or horizontal). Maps of coal bed stress can help determine where vertical fractures will form and can help minimize vertical fracture formation and excessive water production.

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

Significant Accomplishments
Commercially available membrane for downhole waterless gas production has identified that can exclude water transport while allowing gas transport. Membrane has been tested in laboratory under simulated reservoir conditions and performed as expected.

Experimental apparatus required for the dual-phase mass transfer study designed and constructed, preliminary testing has begun.

Locations for under-pressured coals and sandstone interval in PRB that may serve as locations for re-injection of CBM produced water have been identified and mapped.

Locations where water production will likely be higher than normal due to hydraulically connected coal beds and adjacent sands have been identified.

Preliminary analysis of limited well data set showed about 35% of wells completions caused vertical fracturing in coal beds. Prior work has shown that many wells with vertical fractures have greater than normal water and no gas production.

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

DOE Contract DE-FC26-05NT15549
Recipient - University of Wyoming
Task 1  Membrane-Enhanced CBM to minimize produced water
Anticipated Completion Date – 5-25-07

Principal Investigators
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Brief Summary Statement of Project Goals
The objective of Task 1 is to minimize CBM water production using gas permeable membranes to recover methane. The approach uses a series of five-spot injection/recovery wells. CO$_2$ will be pumped into the four outer injection wells, preferentially binding to the coal and desorbing the methane. The released methane will be pumped from the center recovery well. In addition to eliminating produced waters, this approach also provides an economically feasible means of carbon sequestration.

Executive Summary
A commercially available membrane material that can transmit gases and exclude water has been selected and subjected to preliminary testing to establish the fundamental properties. The membrane selected is micro-porous and allows size exclusion to perform filtration and is hydrophobic in nature to exclude water transfer. The material is a composite tube of 270.3µm O.D. and a 39µm wall. The wall contains a 1µ urethane layer and is filled with fiber lumen. The inner and outer portions of the wall are micro-porous polyethylene that surround and support the urethane layer.

This material was tested to determine the fundamental properties as regards the exclusion of water under operational pressures and the gas transfer rates. The results showed that the exclusion properties as measured by water flux across the membrane were fairly insensitive to pressure. The properties were further tested in a dynamic system where gas was swept over the membrane in a ducted laboratory apparatus. Under these conditions water vapor flux showed some influence to pressure variations, but the overall performance was still relatively insensitive to pressure. The water vapor flux is described by the equation:

$$N_w = \frac{\Delta P}{R_c} + \frac{\Delta VP}{R_d}$$

Measurement of the permeability constants to water showed that air velocity had little effect implying that boundary layer effects were minimal. The data showed that:

- 2.3 g/m²-hr water flux error was introduced for every 1 psia difference in $\Delta P$
- At $\Delta P = 25$ psia, the $\Delta P$ term contributes as much as the $\Delta VP$ term
- $\Delta P$ term could theoretically be neglected with flow-through operation

The next experiments were to determine the relationship between pressure across the membrane and gas transfer expressed as molar flow rate. These tests showed that the gas flow rate was strongly pressure dependent for O$_2$, N$_2$ and CH$_4$. All three gases had similar flow rates with changes in pressure gradient.
These findings allow development of a mathematical model for gas recovery rates for the membrane using the formulation based on model developed by X. Tan et al., Journal of Membrane Science (2005) where:

- Different Boundary Conditions (B.C.s) assumed
- \( \frac{dN_w}{dz} \) includes the \( \Delta P \) term
- \( R_c, R_d, \) and \( R_i \) membrane constants from duct experiments
- MathCad utilized to simultaneously solve ODEs numerically
- ODEs solved for \( N_w \) and \( NCH_4 \) at \( z=L \)

and the recovery rate of water and methane. The diagram below shows a schematic representation of the system modeled with all terms defined.

\[
\frac{dN_w}{dz} = \left( \frac{\Delta P}{R_c} + \frac{\Delta V P}{R_d} \right) 2 \pi fiber
\]

\[
\frac{dN_{CH_4}}{dz} = \left( \frac{\Delta P}{R_i} \right) 2 \pi fiber
\]

\[
\frac{d(P_{CH_4} + P_v)}{dz} = -\frac{8 \mu RT(N_w + N_{CH_4})}{r_{fiber}^4 \pi (P_{CH_4} + P_{H_2O})}
\]

Verification of the model is underway using sealed-end membranes in a pressure vessel where the pressure of water and dissolved gas can be varied and recovery of gas and water vapor measured. Preliminary results show reasonable agreement with the model.

Results

Specific Subtasks

Subtask 1
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.
Figure 1. Micro-porous membrane material.

The figure below shows the flux of water across the membrane over pressure change in a static system. The data show that the water flux is fairly insensitive to pressure changes between 5 and 50psi. Therefore we conclude that flux is essentially constant with increasing pressure.

The next figure shows the water vapor flux across the selected membrane in the ducted system as a function of pressure. The results show the membrane remains relatively insensitive to pressure even when gas is flowing across the system.
The next figure shows the effect of the driving force, gas pressure gradient on mass transfer of gas across the membrane.

Finally, the verification of the mathematical model is proceeding with the preliminary results summarized below in the following figures that show the gas transfer under pressures equivalent to 10 to 100m depth.
**Subtask 2**

Coal characterization study

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

This work is required in order to characterize the sorption properties of PRB coal. This data is necessary to constrain and refine the mathematical model for the performance of the membrane in the field and relate the laboratory experiments to field conditions. Figure 2 below shows the relationships between pore space saturation, capillary pressure, pore radius or crack thickness and relative humidity. The sorption curves show typical non-hysteresis behavior.

![Figure 2. Porosity and Pore size Distribution of Wyoming Coal Sample with Gas Soprtion Curves.](image)

**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.
The experiments investigating membrane gas transfer rates as a function of pressure are nearing completion. Intact coal cores have been collected from two sites located in the Powder River Basin and work on the coal characterization study has also begun. The experimental apparatus, shown in Figure 3, required for the dual-phase mass transfer study has been designed and constructed, and preliminary testing has begun.

**Publications to Date**


**Plans for the Next Report Period**

1. The conceptual coal seam model to evaluate the feasibility of Membrane-Enhanced CBM will be developed.
2. The coal characterization study will be completed and the results from the study will be published.
3. The competitive adsorption and desorption of the various gases will be evaluated and breakthrough curves will be developed.
4. The relative effect of gas type and content on the structural properties of coal will be determined.
Summary Statement of Project Goals
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. Preliminary analysis of ~500 wells indicates that current drilling and completion techniques may be causing hydraulic fracturing of the coal, and possibly the adjacent strata, resulting in inefficient depressurization of coals and excess CBM-water production. Further investigation could yield development of alternative fracturing techniques to maximize gas production and minimize produced water. Through analysis of hydraulic fracturing data obtained by various operators, we will evaluate the feasibility of re-injection of produced waters.

Executive Summary
For re-injection to be feasible, the pore pressure of the aquifer needs to be low, and porosity and permeability of the formation needs to be relatively high. In addition, re-injection can only happen in formations where the quality of water being disposed of is comparable to the water quality of the aquifer. At present we have calculated pore pressures in coal beds and adjacent sandstones within the PRB using water-level data from 220 water-level monitoring wells.

In addition, for the coal beds and sands in Wyoming we have looked at pore pressure changes with time to determine if the overlying sands have similar pore pressure depletion histories to the coal beds and are therefore in communication with each other. We find that for all the coal beds pore pressure decreases significantly with time, whereas most of the sands have negligible changes in pore pressure. This suggests that most of the sands are not in communication with the coal beds they overlie and could be potential sites for re-injection of CBM water. However, these sands are saturated limiting the amount of fluid that can be injected.

Given these results we hope to further identify under-pressured areas of PRB for use as potential re-injection disposal sites. The data can also be used to identify areas where water production will likely be high (coal beds and overlying sands are hydraulically connected). Based on review of about 198 new wells with water enhancement test, about 35% of the wells completions caused vertical fracturing. Many of the wells with vertical fractures had large water and no gas production. We hypothesize that maps of coal bed stress can determine where vertical fractures will form during water enhancement and could help minimize unwanted water production.
Results

Subtask 1: Calculate coal bed and sand pore pressures to determine if there are areas in the basin where pore pressure is under-pressured and are therefore potential sites for re-injection of produced water.

The water-level data from 220 wells that are located in the central part of the PRB in Wyoming and the south central part of the basin in Montana (Figure 1). All of the coal beds and overlying sands analyzed have pore pressures below hydrostatic pressure, which has important implications for re-injection of CBM waters (Figure 2). This determination was based on water level records beginning before production in their section that had initial Pp below hydrostatic (at present, analysis for Wyoming wells only).

Figure 1: Location map of water-level monitoring wells in the PRB. Blue boxes mark the township and range in which each of the water-level monitoring wells are located.
Figure 2: Pore pressure versus depth for the coalbeds and sands analyzed in the PRB for Wyoming and Montana. Note that all the sand and coalbed pore pressures plot below the hydrostatic pore pressure gradient. The black line corresponds to the overburden pressure gradient, the light grey line to the hydrostatic pore pressure gradient and the dark grey line to a best fit pore pressure gradient for the deeper coal beds and wells in Wyoming and Montana.

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

Pore pressure data for CBM wells south of Gillette WY were plotted with time (below) to determine if the pressure in sands adjacent to coal beds changed during production. The expectation is that as water is produced from coal beds lowering the pore pressures, the pore pressure in adjacent sands that are hydraulically connected will show a similar pattern of change. In general, most sands did not show evidence of hydraulic connection.
Subtask 3: Analyze new water enhancement tests to map stress across the basin

We have carried out further analyses on the 198 CBM wells where we obtained water enhancement tests from Cordilleran Compliance Services that supplement the tests previously available (Figure 3). An initial analysis of the 198 wells suggests that 87 were hydraulically fractured during the water enhancement process. Of those 87 wells, 89% have vertical fractures and 11% horizontal fractures. We have also analyzed the production data for the wells with hydraulic fractures and find a similar relationship between water production, gas production and the orientation of fracture propagation as Colmenares and Zoback (in press). Most of the wells with large water production and no gas production are characterized by vertical fractures. Therefore, it is important that we continue to map the coal bed stress across the basin so we can determine where vertical fractures will form.
Publications to Date


Plans for the Next Report Period
1. Analyze new water enhancement tests from UCROSS.
2. Continue to map pore pressure and stress across the basin.
3. Analyze changes in pore pressure with time for the Montana wells.
4. Continue to investigate the geologic factors affecting stress and pore pressure (depth, topography, coal thickness, nature of overburden, etc.).
5. Run fluid flow simulations to see if it is feasible to use CO₂ sequestration as a means for reducing CBM water production while still producing profitable amounts of CH₄.
SURFACE DISPOSAL – TASKS 3, 6, 7 and 8

Conclusions
CBM-water–production rates in Montana are less than predicted suggesting that volume included in overall water management planning should be revised.

Grain size analysis of disposal pond bottoms indicates little correlation between percent shale and rates of infiltration suggesting that maintaining infiltration rates treatment of the produced water before or during storage in disposal ponds is required.

Conveyance losses in stream channels increase as vegetation cover and associated transpiration along the stream channels increase.

Surface water loading at the confluence with the Powder River is most sensitive to soil type. Models of discharge will require incorporation of changes in soil types along stream channels to make accurate predictions.

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

Significant Accomplishments
Compilation of four year continuous monitoring database for single surface discharge site in PRB.

Formulation of unsaturated numerical flow models and demonstration of the applicability of the model to evaluating the important factors that influence fate of produced water during surface discharge.

Calibration of unsaturated numerical flow models with Sr isotopic data.

Demonstration of the utility of hydrogen and oxygen stable isotopes as measure of evaporation of CBM produced water from ponds.

Analysis of CBM-water–production rates in Montana indicating actual water production is less than predicted in the Montana EIS.
Data from a three year period show the amount of infiltration is about 50% of the total water loss from one of the disposal ponds.

Grain size analysis of disposal pond bottoms indicates little correlation between percent shale and rates of infiltration. It appears that sodium in the CBM water causes dispersion of the clays in the pond bottoms slowing and eventually stopping infiltration.

Water losses from disposal ponds via infiltration has decreased slightly through the four year monitoring period at the Beaver Creek site, probably associated with occlusion of pores and/or silting of the ponds. In contrast, conveyance losses in stream channels have increased together with the increase in vegetation cover and associated transpiration.
Surface water loading at the confluence with the Powder River is most sensitive to soil type. Discharge on a per-pond basis has a secondary effect.

**Actual or anticipated problems or delays**

The initial phase of spring 2005 monitoring was delayed due to late receipt of funding from DOE. Site access was complicated by change in operators and poor communication with landowner after primary research contact left University of Wyoming. Site access problem was resolved by reassigning contact to other researchers and formulating payment schedule with landowner.

**Product Produced or Technology Transfer Activities**

**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 accepted for the Billings Land Reclamation Symposium in June, 2006. 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 of this project.


**Website**

[http://mbmiggwic.mtech.edu/](http://mbmiggwic.mtech.edu/)

**Networks or Collaborations fostered**

This group of researchers continues to develop closer professional collaborations. PRB coal samples are being made available to any other members of this project on request.

Water quality samples collected as part of the field effort for this task are split and shared with Dr. Carol Frost (Task 3).
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
Task 3 will develop an understanding of the fate of CBM-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 isotopic ratio of $^{87}$Strontium to $^{86}$Strontium will be used to distinguish waters from different parts of the basin as well as water from coal and sandstone aquifers.

Executive Summary
We have continued periodic monitoring of the two instrumented sites, Beaver Creek and Coal Creek. The data show that produced water from coal beds have a significantly different and more radiogenic strontium isotopic signature compared to groundwater derived from local recharge. There has been little change in Sr isotopic compositions of samples analyzed from the Beaver Creek site over the past year as the hydrologic conditions remain unchanged. The extent of groundwater mounding along the channel determined from numerical modeling agrees with the Sr isotopic identification of wells that contain water originally produced from CBM wells. At Coal Creek we have monitored infiltration as the off-channel pond has gone dry following cessation of production in this area.

New samples from CBM wells near the Beaver Creek Site operated by Williams Corporation have been provided 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. 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. Preliminary results show that the produced water from sandstone intervals has a significantly different isotopic signature.

We have also evaluated the stable isotopic behavior of oxygen and hydrogen to determine if these data can be used to quantify the evaporation rate of CBM produced water when it is disposed in surface ponds. The stable isotopic signatures of hydrogen and oxygen during evaporation have been well documented for other hydrologic settings, but not for CBM evaporation ponds. The isotopic data could offer an inexpensive and highly accurate method to constrain and verify the mathematical models being developed by
Tasks 6 and 7 to predict the fate of produced water during surface disposal. Preliminary results show that the CBM discharge has isotopic values consistent with a meteoric source as expected and show changes during evaporation similar to other documented examples.
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, support 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 EIS and the evaluation of 80 months of data. This analysis significantly decreases the quantity of water that must be included in overall water management planning.

Water quality and water level data networks were maintained during this project. All wells and monitoring sites at five work areas (4 in Montana, 1 in Wyoming) were surveyed for altitude during this period to provide better control on the ground-water gradients and to improve mass balance calculations. One new site was added along the Powder River near where it crosses from Wyoming into Montana during August, 2005. All data collected have been entered into GWIC, an Internet based, publicly available database (http://mbmggwic.mtech.edu/).

Part of the study includes assessment of the ability of leonardite to adsorb sodium from CBM produced water using laboratory column leaching experiments. Preliminary results indicate that TDS increases significantly (more than double) as water moves through leonardite, and after 4 pore volumes the levels remain very high. Surprisingly, TDS values decreased to about half that of CBM water when passed through coal from a mine near Decker, Montana, and have remained low for 5 pore volumes.

Evaluation during the reporting period of existing and new data continues to improve our understanding of the hydrogeologic functions of CBM infiltration ponds. Grain size analysis data, originally thought to support a relationship between percent shale and rates of infiltration, indicate little correlation. Rather, the sodium in the discharge water causes dispersion of the clays (even a very small percentage by weight) in the pond bottoms. This slows and eventually stops infiltration. Ground-water levels beneath and adjacent to ponds raise 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 loads in the underlying and adjacent shallow aquifers increase, then decrease as available salts are flushed from the system and as water levels drop. Both water levels and water quality in ground-water systems affected by infiltrated CBM water are showing trends of returning toward baseline conditions with time, much as seen in coal mine spoils aquifers. It is anticipated that the mobilized salts will eventually be sequestered by the decreased permeability of the pond floors.

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 quality 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.

Continued collection of produced water volumes from CBM wells in Montana has shown that the actual volume of water is significantly less than the amount projected in the EIS (see figure below). The reasons for this situation are unclear but it may be worthwhile to carefully review the assumptions used in the EIS to ascertain the cause of the discrepancy.

![Figure 1. The average rate of water production from CBM wells in Montana is significantly less than was anticipated in the EIS.](image-url)
Continued monitoring of CBM infiltration ponds has produced an improved understanding of the degree of evaporation versus infiltration. Data from a three year period are summarized in the figure below and show the amount of infiltration is about 50% of the total water loss. It appears that the major factor that slows and eventually stops infiltration is the collection of fines in the bottom of the pond that reduces permeability.

The transport of salts from infiltration is also being assessed at the pond sites. Most western soils have a layer of salt accumulation below the land surface since the amount of precipitation is rarely enough to flush the salts derived from atmospheric input through the soil zone into the underlying aquifers. Figure 2 shows that while the initial flush of CBM water through the soil does mobilize the native salts, after a short period the salts are depleted and total dissolved solids (TDS) declines with increasing time.
Figure 2. Beneath a CBM infiltration pond the ground-water levels (7B WL) have decreased in response to lower pond water levels (Pond WL). As the available salts are flushed from along the flow paths, the total dissolved solids in the ground water are decreasing.

Subtask 2

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

Laboratory column experiments (see picture of experimental set-up below) were conducted using leonardite (zeolite), which has been proposed as a treatment to reduce sodium in CBM produced water. Preliminary results indicate that TDS increases significantly (more than double) as water moves through leonardite, and after 4 pore volumes the levels remain very high.
**Subtask 3**

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

This subtask is just beginning and will use multispectral imaging, cross-referenced to field mapping to identify candidate areas for infiltration ponds in order to evaluate application of multispectral analysis of Powder River Basin.

**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 accepted for the Billings Land Reclamation Symposium in June, 2006. 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 of this project.

Wheaton, John R, and Brown, Terry, 2006, Predicting changes in ground-water quality associated with coalbed methane infiltration ponds: in Western Resources Project Final


**Plans for the Next Report Period**

This task is a two-year effort and the following work will continue in to the next funding period.

1. Present preliminary findings at the Billings Land Reclamation Symposium and lead a field trip during that symposium to look at CBM-water management operations.

2. Continue data collection at field sites.

3. Model flow and mass balance at Coal Creek site. This site is the most relevant for future infiltration ponds and the monitoring network and duration of data collection are comprehensive.

4. Complete the column leaching work.

5. Satellite multi-spectral data have been consolidated for the area. These data will be evaluated and field checked. Evaluation of the value of satellite imagery (multi-spectral data) for assessment of potential infiltration pond sites is planned for later this year. The preliminary data sets have been identified and consolidated.

6. 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.

7. 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 numerical 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 four fronts: (1) maintaining and downloading data from remote hydrologic field data collection stations, (2) calibration of numerical models using field data, (3) analyzing long-term trends in water budgets, and (4) use of conveyance loss data to project watershed scale surface water flows for a range of scenarios. To date, we have conducted several trips to the Beaver Creek and Coal Creek sites to download data from the weirs (Beaver Creek only), shallow aquifer/alluvial monitoring wells, and rain gauges. In September and October, 2005, the sites were shut down for the winter, to be reoccupied in Spring, 2006.

Initial analysis of the Beaver Creek water level data indicate a continuing trend of groundwater mounding beneath the stream channel. The rate of water level increase at both of the well sites has decreased compared with the first year deployment (funded by WRPF from July, 2003- July, 2004). The two well nests exhibited a water level increase of 2.6 ft and 3.3 ft from July 2003-2004, and rises of 0.9 ft and ~1.2 ft from July 2004-2005. Infiltration rates in the streambeds are 0.11-0.15 inches/hr and considerably lower infiltration rates in the ponds of ~0.01 inches/hr.

Water losses in infiltration ponds have decreased slightly through time, probably associated with occlusion of pores and/or silting of the ponds. In contrast, conveyance losses in stream channels have increased and vegetation cover and transpiration have increased. Initial numerical modeling of infiltration and groundwater mounding are complete. These models suggest that surface water loading at the confluence with the Powder River is most sensitive to soil type. Discharge on a per-pond basis has a secondary effect.
Results

Subtask 1: Evaluate and quantify controls on fate of discharged waters. Provide both time-averaged and time series of water budgets. Figure 1 shows the location of the instrumentation at the Beaver Creek Site.

![Beaver Creek Study Area](image)

**Figure 1. Location map for Beaver Creek Site showing wells and infiltration study blocks.**

The full time series of water budgets shows that water losses in ponds has decreased slightly through time, probably associated with occlusion of pores and/or silting of the ponds.

In contrast, the figures below show that conveyance losses in stream channels have increased and its seasonality has increased as vegetation cover and transpiration have increased. 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.
**Subtask 2:** Use water budget analyses to evaluate the effects of pond silting and vegetation changes on long-term infiltration rates.

The water budget analysis shows that evaporation is a major element of pond water budgets due to large area. This should remain ~constant over time. Pond conveyance loss rates appear to show long term decline. Under assumption of negligible transpiration (o.k. for ponds), implies infiltration rate decreases over time. We speculate that it is due to settling of fines. This is an important new result. We had raised the question previously, but did not have an adequate time series of data to address it.
**Subtask 3:** Formulate and calibrate models of groundwater flow and surface runoff at the local (km) scale using field observations.

Initial numerical modeling of infiltration and groundwater mounding are promising. Using data from slug tests to constrain aquifer properties, and a soils database for the Powder River Basin, models of infiltration honor existing data, namely: (a) average calculated infiltration rates, (b) constraints from Sr isotopic data on the timing for infiltrating water to reach the water table, and (c) observed groundwater mounding height. From this work, we have established that with reasonable estimates or measurements of soil properties, unsaturated flow models can be a useful predictive tool to assess potential impacts. The most sensitive parameter controlling infiltration rate and thus total conveyance losses appears to be the soil types.
Finally, our simple (and preliminary) watershed routing models show that for the entire Beaver Creek watershed, surface water loading at the confluence with the Powder River is most sensitive to soil type. The figure above shows the effects of soil type on discharge reaching the river based on soil type. Discharge on a per-pond basis has a secondary effect. However, more realistic and complex models are necessary to fully understand and estimate flows in future development scenarios, which include spatial heterogeneity in soils.

Publications to Date:


Plans for the Next Report Period

1. Compare infiltration capacity from field measurements with values from water budget analyses.
2. Use models to project runoff and infiltration in (a) undeveloped watersheds, and (b) for additional development scenarios in a given watershed.
3. Continue to calibrate models using infiltration data and history matching of water levels in monitoring wells and by field monitoring of stream-flow.
4. Continue watershed monitoring, provide database. Continue to determine time series of water budgets and conveyance losses for stream channel and pond environments.
Summary

This project will establish the industry standard field water analysis portable laboratory for evaluating treatment technologies of coalbed-methane-production water by constructing a mobile facility to test proposed treatment units under standardized field conditions which allow direct correlation between performances of treatment units from different manufacturers. Monitored parameters will include: flow from source, clean treated flow, waste stream flow, specific conductance and temperature in and out of treatment system, and energy consumption by treatment system. All parameters will be monitored on a time and volumetric basis. Sampling ports in the plumbing system will allow water-quality samples to be collected from inflow, outflow and the waste stream.
WATER TREATMENT

Conclusions
Experimental runs conducted to date indicate that greater than 92% reductions in salt content can be achieved with an energy cost of approximately 0.8 to 1.1 cents per barrel for CBM produced water containing 3,000 mg/l of dissolved solids.

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

Significant Accomplishments
Laboratory scale ED unit was tested with simulated and actual PRB water.

Post-demineralization treatment to adjust the sodium adsorption ratio (SAR) was formulated and tested.

Experimental show that greater than 92% reductions in solution conductivity (due to salt removal) can be achieved for CBM produced water containing 3,000 mg/l of dissolved solids.

Demonstration of lab water recovery efficiencies of greater than 90% (initial solute content removed).

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 this Period)

Subtask 4. Prototype operation. This task has been initiated and is currently pending. The initial experiments have focused on a comparison of two cationic membranes in the performance of the ED unit. (In Progress)
**Summary of Progress**

Following rigorous characterization of ten produced water samples obtained from two energy development firms in the Powder River and following shakedown and initial testing of the ED unit on synthetic produced water, a large aliquot of produced water was obtained from a Marathon field site near Sheridan, WY where produced water was gathered from multiple CBM wells. Composition of the large aliquot was similar to the composition of most of the samples taken from seven locations in the Powder River Basin; compositional data is shown in Table 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 four 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; and, 4) Post-demineralization treatment to adjust the sodium adsorption ratio (SAR) to levels suited to beneficial use. The laboratory ED prototype is shown in Figure 1.

<table>
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<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>mg/L</td>
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</tr>
<tr>
<td>Calcium</td>
<td>mg/L</td>
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</tr>
<tr>
<td>Magnesium</td>
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<td>Chloride</td>
<td>mg/L</td>
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<td>Conductivity</td>
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<tr>
<td>Alkalinity</td>
<td>mg/L as CaCO₃</td>
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</tr>
</tbody>
</table>

An example of data obtained from the ED unit is shown in Figure 2; in this run, the produced water was demineralized using AMX/CMX-S membranes at under current density of approximately 4 mA/cm². Experimental runs conducted to date indicate that greater than 92% reductions in conductivity (due to salt removal) can be achieved at a reasonable energy input equivalent to 0.14 to 0.2 kWh/lb salt removed from the product water. This translates to an energy cost of approximately 0.8 to 1.1 cents per barrel.

**Figure 1. Laboratory ED Prototype**

**Figure 2. ED Process**
(assuming electricity cost is 6 cents per kWh) for the 92% demineralization of CBM produced water containing 3,000 mg/l of dissolved solids. Overall, the results indicate that produced water recovery efficiencies of greater than 90% are technically achievable. Typically, the pH of the treated water decreases by more than one pH unit during ED processing; in the case shown in Figure 2, the pH was reduced in the ED unit from 8.4 to 7.0. Most significantly, Figure 2 shows that the SAR value was reduced from over 50 to 8 using the ED process alone where greater than 90 percent of the sodium was removed but a portion of the calcium remained in the product water due to the selectivity of the CMX-S membrane. SAR was further reduced from 8 to below 3 by equilibrating the product water with limestone (calcium carbonate); it should be noted that the post-treatment step was able to achieve reduction of SAR without increasing the conductivity. Data analysis is continuing on the comparative performance of the two cationic membranes (i.e. CMX-S versus CMX). Preliminary analysis indicates that though CMX-S selective membrane may significantly reduce the concentrations of divalent calcium and magnesium in the concentrate stream, thereby reducing scaling and fouling rates on the membranes, the power requirements may be increased by more than 20 percent if the selective membrane is used. A cost trade-off analysis of this issue is planned.
Publications to Date


Plans for the Next Report Period

1. Long term membrane stability testing.
2. Improve “Clean In Place” procedures.
3. Perform cost trade-off analysis of the two types of cationic membranes (i.e. higher power cost versus reduced scale forming and fouling potential)
4. Compare ED process energy input of selective and non-selective cation membranes under long term membrane stability testing.
5. Optimize concentrate solution based on power consumption to minimize back diffusion effects.
6. Preliminary economic analysis using vendor information on scaleup and equipment costs.
RE-INJECTION

Conclusions
Preserving beneficial use of the produced water complicates the problem since only shallow sandstones fill the specified criteria.

Shallow injection (above the Lebo Member- see Figure 2) is limited because most zones are water saturated.

Mapping of channel sandstones illustrates the difficulty in finding favorable injection zones; i.e. porous and permeable zones are not present everywhere and will be difficult to locate because of their distribution and geometry.

Schedule Status
Anticipated Completion Date for all Tasks – 7-1-06

Significant Accomplishments
Mapping of the target formations for produced water injection revealed that the narrow and lenticular geometry of the channel bodies greatly limit the potential for disposal by injection in Montana.

Actual or anticipated problems or delays
None

Product Produced or Technology Transfer Activities
Publications to Date:


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

Other products
None during this project period
Brief Summary Statement of Project Goals
This project will evaluate the technical and economic aspects of shallow injection of CBM produced water in order to preserve beneficial use. This requires that the re-injection targets must be shallow enough to preserve beneficial use (be accessible to future users and not degrade the water quality). The target formation must have sufficient permeability to accept the injected water without adding excessive pressure and have a compatible chemistry.

Executive Summary
We have identified potential zones for disposal of CBM produced water in the Tongue River Member of the Fort Union Formation (above the Lebo Shale Member). The study focused on the thick porous and permeable channel sandstone units. The study location is in an area of CBM developments with high SAR produced water. During a previous DOE-funded project, channel sandstones in the Tongue River Member of the Fort Union Formation were successfully identified, correlated and mapped in the area of the Northern Cheyenne Reservation of eastern MT. The techniques developed in that project were applied to this research. In addition, deeper coal beds in the Tongue River Member may also be targets for injection if they are not being developed for CBM.

Subsurface database has been completed and isopach mapping of five channel sandstone intervals in the Tongue River Member, Ft Union Formation, have been completed. The stratigraphic correlation and mapping in the area of current CBM development has identified and correlated coal beds and channel sandstones using geophysical logs for all existing O&G exploration well. These data were loaded into the industry standard Petra software. Isopach mapping of the zones of interest has revealed that the sandstone targets consist of relatively narrow units that cover a fraction of the total area CBM area. Given this geometry locating the narrow channel bodies will be difficult. Many of the sandstones are already saturated sharply limiting potential injectivity. There is some hope that fracture systems in the target sandstones may increase local permeability and enhance the injectivity. Fracture system identification is underway.
Results

**Subtask 1:** Database of subsurface data, tops and thicknesses for coals and channel sandstones has been completed that fit target criteria. PETRA software is used for data compilation and map generation.

The study area is defined by the likely extent of development in the Powder River Basin in Montana (see Figure 1 below). After examination of the geology of the area, the primary target interval was identified based on the criteria: 1) shallow enough to preserve beneficial use; that is accessible to future users, 2) formation mineralogy and chemistry that will cause degradation of injected the water quality; and 3) sufficient permeability to accept the injected water without adding excessive pressure. The most likely candidate that meets these criteria area set of Tongue River Member channel sands that lie above the Lebo Shale Member of the Ft. Union Formation. Figure 2 shows the stratigraphic relationship of these sands.
**Figure 2. Target Stratigraphic Interval of Interest.** Five sandstones (A to E in ascending order) within the Tongue River Member will be mapped.

**Subtask 2:** Isopach maps for 5 channel sandstone intervals in the Tongue River Member of the Ft. Union Formation.

The isopach maps for the five sandstone intervals of the Tongue River Member exhibit a similar typical fluvial channel lenticular geometry. The general orientation of the channels is west-to-east with some thickening to the east. The individual sands are between 25 and 100 feet thick. The aerial extent is limited compared to the underlying coal beds as expected in fluvial deposits. Figure 3 shows a typical pattern of the channel sand geometry.
Figure 3a. Isopach map of ‘A’ Sandstone Channels. Yellow > 50 ft thick, Orange > 100 ft thick.

Figure 3b. Isopach map of ‘A’ Sandstone Channels. Aqua > 50 ft thick, Blue > 100 ft thick.
Subtask 3: *Compilation of fracture systems from available geologic maps and satellite imagery is underway. Areas of fracture intersections may have higher permeability.*

The sandstone permeability is variable, but it is likely to be highest in areas of fracture and fault intersection. In order to evaluate the potential for fracture enhancement of sandstone permeability, satellite photos were mapped for lineaments. Such locations represent favorable sites for injection well sites. Figure 4 shows the study area with added fracture pattern in green. The fractures strike SW-NE with some conjugate sets oriented WNW-ESE, however most are located in the western portion of the State. There appears to be little significant fracture expression in the area of the Powder River Basin.

Figure 4. Satellite view of study area with fracture lineaments as green lines. Montana State outlined in pink.

Subtask 4: *Injection well planning and design is underway. All literature and current operator interviews are underway.*

Plans for optimum injection well design and construction will be formulated in order to offer the industry the best possible re-injection technique.

**Plans for the Next Report Period:** This is a one year project; projected to be completed by the end of June, 2006.
BENEFICIAL USE – AGRICULTURAL APPLICATION

Conclusions
None for this reporting period

Schedule Status
Anticipated Completion Date for all Tasks – 6-1-07

Significant Accomplishments
None for this reporting period

Actual or anticipated problems or delays
The initial phase of research was slated to start in spring 2005 but late receipt of funding from DOE forced temporary suspension of project over the winter months of 2005 into the spring of 2006. The original agricultural site owner withdrew from project after delay in funding. A new agricultural site has been located and matching funds from owner in form of in-kind donation of irrigation equipment secured. Initial site soil samples have been taken and being analyzed.

Product Produced or Technology Transfer Activities
Publications to Date:
None for this reporting period

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

Other products
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 types. 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 wick lysimeters have been installed, and irrigation with CBM water at the Cooksley Ranch (located near Ucross) was initiated during the fall of 2003. The proposed efforts will establish gypsum and sulfur application rates of to maintain soil quality, determine allowable water application rates, and develop models of the soil chemistry.

Executive Summary

Due to the late start because of delay in funding, there are no important accomplishments and new knowledge realized from the project during the reporting period.

Results

Subtask 5.1: Collect baseline soil chemistry, soil hydraulic properties and produced water chemistry at irrigation site.

The irrigation site that will be used to evaluate the use of amendments to prevent degradation of soil structure has been determined. Soils have been characterized using thirteen backhoe pits. Soil samples were collected by horizon and are currently in the laboratory for analysis. The pivot irrigation system locations have been determined (Figure 1). Lance Oil and Gas is expects to install the irrigation system and have it in operation by June 15. PVES has scheduled a Giddings Probe to do detailed soil sampling on the treatment plots during the first week in May 2006.

A monitoring well has been established down slope of the research site near the Powder River. If the piezometer is constructed appropriately, it will be used for background and on-going monitoring.

Figure 1a. Field test site showing projected location of half-pivot irrigation system (green lines) and locations of soil samples (black points).

Figure 1b. Field test site showing projected location of full-pivot irrigation system (green lines) and locations of soil samples (black points).
Subtask 5.2: Installation of lysimeters

Lysimeters will be placed in the soil below the root zone to characterize the drainage water resulting from the irrigation treatment. Purchasing of the appropriate collection systems is underway.

Subtask 5.3: Installation of monitoring wells

A monitoring well is currently located between the irrigation site and the Powder River. If the well is completed properly, it will be used to access potential impacts of irrigation on the adjacent alluvial ground water system. This evaluation has been initiated.

Subtask 5.7: Soil fertility evaluations

Two pivot areas have been evaluated with regard to the impact of amendments on fertility status of the soil. The primary issues are associated with excess water and the application of excess sulfur as an amendment to the soil.

The large amount of natural precipitation that occurred during spring 2005 and the moist soil conditions that existed at the site resulting from the prior years of irrigation caused high levels of Mn and Fe to be available for plant uptake at various locations in the field. As a result, the alfalfa field was characterized by areas of poor growth or dead vegetation. Monitoring will continue at the pivot sites during this growing season. Samples were collected during April but weather conditions prevented the completion of the work. This work is scheduled for early May.

Subtask 5.9: Use of amendments to reclaim sites impacted by CBNG produced water

A sodic soil site (Figure 2) impacted by CBNG produced water was reclaimed during 2005. Samples will be collected from the site during May 2006 to show the status of the reclamation process.
Figure 2. Location of CBM Sodic Soil reclamation site with soil sample locations indicated by green dots.

Publications to Date: None.

Plans for the Next Report Period

1. Complete baseline characterization of the irrigation site.
2. Install research plots at the irrigation site including the application of amendments, installation of lysimeters and moisture/EC probes.
3. Manage irrigation at the research site during the 2006 irrigation season.
4. Sample the irrigation site during the fall to access impacts of the water on soil characteristics.
5. Use data collected to develop a site model using the FAO-SWS irrigation model. This work will include calibration of the model for use in the Powder River Basin.
6. Continue sampling the alfalfa pivots associated with the fertility study.
7. Sample the reclaimed sites to determine status of reclamation.
Summary of Project Goals
Argonne National Laboratory will be the focal point for regulatory analysis. Argonne will provide an initial briefing with the technology developers and periodic written or oral updates as regulations evolve. Argonne staff will interact with state and federal agencies that are likely to establish water management controls to keep them informed of the technology developments. Argonne representatives will also participate regularly in the Interstate Oil and Gas Compact Commission and the Ground Water Protection Council, both of which serve as focal points for oil and gas regulatory officials. As the project team develops new technologies, Argonne will assist with outreach and technology transfer.

A separate monthly report is submitted as part of the deliverables from Argonne National Laboratory.

Subtask 10.1 -- Informing and advising the rest of the project team about the produced water regulatory requirements in effect at the start of the project and the directions in which water policy is moving throughout the duration of the project.
Providing an initial briefing with the technology developers, and periodic written or oral updates as regulatory requirements evolve.

During the reporting period the PI has communicated several regulatory items to the group including information on the Montana State hearings on proposed CBM regulations and regulatory action in Wyoming. The body of the text for each item is below.

Dear Produced Water Team Members -
One of my roles in the produced water research program coordinated through the School of Mines is to keep team members informed of national or regional water issues. Recently, Wyoming has considered two interesting initiatives relating to management of CBM water. One of the ideas just passed the WY legislature this week. It would investigate the idea of collecting and piping CBM water from the Power River Basin to the North Platte River (article from 3/16 issue of BNA's Daily Environment Report is attached).

The other initiative is to consider developing a water quality trading program for CBM water (article from 3/10 issue of BNA's Daily Environment Report is attached).
DENVER--The Wyoming Senate on March 11 approved a bill calling for a study of the prospect of moving coal bed methane water from the Powder River Basin to the North Platte River Basin (H.B. 145).
The Senate adopted conference committee amendments to the measure, sponsored by the Wyoming Legislature's Select Water Committee, on a 25-4 vote. The bill now goes to Gov. Dave Freudenthal (D), who is expected to sign it.
The Omnibus Water Bill includes funding for a task force to consider delivering "produced" coal bed methane water out of the Powder River Basin to the North Platte River Basin. The bill sets aside $500,000 for the task force.
If the state were to move forward with the plan, it would result in a years-long, comprehensive, high-dollar construction project, Patrick T. Tyrrell, Wyoming State Engineer, told BNA.
The study initially was requested by Freudenthal in his "State of the State" address at the beginning of the budget session of the Wyoming Legislature on Feb. 13.
The governor said the study would cover how to address "continuing issues surrounding coal bed methane water." The process of drilling for natural gas brings to the surface large amounts of groundwater -- much of which is contaminated with mineral salts and heavy metals -- posing a threat to soil, wildlife, and crops.
The study would consider use of a pipeline to pump "produced" water out of the basin into the drainage for the North Platte River, which is not faced with the intense level of drilling activity now under way in the Powder River Basin.
It also would help the state in meeting demands related to endangered species and in supplying water to meet requirements in the North Platte basin, Freudenthal said.

WYOMING EYES NOVEL COALBED METHANE WATER QUALITY TRADING PROGRAM
Date: March 10, 2006 -
Wyoming is developing a first-time water quality trading proposal that would allow oil and gas companies that drill for coal bed methane (CBM) in the Powder River Basin to trade credits so the industry's total wastewater discharges during the drilling process comply with stringent standards in downstream Montana waters, state and EPA sources say.

The plan, which would be the first in the nation to allow water quality trading for discharges that occur during CBM drilling, could pave the way for how similar
Wyoming is developing the plan under a grant from EPA. States, environmentalists and the oil and gas industry have continually debated how to handle discharges that occur when companies pump water into coal seams to remove the methane gas trapped underground. The companies can get rid of the water by discharging it to nearby surface waters, treating it and then discharging it or re-injecting it underground. CBM wastewater contains high levels of salt and sediment.

Most companies currently discharge the water untreated because this is the least-costly option. But environmentalists, Wyoming state officials and others have questioned whether this method will allow the companies to meet stringent water quality standards for salinity in downstream Montana -- especially for companies with drilling operations right along the Powder River, which flows into Montana. Wyoming does not currently have numeric water quality standards for CBM discharges, but must comply with downstream Montana standards.

The Wyoming Department of Environmental Quality (DEQ) is now developing a credit trading plan that will allow companies discharging in the Powder River to meet an overall pollution loading cap, rather than facility-by-facility levels, to attain Montana water quality standards.

DEQ expects to publish the proposal in May.

A Wyoming source says the credit trading proposal will likely mean that the numerous dischargers along the Powder River's headwaters will have to treat their discharges because there will not be enough credits to allow large-scale surface water disposal. "The end result is that credits will be the limiting factor," the source says. "There will be less discharge and more treatment."

Water quality credit trading allows dischargers within a common area such as a watershed to collectively meet an overall pollution cap, instead of meeting facility-specific limits. In a trading program between point source dischargers such as oil and gas companies, facilities that are able to reduce pollution beyond their required amount to comply with standards can generate credits that they sell to other facilities that are not able to meet their limits.

Wyoming's current CBM permitting regime requires companies that discharge CBM wastewater to obtain authorization to do so under water discharge permits, or National Pollutant Discharge Elimination System (NPDES) permits. The companies would have to apply for coverage under a general permit to participate in the trading program, in addition to obtaining NPDES permits. The plan will divide among participating companies a pool of credits, each of which will allow a certain amount of wastewater discharge, to comply with Montana water quality standards. "The companies each get a portion of the pie, and then it's a free-market system," the Wyoming source says. DEQ would monitor the credit trades, the source says.

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Under the trading scheme, companies seeking to discharge more wastewater than permitted under their original allocation will be able to do so, if other companies are able to cut discharges below their allocations and sell the credits they do not use. The credits will be specifically allocated for discharging untreated CBM wastewater to surface waters, meaning that companies that re-inject their wastewater or treat it before discharge will not need to use any credits. These companies will then be able to sell their credits to others who wish to dispose of the wastewater via surface discharge.

Companies will receive credits based on the number of acres on which they drill, and the thickness of the coal in the area, the state source says. The source says this method of allocating credits will benefit large companies such as Marathon Oil and Lance Oil & Gas, which together are likely to receive 50 percent of the credits allocated under the trading plan between them. The source says large producers should receive a large proportion of the credits because "they are the ones purchasing the wells." The source says the state expects about 100 companies, of which 10 are large companies, to participate in the trading plan.

Meanwhile, Montana environmentalists are facing difficulties in enacting more stringent CBM water quality controls in the state, after Montana's DEQ last month approved two permits for Fidelity Exploration & Production Co. that allow for increased CBM wastewater discharges into Montana's Tongue River.

The permit approvals are significant in light of a pending petition to DEQ by the Northern Plains Resource Council and several other environmental groups, which asks the state to propose a rule that could mandate more stringent CBM controls. The petition asks the state to impose so-called anti-degradation provisions that could prohibit oil and gas companies from releasing CBM wastewater that would cause Montana's waters to reach their water quality limit for salinity. Instead, the rule would require companies to leave a buffer between the salinity levels in their discharges and state standards.

Montana's environmental review board, which reviews administrative petitions, is scheduled to vote on the rule later this month, after hearing extensive testimony from oil and gas companies, which generally oppose the rule, and environmentalists, who support it.

One environmentalist fears the board will not approve the provisions sought in the environmentalists' petition in the absence of Montana DEQ's support, which now appears lackluster after the department approved two permits allowing greater CBM discharges.

**Subtask 10.2 -- Interacting with state and federal agencies that are likely to establish additional water management controls to keep them informed of the technology developments made by the other project team members and to watch for potential regulatory barriers.**
The PI has maintained interactions with relevant State and Federal agencies during the reporting period. PI testified at that recent Montana hearings regarding proposed regulations for CBM produced water discharge. The text of that testimony is below.

**Veil Testimony for Montana BER Hearings**

Good afternoon. Thank you for the opportunity to participate in today’s hearing. I am here today to offer some observations on whether the proposal follows appropriate procedures and criteria of the Clean Water Act (CWA), the U.S. Environmental Protection Agency (EPA), and Montana statute and regulations. I will point out some apparent regulatory drafting errors or inconsistencies in the proposal. I also plan to share some thoughts relating to scientific and engineering aspects of the proposal from scientists at the Sandia National Laboratories, who were unable to attend the hearing. Both Argonne and Sandia plan to prepare and submit written comments during the remaining comment period. Today’s remarks reflect our preliminary thoughts.

Before I get into my remarks, let me briefly explain my background and experience and how it relates to the issues embodied in the proposal. I have been involved with water quality and water pollution control issues for more than 25 years. From 1980 to 1990, I worked for the State of Maryland agencies that issued National Pollutant Discharge Elimination System (NPDES) permits. During that time, I wrote about 200 industrial NPDES permits. For seven of those years, I managed Maryland’s industrial NPDES program and reviewed more than 1,000 NPDES permits. I wrote and revised some of Maryland’s water pollution control and NPDES regulations. From 1988 to 1990, I also managed Maryland’s Underground Injection Control (UIC) and oil control programs. Since 1990, I have worked for Argonne on water and waste issues that affect the oil and gas, electric power, and coal industries.

My major observations on the proposal are described below.

- The proposal inconsistently characterizes the value of coal bed natural gas (CBNG) produced water. In some places, the proposal refers to it as “wastewater” and emphasizes that some of its constituents are “hazardous parameters.” In other places, the proposal acknowledges the water’s value in both quantity and quality, and implements measures to ensure that the water is available for future beneficial use. This inconsistency is misleading.

- The CWA allows EPA to delegate NPDES authority to states. Montana applied for and received the authority to administer the federal NPDES program. To administer the NPDES program, the state uses regulations that either adopt EPA’s regulations directly by reference or it has promulgated similar and consistent state regulations. The proposal does not follow the CWA guidelines for establishing technology-based limits. The most notable excursion from the guidelines is the proposal’s attempt to force the use of just one or two specific technologies. The BER is within its rights to require zero discharge, assuming that it can show that appropriate water management alternatives are available and affordable.
However, the BER may not specify the type of technology that must be used to achieve zero discharge. In addition to the procedural issues raised by the proposal, this strategy effectively blocks the opportunity for other beneficial and innovative technologies to be used.

- The proposal includes numerical technology-based effluent limits. They are very stringent, and no detailed rationale is provided to explain why they were selected. Traditional methods to evaluate best available technology economically achievable (BAT) and best professional judgment (BPJ) technology-based limits were not followed. BAT is not a specific technology but rather is the performance that can be produced by properly operated “BAT model technology”. The numerical limits that represent BAT should not reflect the best possible treatment under ideal conditions; they are intended to reflect long-term performance under actual industrial conditions. Typically, statistical calculations are used to determine appropriate average and maximum limits. BPJ limits are expected to follow similar procedures to those that EPA uses to establish BAT.

- The effluent limits are much stricter than necessary to meet water quality standards in Montana water bodies. If the proposal had properly demonstrated that these strict limits represented BAT, they could be employed. The proposal does not make such a demonstration, and therefore the limits appear to be unnecessarily stringent. For several of the parameters in the proposed effluent limits (calcium, magnesium, sodium, bicarbonate, and total dissolved solids or TDS), there are no water quality standards. For the other parameters that do have water quality standards, the proposed effluent limits are far stricter than water quality standards in all cases. In other words, dischargers must treat to levels significantly cleaner than the receiving waters.

- The proposal contains several apparent logical inconsistencies. First, the proposal calls for “minimum technology-based effluent limitations” [emphasis added]. The proposed numerical limits in are most likely intended to be maximum limits, not minimum limits. Second, for several parameters, the average concentrations must be kept within a range (e.g., the calcium average concentration must be between 0.1 mg/L and 0.2 mg/L. There is no apparent reason to set a “minimum” standard as a range, nor is there any reason to limit concentrations to a range. Under this provision, a calcium average of either 0.08 mg/L or 0.3 mg/L is out of compliance. Third, the proposed limits create an internally inconsistent situation. The sodium adsorption ratio (SAR) is calculated by a formula that combines sodium, calcium, and magnesium. If the proposed average effluent limits for each of these parameters are entered into the SAR equation, they result in SAR values of 2.5 to 5.3. The proposed SAR effluent limit is 0.5 maximum. Thus it appears that discharges complying with the three component parts of the SAR equation will still be in violation of the SAR limit. This presents an unreasonable regulatory expectation.

- The BER appeared to follow its administrative requirements for reviewing and
acting on the petition. However, two issues are not fully clarified. First, if the petitioners did not fully and accurately meet the content requirements for the petition, can the resulting proposal be dismissed? Second, although a state advisory group, the Water Pollution Control Advisory Council (WPCAC), recommended that the BER should not accept the petition and should not initiate rulemaking, the BER went ahead with the proposal. In fact, the proposal does not discuss or acknowledge the WPCAC’s objections.

Sandia’s major observations on the proposal are described below.

- The proposal suggests that electrical conductivity (EC) and SAR be classified as harmful parameters. SAR and EC are simply measures of water ionic properties and TDS, and all natural waters contain ions and TDS. Some level of TDS is beneficial to both human health and ecologic health. Neither SAR nor EC is harmful under all or even most situations. While high levels of EC and SAR can have negative impacts on plants and animals, low levels can also have negative impacts. The magnitude and interdependence of the EC and SAR values, in relation to the threshold between low risk and high risk, is key to determining whether the quality of a water is harmful or not. Therefore, from a technical standpoint, EC and SAR provide an understanding of overall water quality but, in themselves, are not necessarily harmful parameters.

- The proposal emphasizes reinjection into a suitable geologic formation. In looking at both shallow and deep formations for possible reinjection, there appears to be limited geologic potential in the region for reinjection. The available data (approximately 45 wells have been reviewed) suggest that only about one third of the current reinjection wells drilled are effective for longer than one year. In some regional settings in Montana, injection will be feasible, but in most cases produced water injection opportunities are limited geologically. Both Wyoming and Montana oil and gas agencies understand these geologic limitations and their impact on the feasibility of produced water reinjection.

- The proposed application process for a waiver from reinjection is cumbersome, expensive, and time-consuming. It requires data on all wells in the vicinity, local and regional ground water modeling, pump test data, and injection well performance data. The information required can be redundant, in that the same information is required for each injection well, even for the same formations and locations. Since current geologic and injection well data suggest that reinjection opportunities are limited in this area, most producers will have to request a waiver. Thus, what is perceived as an occasional waiver option could be used in a large percentage of cases. As written, the proposed waiver process will be a heavy burden on both the developers submitting the requests and the regulatory agencies having to review the numerous requests.

- The technologies identified for use to meet the proposed effluent limits, reverse
osmosis and ion exchange, have not been thoroughly evaluated for their performance on the range of CBNG produced waters in the region. In spite of claims by the petitioners, no data have been provided to show that the limits can be consistently met across the range of CBNG produced water in the region in actual field conditions. Treatment to the levels identified can potentially be more detrimental to the environment and ecology than less-stringent effluent limits. Treatment to a SAR of 0.5 and an EC of 233 µmhos/cm may create water quality that is inappropriate for irrigation use, is aggressive to picking up metals from the soil, and could have a negative impact on river and stream habitat.

- The proposed arsenic treatment standard of less than 0.0001 mg/L is 100 times lower than the current standard. The proposed level identified cannot be measured by current monitoring technology, and is lower than current available technology performance by a factor of ten.

- The proposed treatment guidelines, based on current practices, would generate large volumes of concentrate, approximately 20% of the water treated, that would have to be disposed. This will significantly increase the cost and impact of potential treatment processes. Since injection disposal options are limited, other concentrate disposal options will be required. This could require extensive infrastructure including additional roads, storage tanks, and significant tanker traffic.

Summary of Montana Board of Environmental Review (BER) Hearing on a Water Quality Proposal – December 1, 2005 – Helena, MT

The hearing began about 1:30 PM. The chairman of the BER described the format for the hearing. The proponents (Northern Plains Resource Council, NPRC) would have two hours to make testimony followed by two hours of testimony from any opponents. Then each side would be given one additional hour. Persons who testified at the previous two hearings were told not to give the same testimony again. There were no “excited citizens” or obvious members of the press in attendance. The main themes of the presentations are described below.

Proponents

1. Michael Reisner, NPRC
   - described some of the Clean Water Act (CWA) factors that were relevant
   - commented that the Supreme Court had ruled that best available technology (BAT) should reflect the greatest degree of performance as indicated by the best plant within an industry sector
   - introduced other NPRC speakers

2. Sara Macmillan, attorney hired by NPRC
   - CWA requires states to develop water quality standards and effluent limits
- MT Water Quality Act allows development of effluent limits when EPA did not develop national standards
- MT Constitution requires environmental quality to be maintained and improved

3. Tom Myers, hydrogeologist hired by NPRC
- gave overview of CBM production and local geology
- some aquifers respond rapidly to CBM water pumping
  - can drop >100 ft in one year
- described the hydrological model he ran (MODFLOW 2000)
- horizontal flow is much greater than vertical flow in this area
- faults and ridges compartmentalize flows
- recharge rate is 0.28 in/year
- he concluded that there will be drawdown of aquifers because recharge will be slow
  - many springs and streams will be affected
- he suggested that impacts can be avoided by reinjecting into coal seams or other aquifers
- he acknowledged that injection into coal seams would require phasing so it did not interfere with CBM production
- there will be some problems associated with reinjection
  - clogging of pores
  - need for disinfection
  - need to avoid fracking formation
  - don’t want to introduce oxygen into formation
- he was asked by a board member if the MT nondegradation standards apply to aquifer as well as to surface water bodies.
  - he did not know the answer

4. Michael Cavanaugh, economist hired by NPRC
- he evaluated the economic impacts of requiring treatment of CBM water
- he noted that his favorite set of cost estimates came from an ERG report done for EPA Region 8
- he concluded that even at a low gas price of $1.75/mcf, companies could still make a comfortable profit
- he never identified the type of treatment for which costs were estimated and to what effluent limits that treatment would be operated; the ERG report (to the best of my recollection) never attempted to force zero discharge or used limits as strict as those in the proposal, so the comparison is not really relevant
- he noted that establishment of BAT limits does not require a cost/benefit test
- he was asked a question by a board member – How much water is associated with 1 mcf of gas?
  - he did not know the answer

5. James Bauder, professor, Montana State Univ., hired by NPRC
- he stated his opinion that EC and SAR are harmful
- he feels that the 7Q10 flow should be used for assessing water quality standards
- surprisingly, he disagreed with NPRC’s proposed treatment limits, stating that he thought they were too strict

6. Larry Munn, soil science professor, Univ. of Wyoming at Laramie, hired by NPRC
- reported on several recent peer-reviewed papers
- when CBM water is applied to soil, there is a build up of salt and sodium, in spite of using soil supplements
  - this will damage soils
- the worst is yet to come; when they stop irrigating with CBM water and rely on rainfall, the soils will become more sodic
- there has been a transformation of perennial drainage to permanent streams with an increase of sodicity

7. Jim Kuipers, consultant to NPRC, authored the report that served as basis for NPRC petition
- doesn’t like how WY has handled CBM water
  - thinks they have let industry get away with damaging the environment
- was critical of industry speakers, calling all of them “liars”
- he was asked a question by a board member about the use of downhole separation
  - he did not have much information

Opponents

1. John Veil, Argonne National Laboratory
- offered comments on how the proposal did not follow the requirements and criteria of the CWA for setting limits
- BER can require zero discharge if they make the appropriate economic and technical demonstrations [they have not yet done this]; they cannot dictate how companies meet zero discharge
  - thus, the requirement for reinjection to shallow aquifers is not justified
- the proposed limits are much stricter than existing MT water quality standards
- in particular, the arsenic standard is below detection level and the level of treatability
- the numerical limits are not based on any logical, obvious methodology, such as the statistical methods used by EPA’s effluent limitations guidelines program
- there are various internal inconsistencies and drafting errors in the proposal
- the proposal refers to CBM water as “harmful” and “wastewater” in some parts of the proposal but wants to preserve the water for future beneficial use in other parts of the proposal
  - in essence, the rationale changes depending on what point the petitioners are trying to make
- Veil also made some comments that had been provided by Sandia National Laboratories
- there are very limited formations in that area suitable for reinjection
- EC and SAR are not inherently harmful; their impact is a function of how high or low the values are
- in some cases, low values of EC and SAR can harm soils and streams too
- Veil was asked no questions about the content of his remarks but was asked by a board member why he was there and who was paying him
  - he answered that Argonne and Sandia were being paid by DOE but that we were offering our own opinions at this time, not DOE’s opinions
  - the board and the proponents seemed taken aback by Veil’s remarks because: a) many of the remarks were new ones they had not previously heard, and b) he was previously unknown to them

2. Brian Cebull, Nance Petroleum
  - the timing risk for getting the waiver (390 days) will discourage operators from undertaking new projects
  - Nance uses injection in other places but cannot do it well in the Powder River Basin

3. Bill Schaefer, consultant of soils and irrigation
  - the existing standards for EC and SAR are already set conservatively based on a lengthy rulemaking process just a few years ago
  - there is no need to change them now
  - changing the nondegradation standards would create a situation through which the river will not meet EC and SAR standards most of the time

4. Neil Fehringer, consulting agronomist
  - is one of the developers of the successful Agronomic Monitoring and Protection Program (AMPP)
    - this is a form of managed irrigation
  - he indicated that he has many examples with successful irrigation using CBM water and as found no problems with plants or soils

5. John Corra, Director of the Wyoming Dept. of Environmental Quality
  - they have issued 930 permits for CBM discharges; about 500 of these are in the Powder River Basin
    - nearly all require containment structures and/or treatment before discharge
    - there is no evidence of degradation at the Wyoming border
  - in 2001, WY and MT signed an interim Memorandum of Cooperation
    - defined a baseline water quality
    - monitoring
    - shared draft permits
  - he believes the two states are working well together and that the existing rules are sufficient
  - WY DEQ has permitted 316 injection wells for CBM water
    - 47 are currently in use
    - they handle about 2% of all CBM water generated

6. Tom Osborne, Hydrosolutions, consultant to industry
  - the hydrogeology of the region does not lend itself well to injection
  - there is only limited overlap between the shallow water supply wells and the deeper CBM water withdrawal wells
- he suggested that the groundwater model described by the petitioners (Tom Myers) is inaccurate
- injection wells, when successful, only meet the water disposal needs of 2-3 production wells

7. Bob Kimball, CDM, consultant to Fidelity
- CDM wrote a critique/rebuttal of the Kuipers report, particularly reviewing the cost model, which was based on a draft EPA Reg. 8 report
- CDM noted problems with the ratio of bbl or water per mcf of gas
  - Kuipers underestimated the water volume by 2.6 times
- other omissions would cause the Kuipers estimates to be raised by a factor of 6.5 times
- the proposed limits are extremely strict
  - the only way to meet them would be to run the water through a reverse osmosis twice (two-pass mode), then add Ca and Mg back in to adjust the SAR
- the Kuipers report did not discuss brine disposal
  - this will be a big expense and could lead to more disposal wells (not easy in those geological formations or hauling with additional truck traffic)

7. Dave Searle, Marathon
- they drilled 24 injection wells; only 10 were successful
  - 9 of them still are injecting a total of 311 gpm
- most of Marathon’s landowners want the water

8. Kevin Harvey, consultant on irrigation
- developed program for managed irrigation
- can reclaim sodic soil for $2,000/acre

9. Jimmy Goolsby, geological consultant
- tried to find places to inject water in the Powder River Basin, but has not had much success
- Yates Petroleum drilled an injection well to 14,000 ft at a cost of $5 million
  - they don’t know if it will work

10. Joe Olson, Williams
- they have 500 outfalls in WY; only 4 authorize direct discharge
- if the BER adopts the nondegradation requirements, it will cause some projects to not get started

11. Pete Schoonmaker, CEO of Pinnacle
- talked about how Pinnacle tries to work with local communities

12. ?????, Pinnacle
- Pinnacle has the only permit in MT for discharging CBM water
- they have made 3 injection attempts in the Tongue River basin
  - found thick sand layers that looked promising for injection
  - formations did not accept water
- injection is difficult and unpredictable

13. Bruce Williams, VP for Fidelity
- spoke emotionally about how the proposal would hurt business

14. Jeffrey Jones, Lance Oil and Gas
- they drilled some production wells in 1995; they are not yet depleted
- intermittent production and injection as proposed by some of the petitioners would not increase the amount of resources recovered
- both ion exchange and reverse osmosis require addition of acid in the treatment or regeneration process
  - this involves a lot of hauling of acid over rural roads