Annotations for “CBM co-produced water presentation

Slide 5: Conceptually, the system will work by injecting CO2 into the coal seam to competitively desorb the methane from the coal without dewatering the coal bed (or minimal dewatering). Gas permeable membranes located down-hole will allow the gas to be produced with a minimum of water production. The membranes are hydrophobic in nature and the main layer is a thin non-porous urethane membrane that passes gases by molecular diffusion. This membrane is sandwiched betweem 2 Polyethylene microporous, hydrophobic support layers that confer structural strength to the tubular membranes (270.3 μm OD). This research is in the early stages of development, consisting of characterization of the membranes and intact coal cores.

Slide 6: K_O overall gas transfer coefficient
K_M - membrane gas transfer coefficient
K_L - gas liquid film gas transfer coefficient
K_c - aqueous phase water transfer coefficient
K_d - vapor phase water transfer coefficient

Slide 10: Now that the membranes have been characterized, this information can be used to model the performance of a hypothetical system. To produce 550,000 ft3/day gas with downhole gas permeable membranes (assuming the water is saturated with methane but no free gas phase), a curtain 1.7 miles wide made up of 3.3 million fibers would be required. Obviously this is impractical. The limiting factor is K_L, the diffusion of gas through the static boundary layer of water surrounding the membranes.

Slide 11: However, if a free gas phase can be created downhole, this limitation is side-stepped. If a gas phase is present (all of the fibers are surrounded by gas), the total number of fibers drops dramatically to 126,000 which is much more feasible.

Slide 12: The goal of this portion of research is to characterize an intact coal core in terms of its porosity and how the coal will respond to the injection of CO2 gas and to evaluate the efficacy of CO2 as a methane desorbing agent. Coal has a dual porosity system: - microporosity = location of majority of surface area and methane; fracture porosity (cleats) = majority of hydraulic conductivity

Slide 13: To evaluate the distribution of pore sizes, a saturation /desaturation experiment using coal coupons in a controlled humidity environment is being conducted. This is the first time such an experiment has been carried out on intact coal samples. The mass of the samples is recorded after equilibrium is reached at each controlled humidity step and a mathematical relationship is them used to calculate the pore size distribution. The humidity is controlled by varying the amount of water in glycerol.
Glycerol: Non-toxic, non-corrosive
Fully miscible with water
Relatively non-volatile
Keeps fragile micropore structure intact

Slide 14: In addition to starting with dry samples, a concurrent experiment is being carried out that started with saturated samples and the humidity was decreased in a step-wise fashion. Note the long time period required for these experiments.

Slide 16: A Trautwein Permeameter is used to perform injection experiments with intact coal cores. The core is pressurized externally to seal the rubber sleeve against the core so that fluid injected into the core does not “channel” along the wall of the core.

Slide 17: This graph is the results of a core test in the permeameter. Methane was initially injected into the core to re-saturate the core with methane. Next, CO_2 was injected, followed by N_2. The square symbols are the mass flowrate of the gas (left hand axis) resulting from a constant injection pressure. The circles are the change in mass of the core over time and represent the sorption of gas to the coal. Note that in the time frame of this test, the mass flowrate did not decrease which indicates that that the coal did not swell due to the sorption of gas, causing a restriction of the flow-paths. Some initial water loss from the core was noted before stabilizing, the core mass change was corrected for this water loss. The mass of the core initially increased rapidly as methane sorbed to the coal. When the gas was switched to CO_2, the rate of increase slowed, probably due to the fact that methane was being desorbed and CO_2 was sorbed.

Slide 18: Water-enhancement activities, as the operators in the basin call this procedure, consists of pumping 60 bbl of water/min into the coal seam during approximately 15 min. This is done to clean the well-bore and to enhance CBM production. Hydraulic fracturing is of concern because vertical hydraulic fracture growth could extend into adjacent formations and potentially result in excess CBM water production and inefficient depressurization of coals.

Slide 19: Upper left: example water enhancement test data (Enhancement Test: 60 bbl/min for 15 minutes). The instantaneous shut-in pressure corresponds to the “least principle stress” or the pressure required to propagate a fracture. Sv = overburden pressure. The figure in the lower right hand shows the water production history for wells that fractured vertically ($S_3 < S_v$). A fraction of the wells had very high water production (shown in red, defined as water production greater than 10,000 bbl/mo.
Did modeling work to show that excessive water production (and pressure drop) could not result from unfractured flow through confining unit.

Slide 20: Production history for wells with horizontal fractures ($S_3 = S_v$).

Slide 21: The 1/3 of wells with vertical fractures are a major problem in terms of water production. However, vertical fractures are not a problem as such because most of the gas is coming from wells with vertical fractures because wells with horizontal fractures are typically low gas produces. For the wells with vertical fracture and high water production we suspect that the vertical fractures extended through the confining unit into an adjacent water bearing sand. The trick seems to be to limit the extent of the vertical fracture. Note: only ~ 4% of existing wells have been analyzed.

Slide 23: Because water levels have been continuously monitored over time in almost all of the water level monitoring wells in the PRB, we were able to calculate pore pressure changes with time for both the sands and coalbeds. This figure shows example coal-sand pairs that appear to be in hydraulic communication with each other as evidenced by the pore pressure history.

Slide 24: Using paired monitoring wells (wells monitoring coal and overlying sands in close vicinity to each other), we found that in general, sands that are less than ~100 ft from underlying coalbeds have the greatest change in pore pressure with time (Figure 5). To determine if the large changes in pore pressure for the overlying sands is because of hydraulic communication with the underlying coalbeds, we looked at pore pressure changes with time for both the coalbed and overlying paired sand. We plotted the pore pressure changes with time for all paired wells, to see if the overlying sands had similar pore pressure depletion histories as their underlying coalbeds.
-Sands that are more than 200 ft from underlying coals appear not to be in communication with the coalbeds and would be candidates for re-injection of CBM water. Injecting water into sands closer than 200 ft to a coal bed would risk re-pressurizing coal beds.

Slide 25: Geological Finite Element Modeling: Two purposes
1) can excessive water production come from sands in the absence of vertical fractures penetrating confining unit? (No)
2) Potential for reinjection

Slide 26: Should be able to maintain these injection rates for 4000 days (11 years) before hydrostatic pressure is reached (positive wellhead pressure).
Sand properties from BLM hydrogeologic report (2002) Thickness = average thickness of monitored sands
Shallow sand depth to the top = 166-316 ft
Deep sand depth to the top = 1034-1184 ft
Sub-hydrostatic pressure in the sands is widespread

-Sub-hydrostatic sands more than 200 ft from producing coals may be potential sites for re-injection of CBM produced water
Can inject CBM water at rate of ~180 bbls/day in shallow sands and at ~435 bbls/day in deep sands
The water production rates are for the entire production history we have for each well with water enhancement tests.ハ So the total time differs for each well...ハ This is how Colmenares and Zoback reported water production in their paper, so we have been consistent.

Slide 27: Using the Srontium isotope ratio of water to trace the source of the water and also to determine the fate of surface discharged water. The accompanying slides were deleted at the researchers request pending publication of results. However, the following is an executive summary of the work.

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

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

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

Slide 28: Water levels at Beaver Creek monitoring wells continue to indicate infiltration of co-produced waters from the stream channel and ponds.
Water levels vary over time due to seasonal recharge and yearly variations in precipitation and snowmelt.
The rate of water level increase has decreased over time. This is due to (1) spreading of the groundwater mound as the lateral head gradients increase over time, and (2) decreased and intermittent flows to the ponds due to declining water production.

Slide 29: By doing a mass balance on the water traveling through the study site via weir measurements and evaporation pan mesurements, estimations of infiltration rates, evaporation rates, and transpiration rates can be calculated.

 Numbers are liters/sec

Slide 30: Variability (shown by 2-s error bars) largest in summer.
Stream evaporation is negligible, but transpiration is not. The peak summer evaporation-transpiration (E-T) increases systematically over the study period.
The temporal trend will be significant in prediction and management of runoff.
Based on the time series, we separate components of conveyance loss:
Infiltration yields a "baseline" loss rate of 1.5-1.6 in/day.
Transpiration loss increased from ~2 in/day in year 1 to ~6.8 in/day in year 3.

Slide 31: Note the increase in vegetation in the stream channel from the start of CBM discharge (left photo) to a year later (right photo). This increase in plant mass resulted in much higher E-T losses.

Slide 32: Watershed model used to generate stream-flow predictions in following slides.

Slide 33: -Simulated discharge over time since development: 2 miles downstream of a pond (top), and at the confluence with the Powder River (bottom). The peaks correspond to the winter months and the valleys to the summer months when E-T losses result in much lower discharge rates.
-Seasonality of factors controlling conveyance losses should result in a periodic and predictable pattern of surface water loading.
-Peak winter flows increase in constant water production scenario because they are affected by the decreasing pond infiltration. Peak summer flows decrease over time due to increasing E-T.

Slide 34: Evaluation of the performance of a constructed off-channel infiltration pond in Coal Creek. Negative infiltration rates are suspected to be from incorrect water input rates from operator at beginning of project. Note the dramatic decrease in infiltration circa Nov-2004, this is thought to be caused by soil dis-aggregation and subsequent plugging of pores due to the high sodium content of the CBM water.

Slide 35: Calculated vertical hydraulic conductivity of the pond bottom at the Coal Creek Site. Note the sharp drop in conductivity in Nov-2004. Very low infiltration rates have been noted at all sites after a period of time.
Percent clay does not appear to relate to the ultimate infiltration rate.
Percent and types of clays may strongly influence timing of decreased vertical hydraulic conductivity rather than the magnitude.

Slide 36: Cores from the Coal Creek infiltration pond bottom were collected and analyzed for a variety of ions before (blue) and after (red) the pond was in service to measure the impact of CBM water infiltration. Note that the sodium initially present in the soil was flushed down to a depth of 20 feet.

Slide 37: Coal Creek infiltration pond after operations were ceased. We think the salts will stay put - impermeable layer at pond bottom acts as a cap to inhibit further water infiltration
Site to be back-filled this summer and we expect to continue to monitor via monitoring wells.

Slide 38: This is a schematic of our test site for evaluating the use of untreated CBM water for irrigation. The goal of this portion of the project is to evaluate the use of soil amendments(sulfur and gypsum ($CaSO_4$)) to mitigate the soil damage resulting for the use of untreated CBM water. Two center pivot irrigation systems have been installed on the site. Each dot is a test site (7 plots, different amendments of gypsum and/or sulfur and a control. Before irrigation was started, the site was assessed (first such full scale assessment).
- Baseline conditions were established for soil characteristics for chemical and physical parameters. Soil samples were collected from each plot and analyzed for pH, electrical conductivity (EC), sodium adsorption ratio (SAR), percent saturation, bicarbonate, Cl^-, SO_4^{-2}, Ca^{+2}, Mg^{+2}, Na^+, particle size analysis, texture, cation exchange capacity (CEC), and exchangeable sodium percentage (ESP).

Slide 39: 5M by 5M subplots

Slide 40: ECH_2O probes measuring soil water, soil solution salinity and temperature at one-foot depth intervals to a total depth of 6 feet
A Gee Drain Gauge Lysimeter was placed in the soil below the root zone of an intact soil monolith to characterize the drainage water (amount and collect samples for chemical analysis) resulting from the irrigation treatment.
1. A lysimeter was placed at one site to collect water exiting the root zone. Two sites were instrumented to a depth of 6 feet with soil probes to measure continuous soil water content, solution salt content, and soil temperature.
Irrigation was started in late August 2006 - ~11" of water was applied (far less than a normal year) and then soil samples were taken and analyzed.

Slide 41: Significant visual differences were found between the untreated subplots (top) and the treated subplots. (bottom). The top picture shows the untreated soil with the

classical characteristics of a sodic soil condition. The surface is crusted with soil pores plugged and water is ponding on the surface as is shown in the dark, wet areas. The treated soil in the bottom picture displays a great contrast as the surface is not dispersed and soil aggregation is maintained, allowing good water infiltration.
-Due to low water application, preliminary analysis of chemical analysis did not show a major difference.

Slide 42: Food and Agricultural Organization of the United Nations - Soil Water Salinity model(FAO-SWS): The USDA Soil Salinity Laboratory has shown the FAO-SWS model to be an effective tool for irrigation management using CBM co-produced water on irrigated lands in California. We have completed an initial calibration of the model to predict the effect of irrigation with CBM co-produced water on rangeland in the Powder River Basin. The work conducted at the WJ research plot will be used to continue this calibration effort.
-Simulation showing the solution sodium levels by soil depth over the 10-year simulation period. (green – 0; turquoise –1 year; red – 3 years; pink – 5 years; blue – 7 years; dark green – 8.8 years; blue green – 9.3 years) (root zone to about 0.7 m)

Slide 43: A greenhouse study was performed to evaluate the effect of CBM water and soil amendments on the productivity of alfalfa.

Slide 44: We are also investigating the capacity of sulfur and gypsum to reclamate CBM water impacted sites (sodic soil). Baseline soil characteristics were established and then soil amendments were applied and irrigation was begun. After a year, more soil samples were collected but the results of soil analysis not available at this time.
Soil sample analysis is on-going.

Slide 45: This project evaluated 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).

Slide 46: Channel sandstones are probably the best targets for injection because they have more favorable porosity and permeability and because injecting into coal beds may have conflicts with future CBM development. Six channel sandstone units were identified in the Tongue River Member, informally named A through F in ascending order. Clearly evident from isopach maps is that the channels are widely distributed and potential injection targets will not be available in every location where an injection well is desired. In other words, injection may not be technically feasible in all locations at any cost.

Slide 47: Some of the channel sandstones are more than 100 feet thick and have porosities as high as 30%. These sandstone bodies should prove to be excellent zones for injection of CBM produced-water. Engineering injectivity evaluation concludes that re-injection of significant volumes of water into channel sandstone is possible. Reasonable injection rates (200 ミ 4500 B/D) depending on formation sand thicknesses completed, and well pressures that do not exceed an estimated fracture gradient of 0.70 psi/ft can be expected.

Disposal well design was also covered along with water handling facilities.

Slide 49: The analysis indicates that significant, but limited, volumes of water could be injected into zones identified in the Tongue River Member of the Ft. Union Formation. Because of the difficulties in locating well-developed channel sandstones and because the target zones are already at least partly water saturated, a combination of water disposal methods, including surface discharge, infiltration ponds, direct agricultural and domestic use, treatment, and injection, will probably yield the most feasible disposal plans and a balance between environmental and economic constraints.

Slide 50: We have also evaluated the feasibility of using electrodialysis (ED) to treat CBM water to remove ions. Voltage applied to the cathode and anode cause charged ions to pass through treatment membranes resulting in a demineralized product water.

Slide 51: Typical TDS values of the Powder River Basin co-produced water are on the order of a few thousand mg/l, making this water a good candidate for ED.

Slide 52: CBM Produced Water Conditions
pH = 8.4 TDS~1400 mg/L
Conductivity = 1783 uS/cm
Volume = 10 L
Concentrate Solutions
5 g/L, 300 g/L sodium chloride and 50 g/L sodium bicarbonate

Slide 53: 12 hr contact with limestone

Slide 54: Less than 1/2 the cost of conventional RO, Electrodialysis offers potential advantages:
More compatible with clean in place (CIP) protocols / Less prone to fouling
Highly applicable to low to moderate TDS waters
Power use is reasonable: 0.14 kwh/lb salts removed
Cost Effective. Cost is modest for CBM PW treatment: Fully Loaded Cost < $0.25/bbl

Slide 56: Leonardite is a mineral that results from the unsaturated weathering of coal (O2 and H2O) and is readily available and inexpensive in the Powder River Bason. It demostrated the ability to reduce the SAR of CBM water from 54 to less than ~5 when treating 25 pore volumes - (3350 gallons of water/ton of leonardite).