

Mines Student Research Symposium on Carbon Sequestration



**Colorado School of Mines
Ben Parker Student Center
January 24th, 2012**

Thank you for attending the first Mines Student Research Symposium on Carbon Sequestration. We organized this symposium to highlight student research at CSM in the area of carbon sequestration. We thank Schlumberger and Tri-State Generation and Transmission Association, Inc. for their generous support. The Colorado Energy Research Institute (CERI), the Center for Hydrate Research, the Center for Subsurface Environmental Processes (CESEP) and the Departments of Chemical and Biological Engineering, Civil and Environmental Engineering, Geology and Geological Engineering, and Petroleum Engineering are also acknowledged for supporting this symposium.

We hope you enjoy the symposium!

Alexis K. Navarre-Sitchler

&

Jonathan Levine

Co-organizers

Mines Student Research Symposium on Carbon Sequestration

January 24th, 2012

10:00	Opening Remarks	
10:10	Oral Session I	
10:10	A Quantitative Methodology to Assess the Risks to Human Health From CO ₂ Leakage Into Drinking Water Aquifers: Development and Implementation	Erica Siirila <i>Geology and Geological Engineering</i>
10:30	Linking Complex Geochemical and Hydrological Processes Using Streamlines for Highly-Resolved, Reactive Transport CO ₂ Leakage Scenarios	Adam Atchley <i>Geology and Geological Engineering</i>
10:50	Metal Release and Transport in Potential Drinking Water Aquifers Impacted by Stored CO ₂	Alexis Navarre-Sitchler <i>Civil and Environmental Engineering</i>
11:10	Metal Release From Limestones Under Elevated CO ₂ Concentrations: An Experimental Study	Assaf Wunsch <i>Civil and Environmental Engineering</i>
11:30	Fundamental Study of CO ₂ Gas Exsolution and Flow in the Shallow Subsurface During Leakage From a Geologic Sequestration Site	Michael Plampin <i>Civil and Environmental Engineering</i>
11:50	Experimental Study of Capillary Trapping During Supercritical CO ₂ Sequestration Through Analog Test Fluid Injection at Small to Intermediate Laboratory Scales	Luca Trevisan <i>Environmental Science and Engineering</i>
12:10	Lunch	
12:30	Keynote: Carbonate Precipitation Associated With CO ₂ Sequestration at the Pore to Continuum Scale	Carl Steefel <i>Lawrence Berkeley National Laboratory</i>
1:00	Oral Session II	
1:00	Performance Improvement for Palladium Alloy Composite Membranes for Sequestration of Carbon Dioxide from Water-Gas-Shift Mixtures	Øyvind Hatlevik <i>Chemical Engineering</i>
1:20	CH ₄ -CO ₂ Exchange Kinetics in a Hydrate System	Nathan Welch <i>Chemical Engineering</i>
1:40	Relative Permeability Experiments of Carbon Dioxide Displacing Brine and Their Implications for Carbon Sequestration	Jonathan Levine <i>Chemical Engineering</i>
2:00	Effects of Increasing CO ₂ Pressure and Urea Amendments on a Methanogenic Consortium Enriched From Coal From the Powder River Basin, WY	Andrew Glossner <i>Chemistry and Geochemistry</i>
2:20	Geomechanical and Petrophysical Property Changes Due to CO ₂ Injection in a Sandstone Reservoir Using an Integrated Geomechanics Modeling Approach	Sen Guan <i>Petroleum Engineering</i>
2:40	Development of a High-Pressure Triaxial Rock Core Testing System Simulating Deep Saline Aquifers for Geological Carbon Sequestration	Daisuke Katsuki <i>Civil and Environmental Engineering</i>
3:00	Poster Session	

Posters

Carbon Dioxide Utilization: Polylactide-Graft-Lignin Copolymers	Michael Eyser <i>Chemical and Biological Engineering</i>
Carbon Nanotube Sequestration of Carbon Dioxide	Zen Keith <i>Chemical and Biological Engineering</i>
Simulation of Carbon Dioxide Sequestration in Ionic Liquids	Zen Keith <i>Chemical and Biological Engineering</i>
Carbon Dioxide Utilization Using Non-Biodegradable Polymers	David Ruehle <i>Chemical and Biological Engineering</i>
Intermediate Scale Testing and Modeling for Improving Fundamental Understanding of Dissolution Trapping in Deep Geologic Formations	Elif Agartan <i>Civil and Environmental Engineering</i>
Stochastic Analysis of CO ₂ Sequestration in Geologic Formations	Tingting Chen <i>Civil and Environmental Engineering</i>
Exploring Metal Mobilization in Response to CO ₂ -Induced Acidification	Katie Kirsch <i>Civil and Environmental Engineering</i>
Brine and CO ₂ Leakage Rates in the Intermediate Zone as a Result of Geologic Sequestration	Hannah Menke <i>Civil and Environmental Engineering</i>
Material Characterization for Intermediate Scale Testing to Develop Strategies for Geologic Sequestration of CO ₂	Hiroko Mori <i>Civil and Environmental Engineering</i>
Pore Network Changes to Caprocks After Carbon Sequestration Simulation Experiments	Katherine Mouzakis <i>Civil and Environmental Engineering</i>
Analysis of Biofuel Policy and Efficiency Towards Greenhouse Gas Reduction	Mark Petrequin <i>Civil and Environmental Engineering</i>
Characterizing Saline Formations: Implications for Leakage and Monitoring	Assaf Wunsch <i>Civil and Environmental Engineering</i>
Scale Effects on the Elastic Behavior of Fractured Rock Masses	Dong Youn <i>Civil and Environmental Engineering</i>
A Fully Coupled Mathematical Model for Fluid Flow and Reactive Solute Transport During CO ₂ Sequestration in Carbonate Reservoirs	Ronglei Zhang <i>Civil and Environmental Engineering</i>
Compositional Simulation of CO ₂ Enhanced Oil Recovery	Jeff Brown <i>Petroleum Engineering</i>

Keynote Speaker:

Carl Steefel, Ph.D.
Staff Scientist
Lawrence Berkeley National Laboratory

Carl Steefel has over 21 years of experience in developing models for multicomponent reactive transport in porous media and applying them to topics in reactive contaminant transport and water-rock interaction. The reactive transport software CrunchFlow, for which he is the principal developer, is the culmination of this work. He investigated geochemical self-organization and complexity theory in water-rock interaction (Steefel and Lasaga, 1990), while also developing the first routine for multicomponent nucleation and crystal size distributions in the Earth Sciences (Steefel and Van Cappellen, 1990). Soon after, he presented the first multicomponent, multi-dimensional code for simulating water-rock interaction in non-isothermal environments (Steefel and Lasaga, 1994). Steefel applies reactive transport modeling to such diverse settings as hydrothermal, contaminant, chemical weathering, and marine environments. Recently, he has been involved in experimental studies of cation exchange (Steefel et al., 2003) and mineral dissolution and precipitation (Yang and Steefel, 2008), as well as modeling studies of field systems focused on contaminant transport, microbially-mediated biogeochemical reactions, and chemical weathering (Giambalvo et al., 2002; Steefel, 2004; Maher et al., 2009; Li et al., 2009; Steefel and Maher, 2009; Navarre-Sitchler et al., 2011).

Carl Steefel is the project lead for research in Emergent Processes in the Center for Nanoscale Control of Geologic CO₂, a DOE Energy Frontier Research Center. The injection of CO₂ into the subsurface environment drives the fluid-rock system into “far-from-equilibrium” conditions where new behavior may emerge that is not predictable by considering processes in isolation. Under these conditions, the strong coupling between flow, transport, and reaction may result in emergent structures and pattern formation that develop within the porous structure of the subsurface at scales ranging from the nano-pore and macro-pore all the way up to that of a sedimentary basin. These emergent dynamics must be understood in order to predict how CO₂ will behave when injected into the subsurface.

A quantitative methodology to assess the risks to human health from CO₂ leakage into drinking water aquifers: development and implementation

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Leakage of CO₂ and associated gases into overlying aquifers as a result of geologic carbon capture and sequestration may have adverse impacts on aquifer drinking-water quality. Gas or aqueous-phase leakage may occur due to transport via faults and fractures, through faulty well bores, or through leaky confining materials. Here we present a quantitative risk assessment framework to predict potential human health risk from CO₂ leakage into drinking water aquifers. This framework incorporates (1) the potential release of CO₂ into the drinking water aquifer; (2) mobilization of metals due to a decrease in pH; (3) transport of these metals down gradient to municipal receptors; (4) distributions of contaminated groundwater to multiple households; and (5) probabilistic exposure and health risk to individuals using this water for household purposes. Additionally, this framework is stochastic, incorporates detailed variations in geological and geostatistical parameters and discriminates between uncertain and variable parameters using a two-stage, or nested, Monte Carlo approach. This approach is demonstrated using example simulations with hypothetical, yet realistic, aquifer characteristics and leakage scenarios. A highly discretized, regional scale aquifer is utilized to investigate the effect of hydraulic conductivity anisotropy (i.e. the degree of aquifer stratification), regional groundwater velocities, and the effect of modeling assumptions such as equilibrium reactions and pore-scale dispersion. These example simulations show a greater risk for arsenic than for lead for both cancer and non-cancer endpoints, an unexpected finding. The overall risk and the associated uncertainty are also sensitive to the extent of aquifer stratification and the degree of local-scale dispersion. A secondary analysis examines how small (i.e. meter to sub-meter) scale hydro-geologic processes such as pore scale dispersion and kinetic sorption propagate to the field (i.e. kilometer) scale, and ultimately how these processes may impact the risk assessment. Results show a positive feedback between kinetic sorption and pore-scale dispersion, yielding dis-equilibrium behavior in plume transport and risk. This finding suggests the time dependence associated with kinetic sorption may not be negligible in highly stratified aquifers, where movement of contaminants from regions of high to low hydraulic conductivity and from regions of low to high hydraulic conductivity may result in either induced retardation or induced channeling, respectively. These results highlight the importance and necessity of hydrologic modeling in risk assessment. Finally, implications for ranking aquifer vulnerability due to geologic configuration, aquifer mineralogy, and leakage scenarios are discussed.

Linking complex geochemical and hydrological processes using streamlines for highly-resolved, reactive transport CO₂ leakage scenarios

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Simulating reactive transport and geochemical processes over large, finely resolved domains in three-dimensional space has traditionally been computationally infeasible. Subsurface physical heterogeneity and complex chemical processes along with the need to accurately resolve macrodispersion and mixing all contribute to computational expense. However, the ability to accurately model large-scale reactive transport has become increasingly necessary in order to evaluate potential groundwater contamination scenarios, such as those associated with CO₂ leakage from Carbon Capture and Storage (CCS). Here we present a Lagrangian streamline approach where a large, heterogeneous three-dimensional flow field is reduced to a number of one-dimensional transport simulations. Each of these deconvolved, one-dimensional reactive transport problems are solved with an aqueous geochemical model (CrunchFlow) along a streamline, with the aim of representing complex geochemical reactive transport over a large domain in three-dimensional space. The streamline approach allows the mapping of these one-dimensional reactive transport simulations back onto a three-dimensional flow field, thus accounting for spatial heterogeneity within the aquifer and the complex aqueous geochemical processes.

This methodology is demonstrated using a CO₂ leakage scenario from a hypothetical CCS site. In this simulation, a plume of CO₂ is introduced into the aquifer thereby lowering the groundwater pH and mobilizing metals from an existing mineral host-rock distribution. In this set of simulations, ensembles of correlated, Gaussian random fields are used to represent heterogeneity in hydraulic conductivity (K) for cases with increasing of variance in ln(K). Plume migration, related pH buffering and kinetic dissolution/precipitation processes within the aquifer are simulated under varying degrees of subsurface heterogeneity using this streamline-geochemical modeling approach. Metal concentrations and pH at groundwater pumping wells are then evaluated and linked to the degree of physical heterogeneity and geochemical processes. Results show that as the degree physical heterogeneity increases, the pH drops along source-to-well streamlines, lowering the overall observed pumping well pH compared to domains with lower variance. Thus through this novel modeling effort, a link is established between hydraulic heterogeneity and geochemical response. Furthermore, the complex interactions between geochemical processes and dynamic flow paths have implications for understanding the risks and observable outcomes to CCS implementation.

Metal release and transport in potential drinking water aquifers impacted by stored CO₂

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We present reactive transport simulations of CO₂ leakage from underground storage formations into shallow groundwater aquifers. Dissolution of CO₂ into the groundwater creates carbonic acid and decreases groundwater pH eliciting a geochemical response. Simulations were run using PFLOTRAN with different mineral sources of metals (galena and calcite) with multiple realizations of heterogeneous permeability distributions assigned geostatistically to investigate water quality impacts from CO₂ leakage at the basin scale (4 km x 1 km x 0.1 km model domain). Even with fairly coarse grid spacing (~ 9 m x 9 m x 0.9 m), the simulations have > 49 million degrees of freedom and were run on the Jaguar Cray XT5 using 2048 processors.

Simple aquifer mineralogy of quartz with 3% iron oxide and 5% calcite (with 0.1% galena in some cases) was used to isolate sources of pH change and lead to solution. Results from the small ensembles of permeability distribution (5 realizations each of highly stratified and non-stratified aquifers) show that pH decreases more at a pumping well downstream of the leak for aquifers without galena and for highly stratified aquifers relative to non-stratified aquifers. However, in all cases the pH decrease is less than natural variations in pH reported from daily measurements in aquifers. It has been suggested that pH decrease can be used as a diagnostic indicator of a CO₂ leak. However, the studies that provide the basis for this do not account for permeability variations beyond homogeneous layering. Our results suggest that accurate baseline pH is required if pH is to be used as a diagnostic tool for CO₂ leakage. Additionally, pH is a better indicator of CO₂ leakage in highly stratified aquifers than in non-stratified aquifers. Lead concentrations at the pumping well are the same within uncertainty when the source of lead is galena or calcite in highly stratified aquifers. However, in non-stratified aquifers, pumping well lead concentrations are lower when the source of lead is galena compared to trace amounts in calcite. In non-stratified aquifers galena reaches saturation along the flow path before reaching the pumping well and lead concentrations are effectively buffered by low galena solubility. In all of the cases lead concentrations stay well below the maximum contaminant level set by the EPA. Bicarbonate concentrations, another potential indicator of CO₂ leakage, show greater increases in the pumping well when calcite is the lead source relative to when galena is the lead source; likely due to the greater pH decrease in the calcite source simulations. Bicarbonate concentrations nearly double in some cases and in many cases increase by at least 20% suggesting that bicarbonate may be the best geochemical indicator of a CO₂ leak under the conditions simulated here.

Metal release from limestones under elevated CO₂ concentrations – an experimental study

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Carbonate aquifers are an important source of drinking water world-wide, and in the U.S. they constitute about 22% of the public water supply (Maupin and Barber, 2005). The high pumping yields and good water quality associated with carbonate aquifers make them a desirable source of drinking water, yet the high secondary porosity that is typical to carbonate rocks also makes them very sensitive to pollution (Lindsey et al., 2008). In case of CO₂ leakage into carbonate aquifers from geological carbon sequestration sites, the carbonate minerals that are present in the aquifer are expected to dissolve due to the CO₂-induced acidity. Calcites are rarely found in pure form, and often contain metal impurities in solid solution, either substituting for Ca or CO₃ in the mineral lattice. In this work, natural limestones were exposed to aqueous solutions under elevated CO₂ partial-pressures of 0.01, 0.1 and 1 bar. Several metals, such as Co, Ba, Sr, showed strong correlation to Ca release, suggesting that calcite is the source of these elements. As and Cr exhibited release trends similar to Ca under low partial-pressures of CO₂, yet their concentrations increased dramatically under 1 bar CO₂, perhaps due to competition of their oxyanions with the carbonate ion. Pb and Ni were detected in elevated concentrations in one of the samples. Ni was also the only element to exceed a regulatory limit in drinking water. Release of alkaline metals, such as K, Rb and Cs, seems to be controlled by a mechanism different than calcite dissolution, as their release into solution was mostly linear during the experiment.

References:

Lindsey, B.D., Berndt, M.P., Katz, B.G., Ardis, A.F., Skach, K.A., 2008. Factors affecting water quality in selected carbonate aquifers in the United States, 1993-2005. US Geological Survey Scientific Investigations Report 5240.

Maupin, M.A., Barber, N.L., 2005. Estimated withdrawals from principal aquifers in the United States, 2000. U.S. Geological Survey Circular 1279, p. 46.

Fundamental study of CO₂ gas exsolution and flow in the shallow subsurface during leakage from a geologic sequestration site

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Geologic sequestration of CO₂ can potentially reduce the effects of global warming by reducing the amount of greenhouse gases that are emitted into the atmosphere. However, leakage of sequestered CO₂ can cause significant impacts to groundwater resources and ecosystems, so the fate and transport of CO₂ in shallow subsurface environments are important to understand. When supercritical CO₂ leaks from a storage formation, it dissolves into the groundwater or brine into which it leaks. Under certain conditions, this dissolved CO₂ then migrates upward into the shallow subsurface, where it has the potential to come back out of solution (exsolve). Once enough exsolution has occurred, discrete gas phase migration pathways may develop through the system, at which time, two-phase flow of water and CO₂ gas ensues. An experimental study is underway which investigates the fundamental mechanisms of CO₂ gas exsolution and flow. Degassed, deionized water is saturated with CO₂ gas under a specified pressure and then injected at the bottom of a 4.5 meter tall vertical column of highly characterized test sand that is initially saturated with water. The column is equipped with 12 soil moisture, electrical conductivity, and room temperature sensors, as well as 2 soil temperature sensors that all continuously monitor the physiochemical behavior of the system. Water pressure is monitored at 13 locations along the column using a physical multiplexer connected to a pressure transducer. At the top of the column, gas and liquid phase effluents are separated, the pH and CO₂ concentration of the liquid phase is measured continuously, and the mass outflow rate of each phase is monitored. A variety of homogeneous and heterogeneous packing configurations, saturation pressures, and injection rates are used in order to test the effects of these conditions on the dynamics of CO₂ gas exsolution and flow. Results from experiments with homogeneous packings indicate that, 1) when the saturation pressure is greater than the hydrostatic water pressure at the injection port, gas exsolves first at the bottom of the column and the exsolution front coincides with the front of the migrating CO₂-saturated water, and that 2) when the saturation pressure is lower than the hydrostatic water pressure at the injection port, the CO₂-saturated water reaches the top of the column before any gas exsolves, then gas exsolves first at the top of the column and the exsolution front migrates downward. When a layer of fine sand exists between two coarse layers, the initial exsolution behavior is different. For all cases, both homogeneous and heterogeneous, 1) the rate of water outflow, which is initially equal to the inflow rate, increases when gas starts to exsolve, 2) after some time, discrete gas migration pathways develop, which cause the saturation values to stabilize, the gas phase outflow rate to increase from 0 to some positive value, and the water outflow rate to decrease back to the inflow rate, 3) the water pressure distribution in the column is initially hydrostatic, then the pressure increases when injection begins, and increases further when gas phase develops, 4) the final vertical extent of gas phase corresponds to the saturation pressure (for example, when the saturation pressure is equal to 2 meters of water, gas will only exsolve in the top 2 meters of the column), and 5) the final, steady-state gas saturation always approaches 30-40%, regardless of packing, injection rate, or saturation pressure. These results indicate that, once gas exists in the column, there are two subsequent physiochemical processes. The first consists of kinetic mass transfer of CO₂ from the aqueous phase to the gaseous phase, and the second consists of steady two-phase flow of water and CO₂ gas. These results will be used to calibrate numerical tools that are being developed at Los Alamos National Laboratory.

Experimental study of the capillary trapping during supercritical CO₂ sequestration through analogue test fluid injection at small to intermediate laboratory scales

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Geological storage of carbon dioxide in deep formations is being considered as a technical option to reduce greenhouse gas loading to the atmosphere. The processes associated with the movement and stable trapping are complex in deep natural formations. This research approaches the analysis of trapping mechanisms during injection and post-injection process in deep subsurface environments through controlled laboratory experiments at small to intermediate scales. Small scale homogeneous 2-D test tanks will be used to obtain accurate data for process understanding and modeling. The goal is to develop experimental methods and obtain data that will be used as benchmark for more complex experiments conducted under different heterogeneous packing configurations in a 16 ft long tank. The primary objective of the experimental method consists in the selection of surrogate test fluids that can be used in the laboratory under ambient temperatures and pressures. Through the use of dimensionless numbers such as Mobility (M), Capillary number (Ca) and Bond number (Bo) we are able to extrapolate the data to conditions that occur in the field under high temperatures and pressures in deep geologic formations. Methods are also developed to measure the entrapment saturations using x-ray attenuation methods. The modeling analysis to verify whether existing models can capture the observed processes is carried out using TOUGH2/ECO2N codes developed by the Lawrence Berkeley National Laboratory. The results from the tank experiments and these model analyses are presented.

Performance improvement for palladium alloy composite membranes for sequestration of carbon dioxide from water-gas-shift mixtures

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Composite membranes consisting of a thin Pd-Au alloy film supported on a robust, commercially-ready porous substrate have been investigated as a means of improving resistance to embrittlement due to hydride phase formation, increasing performance in purification of hydrogen from water-gas-shift (WGS) reaction mixtures, and maintaining high carbon dioxide pressures for sequestration or other synthetic use. The hydride phase of Pd and Pd alloys have different lattice constants than the metal, and this difference leads to embrittlement and cracking of the membrane. In pure palladium the hydride phase is formed when hydrogen is introduced at temperatures below 292 °C. In a Pd-Au alloy the temperature at which cracking is observed is greatly suppressed to ~125 °C depending on composition. Furthermore, alloying palladium with gold increases membrane performance in mixtures containing CO and H₂S as compared with pure palladium. Performance of the alloy membranes is discussed with respect to gold content in the membrane.

CH₄-CO₂ exchange kinetics in a hydrate system

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CO₂ sequestration has the potential as an enhanced oil/gas recovery technique as well as simultaneously releasing methane locked within naturally occurring hydrates under conditions of low temperatures (< 5°C) and high pressures (> 5 MPa). Previous studies provide qualitative information on the CH₄ production rates during CH₄-CO₂ hydrate exchange reaction. However, the kinetics of CH₄-CO₂ exchange in fine hydrates is unknown and it could have significant implications towards quantifying CH₄ release from various CH₄ hydrate saturations observed in natural settings. In this study we investigate the kinetic behavior of the replacement of CH₄ within the sI gas hydrate cages with CO₂. This work will provide quantitative, well-controlled experimental data on CH₄-CO₂ exchange in liquid CO₂, CO₂-N₂ gas mixture systems.

These experiments are performed using methane hydrate formed from sieved ice particles at 10 MPa and 263 K from CH₄ gas. The CH₄ gas atmosphere is then purged using liquid CO₂ after sufficient hydrate conversion of the particles is achieved. The production of CH₄ from the hydrate structure is quantified from a slow, continuous flow of liquid CO₂ through the sample with a downstream in-line gas chromatograph used to determine exiting stream compositions. The results from experiments with liquid CO₂ injection at various flow rates/soaking times will be presented.

Relative permeability experiments of carbon dioxide displacing brine and their implications for carbon sequestration

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To continue running our civilization on fossil fuels while avoiding global warming and ocean acidification, anthropogenic carbon dioxide must be diverted from atmospheric release. For geologic carbon sequestration, the injection of CO₂ into the lithosphere, to operate at the necessary large scale requires an understanding of the multiphase flow properties of high-pressure CO₂ displacing brine in porous media. A laboratory-scale core flooding reactor has been built to measure flow properties at in situ pressures, salinities, and temperatures. The reported set of experiments was designed to measure CO₂ relative permeability for CO₂ displacing brine at residual brine saturation. Endpoint drainage CO₂ relative permeability was found to be tightly clustered around 0.35-0.4. These values indicate that CO₂ is not strongly nonwetting, and are characteristic of weakly water-wetting or intermediate wetting flow. Based on these results, CO₂ injectivity will be reduced, pressure-limited reservoirs will have reduced capacity, and inclined area-limited reservoirs will have increased capacity. Future reservoir-scale modeling efforts should incorporate sensitivity to relative permeability. Assuming the majority of reservoirs are pressure limited and if the experimental results reported here are found to apply to other lithologies as well, geologic carbon sequestration at scale will require approximately twice the number of storage sites, wells, reservoirs, and the related infrastructure, personnel, and cost.

Effects of increasing CO₂ pressure and urea amendments on a methanogenic consortium enriched from coal from the Powder River Basin, WY

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Deeply buried coal seams are considered as attractive sites for geological CO₂ sequestration due to their high sorption capacity (DOE, 2007). Some coal basins may harbor indigenous microbial communities of economic importance due to their ability to metabolize complex organic molecules associated with the coal into methane. The Powder River Basin (PRB), WY is one such basin with significant accumulations of biogenic methane (Flores et al., 2008), and which has substantial potential to sequester CO₂ (Busby et al., 1995). It has been suggested that subsurface microbes may be able to stimulate biomineralization of injected CO₂ either directly, or via increased pH as a result of urea hydrolysis (Mitchell et al., 2010). Urea is a readily available organic substrate that may be injected into reservoirs with active microbial communities and the capacity to sequester CO₂. In such reservoirs in which the objective is to stimulate enhanced sequestration via biomineralization, urea injection may be a viable strategy. However, the potential impacts of increased pCO₂ and biomineralization on the native methanogenic microbial community in coal beds has not been investigated. Experiments are underway to determine how increasing pCO₂ will affect the microbial community's ability to metabolize coal to methane. Experiments are also underway to determine what effect amending the coal slurry with urea to stimulate biomineralization will have on methanogenesis from coal. Early results suggest that urea amendment with concentrations above 1 g/L cause the pH in microcosms to rise beyond physiologically tolerable levels for methanogenesis (pH 8). Increasing pCO₂ seems to inhibit methanogenesis as well, and this effect is not mitigated by urea amendment thus far. This work could have important implications for understanding methanogenesis in deeply buried coal seams as well as in predicting the potential effects of CO₂ injections in those coal seams in the future.

Geomechanical and petrophysical property changes due to CO₂ injection in a sandstone reservoir using an integrated geomechanics modeling approach

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The caprock integrity and fault instability aspects of CO₂ injection have been the subject of many research studies, while limited publications exist on the geomechanical and petrophysical property changes within the formation. In this study, we investigated the rock property changes caused by injection of CO₂ into a sandstone reservoir and assess the probability of induced shear failure and/or fault reactivation in our research area.

The changes in the conductivity caused by the displacement of high conductivity saline waters with low-conductivity CO₂ could be detected using electrical or electromagnetic surveys. The sonic velocity, bulk density, resistivity are also impacted by injection of CO₂ into the formation. The dipole (or when available full waveform) sonic logs are often used in calculating the geomechanical properties of the formations of interest. Hence, the sonic log data could be utilized as a surveillance tool to monitor the rock property changes at any well location in a CO₂ injected field. Due to the very limited coverage of sonic logs in our study area, we utilized resistivity and density log data and established correlations between sonic, density and resistivity logs and used these correlations to create synthetic sonic logs from which in situ stress and rock properties before and after the CO₂ injection were determined.

A 3D subsurface model was built using a coupled reservoir/geomechanical simulators to determine the in situ stress and rock property alterations. The CO₂ injection schedule from the study field was used along with the 2D seismic data, resistivity and density logs to determine the pore pressure, in situ stress magnitudes and formation mechanical properties before and after CO₂ injection. The 3D model then was implemented to investigate the possibility of any risk associated with formation failure and fault reactivation in the study area. The rock property changes predicted from the geomechanical model was compared to the changes obtained from the synthetic sonic logs. The small changes obtained from the coupled model were used to extrapolate the rock properties changes backward and forward in time to fill in the missing temporal data for the CO₂ enhanced oil recovery project and to provide a better field evaluation for future drilling and development plans.

Development of high-pressure triaxial rock core testing system simulating deep saline aquifers for geological carbon sequestration

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Deep saline aquifers are estimated to have great potential to store carbon dioxide in terms of capacity and accessibility. Reliable predictions of CO₂ injectivity, flow, and migration of CO₂ in reservoirs are of primary importance for ensuring safe injection operation and site integrity. The mobilities of CO₂ and saline water at in situ condition is an indispensable characteristic for CO₂ migration prediction. Development of remote monitoring techniques using acoustic velocity response of rock mass for CO₂ migration is also one of main technical issues. A rock core testing system capable of characterizing the relative permeabilities and acoustic wave velocity response of rock core sample has been developed. Up to 70 MPa of cell pressure is applicable to rock core samples. The injections of pore fluids are regulated by using two precision syringe pumps. The capabilities of the system are demonstrated through characterization of the CO₂- and saline water-relative permeabilities and ultrasonic wave velocity response of Berea sandstone. The relative permeabilities observed are comparable to some literature data. Investigation of the effect of CO₂ content on P-wave velocity during displacement of saline water by CO₂ shows that the P-wave velocity of sandstone core is affected by the spatial distributions of CO₂ and saline water. Analysis of CO₂ content dependency of P-wave velocity using Gassmann's equation during displacement indicates that the fluid distribution during CO₂ displacement shifts from serial piston-like displacement to a layered flow then changes to more homogenized distribution.

Material Characterization for Intermediate Scale Testing to Develop Strategies for Geologic Sequestration of CO₂

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In order to develop effective strategies for safely storing CO₂ in deep geological formations, it is necessary to understand the fundamental processes that contribute to stable entrapment in naturally heterogeneous subsurface formations. As controlled experiments to generate data at all scales of interest are not feasible to perform in the field settings, so the use of intermediate scale laboratory test systems was pursued to generate comprehensive data sets. Intermediate scale testing can be performed under well controlled conditions while offering capabilities of incorporating reasonable complexity encountered in the field. Due to the nature of the CO₂ geological sequestration where supercritical CO₂ is injected under high pressure of > 8 MPa, one of the challenges in conducting such experiments under “ambient laboratory conditions” is the selection of test fluids that can be used as surrogates for supercritical CO₂. In this study, a mixture of Glycerol-water (8:2 by weight) and Soltrol 220 was selected as the surrogate fluids based on the fluid properties such as density and viscosity. The study focuses on the methodology to identify hydraulic properties of the test sands for the above-mentioned fluids that will be used as the fundamental material properties when simulating the intermediate tank experiments.

Carbon dioxide utilization: polylactide-graft-lignin copolymers

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My research involves polylactic acid (PLA) and lignin which are both “carbon neutral” bioplastics. Polylactic acid is fermented from the dextrose from corn. Corn obviously requires carbon dioxide to fuel the photosynthesis process. Lignin is nature’s “glue” and is present in all vascular plants. Carbon dioxide is a main component for all plants to survive and thrive. The process to extract lignin doesn’t require industrial machines which would put carbon dioxide back into the environment. Both PLA and lignin are 100% renewable bioplastics. Indirectly, my research provides carbon dioxide sequestration via the process to derive the materials that are used.

My research involves investigating value-added uses of lignin in the plastics industry as well as the use of a novel solvent in the organosolv process for the removal of lignin from lignocellulosic feedstocks. Lignin removal is required in order to have a viable cellulosic stream for further bioprocessing. Lignin's physicochemical features enable its use in a variety of value-added commercial markets. As a natural adhesive, lignin consists of 15-40% of the total material in the plant cell walls. In this project value-added uses in the plastics industry are being developed and a new organosolv process for lignin removal is being investigated.

Polylactic acid has been successfully grafted with different lignins to form 100% renewable copolymers. A strong indication of the success is provided through a two-phase solubility test in toluene. The toluene soluble butyrate organosolv lignin was converted to toluene insoluble PLA-graft-lignin copolymer. The butyration was completed on both kraft lignin and organosolv lignin.

Melt blended composites between PLA and lignin were also produced. Although the Young’s modulus increased due to the addition of lignin, the impact strength of the composites decreased. This finding is at odds with the hypothesis that lignin should improve the impact properties of plastics. Microscopy studies (optical and field emission scanning electron) revealed that the lignin, independent of functionality, had agglomerated prior to the melt mixing process. Several technical strategies have been formulated, including in situ polymerization of lactic acid, that should be capable of overcoming this technical obstacle and yielding improved composite properties. By overcoming the agglomeration of the lignin via filtration and solution mixing, the hope is to see improved mechanical and thermal properties of the composites.

Two potentially high impact outcomes are possible due to this research project. First and foremost, if the novel solvent proves to be a more effective solvent for lignin removal than the existing hot ethanol organosolv process, the work is potentially revolutionary. Lignin removal is a substantive issue in biorefining of lignocellulosics. Secondly, the value-added use of lignin in the plastics industry also holds the potential to substantially alter value chains in biorefining. Plastic materials sell for upwards of \$1/lb; in many cases specialty plastics bring much higher prices. The use of lignin as a value-added modifier in the plastics industry is accordingly of potentially very high impact.

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Stochastic analysis of CO₂ sequestration in geologic formations

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A one-dimensional, liquid-gas, two-phase flow model with stochastic input parameters is analyzed, with intrinsic permeability, porosity of the formation and the parameters of capillary–water saturation relationship being the stochastic parameters. Several representative mean and standard deviation values are adopted to generate spatially variable input parameters either independently or correlatively during the numerical simulation process. Using uncertainty propagation, the simulation results are used to investigate the effects of stochastic input data on the predicted response of CO₂ injected in geological formations and to obtain probabilistic estimates of volumes of stored/injected CO₂. By providing the confidence bounds for the mean and standard values for the injecting volume ratio, this research will help bound the uncertainties arise from the heterogeneities of the geological formations.

Scale effects on the elastic behavior of fractured rock masses

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Rock masses invariably contain fractures, and the fractures occur in different length scales. Because fractures typically have different material properties compared to the surrounding intact rock, the overall mechanical characteristics of the fractured rock mass are modified and are controlled by the fracture mechanical behavior and the geometrical distributions of the fractures such as fracture lengths, spacing and orientations. Thus, understanding the effects of the fracture geometry is an important factor in the quantification of the behavior of fractured rock masses. Moreover, this understanding is made complicated by the fact that fracture geometry and mechanical behavior are strongly length scale dependent. Understanding of the scale dependency is still not fully understood. The main objective of the research described in this paper is to perform a comprehensive parametric study on the effects of fracture geometry on the elastic stress-strain behavior of fractured rock masses over a wide range of length scales. The study used a combination of Oda's elastic tensor formulation for fractured rock masses and Monte Carlo Simulation (MCS) to generate realizations of geologically realistic fracture geometries and to compute the corresponding equivalent continuum elastic compliance matrices for fractured rock masses. The influence of key descriptors of fracture parameters and their relations to fractured rock mass elastic behavior are studied and discussed. A key concept in the equivalent continuum formulation is the existence or assumption of a Representative Element Volume (REV) which is assumed to provide a representative sample of a fractured rock mass. Using the combined Oda's crack tensor and MCS, the validity of the REV assumption is extensively investigated and guidelines on how to define a proper REV for the fractured rock masses are proposed.

A fully coupled mathematical model for fluid flow and reactive solute transport during CO₂ sequestration in carbonate reservoirs

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We developed a reservoir-scale reactive transport simulator for modeling of CO₂ transport in saline aquifers coupled with geochemical reactions. This simulator is developed based on the TOUGH2 simulator with ECO2N module (Pruess, 2005). In the original TOUGH2/ECO2N program, the mass balance of three components (H₂O, CO₂, NaCl) is solved implicitly. The ECO2N module, in particular, conducts non-iterative phase equilibrium calculations to find the partition of CO₂ and H₂O between gas and aqueous phases as well as the dissolution and precipitation of the salt component. In current study, we focus on a simplified chemical reaction system that includes only CO₂, H₂O and calcite mineral. A fully coupled, non-iterative calculation procedure is formulated to simultaneously solve the phase equilibrium and chemical equilibrium of the system to obtain the partition and concentrations of chemical species. The mass gain and loss of primary chemical components caused by these geochemical reactions are dealt with by the concentration change of related secondary chemical species. The mass changes of primary chemical species are then incorporated into the simulator's mass conservation equations, which now uses H₂O, CO₂, and Ca²⁺ as primary components, allowing a full implicit solution of the reactive transport equations. One example problem (1D radial model of CO₂ injection into an aquifer with calcite mineral) is presented to show the efficacy of the new simulator.

Carbon nanotube sequestration of carbon dioxide

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Carbon nanotube-flue gas systems are simulated in order to identify the ideal size and diameters of the carbon nanotube that results in maximal separation of carbon dioxide from the other flue gas components. In addition to geometric constraints functionalization of the carbon nanotubes are explored. Functionalization with a variety of molecules, such as ionic liquids, is employed to identify the most promising functionalization molecule as it pertains to enhancing carbon dioxide separation.

One property of carbon nanotubes being investigated is the increased flow of liquids (5 times faster than predicted by classical fluid dynamics) through the nanotube in addition to the very rapid transport of ions (such as the hydrated excess proton). Of particular interest is the interface between the solvent and the carbon nanotube, such as at the mouth of the carbon nanotube, and how this interface impacts the transport of solvent, ions, and relatively large molecules. Additionally the pKa of ionizable functionalized groups that are incorporated into the carbon nanotube systems will be evaluated. To gain a greater understanding of the interface the geometry of the carbon nanotube will be modified along with the incorporation of various ionizable moieties.

Through these detailed analysis it will be possible to reveal the underlying physics while developing the necessary knowledge of these systems to allow for the engineering of viable carbon nanotube systems. Such systems would include fuel cells, filtration devices, and biomimetic channels (to name a few). An important feature of using carbon nanotubes (especially when imbedded in a phospholipid bilayers) is their use as a reduced model of biological channels. Therefore, these systems can be used to create biomimetic channels by utilizing the underlying physics that nature has tapped into in biologically relevant channels.

Simulation of carbon dioxide sequestration in ionic liquids

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This project focuses on simulating the sequestration of carbon dioxide in a variety of ionic liquids. Sequestration of carbon dioxide by ionic liquids proceeds through physisorption and is simulated using molecular dynamics. Potentials of mean force calculations for the adsorption event have revealed the critical underlying interactions that drive the favorable adsorption event. In addition to physisorption chemically modified ionic liquids are capable of chemisorption further enhancing the carbon dioxide sequestering properties. Ab initio calculations of the chemisorption event for various functional groups have revealed additional routes to increasing carbon dioxide sequestration in ionic liquids.

These projects will be evaluated utilizing both classical molecular dynamics (MD) and reactive MD. In addition to the MD simulations ab initio calculations will be used to evaluate, at a high level of theory and basis set, the interactions between IL-IL and IL-CO₂.

Brine and CO₂ leakage rates in the intermediate zone as a result of geologic sequestration

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Sequestering carbon in deep geologic formations is one way of reducing anthropogenic CO₂ emissions. Minimizing leakage rates is required for successful sequestration in order to mitigate possible negative impacts to overlying aquifers and human populations. Much work has been done on CO₂ migration within the injection zone. However, leakage rates through the caprock and subsequent movement through the intermediate zone are not known. Considering the multiple pathways for CO₂ leakage from injection formations, we propose three simplified models of CO₂ leakage: diffuse capillary transport, discrete faults, and poorly sealed well bores. The multiphase, multi-component flow and transport model PFLOTRAN was used to perform numerical simulations to gain insight into factors that control leakage rates and explore their significance. We will present results from simulations with variable CO₂ injection rates, multiphase permeability/capillary relationships, and distance from the injection point. In initial simulations of leakage through a fault zone above the injection well, most of the plume dissolves or spreads horizontally at the interface of the caprock and injection formation. However, a small fraction of the CO₂ flows through the fault zone. Breakthrough of the CO₂ into the overlying aquifer happens almost immediately after CO₂ injection begins. Leakage rates through the fault remain constant during the 10-year injection period and taper off after injection ceases. We also see countercurrent brine migration during CO₂ leakage as a result of CO₂ buoyancy.

Compositional simulation of CO₂ enhanced oil recovery

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Sequestration of CO₂ in oil reservoirs has the additional benefit of enhancing the oil recovery from those reservoirs. There are various kinds of trapping of CO₂ that are relevant for sequestration in brine or oil reservoirs; most relevant for CO₂ enhanced oil recovery are displacement trapping and solubility trapping. In oil reservoirs, the partitioning of CO₂ between the oil, vapor, and aqueous phases impacts displacement and solubility trapping. Water-alternating-gas cycles create a significant amount of trapped CO₂ via relative permeability and capillary pressure which undergo hysteresis. This means that the desaturation history is different than the saturation history leading to phase trapping. The hysteresis is a function of changes in the pressure, temperature, and composition of the phases, including the interactions between the three phases, the gain or loss of miscibility, changes in the interfacial tensions, and salinity gradients. Simulation of these effects needs to be incorporated in a successful design for an enhanced oil recovery or sequestration project.

Intermediate scale testing and modeling for improving fundamental understanding of dissolution trapping in deep geologic formations

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Carbon dioxide sequestration has gained increasing importance in recent years to decrease carbon emissions which may cause global climate changes. CO₂ sequestration in deep subsurface formations is one way to prevent the CO₂ leakage to the atmosphere by creating stable conditions for CO₂ to become immobilized through dissolution, entrapment and mineralization. Among those, dissolution is one of the more secure ways to store CO₂ in deep geologic formations because of physical properties of the dissolved CO₂.

Supercritical CO₂ is injected into the deep geological formations. After injection, supercritical CO₂ is started to migrate to the upper parts of the geologic formation because of buoyancy forces. In process of time, supercritical CO₂ starts to dissolve into brine. Because dissolved CO₂ is denser than the brine, buoyancy forces become negligible. When amount of dissolved CO₂ reaches critical point, it starts to move downward by forming fingers. This behavior triggers density dependent convective flow.

The main concern of this study is to improve the fundamental understanding of dissolution trapping in homogeneous deep geologic formations by intermediate scale testing and modeling. Small tank dissolution experiments are conducted to simulate dissolution of CO₂ in brine at laboratory conditions. Numerical model of dissolution of CO₂ is developed for the same conditions with small tank to determine the mechanisms effecting dissolution of CO₂.

Pore network changes to caprocks after carbon sequestration simulation experiments

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The caprock is the main structural trap inhibiting CO₂ leakage into overlying aquifers for the first few hundred years. Reactions on the micrometer to nanometer scale could potentially alter the pore networks, thus altering capillary properties and fluid transport properties of the caprock. It must be determined if these changes to pore networks affect the integrity of the caprock. Caprock samples were reacted with CO₂ and synthetic brine at 160°C and 150 bars to simulate geologic carbon sequestration conditions. Unreacted and reacted samples were analyzed with field emission scanning electron microscopy (FESEM) and small angle neutron scattering (SANS) to determine physical changes to pore networks in two caprock samples, the Gothic shale from the Aneth Enhanced Oil Recovery Project and the Marine Tuscaloosa shale from the Plant Daniel Saline Reservoir Project.

FESEM and SANS provided qualitative and quantitative analysis supporting changes to both of the samples pore networks. FESEM provided high resolution images supporting dissolution and precipitation of minerals in both samples with a greater occurrence of dissolution and precipitation in the Gothic shale. New circular and slit-like pores were imaged in the Gothic shale, however new pores were not evident with the FESEM in the Marine Tuscaloosa shale. SANS experiments provided information on the porosity, surface area, and pore size distribution of connected and unconnected pores in the shale samples. An increase in porosity in connected pores occurred in the Gothic shale while a decrease in porosity in connected pores occurred in the Marine Tuscaloosa shale. This combination of controlled laboratory experiments, neutron scattering and high-resolution imaging provided new detailed information on changes to pore networks of typical shales that lie above geologic carbon sequestration sites.

Carbon dioxide utilization using non-biodegradable polymers

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Carbon sequestration publications have increase exponentially over the past two decades from the need to address human induced climate change [1]. While much work for CO₂ capture and remediation is in for CO₂ storage, there is a push to make valuable products out of captured CO₂ [2]. The research being conducted in the Dorgan group works with renewably derived, non-biodegradable polymer systems that are being used in carpet industry as Nylon 6 replacement, petroleum industry as chemically resistant coatings, and the automotive industry as metal replacement materials that lower vehicle weight [3]. Polymer blending is an established and cost-effective way of developing new polymeric materials with diversified and desirable properties [4].

Nylons are a class of polymers formally known as polyamides which have a variety of uses and can be obtained from renewable resources. Polyamide 6,10 (Nylon 6,10) and Polyamide 11 (Nylon 11) having 60 and 100 weight percent, respectively, renewable content are available. Monomers for both of these polymers come from castor oil. The castor bean is not edible and grows wildly in most tropical regions [5]. Therefore the polymer sources do not compete directly with the food supply and are beneficial for the soil (through nitrogen fixation). Stoichiometric carbon capture ranges from 1.6 to 2.6 pounds of CO₂ for every pound of PA 6,10 and PA 11 respectively. There is a large price disparity between the Nylons, PA 11 at \$4.60/lb and PA 6,10 at \$2.50/lb [6]. The carpeting industry seeks greater sustainability by using renewable materials and reduction in emissions during production [7]. Accordingly, the unique combination of environmental and economic considerations makes the thermo physical properties of these Nylon blends of great interest.

Rislan rigid grade PA 11 was purchased from Arekema and Ultramid® Balance grade PA 6,10 was supplied by Dr. Scherzer from BASF SE. Blends of PA 11/PA 6,10 were prepared by melt mixing in ratios of 0/100, 25/75, 50/50, 75/25, 100/0 wt%. Before blending, material was dried to minimize hydrolysis. The blended material was ground to a pellet size, 2-3 mm. The material was then injection molded into bars for dynamical mechanical thermal analysis (DMTA), impact strength, and tensile strength. Thermal properties were measure by thermo gravimetric analysis (TGA) and differential scanning calorimetry (DSC). Morphology of blends was tested using wide and small angle x-ray scattering and microscopy.

Properties of these carbon sequestering polymers were comprehensively investigated. Melting point depression is observed from DSC runs for the PA 6,10 showing a favorable interaction between it and PA 11 in a melted amorphous state as the volume fraction of PA 6,10 decreases. This suggests the polymer blend is miscible. The glass transition temperatures are relatively close together and difficult to separate from the DSC. The Heat distortion temperature changes monotonically between homopolymer properties. Impact tests shows a greater than monotonic change in impact strength. The measured impact strength of the 0/100, 25/75, 50/50, 75/25, 100/0 blends are 43±8, 51±6, 66±6, 72±14, 70±13 J/m respectively. Young's modulus was measured for the 0/100, 25/75, 50/50, 75/25, 100/0 blends as 1.55±0.05, 1.54±0.05, 1.31±0.03, 1.20±0.02, 0.81±0.04 GPa respectively; showing greater than monotonic change with blend composition. Tensile strength and elongation to break are also greater than monotonic change with blend composition. However, DMTA shows the storage modulus changes monotonically with blend composition.

Different compositions have unique properties which allow their adoption for varying applications. The blends also decrease the cost per pound of polymer compared to PA 11 while increasing the amount of carbon captured compared to PA 6,10, thus increasing the economic viability for carbon capture.

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Exploring metal mobilization in response to CO₂-induced acidification

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Increased acidity resulting from the dissolution of CO₂ at a sequestration site may mobilize metals, with the potential consequence of contaminating underground sources of drinking water were CO₂ to leak into an overlying aquifer. In order to better understand which hazardous elements are most likely to exceed the regulatory limit set by the EPA, we performed a sequential extraction on shale caprock samples and will conduct a batch dissolution experiment on siliclastic aquifer samples. The samples were selected from ongoing CO₂ sequestration projects funded by the US Department of Energy: the Gothic, the Marine Tuscaloosa, and the Kirtland shales currently serve as caprocks at test sites for enhanced oil recovery, saline aquifers, and enhanced coalbed methane, respectively, while the Browns Park Formation is a potential drinking water aquifer overlying the proposed injection formation at the Craig CO₂ Sequestration Project near Colorado's largest single coal-fired CO₂ emissions source. Results from the sequential extraction suggest that uranium, strontium, nickel, barium and potentially chromium would be mobilized most readily. Because there was no significant difference in the partitioning patterns between the easily exchangeable phases (i.e., adsorbed), and the more recalcitrant fraction (i.e. mineral lattice), clays within an aquifer impacted by CO₂ leakage would probably respond similarly to clay caprocks. For the batch dissolution experiment, we expect to observe substantial increases in the concentration of metals, particularly uranium, arsenic, and manganese, which are naturally high in the Browns Park Formation. The rate of metal release for the siliclastic samples, however, may be slower than that for clays where desorption via surface complexation would likely be a more dominant process.

Characterizing saline formations: Implications for leakage and monitoring

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Deep saline formations are considered to be the most promising target reservoirs for geological storage of CO₂. However, competition over pore space in the saline formations, between CO₂ and native waters, will lead to pressure increases and brine displacement. The pressure wave in the saline formation is expected to propagate away from the injection well much farther and faster than extent of the plume of injected CO₂ (Zhou et al., 2010). The pressure buildup will increase the probability of brine leaking from the storage formation. To assess the hazard to overlying freshwater aquifers, the chemical properties of saline formations were characterized through statistical analysis of the NETL NatCarb brine database. Expected concentrations in brine (median and mean), as well as the overall distribution of parameters, were compared to regulatory levels in drinking-water. Brine pH was found to be a poor indicator of far-field brine leakage. The median or mean values of Cl, Fe, Mn, SO₄ and NO₃ exceeded EPA MCLs or secondary standards, yet the overall TDS in a brine-freshwater mixture is expected to be the first parameter to exceed any drinking-water regulatory level. In addition, the risk to freshwater aquifers is presented in an agricultural context, as two-thirds of groundwater withdrawals in the U.S. are for irrigation purposes (Kenny et al., 2009). Again, high TDS is expected to be the main parameter to influence crop yield. Boron concentrations in saline formations are mostly above plants tolerance levels.

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Analysis of biofuel policy and efficiency towards greenhouse gas reduction

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The use of fossil fuels for transportation represents one of the largest anthropogenic contributions to greenhouse gases (GHGs), and the need for clean, renewable, alternative fuel sources to offset this carbon output has become a global priority. It is no wonder that biofuel production has grown exponentially over the past 30 years; biofuels essentially contribute no additional GHG in their carbon life cycle and can be grown in almost any farming region in the world. The current global shift from fossil fuel to biofuel consumption could come to represent one of the largest carbon sequestration trends in human history. However, the rapid expansion of the biofuel market has generated considerable controversy in the practice: many scientific studies have revealed significant variability in the GHG reduction efficiency of different biofuel production methods in relation to fossil fuel displacement, some of which actually result in net increases of GHG emissions.

To address this controversy, this paper reviews the policies behind past and current biofuel production and analyzes the relative efficiencies of different production methods around the world. By assembling and comparing such eclectic data one can identify the primary sources of GHG emissions within the different methods, as well as which general trends in biofuel production show the greatest potential efficiency. This information will be of great assistance to any future policies that plan for a self-sufficient biofuel market with fewer government subsidies.

The results of this study showed that within the wide spectrum of variance for different methods, the greatest factors affecting GHG reduction efficiency were the type of crop grown, the subsequent amount of nitrogen fertilizer required for cultivation, and the amount and type of land converted to farmland for production. In most instances, second-generation biofuels showed clear superiority to first-generation biofuels, though current technological limitations prevent their production on a competitive scale.

Based on these conclusions, any future policies promoting biofuel production in the U.S. must include provisions to diversify the domestic market based on the most efficient crops and methods practiced in similar regions, preferably offering incentives towards responsible land and fertilizer use. Such policies must also promote the development of second-generation biofuel technology to further expand their role in the market.