NETL the ENERGY lab

Carbon Storage Newsletter

May 2015

What's Inside?

Highlights

"Energy Department Projects Reach Milestone to Safely and Permanently Store 10 Million Metric Tons of Carbon Dioxide."

A group of carbon capture and storage (CCS) projects supported by the U.S. Department of Energy (DOE) and managed by the National Energy Technology Laboratory (NETL) has reached a milestone to safely and permanently store carbon dioxide (CO_2). The milestone builds upon the goals of providing clean energy, supporting American jobs, and reducing CO_2 emissions. The projects contributing to the milestone are part of DOE's Regional Carbon Sequestration Partnership (RCSP) Initiative and the Industrial Carbon Capture and Storage (ICCS) Major Demonstrations Program. The RCSP Initiative, which consists of seven partnerships focused on determining the best regional approaches to geologic storage of CO_2, includes more than 400 organizations spanning 43 states and four Canadian provinces. The ICCS Program, which represents a $1.4 billion investment under the American Recovery and Reinvestment Act (ARRA), helps industry to demonstrate CCS technologies that can be readily replicated and commercially deployed in industrial facilities. From *Fossil Energy Techline* on April 22, 2015.

"NETL-Sponsored Study Confirms Vast Energy Resource in Residual Oil Zones."

NETL-sponsored researchers confirmed that CO_2-enhanced oil recovery (EOR) can extract oil from largely untapped areas called "residual oil zones" (ROZs). The researchers, led by the University of Texas-Permian Basin (UTPB), analyzed a geologic core taken during a pilot test from a well at the Goldsmith Landreth San Andres Unit in the Permian Basin, Ector County, Texas, USA. The results provide insight into the potential oil displacement efficiency of the CO_2-EOR process. The UTPB researchers are developing a state-of-the-art geologic model to compare past reservoir performance and current CO_2-EOR flood performance. The goal is to optimize the performance of an ROZ CO_2 flood and share the knowledge with other operators. ROZs are areas of relatively immobile oil that are found below the oil-water contact (the first observance of water) within an oil-bearing reservoir. In these zones, natural water flooding has swept away much of the original oil, leaving residual oil behind; recovery of this oil is not economic using primary or secondary oil recovery, requiring EOR techniques to produce the oil. From *NETL News Release* on February 24, 2015.

Announcements

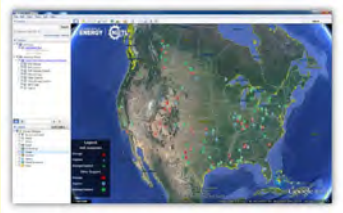
NETL Releases Updated Carbon Storage Website.

DOE's NETL released a new, user-friendly version of the Carbon Storage Program website. The site contains both introductory and in-depth information about the fundamentals of geologic carbon storage, supporting technologies, program developed publications and best practice manuals (BPMs), the status of the latest program-supported research and development (R&D) activities, and more.

Announcements (Continued)

Technical Session on Engineering Geologic CO_2 Storage Systems.

The American Institute of Chemical Engineers' (AIChE) Annual Meeting, scheduled for November 8-13, 2015, in Salt Lake City, Utah, USA, will include a technical session, titled, "Engineering Geologic Carbon Dioxide Storage Systems." Research presentations covering the science and technology of carbon storage, as well as field demonstrations of CO_2 injection, are encouraged. Conference details, abstract submission, and more information are available via the above link.



5th Version of NETL's CCS Database Now Available.

NETL's CCS Database includes active, proposed, and terminated CCS projects worldwide. The information is taken from publically available sources to provide convenient access to information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCS technology. As of November 2014, the database contained 274 CCS projects worldwide, including 69 capture, 60 storage, and 145 for capture and storage in more than 30 countries across 6 continents. While several of the projects are still in the planning and development stage, 128 are actively capturing and injecting CO_2. NETL's CCS Database is available as a Microsoft Excel spreadsheet and also as a customizable layer in Google Earth..

2015 Carbon Management Technology Conference (CMTC 2015).

This conference is scheduled for November 17-19, 2015, at the Sugar Land Marriott Town Square in Sugar Land, Texas, USA. The conference will focus on carbon capture, storage, and utilization technologies that are being performed at large scale and provide options for low greenhouse gas (GHG) emissions while maintaining fuel diversity for sustainable growth.

DOE, Shell Canada to Collaborate on CO_2 Storage.

DOE and Shell Canada announced intentions to collaborate in field tests to validate advanced monitoring, verification, accounting (MVA), and assessment technologies for underground CO_2 storage at Shell's Quest CCS project in Alberta, Canada. The test results are expected to provide additional information that would benefit future large-scale CCS projects around the world.

RGGI Report: Investments Provide $2.9 Billion in Energy Bill Savings.

The nine states of the Regional Greenhouse Gas Initiative (RGGI) released a report, titled, "Investment of RGGI Proceeds Through 2013," that tracks cumulative investments made through 2013 using proceeds from RGGI's CO_2 allowance auctions. The report estimates a return of more than $2.9 billion in lifetime energy bill savings to more than 3.7 million participating households and 17,800 businesses.

Carbon Storage in the News

"UNDEERC Enters Into $2.5 Million Cooperative Agreement with the U.S. Department of Energy."

DOE signed a cooperative agreement with the University of North Dakota's Energy & Environmental Research Center (UNDEERC) to research and develop technologies to reduce CO_2 emissions from fossil fuels. Through the Office of Fossil Energy (FE)-funded and NETL-administered collaboration, EERC will conduct research to assist industry in deploying and commercializing low-carbon technologies. Work will be performed in five task areas: (1) carbon storage R&D, (2) carbon capture R&D, (3) oil and gas R&D, (4) strategic studies, and (5) support of FE. From *U.S. Senator John Hoeven News Release* on May 11, 2015.

"Enhanced Oil Recovery Institute to be Centered in Casper."

The Wyoming Enhanced Oil Recovery Commission announced that the University of Wyoming's Enhanced Oil Recovery Institute (EORI) will center its efforts in Casper, Wyoming, USA, in order to build closer relationships with companies working to improve oil recovery within the state. EORI is part of the University of Wyoming's School of Energy Resources (SER), which focuses on solving potential energy challenges. From *University of Wyoming News Release* on April 21, 2015.

"CO_2 Injection Begins at Aquistore."

The Aquistore Project, an independent research and monitoring project focusing on demonstrating the safe underground storage of CO_2, has begun underground injection into the Deadwood and Winnipeg formations, which underlie the majority of western Canada. During the initial six-month injection period, the project is expected to inject up to 1,000 tons of CO_2 per day. Managed by the Petroleum Technology Research Center (PTRC), Aquistore is the second CO_2 project in Saskatchewan, Canada; the first was the International Energy Agency Greenhouse Gas Research and Development Program's (IEAGHG) Weyburn-Midale CO_2 Monitoring and Storage Project. The $45 million Aquistore Project was founded in 2009 and includes research institutions and industry partners who will gather, analyze, and interpret data through 2017. From *Aquistore News Release* on April 27, 2015.

Carbon Storage in the News (Continued)

"CO_2 Solutions Announces Results of Pilot Testing."

CO_2 Solutions announced the results of the pilot testing of their carbon capture process, confirming the technology can provide reduced operating costs and reduced parasitic load relative to conventional CO_2 capture processes. The testing, which was conducted at UNDEERC, was completed in January 2015. EERC led the performance evaluation of the process, and the test data were used as input for models to simulate CO_2 capture from typical coal- and gas-fired power generation plants. In order to provide a baseline, the models were based on methodology established by DOE. From *CO_2 Solutions News Release* on April 23, 2015.

"Seismos Inc. Secures $4M Funding for Flow Monitoring."

Seismos Inc. has secured $4 million in funding to track underground CO_2 flow during EOR operations. The Seismos method of fluid monitoring consists of field-installed low-impact emitters and seismic sensors connected to a cloud-based data processing platform that generates maps of CO_2 movement over time. From *Seismos, Inc. News Release* on April 8, 2015.

Science

"Arctic Beetles May be Ideal Marker of Climate Change."

According to a team of researchers from McGill University, the feeding habits of Arctic beetles may offer a basis for the future monitoring of potential climate change. While studying more than 460 different species of Arctic beetles, the researchers found that the ecological roles the beetles fulfilled differed depending on the latitude and temperature in which they lived. Published in the journal "PLOS ONE," the study was a large-scale survey of the Artic beetle population and spanned locations ranging from the edge of the boreal forest in Northern Ontario to Ellesmere Island in the far north of Canada. From *ScienceDaily* on April 22, 2015.

"Farmland Management Changes Can Boost Carbon [Storage] Rates."

Well-maintained pastures may boost carbon storage rates more quickly than previously thought, according to researchers from the University of Georgia and the University of Florida. Soil contains a large terrestrial reservoir of carbon, and tilling the fields every year to plant crops releases the soil carbon into the atmosphere. The study, titled, "Emerging land use practices rapidly increase soil organic matter," found that converting the cropland to pastureland replenishes the soil's carbon at a rate high enough that the carbon in the soil could eventually help offset a potential rise in atmospheric CO_2. The study was funded by the National Institute of Food and Agriculture and published in the journal "Nature Communications." From *UGA Today* on May 11, 2015.

Policy

"Norway and Czech Republic Establish Cooperation on CCS."

Norway and the Czech Republic have agreed to a cooperation program, titled, "Pilot Studies and Surveys on CCS Technology," that focuses on raising awareness of CCS and examining the technical and financial possibilities of deploying the technology in the Czech Republic. The program, which will receive funding from Norway, will be composed of four different projects: (1) a pilot project on CO_2 geologic storage in the Czech Republic; (2) a feasibility study of CCS pilot technologies for coal-fired power plants; (3) a project aimed at furthering research on the potential for the application of CCS under existing conditions in the Czech Republic; and (4) a project focused on knowledge sharing and awareness raising on the role of CCS as a climate mitigation tool. From *Bellona* on April 15, 2015.

"European Parliament Committee Supports Energy Security Report."

Members of the European Parliament (MEPs) from the Committee on Industry, Research, and Energy (ITRE) voted in favor of a draft report on the European Energy Security Strategy (EESS). The draft report on EESS, which addresses issues surrounding Europe's energy supply and use, climate action, and economic growth, includes two amendments concerning CCS. The first calls on the Commission to improve deployment conditions of CCS and for funding to be provided for the continued development of CCS. The second calls for funding for the Horizon 2020 Framework Program for Research and Innovation to be protected from any future cuts in order to ensure the improvement of existing CCS technologies, as well as the development of new technologies. From *Bellona* on May 11, 2015.

"An examination of geologic carbon [storage] policies in the context of [release] potential."

The following is the Abstract of this article: "Carbon dioxide (CO_2) injected into geologic reservoirs for long-term [storage], or the brine it displaces, may [release] through natural or manmade pathways. Using a [release] estimation model, [the authors] simulated fluid [release] from a storage reservoir and its migration into overlying formations. The results are discussed in the context of policies that seek to assure long-term [storage] and protect groundwater. This work is based on a case study of CO_2 injection into the Mt. Simon sandstone in the Michigan sedimentary basin, for which [the authors] constructed a simplified hydrologic representation of the geologic formations. The simulation results show that (1) CO_2 [release] can reach [a formation] containing potable water, but numerous intervening stratigraphic traps limit the rate to be orders of magnitude less than the rate of [release] from the storage reservoir; (2) [DOE] guidelines for storage permanence allow for more [release] from larger injection projects than for smaller ones; (3) well [release] permeability is the most important variable in determining [release] processes and substantial [release] requires that numerous wells [releasing] with the anomalously high permeability of $10{-}10\ m^2$; and (4) [release] can reduce the U.S. Environmental Protection Agency's Area of Review." **Jeffrey M. Bielicki, Catherine A. Peters, Jeffrey P. Fitts, and Elizabeth J. Wilson,** *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Policy (Continued)

"Long-term scenarios for reaching climate targets and energy security in UK."

The following is the Abstract of this article: "The construction and subsequent analysis of scenarios using energy systems models is an essential tool in energy policy making. This paper presents two descriptive scenarios for the development of the UK energy system to 2050, using four subsequent decadal time-slices. The two scenarios, K_Scenario and Z_Scenario, were modelled with the use of the Department of Energy and Climate Change (DECC) 2050 Pathways Calculator. K_Scenario is a scenario in which the use fossil fuels with CCS are prominent in the power sector, while Z_Scenario focuses on the development of renewables with energy storage and nuclear power. Both scenarios seek to achieve the UK's legally binding target of an 80 [percent] reduction in GHG emissions from 1990 levels by 2050. Abatement is achieved through numerous developments in each of the scenarios, including the development and use of shale gas, hydrogen, additional wind and solar deployment, the expansion of bioenergy and use of CCS. These developments must be driven by policies designed to pursue dramatic decarbonisation." **Catalina Spataru, Paul Drummond, Eleni Zafeiratou, and Mark Barrett**, *Sustainable Cities and Society*. (Subscription may be required.)

Geology

"Determination of effective stress parameters for effective CO_2 permeability in deep saline [formations]: An experimental study."

The following is the Abstract of this article: "[Potential climate change] has been a major threat to the world for many decades, and CO_2 geo-[storage] in deep saline [formations] has recently been identified as an effective solution due to its ability to greatly mitigate anthropogenic CO_2 emissions to the atmosphere. However, CO_2 [storage]-induced chemical and mineralogical reactions affect the hydro-mechanical characteristics of natural formations, resulting in limited injectability to [formations]. A detailed knowledge of the hydro-mechanical [behavior] of natural formations is therefore important to enhance the safety and effectiveness of the CO_2 storage process. Such understanding can only be gained on the basis of in-depth knowledge of the applied effective stresses on the formations. The aim of this study was therefore to understand the effect of reservoir salinity level on the effective stress parameters of deep saline [formation] rock under various in-situ conditions, including salinity levels ranging from 0 to 30 [percent] (NaCl concentration by weight) and confining pressures ranging 20–35 MPa. Tri-axial permeability tests were conducted for a range of injection pressures (1–12 MPa) under different confining pressures (20, 25, 30 and 35 MPa) at 35°C constant temperature. Comprehensive SEM (scanning electron microscopy) and acoustic emission analyses were also conducted to clarify the observed results. According to the results, the effective stress coefficient (α) for CO_2 permeability decreases with increasing [formation] salinity level, and increasing salinity level from 0 to 30 [percent] causes the effective stress coefficient to be reduced by 31 [percent]. Moreover, the Skempton coefficient (B) increases with increasing salinity level from 0 to 30 [percent] and the increment is about 18 [percent]. Interestingly, the poro-elastic coupling parameter (αB) decreases from 0.89 to 0.72 as the salinity level increases from 0 to 30 [percent] and the reduction is about 19 [percent]. The SEM analysis conducted on tested samples confirmed the deposition of NaCl crystals in rock pore space during the saturation period of one year, and these observed variations in effective stress parameters are probably due to the NaCl crystal deposition in the rock pore space. This significantly alters the rock porosity and pore geometry, causing the simple effective stress law for CO_2 permeability to be inapplicable to saline [formations]." **T.D. Rathnaweera, P.G. Ranjith, M.S.A. Perera, and S.Q. Yang**, *Journal of Natural Gas Science and Engineering*. (Subscription may be required.)

"Co-[storage] of SO_2 with supercritical CO_2 in carbonates: An experimental study of capillary trapping, relative permeability, and capillary pressure."

The following is the Abstract of this article: "In this study [the authors] performed three categories of steady- and unsteady-state core-flooding experiments to investigate capillary trapping, relative permeability, and capillary pressure, in a $scCO_2$ + SO_2/brine/limestone system at elevated temperature and pressure conditions, i.e., 60°C and 19.16 MPa. [The authors] used a Madison limestone core sample acquired from the Rock Springs Uplift in southwest Wyoming. [The authors] carried out two sets of steady-state drainage-imbibition relative permeability experiments with different initial brine saturations to study hysteresis. [The authors] found that the final $scCO_2$ + SO_2 drainage relative permeability was very low, i.e., 0.04. [The authors] also observed a rapid reduction in the $scCO_2$-rich phase imbibition relative permeability curve, which resulted in a high residual trapping. The results showed that between 62.8 [percent] and more than 76 [percent] of the initial $scCO_2$ + SO_2 at the end of drainage was trapped by capillary trapping mechanism (trapping efficiency). [The authors] found that at higher initial brine saturations, the trapping efficiency was higher. The maximum initial and residual $scCO_2$-rich phase saturations at the end of primary drainage and imbibition were 0.525 and 0.329, respectively. Each drainage-imbibition cycle was followed by a dissolution process to re-establish Sw = 1. The dissolution brine relative permeabilities for both cycles were also obtained. [The authors] characterized the $scCO_2$ + SO_2/brine capillary pressure hysteresis behavior through unsteady-state primary drainage, imbibition, and secondary drainage experiments. [The authors] observed negative imbibition capillary pressure curve indicative of possible wettability alteration throughout the experiments due to contact with $scCO_2$ + SO_2/brine fluid system. The trapping results were compared to those reported in literature for other carbonate core samples. [The authors] noticed slightly more residual trapping in [their] sample, which might be attributed to heterogeneity, different viscosity ratio, and pore-space topologies. The impact of dynamic effects, i.e., high brine flow rate imbibition tests, on trapping of the $scCO_2$-rich phase was also explored. [The authors] performed two imbibition experiments with relatively high brine flow rates. The residual $scCO_2$ saturation dropped to 0.291 and 0.262 at the end of the first and second imbibition tests, i.e., 11.5 [percent] and 20.4 [percent], respectively, compared to 0.329 under capillary-dominated regime." **Morteza Akbarabadi and Mohammed Piri**, *Advances in Water Resources*. (Subscription may be required.)

"Salt precipitation and CO_2/brine flow distribution under different injection well completions."

The following is the Abstract of this article: "[CCS] is a viable

Geology (Continued)

technology to reduce the concentration of CO_2 emitted to the atmosphere. Salt precipitation due to dry-supercritical CO_2 causes a reduction of permeability, having adverse effects on well injectivity and pressure build-up. This study evaluated the salt precipitation, brine flux patterns, and pressure build-up for two well constructions, (1) partially perforated (4 injection intervals) and (2) fully perforated throughout the target formation. Both well designs showed non-localized salt precipitation in low-k formations (5×10^{-15} and 50×10^{-15} m^2) and localized precipitation in high-k (250×10^{-15} and 500×10^{-15} m^2). It was also found that two distinct brine flux patterns occurred; under low-k conditions the brine flux was outward and parallel to CO_2 migration and precipitation became limited. While under high-k conditions there developed back-flow of the brine which amplified salt precipitation. When this process occurred, the permeability reduction was orders of magnitude greater than when non-localized salt precipitation occurred. This reduction resulted in pressure build-up near the well in regions of the reservoir in which it occurred. Optimal injection conditions were found to be in reservoirs of mid-range permeability; which allowed for adequate pressure dissipation and minimized salt precipitation." **Ethan Guyant, Weon Shik Han, Kue-Young Kim, Myong-Ho Park, and Byoung-Yeop Kim**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"Factors controlling permeability of cataclastic deformation bands and faults in porous sandstone reservoirs."

The following is the Abstract of this article: "Improving the prediction of sub-seismic structures and their petrophysical properties is essential for realistic characterization of deformed sandstone reservoirs. In the present paper, [the authors] describe permeability contrasts induced by cataclastic deformation bands and faults in porous sandstones (766 data synthesized from field examples and the literature). [The authors] also discuss the influence of several factors, including tectonic regime, presence of a fault, burial depth, host sandstone porosity, and grain size and sorting for their initiation and permeability. This analysis confirms that permeability decrease is as a function of grain-crushing intensity in bands. Permeability reduction ranges from very limited in crush-microbreccia of compaction bands to high permeability reduction in cataclasites and ultracataclasites of shear-dominated bands, band clusters and faults. Tectonic regime, and especially normal-fault regime, with its tendency to localize strain and generate faults, is identified as the most important factor, leading to the formation of cataclastic bands with high permeability contrasts. Moreover, moderate burial depth (1 – 3 km) favors cataclastic bands with high permeability contrasts with respect to the host sandstone. High porosity, coarse-grain size and good grain sorting can slightly amplify the permeability reductions recorded in bands." **Gregory Ballas, Haakon Fossen, and Roger Soliva**, *Journal of Structural Geology*. (Subscription may be required.)

Technology

"SECARB CO_2 Injection Test in Mature Coalbed Methane Reservoirs of the Black Warrior Basin, Blue Creek Field, Alabama."

The following is the Abstract of this article: "The [Southeast Regional Carbon Sequestration Partnership (SECARB)] Black Warrior field verification test employed a diverse suite of well testing and monitoring procedures designed to determine the injectivity, capacity, heterogeneity, and performance of mature coalbed methane reservoirs. A total of 3,250 bbl of water and 252 t of CO_2 were injected into coal in a battery of slug tests. These tests demonstrate that significant injectivity exists in Black Warrior coalbed methane reservoirs and that reservoir heterogeneity is a critical factor to consider when implementing CO_2 [storage] and CO_2-enhanced recovery programs. The primary test well produces coalbed methane at wellhead pressures just above atmospheric, and yet desorption testing indicates that less than 20 [percent] of the original gas in place has been recovered by primary production. Injection of CO_2 was conducted at sustained rates of about 90 t/d of CO_2. Reservoir pressure declined exponentially following the emplacement of each CO_2 slug. Slug and pressure-buildup tests verify that permeability decreases exponentially with depth and also decreased during injection. Monitoring operations included multi-zone pressure logging and gas sampling in deep observation wells and groundwater sampling in a shallow observation well. Results indicate that significant permeability anisotropy exists in each coal group. In the Black Creek coal, pressure response was greatest in the dominant natural fracture direction. In the Pratt coal group, pressure response was dominated by hydrofractures. [Carbon dioxide] broke through to the observation wells only in the Pratt coal group and only along the major fracture directions. No significant flow of CO_2 out of zone was detected, and no impact on shallow groundwater resources was identified." **Jack C. Pashin, Peter E. Clark, Marcella R. McIntyre-Redden, Richard E. Carroll, Richard A. Esposito, Anne Y. Oudinot, and George J. Koperna, Jr.**, *International Journal of Coal Geology*. (Subscription may be required.)

"Quantification of CO_2 masses trapped through free convection process in isothermal brine saturated reservoir."

The following is the Abstract of this article: "Dissolution trapping of supercritical CO_2 into formation brine has been investigated as a potential mechanism for reducing buoyancy force in carbon storage formations. This study attempts to quantify how much CO_2 can be stored through dissolution trapping assuming the free-phase CO_2 will be dissolved continuously on the top of perturbed brine phase. Most former investigations focused on physical explanations of density-driven free convection instability. [The authors'] aim is to compute the amount of CO_2 (by mass) captured by dissolution trapping until the model reservoir reaches steady state. The numerical experimentation is done using dimensionless mass and momentum conservation laws. The major problem parameter here is the Rayleigh number, for which [the authors] carry out an extensive survey to find out its low and high ends based on field and observed data from the literature and in-house database. Because density difference is the main driving force, [the authors] also investigate the effects of impurities retained in CO_2 stream on density contrast. [The authors] study both homogeneous and heterogeneous reservoirs. Also, different boundary conditions (Neumann, Dirichlet, and periodic) are compared to understand their effects. The simulations are run until nearly complete saturation (-99 [percent]) is reached. For a test case (T = 40°C, P = 50 bar) of geologic and thermophysical conditions, [the authors] have found that on average 0.33–15 g CO_2 will dissolve per year until a heterogeneous unit reservoir volume of 1 m^3 reaches complete saturations. For the case of homogeneous reservoir this

Technology (Continued)

amount is 0.28–6 g." **Akand Islam and Alexander Y. Sun**, *International Journal of Heat and Mass Transfer*. (Subscription may be required.)

"Monitoring CO_2 gas-phase migration in a shallow sand [formation] using cross-borehole ground penetrating radar."

The following is the Abstract of this article: "Understanding potential pathways of gaseous CO_2 into and through the shallow subsurface from deep geological storage is one of many requirements related to risk assessment of a CCS site. In this study, a series of field experiments were carried out at a site located in Vrøgum in western Denmark. Up to 45 kg of gaseous CO_2 was injected into a shallow [formation] approximately 8 m below the groundwater table. In the upper 6 m, the [formation] consisted of fine Aeolian sand underlain by coarser glacial sand. The migration of the gaseous CO_2 was tracked using cross-borehole ground penetrating radar (GPR). A total of six GPR-boreholes were installed around the injection well and in the dominant flow direction of the groundwater. The GPR measurements were collected before, during, and after the CO_2-injection. The GPR method proved to be very sensitive to desaturation of the [formation] when gaseous CO_2 evolved and the method was thus useful for mapping the migration of the CO_2 gas plume. The experimental results demonstrated that the migration of the gas plume was highly irregular. Initially, the gaseous CO_2 migrated upwards due to buoyancy effects and subsequently it moved laterally and transversely to the groundwater flow direction. As the injection continued, the main flow direction of the gaseous CO_2 shifted and CO_2 gas pockets with a gas saturation of up to 0.3 formed below lower-permeable sand layers. [Carbon dioxide] gas was detected in a GPR-panel 5 m away from the injection point after 21 h. The GPR measurements showed that CO_2 gas never penetrated the fine Aeolian sand at 6 m depth and that the gas saturation appeared to become constant in the survey area after less than 24 h of CO_2 injection. The results of the experiments have emphasized that lateral spreading is of significance in case of [release] from a CCS site, and that even small changes in the formation texture can create barriers for the CO_2 migration." **R.N. Lassen, T.O. Sonnenborg, K.H. Jensen, and M.C. Looms**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"An investigation into the integrity of wellbore cement in CO_2 storage wells: Core flooding experiments and simulations."

The following is the Abstract of this article: "An important issue for geological storage of CO_2 is the potential for wellbore cements to degrade in contact with the acidic formation waters resulting from CO_2 dissolution. Cement degradation is a two stage process; cement carbonation occurs as various cement phases react to form calcium carbonate. The key second stage is the potential for erosion of the cement as this calcium carbonate dissolves into the formation water. For significant erosion to occur there would need to be a flow of water, under-saturated in calcium and carbonate ions, across the cement to remove dissolved calcium carbonate. This paper, presents a program of work that investigates cement degradation at the cement-formation interface. Two core flooding experiments were conducted at pressures and temperatures representative of storage conditions using composite cement–sandstone core plugs using CO_2 saturated waters with chemistries representative of formation waters. The relatively high permeability of the sandstone allowed sufficient water flow rates for regular water samples to be collected and the chemistry [analyzed]. As the sandstone simply provided a flow path for water, and did not impart any substantial chemical effect, the observations are applicable to a range of situations involving water flow in contact with cement. As the experiments, were structured such that the inflow water flowed across the cement plug surface before passing through the sandstone, each experiment provided two sets of observations with significantly different water flow velocities and chemistries. The measurements of water chemistry were combined with the flow rate observations to calculate the cumulative dissolution of the calcium carbonate and thus estimate the erosion of the cement. This compared well with direct estimates of the volume eroded by the flow across the cement plug surface. Using μXRD it was found that where the cement came into contact with the water it reacted to form calcium carbonate with none of the original cement phases detected. The erosion rate of the cement, when normalized by the water flow rate, had a clear relationship with respect to the difference between the inflow and outflow calcium concentrations. An empirical relationship was used to fit this data, thus providing a mathematical description of the cement erosion rate with respect to water flow velocity and the calcium solubility deficit. This was applied in a simulation model to a series of hypothetical case studies to investigate cement erosion at the cement-formation interface of a well, where there was an initial flow channel, across the geological seal in a CO_2 storage formation." **L. Connell, David Down, Meng Lu, David Hay, and Deasy Heryanto**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Terrestrial

"CO_2 emissions from a forest soil as influenced by amendments of different crop straws: Implications for priming effects."

The following is the Abstract of this article: "In this study, the effects of crop straw amendments on CO_2 emissions from a forest soil were investigated by using a 22-day incubation experiment. Five types of crop straw (winter wheat, rice, maize, soybean, and peanut) were used in the experiment and the soil without straw added was control (CK). There were three levels (0.6, 1.2, and 2.4 g) for each straw type. Soil CO_2 emission rates were measured 1, 2, 4, 6, 8, 11, 15, 18, and 22 days after the crop straw amendments by using an infra-red gas analyzer. Results showed that the basal soil CO_2 emission, i.e. soil organic carbon (SOC) mineralization in CK, was significantly ($P < 0.01$) lower than the CO_2 emission from straw-amended soils. Given a specific straw type, soil CO_2 emission was significantly and positively correlated with the amount of straw inputs, yielding the coefficient of determination (R^2) ranging from 0.9988 ($P = 0.022$) to 1.0000 ($P < 0.001$). The decomposition coefficients, i.e. the slopes of the linear function, of winter wheat, rice, maize, soybean, and peanut straws, were 0.275 ± 0.003, 0.593 ± 0.018, 0.895 ± 0.031, 0.890 ± 0.000, and 1.344 ± 0.039 mg g^{-1} per gram straw, respectively. Winter wheat straw amendment induced an about [two]-fold increase of basal soil CO_2 emission, showing a positive net priming effect (PE). Further investigation indicated that a semi-empirical model based on urease activity, DOC content, and pH could explain 94.5 [percent] ($R^2 = 0.945$) variations in soil CO_2 emissions. This study supports strong vulnerability of SOC in forest in particular under the scenario of changes in land use and agricultural straw

Terrestrial (Continued)

management practice." **Shutao Chen, Yuanyuan Wang, Zhenghua Hu, and Hui Gao**, *CATENA*. (Subscription may be required.)

Trading

"EU Agrees to Overhaul Carbon-Trading System."

The European Union (EU) has agreed to create a stabilization mechanism for the EU Emissions Trading System (EUETS) in order to raise the cost of releasing CO_2 into the atmosphere and encourage the investment in low-carbon technologies. Since the world's first carbon market was established in 2005, the cost of emitting CO_2 has dropped from a high of approximately $34 per ton to less than $9 per ton. Analysts estimate that there are approximately 2 billion excess CO_2 allowances in the carbon market. National EU governments and European Parliament will create a "market stability reserve" from 2019 to act as a "central bank" that has the ability to remove the surplus of allowances. From *The Wall Street Journal* on May 5, 2015.

"Ontario to Sign Cap-and-Trade Agreement with Quebec to Cut Carbon Emissions."

Officials announced that Ontario will sign an agreement to join Quebec in a cap-and-trade system to reduce GHG emissions, with the long-term plan of joining the largest cap-and-trade market, the Western Climate Initiative (WCI). Proceeds from the carbon market will be reinvested in projects to help reduce GHG emissions. Quebec, which currently operates its cap-and-trade system with California, has auctioned off nearly $190 million worth of credits since it was implemented in early 2015. From *CBC News* on April 10, 2015.

"Estimating the public's value of implementing the CO_2 emissions trading scheme in Korea."

The following is the Abstract of this article: "The Korean government set out the CO_2 emissions reduction target as 30 [percent] below business-as-usual by 2020. The CO_2 emissions trading scheme (ETS) was initiated in January 2015 to meet this target. [The authors] attempt to estimate the public's value of implementing the ETS for CO_2 emissions reduction. [The authors] apply the contingent valuation (CV) method using the willingness to pay (WTP) data obtained from a national CV survey of 1000 randomly selected households. The survey was conducted via in-person interviews. Value judgments required of the respondents were within their abilities. The mean WTP to achieve the stated target of CO_2 emissions reduction using ETS is estimated to be KRW 1873 (USD 1.66) per household per month, which is statistically significant at the [one percent] level. The aggregate national value amounts to KRW 409.2 billion (USD 363.4 million) per year. Thus, even though Korea has no obligations to cut emissions under the Kyoto protocol, the public is willing to bear a financial burden to implement the ETS. If its cost is less than this value, implementing the ETS can be socially profitable. The results of this study can serve as a basis for further policy discussions and decisions." **Tae-Ho Song, Kyoung-Min Lim, and Seung-Hoon Yoo**, *Energy Policy*. (Subscription may be required.)

Recent Publications

"CO_2 Capture and Storage in Portugal: A bridge to a low carbon economy."

The following is the Executive Summary of this document: "Aiming to tackle climate change, several countries and regions have been setting mitigation targets, and defining GHG reduction policies and measures, mostly linked with their energy supply, transport and industry. EU vowed to cut 40 [percent] its GHG emissions by 2030 relative to 1990 levels, and perspectives to cut 80 [percent] by 2050, which requires a diverse portfolio of clean technologies, including CCS. This report evaluates the role the CCS technology may play in the Portuguese energy and industry system as a mitigation option to achieve deep GHG emissions reduction. The cost-effectiveness conditions for its deployment, and the risks and additional benefits it may provide for economic development are also [analyzed]. Results show that under a high socio-economic development and -80 [percent] GHG reduction target, CCS technology is deployed as cost-effective technology from 2030, and by 2050 captures more than 20 [percent] of the total GHG emitted in that year compared to a Reference scenario. Power sector and cement production are the only sectors in which CO_2 captured technology is installed and onshore being the primary option for CO_2 storage. Under all mitigation scenarios modelled, CCS is deployed in significant volumes in the cement sector. Given the availability of renewables generation in Portugal, deployment of CCS in the power sector is relatively low and varies significantly depending on the scenario examined. With high socio-economic development and -80 [percent] GHG reduction target, CCS in power sector is only deployed in significant volumes by 2050. With more modest emissions reduction targets (i.e. 60 [percent] rather than 80 [percent] of emissions reductions by 2050) and with high fossil fuel prices, there are negligible amounts of CO_2 captured in the power sector. The difference in the total energy system costs (including supply and demand side, such as industry) between the scenarios with and without CCS, indicate that for all the scenarios, in the long term, earnings surpass costs. The higher the need for abatement, the more significant are the economic benefits of CCS, revealing that alternative mitigation technologies can be more expensive. Under the same climate change policy mitigation scenario, for example, the price of electricity production in 2050 without the availability of CCS will be significantly higher (more than three times) than a scenario where the technology is available."

Legislative Activity

"Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America."

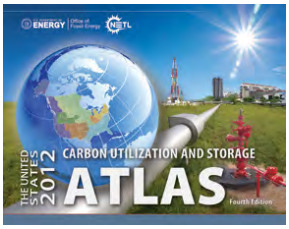
California's Governor issued an executive order to establish a California GHG reduction target of 40 percent below 1990 levels by 2030, making it possible to reach the ultimate goal of reducing emissions 80 percent below 1990 levels by 2050. The state is currently on track to meet or exceed the current target established in California's Global Warming Solutions Act of 2006 (AB 32) of reducing GHG emissions to 1990 levels by 2020. In addition, the executive order also specifically addresses the need for climate adaption and directs the state government to, among other things, incorporate climate change impacts into its infrastructure plan; update the state's climate adaption strategy to identify how potential climate change could affect the state's infrastructure and industry; factor potential climate change into state agencies' planning and investment decisions; and implement measures under existing agency and departmental authority to reduce GHG emissions. From *Office of Governor Edmund G. Brown Press Release* on April 29, 2015.

About DOE's Carbon Storage Program

The Carbon Storage Program is implemented by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory. The program is developing technologies to capture, separate, and store CO_2 in order to reduce greenhouse gas emissions without adversely influencing energy use or hindering economic growth. NETL envisions having a technology portfolio of safe, cost-effective, carbon dioxide capture, transport, and storage technologies that will be available for commercial deployment.

The Carbon Storage Program Overview webpage provides detailed information of the program's structure as well as links to the webpages that summarize the program's key elements.

Carbon Storage Program Resources



The U.S. Department of Energy's 2012 United States Carbon Utilization and Storage Atlas (Atlas IV) shows that the United States has at least 2,400 billion metric tons of potential carbon dioxide storage resource in saline formations, oil and gas reservoirs, and unmineable coal. Data from Atlas IV is available via the National Carbon Sequestration Database and Geographic Information System (NATCARB), which is a geographic information system-based tool developed to provide a view of carbon capture and storage potential.

Newsletters, program fact sheets, best practices manuals, roadmaps, educational resources, presentations, and more are available via the Carbon Storage Reference Shelf.

Get answers to your carbon capture and storage questions at NETL's Frequently Asked Questions webpage.

There are several ways to join the conversation and connect with NETL's Carbon Storage Program:

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About NETL's Carbon Storage Newsletter

Compiled by the National Energy Technology Laboratory, this newsletter is a monthly summary of public and private sector carbon storage news from around the world. The article titles are links to the full text for those who would like to read more.

National Energy Technology Laboratory

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