NETL the ENERGY lab

March 2015

Carbon Storage Newsletter

What's Inside?

Highlights

"Energy Department Project Captures and Stores One Million Metric Tons of Carbon."

The U.S. Department of Energy (DOE) announced that the Midwest Geological Sequestration Consortium's (MGSC) Illinois Basin-Decatur Project successfully captured and stored 1 million metric tons of carbon dioxide (CO_2) and injected it into a saline formation. The CO_2 is captured from the Archer Daniels Midland Company ethanol-production facility in Decatur, Illinois, and is compressed before transport by pipeline and subsequent injection approximately 7,000 feet below the surface into the Mount Simon Sandstone formation. Since initiation in November 2011, the injection has sustained pressure increases below regulatory limits. The injected CO_2 is projected to remain hundreds of feet below a 300-foot thick shale formation that acts as a seal to inhibit CO_2 migration. The project is part of DOE's Regional Carbon Sequestration Partnerships (RCSP) Initiative, which is developing and deploying carbon capture and storage (CCS) technologies across the United States. MGSC, led by the Illinois State Geological Survey, is evaluating CCS options for the 60,000-square-mile Illinois Basin, which underlies most of Illinois, southwestern Indiana, and western Kentucky. From *NETL News Release* on January 8, 2015.

"Department of Energy, 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 technologies under consideration would be tested alongside the state-of-the-art, comprehensive monitoring program Shell has already put in place for the Quest project, which is funded by the Government of Canada and the Canadian Province of Alberta. The test results are expected to provide additional information that would benefit future large-scale CCS projects around the world. DOE is leveraging a Federal investment of approximately $3 million in existing and ongoing projects in their research and development (R&D) program by proposing roughly $500,000 for this collaborative effort. From *NETL News Release* on February 4, 2015.

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

National Energy Technology Laboratory (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

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.

NETL Enhanced Oil Recovery Planning Software.

NITEC LLC developed new software under a cooperative agreement with NETL, called COZView/COZSim, that enables quicker, more affordable technical studies of CO_2-EOR for small- to mid-sized U.S. oilfield operators. The NETL-funded version of the software can be downloaded from the NITEC LLC website free of charge.

Novel Carbon Capture Solvent Begins Pilot-Scale Testing for Emissions Control.

Pilot-scale testing of an advanced technology for capturing CO_2 from flue gas has begun at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama, USA. Under a cooperative agreement with the DOE/NETL, Linde LLC is operating a nominal 1-megawatt-electric pilot plant expected to capture 30 tons of CO_2 per day. The testing will validate performance of the Linde-BASF CO_2 capture technology on actual coal-derived flue gas. The test program consists of three phases: initial start-up and operation with flue gas and solvent recirculation, parametric testing, and long-duration testing for a minimum of 60 days. Following pilot testing, Linde and BASF will pursue opportunities for larger-scale testing.

New Membrane Technology for Post-Combustion Carbon Capture Begins Pilot-Scale Test.

A DOE-sponsored technology for economically capturing 90 percent of the CO_2 emitted from a coal-burning power plant has begun pilot-scale testing. The PolarisTM membrane system, developed by Membrane Technology and Research Inc. (MTR), uses a specially designed CO_2-selective membrane (a microporous film that acts as a semi-permeable barrier) to separate CO_2 from other gases in a coal-burning plant's flue gas.

Carbon Storage in the News

From *Carbon Management Canada News Release* on February 12, 2015

"Federal Government Invests $4.9 Million in Field Research Station."

The Canadian government announced that it will invest $4.9 million to fund a Carbon Management Canada (CMC) Research Institute project that aims to accelerate the development and deployment of technologies that monitor and verify CO_2 storage. Expected to be completed in early 2016, the field research station (FRS) will inject small volumes of CO_2 at an intermediate depth, simulating release into a subcritical geologic horizon. It is anticipated that the project will help to lower the cost of CCS projects and aid in the acceleration of commercialization opportunities in international markets. Since 2008, the Government of Canada has committed more than $580 million to CCS research, development, and demonstration (RD&D) initiatives.

"CO_2 Solutions Provides Update on Carbon Capture Project."

CO_2 Solutions, Inc. announced that the procurement of components for the pilot plant at Husky Energy's Pikes Peak South site in Saskatchewan is now complete and construction has begun. The pilot unit will be constructed and tested onsite in the Montreal, Canada, area before being transported to Saskatchewan, Canada. The project is currently on schedule and within budget; installation and commissioning at the site is anticipated for the second quarter of 2015, with operation planned through September 2015, representing more than 2,500 hours of field operation. The project is funded, in part, by the Government of Canada's ecoENERGY Innovation Initiative (ecoEII) Program. From *CO_2 Solutions News Release* on February 3, 2015.

Carbon Storage in the News (Continued)

"UK Member Joins International CCS Test Centre Network."

The U.K. CCS Research Center's (UKCCSRC) Pilot-Scale Advanced Capture Technology (PACT) facilities have joined the Technology Centre Mongstad (TCM)-founded CCS Test Center Network. The purpose of PACT, which is jointly funded by the U.K. Department of Energy and Climate Change (DECC) and the Engineering and Physical Sciences Research Council (EPSRC), is to support industrial and academic R&D by providing testing facilities to accelerate the development and commercialization of technologies for carbon capture and clean power generation. Initiated by TCM in 2012, the International Test Center Network provides a platform for carbon capture test facilities around the world to progress technologies and share knowledge. From *Carbon Capture Journal* on February 24, 2015.

"CCS Performance Data Exceeding Expectations at World-First Boundary Dam Power Station Unit #3."

SaskPower released the preliminary performance numbers for the operation of Unit #3 at the Boundary Dam Power Station (BD3). The coal-fired, CCS technology-equipped commercial power plant now has more than 130 days of commercial operating experience. SaskPower has invested approximately $1.2 billion in the BD3 CCS project, with the Canadian government contributing an additional $240 million. Since its official launch on October 2, 2014, the plant has captured approximately 135,000 metric tons of CO_2; the plant has the capacity to capture up to 1 million metric tons of CO_2 in 2015, and is currently on pace to meet that goal. From *SaskPower CCS News Release* on February 11, 2015.

Science

"Global Warming Could Increase Risk of U.S. Megadroughts."

According to a new study, droughts in the southwest and Central Plains of the United States during the second half of the 21st century could be longer and drier than those in the same regions during the last millennium. A team of scientists from the NASA Goddard Institute for Space Studies and the Lamont-Doherty Earth Observatory claim that the severity of the drought would surpass any of the decades-long "megadroughts" that occurred much earlier during the past millennium. The research article, titled "Unprecedented 21st century drought risk in the American Southwest and Central Plains" and published in the journal "Science Advances," is based on projections from several climate models and is the first to state that such drying could exceed conditions of the past. Researchers used data from the North American Drought Atlas to represent past climates, applying three different measures for droughts – two soil measurements at various depths and a measurement that gauges the net input of water into the land. They also compared two different potential climate change scenarios: a business-as-usual scenario (projecting a continued rise in greenhouse gas [GHG] emissions) and a scenario in which emissions are moderated. From *Sci-News.com* on February 13, 2015.

Policy

"Nations Agree Draft Text for Deal to Fight Climate Change."

Government delegates from nearly 200 countries have agreed to a draft text for a deal to address potential climate change. The draft will be used as the basis for negotiations later in 2015. The United Nations required negotiators to agree on official text six months prior to the December 2015 United National Climate Change Conference in Paris, France. From *Reuters* on February 13, 2015.

"Swiss to Reduce Greenhouse Gas Emissions."

Switzerland's environment ministry unveiled plans to reduce GHG emissions by 50 percent by 2030 in relation to 1990 levels, with a minimum of 30 percent being achieved domestically. Originally approved by the Federal Council in November 2014, Switzerland will officially announce its commitment at the United Nations Framework Convention on Climate Change (UNFCCC), ahead of the December 2015 United Nations Climate Change Conference in Paris, France. According to a statement released by the environment ministry, Switzerland was responsible for 0.1 percent of global GHG emissions. From *swissinfo.ch* on February 27, 2015.

"Host community compensation in a carbon dioxide capture and storage (CCS) context: Comparing the preferences of Dutch citizens and local government authorities."

The following is the Abstract of this article: "The prospect of negative local impacts in combination with the absence of local benefits can be a reason for people to oppose plans for the siting of a CCS project in their community. Local public opposition may be reduced by implementing compensation measures that redress the balance between perceived local costs and benefits. Here, [the authors] examine evaluations and relative preferences of Dutch citizens and local government authorities (LGAs) concerning five different types of compensation measures. The results of a survey experiment show that citizens and LGAs were equally (and most) positive about the establishment of a fund for the compensation of damage or other negative local impacts associated with nearby CCS activities. They differed in how they judged the other measures though: Citizens were more positive about compensation in the form of measures to improve the local economy, monetary payments to individual households, and improvements to local recreational amenities; LGAs were more positive about a grant to local government. Citizens assumed that LGAs would be more positive about four of the five compensation measures than they actually were, whereas LGAs performed well in estimating the judgments of citizens. Implications for compensation policy are discussed." **Bart W. Terwel and Emma ter Mors**, *Environmental Science & Policy*. (Subscription may be required.)

Geology

"Experimental investigation of trace element dissolution in formation water in the presence of supercritical CO_2 fluid for a potential geological storage site of CO_2 in Taiwan."

Geology (Continued)

The following is the Abstract of this article: "The Pliocene Yutengping Sandstone (depth 1642–1882 m) and its overlying caprock shale (depth 1395–1642 m) in Hsinchu City, central Taiwan, were intended for a storage site of CO_2. Formation water was collected from a gas well located at a depth of 1827–1846 m. This study investigated changes in water chemistry and dissolution of trace elements from the sandstone and shale at 25 MPa and 90°C in the presence and absence of supercritical CO_2 ($scCO_2$) over [seven] days. The results showed substantial dissolution of V, Cr, Co, Cu, and Rb from the sandstone and shale into formation water in the presence of $scCO_2$ fluid, while the release of Zn, Se, Mo, and Cd from the sandstone and shale was minimal. Desorption of V, Cr, Mn, Fe, Sr, and Ba was more pronounced from the sandstone than from shale, whereas Co, Ni, Cu, As, and Mo desorbed more from the shale. The concentration of As in formation water increased from 1.4 µg/L to 130 µg/L after in contact with $scCO_2$. Such a high As concentration may present a significant threat to shallow groundwater quality in this region, particularly if [release] along faults and rock fractures in the region occurred." **Jiin-Shuh Jean, Chien-Lih Wang, Hsing-I. Hsiang, Zhaohui Li, Huai-Jen Yang, Wei-Teh Jiang, Kenn-Ming Yang, and Jochen Bundschuh**, *Journal of Natural Gas Science and Engineering*. (Subscription may be required.)

"Efficiently Engineering Pore-Scale Processes: The Role of Force Dominance and Topology during Nonwetting Phase Trapping in Porous Media."

The following is the Abstract of this article: "[The authors] investigate trapping of a nonwetting (NW) phase, air, within Bentheimer sandstone cores during drainage-imbibition flow experiments, as quantified on a three dimensional (3D) pore-scale basis via x-ray computed microtomography (x-ray CMT). The wetting (W) fluid in these experiments was deionized water doped with potassium iodide (1:6 by weight). [The authors] interpret these experiments based on the capillary-viscosity-gravity force dominance exhibited by the Bentheimer-air-brine system and compare to a wide range of previous drainage-imbibition experiments in different media and with different fluids. From this analysis, [the authors] conclude that viscous and capillary forces dominate in the Bentheimer-air-brine system as well as in the Bentheimer-supercritical CO_2-brine system. In addition, [the authors] further develop the relationship between initial (post-drainage) NW phase connectivity and residual (post-imbibition) trapped NW phase saturation, while also taking into account initial NW phase saturation and imbibition capillary number. [The authors] quantify NW phase connectivity via a topological measure as well as by a statistical percolation metric. These metrics are evaluated for their utility and appropriateness in quantifying NW phase connectivity within porous media. Here, [the authors] find that there is a linear relationship between initial NW phase connectivity (as quantified by the normalized Euler number) and capillary trapping efficiency; for a given imbibition capillary number, capillary trapping efficiency (residual NW phase saturation normalized by initial NW phase saturation) can decrease by up to 60 [percent] as initial NW phase connectivity increases from low connectivity to high connectivity. [The authors] propose that multiphase fluid-porous medium systems can be efficiently engineered to achieve a desired residual state (optimal NW phase saturation) by considering the dominant forces at play in the system along with the impacts of NW phase topology within the porous media, and [the authors] illustrate these concepts by considering supercritical CO_2 [storage] scenarios." **Anna L. Herring, Linnéa Andersson, Steffen Schlüter, Adrian Sheppard, and Dorthe Wildenschild,** *Advances in Water Resources*. (Subscription may be required.)

"Sedimentary reservoir oxidation during geologic CO_2 sequestration."

The following is the Abstract of this article: "Injection of [CO_2] into subsurface geologic reservoirs during geologic carbon [storage] (GCS) introduces an oxidizing supercritical CO_2 phase into a subsurface geologic environment that is typically reducing. The resulting redox disequilibrium provides the chemical potential for the reduction of CO_2 to lower free energy organic species. However, redox reactions involving carbon typically require the presence of a catalyst. Iron oxide minerals, including magnetite, are known to catalyze oxidation and reduction reactions of C-bearing species. If the redox conditions in the reservoir are modified by redox transformations involving CO_2, such changes could also affect mineral stability, leading to dissolution and precipitation reactions and alteration of the long-term fate of CO_2 in GCS reservoirs. [The authors] present experimental evidence that reservoirs with reducing redox conditions are favorable environments for the relatively rapid abiotic reduction of CO_2 to organic molecules. In these experiments, an aqueous suspension of magnetite nanoparticles was reacted with supercritical CO_2 under pressure and temperature conditions relevant to GCS in sedimentary reservoirs (95-210°C and ~100 bars of CO_2). Hydrogen production was observed in several experiments, likely caused by Fe(II) oxidation either at the surface of magnetite or in the aqueous phase. Heating of the Fe(II)-rich system resulted in elevated $_PH_2$ and conditions favorable for the reduction of CO_2 to acetic acid. Implications of these results for the long-term fate of CO_2 in field-scale systems were explored using reaction path modeling of CO_2 injection into reservoirs containing Fe(II)-bearing primary silicate minerals, with kinetic parameters for CO_2 reduction obtained experimentally. The results of these calculations suggest that the reaction of CO_2 with reservoir constituents will occur in two primary stages (1) equilibration of CO_2 with organic acids resulting in mineral-fluid disequilibrium, and (2) gradual dissolution of primary minerals promoting significant CO_2 reduction through the release of Fe(II). The reduction of CO_2 is identified as a new trapping mechanism that could significantly enhance the long-term stability of GCS reservoirs. Identification of reservoir characteristics that promote CO_2 redox transformations could be used as an additional factor in screening geologic reservoirs for GCS." **Laura N. Lammers, Gordon E. Brown, Dennis K. Bird, Randal B. Thomas, Natalie C. Johnson, Robert J. Rosenbauer, and Katherine Maher**, *Geochemica et Cosmochimica Acta*. (Subscription may be required.)

"CO_2 geological storage in olivine rich basaltic aquifers: New insights from reactive-percolation experiments."

The following is the Abstract of this article: "To test the impact of fluid flow on the reactivity of porous (ultra-)mafic rocks, reactive percolation experiments were realized during which CO_2-enriched water was injected at two different injection rates (Q = 0.1 and 1 mL h^{-1}) through sintered analogues of olivine-accumulation zones in basaltic flows at temperature and fluid composition conditions (T = 180°C; $NaHCO_3$ buffered solution) favorable for

Geology (Continued)

CO_2-mineralization (carbonation). All experiments resulted in silicate dissolution, carbonate precipitation upstream and (proto-)serpentine formation downstream indicating a decrease in the fluid reactivity along flow paths. The measured bulk carbonation rates ranged from 4 to 7×10^{-8} s^{-1}; these values were significantly lower than previously published values of olivine carbonation rate obtained on powders in closed batch and flow-through reactors. [The authors'] study show complex couplings, at pore scale, between fluid flow, localization of reaction zones, and chemical reaction kinetics which in turn control hydrodynamic properties, carbonation rate and efficiency and fluid reactivity. This results in carbonation rates being higher when injection rates are high and permeability ultimately controlling carbonation reactions by limiting fluid input. During experiments, notable changes in permeability occurred for only minor changes in porosity indicating a control by the geometry of the porous network: heterogeneities in the distribution of flow paths favored the localization of precipitated minerals which in turn resulted in the closure of flow paths. This mechanism was particularly efficient at low injection rates. These results imply that controlling the injection rate could allow enhancing/limiting the efficiency of in situ carbonation." **Steve Peuble, Marguerite Godard, Linda Luquot, Muriel Andreani, Isabelle Martinez, and Philippe Gouze**, *Applied Geochemistry*. (Subscription may be required.)

Technology

"Recent developments in carbon dioxide capture technologies for gas turbine power generation."

The following is the Abstract of this article: "This paper describes the status of various carbon capture technologies investigated and outlines challenges and opportunities of carbon capture in gas turbine power generation for EOR. Technical achievements, maturity, drivers, barriers and gaps in knowledge are described for four technologies: novel chemical solvents and processes, low temperature separation, membranes and exhaust gas recirculation (EGR) in gas turbines. As a near-term application, carbon capture in gas turbine power generation for EOR is analyzed and drivers, requirements and challenges are outlined. The paper is structured as follows: the first section describes the current global status of CCS, second section explains the approach followed in the paper, third section presents a literature review, fourth section provides a technical analysis of the focus technologies, fifth section describes challenges and opportunities of carbon capture from gas turbines for CO_2-EOR applications and finally sixth section provides conclusions." **Miguel Angel González-Salazar,** *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"Seismicity characterization around the Farnsworth field site for combined large-scale CO_2 storage and EOR."

The following is the Abstract of this article: "Induced seismicity at levels noticeable to the public or higher is a concern for long-term, large-scale geologic carbon storage. To lower the risk of induced seismicity, it is desirable to [store] CO_2 within a region where earthquakes are rare. [The authors] characterize the natural seismicity around the Farnsworth field site for the Phase III project of the U.S. Southwest Regional Partnership on Carbon Sequestration. [The authors] study all available catalog earthquake information within a region of approximately 180 km × 220 km (2 × 2 degrees) centered at the Farnsworth field. [The authors] find that there is no recorded catalog earthquake within a region of approximately 30 km in radius from planned CO_2 injection well No. 13-10A. The earliest earthquake recorded within [the] study region occurred in 1907, and the maximum magnitude of all recorded earthquakes since then is 4.8. Out of all the earthquakes recorded in this region, only four of them have magnitudes larger than 4. [The authors'] seismicity study indicates that the seismic risk for large-scale geologic carbon storage combined with [EOR] at the Farnsworth field may be relatively low. This characterization of natural seismicity around the Farnsworth field also benefits the ongoing monitoring of induced seismicity at the site." **Ting Chen and Lianjie Huang**, *International Journal of Greenhouse Gas Control.* (Subscription may be required.)

"TOUGH2Biot – A simulator for coupled thermal-hydrodynamic-mechanical processes in subsurface flow systems: Application to CO_2 geological storage and geothermal development."

The following is the Abstract of this article: "Coupled thermal–hydrodynamic–mechanical processes have become increasingly important in studying the issues affecting subsurface flow systems, such as CO_2 [storage] in deep saline [formations] and geothermal development. In this study, a mechanical module based on the extended Biot consolidation model was developed and incorporated into the well-established thermal–hydrodynamic simulator TOUGH2, resulting in an integrated numerical THM simulation program TOUGH2Biot. A finite element method was employed to discretize space for rock mechanical calculation and the Mohr-Coulomb failure criterion was used to determine if the rock undergoes shear-slip failure. Mechanics is partly coupled with the thermal–hydrodynamic processes and gives feedback to flow through stress-dependent porosity and permeability. TOUGH2Biot was verified against analytical solutions for the 1D Terzaghi consolidation and cooling-induced subsidence. TOUGH2Biot was applied to evaluate the thermal, hydrodynamic, and mechanical responses of CO_2 geological [storage] at the Ordos CCS Demonstration Project, China and geothermal exploitation at the Geysers geothermal field, California. The results demonstrate that TOUGH2Biot is capable of analyzing change in pressure and temperature, displacement, stress, and potential shear-slip failure caused by large scale underground man-made activity in subsurface flow systems. TOUGH2Biot can also be easily extended for complex coupled process problems in fractured media and be conveniently updated to parallel versions on different platforms to take advantage of high-performance computing." **Hongwu Lei, Tianfu Xu, and Guangrong Jin**, *Computers & Geosciences*. (Subscription may be required.)

"Key techniques of reservoir engineering and injection-production process for CO_2 flooding in China's SINOPEC Shengli Oilfield."

The following is the Abstract of this article: "This paper addresses the geological problems and engineering hot points of the CO_2 flooding, such as the big vertical span of the beach-bar sand, the strong reservoir heterogeneity, the distribution of residual oil, and the problem of gas channeling. The core identification, log analysis, seismic interpretation, laboratory test and numerical simulation of reservoir engineering are integrated to investigate the geological characteristics of the

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reservoir in the demonstration zone of SINOPEC Shengli Oilfield. It demonstrates the reservoir is large but it has thin thickness, low porosity and super-low permeability. Due to some great differences between the beach sand and the bar sand, the oil reservoirs of demonstration zone are divided into 2 sand groups, 8 small layers, and 17 sand bodies in total. Then, a 3D geological model and qualitative evaluation system of safety of vertical faults are built. The optimal evaluation method of CO_2 flooding and [storage] is established. According to the engineering optimization of the CO_2 flooding, the results of a recommendation scheme indicate that the [EOR] can increase by 6.7 [percent], the total injection volume is expected to reach to 563 × 104 t, and CO_2 [storage] rate is 60.5 [percent]. Finally, the multi-level umbrella downhole gas separator is designed, and the high gas–oil ratio (GOR) production string and free kill gas injection string are also successfully developed for the CO_2-EOR." **Guangzhong Lv, Qi Li, Shijie Wang, and Xiaying Li**, *Journal of CO_2 Utilization*. (Subscription may be required.)

"Application of tracers to measure, monitor and verify breakthrough of sequestered CO_2 at the CO2CRC Otway Project, Victoria, Australia."

The following is the Abstract of this article: "At the Cooperative Research Centre for Greenhouse Gas Technology's (CO2CRC) field site in the Otway Basin of Victoria, Australia, investigations into the storage of CO_2-rich gas in a depleted hydrocarbon gas field have been conducted in the Waarre C reservoir. The injected gas from the nearby Buttress field contained 75 mol% CO_2, 21 mol% CH_4 with the remaining balance being a mixture of wet hydrocarbons, condensate and nitrogen. Chemical tracers (sulphur hexafluoride, SF6; krypton, Kr; perdeuterated methane, CD_4) were added on the basis of literature surveys and small volume trials at the Frio II Brine experiment in Texas. The aim of the project was to measure, monitor and verify the presence of injected CO_2 in a depleted gas field and that the arrival of tracers was a major component of demonstrating breakthrough of CO_2 at the monitoring well, Naylor-1. The paper focuses on methods developed for the injection, recovery and analysis of samples collected at the Naylor-1 well. Results of tracer analysis compare well with other data collected (including pH and density measurements) to demonstrate breakthrough. A slip-stream injection system was designed to deliver the tracers mixed with the CO_2-rich gas into the subsurface at the CRC-1 well. The tracers were added to the gas stream 17 days after the start of injection (CO_2 injection commenced March 18, 2008) into the depleted natural gas field at Naylor. A U-tube system was used to retrieve the samples from the Naylor-1 monitoring well. Collected gas and formation water samples were [analyzed] in detail for gas composition, tracers, isotopes (13C CO_2 mainly) and inorganic geochemistry for the broader project. The tracer results confirm that CO_2 breakthrough at the monitoring well occurred within the predicted times. However the interval between samples taken from the U-tubes was too coarse to resolve detailed differences in arrival times between the CO_2 and tracers. Of the three tracers used, SF6 provided the clearest evidence of breakthrough at U-tube 2. Kr, because of its abundance in air, and its potential to be present in the subsurface, was more prone to contamination and had higher background levels prior to breakthrough. CD_4 was expected to provide some more unique data based on the presence of abundant CH_4 in the reservoir interval. With hindsight, larger volumes should have been injected to facilitate comparisons with the other tracers and add value to the data set. The test of CD_4 however acted as a suitable proof of concept that CD_4 could be used in such a high background of CH_4. Further work is ongoing to generate data for partition coefficients between supercritical CO_2, CH_4 and water under the injection conditions." **Linda Stalker, Chris Boreham, Jim Underschultz, Barry Freifeld, Ernie Perkins, Ulrike Schacht, and Sandeep Sharma**, *Chemical Geology*. (Subscription may be required.)

"Bioinspired Silica Nanocomposite with Autoencapsulated Carbonic Anhydrase as a Robust Biocatalyst for CO_2 Sequestration."

The following is the Abstract of this article: "Here, [the authors] report on the development and characterization of a carbonic anhydrase (CA)-based biocatalyst encapsulated in a biosilica matrix for use in environmental CO_2 [storage]. Encapsulation occurred simultaneously with autonomous silica synthesis by silica-condensing R5 peptide that was fused to recombinant CA. The encapsulation efficiency was greater than 95 [percent], and the encapsulated CA was not leached from the silica matrix, demonstrating the highly efficient R5-mediated autoencapsulation process. The catalytic efficiencies for both esterase and CO_2 hydratase activities tended to increase with increasing pH; however, the catalytic efficiency for CO_2 hydration was much more pH dependent, suggesting that proton transfer from silica to water is a rate limiting step, especially for CO_2 hydration. In addition to good reusability, the encapsulated CA exhibited outstanding thermostability, even retaining 80 [percent] activity after 5 days at 50°C. The thermoactivity was also remarkable, showing ~10-fold higher activity at 60°C compared to that at 25°C. The physical structure was observed to be highly compact with a low surface area, stressing the importance of the outermost surface for catalytic performance. [The authors] also demonstrated the applicability of the silica nanoparticle to the [storage] of CO_2 in carbonate minerals. The rate of $CaCO_3$ precipitation was remarkably accelerated by the encapsulated biocatalyst. The biosilica nanocomposite exhibited ~60 [percent] of the CO_2 [storing] power of the free enzyme, which is expected to be the maximal ability of the encapsulated CA. Thus, this silica-CA nanocomposite, efficiently synthesized via a biomimetic green route, can be successfully used as a robust biocatalyst for biomimetic [storage] of the [GHG] CO_2." **Byung Hoon Jo, Jeong Hyun Seo, Yun Jung Yang, Kyungjoon Baek, Yoo Seong Choi, Seung Pil Pack, Sang Ho Oh, and Hyung Joon Cha**, *ACS Catal*. (Subscription may be required.)

"Potassium salt-assisted synthesis of highly microporous carbon spheres for CO_2 adsorption."

The following is the Abstract of this article: "Highly microporous carbon spheres for CO_2 adsorption were prepared by using a slightly modified one-pot Stöber synthesis in the presence of potassium oxalate. Formaldehyde and resorcinol were used as carbon precursors, ammonia as a catalyst, and potassium oxalate as an activating agent. The resulting potassium salt-containing phenolic resin spheres were simultaneously carbonized and activated at 800°C in flowing nitrogen. Carbonization of the aforementioned polymeric spheres was accompanied by their activation, which resulted in almost five-time higher specific surface area and total pore volume, and almost four-time higher micropore volume as compared to analogous properties of the carbon sample prepared without the salt. The proposed synthesis resulted in microporous

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carbon spheres having the surface area of 2130 $m^2 g^{-1}$, total pore volume of 1.10 $cm^3 g^{-1}$, and the micropore volume of 0.78 $cm^3 g^{-1}$, and led to the substantial enlargement of microporosity in these spheres, especially in relation to fine micropores (pores below 1 nm), which enhance CO_2 adsorption. These carbon spheres showed three-time higher volume of fine micropores, which resulted in the CO_2 adsorption of 6.6 mmol g^{-1} at 0°C and 1 atm." **Jowita Ludwinowicz and Mietek Jaroniec**, *Carbon*. (Subscription may be required.)

Terrestrial

"Evaluation of atmospheric CO_2 sequestration by alkaline soils through simultaneous enhanced carbonation and biomass production."

The following is the Abstract of this article: "A series of microcosm experiments were conducted. The objectives were to evaluate the effects of Ca/Mg-bearing materials on CO_2 [storage] in highly alkaline sodic soils (Sodosol) through carbonation and biomass production. Application of gypsum resulted in an increase in inorganic carbon and a decrease in organic carbon. The addition of talc did not significantly enhance carbonate formation. Soluble CaCl2 and MgCl2 did not have significantly better effects on soil carbonation, as compared to gypsum. The one-year growth experiment using five widely cultivated pasture grasses revealed that accumulation of carbonates following gypsum application could be inhibited by plant growth; the organic acids secreted from plant roots were likely to facilitate soil carbonate dissolution. In comparison with pedogenic carbonation, carbon [storage] by biomass production was much more evident. However, the biomass carbon gain varied markedly among the five species with *Digitaria eriantha* showing the highest biomass carbon gain. This further enhanced the accumulation of soil organic carbon. At the end of the experiment, an estimated CO_2 [storage] capacity of 93 t/ha was achieved. The research findings have implications for cost–benefit analysis of alkaline soil reclamation projects." **Emohamed Maryol and Chuxia Lin**, *Geoderma.* (Subscription may be required.)

"Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis."

The following is the Abstract of this article: "A promising option to [store] carbon in agricultural soils is the inclusion of cover crops in cropping systems. The advantage of cover crops as compared to other management practices that increase soil organic carbon (SOC) is that they neither cause a decline in yields, like extensification, nor carbon losses in other systems, like organic manure applications may do. However, the effect of cover crop green manuring on SOC stocks is widely overlooked. [The authors] therefore conducted a meta-analysis to derive a carbon response function describing SOC stock changes as a function of time. Data from 139 plots at 37 different sites were compiled. In total, the cover crop treatments had a significantly higher SOC stock than the reference croplands. The time since introduction of cover crops in crop rotations was linearly correlated with SOC stock change (R^2 = 0.19) with an annual change rate of 0.32 ± 0.08 Mg ha^{-1} yr^{-1} in a mean soil depth of 22 cm and during the observed period of up to 54 years. Elevation above sea level of the plot and sampling depth could be used as explanatory variables to improve the model fit. Assuming that the observed linear SOC accumulation would not proceed indefinitely, [the authors] modeled the average SOC stock change with the carbon turnover model RothC. The predicted new steady state was reached after 155 years of cover crop cultivation with a total mean SOC stock accumulation of 16.7 ± 1.5 Mg ha^{-1} for a soil depth of 22 cm. Thus, the C input driven SOC [storage] with the introduction of cover crops proved to be highly efficient. [The authors] estimated a potential global SOC [storage] of 0.12 ± 0.03 Pg C yr^{-1}, which would compensate for 8 [percent] of the direct annual [GHG] emissions from agriculture. However, altered N_2O emissions and albedo due to cover crop cultivation have not been taken into account here. Data on those processes, which are most likely species-specific, would be needed for reliable [GHG] budgets." **Christopher Poeplau and Axel Don**, *Agriculture, Ecosystems & Environment*. (Subscription may be required.)

Trading

"California Carbon Permits Fetch $12.21 [per Metric Ton] at Auction ."

All carbon permits offered in California's first cap-and-trade program auction of the year were sold at $12.21 per metric ton, the state announced. It was the first auction held since the program nearly doubled in size in January. All 73.6 million carbon permits offered to cover 2015 emissions and 10.4 allowances offered to cover emissions in 2018 were sold, with the 2018 permits selling at $12.10 per metric ton (the minimum price allowed under auction rules). The auction was the state's 10th overall and the second since partnering with the province of Quebec, Canada. Previous auctions raised more than $969 million, which California plans to invest in, among other things, energy efficiency and clean energy programs. The state's cap-and-trade program is looking to reduce its emissions to 1990 levels by 2020. From *Reuters* on February 25, 2015.

"Quantifying CO_2 abatement costs in the power sector."

The following is the Abstract of this article: "[Carbon dioxide] cap-and-trade mechanisms and CO_2 emission taxes are becoming increasingly widespread. To assess the impact of a CO_2 price, marginal abatement cost curves (MACCs) are a commonly used tool by policy makers, providing a direct graphical link between a CO_2 price and the expected abatement. However, such MACCs can suffer from issues related to robustness and granularity. This paper focuses on the relation between a CO_2 emission cost and CO_2 emission reductions in the power sector. The authors present a new methodology that improves the understanding of the relation between a CO_2 cost and CO_2 abatement. The methodology is based on the insight that CO_2 emissions in the power sector are driven by the composition of the conventional power portfolio, the residual load and the generation costs of the conventional units. The methodology addresses both the robustness issue and the granularity issue related to MACCs. The methodology is based on a bottom-up approach, starting from engineering knowledge of the power sector. It offers policy makers a new tool to

Trading (Continued)

assess CO_2 abatement options. The methodology is applied to the Central Western European power system and illustrates possible interaction effects between, e.g., fuel switching and renewables deployment."

Kenneth Van den Bergh and Erik Delarue, *Energy Policy.* (Subscription may be required.)

Recent Publications

"Experimental Characterization of Marcellus Shale Outcrop Samples, and their Interactions with Carbon Dioxide and Methane."
The following is from the Executive Summary of this document: "Organic-rich shale formations that have been depleted of hydrocarbon through a period of primary production have been proposed as candidates for geologic storage of CO_2 and beneficial utilization of CO_2 for enhanced hydrocarbon recovery. To evaluate the potential of such CO_2 utilization and storage scenarios, investigators working at the NETL and partner universities are conducting research through the Industrial Carbon Management Initiative (ICMI), funded by the American Recovery and Reinvestment Act of 2009 (ARRA). The research focuses on developing insights into important attributes of depleted organic shale reservoirs through experimental characterization, simulation of formation performance under CO_2 storage and enhanced gas recovery (EGR) scenarios, and a techno-economic assessment.This report provides a detailed description of results of experimental work completed to date and a preliminary discussion of findings and insights. It fulfills a milestone requirement for the ICMI Carbon Storage in Depleted Shale task to report findings of initial experimental assessment of shale gas formation storage. The set of analyses and experiments being performed are intended to improve the science base with respect to important shale matrix properties that may influence CO_2/shale interaction, measure CO_2 and methane (CO_4) adsorptive capacity on shales to understand storage and EGR potential, and improve understanding of effective permeability/porosity in shales. Samples taken from ten outcrops of the Middle Devonian Marcellus shale formation have been designated as the base sample set for the ICMI and are thought to be representative of the range of rock properties across the Marcellus interval including, but not limited to, the organic- rich "main pay" interval that is a subset. Analyses performed to date include fourier transform infrared spectroscopy (FTIR), shale digestion/total metals analysis, semi-quantitative X-ray diffraction (XRD) mineralogical analysis, total organic and inorganic carbon analysis (TOC and TIC), high resolution computed tomography (CT) imaging of shale cores/plugs, optical petrography, and petrophysical analysis of matrix effective porosity/permeability. It is intended that findings of this work will be applied to refine reservoir simulation of CO_2 storage in and EGR from shale and improve confidence in techno-economic screening that are also being developed in this ICMI task."

Legislative Activity

"Heitkamp Reintroduces Key Legislation to Provide a Path Forward for Coal."

U.S. Senator Heidi Heitkamp reintroduced legislation, the "Advanced Clean Coal Technology Investment in Our Nation Act," to encourage coal plants to lower emissions through the use of advanced clean coal technologies. The bill aims to provide a path forward for clean coal energy production. Senator Heitkamp has (1) worked with DOE to emphasize the need for clean coal energy R&D; (2) talked with the U.S. Environmental Protection Agency (EPA) about proposed regulations; (3) called for more time to review proposed EPA rules regulating CO_2 emissions from existing power plants; and (4) brought together industry, lawmakers, and academics to discuss a path forward for coal. A summary of the bill is available. From *Senator Heidi Heitkamp Press Release* on February 26, 2015.

"House Advances Bill that Would Certify CO_2 Stored in Wyoming Oil Fields."

A Wyoming House of Representatives committee advanced a bill that would create a program for the state to certify the amount of CO_2 stored for use during EOR. Senate File 84 would allow the state to review an oil company's CO_2 storage plan and certify the amount being stored. The committee amended the bill to allow the Wyoming Oil and Gas Conservation Commission and the Wyoming Department of Environmental Quality to establish certification rules. From *Casper Star-Tribune Review* on February 19, 2015.

"Williams Introduces Bill to Protect Underground Water."

A California Assembly member introduced Assembly Bill 356, which would require groundwater monitoring near Class II injection wells to protect underground sources of drinking water (USDWs) from oil and gas wastewater and EOR. The bill provides the State Water Resources Control Board with the authority to review groundwater monitoring plans as part of a permit application or notice of intent for injection wells. From *Assembly Member Das Williams News Room* on February 17, 2015.

"[Illinois] Bill Calls for Cap-and-Invest Program to Meet EPA Carbon Goal."

A group of Illinois lawmakers proposed measures (SB 1485 and HB 2607) that would expand the state's energy efficiency and renewable energy requirements and create a carbon market. The carbon market program would cap CO_2 emissions and create an allowance auction with approximately two-thirds of the proceeds contributed toward

Legislative Activity (Continued)

renewable energy and efficiency. The cap-and-invest proposal would establish a framework for the Illinois EPA to meet carbon reduction targets and be limited to the electricity sector. In addition to no free allowances, carbon offsets would also not be allowed. In addition, the legislation permits Illinois to enter multi-state agreements for compliance purposes. The bills would also require a 20 percent reduction in electricity use by 2025 and expand Illinois' renewable energy standard to 35 percent by 2030. From *EnergyWire* on February 20, 2015.

"California Climate Leadership Package Announced."

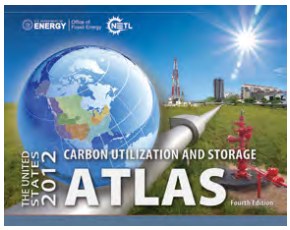
A package of proposals was introduced in the California Senate that includes benchmarks for emissions reduction, energy efficiency, and petroleum use. SB 32 sets an emissions reduction target of 80 percent below 1990 levels by 2050. SB 350 aims to reduce petroleum use by 50 percent, have 50 percent of electricity from renewable sources, and increase energy efficiency in all existing buildings by 50 percent (all measures by 2030). SB 189 proposes that a committee of experts advise and inform state clean energy and climate actions to ensure job creation and economic benefits. Details of the proposals, including the bills, charts, articles, and statements from a broad coalition of supporters, are available online. From *Senate President pro Tempore Kevin de León Press Release* on February 10, 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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