Carbon Storage Newsletter

March 2014

What's Inside?

Highlights

"President Requests $711.0 Million for Fossil Energy Programs."

The President's Fiscal Year (FY) 2015 budget seeks $711.0 million for the U.S. Department of Energy's (DOE) Office of Fossil Energy (FE)

to advance technologies related to the reliable, efficient, affordable, and environmentally sound use of fossil fuels (as well as manage the Strategic Petroleum Reserve and Northeast Home Heating Oil Reserve). The request includes $475.5 million for FE Research and Development (R&D). FE leads the government's research, development, and demonstration (RD&D) efforts on advanced carbon capture and storage (CCS) technologies. In FY 2015, FE R&D will continue to focus on CCS activities that increase the efficiency and availability of systems integrated with CCS. Under CCS Demonstrations, FE manages the Clean Coal Power Initiative (CCPI) Program, along with two American Recovery and Reinvestment Act (ARRA) CCS demonstration programs. In FY 2015, FE will establish the Natural Gas Carbon Capture and Storage (NG-CCS) Program to support projects that capture and store carbon dioxide (CO_2) emissions from natural gas power systems. The CCS and Power Systems Program conducts research to reduce CO_2 emissions by improving the performance and efficiency of fossil energy systems and CCS technologies. The FY 2015 budget request for the program is $277.4 million, including $34.0 million for the National Energy Technology Laboratory (NETL) to conduct in-house coal R&D. The FY 2015 budget requests $77.0 million for carbon capture R&D. The FY 2015 budget requests $80.1 million for carbon storage R&D under the Carbon Storage Program. The overall goal of the Carbon Storage Program is to develop and validate technologies that ensure safe, permanent geologic CO_2 storage. From *DOE Fossil Energy Techline* on March 4, 2014.

Announcements

SAVE THE DATE: DOE/NETL Carbon Storage R&D Project Review Meeting.

DOE's 2014 Carbon Storage R&D Project Review meeting will be held at the Sheraton Station Square Hotel in Pittsburgh, Pennsylvania, USA, on August 12-14, 2014. Among a number of other technical sessions, this year's meeting will include plenary sessions on a number of carbon storage topics and lessons learned over the past 10 years from the Regional Carbon Sequestration Partnerships (RCSPs). Participants will share knowledge and resources to assist in planning future carbon storage efforts. Based on past attendance, this meeting is expected to attract 200 or more attendees.

NETL Funding Opportunity Announcement.

NETL released Funding Opportunity Announcement (FOA) DE-FOA-0001037, titled, "Research for Safe and Permanent Geologic Storage of CO_2." Application forms and/or instructions are available online. Projects selected under this FOA

Announcements (Continued)

develop characterization tools, technologies, and/or methodologies that improve the ability to predict geologic storage capacity within 30 percent, improve the utilization of the reservoir by understanding how faults and fractures in a reservoir affect the flow of CO_2, and ensure storage permanence.

DOE Releases $8 Billion Solicitation for Advanced Fossil Energy Projects.

DOE published a solicitation in December 2013, making up to $8 billion in loan guarantee authority available to support innovative advanced fossil energy projects that avoid, reduce, or store greenhouse gases (GHGs). The loan guarantees under this new solicitation will help provide financing to support new or significantly improved advanced fossil energy projects, such as advanced resource development, carbon capture, low-carbon power systems, and efficiency improvements, which reduce emissions of CO_2, methane (CH_4), and other GHGs.

2014 CO_2 Capture Technology Meeting.

The 2014 CO_2 Capture Technology meeting will feature more than 50 DOE-sponsored CO_2 capture technology projects. The meeting is scheduled for July 29-August 1, 2014, at the Sheraton Station Square Hotel in Pittsburgh, Pennsylvania, USA. The projects included span three primary technology areas (post-combustion, pre-combustion, and advanced combustion systems) and various stages of development (lab-scale, bench-scale, and small pilot-scale). Presentations will be included on solvent, sorbent, membrane, oxy-combustion, and chemical looping combustion technologies, as well as systems studies and modeling.

International Workshop on Public Education, Training, and Community Outreach for Carbon Capture and Storage.

This workshop is scheduled for July 30-31, 2014, at the National Sequestration Education Center (NSEC) in Decatur, Illinois, USA. The technical program features tools and techniques for public education, training, and community outreach on CCS. Workshop attendees will tour the commercial-scale CCS project at the Archer Daniels Midland facility. The workshop also includes a full day of programming for K-12 teachers with interactive lesson plans related to CCS and Science, Technology, and Mathematics (STEM). To present a paper, submit an abstract to dlarrick@richland.edu on the following topics: (1) Ongoing Programs in CCS Education and Training; (2) Project Developer/Industry Experience in Public Communications; (3) Sharing Knowledge/Lessons Learned for Effective CCS Outreach; or (4) Advancing CCS Education, Training, and Outreach Programs, Key Messages, and FAQs. Abstracts are due March 31, 2014.

12th International Conference on Greenhouse Gas Control Technologies.

GHGT-12 will be held on October 5-9, 2014, in Austin, Texas, USA. This will be the first visit by the conference series to Austin and more than 1,600 participants are expected to attend. The event will be hosted by the University of Texas at Austin and the IEA Greenhouse Gas R&D Programme (IEAGHG).

RGGI Releases Report: Regional Investment of RGGI CO_2 Allowance Proceeds, 2012.

The Regional Greenhouse Gas Initiative (RGGI) released a report summarizing the consumer, economic, and environmental impact of investments made from 2009 to 2012 using proceeds from RGGI's CO_2 allowance auctions. The report estimates that RGGI investments in energy efficiency, clean and renewable energy, and other strategic energy programs will return more than $2 billion in lifetime energy bill savings to more than 3 million participating households and more than 12,000 businesses in the region.

RGGI Releases Fourth Quarter Secondary Market Report.

Potomac Economics, the independent market monitor for RGGI, released a report, titled, "Report on the Secondary Market for RGGI CO_2 Allowances: Fourth Quarter 2013." According the report, CO_2 allowance prices rose from approximately $2.70 in early October to approximately $3.35 in late December, and secondary market prices were consistent with the auction clearing price. The report also found that volumes increased during the quarter for both the physical transfers of CO_2 allowances and the trading of CO_2 allowance futures and options.

Carbon Storage in the News

"Celebrating a Decade of Carbon Storage Research Through Partnership."

For the past decade, DOE's NETL has managed a nationwide network of partnerships that team government, industry, academia, and nonprofit organizations to identify the best approaches for permanently storing CO_2 in deep geologic formations. Research performed by the seven RCSPs helps validate the most suitable technologies and infrastructure needs for

Carbon Storage in the News (Continued)

CCS. To augment the information-sharing that occurs through avenues such as research papers, scientific conferences, and technical reports, DOE is posting a short series of lessons learned from the RCSPs' carbon storage projects over the next several weeks. These online blog posts include topics such as site characterization; industry partnerships; public outreach and education; and monitoring, verification, and accounting. More information on the RCSPs is available via the NETL website. From *DOE Fossil Energy Techline.*

"SaskPower to Roll Out World's First Carbon Capture-Embedded Power Plant."

SaskPower will soon open a power plant installed with CCS technology in Estevan, Saskatchewan, Canada. Backed by $240 million of funding from the Canadian government, the $1.35-billion Boundary Dam Carbon Capture Project includes a coal-fired power plant at Boundary Dam Unit 3 rebuilt with a unit capable of storing CO_2 emissions. New Canadian federal regulations require all coal-burning power plants more than 50 years old to either be shut down or converted to emit 420 metric tons or less of CO_2 per gigawatt-hour by July 2015. Boundary Dam Unit 3 currently emits 1,100 metric tons of CO_2 per gigawatt-hour; however, after the CCS upgrade, emissions are expected to be reduced to 140 to 150 metric tons. From *Financial Post* on February 14, 2014.

"Shell Signs Agreement to Advance Major Clean Energy Project at Peterhead."

An agreement has been reached between the United Kingdom (UK) government and Shell to progress the Peterhead CCS project to the next phase of design. The project, led by Shell and with support from SSE (owners of the Peterhead gas power station in Aberdeenshire), has a goal of capturing 10 million metric tons of CO_2 over 10 years. If successful, the Peterhead project will be an industrial-scale application of CCS technology at a gas-fired power station. The agreement marks the start of Front-End Engineering and Design (FEED), which is expected to continue until 2015. This timeline is subject to future investment decisions by Shell and the UK government and the receipt of all required consents and permits. If these conditions are met, the Peterhead project could be operating by the end of the decade. From *Shell Media Release* on February 24, 2014.

"TCM Delivers New Benchmark Tests for Global CCS Progression."

The CO_2 Technology Centre Mongstad (TCM) has completed large-scale tests of the amine solvent monoethanolamine (MEA) on a gas-fired source. TCM, in cooperation with Aker Solutions, has been operating the amine plant since August 2012. MEA is a baseline solvent used in post-combustion carbon capture studies to compare the performance of amines and other CO_2 removal processes. The new tests included the measurement and evaluation of a number of parameters, such as energy consumption, emissions, and degradation. The testing will provide an MEA baseline for a variety of CCS applications in both the process industry and power production. TCM's laboratory collects data from more than 4,000 measuring points connected to online instruments and tests samples each day. The results of the MEA tests will be shared with the CCS community to accelerate global CCS implementation. TCM is comprised of two CO_2 capture plants, each with the capacity to capture approximately 80,000 tons of CO_2 from the nearby refinery or 20,000 tons from a gas-fired power plant; the center also has space and infrastructure available for next generation technologies. From *TCM Press Release* on February 24, 2014.

Science

"Drought, Fires Impact Ability of Amazon to Hold Carbon Dioxide."

According to research published in the journal "Nature," fires and drought in the Amazon could potentially reduce the forest's ability to store CO_2 emissions. The research shows that when coupled together in the Amazon, dry weather conditions and fires could potentially lead to the forest losing its ability to store more CO_2 than it releases. Using aircraft to study the CO_2 release, researchers found that the forests stored less of the CO_2 that comes with fires. Coupled with a slowdown in photosynthesis, this led to an upswing in CO_2 emissions from the forest dome. During wetter years, the forests offset emissions from the fires; however, this was not the case during the drought year that was studied, leading researchers to believe that if droughts and fires continue, the Amazon could potentially lose its ability to be a carbon sink. From *Phys.org* on February 25, 2014.

Policy

"A public choice view on the climate and energy policy mix in the EU – How do the emissions trading scheme and support for renewable energies interact?"

The following is the Abstract of this article: "In this paper, [the authors] analyze the rationale for an energy policy mix when the European Emissions Trading Scheme (ETS) is considered from a public choice perspective. That is, [the authors] argue that the economic textbook model of the ETS implausibly assumes (1) efficient policy design and (2) climate protection as the single objective of policy intervention. Contrary to these assumptions, [the authors] propose that the ETS originates from a political bargaining game within a context of multiple policy objectives. In particular, the emissions cap is negotiated between regulators and emitters with the emitters' abatement costs as crucial bargaining variable. This public choice view yields striking implications for an optimal policy mix comprising RES supporting policies. Whereas the textbook model implies that the ETS alone provides sufficient climate protection, [the authors'] analysis suggests that support for renewable energies (1) contributes to a more effective ETS-design and (2) may even increase the overall efficiency of climate and energy policy if other externalities and policy objectives besides climate protection are considered. Thus, [the authors'] analysis also shows that a public choice view not necessarily entails negative evaluations concerning efficiency

Policy (Continued)

and effectiveness of a policy mix." **Erik Gawel, Sebastian Strunz, and Paul Lehmann**, *Energy Policy*. (Subscription may be required.)

"Pricing Contracts Under Uncertainty in a Carbon Capture and Storage Framework."

The following is the Abstract of this article: "CCS has been demonstrated as a viable option for reducing carbon emissions to the atmosphere. [The authors] consider a situation where a tax on emissions is imposed on CO_2 producers to encourage their participation in CCS. Operators of CO_2 transportation pipelines and storage sites enter into individual contracts with emissions producers to store CO_2. [The authors] study the problem of selecting the optimal price and volume of these contracts under both cost and emissions uncertainty to optimize the storage operator's expected profit." **W. Caia, D.I. Singhamb, E.M. Craparob, and J.A. Whitec**, *Energy Economics*. (Subscription may be required.)

"Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?"

The following is the Abstract of this article: "Economists traditionally view a Pigouvian fee on CO_2 and other GHG emissions, either via carbon taxes or emissions caps and permit trading ('cap-and-trade'), as the economically optimal or 'first-best' policy to address climate change-related externalities. Yet several political economy factors can severely constrain the implementation of these carbon pricing policies, including opposition of industrial sectors with a concentration of assets that would lose considerable value under such policies; the collective action nature of climate mitigation efforts; principal agent failures; and a low willingness-to-pay for climate mitigation by citizens. Real-world implementations of carbon pricing policies can thus fall short of the economically optimal outcomes envisioned in theory. Consistent with the general theory of the second-best, the presence of binding political economy constraints opens a significant 'opportunity space' for the design of creative climate policy instruments with superior political feasibility, economic efficiency, and environmental efficacy relative to the constrained implementation of carbon pricing policies. This paper presents theoretical political economy frameworks relevant to climate policy design and provides corroborating evidence from the United States context. It concludes with a series of implications for climate policy making and argues for the creative pursuit of a mix of second-best policy instruments." **Jesse D. Jenkins**, *Energy Policy*. (Subscription may be required.)

Geology

"Combination of CO_2 geological storage with deep saline water recovery in western China: Insights from numerical analyses."

The following is the Abstract of this article: "[Carbon dioxide] geological storage, when combined with deep saline water recovery (CO_2-EWR), not only achieves the relatively secure storage of CO_2 that was captured from the coal chemical industry, due to lower pressure, but also enhances saline water for drinking and industrial or agricultural utilization. This storage will undoubtedly become a win–win choice for the enhancement of energy security and for the promotion of regional development in China, particularly for western regions with a relative shortage of water resources and a more fragile ecological environment. In this paper, a three-dimensional injection–extraction model is established that uses the TOUGH2/ECO2N program according to typical formation parameters of a coal chemical industry in the Xinjiang Uyghur Autonomous Region. Numerical results showed that under the guarantee of sufficient water conditions, 1.73 × 108 tons of saline water could be produced when the CO_2-EWR is adopted. Well arrangements and formation parameters are also analyzed, and the following conclusions can be drawn: arrangements of pumping wells, such as pumping well number, pumping rate and distance, have considerable influences on the reservoir pressure, and in addition, the sensitivity of pressure on the distance and pumping rate decreases as their values increase. In view of these features, it is necessary to find an optimal point to achieve the best combination of pressure, the [release] time and the amount of dissolution. Formation parameters primarily control the mechanism of CO_2 migration and dissolution. Salinity in the salt water has the greatest impact on CO_2 dissolution trapping followed by permeability and porosity. The arrival time that is allowable for saline water production primarily depends on porosity followed by the permeability ratio and the arrangements of pumping wells. The reservoir pressure change that is caused by parameters is not obvious compared with setting pumping wells. Overall, CO_2-EWR technology is a potential strategic choice for China, particularly in western regions. Additionally, the analysis results provide a reliable guide and reference for CO_2 storage site selection, as well as the practical arrangements of wells." **Qi Li, Ya-Ni Wei, Guizhen Liu, and Qing Lin**, *Applied Energy*. (Subscription may be required.)

"Geochemical modeling of CO_2–water–rock interactions for two different hydrochemical types of CO_2-rich springs in Kangwon District, Korea."

The following is the Abstract of this article: "Naturally outflowing CO_2-rich springs are a natural analogue of the seepage of [stored] CO_2 in geological storage sites. In Kangwon district of South Korea, two hydrochemically different types of CO_2-rich springs (i.e., Ca–HCO_3-type and Na–HCO_3-type) occur together in a granitic terrain. Hydrochemical and water-isotope data (i.e., $\delta^{18}O$–δD and tritium) show that Na–HCO_3-type springs have experienced significant silicate weathering processes over a long residence time at depths, while Ca–HCO_3-type springs were formed by the mixing of Na–HCO_3-type springs with shallow groundwater during ascent. In this study, diverse geochemical models including mixing, ion exchange and reaction path were investigated to verify the geochemical processes accounting for the occurrence of two contrasting types of CO_2-rich springs. The mixing and ion exchange models reveal that Ca–HCO_3-type springs are well explained by reverse cation exchange occurring during the mixing of Na–HCO_3-type springs with shallow groundwater. The Na–HCO_3-type springs are well explained by the reaction path modeling including the dissolution of silicate minerals (plagioclase, K-feldspar and biotite) and the precipitation of secondary minerals (calcite, kaolinite, muscovite and Mg-beidellite), implying that dissolved carbon is [stored] by calcite precipitation (i.e., mineral trapping). However, the concentrations of K in [the authors'] modeling results are far below those of K observed in Na–HCO_3-type springs, because of the precipitation of muscovite

Geology (Continued)

considered in the model, suggesting the partial disequilibrium state of the [formation] during the hydrolysis of K-feldspar under high PCO_2 conditions. This result implies that to better predict long-term CO_2–water–rock interactions in a geological storage site with abundant K-feldspar, the secondary K-bearing minerals should be carefully predicted, because a target [formation] can be far from chemical equilibrium during the storage period. This study shows that geochemical modeling can be effectively used to predict the hydrochemical changes of groundwater during long-term CO_2–water–rock interactions and subsequent [release] toward surface in K-feldspar rich [formation], although it should be included in a fully coupled computational approach between fluid flow, heat transfer and reactive mass transport processes in the future research." **Byoung-Young Choi, b, Seong-Taek Yun, Kyoung-Ho Kim, Hyeon-Su Choi, Gi-Tak Chae, Pyeong-Koo Lee**, *Journal of Geochemical Exploration*. (Subscription may be required.)

"Fluid flow and CO_2–fluid–mineral interactions during CO_2-storage in sedimentary basins."

The following is the Abstract of this article: "Modelling the progress of geochemical processes in CO_2 storage sites is frustrated by uncertainties in the rates of CO_2 flow and dissolution, and in the rates and controlling mechanisms of fluid–mineral reactions that stabilize the CO_2 in geological reservoirs. Dissolution of CO_2 must be controlled by the complexities of 2-phase flow of CO_2 and formation brines and the smaller-scale heterogeneities in the permeability in the reservoirs which increase the fluid contact areas. The subsequent fluid mineral reactions may increase storage security by precipitating CO_2 in carbonate minerals but the consequences of fluid–mineral reactions on caprock rocks or potential [release] pathways up fault zones are less certain as the CO_2-charged brines may either corrode minerals or decrease permeabilities by precipitating carbonates. Observations from CO_2-injection experiments and natural analogues provide important constraints on the rates of CO_2 and brine flow and on the progress of CO_2 dissolution and mineral–fluid reactions. In these experiments brines in contact with the propagating plume appear to rapidly saturate with CO_2. Dissolution of the CO_2 drives the dissolution of oxide and carbonate minerals, on times scales of days to weeks. These reactions buffer fluid pH and produce alkalinity such that carbonate dissolution moves to carbonate precipitation over time-scales of weeks to months. The dissolution of Fe-oxide grain coatings and the release of Fe to solution is important in stabilizing insoluble Fe–Mg–Ca carbonate minerals but the rate limiting step for carbonate mineral precipitation is the transport of CO_2-charged brines and silicate mineral dissolution rates. Observations from CO_2-EOR experiments and natural analogues suggest that the silicate mineral dissolution reactions are initially fast in the low pH fluids surrounding the CO_2 plume but that reaction progress over months to years drives minerals towards thermodynamic equilibrium and dissolution rates slow over 2–5 orders of magnitude as equilibrium is approached. The sluggish dissolution of silicate minerals is likely to preside over the long-term fate of the CO_2 in geological reservoirs. Observations from injection experiments and natural analogues suggest that the potentially harmful trace elements mobilized by the drop in pH are immobilized as adsorbed and precipitated phases as fluid pH is buffered across mineral reaction fronts." **Niko Kampmana, Mike Bickle, Max Wigley, Benoit Dubac**, *Chemical Geology*. (Subscription may be required.)

"Long-term assessment of geochemical reactivity of CO_2 storage in highly saline [formations]: Application to Ketzin, In Salah and Snøhvit storage sites."

The following is the Abstract of this article: "Saline [formations] are choice targets for geological storage of CO_2 because of their storage potential and because these formations are not suitable for other uses. Geochemical modeling is an interesting tool to assess the geochemical behavior of CO_2 in the saline [formation], including its dissolution in the brine and its interactions with minerals. Two key parameters which determine the confidence one can have in the results of geochemical modeling are tested in this paper: (i) the establishment of the conceptual model, including the selection of the primary and secondary minerals expected to react; and (ii) the activity model and the associated thermodynamic databases to calculate the interaction energies within the saline solution. In this study, [the authors] performed an analysis of a large set of CO_2 storage natural analogs, which makes it possible to identify the minerals that are likely to precipitate and dissolve during CO_2–brine–rock interactions. Interestingly, this analysis indicates a strong dependence of Dawsonite precipitation on the initial sandstone mineralogy. Dawsonite can precipitate in lithic and feldspar rich sandstones but was not observed in quartz rich sandstones. These observations on mineral reactivity are used to establish reactivity conceptual models for three CO_2 storage case-studies in saline sandstone [formations] (Ketzin, In Salah and Snøhvit) and a methodology is proposed to evaluate the long-term geochemical reactivity of these saline [formations] as a result of CO_2 injection. Noticeable differences are obtained between the case-studies as a function of the initial mineralogy and chemical conditions in the sandstones, which highlight that CO_2 mineral trapping can take place in a given storage site but can be almost absent in other storage sites. Regarding the activity model and the database, the Pitzer interaction model is rarely used for simulating CO_2 geochemical behavior in saline [formations] despite the fact that more conventionally used activity models are not valid for such salinities. A comparison between calculated mineral solubility evolution with salinity versus experimental data is performed here using both B-dot and Pitzer activity models as well as six different databases. This comparison exercise shows that chemical interactions within saline solutions can only be reproduced using the Pitzer model, even though Pitzer databases are still incomplete or are not coherent for a wide range of chemical species and temperatures. The geochemical simulations of CO_2 injection in Ketzin, In Salah and Snøhvit saline [formations] give divergent results using different activity models and databases. A high uncertainty on the simulation results is then linked to the database choice and this study clearly stresses the need for a Pitzer database that can be confidently used in all physical/chemical conditions found in deep sedimentary [formations]." **Joachim Trémosa, Christelle Castillo, Chan Quang Vong, Christophe Kervévan, Arnault Lassin, and Pascal Audigane**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"Life cycle and cost assessment of mineral carbonation for carbon capture and storage in European power generation."

The following is the Abstract of this article: "Large-scale GHG emission reductions are crucial for achieving the European goals for climate change mitigation. A frequently discussed option is CCS, where CO_2 emissions from point sources are captured and stored in geologic structures.

Geology (Continued)

However, concerns about risks of [releases] of CO_2 from geological storage have been raised. These risks could be avoided with ex situ mineral carbonation, where the captured CO_2 is stored in an inert and stable solid form after reacting with calcium and magnesium silicates. For a comprehensive assessment of the environmental and economic performance of this CO_2 storage option in fossil-fueled power generation chains, LCA and levelized cost of electricity (LCoE) calculations are performed. The implementation of CCS using mineral carbonation leads to life cycle GHG emission reductions of 15–64 [percent] and LCoE increases of 90–370 [percent] on a per kWhel basis compared to a reference power plant without CCS. The life cycle GHG emission reduction achievable with mineral [storage] is less substantial than with geological storage of CO_2 due to significant energy and chemical additives requirements. Accordingly, LCA results for other environmental indicators are worse than those of the reference plant without CCS and the geological CO_2 storage option." **Stylianos Giannoulakis, Kathrin Volkart, and Christian Bauer**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Technology

"Effect of accelerated carbonation on AOD stainless steel slag for its valorisation as a CO_2-sequestering construction material."

The following is the Abstract of this article: "Non-stabilized Argon Oxygen Decarburization (AODNS) slag in powdered form was examined for its CO_2 [storage] capacity and for its potential utilization in the fabrication of high value building materials. The curing of the sample was carried out in two accelerated carbonation environments: i) in a carbonation chamber, maintained at atmospheric pressure, 22°C, 5 vol.% CO_2 and 80% RH; and ii) in a carbonation reactor, where the CO_2 partial pressure (pCO_2) and temperature could be further increased. In the carbonation chamber, an average compressive strength of over 20 MPa, on a 64 cm^3 cubic specimen, was obtained after one week of curing, which is sufficient for many construction applications. Further carbonation resulted in a linear increase of strength up ~30 MPa after three weeks. The CO_2 uptake followed a similar trend, reaching a maximum of 4.3 wt%. In the reactor, the compressive strength improved with an increase in pCO_2 up to 8 bar, temperature up to 80°C, and duration up to 15 h where the maximum CO_2 uptake was 8.1 wt%. The reduction in porosity in the carbonated specimens was approximately in line with the strength gain in the samples. Phase analysis by X-ray powder diffraction and inspection by scanning electron microscopy showed the precipitation of calcite and formation of significant amounts of amorphous material after carbonation. Infrared spectroscopy also pointed to the presence of aragonite and vaterite. In the carbonation chamber, the calcite morphology was uniform throughout the specimen. In the reactor, however, the calcite crystals near the outer edges of the cubes had different morphology than those near the core. Carbonation of the slag resulted in the reduction of basicity by up to one pH unit, and contributed to controlling the leaching of several heavy metals and metalloids." **Muhammad Salman, Özlem Cizer, Yiannis Pontikes, Rafael M Santos, Ruben Snellings, Lucie Vandewalle, Bart Blanpain, Koen van Balen**, *Chemical Engineering Journal*. (Subscription may be required.)

"Estimating the likelihood of pipeline failure in CO_2 transmission pipelines: New insights on risks of carbon capture and storage."

The following is the Abstract of this article: "Previous studies of risks associated with CO_2 pipelines for future CCS activities have used either the frequency of incidents associated with existing CO_2 pipelines or from natural gas pipelines as a proxy. Risks of CO_2 pipeline failure have been estimated as in the range of 1.2×10^{-4} to 6.1×10^{-4} km^{-1} yr. This paper demonstrates that for U.S. natural gas pipeline data, incident/failure metrics are not correlated with fatality rates. Both CO_2 and natural gas pipelines are fabricated from the same grades of carbon steel, and both are installed using the same equipment and practices. However, natural gas is lighter than air and explosive in air, whereas CO_2 is nonflammable but toxic (and heavier than air). Their risk profiles are therefore not identical, and the differences in hazard certainly impact the nature of individual and societal risk. This study focuses on the likelihood of events that could result in fatalities or injuries. The average fatality rate for natural gas transmission pipelines constructed over the last [three] decades is $1.0 \times 10{-}6$ km^{-1} yr. This value can be viewed as an upper bound for estimating individual risks associated with CO_2 transmission pipelines. Use of incident rates to model individual risks for CO_2 pipelines, has overestimated these risks by 2–3 orders of magnitude. When pipelines are designed with factors of safety required by regulators for populated areas, analysis of natural gas pipeline data demonstrates that risks of significant accidental releases are extremely low. These results require a significant rethinking of previous notions of the risks associated with CO_2 pipelines." **Ian J. Duncan and Hui Wang**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"Model complexity in carbon [storage]: A design of experiment and response surface uncertainty analysis."

The following is the Abstract of this article: "Geologic carbon [storage] (GCS) is considered a promising means of reducing atmospheric CO_2. In Wyoming, GCS is proposed for the Nugget Sandstone in Moxa Arch, a deep, regional-scale saline [formation] with a large CO_2 storage potential. For a proposed storage site, this study builds a suite of increasingly complex conceptual geologic model families, using subsets of the site characterization data: a homogeneous model family (FAM1), a stationary petrophysical model family (FAM2), a stationary facies model family with sub-facies petrophysical variability (FAM3), and a non-stationary facies model family (with sub-facies variability) conditioned to soft data (FAM4). These families, representing alternative conceptual site models built with increasing data, were simulated with the same CO_2 injection test (50 years at 1/10 Mt (1.0×108 kg) per year), followed by 2950 years of monitoring. Using the design of experiment, an efficient sensitivity analysis (SA) is conducted for all families, systematically varying uncertain [formation] parameters, while assuming identical well configuration, injection rate, bottomhole pressure constraint, and boundary conditions, i.e., the model is considered a part of a larger, semi-infinite system, where both the injected CO_2 and the formation brine can flow out. The SA results are compared among the families to identify parameters that

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have 1st order impact on predicting CO_2 storage ratio (SR) at two different time scales, i.e., end of injection and end of monitoring. This comparison indicates that, for this deep [formation] with a gentle incline, geologic modeling factors do not significantly influence the short-term prediction of the CO_2 storage ratio. However, these factors become more important over the monitoring time, but only for those families where such factors are accounted for (in other words, their long-term importance cannot be revealed by the relatively simple conceptual models). Based on the SA results, a response surface analysis is conducted to generate prediction envelopes of the storage ratio, which are also compared among the families, and at both time scales. Results suggest a large uncertainty in the predicted storage ratio, given the uncertainties in model parameters and modeling choices: the SR varies from 5–60 [percent] (end of injection) to 18–100 [percent] (end of monitoring), although its variation among the model families due to different modeling choices is relatively minor. Moreover, long-term [release] risk is considered small at the proposed site. This is because, in the lowest-SR scenarios, all model families predict gravity-stable supercritical CO_2 migrating toward the bottom of the [formation]. In the highest-SR scenarios, supercritical CO_2 footprints are relatively insignificant by the end of monitoring." **Shuiquan Li and Ye Zhang**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Terrestrial

"The effects of urea fertilization on carbon [storage] in Douglas-fir plantations of the coastal Pacific Northwest."

The following is the Abstract of this article: "If long-term carbon (C) [storage] can be quantifiably attributed to forest plantation nitrogen (N) fertilization, the net C credits could be used to offset the rising cost of fertilization and C released during the production, transportation, and application of N fertilizer and the effect of [nitrogen oxide (NO_X)] volatilized after application. The purpose of [the authors'] study was to determine the net change in C [storage] following N fertilization of second-growth Douglas-fir plantations in the Pacific Northwest. The C content of the trees, understory vegetation, forest floor, and mineral soil was quantified at age 26–33 at five sites, each with a fertilized plot that received a total of 896–1120 kg N ha^{-1} as urea over 16 years paired with an unfertilized control plot. Tree biomass was estimated using biometric equations and by subtracting the difference between treatment and control at the year of site establishment from the difference between treatment and control final measurement. Understory vegetation on the fertilized plots contained significantly more C than on the control plots (0.2 Mg C ha^{-1}, S.D. 0.2). Nitrogen fertilization significantly increased C [stored] per tree by 2.2 Mg C ha^{-1} (S.D. 1.8), but there was no significant increase in C [stored] in trees per plot. No significant change was found in forest floor, A horizon, and subsoil C contents due to fertilization. These results indicate that, while there is a greater amount of C stored per tree after fertilization, there was more difficulty in accessing C [stored] in forest plantations due to tree mortality and assumed soil variability between plots." **Benjamin Shryock, Kim Littke, Marcia Ciol, David Briggs, and Robert Harrison**, *Forest Ecology and Management*. (Subscription may be required.)

Trading

"CO_2 Allowances Sold at $4.00 at 23rd RGGI Auction."

The states participating in RGGI announced that 23,491,350 CO_2 allowances were sold at the 23rd auction of CO_2 allowances at a clearing price of $4.00. Allowances sold include the 18,491,350 allowances offered for sale by the nine participating states and all of the 5,000,000 allocation year 2014 cost containment reserve (CCR) allowances. Bids for the CO_2 allowances ranged from $2.00 to $11.85 per allowance. The CCR is a fixed additional supply of allowances that are available for sale only if CO_2 allowance prices exceed certain price levels. There are no more CCR allowances available for sale in 2014. According to an independent market monitor's report, electricity generators and their corporate affiliates have won 78 percent of CO_2 allowances sold in RGGI auctions since 2008. The auction generated $93.96 million for reinvestment in a variety of consumer benefit initiatives, including energy efficiency, renewable energy, direct bill assistance, and GHG abatement programs. Cumulative proceeds from all RGGI CO_2 allowance auctions currently total more than $1.6 billion dollars. From *RGGI News Release* on March 7, 2014.

"Qingdao City Next In Line to Set Up Emissions Market in China."

Advisors are negotiating rules for an emissions trading scheme in Qingdao, a Chinese city of 3 million people in the northeastern Shandong province. Qingdao plans to institute CO_2 caps on up to 300 companies and launch a market for trading CO_2 permits by 2015, with a target of reducing CO_2 emissions per unit of GDP to 19 to 20 percent below 2010 levels by 2015. From *Reuters* on February 18, 2014.

"Another $329.7 Million Spent on California Carbon Permits."

California state officials announced that the state's most recent carbon permit auction, the sixth state-run auction since the cap-and-trade market system began in 2012, raised $329.7 million. Allowances that can be used in 2014 sold for $11.34 per ton, while future permits that can be used in 2017 sold for $11.38. Since the program began, California firms have spent a total of $1.54 billion for the right to emit GHGs, according to the California Air Resources Board (CARB). From *The Sacramento Bee* on February 24, 2014.

Recent Publications

"The Global Status of CCS: February 2014."

The following is from the Executive Summary of this document: "This report, 'The Global Status of CCS: February 2014,' [summarizes] the current status of large-scale integrated CCS projects worldwide and provides an overview of significant international CCS project and policy, legal and regulatory developments. CCS is essential to keep global temperature increases below two degrees Celsius. It is a vital part of a least cost portfolio of low-carbon technologies required to deal with climate change. In the past few months there have been a series of expert reports acknowledging this reality. A broad chorus of leading voices is to be welcomed, especially if it encourages decision makers to take action to progress CCS technology. Despite continuing progress in large-scale CCS projects moving into construction and operation in most regions, the overall global effort to date has been slower than ideal. Nonetheless, there are positive signals that decision makers may act to accelerate CCS implementation. The 5th Carbon Sequestration Leadership Forum (CSLF) Ministerial Meeting in November 2013 [emphasized] the importance of CCS in tackling climate change and identified actions to [reenergize] the global momentum for the deployment of CCS. This is needed to support existing activity and advance new projects. As of February 2014 there are 12 projects in operation globally, nine under construction and another 39 in various stages of development planning, of which six may make a final investment decision during 2014. The 21 projects in operation or under construction represent a 50 [percent] increase since 2011, a sign of growing confidence in the application of CCS technology at large scale. North America is leading in the implementation of CCS technology and China is quickly increasing in importance. Momentum has been regained in the UK though prospective project start dates are towards the end of this decade. Continental Europe on the other hand has lost a project leadership position that it aspired to several years ago, though the importance of CCS technologies at large scale and continued robust research and development efforts have been [recognized] by a number of European bodies in recent months. The first large-scale CCS projects in the power sector – the Boundary Dam Integrated Carbon Capture and Sequestration Project and the Kemper County Integrated Gasification Combined Cycle (IGCC) Project – are nearing operational status in North America. These projects are of global importance to the development of CCS. Similarly, in the Middle East, the world's first large-scale CCS project in the iron and steel sector has progressed into construction. Projects such as these will build confidence by showing the technology in action, and through innovation combined with advances in capture technology, bring down costs."

"Cleaner Fossil Power Generation in the 21st Century – Moving Forward."

The following is from the Executive Summary of this document: "CCS has a pivotal role to play if the use of fossil fuels in power stations and vital energy-intensive industries is to keep in step with the low-carbon agenda. Globally, recognition is growing that CCS must be at the forefront of efforts to limit increases in average temperatures caused by climate change; it has been calculated that, in the UK, successful deployment could cut the cost of meeting carbon reduction targets by up to [one percent] of Gross Domestic Product (GDP) by 2050. Yet the annual amount of CO_2 captured and stored worldwide currently totals tens of megatons, compared to the thousands of megatons that need to be achieved by the middle of the 21st century. This technology strategy aims not only to confront the challenge and help unleash the potential but also to keep the UK at the vanguard of CCS technology development and [commercialization]. [Decarbonizing] the UK's energy system; achieving major cuts in industrial carbon emissions; boosting energy security; generating billions of pounds in income and tens of thousands of jobs for 'UK plc' – these benefits are all within reach if large-scale deployment of CCS becomes a reality in this country. Taking full and realistic account of work currently under way and wider developments in the UK and worldwide, as well as the recommendations of the UK's CCS Cost Reduction Task Force (CRTF), this strategy sets out a clear vision that has three components: [1] Adoption of a target of around 10 [percent of UK electricity to be generated from fossil fuel plant fitted with CCS by 2025. [2] Creation of capability that enables CCS to make a major contribution to meeting the UK's target of an 80 [percent] cut in [GHG] emissions by 2050. [3] Positioning of the UK to succeed in global CCS markets and to play an influential role in the CCS policy dialogue at both European Union (EU) and global level. [Realizing] this vision presents several challenges. These include: cutting costs and risks so that CCS is economically competitive with other low-carbon technologies; putting appropriate, effective market frameworks in place; and removing a range of barriers to deployment. In close conjunction with other [organizations] wherever appropriate, the APGTF will work to pursue this vision and address these challenges. This document sets out Strategic targets and Technology Implementation targets, plus a suite of research, development and demonstration (RD&D) priorities and other recommendations designed to ensure that key CCS development criteria – in terms of scale, cost and timelines – can be met effectively."

"Carbon Capture and Storage in the EU's 2030 climate and energy framework."

The following is from the Introduction of this document: "Europe was at one time the world leader in supporting CCS. In 2007, the European Council called for 12 demonstration projects to be in operation by 2015: not one has been delivered to date. In the light of the economic crisis, EU CCS policy has failed to deliver a sufficiently bankable business case for individual CCS projects, and has not provided credible long-term signals to stimulate the development of supply chains, CO_2 infrastructure investments or the proactive [characterization] of geological CO_2 storage. Previous European technological leadership on CCS is now at risk as commercial-scale projects for power generation and industrial sources of emissions enter into operation and construction in Canada, USA, Australia, China and the United Arab Emirates. The Global CCS Institute warns that Europe is now 'lagging behind.' Without explicit actions to address the weaknesses of EU CCS policy, the new EU2030 framework on climate and energy will also fail to deliver. This would leave Europe facing higher costs of [decarbonization] and increased risk of employment loss from carbon intensive and process industries from energy intensive and process industries. In November

Recent Publications (Continued)

2013, SCCS published 'Unlocking North Sea CO_2 Storage for Europe: Practical actions for the next five years.' [The SCCS] report identified how decisions to improve the policy context and undertake practical enabling actions could combine to rebuild momentum for CCS deployment in the EU. [SCCS] set these out as a five-year framework and highlighted key elements on the critical path to deploying CCS in the EU, focusing on the North Sea as the prime location in Europe for the geological storage of CO_2. This briefing follows on from that analysis and identifies decisions that the European Council can take in March 2014 to accelerate progress on CCS. The recommendations above relate closely to the headline findings from [the] report, which included calls for: a strategic vision for CCS in 2030; policies and incentives that drive investment; and the sourcing of low-cost CO_2."

Legislative Activity

"Pipeline Bill Headed to Senate."

A bill requiring any privately built intrastate pipeline to open the line for public use was discussed in the Mississippi Senate. By declaring eminent domain, Senate Bill 2568 would open up such pipelines, referred to as "common carriers," to other companies able to access them. As a result, property owners containing CO_2 reserves would be able to utilize the pipelines for enhanced oil recovery (EOR) and create jobs and revenue streams within the state. In addition, the bill would allow the Mississippi Public Service Commission to regulate disputes between shippers of natural gas and its derivatives and pipeline owners. From *Hattiesburg American* on February 10, 2014.

"House Approves Outman Bill Allowing Enhanced Oil Recovery."

The Michigan House approved a four-bill package that will enable the statewide development of CO_2 enhanced oil and gas recovery, reduce the amount of CO_2 released into the atmosphere, generate new revenue for the Natural Resources Trust Fund, and create jobs within the state. House Bill 5254, which requires Senate approval, also updates the definition of a pipeline to include transportation of CO_2 to a well site. From *Michigan House Newsroom* on February 17, 2014.

"Steinberg Announces Major Proposal to Strengthen CA Climate Policy."

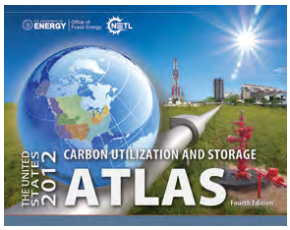
California's Senate President pro Tempore announced a plan that would incentivize reduced fuel consumption and strengthen California's climate policies through 2050. The Senate leader announced a proposal to set targets in statute, beyond 2020, related to fossil fuel consumption and reinforce the climate goals of AB32 through 2030 and 2050; continue cap-and-trade for industrial plants but replace its current 2015 expansion into a carbon tax of a similar amount; return two-thirds of the carbon tax revenues to Californians through a state earned income tax credit; and invest the remaining carbon tax revenues into developing California's mass transit infrastructure. Full text of the speech is available here. From *California Senate President Pro Tempore Darrell Steinberg News Release* on February 20, 2014.

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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