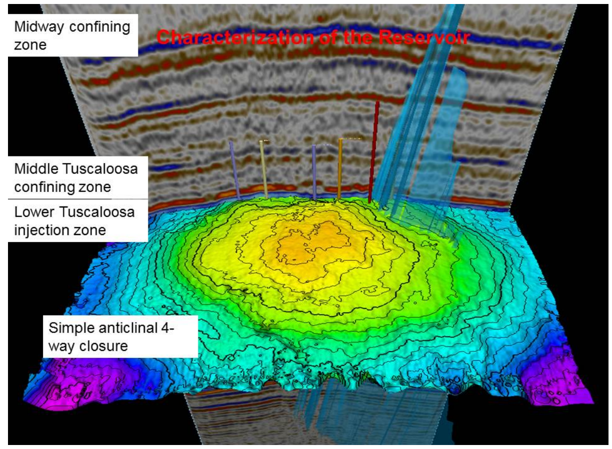
Monitoring Methods Optimization: Cranfield Monitoring Overview

Project Description

GCCC has participated in the Southeast Regional Carbon Sequestration Partnership (SECARB) since its initiation in 2003. SECARB is funded under the Regional Carbon Sequestration Partnerships (RCSP) program, funded by the U.S. Department of Energy (DOE) through the National Energy Technology Laboratory (NETL). SECARB is led by the Southern States Energy Board.



Baseline 3D survey with interpreted structure on base of Tuscaloosa, showing key units. The crestal graben fault is shown in blue.

GCCC has participated in SECARB principally through leading a two-stage field experiment in monitoring at Denbury Onshore LLC's Cranfield field CO_2 enhanced oil recovery (EOR) project. The first test program, known as Phase II, was conducted from 2008 to 2011 within the EOR injection-production patterns and tested the above-zone monitoring interval (AZMI) pressure monitoring as a surveillance tool to assess isolation. The second stage of testing, known as Phase III, or the SECARB "early test," assessed many elements of field-scale monitoring, such as reservoir pressure surveillance, wireline logging of the reservoir interval, 4D seismic surveillance of the reservoir and zones above it for change in fluid composition, AZMI pressure monitoring, groundwater geochemical sampling, and airborne magnetic and conductivity surveys. In addition, an intensive study was conducted at the detailed area of study (DAS), where two observation wells were placed 100 m downdip of an injection well in the water leg below the oil-water contact. An intensive multistage, multiresearcher effort was conducted to characterize the reservoir, monitor flow, and model the system response to CO_2 injection at the DAS.

Accomplishments

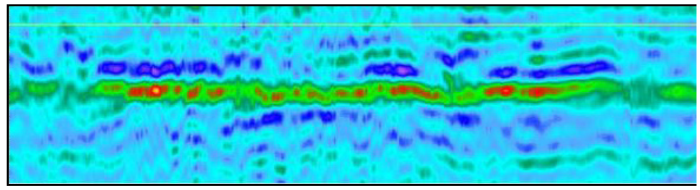
The GCCC-led SECARB projects at Cranfield have accomplished a number of things for the RCSP program:

- Monitored a large-volume injection (5 million metric tons CO_2 stored).
- Monitored at a commercial EOR site.
- Monitored over a very long timeframe (2008–14).
- Provided information about the feasibility and limitations of common monitoring approaches such as 4D seismic surveillance and groundwater geochemical testing programs.
- Created highly collaborative opportunity for industry, national lab, U.S. Geological Survey, and academic interaction. Hosted many experiments within and outside of the RCSP, such as the National Risk Assessment Partnership (NRAP), the Carbon Capture Project (CCP), GEO-SEQ, the Center for Frontiers of Subsurface Energy Security (CFSES), and other targeted projects.
- Provided dense data that can be used for capacity assessment.
- Published numerous results (see list of citations below).
- Led the way toward the next phase of more commercially oriented monitoring.

Accomplishments (continued)

In addition, significant R&D was undertaken as part of this study:

- The second geologic CO_2 storage tests of cross-well electrical resistivity tomography (ERT) for detection of CO_2 substituting for brine were performed. (The first was the small shallow deployment at Ketzin, Germany.) The favorable outcome showed good sensitivity, even with significant noise from the instruments, and possible sensitivity to increases in saturation beyond the range of seismic detection.
- The second geologic CO_2 storage tests of gravity (after the seafloor gravity measurement at Sleipner, North Sea) were performed. The wellbore instrument was able to detect and reasonably quantify CO_2 substitution for brine. (This work was done as part of CCP.)
- Exsolution of methane from brine as a result of CO_2 dissolution was observed.



Colors in the 3D seismic map flattened in the lower Tuscaloosa. Sand in brighter colors and lower quality reservoir in blue-green, with methane gas in yellow.

- The complexities of interaction between reservoir heterogeneity and injection rate in the two-phase-flow field were documented. Efficiency of occupancy was dependent on injection rate.
- This project supported development and demonstration of the process-based soil gas method for attribution of the source of anomalies. This method is sensitive to very small (insignificant) fluxes. (See Natural Analog Studies Theme for more.)
- No microseismicity was detected from the injection. (This work was done as part of the Research Institute of Innovative Technology for the Earth [RITE].)

Impacts

Complex responses of many parts of the system during monitoring led to difficulty in uniquely matching fluid-flow models to observation. Also, observed limitations on detectability of response—for example, inability to reliably "map the plume edge" above noise using 4D surface seismic or vertical seismic profiling (VSP)—are important outcomes in terms of regulatory expectations. This finding leads to the development of the concept of assessment of low-probability material impacts (ALPMI) described in the EPA –CCS site-specific sensitivity study (see Site-Specific Topic in this Theme), where neither continually updated history match nor comprehensive monitoring of plume movement is needed. The ALPMI method requires assessment of the material impacts and the signal that would precede the impact, and designs monitoring to intercept the unacceptable low-probability reservoir responses. Use of modeling becomes primarily an up-front activity, which only needs updating if major flaws are observed that potentially lead to project failure.

Another outcome of observations at Cranfield is that near-surface monitoring requires deep and substantive characterization if it is to be effectively used to show no change during and after injection. Many changes are already under way in near-surface settings, and changes in climate, development, or recovery from past use are expected. We recommend careful characterization of the near surface to identify (1) the natural range and trend of variability and (2) the response of the system should it be perturbed as a result of injection. For example, the signal produced should CO_2, brine, or other fluids migrate from the reservoir to shallow depths or the surface. We do not recommend that groundwater soil gas be systematically sampled with the expectation of detecting a signal if, as expected, the noise is high and complex. These data are valuable should an unexplained change occur so that project personnel can determine if the response is a result of injection.

Major Participants

- Susan Hovorka, PI
- Ramon Treviño, Project Manager
- Tip Meckel
- Changbing Yang
- Jiemin Lu
- Seyyed Hosseini
- Katherine Romanak
- Vanessa Nuñez

Major Collaborators

- National Energy Technology Laboratory (NETL): major funding
- Denbury Onshore LLC: site host
- Sandia Technologies: field service provider
- Lawrence Berkeley National Laboratory (LBNL)
- Lawrence Livermore National Laboratory (LLNL)
- Oak Ridge National Laboratory (ORNL)
- Schlumberger Carbon Services
- Mississippi State University
- University of Mississippi
- The University of Texas at Austin, Department of Geological Sciences
- University of Edinburgh
- University of Durham
- Research Institute of Innovative Technology for the Earth (RITE)
- Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

Annotated Citations

The SECARB "early" test at Cranfield is reviewed in papers. Many, but not all, of these papers have a significant monitoring component; for completeness all are included in this section. In addition, papers from these GCCC-led projects by non-GCCC authors and relevant papers from before 2011 are included.

Overviews of the SECARB project

Hovorka, S. D., 2013, Three-million-metric-ton-monitored injection at the SECARB Cranfield project—project update: Energy Procedia, v. 37, p. 6412–6423 DOI information: 10.1016/j.egypro.2013.06.571

Hovorka, S. D., Choi, J.-W., Meckel, T. A., Treviño, R. H., Zeng, H., Kordi, M., Wang, F. P., and Nicot, J.-P., 2009, Comparing carbon sequestration in an oil reservoir to sequestration in a brine formation—field study, *in* Energy Procedia (v. 1, no. 1), Proceedings of 9th International Conference on Greenhouse Gas Control Technologies GHGT9, November 16–20, Washington, D.C., p. 2051–2056.

Hovorka, S. D., Meckel, T. A., and Nicot, J-.P., 2013 Mid-project assessment of the SECARB early test at Cranfield, Mississippi: International Journal of Greenhouse Gas Control.

Hovorka, S. D., Meckel, T. A., and Treviño, R. T, 2013, Monitoring a large-volume injection at Cranfield, Mississippi—project design and recommendations: International Journal of Greenhouse Gas Control, v. 18, p. 345–360, http://dx.doi.org/10.1016/j.ijggc.2013.03.021.

Annotated Citations (continued)

Hovorka, S. D., Meckel, Timothy, Treviño, R. H., Lu, Jiemin, Nicot, J.-P., Choi, Jong-Won, Freeman, D., Cook, P. G., Daley, Tom, Ajo-Franklin, J., Freifeld, Barry, Doughty, C. A., Carrigan, C. R., La Brecque, D., Kharaka, Yousif, Thordsen, J. J., Phelps, Tommy, Yang, Changbing, Romanak, Katherine, Zhang, Tongwei, Holt, R. M., Lindler, J. S., and Butsch, R. J., 2011, Monitoring a large volume CO_2 injection: year two results from SECARB project at

Denbury's Cranfield, Mississippi, USA, *in* Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 3478–3485.

Hovorka, S. D., Meckel, T. A., Treviño, R. H., Nicot, J. –P., Choi, J. –W., Yang, C., Paine, J., Romanak, K., Lu, J., Zeng, H., and Kordi, M., 2009, Southeast Partnership Early Test Update – Cranfield field, MS: presented at the Eighth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 4-7, 2009.

Characterization Reservoir, regional seal, overburden, groundwater and the near surface were characterized using published field history, historic and current production data, a 2007 3-D seismic survey prior to CO_2 injection, historic and modern wireline logs, 4 cores, published and newly collected groundwater data, and airborne surveys.

Kordi, Masoumeh, 2013, Characterization and prediction of reservoir quality in chlorite-coated sandstones: evidence from the Late Cretaceous Lower Tuscaloosa Formation at Cranfield Field, Mississippi, U.S.A., PhD Dissertation, the University of Texas at Austin, 193p.

Lu, Jiemin. Kordi, Masoumeh, Hovorka, S.D. , Meckel, T.A., Christopher, C.A, 2013., Reservoir characterization and complications for trapping mechanisms at Cranfield CO2 injection site. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.10.007

Lu, Jiemin, Milliken, K., Reed, R. M., and Hovorka, S. D., 2011, Diagenesis and sealing capacity of the middle Tuscaloosa mudstone at the Cranfield carbon dioxide injection site, Mississippi: Environmental Geosciences, v. 18, no. 1, p. 35–53.

A time lapse (4D) seismic survey was created by collecting a second 3D survey over part the area that had been flooded with CO_2 after two years of CO_2 injection. A 3D VSP was also conducted under funding from NRAP.

Carter, R.W., Spikes, K.T., 2013, Sensitivity analysis of Tuscaloosa sandstones to CO_2 saturation, Cranfield field, Cranfield, MS. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.006

Daley, T.M., Henderickson, Joel, and Queen, in press, Analysis of Time-Lapse Offset VSP For Monitoring of CO2 Storage at Cranfield, MS, SEG.

Daley, T.M., Ajo-Franklin, J.B., Doughty, C., Hovorka, S., 2010, Seismic monitoring and reservoir modeling at SECARB's Phase-III Cranfield Site, Ninth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, May 10-13, 2010.

Ditkof, J., Caspar E, Pevzner, R., Urosevic, M., Meckel, T. A., Hovorka, S. D., in press, Time lapse seismic signal analysis for EOR and CCS site, Cranfield field, Mississippi, Geophysics.

Ditkof, Julie N., 2013, Time-lapse seismic monitoring for enhanced oil recovery and carbon capture and storage field site at Cranfield field, Mississippi, University of Texas Jackson School of Geosciences Master's thesis; http://hdl.handle.net/2152/23200.

Annotated Citations (continued)

Zhang, R., Ghoshe, Ranjana, Sen, M. K, Srinivansan, Sanjay, 2013, Time-lapse surface seismic inversion with thin bed resolution for monitoring CO2 sequestration: A case study from Cranfield, Mississippi. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.08.015.

Zhang, Rui, Song, Xiaolei, Fomel, Sergey, Sen, Mrinal, Srinivasan, Sanjey, in press, Time-lapse pre-stack seismic data registration and inversion for CO_2 sequestration study at Cranfield.

A well-based monitoring program to image a segment of the flood with high spatial and temporal resolution, using many technologies was conducted at the Detailed Area Study (DAS) where two observation wells were placed in a 100m transect downdip of an injection well in the water leg of the reservoir.

Ajo-Franklin, J.B., Peterson, J, Doetsch, J., Daley, T.M., 2013, High-resolution characterization of a CO_2 plume using crosswell seismic tomography: Cranfield, MS, USA., Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2012.12.018

Butsch, Robert, Brown, A. L., Bryans, Bradley, Kolb, Conrad, Hovorka, Susan, 2013, Integration of well-based subsurface monitoring technologies: Lessons learned at SECARB study, Cranfield, MS, Int. J. Greenhouse Gas Control

Carrigan, C.R., Yang, Xianjin, LaBrecque, D. J., Larson, Dennis, Freeman, David, Ramirez, A. L., Daily, William, Aines, Roger, Newmark, Robin, Friedmann, Julio, Hovorka, Susan, 2013, Electrical resistance tomographic monitoring of CO_2 movement in deep geologic reservoirs. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.04.016

Dodds, Kevin, Krahenbuhl, Richard, Reitz, Anya, Li, Yaoguo, Hovorka, Susan, 2013, Evaluation of time lapse borehole gravity for CO_2 plume detection SECARB Cranfield . Int. J. Greenhouse Gas Control (2013)

Doetsch, Joseph, Kowalsky, M. A. Doughty, Christine, Finsterle , Stefan, Ajo-Franklin, J. B., Carrigan, C. R., Yang, Xianjin, Hovorka, S. D., Daley, T. M., 2013, Constraining CO_2 simulations by coupled modeling and inversion of electrical resistance and gas composition data. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.04.011

A series of **fluid-flow models** were constructed to assess the response of the reservoir.

Chang, K.-W., Hesse, M. A., Nicot, J. -P., and Hovorka, S. D., 2011, Effects of adjacent mud rocks on CO_2 injection pressure: model case based on a typical U.S. Gulf Coast salt diapir field under injection, in Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 4567–4574.

Choi, Jong-Won, Nicot, J. -P., Meckel, Timothy, and Hovorka, S. D., 2011, Numerical modeling of CO_2 injection into a typical U.S. Gulf Coast anticline structure, in Energy Procedia, v. 4, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies GHGT10, September 19–23, Amsterdam, The Netherlands, p. 3486–3493.

Choi, J.-W., Nicot, J.-P. Hosseini, S. A., Clift, S. J., and Hovorka, S. D., 2013, CO_2 recycling accounting and EOR operation scheduling to assist in storage capacity assessment at a U.S. gulf coast depleted reservoir. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.033

Delshad, Mojdeh, Kong, Xianhui, Tavakoli, Reza, Hosseini, S. A. Wheeler, M. A., 2013., Modeling and simulation of carbon sequestration at Cranfield incorporating new physical models. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.

Annotated Citations (continued)

Doughty, Christine, and Freifeld, Barry, in review, Modeling CO_2 injection at Cranfield Mississippi, Inversion of methane and temperature effects.

Hosseini, S.A., Lashgarib, Hamidreza, Choi, J.-W., Nicot, J.-P., Ju, Jiemin, Hovorka, S. D, 2013., Static and dynamic reservoir modeling for geological CO_2 sequestration at Cranfield, Mississippi, U.S.A. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.11.009

Hosseini, S. A., and Nicot, J. -P., 2012, Numerical modeling of a multiphase water–oil– CO_2 system using a water–CO2 system: application to the far field of a U.S. Gulf Coast reservoir: International Journal of Greenhouse Gas Control, v. 10, p. 88–99.

Kim, Seunghee, and Hosseini, S. A., 2013, Above-zone pressure monitoring and geomechanical analysis of a field scale CO_2 injection, Cranfield Mississippi, Greenhouse Gases Science and Technology, Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.1388

Lu, J., Cook, P. J., Hosseini, S. A., Yang, C., Romanak, K. D., Zhang, T., Freifeld, B. M., Smyth, R. C., Zeng, H., and Hovorka, S. D., 2012, Complex fluid flow revealed by monitoring CO_2 injection in a fluvial formation: Journal of Geophysical Research, v. 117, B03208, doi:10.1029/2011JB008939.

Mukhopadhyay, S., Birkholzer, J. T., Nicot, J. -P., and Hosseini, S. A., 2012, A model comparison initiative for a CO2 injection field test: an introduction to Sim-SEQ: Environmental Earth Science, v. 67, p. 601–611.

Risk and well performance were considered.

Meckel, T.A., Zeidouni, Mehdi, Hovorka, S. D., Hosseini, S.A., 2013, Assessing sensitivity to well leakage from three years of continuous reservoir pressure monitoring during CO_2 injection at Cranfield, MS, USA. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2013.01.019

Nicot, J.-P., Oldenberg, C. M., Houseworth, J. E., Choi, J.- W, 2013 Analysis of potential leakage pathways at the Cranfield, MS, U.S.A., CO2 sequestration site. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.10.011

Tao, Qing, Bryant, S. L., Meckel, T. A., 2013., Modeling above-zone measurements of pressure and temperature for monitoring CCS sites. Int. J. Greenhouse Gas Control (2012), http://dx.doi.org/10.1016/j.ijggc.2012.08.011

Geochemical studies of fluid response to the CO_2 injection found CO_2–mineral reaction produced only small changes, however, exsolution of methane as a result of CO_2 dissolution was identified for the first time.

Hosseini, S. A., Mathias, S. A., and Javadpour, F., 2012, Analytical model for CO2 injection into brine aquifers containing residual CH4: Transport in Porous Media, v. 94, p. 795–815.

Lu, Jiemin, Kharaka, Y. K., Thordsen, J. J., Horita, J., Karamalidis, A., Griffith, C., Hakala, J. A., Ambats, G., Cole, D. R., Phelps, T. J., Manning, M. A., Cook, P. J., and Hovorka, S. D., 2012, CO2–rock–brine interactions in Lower Tuscaloosa Formation at Cranfield CO2 sequestration site, Mississippi, U.S.A.: Chemical Geology, v. 291, p. 269–277.

Verma, Sandeep, Oaks, C.S., Chugunov, N., Ramakrishnan, T. S., Hosseini, Hovorka, S.. 2013, Reservoir fluid monitoring in carbon dioxide sequestration at Cranfield, Energy Procedia, 37, p. 4344-4355.

Annotated Citations (continued)

Near surface groundwater monitoring found, as expected, no impact from groundwater as a result of large volume injection at 10,000ft depth. A push-pull test was used to identify the signal that would result if migration should occur.

Yang Changbing, Mickler, P. J , Reed Robert, Scanlon, B. R, . Romanak, K. D., Jean-Philippe Nicot J.-P.,. Hovorka, S. D., Trevino, R. H., Larson, Toti, 2013, Single-well push–pull test for assessing potential impacts of CO2 leak-age on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi. Int. J. Greenhouse Gas Control (2013), http://dx.doi.org/10.1016/j.ijggc.2012.12.030

Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO_2 leakage detection by vadose zone gas monitoring at geologic CO2 storage sites: Geophysical Research Letters, v. 39, L15405, doi:10.1029/2012GL052426.

Yang, Changbing, Romanak, Katherine, Holt, R. M., Linder, J., Smith, L., Treviño, R. H., Roecker, Frank, Xia, Y., and Rickerts, J., 2012, Large volume of CO_2 injection at the Cranfield, early field test of the SECARB Phase III: near-surface monitoring, in Carbon Management Technology Conference, 7–9 February, Orlando, Florida, USA, SPE 163075 DOI: 10.7122/151428-MS.

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