Geologic Sequestration Training and Research

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CCUS

Pittsburgh, Pennsylvania
August 21-23, 2012

Project Objectives

- Evaluation of the sealing capacity of caprocks serving as barriers to upward migration of CO_2 sequestered in geologic formations.
- Education and training of undergraduate and graduate students, through independent research on geologic sequestration.
- Education, through an advanced undergraduate/graduate level course on coal combustion and gasification, climate change, and carbon sequestration.
- Simulation of CO_2 migration and trapping in storage reservoirs and potential for seepage through seal layers.

Relationship to Carbon Storage Program Goals

Program Goals

- Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ± 30%.
  - Critical CO_2 column height for onset of seepage through caprock determines formation's storage capacity.
- Develop technologies to demonstrate that 99% of injected CO_2 remains in the injection zones.
  - In presence of seepage, permeability of caprock determines rate of loss.
- Conduct field tests through 2030 to support the development of best practices manuals for site selection, characterization, site operations, and closure.
  - Collaboration with SECARB Anthropogenic Test at Alabama Power Plant Barry.

Benefits

- Measurements of rock properties, to provide reassurance to stakeholders that geologic sequestration is safe and secure.
- Contributions to the development and utilization of actual geologic sequestration sites.

Project Participants

- Peter Walsh, Principal Investigator,
  Research Professor, Dept. of Mechanical Engineering, UAB

- Richard Esposito, Senior/Key Co-Investigator,
  Principal Research Geologist, Southern Company

- Konstantinos Theodorou, Graduate Research Assistant,
  Ph.D. Candidate, Interdisciplinary Engineering, UAB

- Michael Hannon, Graduate Research Assistant,
  Ph.D. Candidate, Interdisciplinary Engineering, UAB

- Kirk Ellison, Ph.D. Candidate, Interdisciplinary Engineering, UAB
  Research Scientist, Southern Company

- Aaron Lamplugh, Undergraduate Research Assistant,
  Global and Community Leadership Honors Program, UAB

Measurement of Rock Properties

Michael Hannon, Aaron Lamplugh, Richard Esposito, Peter Walsh

Samples:

SECARB Black Warrior
CO_2 Storage Project

Montana State University,
Advanced CO_2 Leakage Mitigation using Engineered Biomineralization Sealing Technologies

SECARB Phase III
25-MW CCS Demo,
Alabama Power Plant Barry

Advanced Resources International,
Commercial-scale CO_2 Injection and Optimization of Storage Capacity in the Southeastern United States

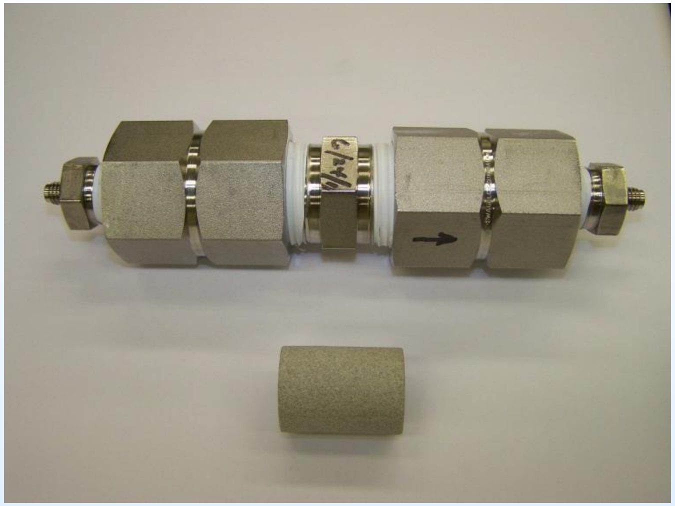
Measurements:

Porosity by imbibition

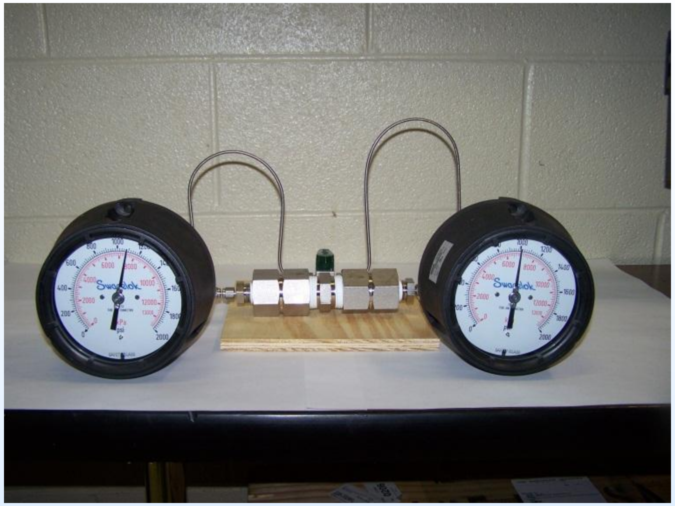
Permeability using N_2, He, and CO_2

Minimum capillary displacement pressure using brine and N_2 or CO_2

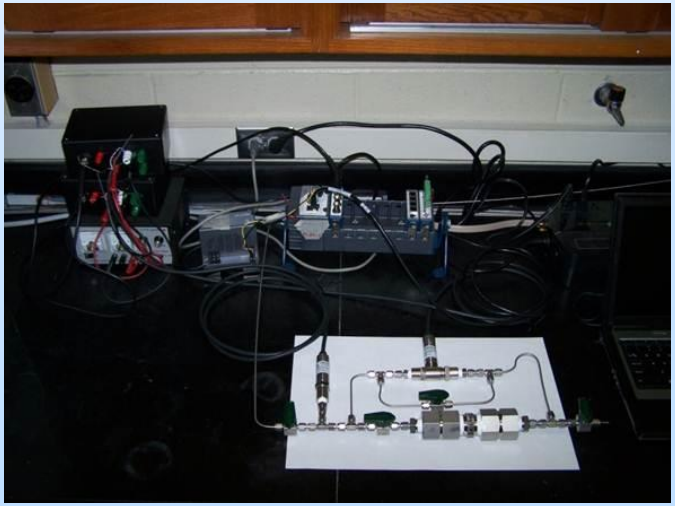
Measurement of Permeability



Rock sample and cell



Pressure-pulse decay



Pressure-pulse decay
with data acquisition

Steady flow

Permeability by Pressure-Pulse Decay

Michael Hannon

Sample: Sandstone

Upper Pottsville Formation

From Fishtrap Mine, near Alabama Power Plant Miller

Perpendicular to bedding

22 mm in diameter by 57 mm long

Fluid: Helium

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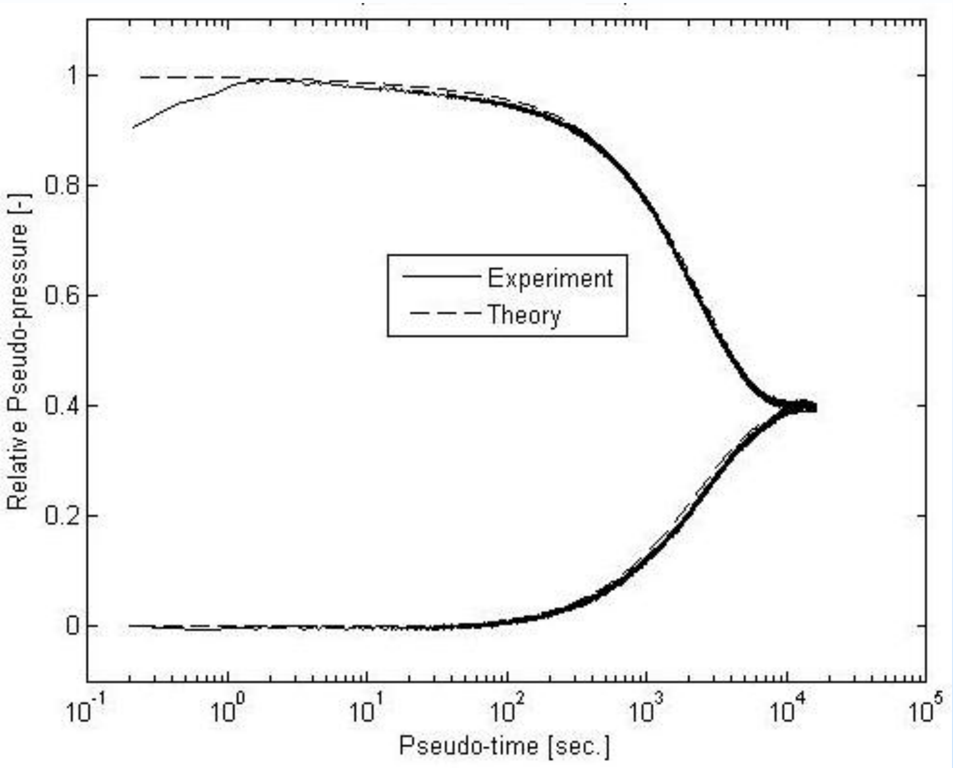
Porosity: 3.8%

Permeability: 1.6 µdarcy



Comparison between the series solution (Hsieh et al., 1981; Haskett et al., 1988) and the transient pressure-pulse measurements.

Haskett, S. E., G. M. Narahara, and S. A. Holditch, "A method for simultaneous determination of permeability and porosity in low-permeability cores," *Society of Petroleum Engineers Formation Evaluation*, September **1988**, *219*, 651-658.

Hsieh, P. A., J. V. Tracy, C. E. Neuzil, J. D. Bredehoeft, and S. E. Silliman, "A transient laboratory method for determining the hydraulic properties of 'tight' rocks—I. Theory," *International Journal of Rock Mechanics and Mineral Sciences & Geomechanics*, **1981**, *18*, 242-252.

Permeability of Caprock

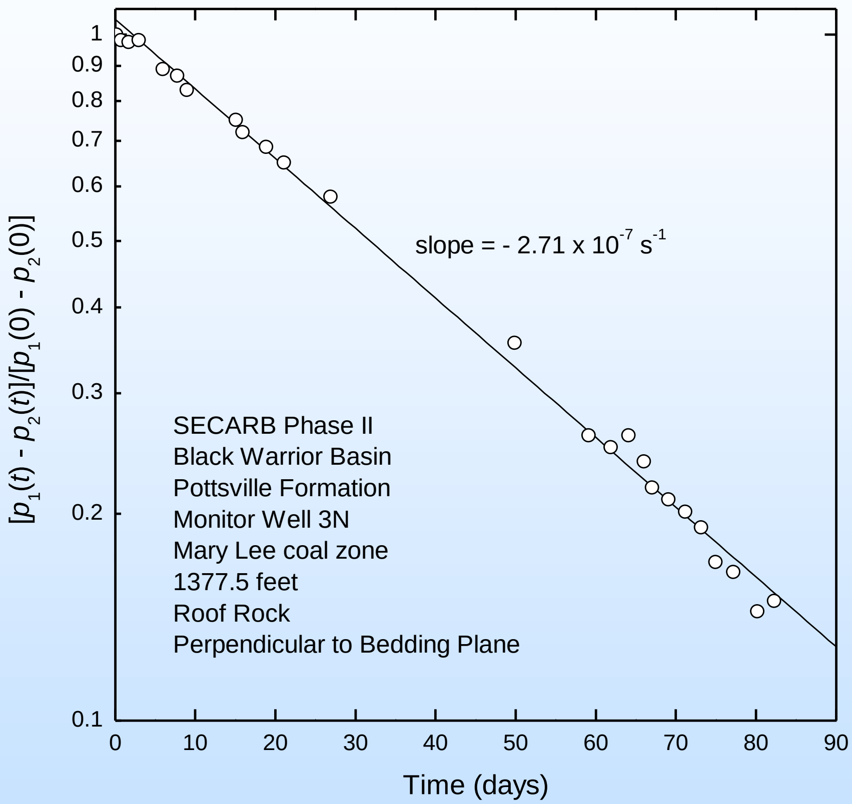
Roof rock (shale) from Mary Lee coal seam in the Black Warrior Basin of Alabama.

Sample from Southeast Regional Carbon Sequestration Partnership and Geological Survey of Alabama.

Sample cut perpendicular to bedding plane. 22 mm in diameter by 11 mm long.

Measurement by pressure-pulse decay using nitrogen at 1000 psig.

Permeability is 0.3 nanodarcy.



Time dependence of dimensionless differential pressure across the sample.

Minimum Capillary Displacement Pressure*†

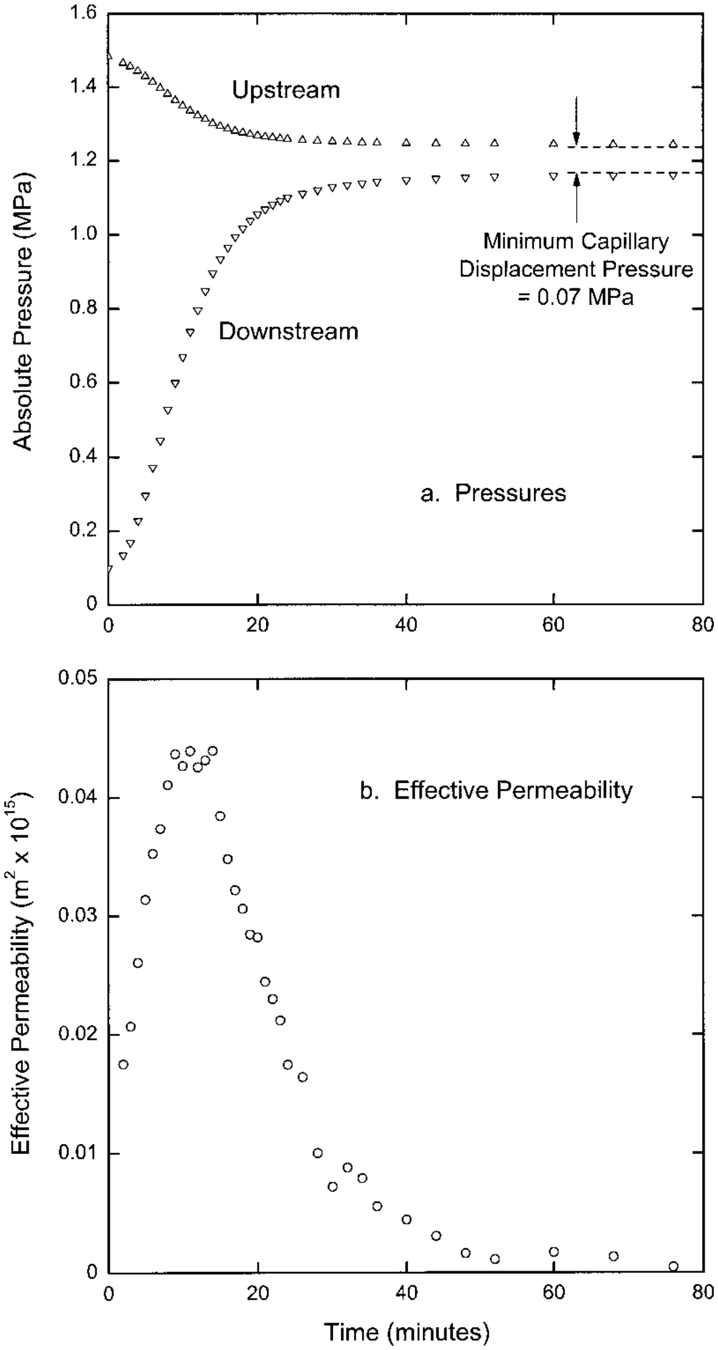
Decay of a pressure pulse imposed across a sample initially saturated with brine.

Boyles Sandstone, Pottsville Formation, Etowah County, AL. 22 mm in diameter by 54 mm long. Single-phase permeability, 0.44 mdarcy.

Upstream-downstream pressure difference approaches an asymptotic value equal to the capillary pressure at the narrowest throat in the highest conductivity pore.

Minimum pressure at which gas would break through brine-saturated rock, given enough time.

Better estimate of breakthrough pressure than obtained by increasing upstream pressure until gas appears at the downstream face.



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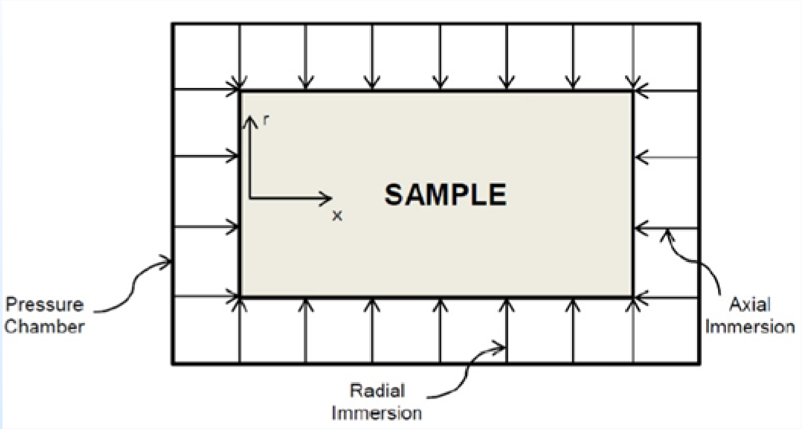
*Hildenbrand, A., S. Schlömer, and B. M. Krooss, "Gas breakthrough experiments on fine-grained sedimentary rocks." *Geofluids*, **2002**, *2*, 3-23.

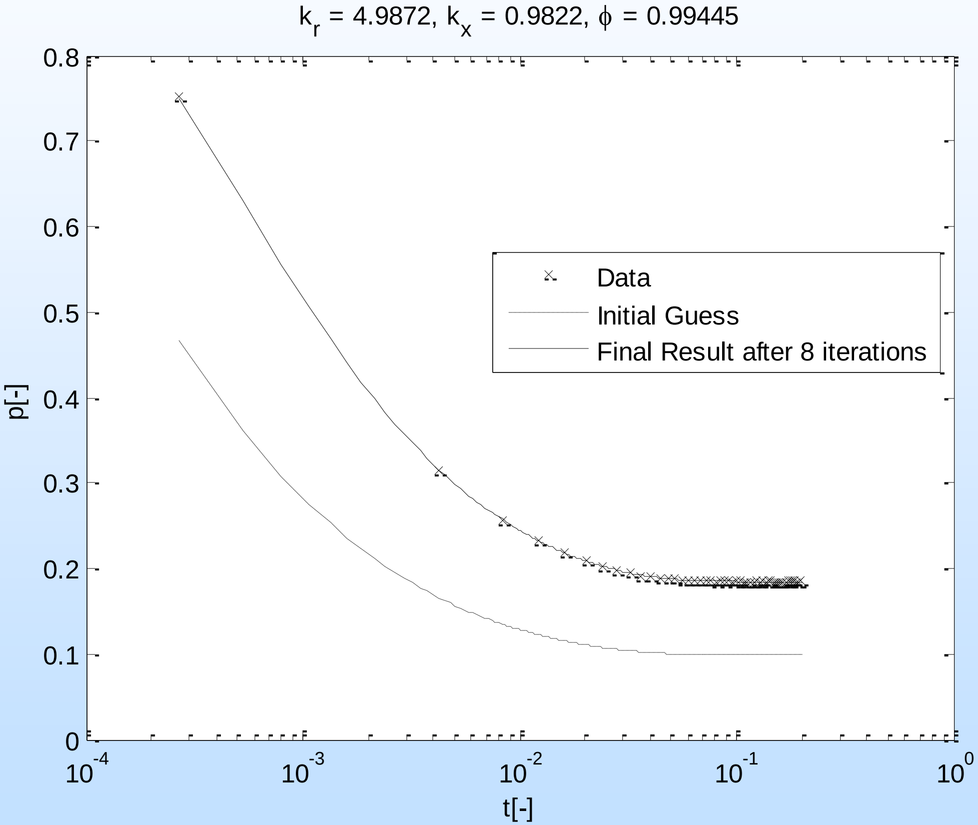
†Hildenbrand, A., S. Schlömer, B. M. Krooss, and R. Littke, "Gas breakthrough experiments on pelitic rocks: comparative study with N_2, CO_2 and CH_4," *Geofluids*, **2004**, *4*, 61-80.

Determination of Axial and Radial Permeability in a Single Experiment

Michael Hannon

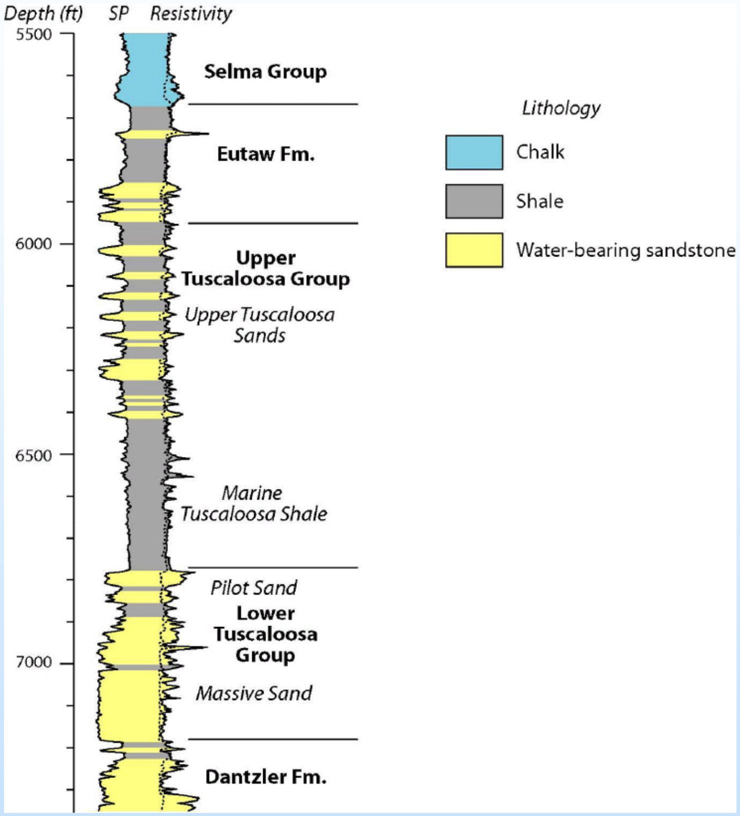


Fit of numerical model to mock data from a sample having $k_r = 5$, $k_x = 1$, and $\phi = 1$, from an initial guess of $k_r = 8$, $k_x = 0.75$, and $\phi = 1.5$



Capacity for CO_2 Storage in Citronelle Dome, Southwest Alabama

Richard Esposito, Jack Pashin, Peter Walsh*



Estimate of CO_2 Storage Capacity in Citronelle Dome

Eutaw and Upper Tuscaloosa Sands:	150 - 600 million tons
Lower Tuscaloosa, Pilot Sand:	40 - 160 million tons
Lower Tuscaloosa, Massive Sand:	200 - 790 million tons
Middle Donovan Sands:	24 - 100 million tons
Donovan oil-bearing Sands:	115 - 460 million tons
Total:	**500 - 2000 million tons**

Alabama Power Plant Barry, 10 miles from Citronelle.

Coal-fired units produce 10-12 million tons CO_2/year.

Citronelle Dome could provide 45 years of storage.

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*R. A. Esposito, J. C. Pashin, and P. M. Walsh, *Environmental Geosciences 15*, **2008**, 53-62.

Critical CO_2 Column Height vs. Formation Thickness

Konstantinos Theodorou and Peter Walsh

Estimate of the critical height of the column of CO_2 that caprock can "support" (Berg, 1975).

Difference in capillary pressures, between pore throats in caprock and pores in the saline formation, *vs.* the buoyant force on the column of CO_2:

$$\text{Critical Height} = \frac{\dfrac{2\gamma}{g}\left[\dfrac{1}{r_{t,cap}} - \dfrac{1}{r_{p,res}}\right]}{\rho_w - \rho_{CO_2}}$$

γ	surface tension of brine against CO_2 = 0.026 N/m (Chalbaud et al., 2009)
$r_{t,cap}$	radius of pore throats in the caprock = 0.15 µm
$r_{p,res}$	radius of pores in the reservoir rock = 5 and 15 µm
g	acceleration due to gravity = 9.8 m/s^2
ρ_w	density of brine = 1000 kg/m^3
ρ_{CO_2}	density of carbon dioxide = 647, 702, and 715 kg/m^3, depending on depth (Lemmon et al., 2007)

Estimates of the critical CO_2 column heights range from 95 to 120 m, greater than the thickness of the formations considered for CO_2 storage in Citronelle Dome, except the Upper Donovan Sands.

Berg, R. R., Capillary Pressures in Stratigraphic Traps, *AAPG Bulletin*, **1975**, *59* (6), 939-956.

Chalbaud, C., M. Robin, J.-M. Lombard, F. Martin, P. Egermann, and H. Bertin, Interfacial tension measurements and wettability evaluation for geological CO_2 storage, *Advances in Water Resources*, **2009**, *32*, 98-109.

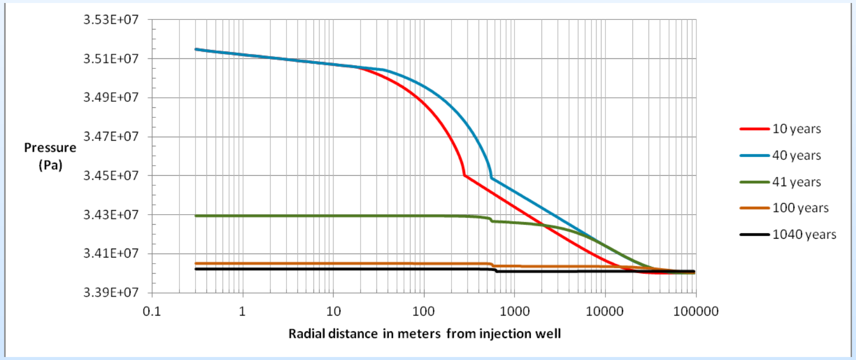
Lemmon, E. W., M. L. Huber, M. O. McLinden, REFPROP Reference Fluid Thermodynamic and Transport Properties, NIST Standard Reference Database 23, Version 8.0, Physical and Chemical Properties Division, U.S. Department of Commerce, 2007.

Simulation of CO_2 Migration and Trapping

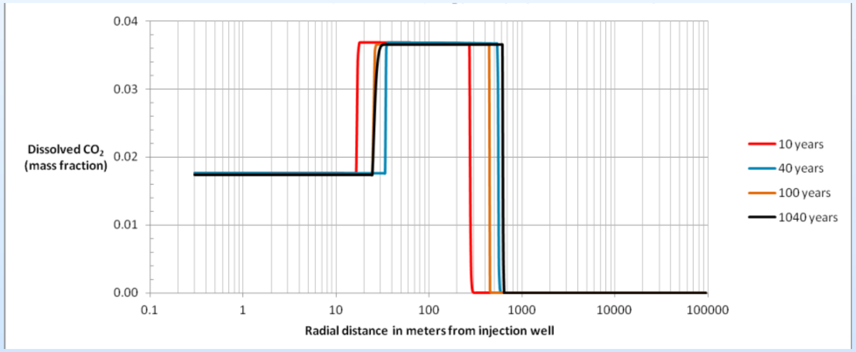
Konstantinos Theodorou

Calculations using the TOUGH2 and TOUGHREACT Software Packages for simulation of CO_2 injection, migration, and trapping in saline formations, with the ECO2N Module for fluid properties. Lawrence Berkeley National Laboratory (Pruess et al., 1999; Xu et al., 2004; Pruess and Spycher, 2006).

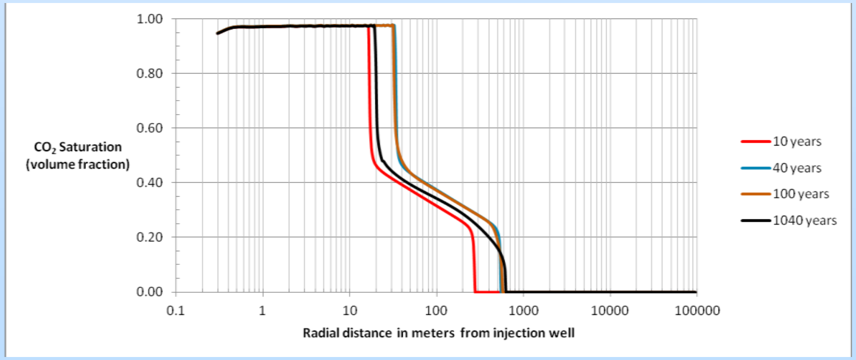
CO_2 was injected through a single well into the Middle Donovan Sand in Citronelle Dome at the rate of 50 tons/day for 40 years. The figures show (clockwise from top left) pressure, the concentration of CO_2 dissolved in brine, supercritical CO_2 saturation, and the volume fraction of precipitated NaCl as functions of distance from the injection well and time.



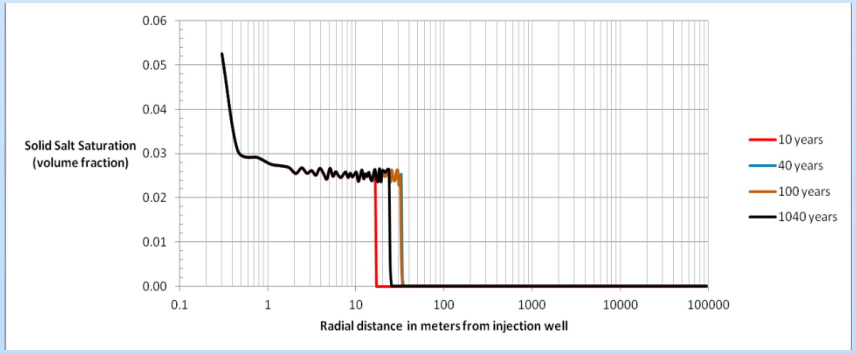
Pressure



Solution-trapped CO_2



Supercritical CO_2 Saturation



Solid NaCl

Student Training through Formal Course Work

Peter Walsh and Richard Esposito

- Advanced undergraduate/graduate course in Combustion offered in Fall 2010 and Fall 2012.
- Focused on coal combustion and gasification for electric power generation, including carbon sequestration, climate change, and energy resources.

Energy resources and utilization:	2	classes
Coal combustion (air and oxygen):	13	"
Gasification and IGCC:	2	"
Control of NO_X, SO_X, and PM:	2	"
CO_2 and greenhouse effect:	2	"
Carbon capture and storage:	3	"
Reviews and exams:	6	"

Y. Yan, G. Lu, and S. J. Rodrigues,
School of Engineering and Digital Arts, The University of Kent, UK
http://www.eda.kent.ac.uk/research/theme_project.aspx?pid=140

- Guest lecture by Richard Esposito on CCUS research, development, demonstration, and commercialization by Alabama Power, Mississippi Power, and Southern Company, including work at the National Carbon Capture Center.
- Field trip to Alabama Power Plant Miller.
- Favorable student ratings, 4.93/5.00. Comment from a student in her application to graduate school: "I was excited to learn that my interest in combustion products, their effects on the atmosphere, and methods of capturing them, could be turned into a career in science ...."

Summary and Accomplishments

- Laboratory established for measurement of rock properties. Permeabilities of rock samples determined over the range from 0.3 ndarcy to 30 mdarcy. Successful measurement of minimum capillary displacement pressure.
- Senior/Key Co-Investigator Richard Esposito was awarded the Ph.D. for his dissertation, entitled, "Business models for commercial-scale carbon dioxide sequestration; with focus on storage capacity and enhanced oil recovery in Citronelle Dome," December 2010.
- A method is under study for determination of both axial and radial permeabilities of core samples in a single test.
- Estimates of critical CO_2 column height for saline and hydrocarbon-bearing formations in Citronelle Dome in Southwest Alabama.
- Simulation of CO_2 migration, salt precipitation, and solution trapping in the Middle Donovan Saline Formation, Citronelle Dome, Southwest Alabama, using the TOUGH2, ECO2N, TOUGHREACT software suite from LBNL (K. Pruess, T. Xu, and coworkers).
- 25 students completed the first offering of the course on coal combustion and gasification, climate change, and carbon sequestration, Fall 2010. 25 students are already enrolled for Fall 2012.

Appendix

Project Schedule

Tasks	Planned Completion	Actual Completion
Task 1.1. Project Management Plan	3/26/2010	1/19/2010
Task 2.1. Assemble the experimental apparatus	1/31/2011	1/31/2011
Task 2.2. Collection of Cap Rock, Brine and CO_2	8/31/2011	5/28/2010
Task 2.3. Measurements of Displacement Pressure and Permeability	8/31/2011	5/30/2011
Task 2.4. Evolution of Cap Rock Properties in the Presence of Carbon Dioxide	9/30/2012	10% complete
Task 3.1. Sequestration Research by Undergraduates	11/30/2012	5/12/2012
Task 3.2. Research on Geological Sequestration by Master's Degree Students	11/30/2012	Please see note*
Task 3.3. Research on Geologic Sequestration by Doctoral Students	11/30/2012	75% complete
Task 4.1. Develop New Lecture Course on Coal Combustion and Gasification, Climate Change, and Carbon Sequestration	8/20/2010	8/18/2010
Task 4.2. First Offering of New Lecture Course, Fall 2010	12/15/2010	12/15/2010
Task 4.3. Second Offering of New Lecture Course, Fall 2012	11/30/2012	To be offered Fall 2012
Task 5.1. Calculations of CO_2 storage capacity and injectivity	8/31/2010	4/3/2010
Task 5.2. Simulation of CO_2 migration	3/31/2011	3/31/2011
Task 5.3. Calculation of CO_2 pressures under seal layers	10/31/2011	12/31/2011
Task 5.4. Simulation of CO_2 seepage in the absence of chemical reactions	5/31/2012	3/31/2012
Task 5.5. Simulation of CO_2 seepage in the presence of chemical reactions	11/30/2012	25% complete

*All four of the graduate students working on the project have been Ph.D. candidates.

Project Milestones

Milestone	Planned Completion Date	Actual Completion Date
1. HQ Milestone: Project Kickoff Meeting	3/31/2010	1/14/2010
2. HQ Milestone: Educational Program Instituted	6/30/2010	4/26/2010
3. HQ Milestone: Semi-Annual Progress Report	9/30/2010	7/30/2010
4. HQ Milestone: Yearly Review Meeting	3/31/2011	2/23/2011
5. HQ Milestone: Yearly Review Meeting	3/30/2012	8/22/2012
6. Revise initial Project Management Plan	3/26/2010	1/19/2010
7. Complete the assembly of the experimental apparatus	1/31/2011	1/31/2011
8. Complete the measurements of permeability and displacement pressure	8/31/2011	5/30/2011
9. Complete the development of new lecture course	8/20/2010	8/18/2010
10. Completion of first offering of new lecture course	12/15/2010	12/15/2010
11. Completion of second offering of new lecture course	11/30/2012	To be offered Fall 2012
12. Completion of the calculation of storage capacity and injectivity of reservoir	8/31/2010	4/3/2010
13. Completion of CO_2 migration simulation	3/31/2011	3/31/2011
14. Simulation of CO_2 seepage in the absence of chemical reactions	5/31/2012	3/31/2012
15. Simulation of CO_2 seepage in the presence of chemical reactions	11/30/2012	25% complete

Peer-Reviewed Journal Publication

Esposito, R. A., Monroe, L. S., and Friedman, J. S., 2011, Deployment Models for Commercialized Carbon Capture and Storage. *Environmental Science & Technology*, v. 45, pp. 139-146, available at: http://pubs.acs.org/doi/abs/10.1021/es101441a