DOE Cooperative Agreement Number DE-FC26-06NT43029
University of Alabama at Birmingham

Carbon-Dioxide-Enhanced Oil Production from the Citronelle Oil Field in the Rodessa Formation, South Alabama

Quarterly Progress Report

Principal Investigator:

Peter M. Walsh
University of Alabama at Birmingham, Birmingham, AL

Co-Investigators:

Ermson Z. Nyakatawa and Xiongwen Chen
Alabama Agricultural and Mechanical University, Normal, AL

Jack Harper, Gary N. Dittmar, Mark Rainer, and Alec Bailey
Denbury Resources, Inc., Plano, TX, and Citronelle, AL

Jack C. Pashin, Denise J. Hills, and David C. Kopaska-Merkel
Geological Survey of Alabama, Tuscaloosa, AL

Richard A. Esposito
Southern Company Services, Inc., Birmingham, AL

Eric S. Carlson and Peter E. Clark
University of Alabama, Tuscaloosa, AL

Konstantinos Theodorou, Alan M. Shih, and Gary Cheng
University of Alabama at Birmingham, Birmingham, AL

Shen-En Chen
University of North Carolina at Charlotte, Charlotte, NC

Graduate Research Assistants:

Kathleen Roberts
Alabama Agricultural and Mechanical University, Normal, AL

Wenya Qi
University of North Carolina at Charlotte, Charlotte, NC

Report of work performed during the period:
October 1 to December 31, 2007

Report issued: January 30, 2008

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Executive Summary

The team of Alabama Agricultural and Mechanical University, Denbury Resources, Inc., Geological Survey of Alabama, Southern Company Services, Inc., University of Alabama, University of Alabama at Birmingham, and University of North Carolina at Charlotte are engaged in a Cooperative Agreement with the U.S. Department of Energy, National Energy Technology Laboratory, to evaluate the potential for carbon-dioxide-enhanced oil recovery and carbon dioxide sequestration in the Citronelle Oil Field in Mobile County, Alabama. The project is now entering its second year, following approval of its continuation by DOE on December 20, 2007. The present report describes work and accomplishments during the fourth quarter of the first year, from October 1 to December 31, 2007.

The work to be done has the following components, with the organizations having the relevant expertise and resources identified in parentheses following each topic: 1. Communication and Technology Transfer (University of Alabama and University of Alabama at Birmingham), 2. Geology and Petrology (Geological Survey of Alabama and Southern Company), 3. Reservoir Fluid Properties and Phase Behavior (University of Alabama), 4. Petroleum Reservoir Simulation (University of Alabama), 5. CO_2 Liquefaction, Transportation, and Storage (Southern Company and Denbury Resources), 6. Well Preparation and CO_2 Injection (Denbury Resources), 7. Surface Monitoring (Alabama A&M University), 8. Seismic Monitoring (University of North Carolina at Charlotte), 9. Saline Formation Simulation (University of Alabama at Birmingham), 10. Visualization of Geologic Structure and Flows (all partners), and 11. Reservoir Management Plan and Economic Analysis (all partners). Subcontracts for the second year of work by the partners will be placed during January 2008.

Technology transfer during the quarter under review was accomplished by publication of a paper in the *Gulf Coast Association of Geological Societies Transactions* describing the geology and petrology of the Citronelle Oil Field and adjacent saline formations (R. A. Esposito, J. C. Pashin, and P. M. Walsh, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," Vol. *57*, 2007, pp. 213-224). The estimated capacity of Citronelle Dome, including saline formations in the Lower and Upper Tuscaloosa Groups and Eutaw Formation, and the oil-producing zones of the Rodessa Formation, is a total of 0.5 to 2 billion short tons of CO_2. The most recent work on geology, petrology, and sedimentology of Citronelle Dome was presented by Jack Pashin of GSA at the Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, held in Corpus Christi, TX, in October.

Xiongwen Chen and Yong Wang of AAMU prepared a paper on the emerging spatial pattern of herpetofauna (reptiles and amphibians) in Alabama, accepted for publication in *Acta Herpetologica*. The paper documents the dependence of species richness and species density on location and environmental factors, and presents a state-

wide view of the emerging species distribution, upon which those in Mobile County and the region of Citronelle, AL, are superimposed. This will help to determine whether changes observed at Citronelle might be associated with carbon storage, or with changes due to other phenomena occurring on a larger spatial scale.

Citronelle Unit B-19-10 #2 well (Permit 3232) will serve as the CO_2 injector for the first field test. CO_2 will be injected into the 14-1 and 16-2 sands, and the sands will be water flooded for six to eight months prior to CO_2 injection. The purposes of the water flood are: 1. to establish the conditions that will exist at other wells in the field when they are converted from water injection to CO_2, 2. to establish a baseline for production under water flood conditions, with which to compare production during CO_2 injection, and 3. to repressurize the formation with water rather than CO_2, in order to have the maximum amount of CO_2 available to sweep the formation.

All of the available spontaneous potential, resistivity, sonic, density, and gamma-ray logs over a four-square-mile area around the test injection well have been digitized, providing a dense grid of well-log cross sections covering the area surrounding the well. Correlation of the target sands is revealing critical controls on sand-body architecture. In most parts of the area of interest, mud-plugged channels in the upper parts of the sandstone units are an important control on pay thickness and interwell hetergeneity. Both of the target sandstone units are apparently truncated below mud plugs. Thin-section petrography of cores shows that the pore system in these rocks is a complex product of: 1. small-scale intercalation of petrophysically distinct rock types, 2. selective preservation of primary interparticle pores in the face of widespread compaction and cementation, and 3. creation of secondary porosity by dissolution of feldspar particles.

A rolling ball viscometer is being assembled to measure minimum miscibility pressure, viscosity, and density of oil-CO_2 mixtures at reservoir temperature and pressure. This instrument will provide the means to determine oil-CO_2 mixture properties for oil samples from all locations in the Field and construction of maps of mixture properties, should there be significant variation from sand to sand. A component of the proposed advanced CO_2-EOR technology recommended by Kuuskraa and Koperna (2006) is the extension of oil-CO_2 miscibility by addition of other gas constituents to CO_2. The rolling ball viscometer is an excellent tool with which to evaluate the gas composition dependence of oil-solvent mixture properties.

All indications based upon present economic conditions and estimates of EOR performance are that a CO_2-EOR project in Citronelle would be profitable and would add approximately 30 million barrels of oil to economically recoverable U.S. oil reserves.

Work during the coming quarter will be focused on development of the flexible framework for computation, visualization, and communication, continuing analyses of the cores and well logs, completion of the rolling-ball viscometer for determination of oil-CO_2 minimum miscibility pressure, viscosity, and density under reservoir conditions, dynamic simulations of CO_2 storage, baseline characterization of the test site, analysis of options for seismic monitoring of CO_2 migration, initiation of the water flood, and planning for CO_2 injection in October.

Contents

Executive Summary iii

List of Tables vii

List of Figures viii

1. Introduction 1

    1.1 Background 1
    1.2. Objectives 2
    1.3. Scope of Work 2
    1.4. Deliverables 2

2. Research Plan - Phase I 4

    2.1. Communication and Technology Transfer 4
    2.2. Geology and Petrology 4
    2.3. Reservoir Fluid Properties and Phase Behavior 5
    2.4. Petroleum Reservoir Simulation 5
    2.5. CO_2 Liquefaction, Transportation, and Storage 5
    2.6. Well Preparation, Water Flood, and CO_2 Injection 6
    2.7. Surface Monitoring 6
    2.8. Seismic Monitoring 7
    2.9. Saline Formation Simulation 7
    2.10. Visualization of Geologic Structure and Flows 7
    2.11. Reservoir Management Plan and Economic Analysis 7

3. Progress of the Work 9

    3.1. Communication and Technology Transfer 9

        3.1.1. Presentations and Publications 9
        3.1.2. Citronelle Field Data 10
        3.1.3. Meetings of the Research Group 10

    3.2. Geology and Petrology 10

        3.2.1. Development of Subsurface Databases 10
        3.2.2. Characterization of Reservoir Petrology 11

    3.3. Reservoir Fluid Properties and Phase Behavior 15
    3.4. Petroleum Reservoir Simulation 17
    3.5. CO_2 Liquefaction, Transportation, and Storage 18
    3.6. Well Preparation and CO_2 Injection 18

Contents (continued)

3.7. Surface Monitoring 18

3.7.1. Atmospheric Measurements and Citronelle Flora 18
3.7.2. Soil Flux Measurements 19

3.8. Seismic Monitoring 20
3.9. Saline Formation Simulation 24
3.10. Visualization of Geologic Structure and Flows 26
3.11. Reservoir Management Plan and Economic Analysis 26

4. Project Status 28

4.1. Task and Milestone Status 28
4.2. Findings and Accomplishments 30
4.3. Technology Transfer 31

5. Conclusions 32

Acronyms 35

References 36

Appendix A: Statement of Work, December 20, 2007 ..... A1

A.1. Tasks to be Performed A1
A.2. Project Schedule A8
A.3. Milestones A9

Appendix B: Presentations, Publications, and Reports B1

B.1. Presentations and Workshops B1
B.2. Publications B1
B.3. Reports B2

Appendix C: Bibliography of Publications on the Citronelle Oil Field and Southwest Alabama Geology C1

List of Tables

3.8.1. Geophysical Studies of CO_2 Flooding of Carbonate Sinks from the Colorado School of Mines. 21

List of Figures

3.2.1. Stratigraphic cross section showing facies relationships in the upper Donovan Sand in the northeastern part of Citronelle Field, including well no. B-19-10 #2, chosen as the injection well for the first field test. 12

3.2.2. Cross-laminated, silty, micaceous sandstone. Permit No. 3336; 11,511 feet. ... 13

3.2.3. Porous sandstone. Most pores are primary interparticle voids or molds of unstable particles. Permit No. 3232; 10,977 feet. 14

3.2.4. Oysters in very fine-grained sandstone. Permit No. 3336; 11,371 feet. 15

3.3.1. Rolling ball viscometer. 16

3.3.2. Key components of the rolling ball viscometer. 17

1. Introduction

1.1. Background

Combustion of fossil fuels for electric power generation and in the transportation, industrial, commercial, and residential sectors in the Southeastern U.S. makes this region a major contributor to nationwide anthropogenic CO_2 emissions (Pashin et al., 2005). Separation of carbon dioxide from combustion products followed by storage in geologic formations is among the most promising approaches to reducing the rate at which CO_2 accumulates in the atmosphere as a result of both human activity and natural processes (Stevens et al., 2001; Friedmann and Homer-Dixon, 2004).

The State of Alabama is endowed with a wealth of potential geologic carbon dioxide sinks, including conventional oil and gas reservoirs, coal bed methane reservoirs, and saline formations (Pashin et al., 2005; Esposito, 2006). Sequestration of carbon dioxide in coal beds, coupled with enhanced methane recovery, is the subject of an investigation by the Southeastern Regional Carbon Sequestration Partnership (Pashin et al., 2004, 2005, 2006). The present team of Alabama A&M University, Denbury Resources Inc., Geological Survey of Alabama, Southern Company, University of Alabama, University of Alabama at Birmingham, and University of North Carolina at Charlotte, will demonstrate enhanced oil recovery using carbon dioxide (CO_2-EOR) to increase oil yield and extend the productive life of the Citronelle Oil Field in Mobile County, Alabama. A parallel investigation will assess the capacity of the oil reservoir and adjacent saline formations for sequestration of carbon dioxide, when tertiary oil recovery operations are complete.

The Citronelle Oil Field is the largest oil producer in the State of Alabama. According to criteria proposed by Kovscek (2002), the field is an ideal site for CO_2 EOR and sequestration: (1) from the reservoir engineering prospective, the site is mature and water-flooded, with existing infrastructure, including deep wells, and (2) from the geological prospective, the field consists of fluvial-deltaic sandstone reservoirs in a simple structural dome and, because of the presence of the regionally extensive Ferry Lake Anhydrite seal, four-way structural closure, and lack of faulting, is naturally stable with respect to CO_2 storage. However, the geology of the heterogeneous siliciclastic rocks in this field is very different from those where CO_2-EOR has been applied commercially, such as in carbonate strata of the Permian Basin in Texas and New Mexico and in the Williston Basin in North Dakota and Montana. The proposed demonstration will introduce CO_2-EOR for tertiary recovery from Alabama's uniquely structured energy resources and realization of benefit to the Nation from additional petroleum production.

1.2. Objectives

The principal objective of the project is to provide the geologic and reservoir engineering analysis and field testing that will permit the operators of the Citronelle Oil Field to successfully apply CO_2-EOR to increase oil recovery and extend the productive life of the field. The project will proceed from the analysis of existing well logs to determine, in the greatest detail possible, the structure of the Rodessa Formation in the vicinity of the Citronelle Field, through seismic measurements to improve spatial resolution of the stratigraphy and movement of CO_2, to a demonstration of increased production from the wells. A second objective is to establish and transfer to industry the engineering expertise with which apply CO_2-EOR at other sites having geologic structure similar to that of the Rodessa Formation, which is very different from the Permian Basin structure where CO_2-EOR is a well established and successful tertiary oil recovery technology.

1.3. Scope of Work

Phase I. Baseline characterization of the reservoir and its fluids will be conducted, and a CO_2 injectivity test will be run in a selected test area. An analysis of the test data and associated environmental measurements will be done, as well as a determination of whether seismic instruments are able to detect changes in the formation and the presence and migration of CO_2 in the reservoir.

Phase II. Studies will include the effect of nitrogen on oil-CO_2 interaction, a stability analysis of the anhydrite dome overlying the reservoir, and refined reservoir simulations and visualizations. A second CO_2 injectivity test will be run, either in the same or in a new test area. An analysis of the test data and associated environmental measurements will be performed, as well as an analysis of whether seismic measurements are able to detect the migration of CO_2 in the formation, and comparison of simulation versus field test results.

Phase III. Migration of CO_2 and stability of the formation will continue to be monitored at the first two field test sites. The reservoir management plan will be refined and a third field test conducted. An analysis of all of the test data and associated environmental measurements will be performed, a comprehensive assessment compiled, and the results disseminated.

1.4. Deliverables

Quarterly Progress and Financial Status Reports will be submitted within 30 days after the end of each quarter.

Special Status Reports will be submitted immediately (within 3 working days), to transmit results having major impact on the course of the project.

Informal Reports will be submitted to the DOE Contracting Officer's Representative on completion of Critical Path Milestones.

A Topical Report will be prepared on the Rodessa Formation CO_2 sequestration capability (Task 50). Other Topical Reports will be submitted, when appropriate, to describe significant new technical advances.

Each investigator plans to present the results of his work at a workshop, at a conference, or by publication at least once a year, beginning in the second year of the project. Because there are many investigators associated with the project, this will represent a substantial and effective means by which to communicate the results of the work to the petroleum, electric utility, and industrial combustion communities. This reporting will continue even after the current project ends.

Patent and Property Certifications will be submitted at the conclusion of the project, on December 31, 2011. The Final Scientific/Technical Report and Final Financial Status Report will be submitted within 90 days after the end of the project, before March 30, 2012.

2. Research Plan - Phase I

The principal components of the work, the leaders of each activity, and the tasks from the Statement of Work to be executed under each component in Phase I (January 1, 2007 to August 31, 2008) are described below (please see the Appendix for the complete statement of work by task for the 5-year project).

2.1. Communication and Technology Transfer

Peter Walsh, University of Alabama at Birmingham
Eric Carlson, University of Alabama.

Task 1. Establish collaboratory environment. The investigators are located at multiple sites. To facilitate the research work and report preparation, a web-based system will be set up for on-line discussion, exchange of data, distribution of information, and monitoring of project activity. It will be a secure web site to which only the project partners will have access, where all data and documents related to the project will be stored, and where all members of the group can contribute to the preparation and revision of reports and other publications.

Task 2. Establish publicly accessible web site for two-way communication with industry. To facilitate technology transfer and feedback from industry, a website describing the project will be set up through which to disseminate results and receive suggestions and comments from industry and the public. This will be the site where any interested person can learn about the partners, purpose, objectives, and progress of the project. It should be of the highest quality, with respect to both technical content and graphic design. It will be constantly evolving over the life of the project and beyond.

2.2. Geology and Petrology

Jack Pashin and Denise Hills, Geological Survey of Alabama
Richard Esposito, Southern Company
Mark A. Rainer, Denbury Resources, Inc.

Task 6. Construct advanced geologic models of Rodessa reservoirs. An analysis of the geologic data available at the time was done for DOE by BDM Petroleum Technologies (Fowler et al., 1998) during their evaluation of the Citronelle Field for waterflood optimization. That work is being augmented by Southern Company Geologist Richard Esposito, in connection with a Southern Company/University of Alabama at Birmingham project to be completed at the end of this calendar year. We will incorporate in the model the results of his analysis and information from the updated site stratigraphy provided by the newly available cores mentioned in Task 4, above. Reservoir architecture and heterogeneity will be quantified and visualized using methods (i.e. architectural element

analysis and sequence stratigraphy) and technologies (immersive 3D visualization) that were not employed in the earlier work by Fowler et al. This effort will improve the accuracy and level of detail in the geologic model, building upon, but not duplicating past work.

Task 4. Analysis of rock samples. Denbury Resources recently discovered drill cores from a previous DOE project that was initiated in the Citronelle Oil Field, but not fully implemented. Denbury is in the process of donating these cores to the Geological Survey of Alabama. The cores comprise eight complete, 800 foot sections through the full Rodessa Formation, from locations throughout the field. Because the cores are continuous, they are an invaluable resource for interpretation of existing well logs and construction of a detailed cross-section of the site. These cores have not been analyzed previously, so this new information will permit an updated review of Citronelle Oil Field geology for CO_2 EOR and sequestration. The cores to be examined first will be those most closely linked to target areas for the field tests. The measurements will include porosities, permeabilities, and microscopic analyses.

2.3. Reservoir Fluid Properties and Phase Behavior

Peter Clark, University of Alabama

Task 5. Analysis of oil and oil-CO_2 interaction. Determination of minimum miscibility pressure. Evaluation of propensity for oil components to precipitate in the presence of CO_2. Measurement of viscosity of the oil as functions of temperature and CO_2 pressure.

2.4. Petroleum Reservoir Simulation

Eric Carlson, University of Alabama
Konstantinos Theodorou, University of Alabama at Birmingham

Task 7. Reservoir simulation. Examine the available reservoir simulators, such as MASTER 3.0, Eclipse, and TOUGH2, and choose the one best suited for simulation of oil production using CO_2 EOR. Perform simulations throughout Phase I of the project to provide analysis that will assist in selection of the test and monitoring wells (Task 8), development of the reservoir management plan (Task 11), the economic and market analysis (Task 12), and visualization of the flows (Task 13).

2.5. CO_2 Liquefaction, Transportation, and Storage

Richard Esposito, Southern Company
Jack Harper, Denbury Resources

The logistics of procuring, transporting, and storing CO_2 at the injection site in Citronelle were not called out as a separate task in the original proposal. However, it has become clear that there are a number of options that need evaluating and that the timing, costs, and availability of equipment pose significant challenges.

2.6. Well Preparation, Water Flood, and CO_2 Injection

Jack Harper, Gary Dittmar, Mark Rainer, and Alec Bailey, Denbury Resources
Richard Esposito, Southern Company
Peter Walsh, University of Alabama at Birmingham

Task 3. Application for permit to conduct Field Test No. 1. A Class II Underground Injection Control (UIC) permit from the State of Alabama will be required for the injection of CO_2 at the site. The application process will be begun at this early stage, so lack of the permit does not result in delays. At this point we intend to list all of the likely candidate wells, then amend the application as the list of potential test wells is narrowed down.

Task 8. Selection of test and monitoring wells. Based upon analysis of drill cores from the Geological Survey of Alabama collection, production records of the State Oil and Gas Board of Alabama, and calculations using the reservoir simulator, choose an injection well and four surrounding wells for testing.

Task 14. Preparation of wells for Field Test No. 1. Preparation of the test wells for CO_2 injection. In addition to updating Citronelle Oil Field and Rodessa Formation geology, the Southern Company Geologist, Richard Esposito, will serve as interface with Denbury regarding the logistics of transport, storage, and injection of CO_2 for the project. This includes provision for onsite storage of CO_2, installation of CO_2-compatible flow lines, the skid for the compressor, refitting the well head, and possible workover of the well. Since Southern Company's objectives are to supply CO_2 for future EOR projects, including identification of sites for CO_2 storage, its involvement in the field operations will facilitate the establishment of mutually beneficial source-sink relationships.

Task 15. Field Test No. 1. Injection of 5000 tons of carbon dioxide into the reservoir for measurement of transient behavior (pressure decay following an injection pulse) and flow versus pressure. Monitor adjacent wells for produced oil, water, and gas, including CO_2.

Task 19. Analysis of data from Field Test No. 1. Perform complete analysis and summary of the test data and associated environmental measurements.

2.7. Surface Monitoring

Ermson Nyakatawa, Alabama A&M University
Xiongwen Chen, Alabama A&M University

Task 10. Baseline soil CO_2 fluxes and ecology. Establish baseline CO_2 concentrations and fluxes from soil and vegetation and the ecology of the field and surrounding landscape, as found.

Task 17. Ecological processes dynamics. Monitor changes in the surrounding landscape during and following injection of carbon dioxide into the oil reservoir. Work under this task monitors any evolution of the types, populations, and spatial distributions of vegetation on the site and surrounding landscape over the course of the project. Even in

the likely event that any CO_2 seepage is completely absorbed by soil and water, it might still influence ecological processes in soil biological communities.

Task 18. Monitor for seepage. Monitoring of CO_2 and fluorocarbon tracer in shallow boreholes and concentration profiles in soil near the surface to determine whether CO_2 seeps from the formation to the atmosphere.

2.8. Seismic Monitoring

Shen-En Chen, University of North Carolina at Charlotte

Task 9. Site characterization by geophysical testing. Perform seismic measurements to provide more detail in the vicinity of the test wells.

Task 16. Geophysical testing for influence of CO_2. Determine if seismic measurements are able to detect changes in the formation and the presence and migration of CO_2.

2.9. Saline Formation Simulation

Konstantinos Theodorou, University of Alabama at Birmingham

Simulation of CO_2 injection and analysis of the fate of CO_2 injected into saline formations were not explicitly called for in the original statement of work, though the possibility of CO_2 storage in formations adjacent to the oil reservoir is mentioned in the text of the proposal and contract. It has become increasingly clear that the saline formations above, between, and below the oil-bearing strata are likely to have much larger capacity for storage of CO_2 than the depleted oil reservoirs, so this topic has assumed greater importance.

2.10. Visualization of Geologic Structure and Flows

Alan Shih, University of Alabama at Birmingham
` Jack Pashin, Geological Survey of Alabama
Eric Carlson, University of Alabama
Konstantinos Theodorou, University of Alabama at Birmingham

Task 13. Visualization of geologic structure and flows. Display, in the UAB Enabling Technology Laboratory and on the project web site, of the geologic structure in the vicinity of the test wells and the results of the calculations of oil, water, and CO_2 flows using the reservoir simulator.

2.11. Reservoir Management Plan and Economic Analysis

Peter Walsh, University of Alabama at Birmingham.

Task 11. Reservoir management plan. On the basis of the available data, develop a preliminary CO_2 injection strategy to ensure efficient oil sweep.

Task 12. Economic and market analysis. Verify that production using CO_2 EOR at this site is viable under current and projected economic conditions. Input to the analysis will

be obtained from the results of the analysis of miscibility (Task 5), geologic modeling (Task 6), reservoir simulation (Task 7), and development of the reservoir management plan (Task 11).

Task 20. Justification for proceeding to Phase II. Update economic and market analysis in light of results obtained to date and reevaluate the long-term viability of the project.

3. Progress of the Work

3.1. Communication and Technology Transfer

Jack C. Pashin, Geological Survey of Alabama
Richard A. Esposito, Southern Company Services
Xiongwen Chen, Alabama A&M University
Peter M. Walsh, University of Alabama at Birmingham

3.1.1. Presentations and Publications

Jack Pashin presented the paper, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," coauthored with Richard Esposito, at the 2007 Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, in Corpus Christi, TX, October 21-23, 2007. A written version of the paper, having the same title, was published in the *Gulf Coast Association of Geological Societies Transactions,* Vol. *57*, 2007, pp. 213-224.

An expanded and updated study of the Citronelle Dome, also entitled, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," by Richard Esposito, Jack Pashin, and Peter Walsh, has been accepted for publication in *Environmental Geosciences*, the archival journal of the Division of Environmental Geosciences of the American Association of Petroleum Geologists. The paper documents the analysis of the Citronelle Oil Field and associated saline formations that make them, respectively, ideal sites for CO_2-EOR and CO_2 storage, and includes estimates of the CO_2 storage capacities of the individual zones and the total capacity of the formations analyzed.

Xiongwen Chen and Yong Wang of AAMU prepared a paper on the emerging spatial pattern of herpetofauna (reptiles and amphibians) in Alabama, that has been accepted for publication in *Acta Herpetologica*. The paper documents the dependence of species richness and species density on location and environmental factors, such as latitude, elevation, annual average temperature and precipitation. It presents a state-wide view of the emerging species distribution upon which those in Mobile County and the region of Citronelle, AL, are superimposed. This will help to determine whether changes observed at Citronelle might be associated with carbon storage, or with changes due to other phenomena occurring on a larger spatial scale.

3.1.2. Citronelle Field Data

A bibliography of publications containing data and information on the Citronelle Oil Field and Southwestern Alabama geology is attached as Appendix C to this report. The bibliography is revised as additional past papers and reports are found and as new studies of the Field and region are published, including those resulting from work under the present project.

3.1.3. Meetings of the Research Group

Richard Esposito has been meeting on a regular basis with Jack Pashin, Denise Hills, and David Kopaska-Merkel at the Geological Survey of Alabama, to participate in the petrographic analysis of drill cores from Citronelle provided by Denbury Resources. The results of that work are described in Section 3.2 of the present report, below.

Xiongwen Chen and Ermson Nyakatawa of Alabama A&M University, and their students, will meet with Peter Walsh of UAB and Alec Bailey of Denbury Resources at Citronelle on January 31 and February 1, to make measurements of the CO_2 background in air and soil at the CO_2 test injection site.

The next meeting of the full research group is tentatively planned for February 21, 2008, at the Citronelle Field, to view the injection and monitoring wells chosen for the first CO_2 test injection, gather information from records stored at the site, discuss the design and plans for the water flood to be conducted prior to CO_2 injection, and further develop the plan for the CO_2 injection itself.

3.2. Geology and Petrology

Jack C. Pashin, Denise J. Hills, and David C. Kopaska-Merkel,
Geological Survey of Alabama
Richard A. Esposito, Southern Company Services

3.2.1. Development of Subsurface Databases

All of the available spontaneous potential, resistivity, sonic, density, and gamma-ray logs over a four-square-mile area around the test injection well (Citronelle Unit B-19-10 #2; Permit 3232) have been digitized. Rasters of the available micrologs are currently being entered into the system. Denise Hills has developed a dense grid of well-log cross sections in this area. Spontaneous potential and resistivity logs have been used for most wells, although where these logs are of poor quality, gamma-ray and density logs have been substituted. All logs have been correlated using the base of the Ferry Lake Anhydrite as a datum.

The Geological Survey of Alabama is in the process of correlating all the well logs in the cross sections, and emphasis is being placed on characterization of the 14-1 and 16-2 sands, which will be used for the CO_2 injection test. Correlation of the target sands requires meticulous attention to detail and is revealing critical controls on sand-

body architecture. In most parts of the area of interest, mud-plugged channels in the upper parts of the sandstone units are an important control on pay thickness and interwell hetergeneity. An important feature to note is that both sandstone units that will be used for CO_2 injection in the B-19-10 #2 well are apparently truncated below mud plugs, as shown in Figure 3.2.1.

An inventory of all available core in Citronelle Field has been completed. Slabbing and description of cores throughout the field continued, and graphic logs have been constructed. Samples showing key depositional features have been photographed. Numerous samples have been sent out for thin sectioning. Standard 1-inch plugs have been made of the 14-1 and 16-2 sands in the B-19-10 #2 well at 1-foot intervals for determination of porosity and permeability. Nineteen plugs have been sent to Core Laboratories (Houston, TX) for analysis. The results are expected in February 2008.

3.2.2. Characterization of Reservoir Petrology

David Kopaska-Merkel has begun performing petrographic analysis of the Donovan Sand in the Citronelle Field. Thin section specimens from selected wells have been described. A photomicrograph of a thin section from a section of core containing interbedded mudstone and sandstone is shown in Figure 3.2.2. The sandstone is cross-laminated, silty, very fine micaceous sandstone containing clay pebbles and abundant fine to medium sand-sized mica flakes. Other parts of the same thin section consist of thinly laminated or lensoid clay, quartzose siltstone, and tightly packed fine to medium mica flakes, or contain sparse vertical burrows. The clay pebbles incorporate quartz silt and sand as well as larger mica flakes, indicating that they picked up relatively coarse material from the sediment surface before deposition. These features, taken together with macroscopic sedimentologic features such as flaser and lenticular bedding, low-angle ripples, and the associated oyster biostromes, suggest deposition on a tidal flat.

Some thin sections contain inter-laminated claystone and muddy sandstone. These samples exhibit complex and disturbed fabrics, which are characteristic of soils. They contain no mica and almost no plagioclase feldspar, but have a great deal of clay, which is a common weathering product of both feldspar and mica. By contrast, a thin section from an interval containing invertebrate burrows does contain a significant amount of mica and exhibits no soil characteristics. This thin section is probably a lagoonal or tidal flat deposit.

Samples of burrowed or cross-bedded, very fine- to fine-grained sandstone contain up to 20% porosity locally. This type of sandstone is typical of reservoir facies in Citronelle Field, shown in Figure 3.2.3. The reservoir rocks typically contain up to about 10% interparticle porosity. Pyrobitumen occupies parts of some of the pores. Silt and clay are virtually absent, and grain-size pores locally indicate enhancement of porosity by dissolution of feldspar. Porosity may have originally exceeded 30% in some areas but has been reduced substantially by compaction.

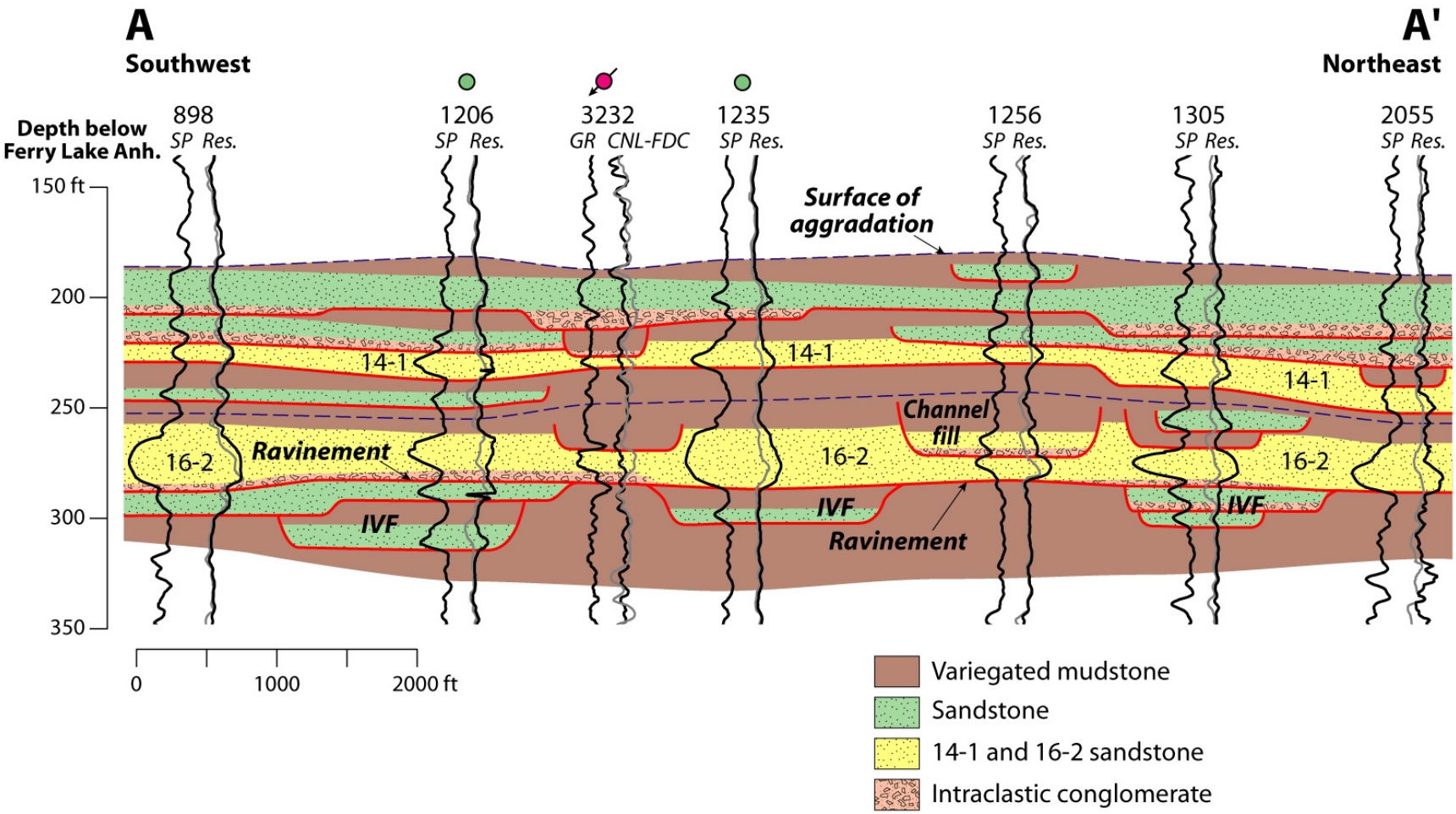


Figure 3.2.1. Stratigraphic cross section showing facies relationships in the upper Donovan Sand in the northeastern part of Citronelle Field, including well no. B-19-10 #2 (Permit No. 3232, to left of center, above), chosen as the injection well for the first field test (Geological Survey of Alabama). "IVF" (three places along the lower part of the figure) is "incised valley fill."

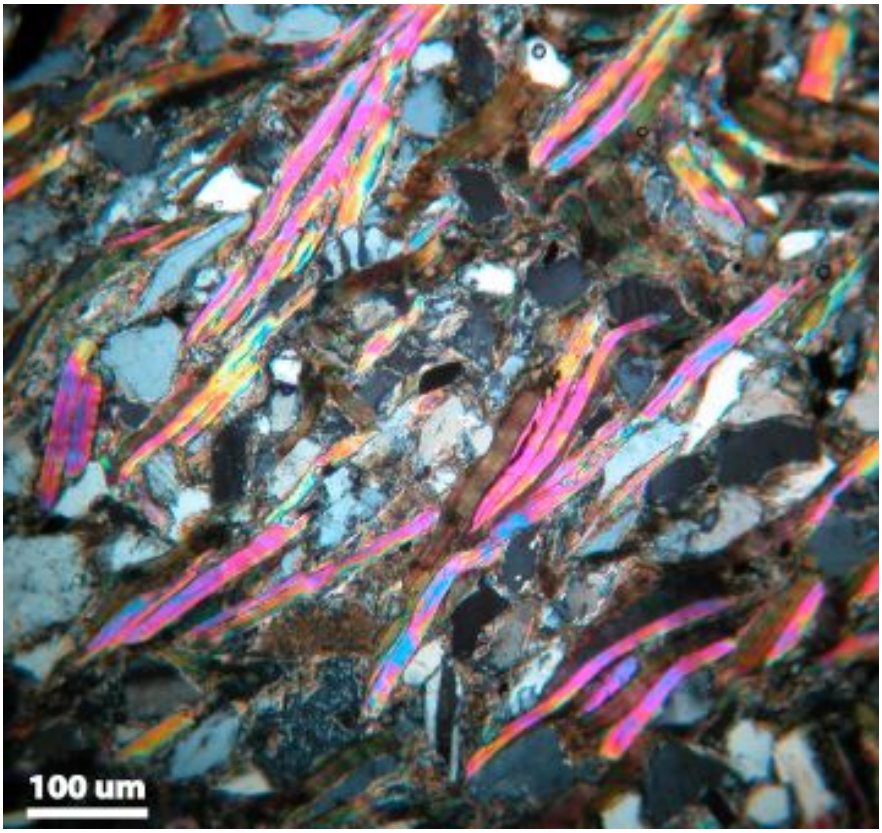


Figure 3.2.2. Cross-laminated, silty, micaceous sandstone (Geological Survey of Alabama). Permit No. 3336; 11,511 feet.

An upward-fining sandstone unit containing an oyster biostrome was sampled (see Figure 3.2.4). This unit is cross bedded and cross laminated in part, but also heavily burrowed in the upper part. Most samples are very fine sandstone in which carbonate cement occludes former interparticle pore space. Porosity currently ranges from nil to, locally, about 15%. Most of this porosity formed by dissolution of unstable feldspar particles. Abundant oysters, some possibly in life position, indicate that this is a lagoonal or estuarine deposit.

In general, preliminary thin-section petrography of Citronelle cores has confirmed naked-eye observations of the slabbed cores. However, it is clear that the pore system in these rocks is a complex product of (1) small-scale intercalation of petrophysically distinct rock types, (2) selective preservation of primary interparticle pores in the face of widespread compaction and cementation, and (3) creation of secondary porosity, primarily by dissolution of feldspar particles.

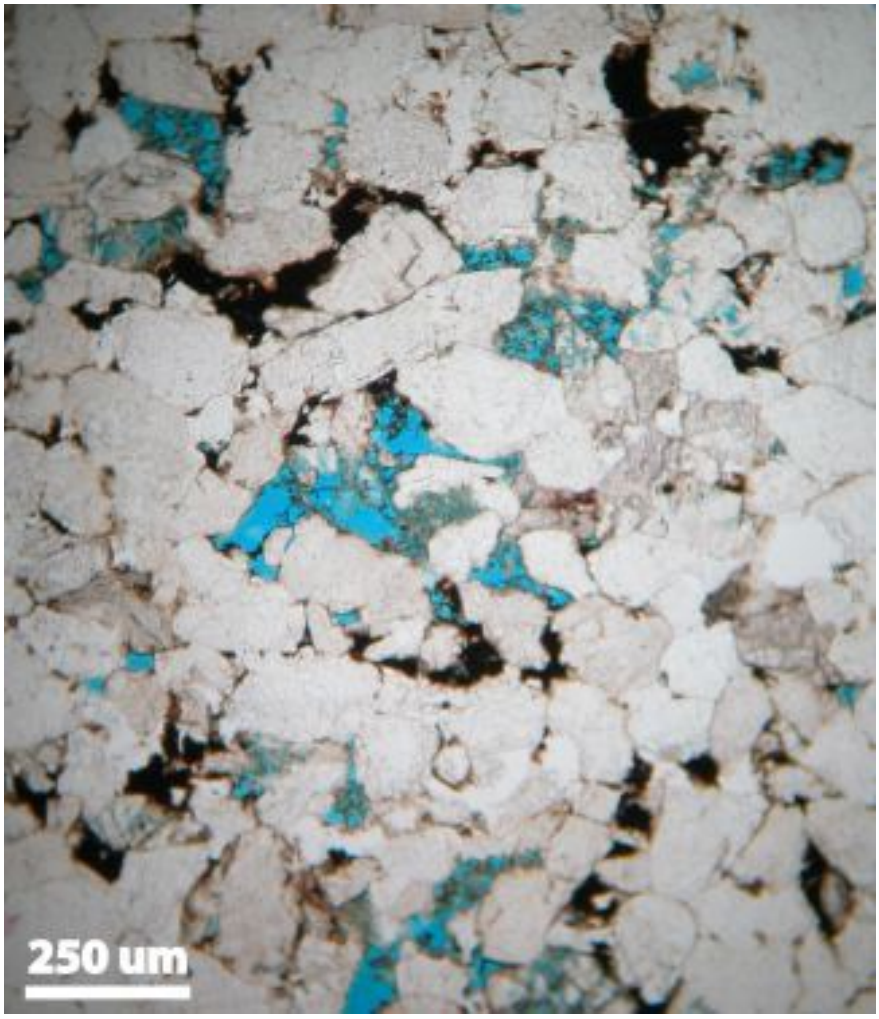


Figure 3.2.3. Porous sandstone (Geological Survey of Alabama). Most pores are primary interparticle voids or molds of unstable particles. Blue epoxy fills open pores. Permit No. 3232; 10,977 feet.

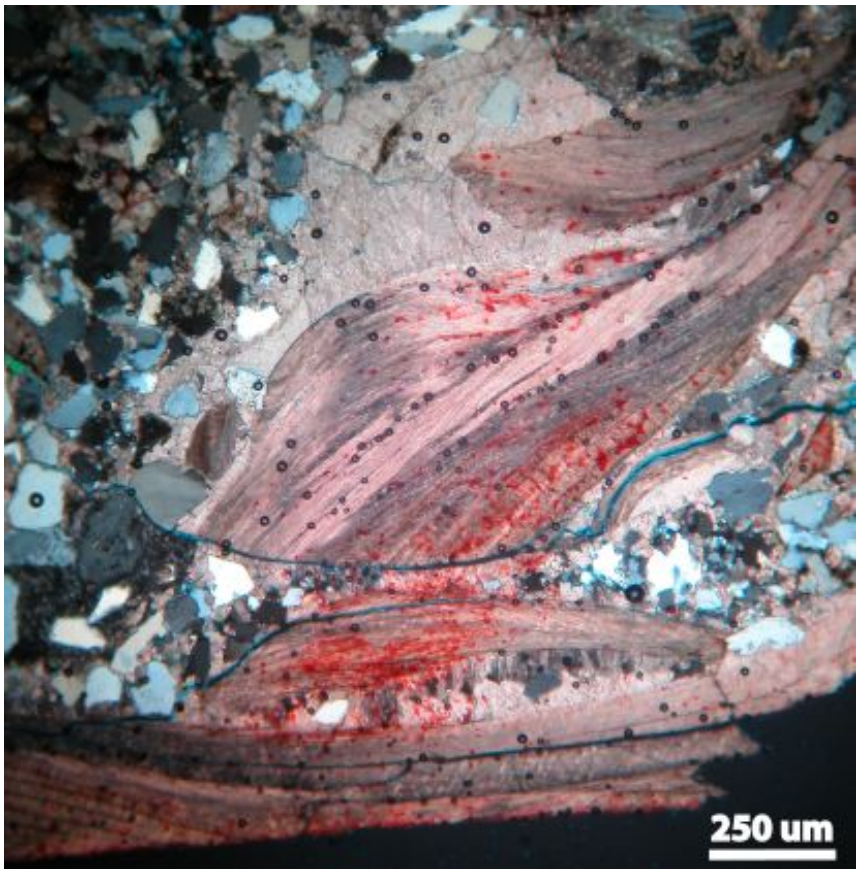


Figure 3.2.4. Oysters in very fine-grained sandstone (Geological Survey of Alabama). Permit No. 3336; 11,371 feet.

3.3. Reservoir Fluid Properties and Phase Behavior

Peter E. Clark, University of Alabama

In order to obtain more quantitative measurements of minimum miscibility pressures (MMP) than are possible using the traditional slim-tube method, a high-pressure rolling ball viscometer, shown in Figures 3.3.1, is being constructed. A rolling ball viscometer relies on timing the movement of a ball down a measurement tube containing the fluid of interest. In addition to MMP, this instrument also offers the promise of determining viscosity and density as a function of carbon dioxide partial pressure, at reservoir temperature, for oil samples from all locations in the Field and construction of maps of oil-CO_2 mixture properties, should there be significant variation from sand to sand.

Advanced Resources International (Kuuskraa and Koperna, 2006) examined the benefits and costs of a number of possible improvements to traditional CO_2-EOR practice. One component of the proposed advanced CO_2-EOR technology is the extension of oil-CO_2 miscibility by addition of other gas constituents to CO_2. The rolling

ball viscometer is an excellent tool with which to evaluate the gas composition dependence of oil-solvent properties.

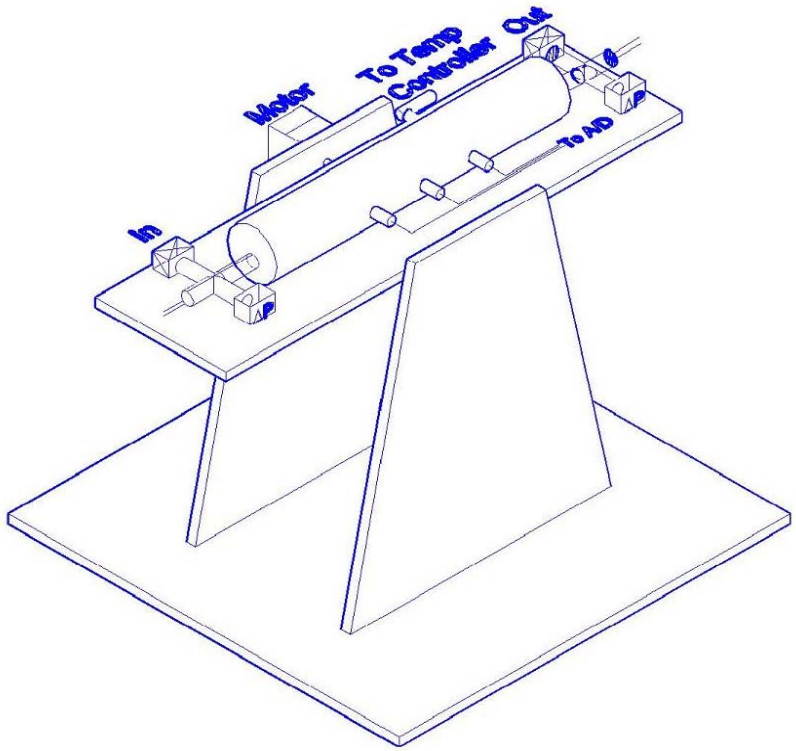


Figure 3.3.1. Rolling ball viscometer (Peter E. Clark, University of Alabama).

During the quarter under review, the frame to hold the rolling ball viscometer was designed and constructed. It is large enough to hold the heater, the tube containing the rolling ball, high pressure valves at both ends, pressure transducers at each end, and the RTD probes. We have also explored various ways of measuring the progress of the ball as it rolls down the tube. Finding an off-the-shelf transducer that would work over the temperature range envisioned for the device was the primary challenge. We found a linear Hall-effect transducer from Allegro Microsystems that operates up to 150 °C, which is significantly higher than the Citronelle reservoir temperature. The circuits needed to drive the transducers and amplify the output signal have been built and tested. We have designed and constructed a mounting bracket for the transducers so they can be placed in close proximity to the measurement tube. Preliminary tests indicate that the transducers are sensitive and fast enough to time the ball rolling through an empty tube so they should work just fine when the tube is filled with liquid.

We also completed the move to a new laboratory that is much better suited for the present project. It has a hood large enough to acommodate the rolling ball viscometer, the CO_2 cylinder, the floating piston accumulator, and the Ruska pump. This will provide a level of safety that was not possible in the previous laboratory space. During the next quarter, we will complete the construction of the instrument and begin its calibration and testing.

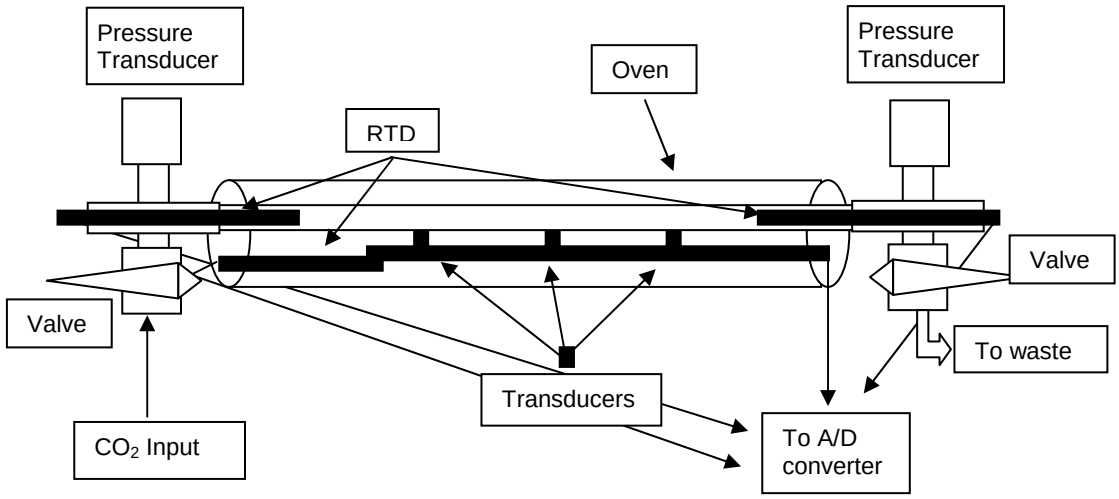


Figure 3.3.2. Key components of the rolling ball viscometer (Peter E. Clark, University of Alabama).

3.4. Petroleum Reservoir Simulation

Eric S. Carlson, University of Alabama
Konstantinos Theodorou, University of Alabama at Birmingham

Results of a simulation of Citronelle reservoirs using the US DOE/NETL MASTER 3.0 reservoir simulator (Zeng, Grigg, and Chang, 2005) were presented in the first Quarterly Progress Report (April 30, 2007). Static estimates of CO_2 capacity following enhanced oil recovery were also presented in that report, then refined in the second Quarterly Progress Report (July 30, 2007). A more detailed simulation, for example using the SENSOR simulation tools from Coats Engineering Inc., will begin when correlation of the well logs in the 64-quarter area around the injection well and collection and measurement of porosity and permeability data for the sands are complete.

The team has manually downloaded all of the (695) well files for Citronelle and all of the (469) well production data files from the Alabama Oil and Gas Board web site. These include historical production records from 1955 through October 2007. All of the production data have been plotted, and curve fits have been attempted for wells that are still producing. However, most of these fits are not useful for assessment of future performance, since few wells exhibit any clear oil production trends.

Assembly of these data is the first step in a comprehensive assessment of field-wide production performance. After acquisition of injection data, the team will attempt to determine "typical" well production behavior, and will search for spatial trends in performance. This work has two purposes and objectives: (1) It constitutes the data set with which the reservoir simulation will be tested and validated, and (2) It provides the base line against which to quantify response to injection of CO_2.

3.5. CO_2 Liquefaction, Transportation, and Storage

Richard A. Esposito, Southern Company Services

Denbury Resources and Southern Company jointly prepared and sent letters to six gas service providers, requesting pricing and possible cost share for liquefaction and delivery of CO_2 to Citronelle.

3.6. Well Preparation and CO_2 Injection

Jack Harper, Gary Dittmar, Mark Rainer, and Alec Bailey, Denbury Resources
Jack C. Pashin and Denise J. Hills, Geological Survey of Alabama
Richard A. Esposito, Southern Company Services
Peter M. Walsh, University of Alabama at Birmingham

Two important decisions have been made, regarding the preparation of the B-19-10 #2 well that will serve as the CO_2 injector for the first field test: (1) CO_2 will be injected into both the 14-1 and 16-2 sands, rather than into just the 16-2 sand, and (2) the sands will be water flooded for six to eight months, prior to CO_2 injection.

The reasons for first conducting a water flood are: (1) to establish the conditions that will exist at other wells in the field when they are converted from water injection to CO_2, (2) to establish a baseline for production under water flood conditions, with which to compare production during CO_2 injection, and (3) to repressurize the formation with water rather than CO_2, in order to have the maximum amount of CO_2 available to sweep the formation.

Work-over of the injector and producers is well underway. Water flooding is expected to begin in February 2008.

3.7. Surface Monitoring

Xiongwen Chen, Ermson Z. Nyakatawa, and Kathleen Roberts
Alabama A&M University

3.7.1. Atmospheric Measurements and Citronelle Flora (X. Chen and K. Roberts)

The accomplishments of this research group during the period under review were the following: (1) Development of GIS layers for layout of monitoring sites, based upon maps of roads, oil wells, and sand depths, (2) Literature review, showing that much of the literature on CO_2-EOR does not include ecological and environmental assessments, (3) Historical data of air quality in Mobile County was collected with the help of the office of the U.S. Environmental Protection Agency, (4) Two visits to Citronelle for monitoring of the atmospheric concentrations of CO_2, O_2, CH_4, SO_2, H_2S and aerosol at public sites such as schools, churches, and at the roadside, (5) Kathleen Roberts, the AAMU Graduate Research Assistant supported by the project, used information from the original proposal, with guidance from Dr. Chen, to develop a mini-proposal regarding the spatial distribution pattern of wildflowers in Citronelle, was awarded a scholarship (with limited finding) for her work from the Alabama Wildflower Society, and (6) Dr. Chen's paper on

the emergent spatial pattern of herpetofauna in Alabama (Chen and Wang, 2007), based upon work supported in part by the present project, was accepted for publication by *Acta Herpetologica*.

3.7.2. Soil Flux Measurements (E. Nyakatawa)

Dr. Nyakatawa will visit the proposed research area in Citronelle on January 31 and February 1,2008 with Peter Walsh, Xiongwen Chen, and Denbury host Alec Bailey, for a visual tour and inspection of the area. The objective is to understand the nature of the terrain and equipment, for planning of the number and locations of sampling points.

During February and March of 2008 Dr. Nyakatawa and his research assistants will again visit the research area in Citronelle to collect baseline soil characterization samples for assessment of the inherent soil physical, biological, and chemical properties that may have an impact on CO_2 movement and the potential for carbon sequestration in the ground.

The following data will be collected.

1. Vegetation - types
2. Management history
3. Landscape and soil profile attributes
4. Climatic attributes (long- and short-term); Air temperature (min, max), precipitation, relative humidity, wind speed, solar radiation, and soil temperature, and
5. GPS coordinates of each sampling location.

Soil samples will be collected using the core method at depth increments of 0-20, 20-40, 40-60, 60-80, and 80-100 cm. Five soil cores will be collected from each sampling station and composite samples prepared for each location. The relevant soil properties and the methods used to determine them are summarized below:

Physical Properties. Soil bulk density (intact core procedure by Blake and Hartge, 1986), soil texture (Bouyoucos, 1936; Day, 1965), infiltration rate, soil porosity, hydraulic conductivity, available water capacity and field capacity (Klute, 1986).

Chemical Properties. Soil pH (Orion A290 pH meter, Orion Research Inc., Boston, MA), total soil organic carbon (LECO CN analyzer, LECO Corp, St. Joseph, MI), total soil N, extractable ammonium N and nitrate N (NH_4-N and NO_3-N, Easy Chem, Systea Scientific), soluble salts conductivity (conductance/resistance meter) (Bower and Wilcox, 1965), total and extractable P, K, Ca, and Mg (Inductively Coupled Plasma Emission, Maxfield and Mindak, 1985; Mehlich, 1985).

Biological Properties. Soil microbial C and N will be estimated by extracting 25-g and 5-g oven-dry equivalents of field-moist soil samples respectively in 0.5*M* K_2SO_4 using the chloroform-fumigation-extraction method as described by Vance et al. (1987) and Brookes et al. (1985). Concentration of organic C and N in the extracts will be

determined using a CN analyzer after acidification with a drop of 2*M* HCl to remove any dissolve carbonate. Microbial biomass C and N will be calculated using k_{EC} and k_{EN} factors of 0.30 (Sparling et al., 1990) and 0.45 (Jenkinson, 1988), respectively.

Plant Nutrient Data Collection. Plant data analyses will be done to investigate the potential of the plant to remove nutrients from the soil. This data will include total C, N, P, Ca, Mg, and Zn contents of plant residues and plant biomass (above ground).

Baseline Soil CO_2 Gradient Levels. These data will be used to establish existing trends in CO_2 concentration in the soil profile prior to injection of CO_2 into oil wells. Dr. Nyakatawa proposes to use the Gas Vapor Probe gas sampling system (AMS, Inc.) to collect gas samples from various soil depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm). The control will be a gas sample withdrawn from the air. This system is specially designed for taking samples to monitor gas movement in the ground and is extensively used in gas and oil exploration systems. The system permits periodic sampling of gas without disturbing the sampling area and without affecting gas fluxes, by having special sampling tips permanently installed in the ground. The samples will be collected into vials using a special pump, then sealed and transported to the laboratory, where a GC will be used to measure CO_2 concentration. The sampling locations will be chosen at various distances from the injection point and will be replicated to account for variability.

3.8. Seismic Monitoring

Shen-En Chen and Wenya Qi, University of North Carolina at Charlotte

An excellent series of theses and dissertations reporting geophysical studies associated with CO_2 flooding of carbonate reservoirs has been published by the Colorado School of Mines. These reports are useful because they describe measurements at various stages of CO_2 flooding at two key sites: the Weyburn Field in Saskatchewan and the Vacuum Field in New Mexico. Both are carbonate reservoirs, but under different geological conditions. Extensive data collection and analyses have been conducted at the two fields. The Weyburn Field was water flooded beginning in 1964, and the Vacuum Field was water flooded during the 1980s. Weyburn oil production zones include both thin (from 1 to 3 m at Midale Marly) and thick (from 10 to 22 m at Vuggy) zones. The Vacuum in the San Andres formation, on the other hand, is very thick (460 m). To illustrate the effects of CO_2 flooding, several parameters were studied, including formation anisotropy, wave speeds, etc.

We present here a review of the Colorado School of Mines documents, focused on the following features:

1. Geophysical testing methodologies,
2. Signal processing techniques,
3. Analytical techniques, and
4. Parameters of interest for CO_2 flooding.

Table 3.8.1 shows a comparison between the reported test methods and analyses at different phases of the respective studies. All of the reported methods are based upon seismic measurements.

Table 3.8.1.
Geophysical Studies of CO_2 Flooding of Carbonate Sinks from the Colorado School of Mines.

Field	Author	Test Method	Notes
	Colorado School of Mines	**Dynamic data from time-lapse (4D), multicomponent (9C) seismic surveys & static information from well logs and VSP surveys**	**Different phases of the Reservoir Characterization Project (RCP)**
Weyburn Field, Saskatchewan, Canada **• Thin, fractured carbonate reservoir,** **• Depth range 1300m-1500m)**	Royer, 2005	4D P-wave seismic amplitude differences (changes of both of the cross-equalized monitor surveys for full-offset and limited-angle stacks)	• Two repeat surveys were shot after baseline survey and CO_2 injection with 1 year interval. • Cross-equalization is used to minimize the differences in the static portion (above reservoir zone) between the monitor surveys and baseline survey. • By dividing the data in limited-angle stacks, greater insight into the full-offset P-wave seismic is gained.
	Bunge, 2000	Fracture characterization from core and image logs	Fracture height, aperture, density, and orientation were quantified for three sets of open fractures, providing important information for angle stacks analysis.
	Brown, 2002	4D RMS amplitude (percentage & absolute) change for P-wave data	• Limited by having only one monitor survey to evaluate • Some results conflict with Royer's and Herawati's. • Further refinement needed due to the lack of cross-

			equalization.
	Herawati, 2002	4D P-wave impedance inversion (both sparse-spike and model-based), with cross-equalization applied before inversion	• With well logs introduced into the inversion procedure, separate reservoir units in different geo zones were characterized, which is not possible from the stacked seismic data alone. • Results generally similar to those of 4D seismic amplitude
	Jenner, 2001	Azimuthal anisotropy of 3-D P-wave seismic data (variations of P-wave normal moveout velocities and azimuthal amplitude versus offset variations are investigated)	With no monitor surveys to analyze, this work is used as a predictive tool for potential fracture zones identification and provides a good analog for comparison with 4D data.
	Cardona, 2002	Fracture characterization and anisotropy analysis using P-wave and S-wave seismic data	• The azimuthal variation of the normal moveout velocities of P-waves for baseline seismic survey and the polarizations and splitting of shear-waves estimated from travel times were determined. • A greater understanding of how fluid moves occurs through gained insight on the fracture symmetry regimes. • Results consistent with Royer's
Vacuum Field, New Mexico **• Porous, fractured dolomitized carbonate reservoir** **• Located on faulted anticline** **• Huff-and-Puff**	Cabrera-Garzon, 2001	Post-stack seismic attributes including P- and S_1-wave amplitudes, velocity ratios, and shear wave anisotropy were incorporated into the petrophysical description of the reservoir by using a combination of 2D and	Attribute from multicomponent seismic data especially <u>4D shear wave anisotropy anomalies</u> provide a better determination of the petrophysics of a reservoir than by using P-wave attributes only. • The cross correlation analysis of post-stack trace

CO_2 injection program was performed in 1995. **• 6 CO_2 injectors**		3D geostatistical methods.	pairs provided a global estimate of uncertainty. • Understanding of local estimates of uncertainty is needed by using the cross correlation analysis in the pre-stack domain or common trace pairs from partial stacks.
	Duranti, 2001	• Both 4D 9C and surface 3D seismic analysis were employed. • Post-stack analysis for both P- and S-wave data (cross-equalization for P-waves & a combination of layer stripping and cross-equalization for S-waves)	• 4D S-wave splitting can be a powerful indicator of saturation changes in the presence of corrugated fracture sets. • 4D seismic anomalies need to be corroborated by additional independent measurements such pore pressure and stress measurements at well sites (VSP, crossdipole logging) to study fracture detection as a function of frequency.
	Michaud, 2001	4D 9C borehole seismic • Downgoing waves were used to minimize the difference in seismic data due to the difference in acquisition tools and near-surface conditions. • Polarization angles and time delays are detected for S-wave analysis • 3D P-wave data was analyzed to indicate faults and fracture in the vicinity of the VSP well • Cross-equalization is used in processing.	• Borehole seismic data reveal near-surface properties, which cannot be easily retrieved from surface seismic data. • Intrinsic Q factor could be retrieved by the autocorrelatioin of both downgoing and upgoing waves at each geophone location. • Fast and slow S-waves indicated different changes (fast one shows a velocity decrease and an attenuation increase, whereas the slow one presents the opposite behavior.) The changes observed on the slow S-waves corroborate those observed on P-waves.
	Lorenzen, 2000	• Poststack sparse-spike inversion method	• Comparison of the inverted VSP data and the

		was used on the seismic data to extract impedances of the fast and the slow S-waves. • Cross-equalization method was used in seismic inversion. • Polarization analysis was done for the pre- and post-CO_2 S-wave data.	inverted surface seismic data shows excellent correlation of the observed 4D changes. • S-waves are sensitive to fluid changes in a fractured medium. (Fast S-wave is good indicator of porosity in a carbonate reservoir.) • Anisotropy measured from vertical S-wave splitting is an important parameter. • The resolution is limited by the seismic bandwidth. • The estimated impedance does not separate the velocity and density effects.

During the quarter under review, the UNCC group continued to work on the identification of computer simulation software for study of the propagation, through geologic formations, of stress waves due to hydraulic fracturing and seismic-induced waves. The most cost-effective software for the purpose has not yet been definitely identified. They will attempt to complete this evaluation and acquire the software during the next quarter.

3.9. Saline Formation Simulation

Konstantinos Theodorou, University of Alabama at Birmingham

In our previous Quarterly Progress Report (October 27, 2007), Richard Esposito, Jack Pashin, and Peter Walsh presented static estimates of the storage capacity of Citronelle Dome, including saline formations in the Lower and Upper Tuscaloosa Groups and Eutaw Formation, and the oil-producing zones of the Rodessa Formation. The estimate was a total capacity of 500 million to 2 billion short tons of CO_2. In order to refine this calculation and determine injectivity as well as the capacity of the formations, and to assess the long-term migration and fate of stored CO_2, including mineralization, the next stage is a dynamic simulation of the process, including chemistry. The software chosen for this phase of the work is the TOUGH2 numerical simulation program for multi-phase fluid flow in porous and fractured media, from Lawrence Berkeley National Laboratory (Pruess, Oldenburg, and Moridis, 1999). A fluid property module, ECO2N (Pruess, 2005), specifically designed for study of CO_2 storage in saline formations, is also available.

The focus of simulation activities during the period under review, has been on the calibration of the TOUGH2 simulator. To verify proper software installation and operation the TOUGH2 user's guide provides twelve sample problems spanning the

diverse capabilities of the simulator. The emphasis of the sample problems is demonstration of the preparation of input data and illustration of the code's capabilities. The sample problems also provide benchmarks to test proper code installation. Although TOUGH2 will be used primarily for the analysis of CO_2 injection into the Citronelle saline formations it is necessary to reproduce the results of all twelve sample problems.

As a multipurpose simulator, TOUGH2 consists of a number of functional units having flexible and transparent interfaces. The code is written in standard Fortran 77 and can be run on any platform including PCs for which appropriate Fortran compilers are available. The compiler selected for use in our applications was the Intel Visual Fortran Compiler 10.1 with built-in optimization.

Work on testing of the simulator was begun by attempting to emulate the first sample problem provided in the TOUGH2 user's guide. During compilation, a number of errors appeared, which were attributed to erroneous compiler settings. Information in the TOUGH2 guide regarding compiler settings is limited, due to the wide variety of compiler versions and types that are available. As a result, the appropriate settings for successful compilation and linking of the simulator code components were not completely known.

After some trial and error and intuitive adjustments to the compiler settings the sample program did compile. However, the executable, when invoked, would initiate the simulation, but suspend it after displaying the software logo and echoing part of the parameter initializations. In an effort to identify the reason for the simulator's suspending its execution, the sample program was also run on a UNIX compiler, with the assistance of Gary Cheng. However, the program performed the same on the UNIX system as in the PC runs and suspended execution at the same point in the simulation.

We then consulted the program developers and their coworkers at Lawrence Berkeley National Laboratory, including Karsten Pruess, Qian Xu, George Moridis, and Mike Kowalski. Dr. Moridis and Mr. Kowalski worked with us by e-mail and telephone for almost two months to identify the problem. In the end, with their help, a new version of the main TOUGH2 program component and two auxiliary modules were installed, all the appropriate compiler settings were established, and the twelve sample problems were successfully emulated.

Work will continue with the implementation of ECO2N (Pruess, 2005), a fluid property module for mixtures of water, NaCl and CO_2. The module is designed for application to geologic sequestration of CO_2 in saline formations. It includes modeling of salt precipitation and dissolution processes taking place in the saline environment as well as equilibrium partitioning among the three phases: solid, aqueous solution, and gas. Associated changes in rock porosity and permeability may also be modeled. ECO2N is also written in Fortran 77 and is compatible with TOUGH2, Version 2.0.

3.10. Visualization of Geologic Structure and Flows

Eric S. Carlson, University of Alabama
Alan M. Shih, University of Alabama at Birmingham

The visualization of flows, following CO_2 injection into the hydrocarbon reservoirs and saline formations of Citronelle Dome awaits the simulation of these cases using the SENSOR (Coats Engineering) and TOUGH2/ECO2N (Lawrence Berkeley National Laboratory) simulators, respectively. Simulation of the hydrocarbon reservoirs will begin when the correlation of well logs and measurements of porosity and permeability are complete. Simulation of the saline formations will begin when the ECO2N module is successfully implemented with the TOUGH2 code, as described in Section 3.9.

3.11. Reservoir Management Plan and Economic Analysis.

Peter M. Walsh, University of Alabama at Birmingham

In the previous Quarterly Progress Report (October 27, 2007) we presented a summary of a study by Advanced Resources International (Kuuskraa and Koperna, 2006) of the benefits and costs of possible improvements to traditional CO_2-EOR practice. The advanced CO_2-EOR technology proposed by Kuuskraa and Koperna has the following components: (1) Increased volume of CO_2 injection, to 1 to 2 hydrocarbon pore volumes, (2) Innovative flood design and well placement, (3) Reduction of mobility ratio by enhancement of water viscosity during water-alternating-gas (WAG) recovery, (4) Extension of oil-CO_2 miscibility by addition of gas constituents to CO_2, and (5) Implementation of flood performance diagnostics and improved flood control. By making these proposed improvements in CO_2-EOR, cumulative recovery by all methods (primary, secondary, and enhanced), was predicted to increase from the present value near 35% (primary and secondary recovery) to approximately 60%.

In the same report by Kuuskraa and Koperna (2006), an analysis of the costs and benefits from implementing advances in CO_2-EOR technology, showed that, with high oil prices and adequate CO_2 supply (CO_2 price tied to oil price), increasing oil recovery by increasing the amount of CO_2 injected to 1.5 HCPV, addition of one horizontal and one vertical well to each injection-production well pattern, use of viscosity enhancers in injected water, enhancement of miscibility by addition of other gases to CO_2, implementation of flood performance diagnostics, and employment of a professional technical team, was expected to increase the productive life and oil recovery from the majority of U.S. oil fields examined.

The specific forms that the proposed innovations could take in the context of the CO_2 flood being planned for the Citronelle Oil Field were outlined in our October 27, 2007 report. Though not all of the features of next generation CO_2-EOR discussed by Kuuskraa and Koperna may be adopted at Citronelle (e.g. drilling horizontal wells), and the behavior of Citronelle sands under CO_2 injection is known only from the pilot CO_2 flood conducted in the early 1980's (Kennedy et al., 1983), indications based upon present economic conditions and the other information currently available are that a CO_2-

EOR project in Citronelle would be profitable and would add approximately 30 million barrels of oil to economically recoverable U.S. oil reserves.

4. Project Status

4.1. Task and Milestone Status

Please see Appendix A for the Statement of Work for Phase I (pages A1 to A3) and Project Schedule (page A8). Nine tasks were scheduled for completion at the end of the first year: Tasks 1, 2, 3, 4, 8, 9, 10, 11, and 12. The status of work under these tasks is described below.

Task 1. Establish collaboratory environment. A collaboratory framework for the research group was set up by Eric Carlson at <http://citronelle.eng.ua.edu>. The site is based on the open source Moodle (Modular Object-Oriented Dynamic Learning Environment) course management system (Moodle Pty. Ltd., Perth, Western Australia). It has Wiki, blogging, forums, web-page authoring, and instant-messaging tools. Preliminary tests identified some server problems that have been solved. Moodle allows optional account authentication for access, so the system will be set up to distribute materials both publicly and privately. A database of engineering, production, geologic and other data on the Citronelle Field will be established for access by the project team.

Task 2. Establish publicly accessible web site for two-way communication with industry. A web site for the project has been set up at <http://me.eng.uab.edu/co2-eor-sequestration/> for transfer of technology and information to the public, to students, and to other workers in the areas of tertiary oil recovery and carbon sequestration. The members' portal on this site does not have all the features of the Moodle software, described above, for exchange of information among the members of the research group, so the Moodle-based site will be used for collaboratory work and distribution of data.

Task 3. Application for permit to conduct Field Test No. 1. The well chosen for the test injection was originally permitted as an injector, so it only needs to be repermitted as an injector. The supporting documents specified under UIC regulations have been submitted to the State Oil and Gas Board of Alabama. It will need a mechanical integrity test to 1500 psi, being conducted in conjunction with workover of the well to prepare it, first for water injection, then for CO_2.

Task 4. Analysis of rock samples. A comprehensive examination of a drill core from Citronelle Field is being performed by Jack Pashin and his coworkers at GSA, with the most recent results described in Section 3.2. That work has led to significant revision of the conventional geologic model for the field that has been handed down from the early studies of the formation in the 1950's and 1960's. This will have significant bearing on our approach to the test injection and the interpretation of its results. Other cores from Citronelle are being slabbed at GSA, so the examination and interpretation of their

structure will continue, becoming a more ambitious undertaking, and having greater significance than anticipated in the original proposal. Nineteen sample plugs from Sands 14-1 and 16-2 (one sample per foot of formation thickness), the targets of the first CO_2 injection, are undergoing analysis for porosity and permeability. The results are expected in early February.

Task 8. Selection of test and monitoring wells. The five-spot for the first test injection was identified during a meeting of DRI, GSA, SO, and UAB on July 2. Analysis of well logs and cores has shown that the reservoir heterogeneity so characteristic of Citronelle Field is well represented in the chosen test pattern.

Task 9. Site characterization by geophysical testing. Because of the invasive nature of surface excitation methods and the residential character of the oil field, which is interspersed through the Town of Citronelle, and the great depth of the oil reservoirs, geophysical testing is more difficult to arrange than anticipated. UNCC is examining options, as described in Section 3.8 of this report. There is still time to establish an acceptable technique and conduct background measurements during the water flood to be conducted from March to October 2008.

Task 10. Baseline soil CO_2 fluxes and ecology. AAMU has visited Citronelle and made preliminary measurements of the CO_2 background. The next visit is scheduled for January 31 and February 1, 2008. By the time of the first CO_2 injection, in October 2008, background measurements will have been made over most of the yearly plant growth cycle.

Task 11. Reservoir management plan. Features of a reservoir management plan that would qualify the present project as "next generation CO_2-EOR," according to Kuuskraa and Koperna (2006), are: increasing the amount of CO_2 injected to 1.5 HCPV, addition of one horizontal and one vertical well to each injection-production well pattern, use of viscosity enhancers in injected water, enhancement of miscibility by addition of other gases to CO_2, implementation of flood performance diagnostics, and employment of a professional technical team. The costs and benefits of each of these approaches will be assessed during the 1st, 2nd, and 3rd quarters of 2008.

Task 12. Economic and market analysis. Under the lowest likely oil and highest likely CO_2 prices expected to prevail, on average, for the foreseeable future, and incorporating some of the features of "next generation CO_2-EOR" (though not, for example, the drilling of horizontal wells) specified by Kuuskraa and Koperna (2006), an analysis by Advanced Resources International (2006) indicates that the proposed CO_2-EOR project will be profitable. A calculation using the MASTER 3.0 reservoir simulator estimated that CO_2-EOR will add 30 million barrels of oil to economically recoverable U.S. reserves.

4.2. Findings and Accomplishments

Work during the first 11 months of the project (February through December, 2007) was focused on the following components: geology and petrology of the formation, reservoir fluid properties, planning for the first CO_2 injection, and estimates of CO_2 storage capacity. The findings and accomplishments on each of these fronts are described below.

Identification of a five-spot well pattern for the first test injection of CO_2 that is representative of the field, in a remote location away from private homes, and includes a well already permitted as a gas injector.

Minimum miscibility pressure of Citronelle oil is 2800 psi (Gilchrist, 1981).

Design of a rolling ball viscometer for determination of oil-CO_2 minimum miscibility pressure, density, and viscosity at reservoir conditions, for oil samples taken at locations across the field.

Identification of the TVTK/MayaVi package from Enthought Inc. (Austin, TX) as the software of choice for visualization of the reservoir simulations.

Specification of the geologic characteristics that make the Citronelle Dome an attractive site for CO_2-EOR and storage.

Refereed paper on the Citronelle Dome by Richard Esposito, Jack Pashin, and Peter Walsh accepted for publication in the AAPG journal, *Environmental Geosciences*.

Refereed paper on the emerging spatial pattern of herpetofauna by Xiongwen Chen and Yong Wang of AAMU accepted for publication in *Acta Herpetologica*.

Detailed study of the sedimentology of Citronelle well cores, and well logs, showing that the depositional environments in the Rodessa Formation differ significantly from the model developed in early published work on the field, that has guided development and production from the Citronelle Field in the past.

Identification of critical path items and actions needed to prepare for CO_2 liquefaction, transport from Jackson or Eucutta, MS, to Citronelle, storage at the test site, and injection.

Estimates of CO_2 storage potential of the Citronelle Oil Field and saline formations. The total static estimate of storage capacity of the Eutaw Formation, Upper and Lower Tuscaloosa Groups, and Rodessa Formation in the Citronelle Dome is between approximately 500 million and 2 billion short tons of CO_2.

Evaluation of seismic methods for monitoring CO_2 migration at the large depths of Citronelle oil reservoirs (11,500 ft).

Preliminary measurements of background levels of CO_2 in ambient air at the site, showing large variability induced by automobile and truck exhausts and plant respiration.

Application to the State Oil and Gas Board of Alabama for repermitting of Citronelle Unit B-19-10 #2 well for water and CO_2 injection.

4.3. Technology Transfer

A paper presenting a detailed analysis, from the geological perspective, of the characteristics that make the Citronelle Dome an attractive candidate for CO_2-EOR and storage, including estimates of storage capacity, was prepared by Jack Pashin, Richard Esposito, and Peter Walsh. The paper has been accepted for publication in *Environmental Geosciences*, the archival journal of the Division of Environmental Geosciences of the American Association of Petroleum Geologists. Dr. Pashin and Richard Esposito presented their work on the geology and petrology of Citronelle Dome at the Annual Convention and Exhibition of the American Association of Petroleum Geologists in Long Beach, CA, in April, then at the DOE/NETL Sixth Annual Conference on Carbon Capture and Sequestration, in Pittsburgh, in May, and again at the Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, in Corpus Christi, TX, in October.

Eric Carlson conducted a workshop on visualization for reservoir simulation, entitled: "Flow in Porous Media with Emphasis on Modeling Oil Reservoirs," during the Rocky Mountain Mathematics Consortium Summer School held at the University of Wyoming in Laramie, in June.

Shen-En Chen and Wen-Ya Qi of the University of North Carolina at Charlotte presented options for seismic monitoring of CO_2 migration following injection during the 3rd National Conference on Environmental Science and Technology, held at North Carolina A&T State University in Greensboro, during September.

Xiongwen Chen and Yong Wang of AAMU prepared a paper on the emerging spatial pattern of herpetofauna (reptiles and amphibians) in Alabama, that has been accepted for publication in *Acta Herpetologica*.

These publications, presentations, and the workshop have kept the reservoir engineering and carbon storage communities informed about the progress of the work and its implications for successful CO_2-EOR and storage in formations of the type found in Citronelle Dome.

5. Conclusions

The progress, findings, accomplishments, and conclusions from each of the principal research efforts in which the team was engaged during the past quarter (October 1 through December 31, 2007) are summarized below.

Geology and Petrology. All of the available spontaneous potential, resistivity, sonic, density, and gamma-ray logs over a four-square-mile area around the test injection well (Citronelle Unit B-19-10 #2; Permit 3232) have been digitized, providing a dense grid of well-log cross sections covering the area surrounding the well. GSA is in the process of correlating all the well logs in the cross sections, with emphasis on characterization of the 14-1 and 16-2 sands, into which CO_2 will be injected. Correlation of the target sands is revealing critical controls on sand-body architecture. In most parts of the area of interest, mud-plugged channels in the upper parts of the sandstone units are an important control on pay thickness and interwell hetergeneity. Both of the sandstone units are apparently truncated below mud plugs.

An inventory of all available core in Citronelle Field has been completed. Slabbing and description of cores throughout the field continued, and graphic logs have been constructed. Samples showing key depositional features have been photographed. Numerous samples have been sent out for thin sectioning. Standard 1-inch plugs have been made of the 14-1 and 16-2 sands in the B-19-10 #2 well at 1-foot intervals have been sent to Core Laboratories (Houston, TX) for determination of porosity and permeability.

Preliminary thin-section petrography of Citronelle cores has confirmed naked-eye observations of the slabbed cores. The pore system in these rocks is a complex product of: (1) small-scale intercalation of petrophysically distinct rock types, (2) selective preservation of primary interparticle pores in the face of widespread compaction and cementation, and (3) creation of secondary porosity, primarily by dissolution of feldspar particles.

Reservoir Fluid Properties. Peter Clark and his research group at the University of Alabama are completing the assembly of a rolling ball viscometer with which to measure minimum miscibility pressure, viscosity, and density of oil-CO_2 mixtures at reservoir temperature and pressure. This instrument will provide the means to determine oil-CO_2 mixture properties for oil samples from all locations in the Field and construction of a map of minimum miscibility pressure, should there be significant variation from sand to sand. A report from Advanced Resources International (Kuuskraa and Koperna, 2006) examined the benefits and costs of possible improvements to traditional CO_2-EOR practice. One component of the proposed advanced CO_2-EOR technology is the

extension of oil-CO_2 miscibility by addition of other gas constituents to CO_2. The rolling ball viscometer is an excellent tool with which to evaluate the gas composition dependence of oil-solvent properties.

Pilot Injection. Two important decisions have been made, regarding the preparation of the B-19-10 #2 well that will serve as the CO_2 injector for the first field test: (1) CO_2 will be injected into both the 14-1 and 16-2 sands, rather than into just the 16-2 sand, and (2) the sands will be water flooded for six to eight months, prior to CO_2 injection. The reasons for first conducting a water flood are: (1) to establish the conditions that will exist at other wells in the field when they are converted from water injection to CO_2, (2) to establish a baseline for production under water flood conditions, with which to compare production during CO_2 injection, and (3) to repressurize the formation with water rather than CO_2, in order to have the maximum amount of CO_2 available to sweep the formation.

CO_2 Storage Capacity. Static estimates of the storage capacity of Citronelle Dome, including saline formations in the Lower and Upper Tuscaloosa Groups and Eutaw Formation, and the oil-producing zones of the Rodessa Formation are a total of 500 million to 2 billion short tons of CO_2. The TOUGH2 numerical simulation program for multi-phase fluid flow in porous and fractured media, from Lawrence Berkeley National Laboratory (Pruess, Oldenburg, and Moridis, 1999) and the accompanying fluid property module, ECO2N (Pruess, 2005), specifically designed for study of CO_2 storage in saline formations, are being implemented to refine these calculations, determine injectivity of the formations, and assess the long-term migration and fate of stored CO_2, including mineralization.

Surface Monitoring and Ecology. Xiongwen Chen and Yong Wang of AAMU prepared a paper on the emerging spatial pattern of herpetofauna (reptiles and amphibians) in Alabama, documenting the dependence of species richness and species density on location and environmental factors, such as latitude, elevation, annual average temperature and precipitation. It presents a state-wide view of the emerging species distribution upon which those in Mobile County and the region of Citronelle, AL, are superimposed. This will help to determine whether changes observed at Citronelle might be associated with carbon storage, or with changes due to other phenomena occurring on a larger spatial scale.

Seismic Monitoring. Our present thinking is that the microseismic approach, using signals from naturally-occurring seismic events to observe changes in the formation resulting from water injection and migration of the CO_2 plume, would be least disruptive to the Citronelle community, least likely to upset conventional oil production, and of greatest interest to researchers at the forefront of seismic monitoring technology.

Reservoir Management and Economics. Kuuskraa and Koperna (2006) proposed the following improvements in CO_2-EOR technology: (1) Increased volume of CO_2 injection, to 1 to 2 hydrocarbon pore volumes, (2) Innovative flood design and well placement, (3) Reduction of mobility ratio by enhancement of water viscosity during

water-alternating-gas recovery, (4) Extension of oil-CO_2 miscibility by addition of gas constituents to CO_2, and (5) Implementation of flood performance diagnostics and improved flood control. Though not all of the features of next generation CO_2-EOR discussed by Kuuskraa and Koperna may be adopted at Citronelle [e.g. drilling horizontal wells, reduction of mobility ratio (because WAG is not currently planned)], and the behavior of Citronelle sands under CO_2 injection is so far known only from the few data available from pilot CO_2 flood conducted in the early 1980's (Kennedy et al., 1983), indications based upon present economic conditions and estimates of EOR performance are that a CO_2-EOR project in Citronelle would be profitable and would add approximately 30 million barrels of oil to economically recoverable U.S. oil reserves.

Acronyms

AAMU	Alabama Agricultural and Mechanical University, Normal, AL
AAPG	American Association of Petroleum Geologists
DOE	U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA
DRI	Denbury Resources Inc., Plano, TX, and Citronelle, AL
EOR	enhanced oil recovery
GSA	Geological Survey of Alabama, Tuscaloosa, AL
HCPV	hydrocarbon pore volume, dimensionless
LBNL	Lawrence Berkeley National Laboratory, Berkeley, CA
MASTER	Miscible Applied Simulation Techniques for Energy Recovery (Zeng, Grigg, and Chang, 2005)
MMP	minimum miscibility pressure
RTD	resistance temperature detector
SO	Southern Company, Birmingham, AL
SP	spontaneous potential
TVTK	Traits-enabled Visualization ToolKit (Enthought, Inc., Austin, TX)
UA	University of Alabama, Tuscaloosa, AL
UAB	University of Alabama at Birmingham, Birmingham, AL
UIC	Underground Injection Control
UNCC	University of North Carolina at Charlotte, Charlotte, NC
WAG	water-alternating-gas method of enhanced oil recovery

References

Advanced Resources International, "Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Onshore Gulf Coast," Report to U.S. DOE, February 2006.

Albright, J. Dangerfield, J., Johnstad, S., Cassell, B., Deflandre, J., and Withers, R., Seismic Surveillance for Monitoring Reservoir Changes, Oilfield Review, Vol. 6, No. 1, January 1994.

Ammer, J. R., and A. C. Brummert, "Miscible Applied Simulation Techniques for Energy Recovery Version 2.0, User's Guide," U.S. Department of Energy, DOE/BC--91/2/SP, February 1991.

Ammer, J. R., A. C. Brummert, and W. N. Sams, "Miscible Applied Simulation Techniques for Energy Recovery Version 2.0, Technical Manual," U.S. Department of Energy, DOE/BC--91/2/SP, February 1991.

Blake, G. R and K. H. Hartge, "Bulk Density," In: *Methods of Soil Analysis*, 2nd ed., A. Klute (Ed.), Part 1, *Agronomy Monographs No. 9*, Madison, WI, 1986, pp. 363-376.

Bouyoucos, G. J., "Directions for Making Mechanical Analysis of Soils by the Hydrometer Method," *Soil Sci. 42* (3) (1936).

Bower, C. A., and L. V. Wilcox, "Soluble Salts," In: C. A. Black (Ed.). *Methods of Soil Analysis*, Soil Science Society of America, 1965, pp. 933-951.

Brookes, P. C., A. Landman, G. Puden, and D. S. Jenkinson, "Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil," *Soil Biol. Biochem. 17* (1985) 837-842.

Brown, L. T., "Integration of rock physics and reservoir simulation for the interpretation of time-lapse seismic data at Weyburn Field, Saskatchewan," M.S. Thesis, T-5627, Colorado School of Mines, Golden, CO, 2002.

Bunge, R., "Midale Reservoir Fracture Characterization Using Integrated Well and Seismic Data, Weyburn Field, Saskatchewan," M.S. Thesis, T-5419, Colorado School of Mines, Golden, CO, 2000.

Cabrera-Garzon, R., "Time Lapse Mulitcomponent Seismic Characterization of the San Andres Reservoir at Central Vacuum Unit, Lea County, New Mexico," Ph.D. Dissertation, T-5495, Colorado School of Mines, Golden, CO, 2001.

Cardona, R., "Fluid substitution theories and multicomponent seismic characterization of fractured reservoirs," Ph.D. Dissertation, T-5678, Colorado School of Mines, Golden, CO, 2002.

Chen, X., and Y. Wang, "Emergent Spatial Pattern of Herpetofauna in Alabama, USA," *Acta Herpetologica 2* (2), 71-xx, 2007, in press.

Day, P. R., "Particle Fractionation and Particle-Size Analysis," In: C. A. Black (Ed.), *Methods of Soil Analysis*, Part I, Soil Science Society of America, 1965.

Duranti, L., "Time-lapse, Multicomponent Seismic Analysis of Reservoir Dynamics," Ph.D. Dissertation, T-5539, Colorado School of Mines, Golden, CO, 2001.

Esposito, R. A., "An Evaluation of the Carbon Dioxide Sequestration Potential of the Citronelle Oil Field (Rodessa Formation) in the South Alabama Gulf coastal Plain," Dissertation research proposal submitted to the Environmental Health Engineering Program, University of Alabama at Birmingham, March 3, 2006.

Fowler, M. L., L. E. Safley, M. A. Young, R. H. Stechmann, E. S. Blair, and R. E. Crumb, "Reservoir Management Strategy for Citronelle Field, Mobile County, Alabama," Report No. NIPER/BDM-0353, Prepared for the National Petroleum Technology Office, U.S. Department of Energy, Tulsa, OK, by BDM Petroleum Technologies, Bartlesville, OK, 1998.
http://www.osti.gov/bridge/servlets/purl/665964-yeNSuQ/webviewable/665964.pdf

Friedmann, S. J., and T. Homer-Dixon, "Out of the Energy Box," *Foreign Affairs*, Vol. 83, No. 6, November/December 2004, pp. 72-83.

Gilchrist, R. E., "Miscibility Study (Repeat 50% P.V. Slug) in Cores, Citronelle Unit, Mobile County, Alabama," Ralph E. Gilchrist, Inc., Houston, TX, November 3, 1981.

Herawati, I., "The use of time-lapse P-wave impedance inversion to monitor a CO_2 flood at Weyburn field, Saskatchewan," M.S. Thesis, T-5663, Colorado School of Mines, Golden, CO, 2002.

Jenkinson, D. S., "The determination of microbial biomass carbon and nitrogen in soil," In: J. R. Wilson (Ed.) *Advances in nitrogen cycling in agricultural ecosystems*, CAB International, Wallingford, 1988, pp. 368-386.

Jenner, E., "Azimuthal anisotropy of 3-D compressional wave seismic data, Weyburn field, Saskatchewan, Canada," Ph.D. Dissertation, T-5544, Colorado School of Mines, Golden, CO, 2001.

Kennedy, J. R., T. G. Bett, and R. E. Gilchrist, "Reservoir Engineering Study of the CO_2 Project in the Citronelle Unit, Mobile County, Alabama," Ralph E. Gilchrist, Inc., Houston, TX, February 18, 1983.

Klute, A., "Water retention: Laboratory methods," In: *Methods of Soil Analysis*, A. Klute (Ed.), 2nd ed., Part 1, *Agronomy Monographs No. 9*, Madison, WI, 1986.

Kovscek, A. R., "Screening Criteria for CO_2 Storage in Oil Reservoirs," *Petroleum Science and Technology 20*, 2002, 841-866.

Kuuskraa, V. A., and G. J. Koperna, "Evaluating the Potential for 'Game Changer' Improvements in Oil Recovery Efficiency from CO_2 Enhanced Oil Recovery," Report prepared for the U.S. Department of Energy, Office of Fossil Energy, Office of Oil and Natural Gas, by Advanced Resources International, Arlington, VA, February 2006.

Lorenzen, R. J. L., "Inversion of Multicomponent Time-lapse Seismic Data for Reservoir Characterization of Vacuum Field, New Mexico," Ph.D. Dissertation, T-5396, Colorado School of Mines, Golden, CO, 2000.

Maxfield, R., and B. Mindak, "EPA method study 27," Method 200.7 (Trace Metals by ICP), EPA-600/S4-85/05, National Technical Information Service, 1985.

Mehlich, A., "Mehlich 3 soil extractant," *Commun. Soil Sci. Plant Anal. 15* (1984) 1409-1416.

Michaud, G., "Time-lapse, Multicomponent Borehole Seismic Monitoring of a Pilot CO_2 Flood," Ph.D. Dissertation, T-5506, Colorado School of Mines, Golden, CO, 2001.

Pashin, J. C., R. E. Carroll, R. H. Groshong, Jr., D. E. Raymond, M. R. McIntyre, and J. W. Payton, "Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane Fairway, Alabama," Final Technical Report, U.S. Department of Energy, National Energy Technology Laboratory, Contract No. DE-FC26-00NT40927, 2004.

Pashin, J. C., J. W. Payton, and M. G. Gates, Geological Survey of Alabama, Carbon Sequestration Research, Southeastern Regional Carbon Sequestration Partnership (SECARB Phase I), http://portal.gsa.state.al.us/CO2/SECARB1/secarb1.htm#Techtrans, 2005.

Pashin, J. C., P. E. Clark, R. E. Carroll, M. R. McIntyre, M. G. Gates, G. J. Koperna, Jr., and M. Bustin, Geological Survey of Alabama, Carbon Sequestration Research, Southeastern Regional Carbon Sequestration Partnership (SECARB Phase II), http://portal.gsa.state.al.us/CO2/SECARB2/secarb2.htm, 2006.

Pruess, K., "ECO2N: A TOUGH2 Fluid Property Module for Mixtures of Water, NaCl, and CO_2," Report No. LBNL-57952, Lawrence Berkeley National Laboratory, Berkeley, CA, August 2005.

Pruess, K., C. Oldenburg, and G. Moridis, "TOUGH2 User's Guide, Version 2.0," Report No. LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, CA, November 1999.

Royer, T., "Time-Lapse P-Wave seismic monitoring of the CO_2 flood at Weyburn Field, Saskatchewan," M.S. Thesis, Colorado School of Mines, Golden, CO, 2004.

Sparling, G. P., C. W. Feltham, J. Reynolds, A. W. West, and P. Singleton, "Estimation of soil microbial C by fumigation extraction method: Use on soils of high organic matter content, and a reassessment of the k_{EC}-factor," *Soil Biol. Biochem. 22* (1990) 301-307.

Stevens, S., V. Kuuskraa, and J. Gale, "Sequestration of CO_2 in Depleted Oil and Gas Fields: Global Capacity, Costs, and Barriers," Advanced Resources International and IEA Greenhouse Gas R&D Programme, 2001.

Vance, E. D., P. C. Brookes, and D. S. Jenkinson, "An extraction method for measuring soil microbial biomass C," *Soil Biol. Biochem. 19* (1987) 703-707.

Zeng, Z., R. B. Grigg, and S. H. Chang, "Miscible Applied Simulation Techniques for Energy Recovery Version 3.0," Modifications of Version 2.0 User's Guide (Ammer and Brummert, 1991) and Technical Manual (Ammer, Brummert, and Sams, 1991), under DOE Contract No. DE-FG26-01BC15364, U.S. Department of Energy, July 26, 2005. http://www.netl.doe.gov/technologies/oil-gas/Software/Software_main.html

Appendix A: Statement of Work, December 20, 2007

Contents:

A.1. Tasks to be Performed
A.2. Project Schedule
A.3. Milestones

A.1. Tasks to be Performed

The original statement of work (February 6, 2007) was modified, in the contract for the second year (present version, December 20, 2007) by adding water injection to the first field test (Task 15) and moving tasks depending directly on the field test (Tasks 16, 17, 18, and 19) from Phase I to Phase II. The field test now begins with water injection during Phase I, followed by CO_2 injection in Phase II. Task 15 is still included in Phase I. The original task numbers were retained, so the tasks in the list below are no longer in numerical order.

Phase I (January 1, 2007 – August 31, 2008):

Task 1. Establish collaboratory environment.
The investigators are located at multiple sites. To facilitate the research work and report preparation, a web-based system will be set up for on-line discussion, exchange of data, distribution of information, and monitoring of project activity. It will be a secure web site to which only the project partners will have access, where all data and documents related to the project will be stored, and where all members of the group can contribute to the preparation and revision of reports and other publications. UA

Task 2. Establish publicly accessible web site for two-way communication with industry.
To facilitate technology transfer and feedback from industry, a website describing the project will be set up through which to disseminate results and receive suggestions and comments from industry and the public. This will be the site where any interested person can learn about the partners, purpose, objectives, and progress of the project. It should be of the highest quality, with respect to both technical content and graphic design. It will be constantly evolving over the life of the project and beyond. UA

Task 3. Application for permit to conduct Field Test No. 1.
A Class II Underground Injection Control (UIC) permit from the State of Alabama will be required for the injection of CO_2 at the site. The application process will be begun at this early stage, so lack of the permit does not result in delays. At this point we intend to list all of the likely candidate wells, then amend the application as the list of potential test wells is narrowed down. SO, UAB, DRI

Task 4. Analysis of rock samples.
Denbury Resources recently discovered drill cores from a previous DOE project that was initiated in the Citronelle Oil Field, but not fully implemented. Denbury is in the process of donating these cores to the Geological Survey of Alabama. The cores comprise eight complete, 800 foot sections through the full Rodessa Formation, from locations throughout the field. Because the cores are continuous, they are an invaluable resource for interpretation of existing well logs and construction of a detailed cross-section of the site. These cores have not been analyzed previously, so this new information will permit an updated review of Citronelle Oil Field geology for CO_2 EOR and sequestration. The cores to be examined first will be those most closely linked to target areas for the field tests. The measurements will include porosities, permeabilities, and microscopic analyses. UAB, GSA, UA

Task 5. Analysis of oil and oil-CO_2 interaction.
Determination of minimum miscibility pressure. Evaluation of propensity for oil components to precipitate in the presence of CO_2. Measurement of viscosity of the oil as functions of temperature and CO_2 pressure. DRI, UA, UAB

Task 6. Construct advanced geologic models of Rodessa reservoirs.
An analysis of the geologic data available at the time was done for DOE by BDM Petroleum Technologies (Fowler et al., 1998) during their evaluation of the Citronelle Field for waterflood optimization. That work is being augmented by Southern Company Geologist Richard Esposito, in connection with a Southern Company/University of Alabama at Birmingham project to be completed at the end of this calendar year. We will incorporate in the model the results of his analysis and information from the updated site stratigraphy provided by the newly available cores mentioned in Task 4, above. Reservoir architecture and heterogeneity will be quantified and visualized using methods (i.e. architectural element analysis and sequence stratigraphy) and technologies (immersive 3D visualization) that were not employed in the earlier work by Fowler et al. This effort will improve the accuracy and level of detail in the geologic model, building upon, but not duplicating past work. GSA, SO, UA, UAB

Task 7. Reservoir simulation.
Examine the available reservoir simulators, such as MASTER 3.0, Eclipse, and TOUGH2, and choose the one best suited for simulation of oil production using CO_2 EOR. Perform simulations throughout Phase I of the project to provide analysis that will assist in selection of the test and monitoring wells (Task 8), development of the reservoir management plan (Task 11), the economic and market analysis (Task 12), and visualization of the flows (Task 13). UA, UAB, GSA

Task 8. Selection of test and monitoring wells.
Based upon analysis of drill cores from the Geological Survey of Alabama collection, production records of the Alabama State Oil and Gas Board, and calculations using the reservoir simulator, choose an injection well and four surrounding wells for testing. All

Task 9. Site characterization by geophysical testing.
Perform seismic measurements to provide more detail in the vicinity of the test wells. UNCC

Task 10. Baseline soil CO_2 fluxes and ecology.
Establish baseline CO_2 concentrations and fluxes from soil and vegetation and the ecology of the field and surrounding landscape, as found. AAMU

Task 11. Reservoir management plan.
On the basis of the available data, develop a preliminary CO_2 injection strategy to ensure efficient oil sweep. UA, GSA, SO, UAB

Task 12. Economic and market analysis.
Verify that production using CO_2 EOR at this site is viable under current and projected economic conditions. Input to the analysis will be obtained from the results of the analysis of miscibility (Task 5), geologic modeling (Task 6), reservoir simulation (Task 7), and development of the reservoir management plan (Task 11). UA, UAB, SO, DRI

DECISION POINT: Based on the results of the economic and market analysis, UAB will re-evaluate the projected economic viability of the project.

Task 13. Visualization of geologic structure and flows.
Display, in the UAB Enabling Technology Laboratory and on the project web site, of the geologic structure in the vicinity of the test wells and the results of the calculations of oil, water, and CO_2 flows using the reservoir simulator. UAB, UA, GSA, SO

Task 14. Preparation of wells for Field Test No. 1.
Preparation of the test wells for CO_2 injection. In addition to updating Citronelle Oil Field and Rodessa Formation geology, the Southern Company Geologist, Richard Esposito, will serve as interface with Denbury regarding the logistics of transport, storage, and injection of CO_2 for the project. This includes provision for onsite storage of CO_2, installation of CO_2-compatible flow lines, the skid for the compressor, refitting the well head, and possible workover of the well. Since Southern Company's objectives are to supply CO_2 for future EOR projects, including identification of sites for CO_2 storage, its involvement in the field operations will facilitate the establishment of mutually beneficial source-sink relationships. DRI, UAB, UA, SO

Task 15. Field Test No. 1.
Five to six months of water flooding into the well chosen as the injector, to provide background production data, to bring the five-spot to a typical water-flooded condition, and to reach the minimum miscibility pressure, followed by injection of 5000 tons of carbon dioxide into the reservoir for measurement of transient behavior (pressure decay following an injection pulse) and flow versus pressure. Monitor adjacent wells for produced oil, water, and gas, including CO_2. All

Task 20. Justification for proceeding to Phase II.
Update economic and market analysis in light of results obtained to date and reevaluate the long-term viability of the project. UAB, UA, SO, DRI

DECISION POINT: Based on the results obtained from Field Test No. 1, UAB will update the economic and market analyses for CO_2 flooding, and re-evaluate the long term viability of the project.

Phase II (September 1, 2008 – April 30, 2010):

Task 16. Geophysical testing for influence of CO_2.
Determine if seismic measurements are able to detect changes in the formation and the presence and migration of CO_2. UNCC

Task 17. Ecological processes dynamics.
Monitor changes in the surrounding landscape during and following injection of carbon dioxide into the oil reservoir. Work under this task monitors any evolution of the types, populations, and spatial distributions of vegetation on the site and surrounding landscape over the course of the project. Even in the likely event that any CO_2 seepage is completely absorbed by soil and water, it might still influence ecological processes in soil biological communities. AAMU

Task 18. Monitor for seepage.
Monitoring of CO_2 and fluorocarbon tracer in shallow boreholes and concentration profiles in soil near the surface to determine whether CO_2 seeps from the formation to the atmosphere. AAMU

Task 19. Analysis of data from Field Test No. 1.
Perform complete analysis and summary of the test data and associated environmental measurements. All

Task 21. Application for permit to conduct Field Test No. 2.
Another Class II Underground Injection Control (UIC) permit from the State of Alabama will be required for the second injection of CO_2 at the site. At this point we again intend to list all of the likely candidate wells, then amend the application as the list of potential test wells is narrowed down. SO, UAB, DRI

Task 22. Effect of nitrogen on oil-CO_2 interaction.
Determination of the sensitivity of the minimum miscibility pressure and viscosity on the nitrogen content of the gas, to establish the degree of separation of flue gas and other process streams required for successful and economic CO_2 EOR and sequestration. UA, UAB, SO

Task 23. Geomechanical stability analysis.
Geomechanical stability study will be conducted, including production-induced stress analysis and reservoir stability analysis through finite element nonlinear static stress analysis (ANSYS) and Distinct Element Analysis (3DEC from Itasca). A stability analysis of the anhydrite dome will be conducted assuming uplift pressure from supercritical CO_2 permeating into the dome via fault or fracture points. UNCC

Task 24. Refine the reservoir simulation.
Based upon the results of Field Test No. 1, refine the physical submodels and parameters describing the geologic structure and flows to improve the accuracy of the simulation of supercritical carbon dioxide behavior in oil-bearing porous rock formations. UA, UAB, GSA

Task 25. Refine the visualization of oil, water, and CO_2 flows.
Improve the visualization and perform a parametric study of oil yield using the reservoir simulator. UAB, UA, GSA

Task 26. Refine the reservoir management plan.
Incorporate the results from Phase I in an updated reservoir management plan. UA, GSA, SO, UAB

Task 27. Selection of test and monitoring wells for Field Test No. 2.
Based upon the results from Phase I, decide whether to conduct Field Test No. 2 using the same wells, or choose another set of five for testing. The first choice would be to choose different wells, but it is possible that the analysis of the data from Field Test No. 1 will indicate that we should conduct other types of tests, or tests under different conditions, on the same wells. All

Task 28. Geophysical testing.
Continue seismic measurements at the site of Field Test No. 1 and perform measurements at the site of Field Test No. 2, if different wells are selected. UNCC

Task 29. CO_2 fluxes and ecology.
Continue to monitor for CO_2 and tracer seepage at the site of Field Test No. 1 and perform baseline measurements at the site of Field Test No. 2, if different. AAMU

Task 30. Preparation for Field Test No. 2.
Preparation of wells for CO_2 injection, including provision for onsite storage of CO_2, installation of CO_2-compatible flow lines, the skid for the compressor, refitting the well head, and possible workover of the well. DRI, UAB, UA, SO

Task 31. Field Test No. 2.
Injection of 5000 tons of carbon dioxide into the reservoir through the test well under conditions identified in the parametric study using the reservoir simulator and established in the revised reservoir management plan. Measurement of transient behavior (pressure decay following an injection pulse) and flow versus pressure. Monitor adjacent wells for produced oil, water, and gas, including CO_2. All

Task 32. Geophysical testing for influence of CO_2.
Seismic measurements to observe the migration of CO_2 and changes in the formation. UNCC

Task 33. Ecological processes dynamics.
Monitor soil respiration and ecology surrounding the test wells during and following injection of carbon dioxide in Field Test No. 2. AAMU

Task 34. Monitor for seepage.
Monitoring of CO_2 and tracer in shallow boreholes and concentration profiles in soil near the surface to detect seepage from the formation to the atmosphere. AAMU

Task 35. Analysis of data from Field Test No. 2.
Perform complete analysis and summary of the test data and associated environmental measurements. All

Task 36. Justification for proceeding to Phase III.
Update the economic, market, and environmental analyses in light of the results obtained to date and reevaluate the long-term viability of the project. UAB, SO, DRI

DECISION POINT: Based on the results obtained from Field Test No. 2, UAB will update the economic and market analyses for CO_2 flooding, and re-evaluate the long term viability of the project.

Phase III (May 1, 2010 – December 31, 2011):

Task 37. Application for permit to conduct Demonstration.
Another Class II Underground Injection Control (UIC) permit from the State of Alabama will be required for the third injection of CO_2 at the site. At this point we again intend to list all of the likely candidate wells, then amend the application as the list of potential test wells is narrowed down. SO, UAB, DRI

Task 38. Monitoring by geophysical testing.
The geophysical tests conducted in Phases I and II will be repeated on a semiannual basis at the sites of the earlier injections, to monitor the migration of CO_2 and the stability of the formation, and to identify possible deviations from initial projections. UNCC

Task 39. Ecosystem dynamics.
Modeling of the behavior of surrounding ecosystems and landscapes associated with CO_2 injection. The Alabama A & M University Investigators, Xiongwen Chen and Ermson Nyakatawa, are specialists in the effects of land use and soil treatments on soil and landscape ecosystems. This task was formulated under the assumption that there is very limited or no CO_2 emission. However, the absence of CO_2 emission does not necessarily imply no impact to the environment. CO_2 may be absorbed by soil, water, and biological communities. This task will use as input the results from Task 17, with supplemental information about streams, bodies of water, and regional processes such as carbon cycling. Using these data, in combination with the underlying mechanisms of ecological processes, the ecosystem and landscape dynamics in subsequent years will be modeled. Cellular automata and ecosystem dynamics models will be used in the first stage, then, depending on impacts, more comprehensive spatially explicit models can be employed. AAMU

Task 40. Presentation of results as dynamic simulations.
Using the reservoir simulation, display the flow of CO_2, oil, and water as functions of reservoir properties and time, the oil yield by CO_2 EOR, and the capacity of the formation for CO_2 sequestration. UAB, UA

Task 41. Refine the reservoir management plan.
Incorporate results of Phase II in an updated reservoir management plan. UA, GSA, SO, UAB

Task 42. Selection of test and monitoring wells.
Based upon the results from Phase II, decide whether to conduct the Demonstration using the same wells, or choose another set of five. All

Task 43. Geophysical testing.
Continue seismic measurements at the sites of Field Test No's 1 and 2 and perform measurements at the site of the Demonstration, if different wells are selected. UNCC

Task 44. Soil fluxes and ecology.
Continue to monitor for seepage at the site of Field Test No's 1 and 2, and perform baseline measurements at the site of the Demonstration, if different. AAMU

Task 45. Demonstration.
Preparation of wells and injection of as much CO_2 as possible (at least 5000 tons) into the reservoir through the test well under the optimum conditions identified in Field Test No's 1 and 2 and in parametric studies using the reservoir simulator. Collection of detailed surface and

downhole data for refinement of the CO_2 EOR simulation. Monitor adjacent wells for produced oil, water, and gas, including CO_2. All

Task 46. Geophysical monitoring of the flood.
Seismic measurements to monitor the progress of the CO_2 flood and changes in the formation. UNCC

Task 47. Ecological processes dynamics.
Continue to monitor ecology at the sites of Field Test No's 1 and 2 and at the site of the Demonstration. AAMU

Task 48. Monitor for seepage.
Continue to monitor CO_2 and tracer at the sites of Field Test No's 1 and 2 and at the site of the Demonstration. AAMU

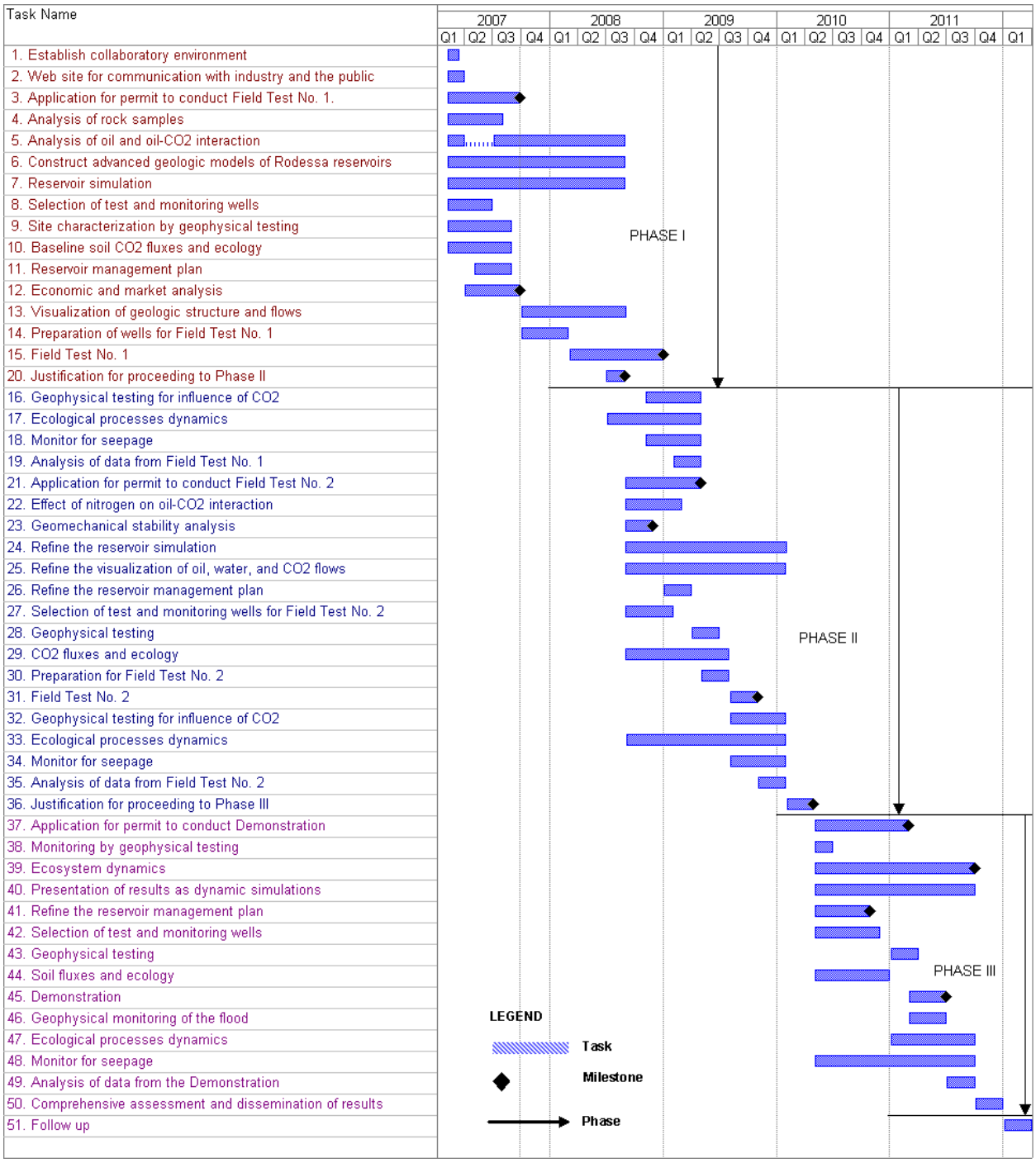
Task 49. Analysis of data from the Demonstration.
Perform complete analysis and presentation of the test data and associated environmental measurements. All

Task 50. Comprehensive assessment and dissemination of results.
Complete analysis of oil recovery, estimates of capacity and integrity of storage, ecological effects, economic and market analysis, and the prospects for separation and sequestration of CO_2 from sources in the region. This will include a topical report on the capability of the Rodessa Formation for storage of CO_2. Dissemination of results via the web site, the final report to DOE, presentations, and publications. All

Task 51. Follow up.
Continue to monitor production, seepage, ecological effects, and progress of negotiations for transition of the Citronelle Oil Field to a CO_2 sequestration site on completion of the wells. Continue to inform industry and DOE of new developments. All

A.2. Project Schedule

The schedule for execution of the tasks is given on the following chart. The project began on January 1, 2007, and its duration is 60 months.



A.3. Milestones

Phase and Critical Path Milestone Description	Task	Planned Dates
Phase I		Jan. 1, 2007 - Aug. 31, 2008
Oil and CO_2 miscibility testing completed	5	Mar. 31, 2007
Economic and market analysis completed	12	Sep. 30, 2007
Permit to conduct Field Test No. 1 issued	3	Sep. 30, 2007
Justification for proceeding to Phase II submitted	20	Aug. 31, 2008
Phase II		Sep. 1, 2008 - Apr. 30, 2010
Geomechanical stability analysis completed	23	Nov. 30, 2008
Field Test No. 1 completed	15	Dec. 31, 2008
Permit to conduct Field Test No. 2 issued	21	Apr. 30, 2009
Field Test No. 2 completed	31	Oct. 31, 2009
Justification for proceeding to Phase III submitted	36	Apr. 30, 2010
Phase III		May 1, 2010 - Dec. 31, 2011
Refinement of the reservoir management plan completed	41	Oct. 31, 2010
Permit to conduct Demonstration issued	37	Feb. 28, 2011
Demonstration completed	45	Jun. 30, 2011
Report on ecosystem and landscape evolution submitted	39	Sep. 30, 2011

Appendix B: Presentations, Publications, and Reports

B.1. Presentations and Workshops

J. C. Pashin and R. A. Esposito, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," Presented at the Annual Convention and Exhibition of the American Association of Petroleum Geologists, Long Beach, CA, April 1-4, 2007.

J. C. Pashin, R. A. Esposito, and P. M. Walsh, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," Poster presentation at the DOE/NETL Sixth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, PA, May 7-10, 2007.

E. S. Carlson, Workshop on visualization for reservoir simulation, Rocky Mountain Mathematics Consortium Summer School, "Flow in Porous Media with Emphasis on Modeling Oil Reservoirs," University of Wyoming, Laramie, WY, June 18-29, 2007.

Wen-Ya Qi, Shen-En Chen, P. M. Walsh, R. A. Esposito, and J. C. Pashin, "Geosensing for CO_2 Sequestration Monitoring in an Oil Field: Possible Global Warming Solution," Presented at the 3rd National Conference on Environmental Science and Technology, North Carolina A&T State University, Greensboro, NC, September 12-14, 2007.

J. C. Pashin and R. A. Esposito, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," Presented at the 2007 Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, Corpus Christi, TX, October 21-23, 2007.

B.2. Publications

R. A. Esposito, J. C. Pashin, and P. M. Walsh, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," *Gulf Coast Association of Geological Societies Transactions*, 2007, *57*, 213-224.

X. Chen and Y. Wang, "Emergent Spatial Pattern of Herpetofauna in Alabama, USA," *Acta Herpetologica 2* (2), 71-xx, 2007, in press.

R. A. Esposito, J. C. Pashin, and P. M. Walsh, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," Accepted for publication in *Environmental Geosciences*, June 2008.

B.3. Reports

P. M. Walsh, E. Z. Nyakatawa, X. Chen, J. Harper, J. C. Pashin, R. A. Esposito, E. S. Carlson, P. E. Clark, G. Cheng, A. M. Shih, K. Theodorou, and S.-E. Chen, "Carbon-Dioxide-Enhanced Oil Production from the Citronelle Oil Field in the Rodessa Formation, South Alabama," Quarterly Progress Report to the U.S. Department of Energy for the period January 1 to March 31, 2007, Contract No. DE-FC26-06NT43029, University of Alabama at Birmingham, Alabama Agricultural and Mechanical University, Denbury Resources, Inc., Geological Survey of Alabama, Southern Company Services, Inc., University of Alabama, and University of North Carolina at Charlotte, April 30, 2007.

P. M. Walsh, E. Z. Nyakatawa, X. Chen, J. Harper, G. N. Dittmar, M. A. Rainer, J. C. Pashin, D. J. Hills, R. A. Esposito, E. S. Carlson, P. E. Clark, K. Theodorou, A. M. Shih, G. Cheng, S.-E. Chen, and W. Qi, "Carbon-Dioxide-Enhanced Oil Production from the Citronelle Oil Field in the Rodessa Formation, South Alabama," Quarterly Progress Report to the U.S. Department of Energy for the period April 1 to June 30, 2007, Contract No. DE-FC26-06NT43029, University of Alabama at Birmingham, Alabama Agricultural and Mechanical University, Denbury Resources, Inc., Geological Survey of Alabama, Southern Company Services, Inc., University of Alabama, and University of North Carolina at Charlotte, July 30, 2007.

P. M. Walsh, E. Z. Nyakatawa, X. Chen, J. Harper, G. N. Dittmar, M. A. Rainer, J. C. Pashin, D. J. Hills, R. A. Esposito, E. S. Carlson, P. E. Clark, K. Theodorou, A. M. Shih, G. Cheng, S.-E. Chen, and W. Qi, "Carbon-Dioxide-Enhanced Oil Production from the Citronelle Oil Field in the Rodessa Formation, South Alabama," Quarterly Progress Report to the U.S. Department of Energy for the period July 1 to September 30, 2007, Contract No. DE-FC26-06NT43029, University of Alabama at Birmingham, Alabama Agricultural and Mechanical University, Denbury Resources, Inc., Geological Survey of Alabama, Southern Company Services, Inc., University of Alabama, and University of North Carolina at Charlotte, October 27, 2007.

Appendix C: Bibliography of Publications on the Citronelle Oil Field and Southwest Alabama Geology

---

Advanced Resources International, "Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Onshore Gulf Coast," Report to U.S. DOE, February 2006.

Alverson, R. M., "Deep Well Disposal Study for Baldwin, Escambia and Mobile Counties," Alabama, Alabama Geological Survey, Circular 58, 1970.

Anonymous, "Engineering Study and Appraisal Report," Vol. I, Tables and Figures. The report is not dated, but the latest data included in it are from 1987. Contains a profitability analysis, projected operating expenses, predicted water flood performance data, an index of cored wells, production data, fluid rates, porosity and permeability data, oil and water saturations, and pilot water flood performance results.

Bolin, D. E., S. D. Mann, D. Burroughs, H. E. Moore, Jr., and T. L., Powers, "Petroleum Atlas of Southwestern Alabama," Alabama Geological Survey, Atlas 23, 1989.

Claypool, G. E., and E. A. Mancini, "Geochemical Relationships of Petroleum in Mesozoic Reservoirs to Carbonate Source Rocks of Jurassic Smackover Formation, Southwestern Alabama," *AAPG Bulletin*, Vol. 73, 1989, pp. 904-924.

Donahoe, R. J., "An Experimental Study of a Waterflood Enhanced Oil Recovery Case History: The Citronelle Field, Mobile County, Alabama," Final Report for 1986/1987 SOMED Project, Department of Geology, University of Alabama, Tuscaloosa, March 1988.

Eaves, E., "Citronelle Oil Field, Mobile County, Alabama," American Association of Petroleum Geologists Memoir 24, 1976, pp. 259-275.
http://egrpttc.geo.ua.edu/reports/citronelle/eaves.html.

Esposito, R. A., J. C. Pashin, and P. M. Walsh, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," *Gulf Coast Association of Geological Societies Transactions*, 2007, *57*, 213-224.

Fowler, M. L., L. E. Safley, M. A. Young, R. H. Stechmann, E. S. Blair, and R. E. Crumb, "Reservoir Management Strategy for Citronelle Field, Mobile County, Alabama," Report No. NIPER/BDM-0353, Prepared for the National Petroleum Technology Office, U.S. Department of Energy, Tulsa, OK, by BDM Petroleum Technologies, Bartlesville, OK, 1998.
http://www.osti.gov/bridge/servlets/purl/665964-yeNSuQ/webviewable/665964.pdf

Fretwell, J. A., and E. S. Blair, "Optimized Hydraulic Pumping System Keeps Deep Water Flood Economical," *World Oil*, November 1999.

Gilchrist, R. E., "Miscibility Study (Repeat 50% P.V. Slug) in Cores, Citronelle Unit, Mobile County, Alabama," Ralph E. Gilchrist, Inc., Houston, TX, November 3, 1981.

Gilchrist, R. E., "Evaluation of Produced Fluids from the Carbon Dioxide Pilot Area in the Citronelle Unit, Mobile County, Alabama," Ralph E. Gilchrist, Inc., Houston, TX, April 16, 1982.

Grubb, H. F., "Summary of Hydrology of the Regional Aquifer Systems, Gulf Coastal Plain, South-Central United States - Regional Aquifer System Analysis - Gulf Coastal Plain," U. S. Geological Survey, Professional Paper 1416-A, 1998.

Holtz, M. H., V. Núñez López, and C. L. Breton, "Moving Permian Basin Technology to the Gulf Coast: the Geologic Distribution of CO_2 EOR Potential in Gulf Coast Reservoirs," in: *Unconventional Reservoirs*, P. H. Luftholm and D. Cox (Eds.), West Texas Geological Society Publication #05-115, Fall Symposium, October 26-27, 2005.

Huddleston, B. P., & Co., Inc., "Northwest Citronelle Unit, Mobile County, Alabama: Production, Maps, Well Data Sheets, Engineering Worksheets," Vol. III, Houston, TX, November 30, 1978.

Kennedy, J. R., T. G. Bett, and R. E. Gilchrist, "Reservoir Engineering Study of the CO_2 Project in the Citronelle Unit, Mobile County, Alabama," Ralph E. Gilchrist, Inc., Houston, TX, February 18, 1983.

Kopaska-Merkel, D. C., "Jurassic Cores from the Mississippi Interior Salt Basin, Alabama," Alabama Geological Survey, Circular 200, 2002.

Kuuskraa, V. A., R. Lynch, and M. Fokin, "Site Selection and Process Identification for CO_2 Capture and Storage Test Centers," Summary Report: Geologic Assessment of CO_2 Storage Options, Four Proposed Southern Company Power Plants, Prepared under Agreement No. E2-P79/C5887 for the Electric Power Research Institute by Advanced Resources International, Arlington, VA, March 26, 2004.

Mancini, E. A., and D. J. Benson, "Regional Stratigraphy of the Upper Jurassic Smackover Carbonates of Southwest Alabama," *GCAGS Transactions*, Vol. 30, 1980, pp. 151-165.

Mancini, E. A., R. M. Mink, B. L. Bearden, and R. P. Wilkerson, "Norphlet Formation (Upper Jurassic) of Southwestern and Offshore Alabama: Environments of Deposition and Petroleum Geology," *AAPG Bulletin*, Vol. 69, 1985, pp. 881-898.

Mancini, E. A., R. M. Mink, J. W. Payton, and B. L. Bearden, "Environments of Deposition and Petroleum Geology of Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, Southwestern Alabama," *AAPG Bulletin*, Vol. 71, 1987, pp. 1128-1142.

Miller, J. A., "Ground Water Atlas of the United States, Segment 6: Alabama, Florida, Georgia, and South Carolina," U. S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-G, 1990.

Raymond, D. E., "The Lower Cretaceous Ferry Lake Anhydrite in Alabama, Including Supplemental Information on the Overlying Mooringsport Formation and the Petroleum Potential of the Lower Cretaceous," Alabama Geological Survey, Circular 183, 1995.

Tucker, W. E., and R. E. Kidd, "Deep-Well Disposal in Alabama," Alabama Geological Survey, Bulletin 104, 1973.

Unit Manager's Report, "341 Tract Citronelle Unit, Citronelle Field, Mobile County, Alabama," Engineering Subcommittee Meeting, Citronelle, AL, August 1, 1997.

Unit Manager's Report, "Reservoir Analyses of Oil Migration: Citronelle Oil Field, Mobile County, Alabama," July 29, 1999.

Wilson, M. D., and J. R. Warne, "Sand Continuity Study: Citronelle Field, Mobile County, Alabama," Report prepared for Unit Manager, Citronelle Unit, November 25, 1964.